

FAR FROM EQUILIBRIUM

FAR FROM EQUILIBRIUM

(Book II of a Trilogy)

by

Phillip L. Engle

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Dedicated to Henri Poincare, Albert Einstein, Ilya Prigogine, Robert F. DeHaan, John A. Davison, Michael Denton, Gordon Rattray Taylor, and all others who have labored to promote the nonlinear paradigm.

Table of Contents

PART 1: ON SYSTEMS 13

Classical Mechanical Systems 17
 Weak and/or Transient Interaction of Parts 20
 Classical Newtonian Methods 24
 Deterministic and Reversible with Respect to Time 27
 Completely Described by the Hamiltonian Function 28
 Teleological Implications of Classical Mechanical Systems 30

Special Relativistic Systems 39
 Some Results of the Special Theory of Relativity 42
 Teleological Implications of Special Relativistic Systems 46

General Relativistic Systems 49
 Historical Background of the General Theory of Relativity 56
 The Einstein Field Equations 58
 Observational & Experimental Confirmation 60
 Cosmology and Einstein's Theory of General Relativity 63
 Teleological Implications of General Relativistic Systems 66

Quantum Mechanical Systems 77
 The Schrodinger Wavefunction Formulation of QM 82
 Summary of the Essential Principles of QM 86
 Epistemological Issues in QM 88
 An Epistemological QM "Thought Experiment" 94
 The Double-Slit "Thought Experiment" 98
 The Einstein-Podolsky-Rosen "Thought Experiment" 100
 The "Many-Worlds" Interpretation of QM 105
 The "Implicate Order" Interpretation of QM 108
 The "Liouville Space Extension" Of QM 109
 Another "Far-From-Equilibrium" Version of QM 110
 Teleological Implications of QM Systems 111

Nonlinear Dynamic Systems 123
 Work and Kinetic Energy 128
 Conservative Forces and Potential Energy 130

<i>The Law of Conservation of Mechanical Energy</i>	<i>132</i>
<i>More on Potential Energy, Work, and Force</i>	<i>135</i>
<i>More on the Hamiltonian Function</i>	<i>136</i>
<i>Irreversible Time T (“Big T”)</i>	<i>139</i>
<i>The Bowl Game</i>	<i>142</i>
<i>The Hill Game</i>	<i>146</i>
<i>The Saddle Game</i>	<i>150</i>
<i>Four Types of Physical Systems</i>	<i>155</i>
<i>Phase Space and Gibbs Ensembles</i>	<i>158</i>
<i>The Oscillating Pendulum</i>	<i>163</i>
<i>The Rotating Pendulum</i>	<i>167</i>
<i>The Three-Body Gravitational System.....</i>	<i>172</i>
<i>The Ideal Gas</i>	<i>183</i>
<i>Once Again, Irreversible Time T</i>	<i>184</i>
<i>Constitutive Characteristics of Conservative Systems</i>	<i>185</i>
<i>Two Unfair Criticisms of Nonlinear Science</i>	<i>186</i>
<i>Teleological Implications of Nonlinear Dynamic Systems</i>	<i>187</i>

Linear Thermodynamic Systems 191

<i>The Block on the Table</i>	<i>195</i>
<i>Some “Laws of Hierarchy”</i>	<i>202</i>
<i>The Ideal, Reversible, Cyclic Heat Engine</i>	<i>204</i>
<i>The Non-Ideal, Irreversible Cyclic Heat Engine</i>	<i>207</i>
<i>Thermodynamic Forces and Flows</i>	<i>211</i>
<i>Boltzmann’s Formula</i>	<i>216</i>
<i>Chemical Thermodynamics</i>	<i>218</i>
<i>Diffusion Thermodynamics</i>	<i>221</i>
<i>Linear Thermodynamic Forces and Flows</i>	<i>223</i>
<i>Non-Equilibrium Linear Thermodynamics</i>	<i>225</i>
<i>Teleological Implications of Linear Thermodynamic Systems</i>	<i>229</i>

Nonlinear Complex Physical Systems 233

<i>The Pitchfork Bifurcation</i>	<i>239</i>
<i>Benard Cells</i>	<i>242</i>
<i>A Chemical Nonlinear Complex Physical System</i>	<i>247</i>
<i>Memory and History in Nonlinear Chemical Systems</i>	<i>252</i>
<i>Cellular Automata</i>	<i>254</i>
<i>Molecular Biological Systems</i>	<i>263</i>

<i>Morphogenesis</i>	276
<i>The Basic Logistic Equation</i>	278
<i>The General Logistic Equation</i>	283
<i>The Anglo-American Bias Against Nonlinear Science</i>	286
<i>Seven Laws of Hierarchy</i>	288
<i>Teleological Implications of Nonlinear Complex Systems</i>	291

PART 2: ON EVOLUTION..... 299

Basic Assumptions	303
Neo-Darwinism	307
Macrodevelopment	315
The Ten Facts of Biological Evolution	327
1. <i>Biological Nonlinearity and Holism</i>	329
2. <i>Irreducible Complexity and Tychism</i>	329
3. <i>Varieties versus Species</i>	332
The Biological Species Concept (BSC)	334
The Typological Species Concept (TSC)	337
Sources of Intra-Species Variation	339
4. <i>Strongly Uneven in Tempo</i>	342
On “Punctuated Equilibrium”	345
On “Species Selection”	347
5. <i>Strict Typological Hierarchy</i>	348
Evidence for Monophyletic Evolutionary Relationships	354
The Neo-Darwinist Explanation	358
The Macrodevelopmental Explanation	368
6. <i>The “Cambrian Explosion”</i>	374
7. <i>Taxonomic Extinction</i>	381
Mass Extinctions	384
Background Extinctions	391
The Neo-Darwinist Explanation	397
The Macrodevelopmental Explanation	403
8. <i>The Genetic Evidence of Evolution</i>	406
Semi-Meiosis	409
Ploidy Change	412
Theoretical Explanations	415
9. <i>Metamorphosis (and Parallel Evolution)</i>	417
10. <i>The “Possible Fact” of Pre-Adaptation</i>	419

Summary of the Evolutionary Evidence	423
Teleological Implications	429
<i>Man's Place in the Biosphere.....</i>	<i>433</i>
<i>Atheism, Theism, and Theodicy.....</i>	<i>434</i>
<i>Ethics and Morality</i>	<i>438</i>
<i>IDT, BWT, and SOT</i>	<i>441</i>
 <u>APPENDIX</u>	 <u>455</u>
On Proportionalism / Consequentialism	457
On Miracles	463
 <u>BIBLIOGRAPHY</u>	 <u>469</u>
 <u>END NOTES.....</u>	 <u>485</u>

***PART 1:* ON SYSTEMS**

This book, *FAR FROM EQUILIBRIUM*, is book II of a trilogy, and its purposes are the following:

- To act as a brief introduction to science (or, a "crash course" in science!) for the general reader in the 21st century.
- To help resolve important issues in the philosophy of science, including epistemological issues and analogical teleological issues.
- To make clear to the general reader both the importance and implications of nonlinearity in 21st century science.
- And, finally, to propose a nonlinear theory of biological evolution to replace the essentially linear neo-Darwinian theory of evolution.

The intended audience of *FAR FROM EQUILIBRIUM* is the general reader, so don't be afraid of the equations contained in some of the chapters in this book! If you've taken high-school calculus, or perhaps even just high-school algebra, you should have no trouble following along if you read the chapters sequentially. Also, you don't have to have read book I of this trilogy, titled *WORLDVIEWS*, in order to understand book II (though book I is a useful prelude to book II, and it discusses teleological, religious, and especially ethical issues in far more detail than is possible in book II). Note also that, while figures are numbered sequentially throughout this entire book, equations (a.k.a. formulas) are numbered only within major chapter headings. (So don't go too far back in looking for intra-chapter references to prior equations!)

Book I, *WORLDVIEWS*, makes the important point that scientific methods *bracket out the subject* in order to arrive at a *universal objective* view of the universe. By contrast teleological / religious methods *bracket out the object* in order to arrive at a *universal subjective* view of the universe. We also saw in book I that both scientific methods and teleological / religious methods are necessary and have their respective competencies, and that neither set of methods can subsume the other. Finally, we tried to make it clear in book I that both the universal objective viewpoint and the universal subjective viewpoint can always be applied to the same phenomena, so that (for example) it is *not* the case that the universal subjective viewpoint must avoid considering phenomena that the universal objective viewpoint has succeeded in "conquering".

The above considerations open the possibility for a *new dialog between science and religion*, based not on a "God of the gaps" approach, whereby religion deals only with whatever science has not already explained, but rather an *integrated* approach in which science and religion jointly consider the *same* phenomena from their respective points of view, and offer what help

they can towards solving each other's problems. Dialog between science and religion based on an integrated approach is possible because of the existence of parallels between the structure of *physical systems* (scientifically considered) on the one hand and the structure of corresponding *teleological systems* (religiously considered) on the other.

For example, one such parallel is that between temporal *points of constrained chance* in the physical system and temporal *points of decision* in the corresponding teleological system. (By speaking of "constrained" chance, I simply mean that the physical system can go in one of *some finite number* of directions, often just one of *two* directions, as opposed to just "anything goes".)

Another such parallel between the physical and the teleological is that between *internal conditional equifinality* in the physical system and *goal-seeking purpose* (Aristotle's *final cause*) in the corresponding teleological system.

In the discussion that follows we will be dealing at various times with various subject-matters (physics, chemistry, astronomy, biology, and so on), but the overall focus will be on the scientific theory of the *systems* underlying those various subject matters. This approach to science is sometimes called *general systems theory*. *General systems theory* is primarily associated with Ludwig von Bertalanffy,¹ but it is also associated (often under different names and with different emphases) with economist Kenneth Boulding, biomathematician A. Rapoport, Erich Jantsch, Ilya Prigogine (winner of the Nobel prize for his work on far-from-equilibrium thermodynamics), and many others.

Most of the chapters in this book (those found in **PART 1: ON SYSTEMS**) will discuss a certain type of physical system, as described by science. At the end of each such chapter an attempt will be made to relate that type of physical system to a corresponding type of teleological system. The second part of this book, **PART 2: ON EVOLUTION** will then use this joint physical / teleological systems approach to deal with the controversial issue of *biological evolution*. Finally, two notes in this book's **APPENDIX** will deal very briefly with the issues of *proportionalism* / *consequentialism* and *miracles*.

By the time you're done reading *FAR FROM EQUILIBRIUM*, I hope you truly feel that you've had an introduction to science for the 21st century!

In my subsequent book III of this trilogy, *HUMAN SOCIETY*, I hope to use the insights from the earlier books I and II to aid in the discussion of the problems of history and human society.

Classical Mechanical Systems

The scientific theory which successfully explains *classical mechanical systems* was established through the work of Galileo and Sir Isaac Newton. Such systems are often called *Newtonian* systems. What are the important characteristics of Newtonian systems and the theory which explains them?

The fundamental postulates of the theory of classical mechanics are Newton's Three Laws of Motion:

1. **Newton's First Law of Motion (the Law of Inertia):** "Every body persists in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed on it." [Newton's *Principia*]
2. **Newton's Second Law of Motion:** Force = Mass times Acceleration, where Force is the vector sum of all of the forces acting upon a body, Mass is the inertial mass of that body (a scalar), and Acceleration is the resultant acceleration of the body as a vector. ("Vectors" specify direction as well as a numerical amount, while "scalars" specify only a numerical amount.)
3. **Newton's Third Law of Motion:** "To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts." [Newton's *Principia*] In other words, when one body exerts a force on a second body, the second body always exerts a force on the first body that is equal in numerical amount, but opposite in direction.

Because classical mechanics is such a vast subject, and because the basics of classical mechanics are taught to almost everyone, I will not discuss the actual *content* of classical mechanics any further, except to note Newton's most famous law deriving from his three laws of motion, namely, the *Law of Universal Gravitation*:

Newton's Law of Universal Gravitation states that: The gravitational force between any two particles having masses m_1 and m_2 separated by a distance r is an attraction acting along the line joining the particles whose magnitude F is given by the following formula: $F = G (m_1 m_2 / r^2)$, where G is a universal constant having the same value for all pairs of particles.²

A more-detailed picture of the actual *subject-matter* of classical linear Newtonian dynamics will be presented as part of our later chapter on **Nonlinear Dynamic Systems**. The remainder of *this* chapter will instead focus on classical Newtonian mechanics from the point-of-view of general

ON SYSTEMS

systems theory, and only indirectly will it deal with the actual content of classical mechanics.

Weak and/or Transient Interaction of Parts

Classical mechanical systems consist of parts that interact weakly and/or transiently, rather than strongly and persistently.

For example, the gravitational attraction between two billiard balls is *persistent* but *weak*, while an elastic collision between these same two billiard balls is *strong* but *transient*. Both of these types of interactions between the billiard balls can be incorporated easily within the framework of classical Newtonian mechanics. However, the gravitational attraction between two stars orbiting around each other as a binary star is *strong* and *persistent*. Similarly, the magnetic attraction between a bar magnet and a piece of metal is likewise *strong* and *persistent*. Such *strong* and *persistent* interactions between the parts of a system can create serious difficulties for Newtonian mechanics when *three or more* parts of the system *strongly* and *persistently* interact.

Because classical mechanical systems consist of parts that *interact weakly and/or transiently*, both the behavior and important physical characteristics of these parts tend to be the same in isolation as when they are incorporated into a larger whole. A further consequence of this weak or transient interaction of parts is that classical mechanical scientific laws are the same (or very similar) for both parts and wholes. Finally, because of the weakness or transience of the inter-part interactions, what Ludwig von Bertalanffy calls *summative* characteristics strongly predominate over *constitutive* characteristics in classical mechanical systems, so that it can truly be said of these systems that *the whole is merely the sum of its parts*:

[S]ummative characteristics . . . are those which are the same within and outside the complex; they may therefore be obtained by means of summation of characteristics and behavior of elements as known in isolation. Constitutive characteristics are those which are dependent on the specific relations within the complex; for understanding such characteristics we therefore must know not only the parts, but also the relations.

Physical characteristics of the first type are, for example, weight or molecular weight (sum of weights or atomic weights respectively), . . . An example of the second kind are chemical characteristics (e.g., isomerism, different characteristics of compounds with the same gross composition but different arrangement of radicals in the molecule).

The meaning of the somewhat mystical expression, "The whole is more than the sum of parts" is simply that constitutive characteristics are not explainable from the characteristics of isolated parts. The characteristics

of the complex, therefore, compared to those of the elements, appear as “new” or “emergent”. . . While we can conceive of a sum as being composed gradually, a system as total of parts with its interrelations has to be conceived of as being composed instantly.³

Two important points need to be made here: The first is that concepts such as “constitutive characteristics”, “emergent properties”, “irreducible complexity”, and “the whole is more than the sum of its parts”, though they have often been put forward as part of attempts to smuggle teleology and subjectivity back into scientific methodology (via theories of “vitalism”, “intelligent design”, and the like), in fact need not entail any particular teleology whatsoever. Rather, such concepts have a perfectly objective meaning. As Bertalanffy puts it:

We must strongly emphasize that order or organization of a whole or system, transcending its parts when these are considered in isolation, is nothing metaphysical, not an anthropomorphic superstition or philosophical speculation; it is a fact of observation encountered whenever we look at a living organism, a social group, or even an atom.⁴

Consider Figure 1, below, taken from Bertalanffy⁵, which schematically depicts the differences between three sets of systems: The difference between system **1a** and system **1b** lies simply in the difference in the *number of elements*, while the difference between system **2a** and system **2b** consists in the fact that the second system (**2b**) contains different *types* (or *species*) of elements, while the first system (**2a**) does not. The differences between all four of these systems (**1a**, **1b**, **2a**, and **2b**) arise solely because of *summative characteristics* of these systems.

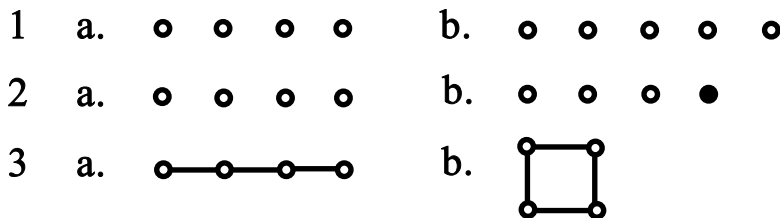


Figure 1 (after Bertalanffy, *General Systems Theory*, p. 54)

But now consider the third set of systems, **3a** and **3b**. In these two systems *strong, persistent interactions* between the elements (which arise from *strong* attractive forces that are *persistent* in duration) are represented by lines joining the elements together. As a result of these *strong, persistent interactions*, the elements in system **3a** arrange themselves in the form of a line, while in system **3b** they arrange themselves in the form of a square. The key point here is that the global “linearity” of system **3a** and the global

ON SYSTEMS

“squareness” of system **3b** are *constitutive characteristics* (i.e., *emergent properties*) of those systems. The *constitutive characteristics* of systems cannot be “reduced” to the properties of their individual elements, *even if the strong, persistent interactions between those elements are themselves treated as additional individual elements*. This is actually a rather simple objective fact that does not depend in any way on teleological presuppositions, such as vitalism or intelligent design.

Of course, by creating an elaborate description of the parts and their relationships (for example, “Draw a small circle, draw a line extending from it, draw another small circle, make a sharp right turn and draw another line . . .” etc.) you can *almost* become convinced that you’ve “explained” any given holistic *constitutive characteristic* in terms of its parts, but in the end this “explanation” is always unconvincing.

The second important point that needs to be reinforced is that *summative* characteristics strongly predominate over *constitutive* characteristics in classical Newtonian mechanical systems precisely because of the *weak or transient interaction* between the parts of those systems. Indeed, the Enlightenment founders of classical physics (i.e., classical mechanics) were strongly predisposed to emphasize *summative* over *constitutive* system characteristics as being of the very essence of their scientific methodology. Again, Bertalanffy:

The second maxim of Descartes’ *Discours de la Methode* was “to break down every problem into as many separate, simple elements as might be possible”. This, similarly formulated by Galileo as the “resolutive” method, was the conceptual “paradigm” of [modern] science from its foundation: that is, to resolve and reduce complex phenomena into elementary parts and processes.⁶

Indeed, it was Aristotle who had said that “the whole is more than the sum of its parts”, and the decisive *rejection* of Aristotle’s point-of-view was a large part of what the modern “scientific revolution” was all about.

But are the interactions between the parts of classical mechanical systems really all that weak or transient?

Fairly evident is the transience of interaction between the parts of classically considered particle systems (systems of colliding billiard balls, randomly colliding molecules in a gas, etc.). But what about simple mechanical machines, such as levers, pulleys, springs, and Rube Goldberg combinations thereof (“Push lever A, which disengages spring B” etc.)? Such machines may seem to have a strong, even purposeful, interaction between their parts, but only when considered as an extension of a far-more complex system, such as a human designer or user. If we consider the machine in isolation from its

human designer or user, we see that its parts are indeed weakly or transiently interacting, merely transmitting in a predetermined way a force that has been applied from outside the machine.

A “borderline case” here is that of a machine which has been designed to flexibly respond to its environment via complex sensors and computer-controlled feedback mechanisms. Such robotic machines have been used to climb down the sides of volcanoes and to explore the Moon and Mars. But even in this borderline case the responsiveness of these robots has been significantly constrained (sometimes with disastrous results) by the limits of what their human designers could anticipate in advance. By contrast, living systems, as we shall see later, are in general much more complex, responsive, and adaptive than robotic machines. And to the extent that robots and computers *do* succeed in displaying the responsive behavior of living systems, they are no longer classical mechanical systems.

But (it may be objected) what about Newton’s famous *law of gravitation*? Doesn’t gravitational force provide for *strong, persistent interactions* between bodies of sufficiently large mass? Doesn’t this disprove the proposition that all classical mechanical systems have *weakly or transiently interacting* parts?

There are several answers to this objection. The first is that gravity is, in fact, a very weak physical force within Newtonian physics. The second answer is that Newton’s theory of gravity was most successful in explaining the earth’s attraction of objects near its surface and the sun’s attraction of the planets and comets. In both of these cases a *single element* within the system is so massive relative to the other system elements that gravitation can be regarded, practically speaking, as a property of that single massive element alone, rather than as a strong, persistent interrelation *between* elements within the system. In other words, the gravitational attraction between objects near the earth’s surface is negligible, as is the gravitational attraction between the planets and comets.

The third answer to this objection is that Newton’s law of gravitation can only be successfully applied where *one* or *two* bodies of significant mass are involved. For nearly 200 years countless fruitless attempts were made to extend Newton’s theory so that it could describe the gravitational attraction between *three* bodies of significant mass (or even between *two* bodies of significant mass and *one* body of *insignificant* mass). This is the famous *three-body problem*. Finally, at the end of the nineteenth century, Bruns and Poincare proved that the three-body problem *cannot be solved* by classical Newtonian methods.⁷ Instead, Poincare showed that the three-body gravitational system is a *nonlinear chaotic system*. (A *nonlinear chaotic*

ON SYSTEMS

system, unlike a Newtonian classical mechanical system, is extremely sensitive both to initial conditions and to subsequent perturbations of the system. We will discuss nonlinear chaotic systems in detail in our later chapters on **Nonlinear Dynamic Systems** and **Nonlinear Complex Physical Systems**.)

Although it was not realized at the time, this surprising inability of Newton's theory of classical mechanics to solve the three-body problem decisively marked the end of the grand dream to explain all of the systems of nature in terms of classical deterministic physics: The scientific picture of the universe as a vast clock-like machine had to be abandoned (though it lives on in the ideology and philosophy of many scientists).

Classical Newtonian Methods

But what are these “classical Newtonian methods” that have proved so useful in explaining some physical systems, but not others?

*Scientific laws for classical mechanical systems can be formulated through the methods of the calculus of variations (invented by Newton and Leibniz) by using **differential equations** which are integrable (i.e., solvable), linear, and (usually) homogeneous.*

A **differential equation** with respect to *time* expresses the instantaneous rate of change in a certain measurable quantity, which we'll call q , with respect to a measure of time, which we'll call t . As one important example, the instantaneous rate of change in the *position* q of a particle with respect to time t is its instantaneous *velocity*, expressed by the *first derivative*, dq/dt . The rate of change in this instantaneous velocity, in turn, is the instantaneous *acceleration* (constant in the simplest case), which is expressible as either the *first derivative* of the velocity, dv/dt , where v is velocity and t is time, or as the *second derivative* of the position, d^2q/dt^2 .

A differential equation is said to be *first-order* if the highest derivative of the quantity q in the equation is its first derivative, while a differential equation is said to be *second-order* if the highest derivative of the quantity q in the equation is its second derivative.

A first-order differential equation is said to be **integrable** (i.e., **solvable**) if it can be solved in such a way as to yield an equation that expresses the value of q as a function of t , plus-or-minus an arbitrary constant C . (For example, the differential equation $dq/dt=2t$ can be easily integrated in accordance with the rules of elementary calculus to produce the equation $q=t^2+C$.)

Furthermore, the arbitrary constant C can be made to meaningfully represent

the initial state of the system, such as the initial value of q , which we might call q_0 .

A differential equation is defined to be **linear** and **homogeneous** if and only if it exactly satisfies the **superposition principle**. (Non-homogeneous linear differential equations satisfy the superposition principle *approximately*.) And a differential equation is said to satisfy the **superposition principle** if and only if the sum of every pair of solutions yields another solution, and a constant multiple of every solution yields another solution. In other words, a differential equation is said to satisfy the superposition principle if its set of solutions is closed under addition and constant multiplication.

An example of a homogeneous linear differential equation is $dq/dt = 3tq$. For, suppose the functions $Q_1(t)$ and $Q_2(t)$ are both solutions to this differential equation. Then they both satisfy the differential equation, and so $dQ_1/dt = 3tQ_1$ and $dQ_2/dt = 3tQ_2$. Adding these two equations together, we obtain

$$dQ_1/dt + dQ_2/dt = 3tQ_1 + 3tQ_2$$

and, therefore

$$d(Q_1 + Q_2)/dt = 3t(Q_1 + Q_2)$$

so that $(Q_1 + Q_2)$ also satisfies the differential equation and thus must also be a solution. Thus, the sum of every pair of solutions is also a solution. Similarly, if c is any constant, we may multiply it into $dQ_1/dt = 3tQ_1$ to obtain

$$c(dQ_1/dt) = c(3tQ_1)$$

and, therefore

$$d(cQ_1)/dt = 3t(cQ_1)$$

And so cQ_1 is also a solution, so that a constant multiple of every solution is also a solution.⁸

The fact that any classical mechanical system can be described by a set of *linear* differential equations that obey the *superposition principle* is intimately connected with that fact that the parts of a classical mechanical system are *weakly and/or transiently interacting* (or are *non-interacting*). Suppose, for example, that q_1 is a measure of q for one part of the system, while q_2 is a measure of q for another part of the system. Suppose further that the rate of change in each of these variables at any moment in time is dq_1/dt and dq_2/dt respectively. If two equations that express the value of these two derivatives as a function of time are part of a system of homogeneous *linear* differential equations, then the integral that solves for the quantity $(q_1 + q_2)$ *jointly* as a function of time is simply the sum of the integrals that solve for q_1

ON SYSTEMS

and q_2 separately as a function of time. This is a reflection of the fact that the parts of a classical mechanical system are *weakly and/or transiently interacting* (or are *non-interacting*), so that the total value of q for the *entire* system is always, at every moment in time, simply the arithmetic sum of the q -values for all of the *parts* of the system ($q = q_1 + q_2 + q_3 \dots + q_n$). In other words, total q is a *summative* characteristic of the system, not a *constitutive* characteristic. By contrast, systems of *nonlinear* differential equations, because they represent physical systems characterized by a *strong, persistent interaction* between their parts, do *not* obey the superposition principle, and their corresponding physical systems *do* consequently have important *constitutive* characteristics (i.e., “emergent properties”) that are not merely summative.

If the function contains only one non-time variable, e.g. q , then the most general form for a *homogeneous* linear differential equation is $dq/dt = f(t)q$. By contrast, *nonhomogeneous* linear differential equations (sometimes called *driven* linear differential equations) have the general form $dq/dt = f(t)q + g(t)$ and are also called *linear*, because they *almost* satisfy the superposition principle. In these two equations $f(t)$ and $g(t)$ are any arbitrary continuous functions of t . They may also be constants. It is also permissible for q to be absent from the right side of these equations, so that dq/dt is a function of t only. The laws of classical mechanics are *always* linear and are *usually* homogeneous (i.e., they usually satisfy the superposition principle *exactly*).

Notice, from the equations in the previous paragraph, that a *linear* differential equation *cannot* contain any power of q or dq/dt higher than 1 and, moreover, *cannot* contain any other composed function of q or dq/dt . In other words, if (for example) q^2 , q^3 , q^4 , $\sin(q)$, e^q , or $(dq/dt)^2$ were to appear in the differential equation, then that differential equation would *not* be linear. Among other things, this means that $dq/dt=f(t)$ is *always* linear, while both $dq/dt=f(q)$ and $dq/dt=f(q,t)$ are *not generally* linear. In other words, if the rate of change in q is *recursively dependent on q itself*, then the resulting differential equation is *not generally* linear. (That is one reason why chemical systems that involve autocatalysis and biological systems that involve reproduction are *not* classical mechanical systems.)

An example of a set of classical *linear* differential equations are those governing the electric field. That is why, in calculating the electric field produced by two point charges, one need only calculate the electric field due to the first charge, then calculate the electric field due to the second charge, and (finally) just add them up: There is no “interaction term” between the two point charges which needs to be factored in.

By contrast, whenever *strong, persistent interactions* occur between the parts of a system, terms that have to do with those interactions always have at least a squared (or higher degree) factor. This is because one is multiplying a term corresponding to the first part of the system with a term corresponding to the second part of the system (and so on, if more than two strongly, persistently interacting parts are involved). Such differential equations which include interaction terms are therefore *nonlinear* and do *not* obey the superposition principle.⁹ In general, *nonlinear* differential equations are far more difficult to solve than are *linear* differential equations, and *systems* of *nonlinear* differential equations are *impossible* to solve unless limiting “special case” assumptions are made for purposes of numerical computer simulation.¹⁰

Deterministic and Reversible with Respect to Time

*Scientific laws for classical mechanical systems are **deterministic and reversible with respect to time.***

In a classical mechanical system, the only *important* point in time that is characterized by *constrained chance* is the point in time of the (arbitrary) *initial conditions*. This point in time defining the initial conditions is generally thought of as occurring at the *temporal starting point* of the system, but it can be chosen to be *any* point during the “history” of the system. Whatever point in time is chosen, the complete state of the classical mechanical system can be calculated for *every* other point in time by simply calculating either forwards or backwards from the initial conditions.

The only other moments of *constrained chance* in a classical mechanical system are those moments when a trajectory may become (briefly) intrinsically indeterminate. For example, if a ball is carefully placed on the very top of a smooth hill, which way it rolls down the hill will depend on *infinitesimal forces*, and its exact future trajectory is therefore uncertain. Also, depending on minute differences in the force applied, a forced pendulum may either *oscillate* or *swing around* its point of suspension.¹¹ But such brief moments of indeterminate trajectory were regarded as unimportant “blemishes” on an otherwise perfect deterministic model.

Most remarkable is the fact that time has no preferred direction in classical mechanical systems, because its laws are completely *time-reversible*. As Ilya Prigogine and Isabelle Stengers have written in their book *Order Out of Chaos*:

[R]eversibility may be taken to be the very symbol of the “strangeness” of the world described by [classical] dynamics. Everyone is familiar with the absurd effects produced by projecting a film backward – the sight of a match being regenerated by its flame, broken ink pots that reassemble

ON SYSTEMS

and return to a tabletop after the ink has poured back into them, branches that grow young again and turn into fresh shoots. In the world of classical dynamics, such events are considered to be just as likely as the normal ones.

We are so accustomed to the laws of classical dynamics that are taught us early in school that we often fail to sense the boldness of the assumptions on which they are based. A world in which all trajectories are reversible is a strange world indeed.¹²

Completely Described by the Hamiltonian Function

Classical mechanical systems can be described completely by the Hamiltonian function.

The following brief discussion of the properties of this Hamiltonian function will both summarize and shed further light on what we have so-far said about classical mechanical systems. Again, Prigogine and Stengers:

[The Hamiltonian] function is simply the total energy, the sum of the system's potential and kinetic energy. However, this energy is no longer expressed in terms of positions and velocities, conventionally denoted by q and dq/dt , but in terms of so-called *canonical* variables – coordinates and momenta – for which the standard notation is q and p . In simple cases, such as with a free particle, there is a straightforward relation between velocity and momentum ($p = m dq/dt$), but in general the relation is more complicated.

[This] single function, the Hamiltonian, $H(p,q)$, describes the dynamics of a system *completely*. All our empirical knowledge is put into the form of H . Once this function is known, we may solve, at least in principle, all possible problems. For example, the time variation of the coordinates and of the momenta is simply given by the derivatives [i.e., the rate of change] of H in respect to p or q [respectively]. . . The equations which, through the derivatives of the Hamiltonian, give the time variation of the coordinates and momenta are the so-called canonical equations. They contain the general properties of all dynamic changes. Here we have the triumph of the mathematization of nature. All dynamic change to which classical dynamics applies can be reduced to these simple mathematical equations.¹³

(We will discuss the Hamiltonian function in more detail in our subsequent chapter on **Nonlinear Dynamic Systems**.)

The *time-reversibility* of classical mechanical laws is made manifest by the Hamiltonian function because “[t]he canonical equations are *reversible*: time inversion is mathematically the equivalent of velocity inversion.”¹⁴

Similarly, the earlier-discussed limitation of the applicability of classical mechanical laws to systems where the parts *interact weakly and/or transiently* is likewise further explained by the Hamiltonian function because,

by a suitable selection of the pair of canonical variables q and p , we can usually obtain a description of any classical mechanical system such that the parts of that system *do not interact at all*:

[T]here exist many points of view or “representations” in which the Hamiltonian form of the equations of motion is maintained. They correspond to various choices of coordinates and momenta. One of the basic problems of [classical] dynamics is to examine precisely how we can select the pair of canonical variables q and p to obtain as simple a description of dynamics as possible. For example, we could look for canonical variables by which the Hamiltonian is reduced to kinetic energy and depends only on the momenta (and not on the coordinates). What is remarkable is that in this case momenta become constants of motion. Indeed, as we have seen, the time variation of the momenta depends, according to the canonical equation, on the derivative of the Hamiltonian in respect to the coordinates. When this derivative vanishes, the momenta indeed become constants of motion. This is similar to what happens in a “free particle” system. What we have done when we go to a free particle system is “eliminate” the interaction through a change of representation. [Such a] system may thus be represented as a set of units, *each changing in isolation, quite independently of all the others*, in that eternal and immutable motion Aristotle attributed to the heavenly bodies.¹⁵ [*italics mine*]

Where such a representation can be found, the Hamiltonian function also illuminates the *deterministic* character of classical mechanical systems:

We have already noted that in [classical] dynamics “everything is given”. Here this means that, from the very first instant, the value of the various invariants of motion is fixed; nothing may “happen” or “take place”. Here we reach one of those dramatic moments in the history of science when the description of nature was nearly reduced to a static picture. Indeed, through a clever change of variables, all interaction could be made to disappear. . . Generations of physicists and mathematicians tried hard to find for each kind of systems the “right” variables that would eliminate the interactions.¹⁶

As a grand design for all of science, this project failed when Poincare proved that the three-body problem was unsolvable by classical mechanics.

But Jules-Henri Poincare did much more than just show the unsolvability of the three-body problem. He also demonstrated that *most* dynamic systems are unsolvable (i.e., nonintegrable) and are therefore *not* classical mechanical systems! Furthermore, he showed *why* this is so. He did this by proving that for *most* dynamic systems it is *impossible* to find a Hamiltonian representation such that *all* of the energy in the system is kinetic energy and *none* of the energy in the system is potential energy. (Potential energy is energy that is dependent on the co-ordinates q .) Furthermore, he showed that this potential energy that *cannot* be eliminated from these dynamical systems is the result of *strong, persistent interaction* between the parts of the system.

ON SYSTEMS

And, finally, Poincare proved that, because all potential energy *cannot* be eliminated from these dynamical systems, *resonances* (now called *Poincare resonances*) arise within these dynamic systems which cause the trajectories of their parts to diverge from *any possible* pre-computed path! That's why the dynamic equations for *most* mechanical systems are *nonlinear*, *nonintegrable*, and therefore are *not solvable*. For a long time, however, the vital importance of Poincare's findings were overlooked, so unwilling were scientists to depart from the Newtonian ideal.¹⁷ (See our later chapter on **Nonlinear Dynamic Systems** for both a further discussion of Poincare's findings and a much-more detailed treatment of the actual *subject-matter* of dynamics.)

Teleological Implications of Classical Mechanical Systems

Today we know that classical mechanical systems constitute only a small percentage of the physical systems in the universe that are within our experience. Moreover, we also have seen that a classical mechanical system has only one *important* point in time of *constrained chance*, namely, the point in time of the *initial conditions* (though a few brief points in time also exist where, say, a ball or pendulum has an *uncertain trajectory*). Since points of *constrained chance* in physical systems are the analogs of *decision points* in teleological systems, it is evident that any teleological system which is analogous to a classical mechanical system will be radically impoverished, extremely limited in its application, and (therefore, one would think) not of much interest.

However, for historical reasons such teleological systems *are*, in fact, of much interest. The reason is that, from the time that Newton's *Principia* was presented to the Royal Society of London in 1686 through the end of the 19th century, when Henri Poincare proved the insolvability of the three-body problem, it was thought by scientists and intelligent lay people alike that *all* physical systems are, at bottom, classical mechanical systems, and that it was only a matter of time before all of astronomy, chemistry, thermodynamics, biology, psychology, and sociology would be "reduced" to classical mechanics.

Because it was erroneously thought that both human society and the universe as a whole are classical mechanical systems, correspondingly erroneous teleological theories of theology, ethics, and government became both prevalent and highly influential, *and they remain influential to this day!*

Newton himself was lionized during his own lifetime, and the vision of the entire universe as a clock-like classical mechanical system powerfully took hold in the imaginations of the intelligentsia in all fields of intellectual

endeavor. Alexander Pope proposed the following epitaph for Sir Isaac Newton, who died in 1727:

Nature and Nature's laws lay hid in night:
God said, let Newton be! and all was light.¹⁸

And, in 1728, J.T. Desaguliers wrote the following about Newton in a poem entitled, "The Newtonian System of the World, the Best Model of Government: an Allegorical Poem":

Nature compelled, his piercing Mind obeys,
And gladly shows him all her secret Ways;
'Gainst Mathematicks she has no Defence,
And yields t'experimental Consequence.¹⁹

There were a few dissenting voices. In 1802 the poet and artist William Blake wrote to Thomas Butts:

. . . May God us keep
From single Vision and Newton's sleep!²⁰

But until the twentieth century such voices "crying in the wilderness" were few and far between.

Historically, the most important teleological theory that tried to correspond to classical mechanical theory was the *social contract* theory. (We have discussed this theory in Book I, *WORLDVIEWS*, and we will deal with it in far more detail in Book III, *HUMAN SOCIETY*.)

The strong analogies between social contract theory and classical Newtonian mechanics are clear: Just as a classical mechanical system consists of *independent, weakly (and/or transiently) interacting parts*, so the social contract theory viewed society as consisting of *radically autonomous human individuals* whose freedom was limited only by contracts that they themselves explicitly made. And, just as a classical mechanical system had no significant *constitutive* properties, but only *summative* properties added up from its individual component parts, so human society as envisioned by the social contract theory likewise had no *teleologically constitutive* properties (such as *group subjectivity*), but rather only *summative* properties added up from the human individuals who composed it. Furthermore, just as a classical mechanical system is essentially a linear, near-equilibrium *machine*, so (in social contract theory) society is essentially a *machine* to serve the needs of the radically autonomous human individuals who comprise it.

Finally, just as the only *important* moment of *constrained chance* in a classical mechanical system is the moment for which its *initial conditions* are defined (usually, at the temporal startup of the system), so the only important *decisive moment* for society in social-contract theory is that moment when *the*

ON SYSTEMS

original social contract was made between radically autonomous individual human beings living completely free in “the state of nature”. Surprisingly, many Enlightenment social-contract thinkers actually viewed this original social contract, made in the state of nature at the very beginning of the formation of human society, to be not just a useful abstraction, but an *actual historical fact* – in a sense the *only* historical fact of any real importance for social and ethical theory.²¹

In all of this, it can easily be seen that the Enlightenment social-contract thinkers were trying to create, in the social-contract theory, a close teleological analog to “the latest findings of modern science”, namely, classical Newtonian mechanics.

Alasdair MacIntyre, in his famous book *After Virtue*, decisively exposed the failure of the Enlightenment thinkers to successfully ground ethics on the basis of the supposedly radically-autonomous human individual.²² (We extensively discussed *After Virtue* in Book I, *WORLDVIEWS*, and our critique specifically of social-contract theory will also continue in Book III, *HUMAN SOCIETY*.)

But here we need to point out one additional serious problem with social-contract theory as a teleological analog of classical mechanics: If all physical systems are, at bottom, classical mechanical systems (as the Enlightenment thinkers believed), then the *parts* of a classical mechanical system must *themselves* be classical mechanical systems. After all, at the heart of the excitement over Newton’s *Principia* was Book III, which included Newton’s *universal* law of gravitation. Newton titled Book III *The System of the World*, and in it he demonstrated that the *same* gravitational law which explained the motion of planets around the sun also explained the motion of falling bodies near the earth.²³

Analogically, then, if society is a deterministic, machine-like classical mechanical system (from the physical point-of-view), then its parts, individual human beings, should also be deterministic, machine-like classical mechanical systems (from the physical point-of-view). Yet social contract theory required that human individuals be viewed as *radically autonomous*, not only in the sense of their *independence* and *weak and/or transient interaction*, but also in the sense of being able to *decide freely*. Individual human beings (whether conceived of as *radically* autonomous or not) frequently *make decisions*. Corresponding to these many *decisions* in the *teleological* theory of human individuals, one would expect to see many moments of macroscopic *constrained chance* in the *physical* theory of individual human beings. But if individual human beings are ultimately deterministic, machine-like classical mechanical systems, then, on the

contrary, one would expect to see few (or no) moments of constrained chance in their behavior (except for the one at the moment of their creation).

Enlightenment thinkers themselves recognized this as a serious problem, which led to many arguments over *free-will vs. determinism*. These arguments were interminable and irresolvable, so long as the proposition that all physical systems are ultimately classical mechanical systems remained unchallenged. (In this respect of course, the belief that all physical systems are classical mechanical systems indirectly undermined *all* teleological systems of any significance, not just the social-contract theory.)

Social-contract theory is not the only interesting teleological analog to classical mechanics. A very interesting *theological* analog to classical mechanics is *deism*, which *Webster's New World Dictionary* defines to be:

belief in the existence of a God on purely rational grounds without reliance on revelation or authority; esp., the 17th- and 18th- cent. doctrine that God created the world and its natural laws, but takes no further part in its functioning.²⁴

Many Enlightenment thinkers, including many of the American founding fathers, were deists.

If the entire universe is regarded to be a giant clock-like classical mechanical system, composed of other clock-like classical mechanical systems, then it is easy to see how deism is teleologically analogous to classical mechanics. For, then, the only moment of truly *significant* constrained chance in the “history” of the entire physical universe would be the moment of the *initial conditions*, which could be identified with the moment of the *universe's creation*. Since moments of *constrained chance* in physical systems are analogous to moments of *decision* in teleological systems, the only moment that God could decisively act in any teleologically significant way within the universe's “history” would then be at the moment of the universe's creation. At that point, God could both set the universe's *initial conditions* and create the *natural laws* according to which it would subsequently function. Thereafter, however, there would be no significant moments of constrained chance which could possibly correspond to a decisive action of God, for everything that happened subsequent to the moment of the universe's creation would be deterministically fixed in accordance with the classical-mechanical natural laws.

Of course, there would still be a few moments of *insignificant* constrained chance within a purely classical mechanical universe – moments where a part might briefly have an *indeterminate trajectory*. And so God *could* sometimes act within the subsequent “history” of such a universe by occasionally giving a divine nudge to a ball balanced precariously on the top of a hill, or to a

ON SYSTEMS

forced pendulum uncertain whether to rotate or to oscillate. But this would hardly seem to be a worthwhile occupation for God Almighty! So, given the assumption that all physical systems are classical mechanical systems, deism was an eminently “reasonable” theology. However, the subsequent disproof of this assumption via later scientific discoveries had the indirect effect of undermining deism.

One final rather whimsical teleological being needs to be mentioned. Although the great mathematical physicist Laplace had no place for the “hypothesis” of God within the world system (“Je n’ai pas besoin de cette hypothèse”, he replied to Napoleon²⁵), Laplace did speculate about the possibility of a demon (“Laplace’s demon”) who would know the positions and velocities of every mass in the universe for some particular instant in time, from which point in time that demon could then perfectly calculate (both backwards and forwards) positions and velocities for all masses for every other instant of time in the “history” of the physical universe. Prigogine and Stengers write:

Of course, no one has ever dreamed that a physicist might one day benefit from the knowledge possessed by Laplace’s demon. Laplace himself only used this fiction to demonstrate the extent of our ignorance and the need for a statistical description of certain processes. The problematics of Laplace’s demon are not related to the question of whether a deterministic prediction of the course of events is actually possible, but whether it is possible in principle, *de jure*. This possibility seems to be implied in mechanistic description, with its characteristic duality based on dynamic law and initial conditions.

. . . In the context of classical dynamics, a deterministic description may be unattainable in practice; nevertheless, it stands as a *limit* that defines a series of increasingly accurate descriptions. . .

Nature speaks with a thousand voices, and we have only begun to listen. Nevertheless, for nearly two centuries Laplace’s demon has plagued our imagination, bringing a nightmare in which all things are insignificant. If it were really true that the world is such that a demon – a being that is, after all, like us, possessing the same science, but endowed with sharper senses and greater powers of calculation – could, starting from the observation of an instantaneous state, calculate its future and past, if nothing qualitatively differentiates the simple systems we can describe from the more complex ones for which a demon is needed, then the world is nothing but an immense tautology. This is the challenge of the science we have inherited from our predecessors, the spell we have to exorcise today.²⁶

Yet we must go on to ask the question, what about *nonlinear chaotic systems*, such as the three-body gravitational system mentioned earlier? (Also, we will see later that there are many other *nonlinear far-from-equilibrium systems*, including biological systems such as our own human bodies, which are not chaotic, but which nevertheless contain many moments of macroscopic

constrained chance over time.) Such nonlinear systems are far more common than classical mechanical systems. Where does Laplace's demon stand in relation to *these* systems?

It turns out that such nonlinear physical systems continue to be *deterministic* from the point-of-view of a transcendent, all-knowing, and all-powerful God. However, in spite of modern strained definitions of "determinism" to the contrary, such systems are *not* deterministic from the point-of-view of Laplace's demon, human beings, or any other *imperfect* conscious beings ("imperfect" here meaning "can generally only perceive and calculate to within a *finite* number of decimal places, and act with corresponding imprecision"). One reason for this is that these nonlinear systems are *extremely sensitive to their initial conditions*. In other words, the *slightest change* in the initial conditions can result in a *radical change* in the subsequent behavior of the nonlinear system. As Prigogine and Stengers put it: "Arbitrarily small differences in initial conditions are amplified."²⁷

Moreover (and here's where even Laplace's demon ultimately fails), even if the "initial conditions" of the nonlinear system at some *one* point in time *are* (by some miracle) perfectly known, many *subsequent* (and/or *prior*) temporal points in the evolution of the nonlinear system always exist (called *saddle points*, or *hyperbolic points*) where the precise states of the nonlinear system at *those* points must *also* be perfectly and uniquely specified. This is because precise nonlinear-system behavior between saddle points cannot be predicted by any scientific law without *infinitely precise* re-measurements at *each* of these many saddle points: A perfect, transcendent being, such as God, can do this, but nobody else can even come close.

As a result, the Enlightenment program to interpret all physical systems as classical mechanical systems (by approaching the knowledge of Laplace's demon via a series of increasingly accurate descriptions of initial conditions and natural laws) completely breaks down: It breaks down because increasingly accurate descriptions of the initial conditions of *nonlinear* systems tells you *nothing deterministic* or even *quasi-deterministic* about the subsequent behavior of those nonlinear systems *until* you attain a *perfect* description of the initial conditions (something which even Laplace admits is humanly impossible). Furthermore, even if, by some miracle, a scientist (or Laplace's demon) *could* determine *perfectly* the initial conditions of a nonlinear dynamic system at some particular point in time and then use that information (together with the "laws of nature") to calculate future (or past) trajectories of the system's parts, uncertainty at subsequent (or previous) *saddle points* in the history of the system would cause *those* physical trajectories to diverge widely from the scientist's predictions.²⁸ In other

ON SYSTEMS

words, the Enlightenment program to achieve a complete deterministic description of nature by *asymptotically approaching* the deterministic knowledge of a perfect, transcendent being turns out to be impossible, since an irreducible element of *absolute chance* is a basic feature of *immanent* objectivity for all imperfect beings existing within the physical universe. (See our later chapter on **Nonlinear Dynamic Systems** for further discussion of this vital point.)

This does *not* mean, however, that a scientist can tell *nothing* about the future behavior of a nonlinear system from a study of its initial conditions. Often, for example, if the initial values for the control variables fall within a certain range, then the nonlinear system will exhibit *cyclical* behavior, while for another range of initial values it will exhibit *chaotic* behavior, and for still a third range of initial values it will always eventually arrive at a certain stable state, thus displaying *equifinality*. But this humanly possible knowledge of the future behavior of nonlinear systems *can never be moment-to-moment deterministic*. For this reason, temporal points of *constrained chance* (which occur even on a macroscopic scale) must be regarded as *real* objective features of the nonlinear system, from a human, immanent point-of-view: These moments of constrained chance *cannot* simply be regarded as “errors” or “imperfections” which will disappear as human knowledge of “initial conditions” and “natural laws” becomes more refined.

If we further examine this situation teleologically, we can arrive at a basic solution to the ancient problem of “free-will vs. determinism” that so bothered Enlightenment thinkers (and prior thinkers as well): For God, who is assumed to have both perfect knowledge and the power to determine perfectly all specific physical conditions and all physical laws, everything that happens is determined and destined by the decisions of His omnipotent will from a *transcendent* point-of-view. But, for man, *individual human decisions* (which are teleologically analogous to certain moments of *immanently-objective constrained chance* in the physical human-body system) are equally real, only from an *immanent* point-of-view rather than a *transcendent* point-of-view. Therefore human free-will must (from the human point-of-view) be real as well. In other words, the teleological reality of our *relatively* free-will is correlated with our *imperfect* knowledge, while the teleological reality of God’s *absolute* free-will is correlated with His *perfect* knowledge.

By the way, this suggests one argument for God’s *transcendence*, since an *absolute* free-will having *absolute* knowledge has no analogical correlate with anything *within* the physical universe, including the physical universe taken as a whole. Furthermore, the existence of *saddle points* within nonlinear physical systems analogically eliminates *deism* as a viable corresponding

teleology, since God could *not* determine the destiny of the universe by simply deciding on a particular set of “initial conditions” and “natural laws”, and then leaving the universe to “run itself”. In other words, God does not *pre-determine* or *pre-destine* what happens in the universe, but rather He *determines* and *destines* what happens in the universe *at every moment in time* via His timeless omnipotent will. (This includes God’s making use of the *immanently real* decisions and *immanently real* actions of imperfect human beings *within* time.) Nor does God’s omnipotent will make the world “an immense tautology”, since, for man, human free-will is completely real as well, from an *immanent* point-of-view.

The foregoing teleological analysis also reveals a deep link between the two fundamental errors of the Enlightenment: The fundamental *physical* error of the Enlightenment thinkers was their belief that human beings could approach God’s perfect deterministic knowledge of the physical universe by means of successively better approximations. The correlated fundamental *teleological* error of the Enlightenment thinkers was their belief that the free-wills of individual human beings are as radical, absolute, and authoritative as is God’s free-will. Both of these fundamental errors, in turn, have their ancient root in what the Judeo-Christian tradition names as “original sin” – the eternal temptation of human beings to regard themselves to be “like gods”, with the power and right to legislate their own individual destinies and moralities absolutely.

Special Relativistic Systems

In 1905 a then-unknown Albert Einstein published no less than five groundbreaking scientific papers. One of these papers, called “On the Electrodynamics of Moving Bodies”, proposed what Einstein later called the Special Theory of Relativity (to distinguish it from the General Theory of Relativity, which he discovered later).

The Special Theory of Relativity is based on two basic postulates. The first is:

1. *No physical measurement can distinguish one inertial frame of reference from another.*

An *inertial frame of reference* (in this context) is a three-dimensional system of coordinates which has a *constant velocity* with respect to certain other systems of coordinates. These other systems of coordinates are also regarded as being *inertial frames of reference* with respect to one other, and a total set of these systems of coordinates is called an *inertial system*. By contrast, if one three-dimensional system of coordinates is *accelerating* or *rotating* with respect to another such system of coordinates, then those two systems of coordinates are *not* in the same *inertial system*. (A three-dimensional *system of coordinates* may be thought of as three abstract number lines crossing at mutual right angles to one another in three-dimensional space. These are the x , y , and z axes respectively, and any point in three-dimensional space can be identified by specifying its signed “distance” from each of the three mutually perpendicular planes containing these three axes. These three signed “distances” are the x , y , and z coordinates of the point in space.)

What this postulate essentially means is that there is no absolute or preferred frame of reference among *inertial systems* (i.e., systems which are in a state of *constant velocity* with respect to one another). Another way of putting this is that the laws of physics do not change with uniform motion, so that no physical experiment can distinguish between a state of absolute rest and a state of constant velocity.

The second basic postulate of the Special Theory of Relativity is:

2. *The speed of light (in a vacuum) is constant in all inertial frames of reference, regardless of any motion of the source.*

This means that if, say, a light source is moving at three-quarters of the speed of light with respect to myself (either away from me or towards me, it doesn't matter), I will still measure the speed of the light I receive from that source as a constant c , which is approximately 300,000 kilometers per second, or 186,000 miles per second. (More exactly, $c = 2.99792458 \times 10^8$ meters per second.)

ON SYSTEMS

Needless to say, this second postulate is tremendously counter-intuitive with respect to everyday experience. According to my ordinary experience, which corresponds to *Galilean* relativity rather than Einstein's relativity, if a light source is coming *towards* me at three-quarters of the speed of light ($.75c$), then I should measure the speed of that light as $c + .75c$, or $1.75c$. By contrast, if the light source is moving *away* from me at $.75c$, then I should measure the speed of that light as $c - .75c$, or $.25c$. Instead, I continue to measure the speed of the light as c !

Einstein initially arrived at this principle of the constancy of the speed of light in all inertial frames of reference by means of a "thought experiment" in which he imagined what it would be like if he could "catch up" with light and observe it "at rest". He realized that what he would observe in that case would be an impossibility. Einstein writes:

If I pursue a beam of light with the velocity of c (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations.²⁹

This strange constancy of the speed of light can be better understood when we realize that it really has nothing to do with *light* at all. Rather, it arises because of the unusual nature of the link between the *time* dimension and the other three *space* dimensions of the four-dimensional space-time continuum. From this four-dimensional point-of-view, the "speed of light" is simply a *conversion constant* for converting *time units* (such as seconds) into *distance units* (such as kilometers), so that all four space-time dimensions can be measured in the same way.³⁰

Seen from this point-of-view, c is (loosely) analogous to the equally "arbitrary" geometrical constant π (which, of course, has a value of approximately 3.14159 and is the ratio of the length of the circumference of every circle to its diameter).

Some Results of the Special Theory of Relativity

But if the *speed of light* is constant in all inertial frames of reference, then measurements of length, time, and mass are *not* the same in all inertial frames of reference. Consider an inertial frame of reference F , which we will arbitrarily regard as being at rest. Consider also another inertial frame of reference F' , which we will arbitrarily regard as being in motion with a constant velocity of v with respect to F . Then the following *Lorentz transformations* can be proved from the two basic postulates of the Special Theory of Relativity:

- *Lorentz-Fitzgerald Contraction*

Suppose that a certain object which is at rest relative to F' has a length of L' as measured by an observer who is also at rest relative to F' . Suppose furthermore that this length L' is measured along the line of motion of F' relative to F . Then, according to the Special Theory of Relativity, if an observer who is at rest relative to F measures this same length, he will obtain the value:

$$L = L' \text{ times the square root of } (1 - v^2/c^2)$$

where v is the velocity of F' relative to F and c is the constant speed of light in a vacuum.

In other words, the observer at rest relative to F will measure the length of the object as *shorter* than the observer who is at rest relative to F' . This is known as the *Lorentz-Fitzgerald contraction*.

- *Time Dilation*

Suppose instead that the observer who is at rest relative to F' measures a time interval t' between two events. Then this same time interval as measured by an observer at rest with respect to F is:

$$t = t' \text{ divided by the square root of } (1 - v^2/c^2)$$

In other words, the observer at rest relative to F will measure the time interval as *longer* than the observer who is at rest relative to F' . This is known as *time dilation*.

- *Mass Dilation*

Finally, suppose that an observer who is at rest relative to F' measures the mass of a certain object m' which is also at rest relative to F' . Then this same mass as measured by an observer at rest with respect to F is:

$$m = m' \text{ divided by the square root of } (1 - v^2/c^2)$$

In other words, the observer at rest relative to F will measure the object as *heavier* than will the observer who is at rest relative to F' .

All of the above formulas, taken together, are called *Lorentz transformations*.

Notice that all of the above equations depend critically on the expression *square root of* $(1 - v^2/c^2)$. When v is small relative to c (which is what we experience in our everyday lives), then this expression is very nearly equal to 1 and we can (practically speaking) ignore all of these relativistic effects. On the other hand, if we set $v = c$ then this expression is equal to zero and the results of the above equations become absurd (since lengths contract to 0,

ON SYSTEMS

while time intervals and masses dilate to infinity). This illustrates another important result of the Special Theory of Relativity: *The speed of light is an absolute speed limit within the physical universe: Nothing can travel faster than the speed of light.*

If v is not small relative to c and moreover v is not equal to c (in other words, if v is a substantial fraction of c), then it becomes very important to take into account these relativistic effects. Practically speaking, the only time we observe physical objects moving at such high velocities is either by measuring high-speed sub-atomic particles (such as natural cosmic rays or sub-atomic particles that have been artificially accelerated by a particle accelerator), or by inferring the velocity of far-off galaxies.

Yet another important result of the Special Theory of Relativity is the fact that two events which are *simultaneous* for an observer at rest with respect to an inertial frame F may *not* be simultaneous for another observer who is at rest with respect to a different inertial frame F' .

And still another important result of Special Relativity is the *principle of equivalence between energy and mass*, expressed by Einstein's famous formula $E=mc^2$ (where E is energy, m is mass, and c is the constant speed of light). This means that c is not only a conversion constant enabling the conversion of *time* units into *distance* units: This same constant c also enables the conversion of *mass* units into *energy* units.

All of these intuitively strange results of the Special Theory of Relativity can be derived from the following statement:

The time dimension, together with the three space dimensions, jointly constitute a four-dimensional space-time continuum. The "distance" between any two points in this four-dimensional space-time continuum is represented by the following formula:

$$d^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 - c^2(t_2 - t_1)^2$$

where d is the "distance" between two points in the four-dimensional space-time continuum, c is the constant speed of light, (x_1, y_1, z_1, t_1) are the coordinates of the first point, and (x_2, y_2, z_2, t_2) are the coordinates of the second point.

Note that d^2 is the same for all observers within the same set of three-dimensional inertial frames of reference, regardless of how high their constant velocities are with respect to one another (limited only by the speed of light). It can also be proved that d^2 is invariant under four-dimensional translations and rotations, and furthermore that the Lorentz transformations (apart from a different algebraic sign due to the special character of time) are nothing but

rotations of the four-dimensional co-ordinate system within this four-dimensional space. In fact, the *entire* Theory of Special Relativity can be derived from this formula for d^2 alone!

Notice that this d^2 formula is based on the familiar Pythagorean Theorem that is used to calculate the distance between any two points within an ordinary three-dimensional-space coordinate system. Also, notice that the expression for the time dimension has a *negative sign* with respect to the corresponding expressions for the other three space dimensions and that, moreover, this time dimension uses the *conversion factor* c to convert time from time units to distance units (thus making the time dimension compatible with the space dimensions).

Now, if d^2 has a *positive* sign, then this measure of four-dimensional distance is said to be *spacelike*. On the other hand, if d^2 has a *negative* sign, then this measure of four-dimensional distance is said to be *timelike*. Finally, if d^2 is equal to *zero*, then this measure is said to be *lightlike*.³¹

It was the mathematician Herman Minkowski who first discovered the four-dimensional representation of the Special Theory of Relativity. This representation requires the use of a four-dimensional *tensor calculus* that is a straightforward extension of the ordinary Newton/Leibniz *vector* calculus.

There is one final very important point we need to make concerning Special Relativistic Systems:

*Special Relativistic Systems have almost all of the characteristics of Classical Mechanical Systems that we discussed in our earlier chapter: Their parts have only **weak and/or transient interactions**; their laws can be expressed as **differential equations** that are both **integrable** and **linear**; they are **deterministic** and **time-reversible**; they obey the **principle of superposition**, etc.*

The Special Theory of Relativity has been experimentally verified many times, especially in the day-to-day operations of particle accelerators. Famous experimental confirmations include the *Michelson-Morley experiment* (which showed the speed of light to be identically the same when measured at right angles within a plane parallel to the surface of the earth, in spite of the motion of the earth itself) and the *Hafele-Keating experiment* (in which time as measured by atomic clocks that were sent around the earth on fast commercial jets differed from time as measured by atomic clocks that had remained stationary with respect to the surface of the earth).

ON SYSTEMS

Teleological Implications of Special Relativistic Systems

Because Special Relativistic Systems are identical to Classical Mechanical Systems in every way that could have analogical teleological significance, everything we have said about teleology with respect to Classical Mechanical Systems applies equally to Special Relativistic Systems. And, because Special Relativity is mainly of interest in the study of fast-moving sub-atomic particles and far-off galaxies, Special Relativistic Systems are encountered in everyday life with far less frequency than even Classical Mechanical Systems. Nevertheless, there are a few additional comments we need to make concerning Special Relativity and teleology:

The first comment is that the Theories of Relativity, both Special and General, have *nothing whatsoever* to do with those teleological theories of moral *relativism*, multiculturalism, and moral emotivism which we analyzed, refuted, and condemned in our Book I, *WORLDVIEWS*. In other words there is nothing teleologically significant about the fact that the word “relative” is used in both of these contexts. This point has been made by a number of scientists and philosophers of science, but I will quote only one, Hans Reichenbach:

[W]hat has been called the philosophy of relativity represents, to a great extent, the fruit of misunderstandings of the theory rather than of its physical content. Philosophers who regard it as an ultimate wisdom that everything is relative are mistaken when they believe that Einstein’s theory supplies evidence for such a sweeping generalization; and their error is even deeper when they transfer such a relativity to the field of ethics, when they claim that Einstein’s theory implies a relativism of men’s duties and rights. . . [T]he parallelism between the relativity of ethics and that of space and time is nothing more than a superficial analogy, which blurs the essential logical differences between the fields of volition and cognition.³²

A second related problem that needs to be commented on arises from the following objection: “You say that the methods of science cluster centrally and necessarily around the idea of ‘bracketing out the subject’, as opposed to religious or teleological methods that ‘bracket out the object’. Yet clearly the subject is *not* ‘bracketed out’ by Special Relativity: For measurements of length, time, and mass within Special Relativity are all *relative to the observer* and depend on his velocity with respect to the object(s) he is observing.”

The answer to this objection is that, while it is true that measurements of length, time, and mass *are* relative to the observer in Special Relativity, fortunately the speed of light in a vacuum is *not*. This fact enables any observer in any of the frames of reference within a given inertial system to

calculate how any other observer within that inertial system would measure the object(s) *he* is observing. In other words, the Lorentz transformations have exactly the effect of “bracketing out the subject” and returning us to a state in which the measurements of all inertial observers can be referred to a common, abstract “universal observer”. This is reflected in the fact that the “distance” *d* in the four-dimensional formulation of Special Relativity is the same for *all* observers within an inertial system, regardless of the magnitude of their constant velocity of motion with respect to the phenomenon being observed.

The third comment we need to make is that the widespread acceptance by scientists of the fact of the non-Euclidean four-dimensional nature of space-time *directly* undermined the Kantian rationalist position that space can be known *a priori* to be three-dimensional and Euclidean on the basis of the structure of the radically autonomous human individual’s pure reason alone. This *direct* blow to Kantian rationalism in the *scientific* sphere had the *indirect* effect of undermining Kantian rationalism in the *ethical* and *teleological* spheres (the “categorical imperative”, and so on.), thus contributing to the ethical situation of *implicit emotivism* in which we find ourselves today. (See our Book I, *WORLDVIEWS*, for a more-complete discussion of this subject.)

Overall, however, the *Special* Theory of Relativity provides us with no new opportunities for teleological analogs, over and above what was already present in classical Newtonian mechanics. However, as we shall see, the *General* Theory of Relativity is somewhat more interesting in this regard.

General Relativistic Systems

The Special Theory of Relativity, which we considered in the previous chapter, deals only with *inertial systems*, i.e., systems of coordinates (frames of reference) which are in a state of *constant velocity* with respect to one another. But what about frames of reference that are in a state of *constant acceleration*, *constant rotation*, or some other state of *non-uniform velocity* with respect to one another? This is the key question dealt with by the *General Theory of Relativity*, first presented by Einstein in 1916 in a paper titled “The Foundation of the General Theory of Relativity”.

Recall that one of the two basic postulates of Special Relativity is that *no physical measurements can distinguish one inertial frame of reference from another*. However, if one frame of reference is *uniformly accelerating* (as opposed to merely moving at a *uniform velocity*) with respect to another frame of reference, then it would seem that physical measurements *can* distinguish between these two frames of reference (i.e., between the *non-inertial* frame of reference and the *inertial* frame of reference).

For example, an observer who is at rest with respect to the *accelerating* frame of reference of an accelerating elevator in which he is riding will feel pressure on his feet, and a dropped object which he releases will accelerate away from him towards the floor of the elevator, even if we assume that the elevator is not near any gravitational field. By contrast, if the elevator is either *at rest* or is moving at a *uniform velocity* (and, furthermore, it is away from any nearby gravitational field), then this same observer feels no such pressure on his feet, and an object released by him will float near him in a state of weightlessness. Thus, both physical measurements and the laws of physics appear to be different for the *accelerated* observer than they are for the *stationary* observer (or the observer moving at *constant velocity*).

However, Einstein realized that the Theory of Relativity could be extended to *also* include *non-inertial* frames of reference. He came to this realization by means of “thought experiments” such as the following: Imagine that an observer is locked inside of a cosmic “elevator” that is floating far out in space, away from any measurable gravitational field. This elevator is windowless, so that the observer cannot see outside of it, and the elevator is either at rest or is moving with constant velocity. Under these conditions, the observer would feel that he is weightless, and various objects might also float weightlessly beside him. Suppose, now, that suddenly the observer feels continuous pressure on his feet, and the objects floating around him fall to the floor of the elevator. In the imaginary situation just described, the observer would not be able to tell whether the elevator car was suddenly being subjected to a force that was *accelerating* it “upwards”, or whether, on the contrary, the elevator had suddenly come to rest on a body with large mass

ON SYSTEMS

that was exerting a “downward” *gravitational force* upon both himself and the other objects inside the elevator. In other words, this observer would not know whether he was *accelerating* in free space or (on the contrary) was *at rest* within a significant gravitational field. Furthermore, even our earlier assumption that the elevator was initially at rest or moving at constant velocity is suspect from this point-of-view, because if the elevator was instead initially in a state of *free fall* within a gravitational field, the observer would have experienced exactly the same sense of “weightlessness” as if he were at rest or moving at constant velocity far from any gravitational field.

“Thought experiments” such as the foregoing led Einstein to propose the following *fundamental postulate of the General Theory of Relativity*:

The fundamental postulate of the General Theory of Relativity is the Principle of Equivalence, which states that inertia and gravitation have essentially the same nature.

We will refine the above rather loose formulation of the *Principle of Equivalence* by quoting from Albert Einstein’s 1921 lecture at King’s College in London, England:

[C]lassical mechanics exhibits a deficiency which directly calls for an extension of the principle of relativity to spaces of reference which are not in uniform motion relative to each other. The ratio of the masses of two bodies is defined in mechanics in two ways which differ from each other fundamentally; in the first place, as the reciprocal ratio of the accelerations which the same motive force imparts to them (*inertial mass*), and in the second place, as the ratio of the forces which act upon them in the same gravitational field (*gravitational mass*). The equality of these two masses, so differently defined, is a fact which is confirmed by experiments of very high accuracy (experiments of Eotvos), and classical mechanics offers no explanation for this equality. It is, however, clear that science is fully justified in assigning such a numerical equality only after this numerical equality is reduced to an equality of the real nature of the two concepts.

That this object may actually be attained by an extension of the principle of relativity, follows from the following consideration. A little reflection will show that the law of the equality of the inertial and the gravitational mass is equivalent to the assertion that the acceleration imparted to a body by a gravitational field is independent of the nature of the body. For Newton's equation of motion in a gravitational field, written out in full, is

$$(Inertial\ mass) * (Acceleration) = (Intensity\ of\ the\ gravitational\ field) * (Gravitational\ mass)$$

It is only when there is numerical equality between the inertial and gravitational mass that the acceleration is independent of the nature of the body. Let now K be an inertial system. Masses which are sufficiently far from each other and from other bodies are then, with respect to K , free from acceleration. We shall also refer these masses to a system of co-

ordinates K' , uniformly accelerated with respect to K . Relative to K' all the masses have equal and parallel accelerations, [and] with respect to K' they behave just as if a gravitational field were present and K' were unaccelerated. Overlooking for the present the question as to the “cause” of such a gravitational field, which will occupy us later, there is nothing to prevent our conceiving this gravitational field as real, that is, the conception that K' is “at rest” and a gravitational field is present we may consider as equivalent to the conception that only K is an “allowable” system of co-ordinates and no gravitational field is present.

The assumption of the complete physical equivalence of the systems of co-ordinates, K and K' , we call the “principle of equivalence”; this principle is evidently intimately connected with the law of the equality between the inertial and the gravitational mass, and signifies an extension of the principle of relativity to co-ordinate systems which are in non-uniform motion relatively to each other. In fact, through this conception we arrive at the unity of the nature of inertia and gravitation. For, according to our way of looking at it, the same masses may appear to be either under the action of inertia alone (with respect to K) or under the combined action of inertia and gravitation (with respect to K').

The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature gives to the general theory of relativity, according to my conviction, such a superiority over the conceptions of classical mechanics, that all the difficulties encountered in development must be considered as small in comparison with this progress.³³

Imagine a finite region of space in which bodies are far enough apart so that they move with respect to one another with only *uniform velocities* (i.e., no acceleration or rotation). Within such a finite region of space we know that the laws of the Special Theory of Relativity hold with remarkable accuracy. Einstein calls such a finite region of space a *Galilean region*. Here is another excerpt from Einstein’s 1921 lecture at King’s College:

The principle of equivalence demands that in dealing with Galilean regions we may equally well make use of non-inertial systems, that is, such co-ordinate systems as, relative to inertial systems, are not free from acceleration and rotation. If, further, we are going to do away completely with the vexing question as to the objective reason for the preference of certain systems of co-ordinates, then we must allow the use of arbitrarily moving systems of co-ordinates. As soon as we make this attempt seriously we come into conflict with that physical interpretation of space and time to which we were led by the special theory of relativity. For let K' be a system of co-ordinates whose z -axis coincides with the z -axis of K , and which rotates about the latter axis with constant angular velocity. Are the configurations of rigid bodies, at rest relative to K' , in accordance with the laws of Euclidean geometry?

Since K' is not an inertial system, we do not know directly the laws of configuration of rigid bodies with respect to K' , nor the laws of nature, in general. But we do know these laws with respect to the inertial system K ,

ON SYSTEMS

and we can therefore infer their form with respect to K' . Imagine a circle drawn about the origin in the $x' y'$ plane of K' , and a diameter of this circle. Imagine, further, that we have been given a large number of rigid rods, all equal to each other. We suppose these laid in series along the periphery and the diameter of the circle, at rest relative to K' . If U is the [total length] of these rods along the periphery, D the [total length] along the diameter, then, if K' does not rotate relatively to K , we shall have

$$U/D = \pi$$

But if K' rotates we get a different result. Suppose that at a definite time t of K we determine the ends of all the rods. With respect to K all the rods upon the periphery experience the Lorentz contraction, but the rods upon the diameter do not experience this contraction (along their lengths). It therefore follows that [with respect to K' , in order to compensate for this effect within K]:

$$U/D > \pi$$

It therefore follows that the laws of configuration of rigid bodies with respect to K' do not agree with the laws of configuration of rigid bodies that are in accordance with Euclidean geometry. If, further, we place two similar clocks (rotating with K'), one upon the periphery, and the other at the center of the circle, then, judged from K , the clock on the periphery will go slower than the clock at the center. The same thing must take place, judged from K' , if we do not define time with respect to K' in a wholly unnatural way (that is, in such a way that the laws with respect to K' depend explicitly upon the time). Space and time, therefore, cannot be defined with respect to K' as they were in the special theory of relativity with respect to inertial systems.

But, according to the principle of equivalence, K' may also be considered as a system at rest, with respect to which there is a gravitational field (field of centrifugal force, and force of Coriolis). We therefore arrive at the result: the gravitational field influences and even determines the metrical laws of the space-time continuum. If the laws of configuration of ideal rigid bodies are to be expressed geometrically, then in the presence of a gravitational field the geometry is not Euclidean.³⁴

In fact, a geometry in which $U/D > \pi$ is a type of non-Euclidean geometry in which space (or space-time) is *curved*. Of course, the Einstein/Minkowski geometry for the Special Theory of Relativity is also in a sense non-Euclidean, because it is four-dimensional, rather than three-dimensional, with time as a special extra dimension. However, the Einstein/Minkowski geometry is still *quasi-Euclidean* because it is a *flat* geometry in which space-time is *not* curved. By contrast, in the General Theory of Relativity space-time *is* curved to varying degrees, depending on the local presence of bodies having significant mass. It can even be said that, according to the General Theory of Relativity, matter *itself* can be described as being a manifestation of this curvature of space-time. Furthermore, bodies “falling”

within a gravitational field do so because they are simply following a “straight line” (called a *geodesic* in non-Euclidean geometry) along the local curvature of space-time. (This general-relativistic theory of gravity is obviously radically different from Newton’s classical gravitational theory.)

The idea of the curvature of space-time can be better understood by considering an analogy in two-dimensional space, namely, the geometry of measurement on the curved surface of a sphere (e.g., a globe of the earth). If we regard a “straight line” (i.e., a non-Euclidean *geodesic*) to be a great circle (or an arc of a great circle) on the surface of this sphere, then the following holds true: 1) the curvature of the sphere’s surface is *constant* and *positive*, 2) two geodesics (when extended to the maximum) are each finite & closed and always meet in exactly two points, 3) the sum of the angles of a triangle is *greater* than 180 degrees when measured on the curved surface of this sphere, and 4) $U/D < \pi$ for all circles measured on the surface of the sphere.

By contrast, if we instead consider the geometry of measurement on a 2-dimensional surface that is hyperbolic (i.e., shaped like the infinitely extended surface of a horse’s saddle), then the following instead holds true: 1) the curvature of the hyperbolic surface is *constant* and *negative*, 2) geodesics (when extended to the maximum) are infinite, 3) two fully-extended geodesics may meet in at most one point, 4) a fully-extended geodesic is “parallel” to an infinite number of other geodesics passing through a given point lying outside the first geodesic, 5) the sum of the angles of a triangle is *less* than 180 degrees when measured on this curved hyperbolic surface, and 6) $U/D > \pi$ for all circles measured on the hyperbolic surface.

Note that, for sufficiently small areas on either the spherical surface or the hyperbolic surface, the surface may be approximately regarded as “flat”, so that the geometrical rules of ordinary Euclidean geometry will then hold with reasonable precision for triangles, circles, and so on that are small in comparison with the overall curvature of the surface.

Note also that, while we have visualized both the spherical surface and the hyperbolic surface as embedded within three-dimensional space, the properties of these curved surfaces which we have just discussed are actually internal to the geometry of the surfaces themselves. In other words, if we were two-dimensional “flatlanders” living on these surfaces and had no direct experience of the third dimension, we could still detect the effects of the curvature of our two-dimensional “space” by measuring triangles and circles of sufficiently large size.

Finally, it is important to note that the non-Euclidean geometry which Einstein used to describe General Relativistic Systems is actually far more

ON SYSTEMS

complex than the above two-dimensional analogies suggest, because according to General Relativity the curvature of four-dimensional space-time is *not* constant, but rather *varies* at every point according to the local distribution of mass. The “Riemannian” mathematical description of this kind of variable curvature, using tensor calculus, requires the specification of *six* separate components for each point within three-dimensional space, or *twenty* separate components for each point within four-dimensional space-time.³⁵

Historical Background of the General Theory of Relativity

But, to step back for a moment, how did Einstein arrive at his remarkable conception of the General Theory of Relativity? Let’s listen to Einstein’s own words in his “Autobiographical Notes”. He begins by describing the state of physics as it was taught when he was a student of mathematics and physics at the Polytechnic Institute of Zurich:

Now to the field of physics as it presented itself at that time. In spite of all the fruitfulness in particulars, dogmatic rigidity prevailed in matters of principles: In the beginning (if there was such a thing) God created Newton’s laws of motion together with the necessary masses and forces. This is all; everything beyond this follows from the development of appropriate mathematical methods by means of deduction. What the nineteenth century achieved on the strength of this basis, especially through the application of the partial differential equations, was bound to arouse the admiration of every receptive person. . . . What made the greatest impression upon the student, however, was less the technical construction of the mechanics or the solution of complicated problems than the achievements of mechanics in areas which apparently had nothing to do with [classical] mechanics: the mechanical theory of light, which conceived of light as the wave-motion of a quasi-rigid elastic ether, and above all the kinetic theory of gases. . . .

We must not be surprised, therefore, that, so to speak, all physicists of the [19th] century saw in classical mechanics a firm and final foundation for all physics, yes, indeed, for all natural science, and that they never grew tired in their attempts to base Maxwell’s theory of electro-magnetism, which in the meantime, was slowly beginning to win out, upon [classical] mechanics as well. Even Maxwell and H. Hertz, who in retrospect appear as those who demolished the faith in [classical] mechanics as the final basis of all physical thinking, in their conscious thinking adhered throughout to [classical] mechanics as the secured basis of physics. It was Ernst Mach who, in his *History of Mechanics*, shook this dogmatic faith.³⁶

In our previous chapter on **Classical Mechanical Systems** we pinpointed Henri Poincare’s proof at the end of the 19th century that a three-body gravitational system is *chaotic* (and therefore *not solvable* by classical mechanics) as the moment when science’s faith that all physical systems are

really classical mechanical systems became an untenable faith. (In this assessment we relied on Ilya Prigogine and Isabelle Stengers.) Einstein, however, sees serious problems with classical mechanics as beginning even earlier in the 19th century, as a result of the mounting evidence for Maxwell's theory of electromagnetism and light. Again, from Einstein's "Autobiographical Notes":

[T]he incorporation of wave-optics into the [classical] mechanical picture of the world was bound to arouse serious misgivings. If light was to be interpreted as undulatory motion in an elastic body (ether), this had to be a medium that permeates everything; . . . This ether had to lead a ghostly existence alongside the rest of matter, inasmuch as it seemed to offer no resistance whatever to the motion of "ponderable" bodies. In order to explain the refraction-indices of transparent bodies as well as the processes of emission and absorption of radiation, one would have had to assume complicated reciprocal actions between the two types of matter, something which was not even seriously tried, let alone achieved. . .

The factor which finally succeeded, after long hesitation, to bring the physicists slowly around to give up the faith in the possibility that all of physics could be founded upon Newton's mechanics, was the electrodynamics of Faraday and Maxwell. For this theory and its confirmation by Hertz's experiments showed that there are electromagnetic phenomena which by their very nature are detached from every ponderable matter – namely the waves in empty space which consist of electromagnetic "fields". If [classical] mechanics was to be maintained as the foundation of physics, Maxwell's equations had to be interpreted mechanically. This was zealously but fruitlessly attempted, while [Maxwell's] equations were proving themselves fruitful in mounting degree.³⁷

Meanwhile, 19th-century writers such as Ernst Mach were beginning to critique classical Newtonian mechanics on the basis of the arbitrariness of certain of its assumptions. Again, Einstein:

From the standpoint of purely geometrical description, all "rigid" co-ordinate systems are among themselves logically equivalent. The equations of [classical] mechanics (for example this is already true of the law of inertia) claim validity only when referred to a specific class of such systems, i.e., the "inertial systems". . . It is necessary, therefore, in order to justify the necessity of the specific choice [of a particular co-ordinate system or type of co-ordinate system], to look for something which lies outside of the objects (masses, distances) with which the theory is concerned. For this reason "absolute space" as originally determinative was quite explicitly introduced by Newton as the omnipresent active participant in all mechanical events; by "absolute" he obviously means uninfluenced by the masses and by their motion. What makes this state of affairs particularly offensive is the fact that there are supposed to be infinitely many inertial systems, relative to each other in uniform translation, which are supposed to be distinguished among all other rigid systems.³⁸

ON SYSTEMS

According to Einstein, it was H.A. Lorentz who first proposed that an electromagnetic field exists only in empty space, without the necessity of postulating a mechanical medium (“ether”) to transmit its effects:

If one compares this with Newton’s system, the change consists in this: action at a distance is replaced by the field, which thus also describes the radiation. Gravitation is not usually taken into account because of its relative smallness; its consideration, however, was always possible by means of the enrichment of the structure of the field, i.e., expansion of Maxwell’s law of the field. . .

If one views this phase of the development of [physical] theory critically, one is struck by the dualism which lies in the fact that the material point in Newton’s sense and the field as continuum are used as elementary concepts side by side. Kinetic energy and field-energy appear as essentially different things. This appears all the more unsatisfactory inasmuch as, according to Maxwell’s theory, the magnetic field of a moving electric charge represents inertia. Why not then *total* inertia? Then only field-energy would be left, and the particle would be merely an area of special density of field-energy. In that case one could hope to deduce the concept of the mass-point together with the equations of the motion of the particles from the field equations – the disturbing dualism would have been removed.³⁹

In his General Theory of Relativity, Einstein succeeded in accomplishing this program, but only for *gravitational* fields: His attempts, throughout the rest of his life, to integrate the other forces of nature (especially electro-magnetism) with gravity into a *Unified Field Theory* were unsuccessful.

The Einstein Field Equations

The laws of the General Theory of Relativity are expressed by the Einstein Field Equations. These equations are a set of nonlinear differential equations which (like all sets of nonlinear differential equations) are nonintegrable (i.e., unsolvable) in the general case.

To be precise, the Einstein Field Equations are a set of ten coupled hyperbolic-elliptic nonlinear partial differential equations, expressed using *Riemannian tensor calculus* and taking many pages to write down.⁴⁰

From a general-systems point-of-view, this nonlinearity of the Einstein Field Equations represents an extremely significant break with both classical mechanics and the Special Theory of Relativity. Why did Einstein choose to express General Relativity with a set of nonlinear differential equations (and, moreover, insist that any future successful Unified Field Theory would also have to be composed of such a set of nonlinear differential equations), even though he knew in advance that sets of nonlinear differential equations are unsolvable in the general case?

The reason was that systems describable by linear differential equations obey the superposition principle (as we saw in our chapter on **Classical Mechanical Systems**), so that their global characteristics are all *summative* characteristics (i.e., the whole is simply the “the sum of its parts”, which parts interact so weakly and/or transiently that their interactions can be treated theoretically as being nonexistent). By contrast, Einstein knew that he had to mathematically model *strong and persistent* interactions between bodies in order to even begin to accomplish his program of expressing the laws of physics by means of field equations alone. That is why, in his “Autobiographical Notes”, Einstein writes:

The [mathematical] group of . . . general relativity is the first one which demands that the simplest invariant law be no longer linear or homogeneous in the field-variables and in their differential quotients. This is of fundamental importance for the following reason. If the field-law is linear (and homogeneous), then the sum of two solutions is again a solution, as, for example, in Maxwell’s [electromagnetic] field-equations for the vacuum. In such a theory it is impossible to deduce from the field equations alone an interaction between bodies. . . For this reason all theories up to now required, in addition to the field equations, special equations for the motion of material bodies under the influence of the fields.⁴¹

With respect to the possible expansion of the General Theory of Relativity to include electromagnetic and other forces in a Unified Field Theory, Einstein goes on to write:

What can be attempted with some hope of success in view of the present situation of physical theory? At this point it is the experiences with the theory of gravitation which determine my expectations. These equations give, from my point-of-view, more warrant for the expectation to assert something *precise* than all other equations of physics. . . [I]t has, however, already been emphasized above that the true laws cannot be linear. Such linear laws fulfill the superposition principle for their solutions, but contain no assertions concerning the interaction of elementary bodies. *The true laws cannot be linear nor can they be derived from such.*⁴² [*italics mine*]

But, it may be asked, if these nonlinear Einstein Field Equations are *unsolvable* in the general case, what good are they? The answer is that these equations *can* be solved in certain *special* cases, by arbitrarily assuming certain *symmetries*.

For example, if we consider a gravitational system in which a single, large spherical body gravitationally dominates the system completely (e.g., a spherical star at rest, the system of sun plus planets, or the system of the earth plus the small bodies attracted to its surface), then deterministic (or quasi-deterministic) solutions are possible and have been found. (This is not really surprising, since in these cases gravitation can be regarded, practically

ON SYSTEMS

speaking, to be simply a property of the gravitationally dominating body, rather than as a constitutive characteristic of the system as a whole.)

The first such solution was discovered during the First World War by the German astrophysicist Karl Schwarzschild for the case of a single perfectly spherical star at rest, ignoring the effects of the star's interior. The curvature of space-time predicted by this solution became known as *Schwarzschild geometry*, which was greatly influential on later research into gravitation and cosmology.

A few weeks later, Schwarzschild discovered another special-case solution to the Einstein field equations which described the space-time curvature *inside* a single star.

A few months after that, Schwarzschild died of a disease contracted at the Russian front. It took another *fifty years* before his solutions were expanded to include the space-time curvature around a single *spinning* star.

Now, in the 1990s, astrophysicists are using supercomputers to extend the calculations to more complex space-time geometries, including spinning objects that no longer retain their spherical symmetry. Such objects typically exhibit “axisymmetry” – symmetry about one axis (like a football) – or no symmetry at all. The mathematics, however, becomes very difficult to state, let alone solve analytically. . .

If one considers an axisymmetric object, one that exhibits symmetry about a single axis, the equations expand dramatically into dozens of pages. At this point, the equations are so complex they can only be manipulated reliably by special computer software.⁴³

Even with supercomputers equipped with special computer software, the solutions to these more-complex cases are only *approximate numerical solutions*, not true analytical solutions. Also, with very few exceptions, these numerical solutions yield the space-time curvature around only a *single* massive body. In a few cases the gravitational interaction between *two* bodies of significant mass have been successfully studied (for example, the computer model of *two* colliding “black holes” constructed in the 1970s by Bryce DeWitt, Larry Smarr, and Kenneth Eppley at the University of Texas-Austin⁴⁴). But the gravitational *three-body* problem remains as unsolvable by the General Theory of Relativity as it was by classical Newtonian mechanics.

Observational & Experimental Confirmation

In spite of the fact that solutions to the Einstein Field Equations exist for only a few special cases, a great deal of observational & experimental confirmation of the General Theory of Relativity has built up over the past 85 years or so.

The first such confirmation came in 1919 when British teams headed by Sir Arthur Eddington detected and measured the bending of light from the Hyades star cluster as it passed through the gravitational field of the sun during a total solar eclipse. The amount of the bending matched Einstein's predictions, and Einstein became an instant worldwide celebrity. (This example of cooperation between German theoretical science and English observational science gave hope to a world exhausted from the mutual slaughter of the First World War.)

A similar example of this *gravitational lensing* effect was later discovered, the *Einstein Cross*. Visible only from the southern hemisphere, the central dot of the Einstein Cross is a galaxy that is 400 million light-years away, while the four dots around the center are four images of a quasar that is directly behind the galaxy, only at 8 billion light-years away. These four images have been bent around the central galaxy by the gravitational field of that galaxy. (The bending of light by a strong gravitational field is a prediction of the General Theory of Relativity because light would be expected to follow the "straight-line" geodesic of curved space-time as it passes in the immediate vicinity of a massive body. By contrast, of course, Newton's theory of gravity does not predict *any* bending of light in a gravitational field.)

Another confirmation of General Relativity is that the amount of the forward-shift of the planet Mercury's perihelion (its closest point to the sun) with each orbit is correctly predicted by Einstein's theory of gravity, but not by Newton's theory of gravity. (The actual shift is twice as much as Newton's theory predicts.)

General Relativity also predicts that light passing through a gravitational field will have its wavelength shifted towards the red end of the spectrum. This gravitational red-shift has been observed in a number of contexts:

In 1960, Robert V. Pound and Glen A. Rebka demonstrated that a beam of very high energy gamma rays was ever so slightly red-shifted as it climbed out of Earth's gravity and up an elevator shaft in the Jefferson Tower physics building at Harvard University. The red-shift predicted by Einstein's Field Equations for the 74 ft. tall tower was but two parts in a thousand trillion. The gravitational red-shift detected came within ten percent of the computed value. Quite a feat! . . .

In the 1960s, a team at Princeton University measured the red-shift of sunlight. Though small, given the Sun's mass and density, the red-shift matched Einstein's prediction very closely.⁴⁵

Much stronger gravitational red-shifts have been measured for light coming from stars that are much denser than the sun, such as the white dwarf star Sirius B, and various neutron stars.

ON SYSTEMS

General Relativity has passed many other observational and experimental tests as well. However, one prediction of General Relativity that is of great interest to astrophysicists has not yet been directly confirmed, probably due to the smallness of its effects. That prediction is that disturbances in space-time should generate *gravitational waves* analogous to electromagnetic waves. According to General Relativity, *gravitational waves* should travel at or near the speed of light, oscillating the fabric of space-time itself. A gravitational wave arising from even a very strong source and passing through the earth is predicted to alternately stretch and shrink measured distances on the earth by a factor of only 10^{-21} .

Nevertheless, one *indirect* confirmation of the existence of gravitational waves has been found:

By the 1960s, theorists had shown that if an object emits gravitational waves, its mass should decrease. Then, in the mid 1970s, American researchers observed a binary pulsar system (named PSR1913+16) that was thought to consist of two neutron stars orbiting each other closely and rapidly. Radio pulses from one of the stars showed that its orbital period decreases by 75 microseconds per year. In other words, the stars are spiraling in towards each other – and by just the amount predicted if the system were losing energy by radiating gravity waves.⁴⁶

Another sought-for, but not-yet-found, confirmation of General Relativity would be the unambiguous observational discovery of an actual *black hole*. (Black holes were mentioned above in connection with special-case solutions to the Einstein Field Equations):

By definition a black hole is a region where matter collapses to infinite density, and where, as a result, the curvature of space-time is extreme. Moreover, the intense gravitational field of the black hole prevents any light or other electromagnetic radiation from escaping. . .

Applying the Einstein Field Equations to collapsing stars, German astrophysicist Karl Schwarzschild deduced the critical radius for a given mass at which matter would collapse into an infinitely dense state known as a singularity. For a black hole whose mass equals 10 suns, this radius is about 30 kilometers or 19 miles, which translates into a critical circumference of 189 kilometers or 118 miles. . .

If you envision the simplest three-dimensional geometry for a black hole that is a sphere (known as a Schwarzschild black hole), the black hole's surface is known as the *event horizon*. Behind this horizon, the inward pull of gravity is overwhelming and no information about the black hole's interior can escape to the outer universe. . .

At the center of the black hole lies the singularity, where matter is crushed to infinite density, the pull of gravity is infinitely strong, and space-time has infinite curvature. Here it is no longer meaningful to speak of space

and time, much less space-time. Jumbled up at the singularity, space and time cease to exist as we know them. . .

. . . In this bizarre realm in which space and time are broken apart, cause and effect cannot be unraveled. Even today, there is no satisfactory theory for what happens at and beyond the singularity.⁴⁷

There is some observational evidence for the existence of black holes, but no unambiguous “sighting”. For example, there is evidence of black holes in systems like Cygnus X-1 in our galaxy and in two neighboring galaxies called the Magellanic Clouds.⁴⁸

Cosmology and Einstein’s Theory of General Relativity

The publication in 1917 of Einstein’s paper “Cosmological Considerations in General Relativity Theory” marked the beginning of modern scientific *cosmology*, which we may define to be the study of the origin, overall structure, and destiny of the physical universe as a whole.⁴⁹ Cosmology, as it is studied today, certainly involves major quantum-mechanical considerations (especially with respect to theories of the earliest moments of the universe), in addition to general relativistic considerations. However, we will briefly consider cosmology in *this* chapter on General Relativity, since (overall) general relativistic considerations tend to predominate the discussion of cosmology at its most basic level.

According to Einstein’s Theory of General Relativity, the structure of space-time as-a-whole depends on the distribution and motion of matter throughout the physical universe. Even though the curvature of space-time varies *locally* throughout the universe, it makes sense to ask “What is the *average* curvature of space (or space-time) as-a-whole, and is that curvature positive, negative, or zero (flat)?”

Einstein’s 1917 paper made the following three assumptions in trying to answer such questions:

1. On the average, matter should be at rest in a suitably chosen co-ordinate system, and the proper distances of nebulae (i.e., galaxies) should not change with time.
2. The universe is *isotropic*. *Isotropy* means that, in a properly chosen co-ordinate system, an observer looking in different directions will never notice that any of those directions are preferred.
3. The universe is *homogeneous*. *Homogeneity* means that observers placed at different locations within the universe, describing its history in different, but properly chosen co-ordinate systems, will find these histories to be identical in their contents, so that it is impossible in this way to distinguish one place in the universe from another.⁵⁰

ON SYSTEMS

But Einstein found that these three assumptions, taken together, contradicted his original Einstein Field Equations. He therefore modified his original Field Equations to include a small term which has come to be called the *cosmological constant*, symbolized by the Greek letter “lambda”. Using these modified Field Equations, Einstein was able to construct a metric for the universe as-a-whole that had a *positive* curvature (whose two-dimensional analog would be either a *spherical* universe or an *elliptical* universe) and that also satisfied his three assumptions. Because of the “closed” nature of a universe having positive curvature, Einstein’s original metric implied that the universe is finite in volume and contains a finite amount of mass.⁵¹

Subsequent astronomical observations have confirmed that Einstein’s second and third assumptions are approximately true: The universe indeed can be regarded to be (approximately) *isotropic* and *homogeneous*. However, his first assumption (that the proper distances between galaxies should remain approximately the same over time) was disproved by Edwin Hubble’s discovery in the late 1920s of the significant *red-shift* of the light coming from the galaxies: The farther away a galaxy is from us, the greater is its red-shift, and this relationship between the distance of a galaxy and its red-shift is approximately linear for as far as our telescopes can see. The most common and reasonable interpretation of this red shift is that it is a *Doppler effect* resulting from the fact that the galaxies are moving away from us at high velocities: The farther away a galaxy is from us, the faster it is receding from us. Of course, because the universe may be regarded to be both *isotropic* and *homogeneous*, we may also say that *all* of the galaxies (including our own Milky Way galaxy) are receding *away from each other* at velocities that are approximately proportional to their distances from one another. (Equivalently, we may say that this red-shift occurs because the light waves are “stretched” as the universe expands.⁵²) If we “wind this movie backwards”, we can envision a point in time when the entire universe (including all of space) was once crushed into a single tiny singularity. The “explosion” of this singularity to create our present universe is called the *big bang*.

As a result of Hubble’s observations, Einstein abandoned his *cosmological constant* (calling it “the biggest blunder of my life”), since it was not required to account for an *expanding universe*. However, some cosmologists (such as the Belgian priest Father George Lemaitre) continued to use the cosmological constant, and today it is coming back into favor for a variety of theoretical and observational reasons. (One reason is that, without the cosmological constant, calculations based on the Einstein Field Equations estimate that the big bang occurred around 10 billion years ago, which doesn’t seem to be enough time to allow for stellar evolution.) Modern field theory associates the *cosmological constant* with the energy density of the vacuum.⁵³

The basic development of a cosmological model for a “big bang” universe was actually begun before Hubble’s red-shift discoveries. In fact, the classical “big bang” model of the universe was developed by de Sitter (1917), Friedmann (1922), Lemaitre (1927), and Robertson (1929).⁵⁴ (The “big bang” was not, however, generally accepted by scientists until the late 1960s, since, for philosophical reasons, scientists generally preferred Fred Hoyle’s competing *steady state* theory.) The metric which has become the most popular in describing the universe as a whole (partially because it is purely kinematic and makes no dynamical assumptions) is the *Friedmann-Lemaitre-Robertson-Walker (FLRW)* family of solutions to the Einstein Field Equations. These solutions (which are not general solutions, but rather are based on assumed symmetries) are all *homogeneous*, and are either negatively curved, positively curved, or flat, depending on the *critical density* of the universe that is assumed.⁵⁵

“Big bang” theory predicts that we should be able to detect a faint, strongly red-shifted glow from the original big-bang event, no matter which direction in the sky we measure. In 1965, the discovery by radio astronomers Arno Penzias and Robert Wilson of a nearly uniform “glow” from everywhere in the sky of 3-degree-Kelvin cosmic microwave background radiation (abbreviated *CMBR*) provided further strong confirmation of the “big bang” theory, and today either the “hot” big bang theory or a more-recent variant called the “inflationary” big bang theory is accepted by virtually all cosmologists. (Recent satellite measurements of the CMBR fall within 99.9% of what the “big bang” theory predicts: These satellite measurements show the CMBR to be around 2.728 degrees Kelvin.)⁵⁶

But while cosmologists and astronomers for the most part agree on the *origin* of the universe in a “big bang”, the *end*, or ultimate fate, of our physical universe is a much more open question. The answer to this question, like the answer to the question about the curvature of the universe, depends on estimates of the *critical density* of the universe:

[C]osmologists envision two possible fates for the universe:

- Endless expansion
- “The Big Crunch”

The evolution of the universe is determined by a struggle between the momentum of expansion and the pull of gravity. The rate of expansion is determined by the Hubble constant, H_0 , while the strength of gravity depends on the density of the universe. If the density of the universe is less than the “critical density”, which is proportional to the square of the Hubble constant, then the universe will expand forever. If the density of the universe is greater than the “critical density”, then gravity will eventually win and the universe will collapse back on itself. . .

ON SYSTEMS

The density of the universe also determines its geometry. If the density of the universe exceeds the critical density, then the geometry of space is closed and positively curved like the surface of a sphere. This implies that photon paths diverge slowly and eventually return back to a point. If the density of the universe is less than the critical density, then the geometry of space is open, negatively curved like the surface of a saddle. If the density of the universe exactly equals the critical density, then the geometry of the universe is flat like a sheet of paper. Thus, there is a direct link between the geometry of the universe and its fate.

The simplest version of the *inflationary* theory, an extension of the *big bang* theory, predicts that the density of the universe is very close to the critical density, and that the geometry of the universe is flat, like a sheet of paper.⁵⁷

The MAP satellite is currently measuring the very-slight fluctuations which exist in the cosmic microwave background radiation (CMBR). These fluctuations depend on the direction in the sky for which the CMBR is measured. As a result of these measurements, astronomers hope to get further evidence as to whether the physical universe is positively curved, negatively curved, or flat.⁵⁸

Teleological Implications of General Relativistic Systems

General Relativistic Systems often have *significant strong & persistent gravitational interactions* between their parts, and consequently also often have *significant constitutive characteristics* (“emergent properties”).

Furthermore, since General Relativity is expressed by a set of *nonlinear* differential equations that are *unsolvable* in the general case, we may also say that General Relativistic Systems are *implicitly nondeterministic* in the general case. By this I mean that General Relativity cannot deterministically predict the behavior of many (probably most) gravitational systems – in particular, those gravitational systems which involve *strong & persistent* gravitational attraction between *three or more* bodies (at least two of which have significant mass), as well as other gravitational systems for which no deterministic solution to the Einstein Field Equations can be found.

There are, of course, special cases for which the Einstein Field Equations *have* been solved. (The few such solutions which are *analytic* we may regard to be *deterministic*, while the *numerical* solutions we might call *quasi-deterministic*.) However, as in the parallel Newtonian theory of gravity, these special cases tend to be ones in which a single large body (usually spherical) dominates the system gravitationally, so that in these “simple” cases gravity can be regarded to be just a property of the large, dominant body, rather than as a true *constitutive characteristic* of the gravitational system as a holistic unity of significantly and mutually interacting parts. While a few two-body

solutions to the Einstein Field Equations have been found, General Relativity *cannot* deterministically solve the gravitational three-body problem any more than classical mechanics can: Three-body gravitational systems (and, presumably, n-body gravitational systems) therefore remain *chaotic systems*, even from a General Relativistic viewpoint.

All of the above-described *nonlinear* aspects of General Relativistic Systems distinguish them sharply from both Classical Mechanical Systems and Special Relativistic Systems. Of potential teleological interest are the many points of *constrained chance* implicit in many (if not most) General Relativistic Systems. As you will recall, moments of *constrained chance* in physical systems are possible *decision-points* of conscious beings in analogous teleological systems.

Unfortunately, though, the moments of *constrained chance* in General Relativistic Systems are not very promising in this regard, for the following reasons:

1. They exist only *implicitly* within those General Relativistic Systems for which no deterministic solution to the Einstein Field Equations can be found. In other words, General Relativity can tell us nothing *specific* about these moments of constrained chance.
2. They exist only in gravitational systems that are *chaotic*. As we shall see later in our later chapter **Nonlinear Complex Physical Systems**, other types of nonlinear systems, such as *dissipative structures*, are far more likely candidates for teleological analogs than are *chaotic structures*.
3. The large-scale objects-of-study to which General Relativity is usually applied (planets, stars, black holes, galaxies, etc.) are not generally of much teleological interest. (It is true that there are theories, such as the *Gaia hypothesis*, that treat planet earth as a living, conscious being,⁵⁹ and it is also true that Eric Jantsch has suggested that the stars may have certain quasi-living characteristics.⁶⁰ But such ideas, though teleologically suggestive, are not exclusively, or even principally, based on General Relativity.)

Nevertheless, it should be noted that there is one major exception to our statement that the objects-of-study of General Relativity are not of much teleological interest, and that is the *physical universe taken as a whole* (which we'll call, for short, the *cosmos*). The *cosmos* is of interest teleologically, in the first place, because it is the physical analog of the *pantheistic God*, who is conceived to be exclusively *immanent within* (i.e., *not* transcendent with respect to) the cosmos. In other words, the *pantheistic God* is a God who is simply the *World-Soul* of the cosmos, and nothing more. In the second place,

ON SYSTEMS

the cosmos is teleologically interesting because of our natural hope that understanding “the nature and destiny of the universe” will tell us something about our own human destiny and purpose. (This hope, as we shall see, will tend to be disappointed, but it is a natural hope nonetheless.) And yet a third reason to consider the cosmos from a teleological point-of-view is that such a discussion will enable us to deal in a relatively “simple” context with certain basic “science versus religion” issues that tend to get engulfed in the complexity and controversy surrounding the neo-Darwinian theory of biological evolution. (The entire second part of this book will be devoted to biological evolution.)

When Einstein’s first cosmological paper was published in 1917, the *steady-state* theory of the cosmos was supremely dominant. According to this theory, the cosmos had no beginning point in time and will have no end, but rather has existed and always will continue to exist pretty much as we can observe it today. Given this scientific consensus, it is no wonder that Einstein felt that he had to add the cosmological constant to his Field Equations in order to keep the galaxies at approximately a constant distance from one another through time.

But *why* was this erroneous *steady-state* theory so dominant in astronomy, in the absence of actual evidence one way or the other? For the same two reasons that *uniformitarianism* (as opposed to catastrophism) was dominant in geology and *Darwinism* was dominant (and continues to be dominant) in biology.

The first of these two reasons was that *steady-state* theory, *uniformitarianism*, and *neo-Darwinism* all presupposed a worldview in which changes in the physical world were thought to *always* be minute, gradual, and essentially random. Such a worldview was intuitively most consistent with the dominant idea during the 19th and early-20th centuries that each and every physical system would soon be shown to be “nothing but” a classical mechanical system: In a classical mechanical system, you will recall, *nothing* big, surprising, or catastrophic ever really “happens” (except, perhaps, for the possibly-sudden establishment of the “initial conditions” of the system), and *everything* proceeds with a steady, fixed determinism. The only exceptions to this, from the classical mechanical viewpoint, are small, minor, random “errors in measurement”, together with the very few moments in which the trajectory of a classical-mechanical body may be uncertain (e.g., a ball balanced precariously at the top of a hill).

The second of the two reasons for the general philosophical appeal of the *steady-state*, *uniformitarian*, and *Darwinist* theories, for scientists, was that many scientists felt that giving any importance to large, sudden, catastrophic

events (such as asteroid impacts, sudden floods, or the “big bang”) would only give aid and comfort to their theological enemies, who tended to see the actions of God in such dramatic, large-scale events. By limiting, and if possible eliminating, all such dramatic moments of *macroscopic constrained chance* from their physical theories, many scientists hoped to leave God with no major analogical decision-points at which to act within the physical universe.

The prevalence of this kind of thinking in the scientific community is why, even after Edwin Hubble discovered strong evidence of an expanding universe (and therefore of a “big bang”) in the late 1920s, the majority of scientists simply refused to believe it, on the grounds that a universe which had a beginning would have to have a Creator, a proposition which they regarded to be self-evidently unscientific.⁶¹ The fact that one of the major “big bang” theorists was a Catholic priest (Father George Lemaitre) further encouraged their suspicions. In fact, the *steady-state* theory of the universe (advocated especially by the prominent astronomer Fred Hoyle, who actually coined the phrase “big bang” as a term of scorn and derision⁶²) continued to be accepted by the majority of astronomers right up until the discovery of the three-degree cosmic microwave background radiation (CMBR) in 1965. It was that discovery which, more than anything else, resulted in a (very reluctant) scientific consensus in favor of the “big bang” cosmological model, rather than the steady-state model.

Parallel to these astronomical and cosmological developments, later twentieth century geologists (including Walter Alvarez, in the 1960s) discovered major geological features and major geological facts that could *only* be plausibly explained by such geological catastrophes as asteroid hits or sudden floods: This finally resulted in geologists’ (very reluctant) abandonment of Charles Lyell’s original formulation of the principle of geological *uniformitarianism*.

Nevertheless, it is a significant fact in the history of science that dogmatic adherence to the belief that all of science can be reduced to linear, deterministic classical mechanics (or, at least, to a quantum mechanics that is similarly linear and deterministic at the *macroscopic* scale), coupled with an equally dogmatic adherence to atheism, managed to significantly retard the progress of the sciences of astronomy, cosmology, and geology for over thirty years. (In fact, as we shall see in the second part of this book, the completely untenable, yet comfortably linear and gradualistic, neo-Darwinian theory of biological evolution continues to be held by virtually all scientists *to this day*, largely because of the classical-mechanical and atheistic biases we have just mentioned.)

ON SYSTEMS

In spite of the current scientific consensus in favor of the “big bang” model of the universe, many scientists remain uneasy at the opportunity it would seem to provide for a divine Creator to dramatically create the cosmos virtually *ex nihilo* (i.e., out of nothing). Typical is the immensely popular book *A Brief History of Time*, written by the great English physicist Stephen Hawking. In the tradition of Laplace, he goes to great lengths to make clear that he has no need of the hypothesis of God in order to scientifically explain the creation of the cosmos, nor does he even need God to endow the cosmos with purpose or meaning: Rather, he says (or, at least, implies) that a grand, unified theory of relativity and quantum mechanics would provide us with all the sense of meaning and purpose in life that anyone would ever need.

Hawking’s preferred version of the “big-bang” theory is an “inflationary, no-boundary” cosmology in which time did not begin at a specific point, but rather gradually emerged from something more complex, and in which space and time ultimately form a kind of closed surface without boundary.⁶³

Hawking writes:

The idea that space and time may form a closed surface without boundary also has profound implications for the role of God in the affairs of the universe. With the success of scientific theories in describing events, most people have come to believe that God allows the universe to evolve according to a set of laws and does not intervene in the universe to break these laws. However, the laws do not tell us what the universe should have looked like when it started – it would still be up to God to wind up the clockwork and choose how to start it off. So long as the universe had a beginning, we could suppose it had a Creator. But if the universe is really completely self-contained, having no boundaries or edge, it would have neither beginning nor end: it would simply be. What place, then, for a Creator?

[I]f we do discover a complete theory [uniting relativity and quantum mechanics], it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason – for then we would know the mind of God.⁶⁴

How should we respond to this kind of teleological thinking in the popular writings of contemporary scientists?

First, we must admit that these scientists are correct in saying that they have no need for the “hypothesis” of God in order to do science. As we have frequently noted earlier, the essential method of modern science is to “bracket out the subject” in favor of studying the *object*. Consequently, for science, the only subject who ultimately exists is a single universal generic subject, featureless in his characteristics. The particularities of *all* particular subjects

(including God) are “bracketed out” and are not permitted to have *any* part in scientific explanations. (Some teleological interpretations of quantum mechanics would at least indirectly challenge this viewpoint, but we will be deal with that problem in the following chapter on **Quantum Mechanical Systems**.) And so, the reason why science does not need a divine Creator to explain the origin of the cosmos is not because of some complex and controversial mathematical theory of “no-boundary” cosmology, but rather simply because of those scientific methodological considerations that exclude teleological explanations from modern science *a priori*.

To further clarify this point, the following teleological statements are *not* considered to be acceptable modern scientific explanations:

1. In the beginning, God *created* the heavens and the earth.
2. The universe is the way it is because it was *intelligently designed*.
3. The lightening bolt struck the tree because the thunder god Thor *decided* to throw it.
4. The water in the glass is gone because Fred Smith *decided* to drink it.

Yes, I know that explanations similar to number 4 above *do* appear in psychological, sociological, and anthropological scientific literature, but that’s why those sciences are called “soft” sciences, isn’t it? Instead, a proper modern scientific description of the situation in explanation 4 would say something like:

The physical system which is the analog of the teleological being called Fred Smith arrived at a moment of *immanently objective, macroscopic constrained chance* at which that physical system could have either proceeded to pick up the glass of water and consume its contents, or could have proceeded along certain other paths. The physical system proceeded along the first-mentioned path.

But from these considerations it is also clear that the fact that God is neither needed nor welcomed as a scientific explanation does not prove the nonexistence of God, any more than the scientific inadmissibility of statement 4 above proves the nonexistence of Fred Smith. Rather, God, Thor, and Fred Smith are *teleological* beings who may or may not have physical analogs within *physical* reality. Consequently the question of the *existence* of God, Thor, or Fred Smith is a question that must be answered within the context of an overarching *teleological* (e.g., religious) understanding that is based on a “bracket out the object” methodology rather than on the “bracket out the subject” methodology of modern science. (See our Book I, *WORLDVIEWS*, for a full discussion of the difference between these two general methodologies.)

ON SYSTEMS

Of course, it *is* possible to construct an overarching teleological understanding that is founded, in part, on this axiom: “No teleological being can exist unless it has a direct and complete analog within the physical universe.” Such an axiom would *disallow* the existence of a transcendent God, angels, or Laplace’s demon, while it would *allow* for the *possible* existence of an immanent pantheistic God, Thor, or Fred Smith.

However, such a teleological axiom is really no more “scientific” than any other axiom concerning the teleological world. (After all, there exist physical systems, such as classical mechanical systems, which are not analogous to any teleological being, so why can’t there also exist teleological beings who aren’t completely analogous to any physical system?)

Furthermore, we have already seen a number of reasons why virtually all developed religious traditions affirm that God is, in fact, *transcendent* as well as immanent with respect to the physical universe. These include: the intuition that the visible created universe is “fallen” and imperfect, the fact that an all-knowing, all good, and all-powerful God has no conceivable analog within the physical universe, and finally (apropos our current context) the observation that, in order for God to *create* the physical universe, He must in some sense *transcend* it.

The foregoing quotation from Stephen Hawking is also typical of much contemporary popular scientific writing in several other ways. Notice, for example, the quaint 19th century tone of its teleological speculations: It is assumed that most of the few remaining theists must be deists, since the fixed and determined laws of nature supposedly prevent God from acting on the linear, mechanistic, “clockwork” universe at any moment other than the moment of its creation. Notice too Hawking’s dream that the discovery of a theory unifying relativity and quantum mechanics will lead to “the ultimate triumph of human reason”, such that humanity will have the complete “mind of God”: We will then be able to know *everything* that God (if He exists, which Hawking finds doubtful) knows!

Now, as perhaps one of the ten most brilliant physicists on planet earth, Stephen Hawking certainly is aware that the project to explain all physical systems (including the physical universe as-a-whole) as clock-like classical-mechanical systems is as dead as the proverbial dodo: He is certainly aware of Poincare’s proof that all three-body gravitational systems are chaotic, is aware of the insolvability of the nonlinear Einstein Field Equations in the general case, and, furthermore, is undoubtedly aware of the Heisenberg Uncertainty Principle in quantum mechanics (to be discussed in the following chapter). Yet, although classical-mechanical determinism as an overarching *scientific* project is clearly dead, as an *ideology* it continues to march on in

the popular writings of Stephen Hawking and other contemporary scientists, just as if all of twentieth-century science simply *did not happen!*

Particularly poignant is Hawking's hope that a complete theory unifying relativity and quantum mechanics, if discovered, will be understood "in broad principle by everyone, not just a few scientists", ultimately leading to an agreement among everyone as to "why it is that we and the universe exist".

But when "ordinary people" wonder "why it is that we and the universe exist", the "why" they are particularly concerned with is the *teleological* "why": They want to know, above all, what the ultimate *purpose* of life and the universe is. The answer to the *physical* "why" question (whether, for example, the "hot" big bang or the "inflationary" big bang more accurately describes the earliest moments of the physical universe) are of much less importance to them. Yet, because the scientific method rigorously excludes teleological considerations, science is simply not capable of answering this all-important *teleological* "why" question. Rather, the *teleological* "why" question can only be answered via teleological (especially religious) "bracket out the object" methods.

It is a tragic sign of the extreme skewing of contemporary Western culture in favor of scientific methods, as opposed to religious/teleological methods, that we look to prominent scientists (whose job it is to rigorously exclude teleology from their work) to tell us the answer to the ultimately *teleological* question of "why it is that we and the universe exist". It is not surprising, then, that the answers we receive are "slim pickin's" indeed.

Now, while it is perfectly appropriate for contemporary cosmologists to exclude God and "intelligent design" from *scientific* explanations of the origin of the cosmos, nothing prevents us *in principle* from regarding the "big bang" theory to be the physical analog of the *teleological* idea that "In the beginning, God created the heavens and the earth", particularly if this latter statement is interpreted as referring to the sudden divine creation of the physical universe *ex nihilo* (out of nothing) "at the beginning of time". In other words, we *could* regard the "big bang" event to be the physical analog of the divine creation of the cosmos. But is it *wise* to do so?

In my opinion, it is *not* wise to do so, except possibly very tentatively and speculatively. There are several reasons for this. The first is that the divine creation of the physical universe is one of the surest spiritual facts (or spiritual conclusions) in developed religious traditions: It follows almost immediately from the teleologically foundational concept of a *transcendent* God. By contrast, the "big bang" theory (even though it is currently dominant in physical science) remains highly speculative in its details: There are "hot" big bang theories, "inflationary" big bang theories, "multiverse" big bang

ON SYSTEMS

theories in which “black holes” are constantly spawning new “big bang” universes in other dimensions, “self-reproducing” big bang theories in which the cosmos copies itself constantly (perhaps even more than once a second), and so on.⁶⁵ It therefore doesn’t make much sense to try and prove something as *teleologically certain* as God’s creation of the cosmos by identifying it with something as *physically speculative* as the “big bang”.

The second reason for us to be wary of identifying the “big bang” with divine creation is that we are then obligated, it seems to me, to give similar teleological importance to events at the temporal “end” of the physical universe (if, indeed, the physical universe has any temporal “end”). Concerning this question of the possible ultimate fate of the cosmos there is far less agreement among cosmologists than there is concerning the cosmos’ origin in some kind of “big bang”.

Recall that we mentioned earlier two possible fates for the cosmos:

- 1) The expanding universe will continue to expand forever, with the galaxies continuing to recede away from each other into nothingness.
- 2) The expansion will stop, so that all of the galaxies will eventually be gravitationally attracted back together into a “big crunch”. The resulting tiny singularity would then be the *unconditional equifinal* state of the cosmos.

We may also consider a third possibility:

- 3) The cosmos is characterized by *cyclicity* rather than *equifinality*, and will therefore expand and contract in an eternal cycle of “big bang” followed by “big crunch” followed by “big bang” etc.

A fourth possibility suggests itself:

- 4) The cosmos as a whole physical system is not characterized by *expansion into nothingness*, *big-crunch equifinality*, or *never-ending cyclicity*, but rather is simply an eternal *chaotic* system (similar to a three-body gravitational system).

And, finally a fifth possibility:

- 5) The cosmos, in accordance with the second law of thermodynamics, will ultimately, equifinally die a “heat death” that is characterized by pure randomness and

“maximum entropy”. (We will discuss these latter concepts in our later chapter on **Linear Thermodynamic Systems**.)

All five of these possible fates of the cosmos pose significant problems if we are going to interpret them teleologically: The first and fifth possibilities (that the universe will expand eternally into nothingness, or will ultimately die a thermodynamic “heat death”) suggest teleological analogs of the utmost bleakness. The second possibility (the “big crunch”) *does* give the physical universe a dramatic ending to match its dramatic beginning, but it is much harder to relate this “big crunch” to (for example) specific events predicted in the Biblical book of Revelation than it is to relate the “big bang” to chapter 1 of the Biblical book of Genesis. The third possibility (an eternal cycle of “big bangs” and “big crunches”) conforms fairly well to Hindu cosmology, but even Hindus regard *transcendent escape* from these meaningless cycles to be their ultimate goal. Lastly, the fourth possibility (an eternal, *chaotic* cosmos) analogically would suggest a teleology that regards the cosmos to be ultimately teleologically *meaningless* from a human point-of-view (though possibly *not* meaningless from a transcendent divine point-of-view).

The above considerations provide us with yet another reason for regarding God to be *transcendent* (as well as immanent). For the ultimate purpose and goal of a purely immanent *pantheistic* God would have to be teleologically analogical to one of the five possible fates for the physical universe listed above: And we have seen that it is not at all certain that the cosmos even *has* a physically equifinal state. (Instead, the physical universe might ultimately be *cyclical*, *chaotic*, or might just continue forever *expanding into nothingness*.) Furthermore, the remaining two possible equifinal states for the cosmos (a single, final “big crunch” or an ultimate thermodynamic “heat death”) are both speculative and (analogically) teleologically unsatisfactory with respect to suggesting any deep or meaningful ultimate purpose and goal on the part of the pantheistic World-Soul. That is the reason why developed religious traditions have nearly always looked to a *transcendent* God to reveal the ultimate purpose and goal of both humanity and the cosmos.

And so, while there is no conflict between *faith* and *reason*, there *is* a conflict between the affirmation of the *transcendence* of God (on the one hand) and (on the other hand) some arbitrary requirement that every existing teleological being must have a direct and complete physical analog within the physical universe. One important (and nearly universal) meaning of *faith* is therefore the affirmation of God’s *transcendence*.

Quantum Mechanical Systems

The beginning of the twentieth century not only saw the birth of Einstein's Special Theory of Relativity (which revolutionized the scientific view of the macroscopic world), but also the birth of Quantum Theory (which revolutionized the scientific view of the sub-microscopic world). Relativity Theory and Quantum Theory have never been successfully combined (except in a limited way by QED, Quantum Electrodynamics). The eventual unification of these two theories into a grand "Theory of Everything" is the great dream of contemporary physicists such as Stephen Hawking.

Quantum Theory began when the great German physicist Max Planck studied the problem of calculating the total energy inside a heated "black box" (i.e., the energy distribution of "black body radiation"). The basic problem was that classical means of approaching this problem (such as Wien's formula and the Rayleigh-Jeans formula) led to wrong and absurd conclusions, including infinite energies.

To solve this problem, Planck proposed in 1900 that energy changes take place discontinuously and discretely as integral multiples of a small unit of energy he called a *quantum* (plural *quanta*), in accordance with the formula $E = h\nu$, where E is the energy of the quantum, ν is the frequency of radiation, and h is a universal constant of proportionality now known as *Planck's constant*. Planck regarded the quantum to be only a useful statistical fiction, since the idea that light (and other forms of electromagnetic radiation) had a particle-like structure contradicted the prevailing classical view that light is comprised of continuous waves.

It remained for the young physicist Albert Einstein to boldly put forth the idea in 1905 that light is, in fact, *actually* composed of particle-like units of energy (later called *photons*, which are the quanta of light). He did so in the context of explaining the *photoelectric effect*, whereby electrons can be emitted from a thin metal sheet when light strikes its opposite surface. (The light meters in cameras work using this principle.) It turns out that, if the incident light is below a certain frequency (called the *threshold frequency*), *no* electrons are emitted from the metal. However, as soon as the frequency of the light is high enough so that each photon's energy $h\nu$ exceeds a certain minimum value called the *work function of the surface* (ϕ), which varies with the type of metal, electrons begin to be emitted from the opposite surface of the metal with a maximum kinetic energy equal to $h\nu - \phi$. Another way of putting this is that, if h is Planck's constant, ν_0 is the threshold frequency, and ν is some frequency of light greater than the threshold frequency, then the electron will be ejected with a maximum kinetic energy of $h(\nu - \nu_0)$. (This formula was verified by Millikan for ordinary light and by Maurice de Broglie for X-rays.⁶⁶) Einstein also proposed that the momentum p of each

ON SYSTEMS

photon is $p = h/\lambda$, where λ is the wavelength of the light and h is Planck's constant. (In 1921 Einstein won the Nobel Prize in Physics principally for his photoelectric theory, rather than for his relativity theories.)

Einstein concluded a subsequent 1917 paper on the Quantum Theory of radiative equilibrium by writing:

These features of the elementary processes would seem to make the development of a proper quantum treatment of radiation almost unavoidable. The weakness of the theory lies in the fact that, on the one hand, no closer connection with the wave concepts is obtainable and that, on the other hand, it leaves to chance the time and direction of the elementary processes; nevertheless, I have full confidence in the reliability of the way entered upon.⁶⁷

Meanwhile, in 1913, Niels Bohr was able to use the new Quantum Theory to explain both atomic structure and atomic spectra, by showing the connection between the discrete energy levels of an atom's electrons in their various "orbits" or "shells" (which surround an atomic nucleus that consists of protons and neutrons) and the frequencies of light given off and absorbed by the atom. Bohr showed that each electron's associated energy could change only in discontinuous "jumps" as the atom either absorbed or emitted a photon. Concerning this accomplishment, Albert Einstein wrote:

That this insecure and contradictory foundation [of Quantum Theory in 1913] was sufficient to enable a man of Bohr's unique instinct and tact to discover the major laws of the spectral lines and of the electron-shells of the atoms, together with their significance for chemistry, appeared to me like a miracle – and appears to me as a miracle even today. This is the highest form of musicality in the sphere of thought.⁶⁸

In 1924 Louis de Broglie proposed that, not only does light sometimes behave as if it were composed of waves and sometimes behave as if it were composed of particles, but the same is true of subatomic particles like the electron! This hypothesis was confirmed in 1927 by Clinton J. Davisson and Lester H. Germer, who observed the wave phenomenon of the diffraction of a beam of electrons.⁶⁹

During the 1920s Quantum Theory became mathematically formalized as *quantum mechanics* (often abbreviated as *QM*). In 1925 Werner Heisenberg developed the *matrix algebra* formulation of quantum mechanics, while in 1926 Erwin Schrodinger developed the *wavefunction* formulation of QM.

Schrodinger was able to show that if the single electron in a hydrogen atom was really a "standing wave", it would assume frequencies which were exactly equivalent to what Bohr described as discrete orbits [and would also have] energies the same as those calculated by Heisenberg. By showing that the electron's energy levels could be wave patterns,

Schrodinger solved the same problem . . . that Heisenberg had solved with his collection of observables [i.e., his matrix algebra].⁷⁰

Both the Heisenberg and the Schrodinger formulations of QM were soon proved to give identical results, but Schrodinger's formulation has prevailed, largely because physicists are more comfortable and familiar with wavefunction mathematics.

In 1928 P.A.M. Dirac succeeded (in a limited way) in combining the new quantum ideas with Special Relativity. The resulting theory is called *quantum electrodynamics* (abbreviated *QED*), and it succeeded in predicting the existence of anti-particles, including the *positron* (the positively charged anti-particle of the electron).

Other developments in quantum mechanics included *quantum statistics*, presented in one form by Einstein and the Indian physicist S.N. Bose (*Bose-Einstein statistics*, which apply to particles of the type known as *bosons*) and in another form by Dirac and Enrico Fermi (*Fermi-Dirac statistics*, which apply to particles of the type known as *fermions*).

Also of great importance in contemporary quantum mechanics is *quantum field theory*. In quantum field theory, *interactions* between particles result from the exchange of a type of particle called a *gauge boson*. For example, the *electromagnetic force* arises from the exchange of *photons*, the *weak nuclear force* results from the exchange of *W and Z particles*, the *strong nuclear force* derives from the exchange of *gluons*, and (more speculatively) *gravitational force* arises from the exchange of *gravitons*.⁷¹

As a result of extensive experimental evidence gathered through the use of giant *particle accelerators* (some many miles in diameter), over 150 subatomic particles have been studied and cataloged. In addition to the *gauge bosons* mentioned in the preceding paragraph, there are *material particles* divided into three categories: *leptons*, *mesons*, and *baryons*. The article called "The Particle Zoo" in the *Physics FAQ* gives a "crash course" in these particles:

Leptons are particles that are like the electron: they have spin 1/2, and they do not undergo the strong interaction. There are three charged leptons, the electron, muon, and tau [plus their antiparticles, such as the positron], and three corresponding neutral leptons, or neutrinos. (The muon and the tau are both short-lived.)

Mesons and *baryons* both undergo strong interactions. The difference is that mesons have integral spin (0,1,...), while baryons have half-integral spin (1/2, 3/2,...). The most-familiar baryons are the proton and the neutron; all others are short-lived. The most-familiar meson is the pion; its lifetime is 26 nanoseconds, and all other mesons decay even faster.

ON SYSTEMS

Most of those 150+ particles are mesons and baryons, or, collectively, *hadrons*. The situation was enormously simplified in the 1960s by the “quark model”, which says that hadrons are made out of spin-1/2 particles called *quarks*. A meson, in this model, is made out of a quark and an anti-quark, and a baryon is made out of three quarks. We don’t see free quarks (they are bond together too tightly), but only hadrons; nevertheless, the evidence for quarks is compelling.⁷²

Quantum mechanics has proved to be an extremely accurate explainer and predictor of the results of all of these scientific observations and experiments concerning phenomena at the sub-microscopic level.

The above discussion of quantum mechanics has, of course, been merely a superficial overview of an extremely complex subject. However, our main interest here, as you will recall, is not to discuss the specific *content* of scientific theories, but rather to view those scientific theories from a *general systems* perspective, and to deal with *epistemological* and analogical *teleological* issues which may be raised in connection with them. Towards that end, let’s now turn our attention to the general structure of Schrodinger’s wavefunction formulation of quantum mechanics, which is by far the most influential and “standard” formulation of QM.

The Schrodinger Wavefunction Formulation of QM

The first thing we need to note concerning the Schrodinger wavefunction (which is usually symbolized by the Greek letter *psi* ψ) is that it is a *linear* function. We know from our discussion of **Classical Mechanical Systems** and **Special Relativistic Systems** that *linear* functions generally model physical systems that are *deterministic*, *time-reversible*, obey the *superposition principle*, have dominantly (or exclusively) *summative characteristics* rather than constitutive characteristics, and have *weak and/or transient interactions* (or *no interactions* at all) between their parts. All of this is true of the Schrodinger wavefunction as well, so that the ψ function is in this respect more similar to Maxwell’s *linear* electromagnetic equations than to the *nonlinear* Einstein Field Equations of General Relativity.

However, the ψ function also differs from *both* the Maxwell equations *and* the Einstein equations in some very important respects. In the first place, although Schrodinger initially thought of his wavefunction as referring to *physically real* waves, Max Born soon re-interpreted the ψ waves to be *waves of probability*. For example, for a given experimental setup the wave-pattern of the ψ function would indicate the *probability* of detecting an electron at a particular point in space. In spite of some subsequent attempts to once again interpret ψ waves to be physically real waves (such as the *pilot*

wave interpretation of Louis de Broglie and David Bohm,⁷³ the *transactional* interpretation of J.G. Cramer,⁷⁴ and perhaps the *relativistic quantum mechanics* interpretation of E. Marx⁷⁵), for the most part physicists have accepted Max Born's *waves-of-probability* interpretation of the ψ function. One major reason for this is that, while (for example) a simple quantum system such as a hydrogen atom could be easily visualized as being surrounded by a single standing-wave electron field using the ψ function, more complex atoms surrounded by multiple electrons could not be so easily visualized because their ψ function requires three additional dimensions for every electron added to the system (three dimensions for one electron, six dimensions for two electrons, nine dimensions for three electrons, and so on).⁷⁶

Now, because the ψ function is generally regarded to represent waves of probability, *probability itself* has a significance in quantum mechanics that is very different from its significance in classical mechanics. In classical mechanics, scientists use probability to *either* deal with cases where calculating all of the forces is too complex (for example, the flipping of a coin), *or* to deal with cases where so many particles are involved that it makes no sense to try and keep track of each particle (for example, the millions of molecules that comprise a gas bouncing off of each other randomly within a sealed glass container). Nevertheless, within classical mechanics it is always assumed that the complex forces affecting the toss of the coin could *in theory* be specified precisely and that the trajectories of all of the particles in the gas could *in theory* be tracked precisely. However, with respect to probability in quantum mechanics it is not at all clear that we could ever (even *in theory*) “get behind” the probabilistic description of QM's ψ function to arrive at a more-precisely defined description of sub-microscopic reality. In fact, most physicists believe this to be impossible and therefore regard quantum mechanics to be “complete” (in this rather technical and special sense of the word “complete”).

The most-prominent among the few physicists who did *not* accept the “completeness” of quantum mechanics was Albert Einstein. Although (as we have seen) he made absolutely vital contributions to quantum theory prior to the 1920s, during the 1920s he became increasingly uncomfortable with the “final” formulations of QM by Heisenberg and Schrodinger. Instead, he attempted for the rest of his life to formulate a *nonlinear* Unified Field Theory that would be similar to General Relativity, but would include the other forces of nature (the *electromagnetic force*, the *strong nuclear force*, and the *weak nuclear force*) in addition to the *gravitational force* of General Relativity. Ideally, he hoped to entirely replace the concept of a material

ON SYSTEMS

particle and its trajectory with this Unified Field Theory. In this effort he was unsuccessful.

The extreme difficulty of what Einstein was attempting to do is evident from our prior discussions: Both the electromagnetic force and the strong nuclear force represent far more intense *strong and persistent interactions* between physical particles than is the case with the relatively weak gravitational force. Furthermore, even the nonlinear Einstein Field Equations of General Relativity are solvable only where one (or two) massive bodies gravitationally dominate the system (for example, the earth with respect to the objects on its surface, the sun with respect to the planets, a black hole with respect to lighter objects in its vicinity, or the physical universe taken as a whole). By contrast both the electromagnetic force and the strong nuclear force involve *many* sub-microscopic particles (sometimes *millions* of those particles) in intermediate or strong persistent interaction, with no one of these particles being dominant over the others. No wonder most physicists regarded Einstein's approach to be hopeless and a waste of time! By contrast, the "messy details" of all of these individual intermediate/strong sub-microscopic particle interactions can be ignored if we regard Schrodinger's linear, probabilistic ψ function (or some similar statistical function) to be the ultimate "best we can do" in describing sub-microscopic reality.

In addition to Einstein, a few other physicists (notably Louis de Broglie and David Bohm) have attempted to "get behind" the probabilistic ψ function of QM by suggesting that *hidden variables* might exist in the sub-microscopic world that could allow for a non-statistical explanation of sub-microscopic phenomena. But their efforts have ultimately not been any more successful than Einstein's.⁷⁷

If, then, we accept the standard Max Born interpretation that the Schrodinger ψ function describes *probability waves*, we have the following remarkable situation: With respect to the ψ function *taken as a whole*, quantum mechanics is completely *deterministic* – as deterministic, in fact, as classical mechanics. (Time is *reversible*, the *superposition principle* holds, all of the important characteristics of the ψ waves are *summative*, there is *weak, transient, or nonexistent* interaction between the ψ waves, etc.) However, *encapsulated within* these ψ waves at the sub-microscopic level is an *irreducible element* of chance and probability which masks (one may speculate) *strong, persistent, nonlinear interactions* between the individual sub-microscopic particles themselves.

In other words, the ψ function, when applied to a particular experimental situation, will tell you (for example) the *exact probability* that your experimental setup will detect an electron at a particular point in space at a

particular point in time. Furthermore, from a given set of “initial conditions” known at some point in time, the ψ function will enable you to *deterministically* calculate forwards and backwards in time *exactly* what the *probability* of finding an electron at that point in space would have been at any *other* time in the past or future. However, the ψ function *cannot* tell you whether or not you will in fact *actually* detect an electron at that point in space for a given run of the experiment. It is evident, then, that quantum mechanics cannot predict the results of an *individual* experimental run, but can *very accurately* predict the statistical results of a *set* of such experimental runs. This is but one of the fascinating epistemological features of quantum mechanics.

Other unique aspects of the ψ wavefunction arise because it *must* take into account the *discontinuous* and *particle-like* nature of sub-microscopic reality, as well as the *continuous* and *wave-like* nature of that reality. For one thing, this necessitates a revision of the *Hamiltonian function* that we discussed earlier in the context of **Classical Mechanical Systems**. Ilya Prigogine and Isabelle Stengers explain:

First and foremost, a new formulation, unknown in classical physics, had to be introduced to allow “quantitization” to be incorporated into the theoretical language. The essential fact is that an atom can be found only in discrete energy levels corresponding to the various electron orbits. In particular, this means that energy (or the Hamiltonian) can no longer be merely a function of the position and the momentum, as it is in classical mechanics. Otherwise, by giving the positions and momenta slightly different values, energy could be made to vary continuously. But as observation reveals, only discrete levels exist.

We therefore have to replace the conventional idea that the Hamiltonian is a function of position and momenta with something new. The basic idea of quantum mechanics is that the Hamiltonian as well as the other quantities of classical mechanics, such as the coordinates q or momenta p , now become [Hermitian] *operators*. This is one of the boldest ideas ever introduced in science . . .

It is a simple idea, even if at first it seems somewhat abstract. We have to distinguish the operator – a mathematical operation – and the object on which it operates – a function. As an example, take as the mathematical “operator” the derivative represented by d/dx and suppose it acts on a function – say x^2 . The result of this operation is a *new* function, this time $2x$. However, certain functions behave in a peculiar way with respect to derivation. For example, the derivative of e^{3x} is $3e^{3x}$. Here we return to the original function simply multiplied by some number – here, 3. Functions that are merely recovered by a given operator to them are known as *eigenfunctions* of this operator, and the numbers by which the eigenfunction is multiplied after the application of the operator are the *eigenvalues* of the operator.

ON SYSTEMS

To each operator there thus corresponds an ensemble, a “reservoir” of numerical values. This ensemble forms its “spectrum”. This spectrum is “discrete” when the eigenvalues form a discrete series. There exists, for instance, an operator with all the integers 0, 1, 2, . . . as eigenvalues. A spectrum may also be continuous – for example, when it consists of all the numbers between 0 and 1.

The basic concept of quantum mechanics may thus be expressed as follows: To all physical quantities in classical mechanics there corresponds in quantum mechanics an operator, and the numerical values that may be taken by this physical quantity are the eigenvalues of this operator. The essential point is that the concept of physical quantity (represented by the operator) is now distinct from that of its numerical values (represented by the eigenvalues of the operator). In particular, energy will now be represented by the Hamiltonian operator, and the energy levels – the observed values of the energy – will be identified with the [discrete] eigenvalues corresponding to this operator.⁷⁸

In other words, it turns out that for each possible quantity we might want to measure (an *observable*) there is a Hermitian *operator* that is associated with a certain set of special wavefunctions (*eigenfunctions*), each of which, in turn, corresponds to its own unique value (*eigenvalue*) of the quantity we want to measure.

Summary of the Essential Principles of QM

Based on our understanding of these ideas, we are ready to consider David Bohm’s summary of the essential principles of quantum mechanics:

Although there are several alternative formulations of [quantum mechanics] (due to Heisenberg, Schrodinger, Dirac, von Neumann, and Bohr), which differ somewhat in interpretation, they all have the following basic assumptions in common:

1. The fundamental laws of the quantum theory are to be expressed with the aid of a *wavefunction* (in general, many dimensional), which satisfies a *linear* equation (so that solutions can be superposed linearly).
2. All physical results are to be calculated with the aid of certain “observables”, represented by Hermitian operators, which operate *linearly* on the *wavefunction*.
3. Any particular observable is definite (sharply defined) only when the *wavefunction* is an eigenfunction of the corresponding operator.
4. When the *wavefunction* is *not* an eigenfunction of this operator, then the result of a measurement of the corresponding observable cannot be determined beforehand. The results of a series of measurements on an ensemble of systems represented by the same *wavefunction* will fluctuate at random . . . from one case to the next, over the various possibilities.

5. If the *wavefunction* is given by $\psi = \sum C_n \psi_n$, where [Σ represents superposition, i.e. the summing of the following wave expression for eigenvalues 1 through n ,] ψ_n is the eigenfunction of the operator in question corresponding to the n th eigenvalue, [and C_n is a coefficient which defines the composition of the state, then] the probability of obtaining the n th eigenvalue in a large ensemble of measurements will be given by $P_n = |C_n|^2$, [normalized so that the sum of the squares of all the coefficients is equal to 1].
6. Because of the non-commutation of many operators [such as momentum and position] which correspond to variables that must be defined together in classical mechanics, it follows that no *wavefunctions* can exist which are simultaneous *eigenfunctions* of all the operators that are significant for a given physical problem. This means that not all physically significant observables can be determined together, and even more important, that those which are not determined will fluctuate . . . at random . . . in a series of measurements on an ensemble represented by the same *wavefunction*.⁷⁹

Bohm's sixth point above, concerning the non-commutation of many of the Hermitian operators in quantum mechanics, is of special importance and requires further explanation. (For example, Heisenberg's famous *uncertainty principle* follows directly from the fact of the existence of non-commuting operators in QM.) Two of the most important of these *non-commuting operators* in quantum mechanics are the operators for *position* (i.e., *coordinate*) and *momentum*, q_{op} and p_{op} respectively. Again, we turn to Prigogine and Stengers for our further explanation:

One fundamental property results from the relation between operators in quantum mechanics: the two operators q_{op} and p_{op} do not *commute* – that is, the results of $q_{op}p_{op}$ and of $p_{op}q_{op}$ applied to the same function are different. This has profound implications, since only commuting operators admit common eigenfunctions. Thus we cannot identify a function that would be an eigenfunction of both coordinate and momentum. As a consequence of the definition of the coordinate and momentum operators in quantum mechanics, there can be no state in which the physical quantities, coordinate q and momentum p , both have a well-defined value. This situation, unknown in classical mechanics, is expressed by Heisenberg's famous uncertainty relations. We can measure a coordinate and a momentum, but the dispersions of the respective possible predictions as expressed by Δq , Δp are related by Heisenberg's inequality $\Delta q \Delta p \geq h$ [where h is *Planck's constant*]. We can make Δq as small as we want, but then Δp goes to infinity, and vice versa.⁸⁰

This non-commutation between the two operators q_{op} and p_{op} is not unrelated to the fact that, within quantum mechanics, position and momentum are no longer independent variables, but are instead connected via Planck's constant

ON SYSTEMS

h. Recall Einstein's famous formula (which he discovered in connection with his study of the photoelectric effect) $p = h/\lambda$, where p is the momentum, h is Planck's constant, and λ is the wavelength. This formula, of course, enables us to convert a measure of *length* (which is related to *position*) into a measure of *momentum* by using Planck's constant.⁸¹

It is also important to note that position and momentum are not the only non-commuting operators in quantum mechanics. For example, the *spin* property of a sub-atomic particle is specified integrally or half-integrally (depending on the type of particle) with respect to each of the three dimensions of space. However, measurements of this spin along each of the three space dimensions do not commute with one another. In other words, to the extent that we accurately measure the spin of the particle along one dimension of space, its spin along the other two dimensions of space appears to be uncertain and indeterminate.

Epistemological Issues in QM

In spite of the fact that quantum mechanics (QM) has been tremendously successful in predicting statistical experimental results related to the sub-microscopic realm, it is evident from the foregoing discussion that significant *epistemological* problems arise when we try to describe the relationship between our *macroscopic* experimental observations and the *sub-microscopic* quantum realities (what John Bell has picturesquely called the quantum "*beables*" [pronounced *BE-uh-bulls*]⁸²) which are supposed to be the *objective referents* of quantum mechanics. For example, it is often said that when a measurement is made (and the eigenvalue n is thereby determined), then the ψ function "collapses" into that one of its previously-superimposed eigenfunctions ψ_n which corresponds to the measured eigenvalue n . Unfortunately, no epistemological consensus exists as to what the "collapse" of the ψ function might *mean*! That is why some wags have described the dominant epistemological philosophy of most working scientists in the area of quantum mechanics to be "shut up and calculate"!

In a current physics FAQ on the Internet, we find the following listed among the *unanswered questions* of quantum physics:

What is meant by a "measurement" in quantum mechanics? Does "wavefunction collapse" actually happen as a physical process? If so, how, and under what conditions? If not, what happens instead?⁸³

Note that we *cannot* solve these serious epistemological problems by simply declaring that only the individual eigenfunctions are real, while the ψ wavefunction that results from their superposition is not real: Phenomena such as the wave-like diffraction and interference of electron beams require

that we accord the complete superposed ψ wavefunction some kind of “real” status as well.

One particularly dramatic experiment demonstrating the reality of the superposed ψ wavefunction was done in 1996 by Christopher Monroe and his colleagues at the National Institute of Standards and Technology in Boulder, Colorado. In this experiment a single beryllium atom was supercooled with a laser, then prodded with a fast sequence of laser pulses. As a result, the beryllium atom harmonically oscillated in such a way that a superposition of two “coherent-state wave packets” was produced: The atom briefly existed “in the bizarre state of being in two well-separated positions at once” (if you call 80 nanometers “well-separated”!).⁸⁴

These serious epistemological problems of quantum mechanics are often dramatized through the aid of “thought experiments” (in German, *gedanken* experiments) that reveal QM’s paradoxes. Perhaps the most famous of these “thought experiments” is *Schrodinger’s Cat*. Here is the original description of this “thought experiment” in Schrodinger’s own words (translated from the German):

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): In a Geiger counter there is a tiny bit of radioactive substance, so small that *perhaps* in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none. If it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The ψ function for the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.⁸⁵

Only when, at the end of the hour, the box is opened and the cat is “observed” does the ψ function then “collapse” to a single eigenfunction with a single eigenvalue, corresponding to either a live cat or a dead cat. Presumably, prior to the opening of the box, the cat was neither alive nor dead! This type of paradoxical quantum mechanics “thought experiment” is associated with the presumed existence of *macroscopic* quantum superposition states, in defiance of our everyday experience. This, in turn, is closely associated with another measurement problem, as described by Richard B. Griffiths and Roland Omnes in their article “Consistent Histories and Quantum Measurements” in the August 1999 issue of *Physics Today*:

There are actually two measurement problems that conventional textbook quantum theory cannot deal with. The first is the appearance, as the result of the measurement process, of macroscopic quantum superposition states

ON SYSTEMS

such as Erwin Schrodinger's hapless cat. The second problem is to show that the results of a measurement are suitably correlated with the properties the measured system had before the measurement took place – in other words, that the measurement actually measured something.⁸⁶

This second measurement problem is described in more detail later in the Griffiths and Omnes article:

Particle physicists are always designing and building their experiments under the assumption that a measurement carried out in the real world can accurately reflect the state of affairs that existed just before the measurement. From a string of sparks or bubbles, for example, they infer the prior passage of an ionizing particle through the chamber. Extrapolating the tracks of several ionizing particles backward, they locate the point where the collision that produced the particles took place. But according to many textbook accounts of the quantum measuring process, retrodictions that use experimental results to infer what the particle was doing before this kind of measurement was made are not possible. [For example, the QM textbooks will say: "The particle had no definite position before the measurement was made," "The act of measurement caused the ψ wavefunction to collapse to one of its eigenfunctions," and so on.] Should we conclude, then, that experimenters don't take enough courses in quantum theory?⁸⁷

Shortly we will be discussing both of these measurement problems in detail, following closely the presentation of Griffiths and Omnes in the above-mentioned article. Before doing this, however, we need to present both the most commonly accepted solution to the problems of QM epistemology, which is Niels Bohr's "complementarity principle" (a.k.a. the "Copenhagen interpretation", after the Danish city where Bohr lived and worked), and also present what our own approach (based on an idea of Ilya Prigogine) will be.

Niels Bohr explained his "complementarity principle" as follows:

The new progress in atomic physics was commented upon from various sides at the International Physical Congress held in September 1927 at Como in commemoration of Volta. In a lecture on that occasion, I advocated a point-of-view conveniently termed "complementarity", suited to embrace the characteristic features of individuality of quantum phenomena, and at the same time to clarify the peculiar aspects of the observational problem in this field of experience. For this purpose, it is decisive to recognize that, *however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms* [i.e., via a classical description of *macroscopic* measurement events].

. . .

This crucial point . . . implies the *impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear*. . . Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture,

but must be regarded as *complementary* in the sense that only the totality of the phenomena exhausts the possible information about the objects. . .

The main point here is the distinction between the *objects* under investigation and the *measuring instruments* which serve to define, in classical terms, the conditions under which the phenomena appear. . .

In particular, it must be realized that . . . all unambiguous use of space-time concepts in the description of atomic phenomena is confined to the recording of observations which refer to marks on a photographic plate or to similar practically *irreversible* [italics mine] amplification effects like the building of a water drop around an ion in a cloud-chamber. Although, of course, the existence of the quantum of action is ultimately responsible for the properties of the materials of which the measuring instruments are built and on which the functioning of the recording devices depends, this circumstance is not relevant for the problems of the adequacy and completeness of the quantum-mechanical description in its aspects here discussed.⁸⁸

Now, it is vital that several important points be noted in connection with Bohr's presentation of his "complementarity principle": The first is that what is "complementary" is not *primarily* the wave aspect of QM versus the particle aspect of QM (though this is *implied* in what Bohr is saying). Rather, what are "complementary" are *primarily* the various *macroscopic experiments* (and multiple runs of those experiments) which *together* are required to give a *complete* (though apparently paradoxical) picture of a particular *sub-microscopic* quantum reality. As we have seen, not only are *multiple experimental runs* required in order to confirm the *statistical* predictions of QM, but the eigenvalues for non-commuting quantum operators (such as position and momentum) must be measured using *entirely different* experimental setups in order to give accurate results.

A second vital point is that Bohr's presentation of the complementarity principle involves *no* teleological assertions *whatsoever*: Bohr is *not* interested in *subject* versus *object*, or in how the *subject* (i.e., the scientific experimenter) may or may not affect the *object* (i.e., the electrons, photons, or whatever the scientific experimenter is studying). Unlike Werner Heisenberg, David Bohm, John Wheeler, and numerous "mystical" popularizers of quantum mechanics, Bohr is *not* claiming that science can no longer "bracket out the subject" and that subjectivity must therefore now be introduced into the heart of science. Bohr makes this clear in the following paragraph:

On [the occasion of the Fifth Physical Conference of the Solvay Institute held in Brussels in October 1927] an interesting discussion arose also about how to speak of the appearance of phenomena of which only predictions of a statistical character can be made. The question was whether, as to the occurrence of individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on

ON SYSTEMS

the part of “nature” or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the “observer” constructing the measuring instruments and reading their recording. Any such terminology would, however, appear dubious since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, *it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged* [italics mine].⁸⁹

In a later section we will separately consider various possible teleological analogs to quantum mechanical systems (just as we did earlier for classical mechanical systems, Special Relativistic systems, and General Relativistic systems). But for now it is very important to note that quantum mechanics is *not* a violation of the “bracket out the subject” rule that we have contended is of the very essence of the scientific method.

Instead, what *is* of importance for Bohr is that the measuring instruments are *macroscopic* and therefore obey laws of physics which “*must be expressed in classical terms*”, while by contrast the *sub-microscopic* objects being studied obey the very different laws of quantum mechanics. It is also clear that by “*classical*” physics Bohr intends to include not only classical mechanics, but also *classical thermodynamics*. This is evident because of his stress on the “*practically irreversible*” nature of the macroscopic measurement event. As we shall see in a subsequent chapter on **Linear Thermodynamic Systems**, *time* in classical, linear thermodynamics (as well as in far-from-equilibrium thermodynamics and even in nonlinear dynamics) is *irreversible*. By contrast, *time* in both classical mechanics *and* quantum mechanics is *reversible* (as we have already pointed out).

Briggs and Peat explain Ilya Prigogine’s important insights on this point:

In his thermodynamic equations, Prigogine introduces what he calls a “time operator”, T . This operator corresponds to “historical time”, that is, an internal time or age of a system, expressing time’s one-way flow. . .

Prigogine goes on to treat reversible time, t , used by physicists in the equations of classical physics and quantum mechanics, as only a parameter which has to do with the motion of particles [or with changes in the probabilistic ψ wavefunction taken as a whole]. By making a distinction between T and t , Prigogine is able to point out that the Schrodinger cat problem which has so vexed physicists actually results from a confusion between historical time, our time (T), and the abstract motion of possibilities (t).⁹⁰

As Ilya Prigogine himself has written:

The apparatus that performs the measurements, whether a physical construct or our own sensory perception, must follow the extended laws of dynamics, including time-symmetry breaking [i.e., irreversible time

T]. There *do* exist integrable time-reversible systems, but we cannot observe them in isolation. As emphasized by Bohr, we need an apparatus that breaks time-symmetry.⁹¹

We may summarize (and extend) these important insights of Bohr and Prigogine via the following proposition:

Irreversible time T is a constitutive characteristic (i.e., an “emergent property”) both of nonlinear dynamic systems and thermodynamic systems (e.g., macroscopic observational systems) which cannot in any way be additively (or summatively) derived from that reversible time t which is an inherent feature of both classical mechanics and quantum mechanics.

We will defend this proposition in detail in our later chapters on **Nonlinear Dynamic Systems**, **Linear Thermodynamic Systems**, and **Nonlinear Complex Physical Systems**. But for now it is important to recall that there is nothing “mystical”, “vitalistic”, or “teleological” about the idea of the real existence of *constitutive characteristics* (“emergent properties”) of the whole which *cannot* be summatively derived by “adding up” the properties of the parts. Rather, the constitutive characteristics of whole systems are quite prosaic and physically empirical, arising whenever the parts of the system interact *strongly and persistently*. Emergent properties only *seem* to be “mystical” because of the *linear* nature of our usual scientific thought – thought which has been conditioned mainly by classical mechanics, special relativity, and quantum mechanics. (See Figure 1 in our earlier chapter on **Classical Mechanical Systems**, together with the accompanying discussion.)

Many of the greatest minds in physics over the past centuries have tried to derive the *irreversible* time T which is associated with macroscopic observational systems from the *reversible* time t which is postulated by both classical mechanics and quantum mechanics, and in the judgment of most physicists they have all *failed* to do so. As Griffiths and Omnes wrote in their August 1999 article in *Physics Today*:

[T]he problem of showing that a system of classical particles will exhibit thermodynamic irreversibility, a typical macroscopic phenomenon, has not yet been settled to everyone’s satisfaction, despite a continuing effort that goes back to Ludwig Boltzmann’s work a century ago.⁹²

This same *failure* has also characterized all attempts to derive macroscopic temporal irreversibility directly from *quantum mechanics*, which (like classical mechanics) is a *linear* theory that presumes *weak or transient interactions* between parts (“parts” in QM being regarded in this context to be the ψ *eigenfunctions* or *wavefunctions*), and moreover presumes *summative* system characteristics (since the ψ wavefunctions obey the principle of superposition).

ON SYSTEMS

Our conclusion (which is *not* the conclusion of Griffiths and Omnes) is that the irreversibility of macroscopic observational time T has *not* so far been demonstrated to arise from reversible time t because it is *impossible* to do so, due to T 's status as a *constitutive characteristic* (“emergent property”) of nonlinear dynamic systems and thermodynamic systems *regarded as wholes*.

An Epistemological QM “Thought Experiment”

Starting from this perspective, let's examine in detail the discussion by Griffiths and Omnes of the two fundamental epistemological measurement problems of quantum mechanics: 1) the problem of *macroscopic quantum superpositions* (e.g., Schrodinger's cat), and 2) the problem of *correlating* a macroscopic measurement with the immediately-prior sub-microscopic state of the system.

Figure 2, below, which follows Griffiths and Omnes⁹³, shows an experimental situation that in essence parallels the Schrodinger's cat “thought experiment” (though without harming any animals, even in thought!). In the formulas which follow Figure 2, an expression of the form $|a\rangle$ refers to a conceived of as a quantum ψ wavefunction. Such ψ wavefunctions, being *linear*, obey the *superposition principle*, so that they can be simply added together, for example $|a\rangle + |b\rangle$. The arrow \rightarrow in these formulas represents the forward progress in time of the *reversible* time t of Quantum Mechanics.

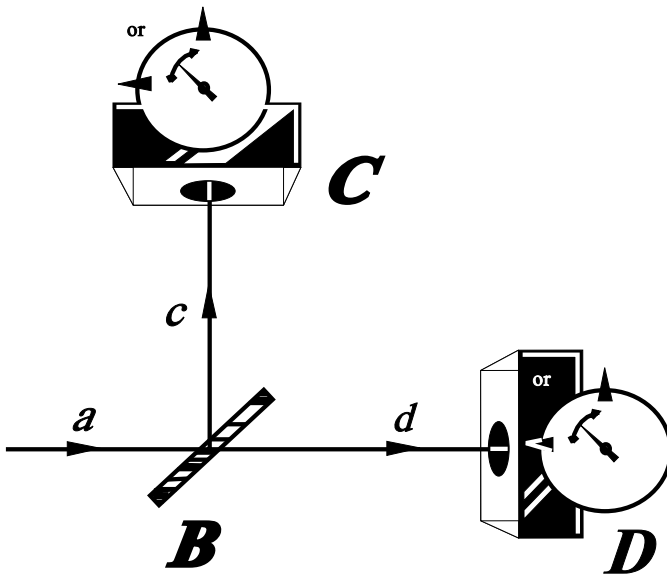


Figure 2 (after Griffiths and Omnes, p. 27)

Here, then, is how Griffiths and Omnes describe the experimental situation represented by our Figure 2:

The two measurement problems . . . can be understood by referring to the simple *gedanken* experiment shown in figure [2]. A photon (or neutron, or some other particle; it makes no difference) enters a beam splitter in the *a* channel and emerges in the *c* and *d* channels in the coherent superposition:

$$|a\rangle \rightarrow |s\rangle = (|c\rangle + |d\rangle) / \sqrt{2} \quad (\text{Formula 1})$$

Here $|a\rangle$, $|c\rangle$, and $|d\rangle$ are wavepackets in the input and output channels, and $|s\rangle$ is what results from $|a\rangle$ by unitary time evolution (that is, by solving the appropriate Schrodinger equation) as the photon passes through the beam splitter.

The photon will later be detected by one of two detectors, *C* and *D*. To describe this process in quantum terms, we assume that $|C\rangle$ is the initial quantum state of *C*, and that the process of detecting a photon in a wavepacket $|c\rangle$ is described by

$$|c\rangle |C\rangle \rightarrow |C^*\rangle \quad (\text{Formula 2})$$

where $|C^*\rangle$ is the triggered state of the detector after it has detected the photon. Once again, the arrow indicates the unitary time evolution produced by solving Schrodinger's equation. It is helpful to think of $|C\rangle$ and $|C^*\rangle$ as physically quite distinct: Imagine that a macroscopically large pointer, initially horizontal in $|C\rangle$, is moved to a vertical position in the state $|C^*\rangle$ when the photon has been detected.

By putting together the processes (1), (2), and the counterpart of (2) that describes the detection of a photon in the *d* channel by detector *D*, one finds that the unitary time development of the entire system shown in figure [2] is of the form:

$$|a\rangle |C\rangle |D\rangle \rightarrow |S\rangle = (|C^*\rangle |D\rangle + |C\rangle |D^*\rangle) / \sqrt{2} \quad (\text{Formula 3})$$

Ascribing some physical significance to the peculiar macroscopic-quantum-superposition state $|S\rangle$ in (3) poses the first measurement problem in our *gedanken* experiment. The difficulty is that $|S\rangle$ consists of a linear superposition of two wavefunctions representing situations that are visibly, macroscopically quite distinct: The pointer on *C* is vertical and that on *D* is horizontal for $|C^*\rangle |D\rangle$, whereas for $|C\rangle |D^*\rangle$ the *D* pointer is vertical and the *C* pointer is horizontal. In Schrodinger's famously paradoxical example, the two distinct situations were a live and a dead cat. A great deal of effort has gone into trying to interpret $|S\rangle$ as meaning that either one detector or the other has been triggered, but the results have not been very satisfactory.⁹⁴

At this point we will briefly depart from the presentation of Griffiths and Omnes to indicate what happens when the photon is in fact *actually measured* by either detector *C* or detector *D* (based on our emergent-property theory of

ON SYSTEMS

macroscopic irreversible time). This *actual macroscopic measurement* can be represented by the following formula:

$$C + D \Rightarrow C^* + D \quad \text{or} \quad C + D \Rightarrow C + D^* \quad (\text{Formula 4})$$

where \Rightarrow represents *irreversible* time T (as opposed to \rightarrow , which is *reversible* time t) and C , D , C^* , and D^* represent the actually (“classically”) measured *macroscopic* states of the detectors. (The $*$ of course means that the detector’s macroscopic pointer has rotated to point upward.)

Now, because of the nature and structure of our macroscopic experimental setup, we have good reason to believe that this upward rotation of one of the two macroscopic pointers was caused (in part) by the detection of a photon by the corresponding detector, C or D . (Analogous to this upward-rotating pointer is the string of bubbles in a bubble chamber, the string of droplets in a cloud chamber, the click of a Geiger counter, or an image on a photographic plate.) We also know (because time T is *irreversible*) that this photon will not subsequently “change its mind” and trigger the other detector instead. Thus our experiment has given us a new piece of *particular information* concerning a situation in the sub-microscopic world. We can, then, use this new piece of particular information to revise quantum formula 3 above to read as follows (returning once more to the presentation of Griffiths and Omnes):

$$\begin{aligned} |a\rangle |C\rangle |D\rangle &\rightarrow |c\rangle |C\rangle |D\rangle \rightarrow |C^*\rangle |D\rangle \\ \mathbf{xor} \text{ [= exclusive or]} \\ |a\rangle |C\rangle |D\rangle &\rightarrow |d\rangle |C\rangle |D\rangle \rightarrow |C\rangle |D^*\rangle \end{aligned} \quad (\text{Formula 5})$$

depending on which detector, C or D , detected the photon. Notice that there are *no* macroscopic superposition states in formula 5, and moreover formula 5 clearly expresses the fact that the photon was in channel c immediately before being measured by detector C (or in channel d immediately before being measured by detector D). This way of looking at things therefore solves *both* of the major quantum measurement problems simultaneously.

By contrast, the typical textbook interpretation of QM replaces both $|c\rangle$ and $|d\rangle$ in formula 5 with their coherent superposition $|s\rangle$. As Griffiths and Omnes put it, a physicist trained in this textbook interpretation

will wait until the measurement takes place and then “collapse” the [superposed $|s\rangle$] wavefunction [to either $|c\rangle$ or $|d\rangle$] for reasons he may not understand very well. But at least they make more sense to him than does the *macroscopic* superposition of state $|S\rangle$ of [formula 3].⁹⁵

Griffiths and Omnes regard the two “exclusive or” formulations in formula 5 to be “consistent histories” within quantum mechanics. In other words, they can *never* be true at the same time, and (in this particular case) they can each be assigned a probability of $1/2$. By contrast, it is *meaningless* to compare *either* version of formula 5 to formula 3 and ask “Which is true, formula 5 or formula 3 ?” That is because, according to Griffiths and Omnes, formulas 5 and 3 are *incompatible* “inconsistent histories”, just as non-commuting operators are *incompatible* in QM. (For example, it is *meaningless* to ask whether the spin of a certain particle is simultaneously $1/2$ along the x axis and $-1/2$ along the z axis, since QM theory cannot represent this situation, nor can actual spin measurements along the x and z axes be done in the same experimental run.⁹⁶) This “consistent histories” approach is sometimes called the “decoherent histories” approach to QM epistemology, and it has also been developed by Murray Gell-Mann and James Hartle.⁹⁷

While in general agreeing with the consistent-histories / decoherent-histories approach, it seems to me important to point out that, once the measurement *has actually been made* and the pointer of either detector C or detector D has turned upward, we do then have more *particular information* at our disposal concerning the sub-microscopic situation. (That is, we *do* have good reason to believe the photon was in channel c if detector C ’s pointer rotated upwards, or in channel d if detector D ’s pointer rotated upwards.) After taking the measurement, we therefore do *in fact* have solid *experimental* grounds for preferring *one* of the formulations of (5) to the description in (3), even though (5) and (3) may be *logically incomparable* (i.e., *incompatible*) from the point-of-view of QM theory. In other words, *we know more after taking the measurement than we did before taking the measurement*.

Furthermore, we can confidently make the above *epistemological* assertion without committing ourselves to any *teleological* assumptions whatsoever (such as, for example, the teleological assumption that “my act of observation caused the photon to appear in channel c instead of channel d ”, or the teleological assumption that “God knew whether the photon was in channel c or channel d even before my experiment revealed it to me”.) Not only that, but the above epistemological approach does not even force us to decide whether or not quantum mechanics is “complete” (i.e., whether or not probability will ever be eliminated from QM, whether or not any “hidden variables” will ever be discovered behind the ψ wavefunction, etc.)

As a final epistemological comment on the experimental situation of Figure 2, it is important to note that, while it is valid and useful from the point-of-view of quantum mechanics to represent macroscopic quantum ψ wavefunctions using expressions such as $|C\rangle$, $|C^*\rangle$, $|D\rangle$, and $|D^*\rangle$, these macroscopic

ON SYSTEMS

quantum descriptions will *never* replace the macroscopic *classical* descriptions C , C^* , D , and D^* . For one thing, *irreversible* time T (represented by the special arrow \Rightarrow in formula 4) makes sense in the context of macroscopic classical thermodynamic & nonlinear-dynamic descriptions, but does *not* make sense in the context of linear *time-reversible* quantum ψ -wavefunction descriptions. And without *irreversible* time T there's no way to make sure that a measurement has really measured anything. Furthermore, irreversible time T is only one out of the many other *constitutive characteristics* ("emergent properties") of thermodynamic & nonlinear-dynamic systems that cannot be derived additively from linear, superposed ψ eigenfunctions.

The points made in the foregoing paragraph are very close to the heart of Niels Bohr's *complementarity principle*. (See our earlier quotations from Bohr.) Nevertheless, the dream of "reducing" the scientific description of *all* macroscopic phenomena to linear *quantum* mechanics (just as earlier generations of physicists had dreamed of "reducing" all of science to linear *classical* mechanics) is a dream that lives on in the hearts of many contemporary physicists. For example, Griffiths and Omnes end their article with the following statements:

Demonstrating that quantum systems actually exhibit irreversible behavior in the thermodynamic sense . . . is not trivial. There are conceptual and computational difficulties similar to those that arise when one considers a classical system of many particles. Nonetheless, there seems at present to be no difficulty, in principle, that prevents us from understanding macroscopic phenomena in quantum terms, including what happens in a real measurement apparatus. Thus, by interpreting quantum mechanics in a manner in which measurement plays no fundamental role, we can use quantum theory to understand how an actual measuring apparatus functions.⁹⁸

By contrast, it seems to me that, while you may apparently *almost* derive the *irreversible* time T of a macroscopic "measuring apparatus" system from the linear, summative characteristics of its parts (whether those "parts" be sub-microscopic particles or ψ wavefunctions), in the end the prize always vanishes, like the proverbial "pot o' gold" at the end of the rainbow.

The Double-Slit "Thought Experiment"

Another paradoxical quantum "thought experiment" that is often discussed (the results of which have actually been experimentally confirmed using neutron beams) is the famous *double-slit* experiment, which is here described very briefly: Fire a parallel beam of particles (e.g., electrons or neutrons) at a thin, flat screen that has been pierced by two narrow slits. Then place a photographic plate (or other suitable detector) at some distance behind this

screen, in order to detect the pattern made by the particles that have passed through these two slits. What you will find is that the particles strike the photographic plate in a pattern of intensity that suggests the *interference pattern* of waves. (Of course, this illustrates the wave/particle duality of quantum mechanics.) But, even more interesting, repeat the experiment, this time firing the particles *one particle at a time*. What you will find this time is that the accumulated photographic image of the particles *still* has a wave-like interference pattern! Perhaps no experiment better illustrates the eerie “timeless” reality of the superposed ψ wavefunction than does this *double-slit* experiment. As Briggs and Peat put it:

There are two logical interpretations of this finding, and neither one makes any classical sense. In the first interpretation we say that each indivisible particle somehow manages to go through both slits at the same time and interfere with itself, contributing to the wave pattern on the [photographic plate], yet somehow registering [as a single point on the photographic plate]. The second interpretation is even worse. We say that somehow each particle “knows” where the particles preceding it have gone and where the ones following will go so that at the end of the experiment they will all together have piled up in a nice [interference] wave pattern for the experimenter to puzzle over. . . [From a classical point-of-view, it seems as though the particle] is either very smart or it is indivisible and divisible at the same time.⁹⁹

In the “Consistent Histories” article from which we quoted earlier, Griffiths and Omnes are able to successfully deal with this *double-slit* experiment (and with the simpler, but formally similar, *Mach-Zehnder interferometer* experiment) using the consistent-histories / decoherent-histories approach:

It turns out that [those mutually exclusive] histories in which the particle passes through *a particular slit* and then arrives at *a particular point* in the interference zone do not satisfy the consistency conditions, and thus do not constitute acceptable quantum beables. This will come as no surprise to generations of students who have been taught that asking which slit the particle passes through is not a sensible question. . .

On the other hand, if there are detectors just behind [each of the] two slits, one’s physical intuition says that it should be sensible to say which slit the particle passes through. . . In that case, the relevant histories, which are analogs of [formula 5, above], turn out to be consistent. Furthermore, even if there are no detectors behind [each of] the slits, there are consistent histories in which the particle passes through a particular slit and then arrives in a spread-out wavepacket in the interference zone, rather than at a particular point.¹⁰⁰

The Einstein-Podolsky-Rosen “Thought Experiment”

The last of the paradoxical quantum “thought experiments” we will discuss is the famous Einstein-Podolsky-Rosen experiment (usually named by the initials *EPR*). In 1935 Albert Einstein, Boris Podolsky, and Nathan Rosen published a paper entitled “Can quantum-mechanical description of physical reality be considered complete?”¹⁰¹ in which they proposed what has become known as the *EPR* paradox. The *EPR* has had a number of slightly variant formulations over the years. Here is a fairly clear formulation by Briggs and Peat:

In the *EPR*, an atomic particle P disintegrates in two, and the two halves, A and B, fly off in opposite directions at high speed. According to the laws of both classical and quantum physics, there is a correlation between the momentum of A and B and also a correlation between the position of A and B. This means that whatever we find out about A gives us corresponding information about B. Now Heisenberg’s uncertainty principle stipulates that as we measure the *position* of particle A, its *momentum* becomes uncertain [because position and momentum are *non-commuting* operators in QM]. But, Einstein and his colleagues asked, how could a measurement of A possibly affect particle B, which is flying towards the other side of the laboratory? Since the momentum and positions of A and B are correlated, then by [measuring A] it should be possible to deduce something about B without actually measuring it. Suppose then that we measure the momentum of A. This also gives us the momentum of B. Without violating the uncertainty principle, we can then measure the position of B. But now we have a paradox. We haven’t violated the uncertainty principle, yet we have managed to obtain both the momentum and position of B, a feat which the uncertainty principle says is impossible!¹⁰²

Not only that, but after measuring the position of particle B, we can also deduce both the position and momentum of particle A as well !

Other formulations of the *EPR* have the measurements of particles A and B taken when they are so far apart that any “signal” between A and B would have to occur at a speed faster than the speed of light, contrary to Einstein’s Theory of Relativity. Still other formulations of the *EPR* use different non-commuting QM operators, such as particle spin with respect to the three axes of three-dimensional space, rather than position and momentum. Finally, yet other formulations stress the *EPR* paradox by saying that the measurement of the position of B cannot actually occur, because the measurement of the momentum of A has determined also the momentum of B, thus rendering B’s position indeterminate and “poisoning” any attempt to measure it directly.

What interpretation should be given to this *EPR* paradox?

First, we should note that the *EPR* is not a significant problem from the point-of-view of Niels Bohr's "complementarity" interpretation of QM: Bohr is able to treat the *EPR* as just another example of how we have to use different experimental setups to "complement" one another in order to get a complete picture of quantum reality. Bohr also regards the *EPR* to be just another example showing "the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality".¹⁰³ The fact that, under the unusual circumstances of the *EPR*, both the position and momentum of a particle seem to be determined, contrary to the Heisenberg Uncertainty Principle, does not seem to him to be stranger than any of the other paradoxes of QM that defy our intuitions concerning causality and physical reality. Einstein summarized his own view of Bohr's position as follows:

Of the "orthodox" quantum theoreticians whose positions I know, Niels Bohr's seems to me to come nearest to doing justice to the [*EPR*] problem. Translated into my own way of putting it, he argues as follows:

If the partial systems A and B form a total system which is described by its ψ -function $\psi/(AB)$, there is no reason why any mutually independent existence (state of reality) should be ascribed to the partial systems A and B viewed separately, *not even if the partial systems are spatially separated from each other at the particular time under consideration*. The assertion that, in this latter case, the real situation of B could not be (directly) influenced by any measurement taken on A is, therefore, within the framework of quantum theory, unfounded and (as the [*EPR*] paradox shows) unacceptable.¹⁰⁴

(In fact, Bohr does not even like to speak of a measurement "influencing" the system measured. Rather, for him, each measurement is a measurement of *the entire experimental setup as a whole, including the measuring apparatus itself*. Various experimental setups taken together then "complement" one another to give us a complete picture of quantum reality.¹⁰⁵)

Einstein then goes on to immediately describe his own position concerning the *EPR* paradox:

By this way of looking at the matter it becomes evident that the [*EPR*] paradox forces us to relinquish one of the following two assertions:

1. The description by means of the ψ -function is *complete*.
2. The real states of spatially separated objects are independent of each other.

On the other hand, it is possible to adhere to (2), if one regards the ψ -function as the description of a (statistical) ensemble of systems (and therefore relinquishes (1)). However, this view blasts the framework of the "orthodox quantum theory".¹⁰⁶

ON SYSTEMS

As might be gathered from this quotation, Einstein was strongly of the opinion that (2) should continue to be affirmed, while (1) should be rejected. The affirmation of assertion (2) is often called the *Principle of Locality*. By contrast, most “orthodox” quantum theorists reject assertion (2) and believe that reality (or, at least, *quantum* reality) is *nonlocal*. In a paper published in 1948 in the journal *Dialectica*, Einstein concisely summarizes why he believes in the Principle of Locality:

The following idea characterizes the relative independence of objects far apart in space (A and B): External influence on A has no direct influence on B. This is known as the Principle of Contiguity [a.k.a., the Principle of Locality], which is used consistently only in field theory. If this axiom were to be completely abolished, the idea of the existence of quasi-enclosed systems, and thereby the postulation of laws which can be checked in the empirically accepted sense, would become impossible.¹⁰⁷

Unfortunately Einstein’s “Principle of Locality” is not as obvious or basic as he makes it sound. Not only does it contradict QM (as the *EPR* paradox shows) but, as we shall see in our later chapter on **Nonlinear Complex Physical Systems**, a macroscopic far-from-equilibrium thermodynamic system that has been modeled using *nonlinear* differential equations (which are the same kind of equations Einstein himself used in his General Theory of Relativity) can also show surprising *nonlocal* correlations between parts that are widely separated in space and/or time. (One example that is popular with scientists who study *chaos theory* is the fact that the flutter of a butterfly’s wings in China can be a “cause” of a hurricane in Florida months later).

Because Einstein’s “Principle of Locality” remains, at the very least, controversial, I don’t believe that the *EPR* paradox proves that QM is “incomplete”. Indeed, it is difficult to think of *any* sufficient proof of the “incompleteness” of QM other than actually discovering and proving a new scientific paradigm for modeling the sub-microscopic world that does *not* include the *irreducible statistical* features of QM. (Einstein’s own tries at creating a Unified Field Theory were unsuccessful attempts to do just that.)

On the other hand, I also believe it to be fruitless to try and prove that the discovery of a successful non-statistical “hidden variables” theory of the sub-microscopic world is *impossible*. For example, a famous mathematical proof by John von Neumann (which showed that “hidden variables” analogous to those used to describe the underlying mechanism of air molecules bombarding a dust particle in Brownian motion would be *fundamentally inconsistent* with the experimental results of QM) has since been shown to be *inconclusive* by David Bohm, because “hidden variables” would not need to follow the Brownian-motion model.¹⁰⁸

In 1964 John S. Bell used an *EPR*-type “thought experiment” to derive an inequality that (purportedly) could be experimentally tested to decide whether or not non-statistical “hidden variables” could ever conceivably be found to underlie QM.¹⁰⁹ In Bell’s version of the *EPR*, particle spin with respect to the three axes of three-dimensional space are the non-commuting QM variables.

Imagine a neutral pion at rest. Suddenly it decays into a pair of photons traveling in opposite directions to one another. Since the neutral pion has zero angular momentum, the two photons must have an opposite spin along any of the three axes of space we choose to measure. Call these opposite spins *up* and *down*, respectively. To continue our discussion, we will now quote from the *Physics FAQ* article on Bell’s inequality by John Blanton (except that, to avoid confusion with our prior discussions, we will call the axes of space X, Y, and Z rather than Blanton’s A, B, and C):

Call the axes X, Y, and Z and call the spin in the X axis X+ if it is *up* in that axis, otherwise call it X- [if it is *down* in that axis]. Use similar definitions for the other two axes.

Now perform the experiment. Measure the spin in *one* axis of one photon and the spin in *another* axis of the other photon. If *EPR* is correct [that is, if “hidden variables” actually exist], each photon will *simultaneously* have properties for spin in each of axes X, Y, and Z.

Look at the statistics. Perform the measurements with a number of sets of photons. Use the symbol N(X+, Y-) to designate the words “the number of photons with X+ and Y-”. Similarly for N(X+, Y+), N(Y-, Z+) , etc. Also use the designation N(X+, Y-, Z+) to mean “the number of photons with X+, Y-, and Z+”, and so on. It is easy to demonstrate that for a set of photons

$$(1) \quad N(X+, Y-) = N(X+, Y-, Z+) + N(X+, Y-, Z-)$$

because all of the (X+, Y-, Z+) and all of the (X+, Y-, Z-) photons are included in the designation (X+, Y-), and nothing else is included in (X+, Y-). You can make this claim if [all of] these measurements are connected to some real properties of the photons [because of the assumed existence of “hidden variables”].

Let n(X+, Y+) be the designation for “the number of measurements of pairs of photons in which the first photon measured X+, and the second photon measured Y+”. Use a similar designation for the other possible results. . . You can’t measure both X and Y of the same photon. Bell demonstrated that, in an actual experiment, if (1) is true (indicating real properties), then the following must be true:

$$(2) \quad n(X+, Y+) \leq n(X+, Z+) + n(Y+, Z-)$$

Additional inequality relations can be written by just making the appropriate permutations of the letters X, Y, and Z and the two signs. This is Bell’s inequality, and it is proved to be true if there are real (perhaps hidden) variables to account for the measurements.¹¹⁰

ON SYSTEMS

In 1982 Alain Aspect and his co-workers published the results of experiments purporting to show that Bell's inequality is false and that, therefore, "hidden variables" behind QM are impossible.¹¹¹ In the last one of these, polarizer angles were changed while the photons were actually "in flight".

At the time, Aspect's final experiment in this series was widely regarded as conclusively proving the impossibility of "hidden variables" behind the statistical ψ wavefunction, and this is the view that appears to this day in popular expositions of quantum mechanics. However, in 1985, Franson showed that Aspect's final experiment was defective because the timing constraints were not adequately controlled and accounted for.¹¹² Also, other physicists have argued on theoretical grounds that there are assumptions behind Bell's view of "hidden variables" (just as there were assumptions behind von Neumann's view of "hidden variables") such that a "hidden variable" theory not based on those assumptions might still be possible.¹¹³ So the "hidden variables" question is still very much open and, in my view, will not be solved until a successful "hidden variables" theory of the sub-microscopic world is actually created and proven experimentally (or, ultimately, fails to be actually created and proven experimentally).

Turning briefly from science to teleology, the *EPR* paradox also *appears* to raise a serious problem for the popular Heisenberg QM teleology, according to which the *experimenter* actually *subjectively causes* the value of a QM variable (such as position or momentum) to become definite for a given sub-microscopic particle merely by doing the measurement, which measurement is said to "collapse the superposed ψ wavefunction to a single eigenfunction having a single eigenvalue". Obviously, if particle A did not even *have* a definite momentum before the experimenter actually measured it, how could the experimenter (or particle A) *instantly* communicate information concerning particle A's momentum to particle B, so that B would "know" what definite complementary momentum value to assume? (Remember that B might be *light-years away* by the time A's momentum is actually measured and that, according to Einstein's Theory of Relativity, *no* communication signal can travel faster than the speed of light.)

Actually this *EPR* problem for the Heisenberg QM teleology is more apparent than real. As we shall argue in our later section on teleological analogs to quantum mechanics, the Heisenberg QM teleology amounts to the assertion that the experimenter is "empowered" to do "real magic" upon sub-microscopic particles that he doesn't even understand all that well. And if you believe yourself to be *empowered* to actually do *real magic*, then instantly deciding the momentum of a particle that is light-years away is just as easy as

instantly deciding the momentum of a particle that has directly interacted with your experimental apparatus!

The foregoing discussion of the epistemology of quantum mechanics has, for the most part, relied upon mainstream, conservative interpretations of QM, such as Niels Bohr's version of the "Copenhagen interpretation" (a.k.a. the "complementarity principle") and the consistent-histories / decoherent histories approach of Griffiths, Omnes, Gell-Mann & Hartle. We have also mentioned a few of the "non-standard" QM interpretations that treat the ψ wavefunction as a "real" wave (or, at least, based on "real" waves), including the views of Louis deBroglie, David Bohm, J.G. Cramer, and E. Marx. For the sake of completeness, we need to also mention a few other QM interpretations, but unfortunately our discussion of these must necessarily be very brief and therefore superficial.

The "Many-Worlds" Interpretation of QM

In 1957 Hugh Everett III first proposed the *many-worlds interpretation* of quantum mechanics (often abbreviated *MWI*). According to this interpretation, every time a ψ wavefunction manifests multiple statistical possibilities, the world (i.e., universe) splits into many worlds, with one world for each different possibility. Each of the resulting worlds is identical to the others, except for the different particular realization of the possibilities inherent in the original ψ wavefunction. These many worlds, in turn, split into still more worlds as new ψ wavefunctions manifest themselves within the original set of worlds. Furthermore, no communication is possible between any of these many worlds, and consequently nobody in one world knows anything about the other worlds. Nevertheless, the people living in each world continue to endlessly split, along with the world(s) in which they live.¹¹⁴

The problems with the many-worlds interpretation of QM seem to me to be as follows:

1. Although some physicists have suggested that quantum interference between the hypothesized adjacent worlds might be detectable, most physicists agree that the *MWI cannot be experimentally tested*.
2. The *MWI* violates (big time!) the scientific principle known as *Occam's Razor*, which states that *entities should not be multiplied unnecessarily*. This principle has been restated in many ways, one of which is that *when you have two competing theories which make exactly the same predictions* (e.g., the Copenhagen interpretation and the many-worlds interpretation), *then the one that is simpler is the better*.¹¹⁵ As Alistaire Rae has written:

ON SYSTEMS

The idea of a near-infinite number of universes which can never interact with each other and whose existence can therefore never be verified seems to most scientists to be an extreme breach of this principle [of economy] and certainly greater than that implied by the de Broglie - Bohm hidden-variable theory.¹¹⁶

3. MWI also has serious problems giving a reasonable account of the notion of *probability*. Albro writes:

[In MWI] there is a serious problem concerning the lack of a valid probability measure for the outcomes of events. Those who subscribe to the MWI typically imagine that the probability distribution for the various possible outcomes of a sequence of quantum events can be associated with the relative number of future “worlds” that contain one set of outcomes versus another, somewhat along the lines of statistical thermodynamics. Unfortunately it’s not that simple, because there is no suitable principle of individuation to distinguish “worlds” in such a way that their relative numbers can be “counted” in any statistically meaningful sense.¹¹⁷

4. Furthermore, because the innumerable worlds generated by the MWI cannot communicate with one another, the observer is (from his point-of-view) basically left with the same epistemological problems concerning quantum measurement that he started with.
5. Lastly, the teleological analog suggested by the MWI is demonstrably false, because it makes a mockery of the idea that that there is *any point at all* in attempting to make ethical choices. As Douglas Jones, a supporter of the MWI, has written:

[If MWI ideas are correct], they have profound implications for our understanding of the nature of the Soul, because the Soul (if there is such a thing) must branch along with the worlds that contain it. It would appear that the writings on which many . . . religions are based make no mention of this idea.¹¹⁸

Although you may think that there are certain alternatives you would never choose, can you really be sure of that? There are a practically infinite number of versions of you, who have all split off at some time in the past from the path you are now following. There may be versions of you that split off five or ten years ago, or perhaps five minutes after you were born, to whom those choices may not seem unthinkable. But in a very real sense, those people are still “you”.¹¹⁹

So, why not go ahead and commit a murder? After all, there will be versions of you who did *not* commit the murder. How could God possibly know which one is “the real you”? Indeed, even the question “Who is the real you?”

becomes meaningless within the teleological framework suggested by the MWI. From the MWI perspective, we are like the characters at the end of Orson Welles' film *The Lady from Shanghai*: We find ourselves endlessly duplicated within a meaningless carnival "funhouse" of mirrors, where all of our moral choices simply *don't matter*, because what we think we *didn't* choose is just as real as what we *did* choose.

While the cynicism and nihilism of MWI's analogical teleology certainly fits in with our Nietzschean, postmodern vision of the "radically autonomous" human individual (the "superman") for whom "everything is permitted", we have strongly argued in our Book I, *WORLDVIEWS*, that such teleological views are false.

Perversely, some scientists regard the implicitly *anti-religious* nature of MWI's analogical teleology to be a *strong point* in MWI's favor, on the theory that anything that is *anti-religious* must be *pro-science*. But, as we have noted earlier, tenaciously holding onto a scientific viewpoint merely to *minimize* the possibility of any *religious* teleological analogy has not proved to be a scientific winning strategy of late. (For example, most astronomers tenaciously held on to the *steady state* cosmology for decades after there was overwhelming scientific evidence against it, and the same can be said of geologists with respect to absolute *uniformitarianism*, and of biologists with respect to the antiquated theory of minutely gradual, step-by-step, *Darwinian evolution*.)

It might be objected that my putting forward a *teleological* argument against MWI violates my oft-stated purpose of keeping teleological arguments clearly separated from physical arguments. And it is obviously true that not all *physical* entities have evident *teleological* analogs (e.g., the hydrogen atom or a gravitational system), nor do all *teleological* entities have evident *physical* analogs (e.g., angels or a transcendent God). Nevertheless, where evident analogs between a given physical system and a given teleological system *do* obviously exist, it seems to me that evidence against (or for) views with respect to one system may be taken as evidence against (or for) corresponding views with respect to the other system. And so, in the present case, MWI can be indirectly (but forcefully) argued against by arguing against its *teleological* analog. (In the **APPENDIX** to this book, I will go the other way and argue against a *teleological* position, ethical proportionalism & consequentialism, by showing the impossibility of its corresponding *physical* presuppositions.)

The “Implicate Order” Interpretation of QM

Turning now to a completely different interpretation of QM, we have already mentioned David Bohm’s role in developing the “non-standard” *pilot-wave* interpretation of QM, as well as his refutation of von Neumann’s proof of the supposed impossibility of discovering *hidden variables* behind the ψ wavefunction. But, additionally, David Bohm has also created an expansive interpretation of quantum mechanics that is much more of a *comprehensive philosophy* than a limited scientific QM interpretation.

One of the most important ideas in Bohm’s comprehensive philosophy is that the *implicate order* of the cosmos is both *higher-dimensional* and *holographic* in nature. (In a holographic plate, an imperfect three-dimensional image of the *whole* exists within each *part* of the plate, as well as each *part* of the plate existing within the *whole*.) Briggs and Peat summarize this aspect of Bohm’s philosophy as follows:

What emerges is a picture of an encoding pattern of matter and energy spreading ceaselessly throughout the universe – each region of space, no matter how small (all the way down to the single photon, which is also a wave or “wave packet”), containing – as does each region of the holographic plate – the pattern of the whole, including all the past and with implications for all the future. Each region will carry this encoding of the whole somewhat differently, as in fact different “parts” of a holographic plate will each give the whole picture but with slightly different limitations on the number of perspectives from which it can be seen.

It is a breathtaking view, an infinite holographic universe where each region is a distinct perspective, yet each contains all.¹²⁰

For Bohm, this *implicate* “enfolded” holographic order becomes the *explicate* “unfolded” order of particular objects and events through the flowing of what he calls the *holomovement*. Bohm writes:

To generalize so as to emphasize undivided wholeness, we shall say that what “carries” an implicate order is the *holomovement*, which is an unbroken and undivided totality. In certain cases, we can abstract particular aspects of the holomovement (e.g., light, electrons, sounds, etc.), but more generally, all forms of the holomovement merge and are inseparable. Thus, in its totality, the holomovement is not limited in any specifiable way at all. It is not required to conform to any particular measure. Thus, *the holomovement is undefinable and immeasurable*.¹²¹

In my Book I, *WORLDVIEWS*, I presented the idea that the basic structure of religious teleological systems is *holographic* – that the whole is within the part, as well as the part within the whole, in such a way that *group subjectivity* is a basic ordering principle of the universe, as viewed *teleologically*. Naturally, therefore, I am extremely sympathetic to Bohm’s view that, analogically, the *physical* universe is implicately structured in a

similarly *holographic* fashion. It seems likely, for example, that the human brain in some way *physically* contains some kind of imperfect structural correspondence with the larger physical universe which it both tries to represent and which, in turn, encompasses it as a physical part. Furthermore, it is commonly noted in biology that the development of a living embryo into an individual of a species does, in some loose analogical sense, image in miniature the *entire history* of the evolution of the species of which that individual is a part.

Nevertheless it seems to me that Bohm's speculations are insufficiently grounded in actual science, and arise more from his immersion in Eastern religion and philosophy than from scientific theory or experiment. Bohm himself stresses that his central concept, the *holomovement*, is "*undefinable and immeasurable*". But it is hard to see how an idea that is *both* undefinable *and* immeasurable can be of much scientific value, *unless* an experimentally testable scientific theory can somehow be wrung from it.

In fairness to Bohm, both he and his co-workers at the University of London's Birkbeck College did work for many years towards such a scientific theory, using ideas such as *co-homology* (a form of topology that does away with the idea of an underlying space-time structure), *Clifford/Grassmann algebras*, and (of course) the *pilot-wave* concept.¹²² But, unfortunately, none of these scientific reformulations of quantum mechanics has achieved general acceptance among physicists.

The "Liouville Space Extension" Of QM

Another extremely interesting "non-standard" version of QM is Ilya Prigogine's "Liouville Space Extension" of quantum mechanics. We have already made significant use of Prigogine's clear distinction between *irreversible* time T and *reversible* time t in our above discussion of QM epistemology. However, Prigogine has since gone much farther than this: His "Liouville Space Extension" of QM actually incorporates *irreversible* time T into the fabric QM itself !

Prigogine has demonstrated that *irreversible* time T arises at the *sub-microscopic* level (as well as at the macroscopic level) because of the existence of *Poincare resonances*, which we mentioned earlier in our chapter on **Classical Mechanical Systems**. (It turns out that these Poincare resonances arise in the context of *quantum* mechanics, as well as in the context of *classical* mechanics.) Of course, the fact that, for Prigogine, *irreversible* time T operates at *both* the macroscopic *and* the sub-microscopic levels of reality makes the solution to QM epistemological problems far easier. Prigogine writes:

ON SYSTEMS

[O]ur approach eliminates the dualistic structure of quantum mechanics, and thus eliminates the quantum paradox. We arrive at a realistic interpretation of quantum theory because the transition from wave functions to ensembles can now be understood as the result of Poincare resonances without the mysterious intervention of an “observer” or the introduction of other uncontrollable assumptions. In contrast to other attempts to extend quantum theory . . . our own approach makes well-defined predictions that are testable. Thus far, they have been confirmed by every numerical simulation performed.¹²³

In fact, I would have preferred to completely follow Ilya Prigogine’s version of quantum mechanics in the QM epistemological discussions above. I did not do so for the following two reasons:

1. Prigogine’s version of QM is not just an epistemological *interpretation* of QM, but is instead a truly non-standard *version* (or *extension*) of QM that is not yet accepted by the majority of physicists. Therefore, for purposes of my epistemological discussion of QM, I wanted to stick to both the standard *version* of QM and (insofar as possible) to “conservative” epistemological *interpretations* of QM (such as Bohr’s Copenhagen interpretation, and the consistent histories / decoherent histories interpretations of Griffiths, Omnes, Gell-Mann, and Hartle).
2. Prigogine’s extension of QM depends strongly on *thermodynamic* ideas that we will not be presenting until our later chapters on **Linear Thermodynamic Systems** and **Nonlinear Complex Physical Systems**.

Another “Far-From-Equilibrium” Version of QM

Finally, Paul Budnik has an interesting non-standard version of QM in which the sub-microscopic discontinuous “jumps” of QM are regarded to be similar to the sudden, discontinuous (sometimes chaotic) changes that occur in many nonlinear, macroscopic, far-from-equilibrium thermodynamic systems. Budnik even manages to work in the “hologramic structure” idea that so-interested David Bohm. So, without further comment, we will end our discussion of the science of quantum mechanics with this quotation from Paul Budnik:

One alternative to classical particles [and “hidden variables”] is to think of observations as focal points in state space of nonlinear transformations of the wave function. Attractors in chaos theory provide one model of processes like this. Perhaps there is an objective physical wave function and QM only models the average or statistical behavior of this wave function. Perhaps the structure of this physical wave function determines the probability that the wave function will transform nonlinearly at a particular location. If this is so, then probability in QM combines two very different kinds of probabilities: The first is the probability associated with our state of ignorance about the detailed behavior of the physical

wave function. The second is the probability that the physical wave function will transform with a particular focal point.

. . . I have advocated a class of models of this type based on using a discretized finite difference equation rather than a continuous differential equation to model the wave function. The nonlinearity that must be introduced to discretize the difference equation is a source of chaotic-like behavior. In this model, the enforcement of the conservation of conservation laws comes about through a process of converging to a stable state. Information that enforces these laws is stored holographic-like over a wide region.¹²⁴

Teleological Implications of QM Systems

Because quantum mechanics basically deals with the physical realm of the *sub-microscopic*, it might be expected that there are *no* interesting teleological systems which are analogous to quantum mechanical systems. While this is essentially true, quantum mechanics is instead associated with a number of important teleological *issues*, due ironically to the fact that scientists *themselves* frequently (and inappropriately) introduce teleological considerations into their discussions of QM epistemology. That is why, in our previous sections on the *science* and *epistemology* of quantum mechanics, we several times had to “jump the gun” and briefly discuss the *teleology* of QM:

- We quoted from Niels Bohr concerning his refusal to embroil his version of the Copenhagen interpretation of QM with *any* teleology. You will recall that Bohr stated that “as to the occurrence of individual [quantum] effects” he rejected *both* Dirac’s view that a *choice* on the part of “nature” was involved *and* Heisenberg’s contrary view that a *choice* on the part of the “observer” determined the outcome of a given quantum experimental measurement, “since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence events which may appear under the conditions he has arranged.”¹²⁵ We strongly endorsed Bohr’s opinion on this matter and correspondingly gave an account of QM epistemology which we believe to be free of teleological assumptions and which, moreover, continues to affirm the foundational “bracket out the subject” methodology of science.
- In connection with our discussion of the Einstein-Podolsky-Rosen paradox (*EPR*) we gave our opinion that the *EPR* presents only an *apparent* problem for the Heisenberg QM teleology because that teleology amounts to the belief that the human experimenter is empowered to do “real magic”, including the ability to (for example)

ON SYSTEMS

instantaneously decide the momentum of a sub-atomic particle that is light-years away merely by measuring its nearby correlative particle.

- One of our five arguments against the many-worlds interpretation of quantum mechanics (MWI) was directed against MWI's *teleological analog*, which was shown to be *teleologically false*.

In *this* section the focus explicitly shifts from the *science* and *epistemology* of QM to the *teleological* issues that are associated with QM. Let's begin our teleological discussion by referring once again to the "thought experiment" depicted in Figure 2, which can be found earlier in this chapter. The *teleological* question which this "thought experiment" raises concerns the *teleological* status of the photon *after* it has encountered the beam splitter but *before* it has been detected by either detector *C* or detector *D*. (Let's say, for purposes of this example, that the photon is subsequently detected by detector *C*.) We've already established that it is scientifically and epistemologically meaningless to ask which channel (*c* or *d*) the photon is in *until* the photon is actually detected by detector *C*, at which point we *know* that the photon was in channel *c* rather than *d*. In the present context, however, our question is how to interpret this situation *teleologically*. While many teleological interpretations are possible, the following three interpretations seem to me to be the most important and interesting:

1. The transcendent all-knowing God exists. During the period of time between the photon's encounter with the beam splitter and the experimenter's detection of it at detector *C*, God knew *exactly* which channel the photon was in (channel *c*) and, moreover, knew *exactly where* the photon was at all times. The human experimenter's detection of the photon at detector *C* revealed to him but a small part of the knowledge that was previously known only to God.
2. The transcendent all-knowing God does *not* exist (or for some other reason is excluded from this teleological discussion). However, a *purely immanent* pantheistic god who shares some of our limitations *does* exist. This immanent god may be identified with what Dirac called "nature". Nature, so defined, did *not* know which channel the photon was in prior to its detection by detector *C* (or, perhaps, she was simply content to leave the photon temporarily "spread out" indeterminately within the ψ -wavefunction). And (of course) nature also did not know (or care to determine) the *position* of the photon prior to its detection. However, during the moment when detector *C* is triggered, nature somehow "decides" which detector the photon is to appear at, and (therefore) which channel the photon was in immediately prior to its detection. (The exact *positions* of the photon

as it traveled through channel *c* are *never* determined or known, either by nature or by the human experimenter.) In this teleological view, nature may be said to have “caused the ψ -wavefunction to collapse” in such a way as to trigger detector *C*.

3. *Neither* the transcendent God *nor* the immanent god (nature) exists. (Or, for some other reason, both are excluded from this teleological discussion.) As in teleological interpretation #2, *after* the photon’s encounter with the beam splitter but *before* its detection by detector *C*, the channel in which the photon was traveling was completely unknown to *anyone*. However, the triggering of detector *C* means that the human experimenter *by his act of measurement* has *caused* the photon to appear at detector *C* rather than detector *D*, and has also thereby *caused* the photon to appear *earlier* in channel *c* (rather than in channel *d*) just before it was detected. (As in teleological interpretation #2, the exact *positions* of the photon as it traveled through channel *c* are *never* determined or known.) Under this teleological interpretation (#3), *the human experimenter, by his act of measurement*, is said to have “caused the ψ -wavefunction to collapse”. This is essentially Werner Heisenberg’s teleological interpretation of QM, and it is by far the most popular with quantum physicists.

What are we to make of these three teleological interpretations of QM?

The first point we need to make is that teleological interpretations of QM must be evaluated *primarily* within the framework of *teleological* (a.k.a., *religious*) truth, rather than within the framework of *physical* (a.k.a., *scientific*) truth. The reason for this is that teleological claims require a teleological methodology (“bracket out the object”) rather than a scientific methodology (“bracket out the subject”) in order to evaluate them properly. (On this important point, see Book I of this trilogy, *WORLDVIEWS*.)

Viewed from this perspective, it is clear that teleological interpretation #1 above is to be strongly preferred: Throughout Book I and Book II, but especially in Book I, *WORLDVIEWS*, we have given numerous reasons for affirming the existence of the *transcendent all-knowing God*. The world’s major religious traditions, almost without exception, concur with this affirmation. In fact, the transcendent, all-knowing God of teleological interpretation #1 is *the* ultimate foundation of universal teleological truth.

By contrast, the actions of the *immanent* god of interpretation #2 (“nature”) do not seem plausible. Why would nature suddenly muster up the *will* (or, perhaps, the *ability*) to “decide” that the photon would appear at detector *C*, thereby “collapsing the ψ -wavefunction” just so the human experimenter

ON SYSTEMS

would have something definite to measure? By this account, nature seems to be either inept, lazy, or a trickster. Of course, she might be all three, but the resulting overall teleological picture is far less satisfactory than interpretation #1.

Teleological interpretation #3, the Heisenberg interpretation, is evidently the *least* satisfactory interpretation of the three, in spite of its extreme popularity among quantum physicists. When I contemplate the Heisenberg interpretation of QM, I can't help but think of a small boy who, upon approaching for the first time one of those automatic doors at the supermarket, is amazed at his ability to open the door just by waving his hand or saying "Open Sesame!" as he approaches.

Within the framework of teleological truth there is a name for the belief that one can open doors just by saying "Open Sesame!" or can force the past trajectory of a particle to appear in a particular channel merely by measuring that particle in the present: That name is *magic*. The practice of *real magic* (as opposed to the performance of *pretend magic* for entertainment purposes) is condemned by virtually all developed religious traditions. (See, for example, *The Catechism of the Catholic Church*, #2117.)

Moreover, contemplating the physical analog to the Heisenberg teleological interpretation results in manifest absurdities, since (as Niels Bohr succinctly points out) "it is certainly not possible for the observer to influence events which may appear under the conditions he has arranged",¹²⁶ *especially* in this case, where such influence would have to travel *backwards* in time, contrary to the immanent-objective physical fact of *forward-irreversible* time.

Yet in spite of its manifest religious deficiencies and analogical physical absurdities, the Heisenberg teleological interpretation of QM reigns supreme among quantum physicists even to this day. In fact, it is often lumped together with Bohr's "complementarity principle", and the two ideas *as one unit* are presented as "the standard Copenhagen interpretation" of QM, a fact which most certainly would *not* have pleased Niels Bohr!

Some scientists have gone much further and have extended the Heisenberg teleological interpretation of QM into a cosmological *Anthropic Principle*. According to this Anthropic Principle, man, merely by means of his *observations* of the physical world, is *the creator of the entire universe*, including himself, back to the very first moment of the "big bang"! This idea was first popularized by the prominent American physicist John Wheeler. Wheeler expresses the essence of his version of the Anthropic Principle this way:

The Universe starts small at the big bang, grows in size, [and] gives rise to life and observers and observing equipment. The observing equipment, in turn, through the elementary quantum processes that terminate on it, takes part in giving tangible “reality” to events that occurred long before there was any life anywhere.¹²⁷

In other words, the Anthropic Principle takes the spurious backwards-in-time causality of the Heisenberg teleological interpretation of QM (with is ordinarily regarded to be of the order of magnitude of a few seconds or microseconds) and extends it billions of years backwards-in-time to the “big bang” itself, thus making man his own creator!

Believers in the Anthropic Principle (who include Stephen Hawking, whom we discussed in our chapter on General Relativity) take all of the evidence of the extraordinary “coincidences” in the physical universe (which show that if either the laws of nature or the universal constants of nature were even very slightly different, life as we know it could not have arisen) and stand this evidence on its head: Ordinarily this evidence would be used to prove the design of the cosmos by a benevolent transcendent God. Not so, say the believers in the Anthropic Principle. Rather, for them this evidence instead proves that man *himself* has designed the cosmos by merely observing it! (Though, admittedly, they don’t usually express this idea quite so baldly.)

British astronomer John Barrow and American mathematical physicist Frank Tipler have their own version of the Anthropic Principle. Calling Wheeler’s version “PAP” (which stands for “Participatory Anthropic Principle”), they call their own version “FAP” (which stands for “Final Anthropic Principle”). Borrowing a page from the ideas of paleontologist Teilhard de Chardin, they regard the entire universe to be moving inevitably towards a final, perfect *Omega Point*. Barrow and Tipler write:

Life will have gained control of all matter and forces, not only in a single universe, but in all universes whose existence is logically possible; life will have spread into all spatial regions in all universes which could logically exist, and will have stored an infinite amount of information, including all bits of knowledge which it is logically possible to know.¹²⁸

In a footnote they declare that “the totality of life at the Omega Point is omnipotent, omnipresent, and omniscient.”¹²⁹ Hugh Ross critically summarizes their position as follows: “Let me translate: the universe created man, man created the universe, and together the universe and man in the end will become the Almighty transcendent Creator.”¹³⁰

Although the vast majority of physicists subscribe to the Heisenberg teleological interpretation of quantum mechanics, only an influential few have gone on to wholeheartedly embrace the Anthropic Principle. In fact, noted and

ON SYSTEMS

respected recreational mathematician, science writer, and magician Martin Gardner has sardonically renamed “FAP” to “CRAP”, which stands for the “Completely Ridiculous Anthropic Principle”!¹³¹

Furthermore, as we demonstrated in our prior discussion of teleological systems that are analogs to General Relativistic Systems, there is no evidence *whatsoever* of any unconditional equifinality for the whole physical universe that would have a teleological analog capable of giving significant *teleological* meaning and purpose to the cosmos. (In other words, there’s no credible evidence for the *Omega Point*.) For this reason, traditional religions (in different ways) have always depended on a *transcendent* God to give meaning and purpose to the universe. (In this context of the Anthropic Principle, it is hard to avoid mentioning G.K. Chesterton’s oft-cited observation that, when people stop believing in God, they don’t believe in *nothing*: they’ll believe in *anything*.)

But *why* have the vast majority of physicists “fallen” (pun intended) for the Heisenberg teleological interpretation of QM (which we have numbered as possibility #3)? To some extent they have done so because it fits in so well with our dominant Enlightenment and post-Enlightenment teleologies: Only possibility #3 allows for that complete atheism (or agnosticism) which prominent physicists such as Steven Weinberg have declared to be a basic requirement to even be considered to *be* a serious physicist. Also, possibility #3 is the only one of the three teleological possibilities that is fully compatible with the modern and post-modern stress on the ultimacy of the *radical autonomy of the human individual*, who ideally is supposed to be self-created, self-empowered, self-actualized, and brimming with self-esteem. (We refuted the various versions of this modern / post-modern teleology in Book I, *WORLDVIEWS*, following the outline and insights of Alasdair MacIntyre’s great book *After Virtue*.)

But there is a much more interesting reason why most physicists have embraced the Heisenberg teleology. And that is because they have incorrectly linked the question of QM teleology to the entirely orthogonal question of whether or not quantum mechanics is *complete*. Recall from our previous discussion that the question of the *completeness* of QM is the question: “Are the random statistical factors existing within QM *ultimate* and *irreducible*, or do *hidden variables* exist whose discovery would eliminate probability and statistics from quantum theory?”

As we argued previously, there is no way to know the answer to this question until someone actually comes up with a provable, superior “hidden variables” theory. We also showed that all attempts to prove the *impossibility* of a successful “hidden variables” theory (such as the attempts of John von

Neumann, John S. Bell, and Alain Aspect) are defective. But, in addition, we noted that all actual attempts to create a proven “hidden variables” theory, including Einstein’s monumental efforts on his Unified Field Theory, have so far been failures. We were able to make all of these observations without any reference to teleological issues whatsoever because, at bottom, the question of the *completeness* of QM is an *epistemological* question, not a *teleological* question.

But most physicists instead reason as follows:

If I were to accept teleological interpretation #1 (that a transcendent God exists who knows which channel the photon is in *before* I measure it), then I would have to admit that a transcendent God exists who knows more about the photon than I do and who, furthermore, knows more about the photon than QM says it is even *possible* to know. I would therefore also have to admit that quantum mechanics is an *incomplete* theory. But I know *in my bones* that only a *statistical* description of sub-microscopic phenomena is scientifically possible and that QM is, therefore, in this sense *complete*. Hence I must reject teleological interpretation #1 in favor of teleological interpretation #3 (that the photon was *not* definitely in channel *c* until the *experimenter* actually *later* measured it at detector *C*).

[For purposes of simplicity here, we’ll ignore teleological interpretation #2.]

Now, there is a very interesting hidden assumption in the otherwise-plausible foregoing argument. It is the assumption that *objective truth from the point-of-view of a transcendent God is of precisely the same nature as objective truth from the point-of-view of man* (or other intelligent being *within* the cosmos). But is this assumption really true? Surprisingly, the answer is *no*. But in order to see *why* we must digress to briefly discuss the *epistemology of probability*.

The fundamental *epistemological* issue associated with the scientific concept of *probability* is the question: “Does a kind of randomness exist within nature that is an *objective fact* of nature, or is all apparent randomness in nature *merely subjective* and due to our *subjective ignorance* of the details of the processes involved?”

Up until the twentieth century, physicists were of the near-unanimous opinion that *all* probability is “merely subjective”. And because nineteenth-century thermodynamics could be explicated in terms of probability, an important corollary of this was the physicists’ belief that macroscopic *irreversible time* is also a “merely subjective” illusion: Only the *reversible time* of Newtonian mechanics was regarded to be truly *objective*.

But as quantum theory developed throughout the first third of the twentieth century, it became increasingly clear that probability *as it appeared within quantum theory* could *not* be dismissed as being “merely subjective”, but

ON SYSTEMS

rather had to be incorporated into QM in such a manner that the random quantum “jumps” of the sub-atomic world were regarded as fundamental, *objective*, and not-further-analyzable in a deterministic way. Nevertheless, physicists continued to regard *thermodynamic* probability and *macroscopic irreversible time* to be “merely subjective”. This *inconsistency* in the way physicists came to treat *quantum* probability as opposed to *thermodynamic* probability is not unrelated to the epistemological problems of quantum measurement that we discussed previously, since experimental measurement is a macroscopically *irreversible* (and therefore “merely subjective” ???) process.

Einstein, de Broglie, Bohm, and a few other physicists sought to resolve this dichotomy between *objective* quantum probability and *subjective* thermodynamic probability by regarding quantum probability to *also* be subjective, just like thermodynamic probability. That is why they sought so earnestly to find “hidden variables” which would eliminate probability as a fundamental, objective feature of quantum mechanics. As we have seen, their search was unsuccessful.

By contrast, the approach of Ilya Prigogine and his colleagues towards resolving this inconsistency is the approach which I support: Their approach is to regard thermodynamic probability to be fundamentally *an immanently objective fact of nature*, just like quantum probability is. This means, among other things, that macroscopic *irreversible time* is also *an immanently objective fact of nature*.

Arguments for this approach will be presented in detail in our later chapters on **Nonlinear Dynamic Systems**, **Linear Thermodynamic Systems**, and **Nonlinear Complex Physical Systems**. But, for now, I will just summarize the epistemological (and teleological) conclusion we will come to:

- *From the point-of-view of human beings (or any other finite conscious beings within the cosmos), fundamental physical descriptions of nature contain an irreducible element of immanently objective chance (both microscopic and macroscopic): By contrast, from the transcendently objective point-of-view of the transcendent God, objective physical reality is fully and deterministically known by His omniscient mind and fully determined by His omnipotent will.*

Since science is a human enterprise (and since, quite evidently, the transcendent God has no need to “do science”), it is the *first* (i.e., human) point-of-view in the above formulation that defines the nature of *scientific* objective truth. And that is why *immanent, scientific, objective truth from the point-of-view of man is not precisely of the same nature as transcendent, physical, objective truth from the point-of-view of the transcendent God*.

An important corollary of the above basic principle is that, for man, time is objectively *irreversible*, while, for God, time is objectively *reversible* and eternal (paradoxically, a sort of “timeless time”). Still another important corollary (which we discussed in the teleological section at the end of our chapter on **Classical Mechanical Systems**) is that human free-will is *completely real* from a *human* point-of-view, but *not* from the *transcendent* divine point-of-view.

Now that we’ve briefly discussed the epistemology (and teleology) of probability and time, we can go back and see where the argument linking QM teleology to the question of QM’s “completeness” goes wrong: In teleological interpretation #1, the fact that the transcendent God *knows* which channel (*c* or *d*) the photon is in prior to the moment when the experimenter measures it is *irrelevant* to the question of whether or not QM is “complete”: If, in fact, it turns out to be the case that the laws of quantum mechanics are among those scientific descriptions of nature which are scientifically *fundamental* (so that no deterministic or quasi-deterministic “hidden variables” are ever found to underlie them), then QM is “complete”. Otherwise, QM is *not* “complete”: The fact of God’s omniscience and omnipotence is *totally irrelevant* to this QM “completeness” question, since *we can never approach God’s transcendentally objective viewpoint by successively refining our own immanently objective viewpoint*. For this reason, His view of the physical universe will *always* be significantly different from our own.

Although scientists have had to give up the idea that scientific knowledge can ever approach the deterministic knowledge of a transcendent God (or of Laplace’s fictional demon) through successive, increasingly-accurate incremental steps, it nevertheless remains difficult for them to also give up the *ideology* of classical Newtonian determinism (as we saw in our earlier discussion of the popular scientific writings of Stephen Hawking). That is perhaps the primary *underlying* reason why most physicists reject QM teleological interpretation #1: They simply *cannot* accept the fact that a transcendent God exists who knows things about the physical universe that they don’t know and *will never even come close* to knowing. But teleological assertions must ultimately be justified on teleological and religious grounds, not on ideological or even scientific grounds. And on teleological and religious grounds we have seen that QM teleological interpretation #1 is clearly the superior choice.

The last QM-related teleological idea we wish to discuss is an idea that is often put forth by both scientists and popular science writers: This is the idea that there would be no human free-will were it not for the Heisenberg Uncertainty Principle. (Sometimes the related idea is put forth that God

ON SYSTEMS

would not be able to act within the physical universe were it not for the Heisenberg Uncertainty Principle.)

Evidently this idea is suggested to these scientists and science writers because of the widespread and erroneous belief that only sub-microscopic *quantum* probability is an *objective fact*, while macroscopic *thermodynamic* probability is supposed to be merely a *subjective illusion*. As we have noted in earlier discussions, *decisions* within *teleological* systems are analogous to *moments of constrained chance* within physical systems. But the only truly objective *moments of constrained chance* that appear within the framework of QM are random quantum “jumps” at the sub-atomic level: That is probably why scientists and science writers often believe that objective physical analogs to human (or divine) decisions can therefore *only* be found at the sub-atomic level.

However, it is evident that this attempt to find *physical* analogs for human decisions at the *sub-microscopic* level is both bizarre and desperate, because of the complete mismatch both in scale and nature between *sub-microscopic* quantum jumps on the one hand and *macroscopically* evident human decisions on the other. Instead, as we shall see in our later chapter on **Nonlinear Complex Physical Systems**, the physical human body is an extremely complex far-from-equilibrium *dissipative structure* that is characterized by *macroscopic* moments of constrained chance which can easily be seen to be physically analogous to *macroscopic* human decisions. These *macroscopic* moments of constrained chance arise ultimately from nonlinear *thermodynamics* rather than *quantum* probability. And since it will be our contention, following Ilya Prigogine, that macroscopic *thermodynamic* chance is just as *immanently objective* as *quantum* chance, it follows that these *macroscopic* moments of constrained chance are just as *immanently objective* as the *sub-microscopic* quantum jumps of quantum mechanics. It therefore makes no sense to try and form a conceptual parallel between *sub-microscopic* quantum jumps and *macroscopic* human decisions when a much more natural *macroscopic* physical parallel exists in the thermodynamic theory of dissipative structures.

Nonlinear Dynamic Systems

The most famous example of a *nonlinear dynamic system* is the chaotic three-body gravitational system. However, as we noted in our earlier chapter on **Classical Mechanical Systems**, the *vast majority* of dynamic systems are nonlinear rather than classical-mechanical (linear), a fact which was proved by Henri Poincare at the end of the 19th century. For this reason, it is important that we consider such systems in more detail.

In our section on **Classical Mechanical Systems** we stated Newton's *three laws of motion* and his *law of gravitation*. In this section we will further discuss the actual subject-matter of dynamics, while exploring the implications of the *nonlinearity* of most dynamic systems. In addition, this chapter is preparatory for our subsequent discussions of **Linear Thermodynamic Systems** and **Nonlinear Complex Physical Systems**. (For example, it turns out that we can initially establish the *irreversibility of time* at the level of nonlinear dynamic systems, rather than at the far-more-complex level of thermodynamic systems!)

Let's begin by summarizing Newton's *three laws of motion* in condensed form:

Newton's first law of motion states that, if the vector sum of the forces acting on an object is zero, then the object will remain at rest or remain moving at constant velocity. Newton's second law of motion states that a net force on an object will accelerate the object at a rate proportional to the strength of the force and in the same direction as the force [i.e., $\mathbf{F} = m\mathbf{a}$, where \mathbf{F} is *force*, m is *mass*, and \mathbf{a} is *acceleration*]. Newton's third law of motion states that an object experiences a force because it is interacting with some other object, and that the force exerted by object 1 on object 2 must be equal to the force exerted by object 2 on object 1 but in the opposite direction.¹³²

An algebraically equivalent way of expressing Newton's second law of motion is $\mathbf{a} = \mathbf{F} / m$. This way of expressing the formula makes it clear that the acceleration of a body under the influence of a force is *directly* proportional to the force and *inversely* proportional to the body's inertial mass. Notice also that in this formula \mathbf{a} and \mathbf{F} are in **bold** type, while m is not. This is because both acceleration and force are *vector* quantities – that is, they have both a magnitude *and* a direction – while inertial mass is a *scalar* quantity, since it has only a magnitude.

Now, as Resnick and Halliday point out in their popular standard textbook *Physics*, Newton's second “law” of motion, $\mathbf{F} = m\mathbf{a}$, is not really a *law* at all, but is rather a *definition* of the concept of force. From this definition of force, “[w]e see . . . clearly that force is a concept that connects the acceleration of the particle on the one hand with the properties of the particle and its environment on the other.”¹³³

ON SYSTEMS

But what are “the properties of the particle and its environment”? These vary for various types of forces, but for a very important class of forces which are both *universal* and *conservative*, the *distance* between two bodies attracted or repelled by the force, plus certain characteristics of the bodies themselves (such as *mass* or *charge*), plus an empirically determined *universal constant*, all play vital roles. Here are two important *force laws* expressing the particle/environment relationships for each of two different universal conservative forces:

1. Newton’s *law of universal gravitation*, $F = G (m_1 m_2 / r^2)$, where m_1 and m_2 are the inertial masses of two bodies, r is the distance between them, G is a universal constant, and F is the magnitude of the force of attraction between them. (Per Newton’s third law of motion, the *direction* of this attractive gravitational force is *opposite* for each of the two bodies, but has the *same magnitude*.)
2. Coulomb’s *law of electrostatics*, $F = (1/4\pi\epsilon_0) (e Q / r^2)$, where e is the negative charge of an electron, Q is the charge on a nearby positively charged sphere, r is the distance from the electron to the center of the sphere, ϵ_0 is a universal constant, π is the ratio of the circumference of a circle to its diameter, and F is the *magnitude* of the electrostatic force between the electron and the charged sphere. (Again, per Newton’s third law of motion, the *direction* of this force is *opposite* for the electron and the sphere.)¹³⁴

Notice that both of these laws are *inverse square laws*: In each case the magnitude of the force is *inversely* proportional to the square of the distance between the two bodies and is *directly* proportional to a property of the bodies themselves (*mass* and *charge*, respectively).

At first the significance of *distance* (r) as a central variable in the force laws for gravitation, electrostatics, and electromagnetism was not appreciated: Rather, these forces were regarded to be properties of *essentially independent* material bodies. As we noted in our chapter on **Classical Mechanical Systems**, this point-of-view in the case of gravitation was aided by the fact that, in the systems successfully modeled (e.g., the sun/planets system and the system of the earth with respect to the objects on its surface), the gravitational effects of a *single body* (the sun and earth respectively) dominate the system, so that gravitation in those systems can be usefully approximated as a property of the dominant body only.

However, as a result principally of the work of Faraday, Maxwell, Hertz, and Lorentz on electromagnetism, distance *as a property of space in relation to force* eventually came to be regarded as vitally important in itself, so that electromagnetic *force* eventually was seen to be intimately connected with the

concept of an electromagnetic *field*. Correspondingly, via Einstein's General Theory of Relativity, gravitational *force* also came to be seen to be intimately connected with the concepts of *space-time* and the gravitational *field*. The acceptance of the fact that these electromagnetic and gravitational fields must be properties of *space* (or *space-time*) did not come easily, however. As Einstein wrote in his "Autobiographical Notes", prior to the work of H.A. Lorentz:

Matter appeared as the bearer of the field, not *space*. By this was implied that the carrier of the field could have velocity, and this was naturally to apply to the "vacuum" (ether) also. Hertz's electrodynamics of moving bodies rests entirely upon this fundamental attitude.

It was the great merit of H.A. Lorentz that he brought about a change here in a convincing fashion. In principle a field exists, according to him, only in empty space. Matter – considered as atoms – is only the seat of electric charges; between the material particles there is empty space, the seat of the magnetic field, which is created by the position and velocity of the point charges which are located on the material particles. . . The particle-charges create the field, which, on the other hand, exerts forces upon the charges of the particles, thus determining the motion of the latter according to Newton's law of motion. If one compares this with Newton's system, the change consists in this: action at a distance is replaced by the field, which thus also describes the radiation. . . The physicist of the present generation regards the point-of-view achieved by Lorentz as the only possible one; at the time, however, it was a surprising and audacious step, without which the later development would not have been possible.¹³⁵

As a result of these developments in field theory, physicists were eventually "forced" (pun intended) to acknowledge that physical systems involving parts that have sustained, strong electromagnetic or gravitational interactions are *holistic systems* with *constitutive characteristics* ("emergent properties") that cannot be derived summatively from their parts: The masses (or charges) of the parts affect the structure of the nearby space-time field, which in turn exerts forces on those same parts. Two of the most important *constitutive characteristics* arising from these intimate interconnections between matter and space-time are the *overall spatial arrangement* of a gravitational or electromagnetic system at a given point in time and the *potential energy* associated with that spatial arrangement.

Note that throughout this chapter on nonlinear dynamic systems we will continue to point out where important *constitutive characteristics* (a.k.a. "emergent properties") arise at the level of dynamics, since it is even today often erroneously asserted that constitutive characteristics arise only at the "higher" levels of thermodynamics, biology, psychology, and sociology. (In

ON SYSTEMS

fact, it is sometimes even still asserted that such “emergent properties” are merely the product of unscientific vitalism and mysticism.)

In showing that extremely important constitutive characteristics arise even at the level of basic dynamics I am not, of course, claiming that thermodynamics, biology, psychology, and sociology can therefore all be “reduced” to physics: On the contrary, the point is that “emergent properties” are as important in elementary physics as they are in the other subject areas of science.

Among the constitutive characteristics of gravitational and electromagnetic systems, *potential energy* holds special importance. We therefore need to consider the dynamic concepts of *work* and *energy* in some detail.

Work and Kinetic Energy

In dynamics, the *work* done on a body by a force is the product of the *distance* the body moves times the magnitude of the *force* along the body’s direction of motion. (For simplicity, we will assume that the *whole* force is acting *entirely* in the direction the body is moving. That way we will only have to consider the *magnitude* of the force, not its *direction*.) In other words, $W = Fd$, where W is the work done (a scalar quantity), F is the magnitude of the acting force, and d is the distance the body moves. Note that this definition of *work* in dynamics is *not* the same as our ordinary-language definition of work: In ordinary language we would say that a person holding a heavy weight out at arm’s length is doing a lot of work. However, because the heavy weight in this case is *not* moving, *no* work is being done from the point-of-view of dynamics.

We can also determine the work done on a body even if the force is not constant, but rather varies in its intensity as the body moves. Let’s say that a body moves from position q_1 to position q_2 under the influence of a force that varies in magnitude (but not direction) as the body moves. First we divide up the line extending between q_1 and q_2 into tiny segments of length Δq . Now, as the force moves the body through any given distance Δq we may regard that force $F(q)$ [read as “ F as a function of q ”] to be of approximately constant magnitude. Therefore, to *approximately* find the *total* amount of work done, all we have to do is add up all of the little $F(q)$ -times- Δq results. We may express this in summation notation as follows: $W \cong \sum F(q) \Delta q$ as the value of q incrementally moves from q_1 towards q_2 . Then, to find the total amount of work *exactly*, we just calculate W as the limit when we let Δq become smaller and smaller, so that Δq approaches zero. The final resulting formula for *work* is then the following *definite integral*:

$$W = \int F(q) dq \quad (1)$$

where dq represents Δq as an infinitesimal quantity.¹³⁶

Suppose a body of mass m is moving with a constant velocity v_0 . A force (constant or variable, it doesn't matter) now acts on that body and accelerates it to velocity v . How much *work* did that force do on that body? From the brief discussion of differential calculus in our chapter on **Classical Mechanical Systems**, together with some elementary algebra, we know that the following relation holds:

$$a = dv/dt = dv/dq \cdot dq/dt = dv/dq \cdot v = v \cdot dv/dq \quad (2)$$

where a represents acceleration, dv/dt is the first derivative of velocity (which also represents acceleration), dq/dt is the first derivative of the position q (i.e., the velocity), and v also represents velocity. Substituting the final expression for acceleration a in (2) above into Newton's second law of motion ($F = ma$), we obtain:

$$F = mv \cdot dv/dq \quad (3)$$

Substituting the expression for force in (3) into our formula for work (1), we get:

$$W = \int mv \cdot dv/dq \cdot dq = \int mv \cdot dv = \frac{1}{2}mv^2 - \frac{1}{2}mv_0^2 \quad (4a)$$

(The last expression in formula 4a is derived via elementary integral calculus by choosing $-\frac{1}{2}mv_0^2$ to be our "arbitrary constant".)

We now define the expression $\frac{1}{2}mv^2$ to be the *kinetic energy* of the body. Formula 4a above then becomes the mathematical expression of the *Work-Energy Theorem*, which states that:

- *The work done by the resultant force acting on a body is equal to the change in the kinetic energy of that body.*

$$W = K - K_0 = \Delta K \quad (4b)$$

where W is the work done by the resultant (constant or variable) force on the body, K is the kinetic energy of the body *after* that resultant force has been applied, K_0 is the initial kinetic energy of the body *before* the resultant force was applied, and ΔK is the change in the kinetic energy caused by the resultant force (which is equal to the work done by that force).¹³⁷

In their standard textbook *Physics*, Resnick and Halliday tell us other important things about *kinetic energy*:

If the kinetic energy of a particle *decreases*, the work done on it by the resultant force is *negative*. [In that case] the displacement and the component of the resultant force along the line of motion are oppositely

ON SYSTEMS

directed. The work done on the particle by the force is the negative of the work done by the particle on whatever produced the force. This is a consequence of Newton's third law of motion. Hence [Formula 4b] can be interpreted to say that the kinetic energy of a particle decreases by an amount just equal to the amount of work which the particle does. A body is said to have energy stored in it because of its motion; as it does work it slows down and loses some of this energy. Therefore, the kinetic energy of a body in motion is equal to the work it can do in being brought to rest. This result holds whether the applied forces are constant or variable.

The units of kinetic energy and of work are the same. Kinetic energy, like work, is a scalar quantity. The kinetic energy of a group of particles is simply the sum of the kinetic energies of the individual particles in the group.¹³⁸

It is particularly important to note in this connection that the *total* kinetic energy of a dynamic system is a *summative characteristic* of that system that can be derived by simply adding up the kinetic energies of the system's individual parts.

Conservative Forces and Potential Energy

Recall that we said earlier that gravitational force and electrostatic force are universal and *conservative* forces. We are now in a position to define *conservative* in the context of work and energy:

- A force is conservative if the work done by it on a body that moves between two points depends only on the position of those two points and not on the path followed. Equivalently, we may say that a force is conservative if the work done by the force on a body that moves through any round trip is zero. Or, again equivalently, a force is conservative if the body upon which the force acts has the same amount of kinetic energy at the end of the round trip as it had at the start (assuming that no other non-conservative forces act upon the body during the round trip).¹³⁹

For example, if you lift a heavy weight up to a height h above the earth, it does not matter what path the weight takes to get to height h : You can lift it with constant or variable force, you can lift it straight up, or you can move it in a zigzag or curve while lifting it up to h . No matter which path the weight takes, you still must do the *same* amount of work *in the vertical direction* to get it to h . (For simplicity we ignore the *horizontal* component of your work as you, perhaps, zigzag the weight.) Now, because of Newton's third law of motion, the *positive* vertical work *you* do in lifting the weight is exactly equal and opposite to the *negative* work that *gravity* does in resisting your efforts. If you then release the weight, letting it fall back to earth, gravity does a

positive amount of work that is exactly equal in magnitude to the *negative* work it did in resisting your original lifting of the weight. When the weight has arrived back at the surface of the earth (thus completing its *round trip*), the *net* amount of work done by gravity after the round trip is *zero*. Gravity is therefore a *conservative* force.

By contrast, suppose instead that you push this same heavy weight around on a roughly finished table. If the weight starts, say, at point *A*, and you push it around on the table, eventually returning it to point *A*, then the *longer* the path taken by the weight, the *more* work you have done. This is because the force of *friction* acting equally and oppositely between the weight and the rough table is a *nonconservative* force that continually *dissipates* some of the work you are doing on the weight into the kinetic energy of millions of molecules at the surfaces of the table and the weight, respectively. (Macroscopically we experience this dissipation as *heat* energy, a subject that we will deal with in our chapter on **Linear Thermodynamic Systems**.)

Therefore the amount of work done by the *nonconservative* force of friction *does* depend on the particular path taken by the weight. (More rarely, a *nonconservative* force can result in *more* kinetic energy for particles completing a round trip instead of *less*: This is the case, for example, with the force of *magnetic induction* which is used to accelerate elementary particles in a particle accelerator.¹⁴⁰) For the remainder of this chapter, however, we will mainly deal with *conservative* forces such as gravitation and the electrostatic force, where the net round-trip work done by the force is zero and particles completing a round trip therefore have the same kinetic energy as before the round trip.

With respect to these *conservative* forces, it makes sense to define the concept of *potential energy*, which is the *energy of configuration* of the entire dynamic system. *Potential energy* (usually represented by *U*) is defined to be that mechanical *stored* energy which is associated with the spatial configuration of the dynamic system *taken as a whole* and which can be fully recovered and converted into kinetic energy.

To illustrate by example what is meant by *potential energy*, consider a simple dynamic system consisting of an ideal massless mechanical spring and a weighted block. If we give the block a push, so that it moves at constant velocity along a frictionless (or nearly frictionless) surface until it strikes the spring head on, the spring will continuously compress until the block is decelerated to a velocity of zero. The spring will then push back on the block as it stretches out again. When the spring is fully extended once more, the block will have recovered all of its kinetic energy, but will be traveling in the opposite direction.

ON SYSTEMS

Now, consider the position of the block just before it hits the spring. When the block returns to this same position after having its motion reversed by the spring, it has the *same* kinetic energy as it did before hitting the spring. From this fact we know that the spring's force is a *conservative* force. (It is not, however, a *universal* conservative force, because it depends on the material the spring is made of and how it is wound. Furthermore, the spring's force is conservative only if it is not stretched beyond a certain limit. Ultimately the spring's force can be traced back to *universal* electromagnetic forces.)

The force law for an ideal massless spring is known as Hooke's law:

$$F = -kq \quad (5)$$

where F is the force exerted by the spring when its free end is moved through a distance q and k is a constant that depends on the configuration and composition of the particular spring.

Before the block hits the spring, all of the mechanical energy of the block/spring system resides in the *kinetic energy* of the block. By contrast, at the point at which the spring has decelerated the block to zero velocity, all of the mechanical energy of the block/spring system has become *potential energy* – i.e., energy associated with the mechanical *configuration* of the block/spring system *as a whole*. Finally, *while* the block is being decelerated or accelerated by the spring, the total mechanical energy of the block/spring system is composed of both kinetic *and* potential energy in varying proportions.

The Law of Conservation of Mechanical Energy

From these considerations we see that a change in the total *kinetic* energy of a *conservative dynamic system* (i.e., a dynamic system involving *conservative* forces only) is always accompanied by an equal and opposite change in the total *potential* energy of that system, so that the total *mechanical* energy (kinetic energy + potential energy) remains constant. This is called the *law of conservation of mechanical energy*. (In our later chapter on **Linear Thermodynamic Systems** we will extend this law to include heat and other forms of energy. The general *law of conservation of energy* will then be seen to apply to *nonconservative* systems as well as conservative systems.)

If K is total kinetic energy, U is total potential energy (i.e., the energy of configuration), ΔK is the change in total kinetic energy, ΔU is the change in total potential energy, and E is the total constant mechanical energy of the conservative dynamic system, then we can express the above observations in the following formulas:

$$\Delta K = -\Delta U \quad (6a)$$

$$\Delta K + \Delta U = 0 \quad (6b)$$

$$K + U = E \quad (7)$$

Now, it is important to emphasize again that the *kinetic-energy* component of total mechanical energy is merely a *summative characteristic* of the dynamic system: To get the total kinetic energy for the system you simply *add up* the kinetic energy of its parts. By contrast the *potential-energy* component of total mechanical energy is a *constitutive characteristic* (i.e., “emergent property”) of the dynamic system *taken as a whole*: There is *no way* to ultimately allocate potential energy to the various individual parts of the system. Resnick and Halliday, in their popular textbook *Physics*, make this clear in their chapter on gravitation. Speaking of a simple gravitational system consisting of a larger body of mass M and smaller body of mass m , they write:

The potential energy is a property of the *system* of bodies, rather than of either body alone. The potential energy changes whether M or m is displaced; each is in the gravitational field of the other. Nor does it make any sense to assign part of the potential energy to M and part of it to m . Often we *do* speak of the potential energy of a body m (planet or stone, say) in the gravitational field of a much more massive body M (sun or earth, respectively). The justification for speaking as though the potential energy belongs to the planet or to the stone alone is this: When the potential energy of a system of two bodies changes into kinetic energy, the lighter body gets most of the kinetic energy. The sun is so much more massive than a planet that the sun receives hardly any of the kinetic energy; and the same is true for the earth in the earth-stone system.¹⁴¹

In fact, within Einstein’s Theory of General Relativity, gravitational potential energy may be viewed as localized within a particular gravitational system only from the point-of-view of a particular reference frame of coordinates: Ultimately gravitational potential energy is regarded by General Relativity to be *a property of space-time as-a-whole*.

Since such “emergent properties” as potential energy arise even in the most-basic dynamic systems described by physics, they clearly cannot be dismissed as “merely subjective” or “mystical”. Notice also that, while we can fairly-straightforwardly calculate *changes* in potential energy U (that is, ΔU), the actual assignment of a base or reference value for U is *arbitrary* (and therefore the base or reference value for E is also arbitrary). Often the reference value for U is chosen to be zero for that spatial configuration of the system in which the influence of the associated force is minimized. So, for example, in the block/spring system we discussed, zero U is usually associated with the configuration of the system just before the block strikes the spring. For general gravitational systems, zero U is usually associated with an *infinite separation* between the attracting bodies. (But for objects

ON SYSTEMS

near the earth's surface it is often more convenient to regard zero U to be at the surface of the earth.)

Of course, the total value of the kinetic energy K of a body or system is also arbitrary, in the sense that it depends on velocity v , which in turn depends on the *reference frame* of the observer, who may be moving at a constant velocity or accelerating or spinning relative to that body or system. Again, Resnick and Halliday:

Hence the important thing about mechanical energy E , which is the sum of the kinetic and the potential energies, is *not* its actual value during a given motion (this depends on the observer) but the fact that this value *does not change* during the motion for any particular observer when the forces are conservative.¹⁴²

It is particularly important to note that different non-inertial (i.e., accelerating or spinning) frames of reference can result in different *proportions* between the total kinetic energy K and the total potential energy U of the system. As we mentioned in our chapter on **Classical Mechanical Systems**, throughout the 19th century physicists strove to discover frames of reference for all known physical systems such that kinetic energy was *maximized*, while potential energy was *minimized* or *eliminated*. For eliminating potential energy meant that both the strong, persistent interactions between the system's parts and the constitutive characteristics ("emergent properties") of the system as a whole could be *ignored* or regarded as being *nonexistent*, so that the system could then be treated as analogous to a "free particle" dynamic system following the deterministic laws of classical mechanics (the whole is analyzable as merely the sum of its parts, the system is linear and solvable by differential calculus, the principle of superposition holds, etc.).

But while it is always possible to find some frame of reference that eliminates all (or virtually all) potential energy from a dynamic system if the number of strongly, persistently interacting bodies that have significant mass or charge is *none*, *one*, or *two*, by contrast this turns out to be *impossible* when *three or more* bodies having significant mass or charge strongly and persistently interact. In fact, this turns out to be *impossible* if only *two* bodies of *significant* mass/charge and *one* body of *insignificant* mass/charge all strongly and persistently interact. (The most famous example of this is the gravitational *three-body problem*, which was proved to be *deterministically unsolvable* by Henri Poincare at the end of the 19th century.) That is why *all* dynamic systems composed of three or more strongly, persistently interacting bodies having significant mass/charge (in other words *most* dynamic systems) are *holistic systems* that have *irreducible* constitutive characteristics (such as potential energy). Furthermore, these *holistic systems* are *nonlinear*, are *deterministically unsolvable* by differential calculus, and generally *violate*

the principle of superposition. Such *nonlinear* dynamic systems also have moments of significant, irreducible, macroscopic *constrained chance* and, in fact, the “simplest” nonlinear dynamic systems (such as the three-body gravitational system) are *chaotic*. Most significantly, *all* of these holistic phenomena occur at the level of *basic dynamics* (as well as at the “higher” levels of thermodynamics, biology, sociology, and so on). Such holistic phenomena therefore *cannot* simply be dismissed as “mystical”, “vitalistic”, or “merely subjective”.

We might also note in passing that, although we have essentially defined the concept of a conservative physical system in terms of moving-body dynamics, other kinds of physical systems may also be conservative. As Gregoire Nicolis and Ilya Prigogine remark:

We should not conclude from the above discussion that conservative systems are confined to classical mechanics. The propagation of light in a vacuum, described by Maxwell’s well-known equations, provides an important example of conservative systems in electromagnetism. Conservative systems also arise in quantum mechanics, in problems that deal with the properties of simple atoms and molecules in the absence of external fields.¹⁴³

More on Potential Energy, Work, and Force

Next, let’s consider the relationships between *potential energy*, *work*, and *force* in conservative dynamic systems in somewhat more detail. If we combine formulas 1, 4b, and 6a above, it is easy to see that:

$$\Delta U = - \int F(q) dq \quad (8a)$$

Implicit in formula 8a is the idea that the change in the potential energy of a system depends only on position q (which is equivalent to saying that potential energy has meaning only in relation to *conservative* forces and *conservative* dynamic systems). Another way to write formula 8a is:

$$F(q) = - dU(q) / dq \quad (8b)$$

To see that formulas 8a and 8b are equivalent, simply substitute the expression for $F(q)$ in 8b back into 8a. With this substitution, 8a reduces to $\Delta U = \int dU(q)$, thus proving the equivalence. Putting formulas 8a and 8b into words, we may say that:

- *Potential energy U is solely a function of position (or distance between the parts) q .*
- *Force F is the negative of the rate of change in potential energy U with respect to position q .*¹⁴⁴

ON SYSTEMS

Because of their intimate connection with potential energy, we may conclude that both conservative *force* and the closely related *force field* are *constitutive characteristics* (i.e., holistic “emergent properties”) of any conservative dynamic system which contains a significant irreducible amount of potential energy. (As we have seen, that means *most* conservative dynamic systems.)

Indeed, even *position q* (which reflects the *distance* between the bodies at a given moment in time) is also a *constitutive characteristic* (“emergent property”) of any such potential-energy-bearing conservative dynamic system. For while the distances between the bodies which compose the conservative dynamic system are *accidental* and *insignificant* with respect to *kinetic energy K* , these same distances are *significant constitutive characteristics* of the system with respect to *potential energy U* . We might therefore speak of such potential-energy-related distances as *tensive distances* because they are associated with the storage of potential energy by the system as-a-whole. Such *tensive distances* are also intimately connected with the existence of *order* within the system.

More on the Hamiltonian Function

Recall that in our chapter on **Classical Mechanical Systems** we made prominent mention of the *Hamiltonian function*. The *Hamiltonian function H* is simply the expression of the *total mechanical energy E* of a conservative dynamic system in terms of *momentum p* and *position q* , rather than in terms of *kinetic energy K* plus *potential energy U* . (In other words $H = H(p, q) = E = \text{constant}$.) But before discussing this Hamiltonian function in more detail, we need to briefly define and discuss the concept of *momentum* in more detail:

- *The momentum p of a single body is defined to be the product of its mass m and its velocity v . We may write this definition as the formula:*

$$\mathbf{p} = m\mathbf{v} \quad (9)$$

Notice that both \mathbf{p} and \mathbf{v} are in boldface type, meaning that they are here regarded to be *vector* quantities rather than *scalar* quantities. (*Vector* quantities, you will recall, have direction as well as magnitude, while *scalar* quantities have only magnitude.) Notice also that although both kinetic energy K and momentum \mathbf{p} are computed using mass and velocity, kinetic energy is a *scalar* quantity (i.e., $\frac{1}{2}mv^2$), while momentum is a *vector* quantity (i.e., $m\mathbf{v}$). Now, using Newton’s second law of motion $\mathbf{F} = m\mathbf{a}$ together with formula 9 above, we can see that the relationship between *force \mathbf{F}* and *momentum \mathbf{p}* is as follows:

$$\mathbf{F} = m\mathbf{a} = m \, dv/dt = d(mv)/dt = d\mathbf{p}/dt \quad (10)$$

In other words:

- *Force is the rate of change in the **momentum** of a body with respect to time.*

It also turns out to be the case (though we will not take the time to prove it here) that, where the sum of the *external* forces acting on a conservative dynamic system of bodies is zero, the *total momentum* \mathbf{P} of the system (obtained by simply adding the momenta of the *parts* of the system in vector fashion) remains constant. We can express this by means of the formula:

$$d\mathbf{P}/dt = \text{zero or } \mathbf{P} = \text{constant} \quad (11)$$

This important principle in physics is known as *the law of conservation of linear momentum*.¹⁴⁵

We are now in a position to derive the Hamiltonian function. Let's say we have a conservative dynamic system consisting of n bodies. We will designate i to represent any one of these bodies individually (where i has an integer value ranging from 1 to n). First, we know from the definition of kinetic energy as $\frac{1}{2}mv^2$, together with the fact that the total kinetic energy of a conservative dynamic system is simply the sum of the kinetic energy of its parts, that the following formula holds:

$$K = \sum \frac{1}{2}m_i v_i^2 \quad (12)$$

Using summation notation (\sum), formula 12 adds up the kinetic energy for all of the values of i from 1 to n , so that K here represents the *total kinetic energy* of the system.

Next, we designate j to represent any one of the bodies from 1 to n that is *different* from i . It then turns out to be the case (though we will not prove this in detail) that the *total potential energy* U of this conservative dynamic system is equal to one-half of the sum of the *interaction potentials* V between each of the bodies i and j ($i \neq j$). We express this by means of the following formula:

$$U = \frac{1}{2} \sum V_{ij} \quad (13)$$

(The expression $\sum V_{ij}$ is multiplied by $\frac{1}{2}$ because V_{ij} is really the same as V_{ji} in every case, where $i \neq j$. Note also that the summation notation in formula 13 does *not* mean that total potential energy U is now really a summative characteristic, because the interaction potentials V_{ij} are both holistic in themselves and influence one another holistically.)

ON SYSTEMS

Combining formulas 7, 12, and 13, we get the following formula for the *total mechanical energy* E for a conservative dynamic system:

$$E = \sum \frac{1}{2} m_i v_i^2 + \frac{1}{2} \sum V_{ij} \quad (i \neq j) \quad (14)$$

At this point, we will begin regarding velocity \mathbf{v} , position \mathbf{q} , and momentum \mathbf{p} to all be *vector* quantities (since we want our Hamiltonian function to be valid in more than just one dimension). We can then make the following substitutions:

Because momentum is defined as $\mathbf{p} = m\mathbf{v}$, we can substitute:

$$\frac{1}{2} m_i v_i^2 = (m_i v_i)^2 / 2m_i = \mathbf{p}_i^2 / 2m_i \quad (15)$$

And because the *interaction potential* V between bodies i and j is solely a function of their positions \mathbf{q}_i and \mathbf{q}_j (since we are assuming that all of the forces involved in this system are *conservative*), we may also substitute:

$$V_{ij} = V_{ij}(\mathbf{q}_i - \mathbf{q}_j) \quad (16)$$

Now, if we actually use formulas 15 and 16 to substitute into formula 14 (and remembering that $H = H(\mathbf{p}, \mathbf{q}) = E = \text{constant}$), we finally arrive at the *Hamiltonian function*:

$$H = H(\mathbf{p}, \mathbf{q}) = \sum \mathbf{p}_i^2 / 2m_i + \frac{1}{2} \sum V_{ij}(\mathbf{q}_i - \mathbf{q}_j) \quad (i \neq j) \quad (17)$$

As we noted in our earlier chapter on **Classical Mechanical Systems**, this Hamiltonian function $H(\mathbf{p}, \mathbf{q})$ in a sense describes the behavior of any conservative dynamic system *completely* (although in most cases, as we have seen, it does *not* enable a *deterministic* calculation of the various positions \mathbf{q}_i over time). We also mentioned in our earlier chapter on **Classical Mechanical Systems** the importance of the so-called *canonical equations*, which are derivable from the Hamiltonian function and which enable us to calculate the time variation of \mathbf{q} and \mathbf{p} by simply taking the partial derivatives of the Hamiltonian with respect to \mathbf{p} and \mathbf{q} respectively. These *canonical equations* (which we will not prove or derive here) are:¹⁴⁶

$$d\mathbf{q}_i/dt = \partial H / \partial \mathbf{p}_i \quad (18a)$$

$$d\mathbf{p}_i/dt = \partial H / \partial \mathbf{q}_i \quad (18b)$$

Note that $\partial H / \partial \mathbf{p}_i$ and $\partial H / \partial \mathbf{q}_i$ are both *partial* derivatives of H because the rate of change for H depends on the rate of change of *both* \mathbf{q}_i and \mathbf{p}_i . We therefore hold *either* \mathbf{q}_i or \mathbf{p}_i *constant* when we calculate the partial derivative of H with respect to the *other* quantity.

Now, the significance of formulas 17, 18a, and 18b from the point-of-view of our earlier discussion is simply this: If we can find a system of coordinates (whether inertial or non-inertial) such that the potential energy term $\frac{1}{2} \sum V_{ij}$ in

the Hamiltonian function of the given conservative dynamic system is *always* equal to *zero* for all time (so that *all* of the energy in the Hamiltonian is forever *kinetic* energy $\Sigma \mathbf{p}_i^2/2m_i$), then it becomes true that:

$$d\mathbf{p}_i/dt = \partial H / \partial \mathbf{q}_i = \text{zero} \quad \text{for all } i, \text{ for all time } t \quad (19)$$

Under these conditions, all of the *positions* of the bodies \mathbf{q}_i vary *linearly* with time, while the *momenta* of the all of the bodies in the system \mathbf{p}_i are *constants of motion* and do not depend at all on the relative positions of those bodies: In other words, the *positions* of the bodies depend *entirely* on their *momenta*, while the *momenta* of the bodies depend *not at all* on their *positions*. That means that *no* strong, persistent interactions exist between *any* of the parts of the system. Therefore there are no bothersome holistic *constitutive characteristics* of the system to worry about (such as potential energy, forces, and force fields). Furthermore, the system can then be regarded to be isomorphic with a “free particle” system, the whole can be seen as merely the sum of its parts (*summative characteristics* only), and the positions \mathbf{q}_i of every body in the system can be deterministically solved for all time via Newton’s calculus of variations. In short, such a conservative dynamic system is a **Classical Mechanical System** like we described in our earlier chapter of that name.

Unfortunately for the classical deterministic, reductionistic hypothesis, such systems are the exception rather than the rule: For mechanical systems in which as few as *three* bodies interact persistently and strongly, deterministic reductionism fails (as Poincare proved over a hundred years ago). Ilya Prigogine explains further:

Poincare studied Hamiltonians in the form $H = H_0(\mathbf{p}) + \lambda V(\mathbf{q})$, which is the sum of an integrable contribution (the “free Hamiltonian” H_0) and a potential energy due to interactions (λ is a scaling factor that will be used later on). He showed that this class of Hamiltonians is generally not integrable, which is to say that we cannot eliminate interactions and go back to independent units. . . [This nonintegrability] is due to diverging denominators associated with Poincare resonances, as a result of which we cannot solve the equations of motion (at least in powers of the coupling constant λ).¹⁴⁷

Irreversible Time T (“Big T”)

So far we have seen that a number of important holistic constitutive system characteristics arise in nonlinear dynamic systems containing as few as three bodies. These constitutive characteristics include potential energy, forces, and force fields. However, there is *one* vital constitutive characteristic of decisive importance which we have *not* yet seen appear, and that is *irreversible time T*. Instead, in all of the systems so far considered (be they classical

ON SYSTEMS

mechanical, quantum mechanical, or relativistic), time is *reversible* (“little t ”). Because the concept of *force* in modern dynamics is most intimately connected with *acceleration*, rather than *velocity* (as Aristotle thought), reversing the direction of time in the dynamical equations by making $t = -t$ has the effect of reversing the direction of the *velocities* of all of the bodies in the system, so that $v_i = -v_i$ for all the bodies i . However, the *accelerations* of these bodies remain the same. In other words, the bodies follow exactly the same trajectories *after* time reversal as they did *before*, only in the reverse direction. The dynamical equations themselves are *indifferent* as to which direction time flows.¹⁴⁸

Nevertheless, as we saw in our previous chapter on **Quantum Mechanical Systems**, we need irreversible time T in order to be convinced that our experimental observations *actually measure* something: It would not do if something which we have just measured could go backwards in time and change its behavior, thereby undoing the validity of our observations. That is why our resolution of the quantum paradoxes of observation (such as Schrodinger’s cat) in our chapter on **Quantum Mechanical Systems** depended vitally on the idea that irreversible time T is a real, objective constitutive characteristic (“emergent property”) of nonlinear dynamic and thermodynamic systems. By contrast, even today most physicists regard irreversible time to be “merely subjective”, arising only in connection with “subjective probability” at the thermodynamic level. But, if true, this would mean that all of the scientific observations of physicists are “merely subjective” as well, a conclusion which (of course) physicists do not wish to accept. For them the paradoxes of quantum measurement therefore remain unresolved.

A strictly analogous problem exists in Einstein’s Theory of Relativity with respect to the vital concept of a *signal* along a “time-like” spacetime world-line between two points A and B . Although Einstein, like most physicists, regarded irreversible time to be a mere illusion associated with “subjective probability” in thermodynamics, the problem of the apparent *irreversibility* of a *signal* within Relativity Theory continued to bother him greatly. As he wrote in his “Reply to Criticisms”:

The problem here involved disturbed me already at the time of the building up of the General Theory of Relativity, without my having succeeded in clarifying it. . .

. . . If it is possible to send (to telegraph) a signal . . . from B to A , but not from A to B , then the one-sided (asymmetrical) character of time is secured, i.e., there exists no free choice for the direction of the arrow [of time]. What is essential in this is the fact that the sending of a signal is, in the sense of thermodynamics, an irreversible process, a process which is

connected with the growth of entropy (whereas, *according to our present knowledge*, all elementary processes are reversible).¹⁴⁹

For all of the various reasons cited above, it is vital that we establish the *objective reality* of irreversible time T as directly and simply as possible.

One way to do this would be to embrace a speculative, non-standard theory such as Roger Penrose's *twistor* theory, which attempts to unify quantum mechanics with Relativity Theory and, in the process (I believe), actually incorporates irreversible, asymmetrical time within the dynamical equations themselves. We will not take this approach, however, because of its speculative nature. (For similar reasons, we did not directly embrace Ilya Prigogine's "Liouville Space Extension" of QM in our chapter on **Quantum Mechanical Systems**.)

We could also take the most-common approach and initially establish the existence of irreversible time T at the level of thermodynamics (where many millions of particles are involved, instead of just the few that are involved in dynamics). However, this would inevitably leave the impression that irreversible T is not a basic phenomenon of nature, but rather is a derivative (and possibly even subjective) physical phenomenon. Furthermore, such an approach would not explain the existence of "arrows of time" other than the thermodynamic: These include the *cosmological* arrow of time (associated with the fact of the Big Bang) and the arrow of time associated with the *T-violation* in elementary particle physics (where for certain restricted processes the equations describing the evolution of the system for positive time t are significantly different from those describing the evolution for negative time $-t$).¹⁵⁰

Instead, we will try to demonstrate the *objective existence* of irreversible time T at the level of *basic nonlinear dynamic systems*, in particular focusing on the *chaotic gravitational three-body system* as our primary example. During the course of doing this, we will have occasion to refine (and even re-define) the concept of *objective truth*. In particular, we will consider the differences between objective truth as viewed by the following four types of teleological beings:

1. *Human beings* and other teleological beings who have an analogical embodied existence within the physical universe. Such beings have an *imperfect* knowledge of the momenta and positions of the bodies within any given dynamical system (i.e., out to only a *finite* number of decimal places). Furthermore (as might be expected), such beings can only *act* with a finite, limited degree of precision. We'll represent human beings by the example of the *scientist*.

ON SYSTEMS

2. *Laplace's demon*, a fictional non-embodied creature who can know perfectly *for one moment in time only* the *exact* momenta and positions of every body within a given dynamical system out to an *infinite* number of decimal places. (That dynamical system can be the entire universe, if desired.) However, for all other moments in time, Laplace's demon has the same finite limitations as the human scientist.
3. *Maxwell's demon*, a fictional non-embodied creature who has all of the capabilities of Laplace's demon, *plus* the ability *for one moment in time only* to instantly *establish* or *alter* the dynamics of the system with infinitely perfect accuracy (for example, by instantaneously and precisely reversing the direction of the velocities of every body in the system, no matter how many of these bodies there are).
4. *The omniscient and omnipotent God*, who has the capabilities of Maxwell's demon (and, therefore also of Laplace's demon) for not just *one* moment in time, but rather for *infinitely many* moments in time (and perhaps for *all* moments in time).

Note that, for purposes of this *epistemological* discussion, it *does not matter* whether you regard the omniscient and omnipotent God to be *real* or *fictional*: Rather, Laplace's demon, Maxwell's demon, and God are here just "benchmarks" for comparison with human beings as part of the process of arriving at a reasonable definition of what "scientific objectivity" means from the point-of-view of conscious, rational, beings embodied within the physical universe (such as the human scientist).

But before we *directly* consider the problem of irreversible time with respect to nonlinear dynamics, we must first take an extended detour that ultimately revolves around the question of the status of *chance* in objective physical reality.

The Bowl Game

Let's begin with a "thought experiment" (really a "thought game") that we'll call the *bowl game*. Imagine a hollow, smooth half-sphere with its *concave* side upwards, resting firmly on a table near the earth's surface. (This is the *bowl*.) Imagine that we also have available a small, heavy, smooth, spherical *ball bearing*. (This is the *ball*.) The contestants in the *bowl game* are: a scientist, Maxwell's demon, and God. (Laplace's demon can't play, because he can't perform an action.) The object of the *bowl game* is to carefully place the ball inside the bowl so that it rests at the very *bottom* of the bowl without moving. (For simplicity, air resistance and air currents are ignored.)

God goes first. (Who else?) Not surprisingly, He succeeds the first time in placing the ball perfectly at the exact bottom of the bowl. He can do this both because He is *omniscient* (i.e., He knows *exactly* where the ball must be placed to an accuracy of an infinite number of decimal places within a 3-dimensional coordinate system) and because He is *omnipotent* (i.e., He has the power to arrange physical processes so that the placement of the ball is done *perfectly*).

Our second contestant in the bowl game is Maxwell's demon. He also succeeds in perfectly placing the ball at the very bottom of the bowl the first time he tries (providing only that we stipulate that he can do this *in a single instant of time*).

Our third contestant is the human scientist. Because of limitations in both his knowledge and his power, the scientist is only able to place the ball *very near* to the exact bottom of the bowl, but he is *never* able to place it *perfectly*, no matter how many times he tries. Through the use of sophisticated observational instruments and robotic technology, the scientist is able (up to a point) to come increasingly close to perfectly placing the ball at the exact bottom of the bowl, but he can never place it with *absolute* precision because his knowledge of the positions of the ball, the bowl, and the earth is always limited to some *finite* number of decimal places.

The result of the scientist's imperfect placement of the ball is that, on a very small scale, it oscillates like a pendulum in an arc that passes through the exact bottom-position of the bowl. The ends of the arc are two *periodic points*, while the exact bottom of the bowl is the *elliptic point* around which this oscillation occurs. If we assume that the bowl and ball are ideal and that there is no friction as the ball rolls inside the bowl, then this oscillation (or vibration) will continue forever if the system is left otherwise undisturbed. Such a dynamic system is said to be an example of *neutral stability*, *orbital stability*, or *Lyapunov stability*.

However, if we assume that there *is* friction between the ball and the bowl, then the ball's kinetic energy will be dissipated as heat because of that friction, and the ball's period of oscillation will become smaller and smaller until it eventually comes to rest at the point that is at the exact bottom of the bowl – a point which in this case is an *attracting fixed point*, also called an *attractor* or *sink*. Such a system is said to be *asymptotically stable*. (A *sink* can also be thought of as a *periodic point* of period one. In the no-friction case the periodic points have a period of two.)

Now, before we analyze this friction case in more detail, it is worth noting that it “makes sense” for the scientist to play the bowl game because, while he can never attain the perfection of God or Maxwell's demon, he *can*

ON SYSTEMS

asymptotically approach this perfection by improving his technology (his measuring apparatus, robotic apparatus, etc.). In fact, in the friction case, the “imperfection” of friction eventually cancels out the scientist’s imperfection in placing the ball bearing, so that the scientist’s ball bearing finally rests just as perfectly at the bottom of the bowl as did the ball bearings belonging to God and Maxwell’s demon. From this we may conclude that, when it comes to dynamical systems which are either *orbitally stable* or *asymptotically stable*, we are justified in regarding objectivity from the point-of-view of the scientist to be *approximately the same* as objectivity from the point-of-view of God or Maxwell’s demon.

Now, as we mathematically consider the friction case further, we need to define some terms: A *map* is a function whose *domain* (possible input values) and *range* (possible output values) are the same. An *iteration* of the map is one application of the map function. If x is a point specified within a system of coordinates, then we will denote the point generated by the first iteration of the map as $f(x)$, the point generated by the second iteration of the map as $f^2(x)$, the point generated by the third iteration as $f^3(x)$, and so on. An *orbit* of x under f is then the set of points $\{x, f(x), f^2(x), f^3(x), \dots\}$. The starting point x of the orbit is the *initial value* of the orbit. A point p is a *fixed point* of the map f if and only if $f(p) = p$. An n -dimensional *manifold* is a set of points (like the 2-dimensional inside-surface of the bowl) which *locally* resembles an n -dimensional Euclidean space in the immediate neighborhood around any given point in the manifold. (This is a two-dimensional flat plane in the case of the immediate neighborhood around each point on the bowl’s inner surface). Furthermore, if p is a fixed point of the map f and p is also an *attractor* (i.e., a *sink*), then the *stable manifold* of p is denoted by $S(p)$ and consists of all points s such that $|f^n(s) - p| \rightarrow 0$ as $n \rightarrow \infty$. (Note that the vertical bars in this formula mean “take the absolute value of whatever is between the vertical bars” and that ∞ represents infinity. Note also that p has no *unstable manifold* if it is an *attractor* in all relevant dimensions.)¹⁵¹

In the friction version of the bowl game mentioned above, the point p is the point at the very bottom of the bowl, and all other points on the inner surface of the bowl are within the stable manifold of p with respect to the free rolling of the ball. Moreover, all of the possible orbits of the free-rolling ball are *attracted* to p and will eventually settle down to point p (the bottom of the bowl) in a *finite* amount of time. However, our definition of “stable manifold” does *not* require that an orbit within the stable manifold actually *arrive* at p within a finite amount of time: Rather the orbit may continually approach p without ever reaching it. (For example, see Figure 3, which follows.)

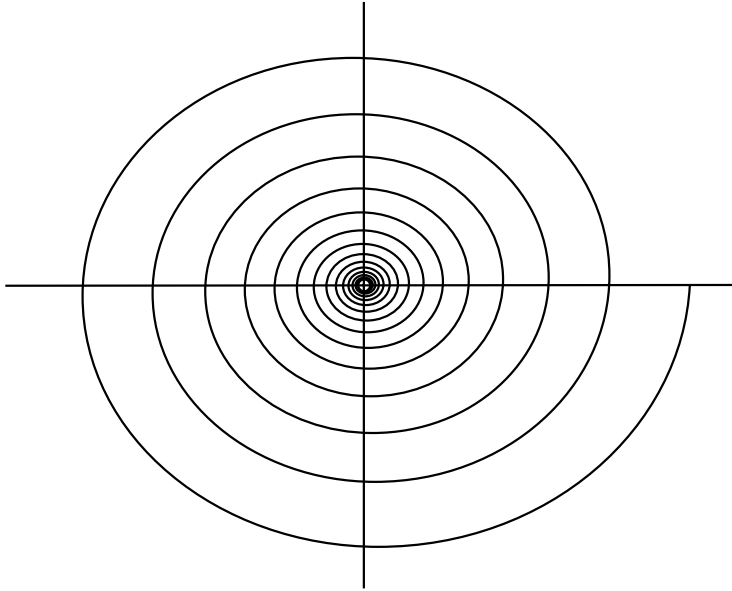


Figure 3

Consider now a small neighborhood of points arbitrarily close (even *infinitesimally* close) to the fixed-point p . This neighborhood is usually called the *epsilon neighborhood* of p , symbolized as $N_\epsilon(p)$. The *epsilon neighborhood* $N_\epsilon(p)$ is defined to be the set of points x in the manifold immediately surrounding p such that $|x - p| < \epsilon$, where ϵ (*epsilon*) is an arbitrarily small positive distance from p . Within the context of this small epsilon neighborhood of p we can determine whether or not the fixed point p is an *attractor* (i.e., a *sink*) by calculating the first derivative of $f(p)$ with respect to a change away from or towards p (if such a first derivative actually exists). (This first derivative is simply the *instantaneous rate of change* in $f(p)$ with respect to a change away from or towards p). We *could* write this first derivative using the notation we have used previously: $df(p)/dp$. But instead we will use the more compact notation $f'(p)$.

Let f be a map function which is continuous and *smooth* (i.e., derivatives of all orders exist everywhere for the function). Let p be a fixed-point of f , so that $f(p) = p$. Then, with respect to at least some sufficiently small epsilon neighborhood of p :

$$\text{If } |f'(p)| < 1, \text{ then } p \text{ is an attractor (i.e., a sink)} \quad (20)$$

We will not prove this theorem rigorously, but it makes sense because it means that, as an x point in the epsilon neighborhood of p approaches p , $f(x)$ approaches $f(p) = p$ even faster. In other words:

ON SYSTEMS

$\lim (x \rightarrow p)$ of $|f(x) - f(p)|$ divided by $|x - p|$ equals $|f'(p)|$, which by hypothesis is a fraction between 0 and 1. Therefore $f(x)$ approaches $f(p) = p$ faster than x approaches p , and so it further follows that p is a sink (at least with respect to its epsilon neighborhood).¹⁵²

This ends our discussion of the *bowl game*.

The Hill Game

Our next “thought experiment” (or “thought game”) we’ll call the *hill game*. Imagine a perfectly smooth half-sphere with its *convex* side upwards, resting firmly on a table near the earth’s surface. (This is the *hill*.) Imagine that we again have available a small, heavy, smooth, spherical *ball bearing*. (This is the *ball*.) The contestants in the *hill game* once again are: a human scientist, Maxwell’s demon, and God. (Again, Laplace’s demon can’t play, because he can’t perform an action.) The object of the hill game is to carefully place the ball on the very *top* of the smooth, convex hemisphere (the *hill*) so that it precisely rests at the top of the hill and does *not* roll off the hill. (Again, air resistance and air currents are ignored.)

Just as was the case in the *bowl game*, God goes first. God is just as successful in the *hill game* as He was in the *bowl game*: He succeeds the first time in placing the ball perfectly at the exact top of the hill. The ball does *not* roll off the hill! God can do this both because He is *omniscient* (i.e., He knows *exactly* where the ball must be placed to an accuracy of an infinite number of decimal places within a 3-dimensional coordinate system) and because He is *omnipotent* (i.e., He has the power to arrange physical processes so that the placement of the ball is done *perfectly*).

Our second contestant in the *hill game* (just as in the *bowl game*) is Maxwell’s demon. Again, Maxwell’s demon succeeds the first time he tries, in this case by perfectly placing the ball at the *top* of the hill (providing only that we stipulate that he can do this *in a single instant of time*).

Finally, our third contestant in the *hill game* is the human scientist. Because of limitations in both his knowledge and his power, the scientist is *completely unable* to place the ball at the top of the hill so that it rests there, no matter how many times he tries. Rather, the ball *always* rolls off the hill at an angle (looking down at the top of the hill) that is, paradoxically, *more unpredictable* the *more accurately* the scientist places the ball! Even though the scientist makes use of increasingly sophisticated observational instruments and robotic technology, he can come no closer to the accomplishments of God and Maxwell’s demon in the *hill game*: In fact, with respect to the *hill game*, the scientist is a *complete loser* because his

knowledge of the positions of the ball, the hill, and the earth is always limited to some *finite* number of decimal places, whereas the infinite number of possible trajectories of the ball that start from infinitesimally close to the top of the hill can shoot off *at any angle* between 0 degrees and 360 degrees (looking downward at the hill). Furthermore, because we have assumed that both the hemisphere and the ball are relatively smooth, *friction* is of no help to the scientist in this case, since the force of friction is quickly overcome by the force of gravity pulling the ball bearing off the hill. The point at the top of the hill is said to be a *repelling fixed point*, also called a *repeller* or a *source*. Such a dynamical system is said to be *unstable*.

Now, before we analyze the hill game in greater mathematical detail, it is important to note that it does *not* make sense for the scientist to continue to play the hill game, because no matter how hard he tries and what sophisticated technology he uses, the scientist *cannot* asymptotically approach the results achieved by God and Maxwell's demon. (As the saying goes, the human scientist is "not even in the same league".) Therefore the fact must be faced that, with respect to the hill game and the similar physical systems which that game represents, *objective physical truth* for the human scientist must be *significantly different* than it is for God or Maxwell's demon. In particular, for God, the deterministic description of dynamical physics in terms of precise trajectories *always* makes sense. By contrast, for the human scientist, the description of dynamical physics in terms of precise trajectories often does *not* make sense, *even as an ideal that might be striven for*. Instead, for the scientist, what *does* always make dynamical sense is a physical description of a certain set of *possible* trajectories, with a probability weight assigned to those various trajectories. As Ilya Prigogine has written:

We need a "divine" point-of-view to retain the idea of determinism. But no human measurements, no theoretical predictions, can give us initial conditions with infinite precision.¹⁵³

A theologian might put it this way: While it is true that human beings are made in the *image* of God, it is also true that an *image* is always less perfect than the *original*. And *any* such imperfection in the divine image is enough to result in a *qualitative* difference between *human* and *divine* objectivity.

More generally, we can rephrase this by saying that there is a *qualitative* difference between *immanent* objectivity and *transcendent* objectivity. (But note, again, that the present discussion does not *require* belief in the actual existence of God or any other transcendent being: Instead all such transcendent beings can, if you wish, be regarded as merely fictional benchmarks whose objectivity can be compared with our own.)

ON SYSTEMS

Later on in this chapter we will further develop our understanding of immanent, human objectivity in the physical sciences by considering the concept of an *ensemble of possible* physical systems in *phase space* (a concept that derives from the work of Albert Einstein and the great American scientist Josiah Willard Gibbs at the beginning of the twentieth century¹⁵⁴). Meanwhile, perhaps the most important conclusion we can derive from our consideration of the *hill game* is the fact that human objectivity with respect to the physical sciences contains an *irreducible, significant* element of *absolute chance* irrespective of the size or scale of the physical system studied. This *immanently objective* element of *absolute chance* will *never* be eliminated from human science. Moreover, *immanently objective chance* can hardly ever be ignored as unimportant (except in the case of those few physical systems which approach the deterministic ideal, such as systems which are *orbitally stable* or *asymptotically stable* like the *bowl game* system). Statements involving *probability* may therefore be (in varying degrees) *subjective* or *immanently objective*, depending on the context or circumstances.

Recall from our discussion in the chapter on **Quantum Mechanical Systems** that before the advent of quantum mechanics (QM), most scientists from the Enlightenment era onwards believed that *all* chance is “merely subjective” and that physical reality is therefore objectively deterministic. By contrast, after the advent of QM, most scientists believe that chance in the submicroscopic world of “elementary particles” is *objective*, while chance in the macroscopic (thermodynamic) world remains *subjective*. (QM essentially encapsulates objective submicroscopic chance into a macroscopic deterministic framework, the Schrodinger wave function.) Furthermore, as we also mentioned earlier, some scientists (such as Einstein, de Broglie, and Bohm) have sought to eliminate this tension between submicroscopic *objective* probability and macroscopic *subjective* probability by arguing that submicroscopic quantum probability is *also* subjective and that deterministic (or quasi-deterministic) “hidden variables” will someday be discovered to underlie the seemingly random submicroscopic quantum phenomena.

By contrast, in this book we are taking the approach of Nobel-prize-winning scientist Ilya Prigogine and his colleagues by arguing that, from the human point-of-view (which is, after all, the only point-of-view from which science realistically *can* be done), an *irreducible* element of *immanent objective chance* exists at both the macroscopic *and* submicroscopic levels of physical reality. As Prigogine has written, to insist that infinitely precise trajectories are the standard for human scientific objective truth is just as foolish as to insist that travel at infinite velocities is an ideal that can be humanly striven

for (in spite of Einstein's proof that travel faster than the speed of light in a vacuum is impossible):

It is true that there is still a trajectory description if initial conditions are known with infinite precision. But this does not correspond to any realistic situation. Whenever we perform an experiment, whether by computer or some other means, we are dealing with situations in which the initial conditions are given with a finite precision. . . Similarly, we could imagine infinite velocities, and therefore we would no longer need relativity theory, which is based on the existence of a maximum velocity – the velocity of light c in a vacuum – but the assumption of velocities greater than c corresponds to no known observable reality.¹⁵⁵

This view that an *irreducible* objective element of chance exists in nature of course has its precursors. For example, in the late nineteenth century the great American philosopher, scientist, and logician Charles Sanders Peirce proposed the existence of what he called *tychism*, which was his unique name for “absolute chance”. He regarded *tychism* (as distinct from mere probability) to be the true logical basis for novelty, spontaneity, growth, and complexity in the universe.¹⁵⁶

A far earlier precursor to the concept of *absolute chance* is the pre-Socratic philosopher Epicurus. A disciple of Democritus, Epicurus was nevertheless bothered by Democritus's fundamental view of reality, which seemed to necessitate a universe consisting merely of atoms falling deterministically through the void. Epicurus's answer to the problem of accounting for novelty and spontaneity in the universe was the *clinamen*, an aspect of physical reality which he said caused the atoms to randomly, but slightly, deviate from their determined course.¹⁵⁷

It is now time to examine the *hill game* in greater mathematical detail by simply extending our discussion of the mathematics of the bowl game. We'll begin by extending our map-function notation, so that $f^{-1}(x)$ means “the value of x just prior to that iteration of the map function f which resulted in the present value of x ”, $f^{-2}(x)$ means “the value of x two iterations prior to the present value of x ”, etc. The orbit $\{x, f^{-1}(x), f^{-2}(x), f^{-3}(x), \dots\}$ is therefore a *time-reversed* orbit starting from the *initial value* of x . If p is a fixed point of the map f such that $f(p) = p$ and p is also a *repeller* (i.e., a *source*), then the *unstable manifold* of p is denoted by $U(p)$ and consists of all points u such that $|f^{-n}(u) - p| \rightarrow 0$ as $n \rightarrow \infty$. (Note that p has no *stable* manifold if it is a *repeller* in all relevant dimensions. Also note that the reversed-time orbit starting from u need not actually arrive at p in a finite amount of reversed time.)

Let f be a map function which is continuous and *smooth* (i.e., derivatives of all orders exist everywhere for the function). Let p be a fixed-point of f , so

ON SYSTEMS

that $f(p) = p$. Then, with respect to at least some sufficiently small epsilon neighborhood $N_\epsilon(p)$ of p :

If $|f'(p)| > 1$, then p is a repeller (i.e., a source) (21)

Again, we will not prove this theorem rigorously. But Alligood, Sauer, and Yorke, in their book *CHAOS: An Introduction to Dynamical Systems*, express the basic reasoning behind this theorem as follows:

[I]f x_1 is a fixed point of a . . . map f and $f'(x_1) = a > 1$, then the orbit of each point x near x_1 will separate from x_1 at a multiplicative rate of approximately a per iteration, until the orbit of x moves significantly far away from x_1 . That is, the distance between $f^n(x)$ and $f^n(x_1) = x_1$ will be magnified by approximately $a > 1$ for each iteration of f .¹⁵⁸

This ends our discussion of the *hill game*.

The Saddle Game

Our next “thought experiment” (or “thought game”) we’ll call the *saddle game*. Imagine a very smooth, hard horse’s saddle, as depicted in Figure 4 below:

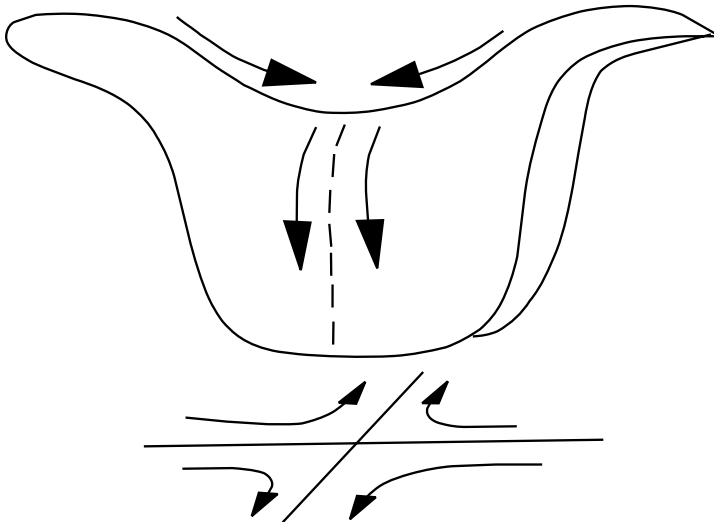


Figure 4 (after Figure 2.13 in Alligood, Sauer, and Yorke, p. 64)

(This is the *saddle*.) Imagine that we again have available a small, heavy, smooth, spherical *ball bearing*. (This is the *ball*.) The contestants in the *saddle game* are once again: a scientist, Maxwell’s demon, and God. (Again, Laplace’s demon can’t play, because he can’t perform an action.) The object

of the *saddle game* is to carefully place the ball on the very *center* of the saddle so that it does *not* roll off the saddle to either side. . (As always, air resistance and air currents are ignored.)

Just as was the case in the bowl game and the hill game, God goes first. God is just as successful in the saddle game as He was in the bowl game and the hill game: He succeeds the very first time in placing the ball perfectly on the exact center of the saddle, such that the ball does *not* roll off the saddle to either side! God can do this both because He is *omniscient* (i.e., He knows *exactly* where the ball must be placed to an accuracy of an infinite number of decimal places within a 3-dimensional coordinate system) and because He is *omnipotent* (i.e., He has the power to arrange physical processes so that the placement of the ball is done *perfectly*).

Our second contestant in the saddle game (just as in the bowl game and the hill game) is Maxwell's demon. Once again Maxwell's demon succeeds the very first time he tries, in this case by perfectly placing the ball on the exact *center* of the saddle (providing only that we stipulate that he can do this *in a single instant of time*).

Finally, our third contestant in the saddle game is the human scientist. Because of limitations on both his knowledge and his power, the scientist is *completely unable* to place the ball at the precise center of the saddle, so that it rests there without rolling off to one side or the other, no matter how many times he tries. Even though the scientist makes use of increasingly sophisticated observational instruments and robotic technology, he can come no closer to the accomplishments of God and Maxwell's demon with respect to the saddle game: That is because his knowledge of the positions of the ball, the hill, and the earth is always limited to some *finite* number of decimal places. Furthermore, because we have assumed that both the saddle and the ball are relatively smooth, *friction* is of no help to the scientist in this case, since the force of friction is quickly overcome by the force of gravity pulling the ball bearing off the saddle to one side or the other.

Nevertheless, the scientist *does* do better than he did in the hill game, in this sense: In the hill game the ball rolled off the hill with increasingly equal probability at *any* angle between 0 and 360 degrees (looking downward) as the scientist placed the ball with correspondingly increasing accuracy on the top of the hill. By contrast, in the saddle game the randomness of the angle of the ball's subsequent trajectory is *constrained*, such that the probability that the ball will roll off following the axis that runs along the *length* of the saddle is *zero*, while the probability that the ball will roll off to one side or the other of the saddle along the axis that runs across the *width* of the saddle is *high*. Furthermore, the probability that the ball will roll off along a trajectory that

ON SYSTEMS

is *intermediate* between these two axes is *greater* the more this intermediate trajectory aligns with the width-of-the-saddle axis, and is *less* to the extent that it aligns with the length-of-the-saddle axis.

Also, because the saddle game system is characterized by *constrained chance*, the phenomenon of *bifurcation* can and does arise. That is, the more precisely the scientist places the ball at the very center of the saddle, the closer to exactly 50% is the probability that the ball will roll to one side of the saddle as opposed to the other: In other words, from the point-of-view of the human scientist, the saddle game system *bifurcates* with equal probability into two very different states. This particular type of bifurcation is called (not surprisingly) a *saddle-node bifurcation*. (As we shall see later when dealing with far-more-complex biological systems, such *bifurcation points* within the physical system may be analogous to *decision points* within the parallel *teleological* system.)

The fixed point at the very center of the saddle is said to be a *saddle point*. This fixed point is also called a *hyperbolic point* because (as was mentioned in our discussion of relativistic systems) the shape of the surface of a saddle that is infinitely extended is a *hyperbolic surface*.

Before analyzing the saddle game in greater mathematical detail, it is important to note that it makes no more sense for the scientist to continue to play the saddle game than it would for him to continue to play the hill game, because it is still the case that no matter how hard he tries and what sophisticated technology he uses, the scientist *cannot* asymptotically approach the results achieved by God and Maxwell's demon. Therefore the fact must be faced that, with respect to the saddle game (just as for the hill game), *objective physical truth* for the human scientist must be *significantly different* than it is for God or Maxwell's demon.

Once again, for God the deterministic physical description of *saddle-game-like* systems in terms of precise trajectories *always* makes sense. By contrast, for the human scientist the deterministic physical description of saddle-game-like systems in terms of precise trajectories (particularly trajectories that pass through the hyperbolic point) often *does not* make sense, *even as an ideal that might be striven for*. Instead, for the scientist, what *does* always make sense in the case of saddle-game-like systems is (once again) a physical description of a certain *set of possible* trajectories, with a probability weight assigned to these various trajectories.

An examination of the mathematics of the *saddle game* reveals that it combines the *attractor* mathematics of the bowl game along the *length* of the saddle with the *repeller* mathematics of the hill game along the *width* of the saddle. If point p is a fixed point $f(p) = p$ and, moreover, p is a *saddle point*

(*hyperbolic point*) located at the center of the saddle, then p has both a *stable manifold* $S(p)$ consisting of the points on the saddle's long axis and an *unstable manifold* $U(p)$ consisting of the points on the saddle's width axis plus all of the non-axis points on the hyperbolic surface of the saddle. (In other words, the saddle's width axis contagiously spreads its "repelling" nature throughout the hyperbolic surface, except for the points directly on the long axis.) This situation is depicted in the two-dimensional projection of the saddle shown in Figure 5, below:

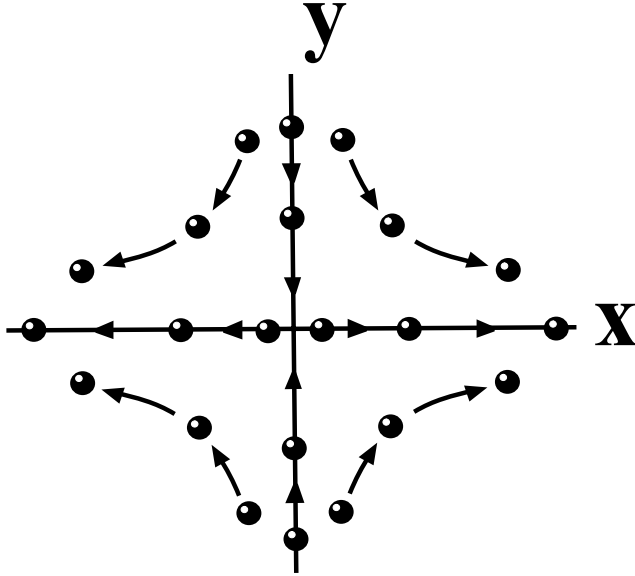


Figure 5 (after figure 2.14 in Alligood, Sauer, and Yorke, p. 65)

In Figure 5 the y axis (i.e., the vertical axis) represents the *long* axis of the saddle. As you can see, any balls placed on this y axis are *attracted towards* the saddle point that is at the center of the saddle. By contrast, the x axis in Figure 5 (i.e., the horizontal axis) represents the *width* axis of the saddle. Any balls placed on this x axis are *repelled away from* the central saddle point, as are any balls placed elsewhere on the saddle's surface (except on the y axis itself). In other words, Figure 5 clearly shows that points on the y axis are *attracted towards* the saddle point as map function f iterates, while all other points on the hyperbolic surface are *repelled away from* the saddle point as f iterates.

As in the *bowl game*, the *stable manifold* $S(p)$ of saddle point p consists of all points s such that $|f^n(s) - p| \rightarrow 0$ as $n \rightarrow \infty$. (These points s are precisely those points that lie on the y axis of the saddle.) As in the *hill game*, the *unstable manifold* $U(p)$ of saddle point p consists of all points u such that

ON SYSTEMS

$|f^{-n}(u) - p| \rightarrow 0$ as $n \rightarrow \infty$. (These points u are those that lie on the \mathbf{x} axis of the saddle, together with all non-axis points on the hyperbolic surface of the saddle.) Note also that, in both the forward-time case $S(p)$ and the reverse-time case $U(p)$, the iterations of f need not result in p being actually reached in a finite amount of time.¹⁵⁹

Figure 6, below, shows the evolution of the *epsilon disk* (a two-dimensional representation of the *epsilon neighborhood*) around a fixed point in the cases of (a) a *sink* (as in the bowl game), (b) a *source* (as in the hill game), and (c) a *saddle point* (as in the saddle game):

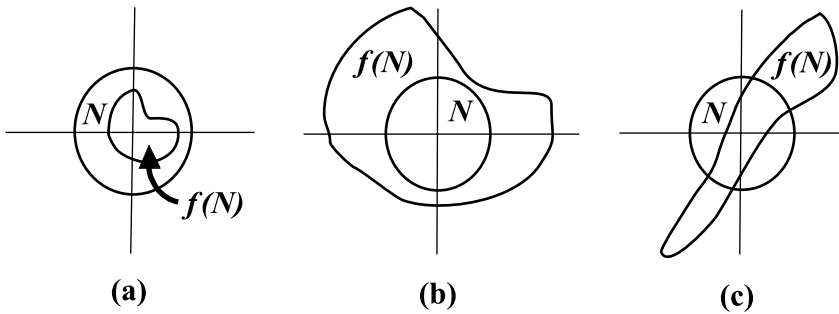


Figure 6 (after figure 2.8 in Alligood, Sauer, and Yorke, p. 59)

Notice that iterations of f on the disk N result in a *contraction* of the disk $f(N)$ if the fixed point is a *sink*, an *expansion* of the disk $f(N)$ if the fixed point is a *source*, and a *contraction* along one direction, but an *expansion* along another direction, if the fixed point is a *saddle point*.

As might be expected from what we said earlier concerning the bowl game and the hill game, if p is a fixed *saddle point*, then $|f'(p)| < 1$ along the \mathbf{y} axis of Figure 5, while $|f'(p)| > 1$ with respect to all other directions on the hyperbolic surface (being greatest along the \mathbf{x} axis itself).

One of the remarkable facts discovered by Henri Poincare as he was working on the three-body gravitational problem in the late 19th century is that, under certain conditions, the stable and unstable manifolds of a fixed saddle point can actually *intersect*. Such an intersection is called a *homoclinic intersection* and the point of intersection is called a *homoclinic point*. If we iterate the map function f on the homoclinic point *forward* in time, then we approach the fixed saddle point without ever reaching it. The same is also true if we iterate the map function f on the homoclinic point *backward* in time. Even more remarkable, the existence of *one* homoclinic point forces the existence of *infinitely many* such homoclinic points. The basic reason for this

is that, because the homoclinic point lies on both the stable *and* unstable manifolds of saddle point p , the *entire orbit* of that homoclinic point (called the *homoclinic orbit*) must *also* lie on both manifolds of p by the very definitions of stable and unstable manifolds. As Alligood, Sauer, and Yorke put it:

The key fact about a homoclinic intersection point is that it essentially spreads the sensitive dependence on initial conditions – ordinarily situated at a single saddle fixed point – throughout a widespread portion of state space.¹⁶⁰

Poincare also discovered that the resulting *homoclinic tangle* is one of the primary reasons why the three-body gravitational system is *chaotic*.

Another interesting situation occurs when the *stable* manifold of *one* saddle point intersects the *unstable* manifold of a *different* saddle point. Such an intersection is called a *heteroclinic intersection*, while the *point* of heteroclinic intersection is called a *heteroclinic point* and the *orbit* of this heteroclinic point is called (not surprisingly) a *heteroclinic orbit*. We will encounter heteroclinic orbits later on in our discussion of the “forced” (i.e., rotating) pendulum.¹⁶¹

Finally, we should note that it is provable that a stable manifold cannot intersect itself, nor can it cross the stable manifold of a different fixed point.¹⁶²

Four Types of Physical Systems

We are now in a position to define four basic types of physical systems, all of which we will illustrate at the level of basic linear and nonlinear dynamics (but which apply to more-complex physical systems as well):

1. **Deterministic** physical systems contain *no* significant immanently objective elements of chance, except at the *one* single moment in time for which the “initial conditions” of the system are specified. Nearly exact trajectories of all bodies in the system can then be calculated (going either forward or backward in time) from these “initial” conditions. Deterministic systems are essentially those discussed in our chapter on **Classical Mechanical Systems**. We will choose the *oscillating pendulum* as our example of a deterministic system.
2. **Tychistic** physical systems are *dominantly deterministic*, but are also punctuated with bifurcations or other moments of *objective constrained chance* at various points in their history. (I have adapted the term “tychistic” from Charles Sanders Peirce’s coinage of the word “tychism” to refer to *absolute objective chance*.) As our simple

ON SYSTEMS

dynamical example of a tychistic system we will choose the “forced” *rotating pendulum*.

3. **Chaotic** physical systems are *dominantly random*. In dynamics such chaotic physical systems usually contain many *saddle points* (i.e., *hyperbolic points*), each of which is often associated with an infinite number of *homoclinic points*. These saddle points and homoclinic points create a *homoclinic tangle* that makes the deterministic prediction of the trajectories of some or all of the bodies in the system *impossible*. Nevertheless, surprising elements of order may unexpectedly arise during the history of a chaotic system. (Alternatively, such touches of order may be discovered “hidden” amongst the dominant randomness.) The famous *three-body gravitational system* will be our example of a chaotic system.
4. **Stochastic** physical systems are *completely random* and contain *no* (or negligible) elements of order at the level of detail being considered. Our example of a *stochastic* system will be an *ideal gas* at equilibrium, considered at the molecular level.

Important notes and qualifications with respect to this classification scheme:

First, it is evident that the four types of physical systems grade continuously into one another and form a continuous “physical spectrum”, which we may imagine as stretching smoothly from left to right as we go from *deterministic* to *tychistic* to *chaotic* to *stochastic* physical systems. Therefore, borderline cases certainly exist which could just as well be put into one category as another.

Second, this classification scheme is relevant to all types and complexities of physical systems, including dynamic, thermodynamic, biological, sociological, and so on. (For example, the biological *tychistic* system of most interest to us personally is probably our own human body.) Nevertheless, in this immediate discussion we will confine ourselves to “simple” dynamic systems, so that no opportunity will exist to dismiss any of these four types of systems as “merely subjective”.

Third, any given particular classification of a physical system is relative to the physical level considered. For example, an ideal gas is stochastic at the *microscopic* level. However, at the *macroscopic* level a quantity of ideal gas clearly has “orderly” properties, such as volume, pressure, and so on. Moreover, at the *sub-microscopic* level each gas molecule is clearly a tightly-bound, dominantly-ordered system (though encapsulating quantum randomness).

Fourth, it is common in the scientific literature for chaotic systems to be called “deterministic”. For example, one often hears of “deterministic chaos” and reads statements to the effect that chaotic systems are only *apparently* random. Such statements may be based on the fact that the force laws describing even chaotic dynamical systems are quite definite and contain no elements of chance. Or such statements may be based on the fact that chaotic dynamical systems are still deterministic from an infinitely-precise, transcendent (e.g., divine) point-of-view. Lastly, such statements may simply represent a scientific ideological commitment to determinism that is essentially a holdover from 19th century thinking. Whatever the case, we will not adopt such terminology in this book, but will instead restrict the term “deterministic systems” to those physical systems where the trajectories of all bodies in the system can be predicted (and retrodicted) with reasonable precision by a human scientist using only the “laws of nature” and *one* particular description of “initial conditions” at *one* moment in time. (This is the “ordinary language” understanding of determinism and is the definition which, in effect, underlies most philosophical discussions of determinism versus indeterminism.)

Fifth, the scientific recognition of the importance of both *deterministic* and *stochastic* physical systems goes back at least to the days of Sir Isaac Newton himself. By contrast, while *chaotic* physical systems were first studied by Henri Poincare and others in the latter part of the 19th century, they were not fully acknowledged and recognized as important by scientists until the 1950s and early 1960s (when mini-computers and personal computers began to become generally available).

Furthermore, the importance (or, sometimes, even the existence) of *tychistic* physical systems has yet to be acknowledged by most scientists, which is why I have had to invent/adapt the term “tychistic” from the writings of Charles Sanders Peirce. I speculate that one reason most scientists have virtually ignored the vast realm of tychistic physical systems is the fact that highly complex tychistic physical systems (i.e., those organized above the dynamic level) often have clear teleological analogs that are, to some degree at least, characterized by *free will*, *purposes*, and *goals*: Acknowledging the existence or importance of such systems would therefore constitute a serious challenge to the deterministic/stochastic worldview of most contemporary scientists, who regard both the universe and all of its component systems to ultimately be teleologically “meaningless and senseless” on *a priori* philosophical grounds.

Before considering particular dynamical examples of the four types of physical systems defined above we need to define the extremely useful

ON SYSTEMS

mathematical concepts of *phase space* (sometimes called *state space*) and *Gibbs ensembles*.

Phase Space and Gibbs Ensembles

Prigogine and Stengers define *phase space* (in the context of dynamical systems) as follows:

The dynamic state of a point particle is specified by position (a vector with three components) and by momentum (also a vector with three components). We may represent this state by two points, each in a three-dimensional space, or by a single point in the six-dimensional space formed by the coordinates and the momenta. This is the phase space. This geometric representation can be extended to an arbitrary system formed by n particles. We then need $n \times 6$ numbers to specify the state of the system, or alternatively we may specify this system by a single point in the $6n$ -dimensional phase space. The evolution in time of such a system will then be described by a [single] trajectory in the phase space.¹⁶³

The number of dimensions of the *phase space* is the number of *degrees of freedom*. For conservative Hamiltonian dynamic systems the number of degrees of freedom is always an *even* number because, as we have seen earlier, the Hamiltonian energy function $H(\mathbf{p}, \mathbf{q})$ describes the state of the dynamical system *completely* in terms of exactly *two* variables, the *momentum* \mathbf{p} and the *position* \mathbf{q} of the system's component particles.

Figure 7, below, is a simplified diagram showing the point p_0, q_0 in a two-dimensional phase space. (One dimension is \mathbf{p} and the other dimension is \mathbf{q}):

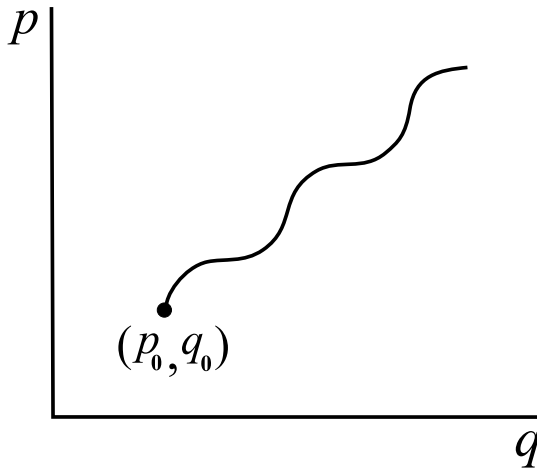


Figure 7 (after Figure 1.3 in Prigogine, p. 32)

Point (p_0, q_0) represents the state of a dynamical system at a particular initial point in time. The squiggly line emanating from point (p_0, q_0) represents the *trajectory* of this dynamic system through phase space as the system temporally evolves. (Although we have shown only two dimensions in Figure 7, we may regard Figure 7 as archetypically representing any dynamical system having an arbitrary, though even, number of degrees of freedom.)

We will see later that for more-complex systems (such a thermodynamic, chemical, and biological systems) we can use phase space to represent other variables, such as *pressure*, *temperature*, *volume*, *concentration*, and so on. But for now our focus is on dynamic systems, so the only variables we require are *momentum* p and *position* q .

Now, because Figure 7 shows a *precise trajectory* of the dynamic system through phase space, it is clear that, while it *exactly* depicts *transcendent* objective reality, it only *approximately* depicts *immanent* objective reality. If instead we wish to *exactly* represent *immanent* objective reality, we need to depict an *ensemble* of *possible* system states around the initial point (p_0, q_0) . Such an ensemble is called a *Gibbs ensemble* after the great American scientist Josiah Willard Gibbs, who first introduced the concept in the late 1900s.

Figure 8, below, shows a Gibbs ensemble at an initial point in time (V_0) and at a subsequent point in time (V_t). Each of these Gibbs ensembles is essentially a “cloud” of points surrounding point (p_0, q_0) , with a probability assigned to each point. Of these points, point (p_0, q_0) itself has the highest probability assigned to it:

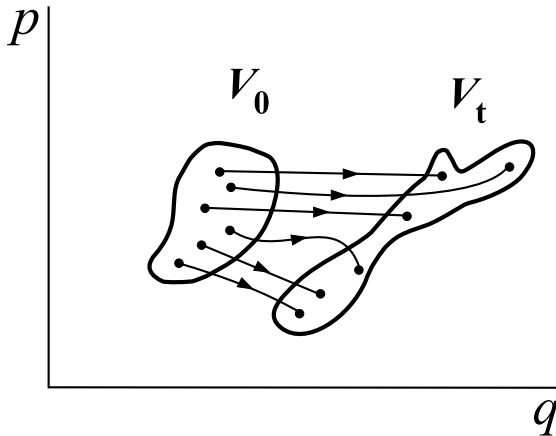


Figure 8 (after figure 35 on page 83 of Nicolis and Prigogine)

ON SYSTEMS

The sum of all of the probabilities associated with the points within any given Gibbs ensemble must equal 1 (i.e., 100%). Since there is in principle no limit to the number of possible systems we may consider, we can let these points be infinite in number within the boundary of V_0 . The probability “density” within volume V_0 would then be highest at point (p_0, q_0) and would approach zero as the boundary of V_0 is reached. However, the *sum* of the probabilities of all of the infinite number of points within volume V_0 would still be 1 (that is, 100%). (And, of course, what we have just said about V_0 is equally true of the subsequent Gibbs ensemble V_t as well.) The Gibbs ensemble, in general, is therefore intimately related to the *probability density function* $\rho(p, q, t)$, which returns the probability that at time t the dynamic system is at point (p, q) in the phase space.¹⁶⁴

Notice that in Figure 8 the Gibbs ensembles V_0 and V_t are depicted as having *different shapes*, yet also as having *the same area*. This illustrates a very important theorem of the French mathematician Joseph Liouville: *Liouville’s theorem* states that *all* conservative dynamic systems (whether they be linear or nonlinear) conserve Gibbs-ensemble *volume* as they evolve through time within the phase space.¹⁶⁵ In other words, conservative dynamic systems temporally evolve in such a way that the probability density function ρ in phase space behaves like an *incompressible fluid*.¹⁶⁶

Epistemologically the key point here is that the *trajectory* representation of the dynamic physical system in Figure 7 is *precisely* true from a *transcendent* objective point-of-view, but is only *approximately* true from an *immanent* objective point-of-view. By contrast, the *Gibbs ensemble* representation of the physical system in Figure 8 *accurately* represents an *immanent* objective point-of-view, but only *approximately* represents the *transcendent* objective point-of-view. These differences arise because of *objective finite limits* to the accuracy of our human measurements and actions. (Note that our *epistemological* interpretation of Gibbs ensembles essentially follows the views of Ilya Prigogine. By contrast Josiah Gibbs himself was of the common opinion among 19th and 20th century scientists that all macroscopic probability is “merely subjective”.¹⁶⁷)

To further illustrate these twin concepts of phase space and Gibbs ensembles, let’s take a look at “generic” phase-space diagrams for both deterministic and chaotic systems.

Figure 9, on the opposite page, is a generic phase-space representation of a *conservative, integrable, deterministic* Hamiltonian dynamic system of the kind we discussed in our chapter on **Classical Mechanical Systems**:

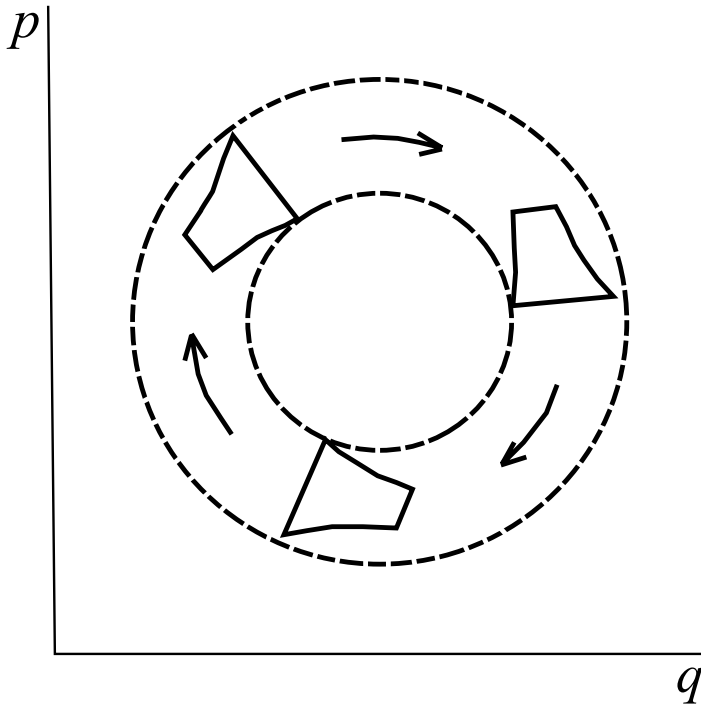


Figure 9 (after figure 32 on page 265 of Prigogine and Stengers)

You will recall that such a conservative *linear* dynamic system is similar to a free-particle system, in that a coordinate system can always be found such that *all* of the system energy is kinetic, and the momenta of *all* of its component bodies are constants of motion.

Notice that Figure 9 shows a small irregular figure (representing a Gibbs ensemble) moving around in a circle in the phase space: Not only is the *area* of this irregular figure constant, *but the shape is constant as well*. That's because *integrable, deterministic* conservative dynamic systems preserve the *shape* of the Gibbs ensemble (as well as its *volume*) as the system temporally evolves. And that's why it makes sense to regard the *trajectory* representation of such a deterministic system to be a meaningful *goal* that can be asymptotically approached by improving our knowledge (thereby shrinking the Gibbs ensemble to a more-pointlike state).

Another important thing to notice about Figure 9 is that the Gibbs ensemble moves round-and-round in a somewhat-confined area of the diagram: In other words, the ensemble does *not* move in such a way as to eventually “cover” all of the phase space. That's because *energy*, represented by the Hamiltonian function $H(p, q, \cdot)$, is not the *only* constant in an integrable, deterministic

ON SYSTEMS

system: Rather, the *momentum* of every body in the system is *also* constant, thus placing further constraints on the system.¹⁶⁸ These further constraints on the system are also why the movement through the phase space of either a point or an ensemble of points representing an *integrable, deterministic* dynamic system is either *periodic* (circular/elliptical) or *quasi-periodic* (processing circular/elliptical).

By contrast, a conservative dynamic system whose *only* constant is *energy* is called an *ergodic system*. As an *ergodic system* evolves through time, its Gibbs ensemble eventually passes through *all* of the points in the phase space, assuming that this phase space consists of all points corresponding to a certain constant energy (that is, a constant Hamiltonian).

As a subset of ergodic systems, we are particularly interested here in conservative *chaotic* dynamic systems, such as the three-body gravitational system. Figure 10, below, shows a generic phase-space representation of a conservative *chaotic* system:

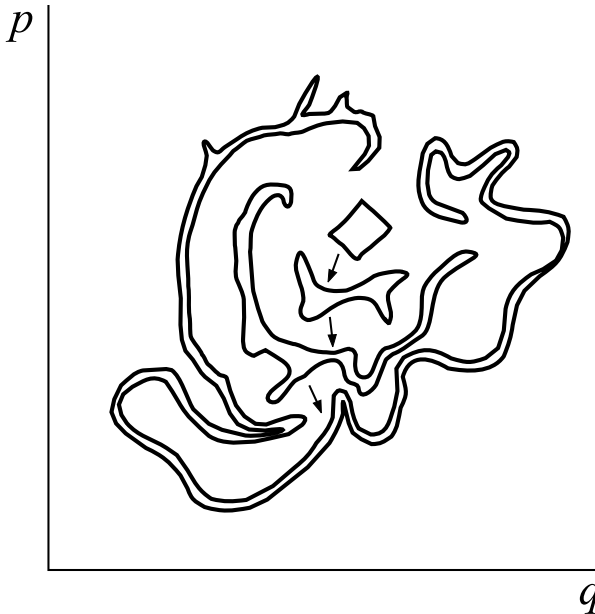


Figure 10 (after figure 34 on page 267 of Prigogine and Stengers)

Notice that, while the Gibbs ensemble for this chaotic system maintains a *constant volume* as it temporally evolves (thus obeying *Liouville's theorem* for conservative dynamic systems), its *shape* becomes *wildly distorted* into ever-thinner, more-twisted filaments, until eventually the entire phase space is visited. As Prigogine and Stengers put it:

No sketch can do justice to the complexity of the actual situation. Indeed, . . . two points as close together in phase space as we might wish may head in different directions. Even if we possess a lot of information about the system, so that the initial cell formed by its representative points is very small, dynamic evolution turns this cell into a true geometric “monster” stretching its network of filaments through phase space.¹⁶⁹

Epistemologically the key point here is that, from an *immanent* objective point-of-view, the conservative *chaotic* dynamical system keeps presenting us with new and novel information that is *not* contained *either* in a description of the initial conditions of the system *or* in the specification of the force laws (“laws of nature”) which the system is obeying. Faced with such a situation, the only reasonable course of action is to keep taking measurements of the system: Each such unique “snapshot” of the chaotic system enables us to redefine the Gibbs ensemble to a more-pointlike shape, thus keeping our understanding of the particular system “on track” as it evolves. In other words, to more-fully understand any particular *chaotic* physical system (or, indeed, even any particular *tychistic* physical system) from an *immanent* objective point-of-view, we need the services of an *historian* as well as the services of a *classical physicist*. (From a *transcendent* objective point-of-view, of course, the chaotic system remains just as deterministic as the classical mechanical system.)

It is now time to discuss in more detail particular dynamic examples of the four types of physical systems.

The Oscillating Pendulum

We begin with the *oscillating pendulum*, which is our chosen example of a *deterministic* dynamic system. On the following page, Figure 11 *physically* depicts the oscillating pendulum, while Figure 12 shows its *phase-space* representation. The oscillating pendulum consists of a round weight (called the “bob”) affixed to the end of a thin, rigid rod of negligible mass. This thin rod (plus its attached bob) swings freely from a swivel point, which is itself securely attached via a suspending framework to the earth’s surface. (As an approximate real-world example, you might think of the pendulum in a grandfather’s clock.)

Two additional points are of importance: First, all four of our example dynamical systems will be regarded as being *conservative* systems. Therefore, we will assume that no friction or air resistance affects either the oscillating pendulum or our other three example systems. Second, we stipulate that the *initial conditions* for our oscillating pendulum are that the bob is lifted up from the downward vertical angle of zero degrees to an angle that is *smaller* than ± 180 degrees (that is, *smaller* than $\pm \pi$ radians) and is then released.

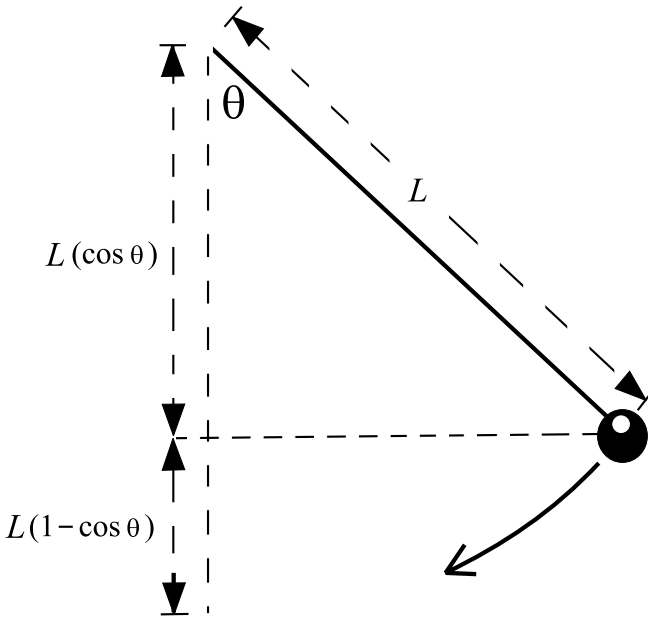


Figure 11

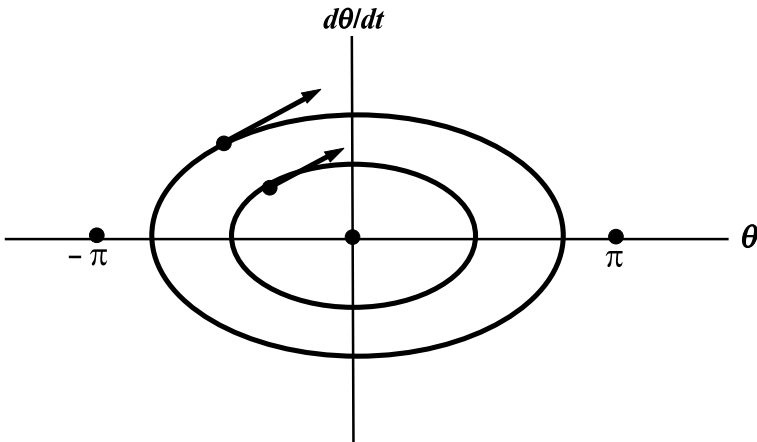


Figure 12 (after figure 20 on page 49 of Nicolis and Prigogine)

($180^\circ = \pi$ radians, $360^\circ = 2\pi$ radians, $90^\circ = \pi/2$ radians, and so on.) In other words, it is not permissible to start the pendulum off by *pushing* it so hard that it rotates in a vertical circle, nor is it permissible to drop the bob from its maximum upwardly-vertical position: To do either of these things would (or, at least, could) result in a *rotating pendulum* (also called a *forced pendulum*), which we will discuss later as our representative example of a *tychistic* dynamical system.

Under the conditions described, it is clear that the pendulum will swing (i.e., *oscillate*) back-and-forth forever. It is also clear that the position where the bob is hanging down vertically at a zero-degree angle is the fixed *elliptical point* (or *center point*) in the phase space around which this oscillation occurs. Furthermore, if we were to allow friction to affect the system, this *elliptical point* would also be an *attractor* or *sink* at which the pendulum would eventually come to rest. (In other words, the oscillating pendulum is a two-dimensional version of the three-dimensional “bowl game” we played earlier.)

Notice also that the oscillating pendulum is essentially a *two-body* system (the weighted bob + thin rod on the one hand, and the swivel/frame/earth on the other). This means that, even though both kinetic *and* potential energy are evident in this system relative to surface-of-the-earth coordinates, we know that *some* coordinate system can be found such that all of the system energy is always kinetic. In this sense the oscillating pendulum can be regarded as similar to a free-particle system (i.e., it may be regarded as a conservative, *deterministic* classical mechanical system having only *summative* characteristics).

Now, it is clear that the oscillating-pendulum system, relative to the earth’s frame of reference, has *maximum* kinetic energy and *minimum* potential energy as the bob passes through the elliptical point at the bottom of the pendulum’s swing. By contrast, the oscillating-pendulum system has *zero* kinetic energy and *maximum* potential energy when the bob stops at the top of its swing to either side of the elliptical point. It therefore makes sense to define the *reference point* of zero potential energy to be where the bob is at its lowest point (i.e., where the pendulum is at an angle of zero radians = zero degrees).

To determine the Hamiltonian function of the oscillating pendulum within this reference frame, we begin by noting that the Hamiltonian must represent the *total energy* of the system, so that $H = K + U$, where H is the Hamiltonian, K is the total *kinetic* energy of the system at a particular point in time, and U is the corresponding total *potential* energy of the system at that same point in time. Since we are making the ideal assumption that all of the mass in the system resides in the bob, the total kinetic energy of the system is always $\frac{1}{2}mv^2$, where m is the mass of the bob and v is the velocity of the bob. Furthermore, since mg is the magnitude of the force of gravity near the earth’s surface on a body having mass m (where g is the gravitational constant of acceleration near the earth’s surface), the gravitational potential energy of the bob’s mass m at a height h above the zero reference point is mgh (which is equal to the vertical work necessary to get mass m to a height

ON SYSTEMS

h in the presence of the opposing force of gravity). From Figure 11 on page 164 it is clear that height h for the oscillating pendulum is given by the formula $L(1 - \cos \theta)$, where L is the length of the thin rod and θ is the angle the thin rod makes relative to downward-vertical. So, our “first cut” at expressing the Hamiltonian for the oscillating pendulum system is therefore given by:

$$H = \frac{1}{2}mv^2 + mgL(1 - \cos \theta) \quad (22a)$$

But because v is always tangent to the trajectory of the mass, it follows that $v = L(d\theta/dt)$. Substituting in formula 22a we get:¹⁷⁰

$$H = mL \left[\frac{1}{2}L(d\theta/dt)^2 + g(1 - \cos \theta) \right] = \text{constant} \quad (22b)$$

Within this Hamiltonian formula the position q is represented by θ , while the momentum $p = mv = mL(d\theta/dt)$. Furthermore, since both m and L are constants, we can also represent momentum p (for the purpose of tracing *changes* in p) as $d\theta/dt$ by itself. Figure 12 on page 164 therefore shows the phase-space representation of the oscillating pendulum embedded in a plane for which the x-axis is θ and the y-axis is $d\theta/dt$. Furthermore, because the oscillating pendulum is a *deterministic* conservative dynamical system, we have chosen a *trajectory* representation of its motion through the phase space. (The *ensemble* representation of such a deterministic dynamic system would just be a “fuzzier” version of the *trajectory* representation.)

Two phase-space trajectories for the oscillating pendulum are shown in Figure 12. The *outermost* ellipse represents the trajectory starting from a *larger* displacement of θ from the vertical, while the *innermost* ellipse represents the trajectory starting from a *smaller* displacement of θ from the vertical ($0 \leq \theta < \pm \pi$ radians). Notice that both θ and $d\theta/dt$ assume both positive and negative values as the *representative point* of the oscillating-pendulum system moves in an ellipse around the central *elliptical point* through the phase space: This is because both q and p (in this case θ and $d\theta/dt$ respectively) are really *vector* quantities (i.e., they have a *direction* as well as a *magnitude*). In the absence of friction, the representative point on each of these phase-space ellipses will loop around forever.

Notice also that, unlike in the generic phase-space diagrams we discussed earlier, *different* energy levels [that is, *different* values of the constant Hamiltonian function $H(p, q)$] are here represented in the *same* phase-space diagram: For example, all of the points on the *outermost* ellipse clearly represent a constant value for the Hamiltonian function that is *higher than* the corresponding constant energy-value of the Hamiltonian function on the *innermost* ellipse. (Because the oscillating-pendulum system is *linear*,

integrable, and *deterministic*, constraints in addition to the requirement of constant energy apply to it.)

The Rotating Pendulum

We next extend our oscillating-pendulum example to include the *rotating pendulum* (also known as the *forced pendulum*). This *rotating pendulum* will serve as our dynamic example of the *second* type of physical system, the *tychistic* system. Figure 13, below, *physically* depicts the rotating pendulum, while Figure 14 shows its *phase-space* representation:

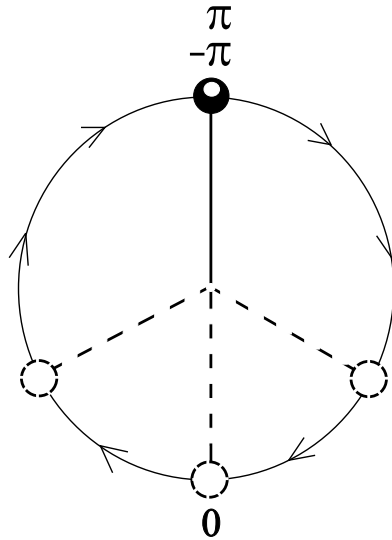


Figure 13

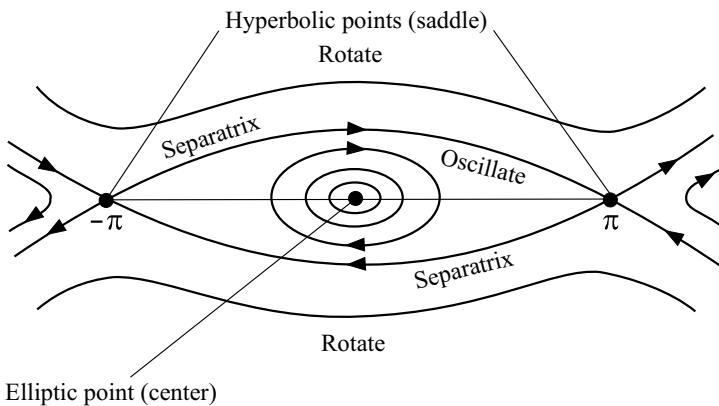


Figure 14 (after figure 40 on page 93 of Nicolis and Prigogine)

ON SYSTEMS

Everything about the *rotating* pendulum is exactly the same as for the oscillating pendulum (including the equation for the Hamiltonian function shown in formulas 22a and 22b), *except* that *additionally* we are now permitted to initiate the system by either *pushing* the bob so hard that the pendulum rotates vertically or by *dropping* the bob from its maximum-possible upward-vertical angle of $\pm\pi$ radians ($= \pm 180$ degrees). (Of course, we are still permitted to lift the pendulum to an angle *less* than $\pm\pi$ radians and release it, just as we did in the case of the *oscillating pendulum*. Again, air resistance and air currents are ignored.)

If we choose to release the pendulum from an angle less than $\pm\pi$ radians, then the *representative point* will trace an *ellipse* in the phase space, just as it did in the case of the *oscillating* pendulum: The small ellipses in Figure 14 are equivalent to the ellipses in Figure 12. (The only difference is that in Figure 14 the vertical $d\theta/dt$ axis has been removed for clarity.)

However, if instead we choose to *push* the bob so hard that the pendulum rotates vertically in a circle, then we will get a physical system that is (in general) just as *integrable* and *deterministic* as the oscillating-pendulum system: The two *waves* drawn in Figure 14 are representative trajectories of this vertical *rotation* of the pendulum when it is initially shoved hard enough. Notice that the rotating pendulum never has zero momentum (i.e., it never comes to a complete standstill). Notice too that the rotating pendulum never reverses its direction of motion (which is why it remains on one side or the other of the horizontal θ axis). Lastly, the rotating pendulum's motion is *periodic*, even though this is not as evident from the phase-space diagram as it was in the case of the oscillating pendulum: This periodicity results from the fact that, as the phase-space wave trajectory passes (for example) π radians, then 3π radians, then 5π radians, etc. on the θ axis, it is really passing through the *same* point in *physical* space.

Because almost all of the possible states of the rotating-pendulum system (whether the pendulum is actually rotating or instead is merely oscillating) are both integrable and deterministic, we have again chosen a *trajectory* representation rather than an *ensemble* representation in phase space.

Nevertheless, there are *two* points shown in Figure 14 where the rotating-pendulum system is *not* integrable and is *not* deterministic: These are the two fixed *hyperbolic points* (i.e., *saddle points*) at zero-momentum and positions $\pm\pi$ radians ($= \pm 180$ degrees) respectively.

To see the significance of these two hyperbolic points, we need to consider the case in which the bob is lifted up to its maximum vertical angle of either π radians or $-\pi$ radians (the sign depending on which way the bob is lifted up) and then is released: Clearly we are then dealing with a two-dimensional

version of the “saddle game”, which we played earlier. As in the saddle game, a perfect transcendent being (such as God or Maxwell’s demon) could release the bob exactly so that it balances forever-motionless above the swivel point. (That’s because such a perfect transcendent being would have exactly accurate information about the momenta and positions of both the pendulum and the earth out to an infinity of decimal places, together with the ability to control both the pendulum and the earth without any error.)

By contrast, whenever a finite human experimenter releases the bob vertically upright at its maximum angle as accurately as he can, the pendulum system *bifurcates* into two possible states having an equal probability. In fact, the system actually experiences *two* such bifurcations simultaneously, giving a combined total of *four* co-equal possibilities for the system: The *first* equally-probable bifurcation is between a system state in which the pendulum begins to fall *clockwise* and a system state in which the pendulum begins to fall *counterclockwise*. This first bifurcation is due to the very slight error in *position q* (i.e., the very slight deviation from $\pm \pi$ radians) when the bob is released. The *second* equally-probable bifurcation is between a system state in which the pendulum falls back into its nearly-largest *oscillation* and a system state in which the pendulum on the contrary achieves its nearly-slowest-possible *rotation*. This second bifurcation is due to the very slight error in *momentum p* (i.e., the very slight deviation from zero momentum) when the bob is released. (Both of these bifurcations are *saddle-node bifurcations* of the type we discussed earlier.)

Notice in Figure 14 that the two *hyperbolic points* (*saddle points*) are connected by two *separatrix* orbits, one on each side of the horizontal θ axis. These two separatrix orbits lie *exactly* between those representative orbits in the phase space that represent *oscillations* and those representative orbits in the phase space that represent *rotations*. Furthermore, each of these separatrices has the following remarkable property: It is the *unstable* manifold for one of the two hyperbolic points and the *stable* manifold for the other. The reason for this is suggested by the following physical fact: If we drop the bob from its maximum vertical angle, it is from one point-of-view *repelled away from* the top point of its physically circular orbit. However from another point-of-view it is also *simultaneously attracted back to* this same top point of the physically circular orbit (as the bob circles back around). As we mentioned in our earlier discussion of the “saddle game”, the intersection of the *unstable* manifold of one hyperbolic point with the *stable* manifold of a different hyperbolic point is called a *heteroclinic intersection*, and the associated orbit is called a *heteroclinic orbit*.¹⁷¹

ON SYSTEMS

From an *immanent objective* point-of-view, the hyperbolic points at momentum zero and positions $\pm\pi$ radians of the rotating pendulum's phase space are clearly associated with physical phenomena that manifest *immanently objective constrained chance*. An *ensemble representation* of one of these hyperbolic points is therefore of great interest. Figure 15, below, shows two greatly magnified views of a Gibbs ensemble surrounding such a hyperbolic point:

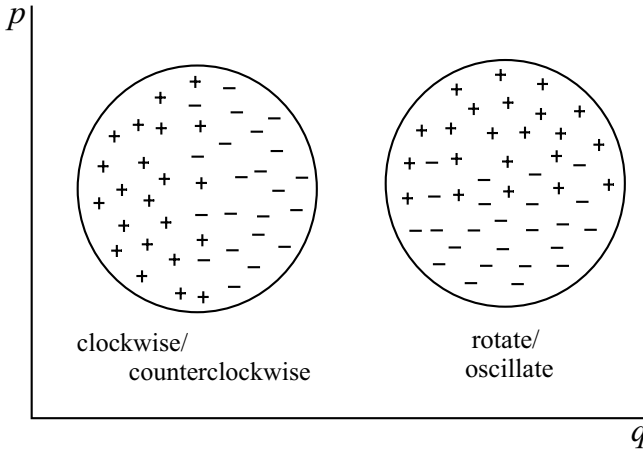


Figure 15 (loosely based on figure 1.5 on page 36 of Prigogine)

In the first such magnified view, *plus-signs* represent points in the Gibbs ensemble whose trajectories will evolve into a *clockwise* movement of the pendulum, while *minus-signs* are points which will evolve into a *counterclockwise* movement. In the second such view, *plus-signs* represent points in the Gibbs ensemble whose trajectories will evolve into a *rotational* movement of the pendulum, while *minus-signs* are points which will evolve into an *oscillating* movement. Furthermore, we assume in Figure 15 that the accuracy of our vertically-upward initiation of the pendulum is not very good, due to poor measurements or inadequate control mechanisms: That's why the pluses and minuses tend to be segregated to one side or the other of their respective circles, with a fuzzy overlap between them.

But what happens if the accuracy of our measurements and actions improves considerably? Figure 16, on the following page, shows a blow-up of a small central portion of *either* of the Figure 15 magnified views. Figure 16 therefore represents a situation in which we have been able to significantly reduce the initial volume of the Gibbs ensemble through improved technology. But notice that shrinking the initial volume of the Gibbs ensemble does *not* enable us to arrive at a deterministic result, due to the extreme sensitivity to initial conditions at the hyperbolic point: The random mixture of pluses and

minuses within the ensemble circle in Figure 16 is intended to symbolize the fact that near a hyperbolic point the trajectories of even infinitesimally close points in the phase space may evolve to radically different results. Indeed, the *more-accurate* our measurements and actions become, the closer to *exactly* 50% is the probability that the pendulum will drop *clockwise* vs. *counterclockwise* (or will *rotate* vs. *oscillate*):

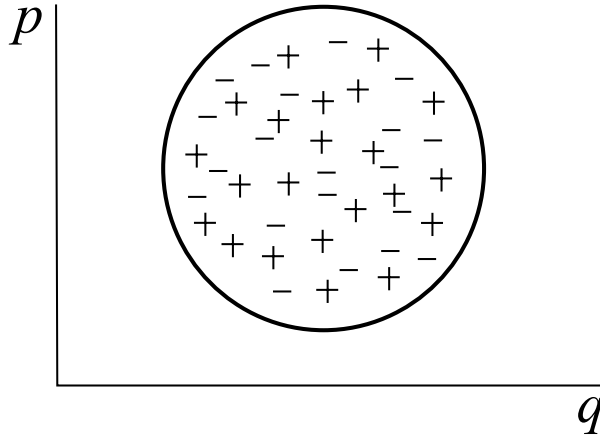


Figure 16 (based on figure 1.6 on page 36 of Prigogine)

This 50% probability therefore *cannot* be dismissed as a “merely subjective” error. Rather, it must be regarded as an *immanent objective* fact – an instance of what Charles Sanders Peirce called *absolute chance*, or *tychism*.

The rotating pendulum is therefore a *tychistic* system – that is, a dominantly deterministic system that is nevertheless punctuated with moments of *absolute constrained chance*. Of course, from the *transcendent* objective point-of-view of a being capable of measurement and action to infinite precision (such as a transcendent God or Maxwell’s demon), tychistic systems such as the rotating pendulum are still completely deterministic, but for *immanent* beings such as ourselves, determinism makes no sense even as an *ideal*, where hyperbolic points and tychistic systems are concerned.

Physical aside: It is interesting to note that during the moment when the bob is being released from its vertically-upward position, the rotating-pendulum system is really a *three-body* system: 1) the bob/pendulum, 2) the earth/frame, and 3) whatever organic or mechanical system is being used to hold and release the bob. This suggests that *even a single moment* of nonintegrable immanently objective chance is associated with the interaction between *three or more* bodies.

ON SYSTEMS

Teleological aside: If the *physical* rotating-pendulum system were much more complex than it is, we would be strongly inclined to relate it to a parallel *teleological* system by saying that the system “decided” to fall clockwise rather than counterclockwise (or “decided” to rotate rather than oscillate). Indeed, a popular science writer might be tempted to use just such language in describing the rotating-pendulum system itself, all the while regarding such talk to be “merely a figure of speech”. But if we were correct in our argument in Book I, *WORLDVIEWS*, that a renewed belief in *animism* is necessary to revive our Western sensitivity to religious truth, then we need to consider the possibility that the rotating-pendulum system in fact really *does* have a very primitive consciousness that enables it to make such “decisions”, since *physical* bifurcations are often analogous to *teleological* decision-points: The rotating pendulum system *is*, in fact, characterized (minimally and simply) with those qualities of external *and* internal conditional equifinality which we will later see to be especially characteristic of those physical systems that have significant teleological analogs (decisions, goals, purposes, and so on).

The Three-Body Gravitational System

The third type of physical system on our “physical spectrum” is the *chaotic* system, and our conservative dynamic example of this type of system is the *three-body gravitational system*. Like the *tychistic* system (of which the rotating pendulum is an example), the *chaotic* system is (from an *immanent* objective point-of-view) a mixture of *determinism* and *absolute chance*. The only difference between these two types of physical systems is that in *tychistic* systems determinism dominates over absolute chance, whereas in *chaotic* systems absolute chance dominates over determinism. (In reality, of course, a continuum exists between *tychistic* systems and *chaotic* systems.) For example, let’s consider several instances of gravitational orbital systems, ranging from the relatively *tychistic* to the relatively *chaotic*:

Our solar system is the most-familiar example of a gravitational orbital system which is relatively *tychistic*: It consists of one massive, central body (the sun) which gravitationally dominates the nine planets, the comets, and the asteroids, all of which orbit about it. The mass of each of these bodies relative to the sun is quite small (though not entirely negligible).

Computerized numerical simulations by G.J. Sussman and J. Wisdom, as well as by J. Laskar, indicate that the solar system has an “exponential separation time” of about 5 million years due to Poincare resonances between the inner planets Mercury, Venus, Earth, and Mars. (These simulations ignore Pluto, whose orbit is not in the same plane as the other planets and is highly sensitive to initial conditions.)¹⁷² Although our solar system may therefore be

regarded as “chaotic” on this very long time scale, it is *nearly deterministic* (or *quasi-deterministic*, and therefore *tychistic*) in the short run. Nicolis and Prigogine explain:

The mass of the planets is about a thousand times less than the mass of the sun, so at first approximation we can neglect their interaction and take into account only their attraction by the sun. In this way we obtain the *two-body problem*, which provides a classic example of an integrable (and exactly soluble) system giving rise to a periodic motion [in phase space] for each individual planet, and a quasi-periodic motion [in phase space] for the entire planetary system.

The interaction between planets, small as it may be, is nevertheless always present and will tend to perturb the keplerian trajectories. . .

Clearly, as long as one is interested in times scales of the order of the inverse of the strength of the perturbation (these would be in the 1000-year range for our planetary system), the effects induced by the latter can be handled straight-forwardly by standard methods. But if we look for solutions valid for very long times and, in particular, if we want to understand the qualitative behavior of the exact solutions, we are immediately faced with a number of formidable difficulties.¹⁷³

It turns out that, where the ratios between the various planetary years (orbital frequencies) are *irrational numbers* (i.e., they are *not* expressible exactly as the ratio between two integers), the trajectory of the corresponding integrable, conservative planetary system in phase space is *quasi-periodic* and traces a *helix* (i.e., a spiral) around a *nonresonant torus* (i.e., an inner-tube or doughnut shape) in such a way that it never crosses itself or closes on itself, but instead eventually passes near every point on the surface of the torus. Such a motion in phase space is called “everywhere dense”.¹⁷⁴ Figure 17, below, shows an early stage in this helical motion of the phase-space trajectory around the torus:

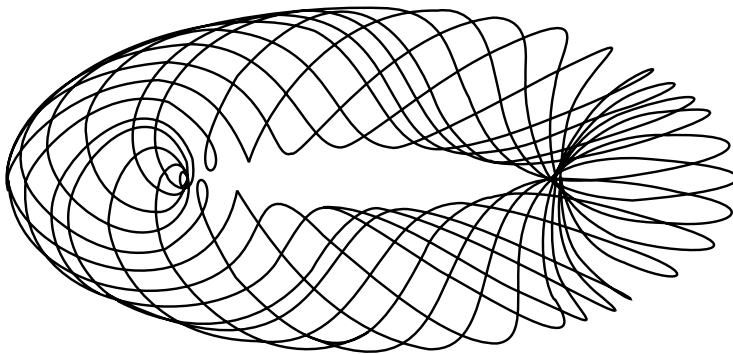


Figure 17 (based on the torus.ds Dynamics Solver example problem file, © 1992-1998 by Juan M. Aguirregabiria.)

ON SYSTEMS

Figure 18, below, shows a *Poincare section* of this same torus at a later stage in the system's evolution:

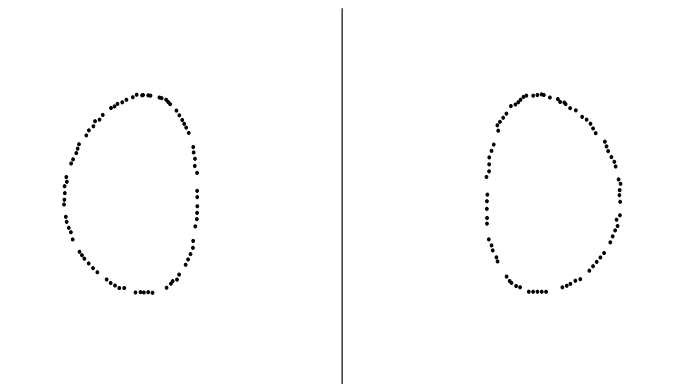


Figure 18 (also based on the `torus.ds` Dynamics Solver file)

The *Poincare section* is an imaginary two-dimensional plane slicing vertically through the center of the torus. Every time the phase-space trajectory of the planetary system pierces this Poincare section, we record a dot. As you can see, these piercings (dots) have formed two closed curves, right where the Poincare section cuts through the torus. Soon we will be dealing with *chaotic* planetary systems, and in such cases it is far easier to just calculate the Poincare section rather than calculating the entire orbit of the phase-space trajectory. (Poincare pioneered this technique in connection with his work on the three-body gravitational system. By the way, the figures in this part of our text were mostly generated using Juan M. Aguirregabiria's excellent *Dynamics Solver* program, which is available on the internet.)

Four observations with respect to this nonresonant torus: First, because a *conservative* dynamical system is being represented, all points on the torus represent *equal total energy* (i.e., the *same* value for the Hamiltonian function). Second, because an *integrable, nearly-deterministic* planetary system is being represented (since the planets have a very small mass in relation to the sun and, furthermore, their orbital-frequency ratios are assumed to be irrational numbers), the surface of the torus reflects additional constraints. Thirdly, because a *conservative* dynamic system *cannot* achieve *asymptotic* stability (as we saw in the case of the no-friction version of the “bowl game”), in practice small perturbations of this planetary system will cause its phase-space trajectory to “jump” between close, concentric toruses.¹⁷⁵ And, fourthly, if the ratios between the various planetary years (orbital frequencies) were allowed to become *rational numbers* (so that they

were expressible exactly as the ratio between two integers), then Poincare resonances between the planetary orbits would become much-more significant, and the system would consequently move from being *tychistic* to being *chaotic*.

Next, let's consider a theoretical gravitational orbital system containing significantly more chaos than the nearly-deterministic tychistic solar planetary system we have been discussing: That system is the *planar restricted three-body gravitational system*. This is the simplified version of the gravitational three-body problem that Poincare actually originally worked on. It is simplified because the physical movement of the three bodies is confined to a flat-plane surface, and one of the bodies is assumed to have negligible mass. Figure 19, below, shows a planar restricted three-body gravitational system within a coordinate frame that *co-rotates* with the two bodies having non-negligible mass:

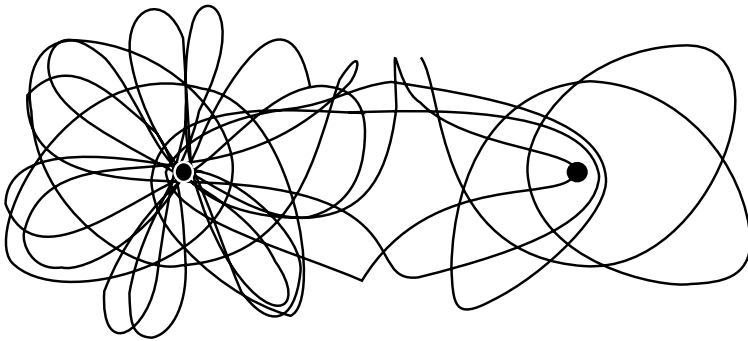


Figure 19 (derived from the r3body1.ds Dynamics Solver example problem file, © 1992-1998 Juan M. Aguirregabiria)

The *chaotic* physical trajectory of the third body, having negligible mass, is what is primarily shown in Figure 19. Figure 20 shows this same system in a *center-of-mass* frame of reference:

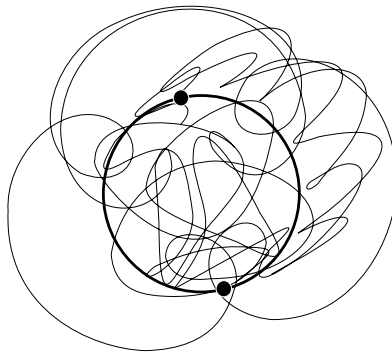


Figure 20 (also derived from the r3body1.ds example file)

ON SYSTEMS

Because the mass of the third body is assumed to be negligible (i.e, zero), the other two masses orbit around each other tracing the exact same circle as their common trajectory, while the third body once more moves in a *chaotic* physical trajectory.

In this intermediate case, the movements of the two bodies having *non-negligible* mass are just as deterministic and integrable as were the movements of the planets in our solar system example (even more so, since this is a purely theoretical example). By contrast, the movement of the third body having *negligible* mass is clearly *chaotic*: Depending sensitively on initial conditions, this third body can be trapped forever in a chaotic orbit around the other two massive bodies, or it can eventually become accelerated enough to escape entirely from the two-body system, or it can crash into one of the two massive bodies.

But what if we allow the third body to *also* have non-negligible mass, while continuing to limit the movement of all three bodies to a flat plane? One version of this theoretical gravitational system arises when we solve *Burrau's problem*: In *Burrau's problem* we assume that the first mass is 4 (of any arbitrary units), the second mass is 3, and the third mass is 5. Furthermore, we assume that the initial conditions are such that these three masses start out at rest at the corners of a 3:4:5 right triangle and then begin moving as a result of mutual gravitational attraction. Figure 21, below, shows the result:

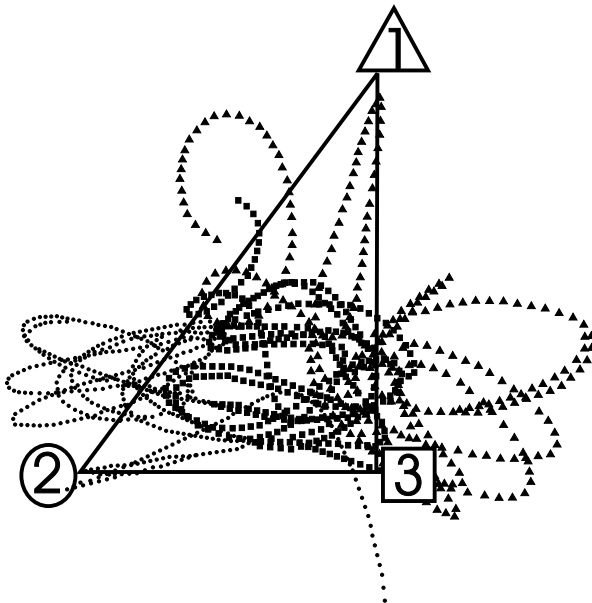


Figure 21 (derived from the 3body.ds Dynamics Solver example problem file, ©1996-1998 Juan M. Aguirregabiria)

As you can see, the movement of *all three* masses is then *chaotic*.

Furthermore, the exact path followed by all three of these masses is *highly sensitive* to the initial conditions. Eventually, after a complex evolution, the second (lightest) mass escapes from the gravitational effects of the other two masses and sails off at constant velocity, leaving the first and third masses to circle one another forever as a deterministic, integrable binary system.

Figures 19, 20, and 21 all show *physical* representations of three-body gravitational systems. But what does a *phase-space* representation of a three-body system look like? Because of the extreme complexity of the movement of the representative trajectory of a three-body system in phase space, only a *Poincare section* of this phase space is generally depicted. Figure 22, below, shows a Poincare section cutting through the phase space of one such three-body system:

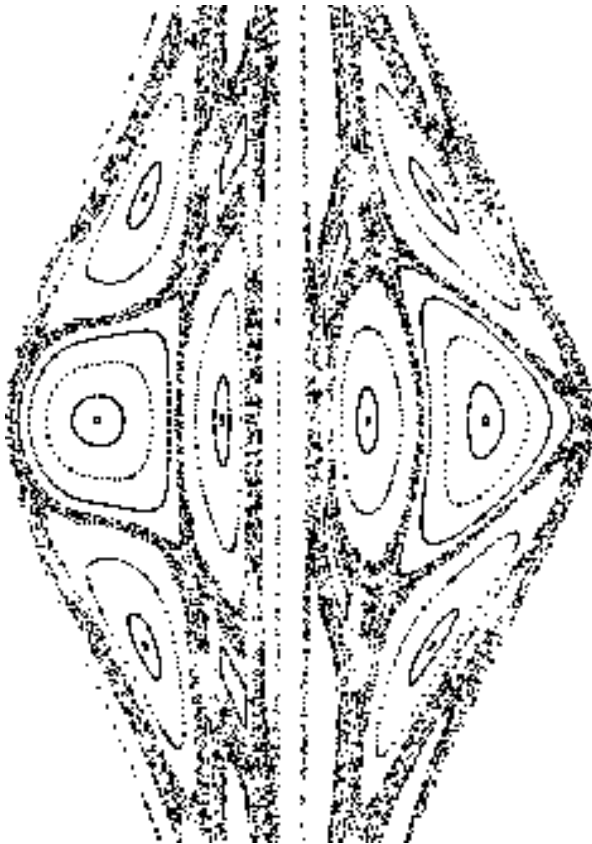


Figure 22 (after a figure depicted in the article “Chaos!” by James P. Sethna, <http://www.physics.cornell.edu/sethna/teaching/sss/jupiter/Web/Chaos.htm>)

ON SYSTEMS

This particular three-body system is a simulation of the Sun/Jupiter/Earth system, *except* that the mass of Jupiter is assumed to be 22,000 times the mass of the earth, rather than only 318 times, which in fact it actually is. (Contrast Figure 22, which depicts the Poincare section for this *chaotic* dynamical system, with Figure 18, which depicts the Poincare section for a *tychistic* dynamical planetary system that is nearly deterministic.)

Notice that Figure 22 contains several sets of paired concentric closed curves. Each of these pairs of closed curves is like the closed curves in Figure 18 and represent regions of the phase space in which the representative phase-space trajectory moves helically around a nonresonant torus in a *quasi-periodic* orbit: Such phase-space regions are characterized by a fairly high degree of determinism and integrability, just as was the case for the tychistic solar planetary system which we studied. However, even in these phase-space regions there is a significant element of absolute chance, reflected in the fact that these paired closed curves occur in *concentric sets*: As we noted earlier, because conservative dynamic systems cannot achieve asymptotic stability, even a slight perturbation of a conservative orbital system will kick its phase-space trajectory onto a nearby concentric torus. (That is what is happening in Figure 22, except that these “kicks” are rather severe and arise from the internal dynamics of the system, rather than from an outside influence.)

Also evident in Figure 22 is something that Figure 18 does not contain at all, namely, dense areas of random dots (comprising the *stochastic sea*) that completely surround the *island* areas containing the concentric curves. These random dots reflect regions in the phase space where the behavior of the three-body system is *chaotic*, is highly sensitive to initial conditions, and is *ergodic* (meaning that continuously equal total energy is the only invariant). *Many* hyperbolic points (saddle points) arise in these chaotic regions of the phase space, and (as we noted earlier) the instability associated with these hyperbolic points is quickly spread throughout a much wider phase-space region due to their associated *homoclinic points*: Recall that the stable manifold and unstable manifold of each *hyperbolic point* can intersect at a *homoclinic point*, whose existence automatically causes the existence of an infinite number of other nearby homoclinic points. As a result, both the stable and the unstable manifolds undulate strongly around each hyperbolic point, thus causing a *homoclinic tangle*. Furthermore, because the system is conservative, no dampening of these undulations can occur and, in the words of Nicolis and Prigogine, “these undulations are associated with ever-larger excursions from the fixed [hyperbolic] point, followed by re-injections back to its vicinity”.¹⁷⁶ As a result the three-body system behaves *chaotically* in those regions of phase space that we have called the *stochastic sea*.

But what actually causes such a three-body system to become *chaotic*? In other words, what causes its representative trajectory in phase space to jump from *tychistic* quasi-periodic behavior (evident in the island areas of concentric curves within the Poincare section) to *chaotic* behavior (evident in the surrounding stochastic-sea areas of dense random dots within the Poincare section)? The complete answer to this question is not known. As George M. Zaslavsky has put it:

The vicinity of the island boundary is *terra incognita*, and, despite significant mathematical effort, it is still poorly understood how a trajectory shifts from regularity to the chaotic regime.

Simulation shows that the vicinity of an island, called the boundary layer, is sticky. This means that a trajectory spends more time in the boundary layer than in a domain of the stochastic sea of the same phase volume but located far from the island . . . The island's boundary can be more or less sticky, depending on the control parameters of the system. There are also special zones located near the island's boundary where a trajectory can be trapped for a long finite time, and the size of these zones depends on the system parameters.¹⁷⁷

Nevertheless, a *partial* answer to the question of *why* a dynamic system such as the three-body gravitational system jumps from tychistic quasi-periodicity to chaos can be found by considering the *Poincare resonances* arising between the *degrees of freedom* in the phase space.¹⁷⁸ (*Poincare resonances* can also be seen as partially accounting for the *non-integrability*, i.e., *non-solvability*, of chaotic dynamic systems.) Recall that one of the conditions for the stable, integrable, quasi-periodic behavior of a planetary system in the phase space is that the ratio between planetary years (orbital frequencies) be an *irrational number* (i.e., *not* expressible evenly as the ratio of integers). If, on the contrary, these ratios are *rational numbers* (or are sufficiently close to being rational numbers), then the planetary system may easily become *unstable*, and very slight perturbations may therefore kick it from *tychistic* quasi-periodic behavior to *chaotic* behavior.

Rational orbital ratios result in *instability* because they are associated with *Poincare resonances*. For example, if we give little shoves to a pendulum at a frequency that is an exact rational ratio of the pendulum's existing frequency, the *resonance* between these two frequencies will cause the pendulum to swing higher and higher. Or, to take another example, if soldiers march on a bridge in a rhythm that is an exact rational ratio of the bridge's undulation frequency, that bridge's undulation amplitude will increase and perhaps cause the bridge to break (which is why soldiers "break step" when they cross a bridge). Similarly, if planetary years (orbital frequencies) have exact (or nearly exact) rational ratios, then the gravitational attraction between the

ON SYSTEMS

planets will tend to magnify orbital perturbations to the point of chaos, such that the system becomes nonintegrable (i.e., not deterministically solvable).

Ilya Prigogine explains:

[C]onsider the case of a [two-planet] system [going around a much-more-massive star, and] characterized by two [orbital] frequencies. By definition, whenever the sum $n_1\omega_1 + n_2\omega_2 = 0$, where n_1 and n_2 are nonvanishing integers [and ω_1 and ω_2 are the two orbital frequencies], we have resonance. This means that $\omega_1/\omega_2 = -n_2/n_1$; the ratio of the frequencies is then a rational number. As Poincare has shown, in dynamics resonances lead to terms with “dangerous” denominators [that are zero, or nearly zero,] such as $1/(n_1\omega_1 + n_2\omega_2)$. Whenever there are resonances (i.e., points in phase space where $n_1\omega_1 + n_2\omega_2 = 0$), these terms diverge [towards infinity]. As a result, we encounter obstacles whenever we try to calculate trajectories.

This is the origin of Poincare’s nonintegrability. The “problem of small denominators” was already known by eighteenth-century astronomers, but Poincare’s theorem shows that this difficulty, which he called the “general problem of dynamics”, is shared by the great majority of dynamical systems. For a considerable length of time, however, the importance of Poincare’s findings was overlooked.¹⁷⁹

Although Poincare and Birkhoff established the foundations of nonlinear dynamics in the late 1900s, it was not until the 1950s that Andrei Kolmogorov, Vladimir Arnold, and Jurgen Moser further developed the theory of nonlinear dynamics in detail. Their results are often called *KAM theory* (after the initials of their last names), and the closed curves within the Poincare sections of chaotic dynamical systems are often called *KAM curves*.¹⁸⁰

Another very important result of KAM theory is here explained by Nicolis and Prigogine:

[A]s the energy of the [chaotic dynamic] system increases, we observe that the islands [of KAM curves] tend to retreat, and the chaotic trajectories progressively invade ever larger portions of phase space. It is difficult to draw qualitative conclusions from such observations, since this regime is hardly accessible to analytical calculations or even to general topological considerations. Still, it is possible to introduce a measure characterizing the instability of the motion and the sensitivity to the initial conditions. This is provided by the *Lyapunov exponents*, which describe the mean rate of exponential divergence of two initially close trajectories.¹⁸¹

We can gain an understanding of *Lyapunov numbers* and *Lyapunov exponents* by building on our results in formulas (20) and (21), which we restate here:

Let f be a map function which is continuous and smooth (i.e., derivatives of all orders exist everywhere for the function). Let p be a fixed-point of f so that $f(p) = p$. Then, with respect to at least some sufficiently small epsilon neighborhood of p :

$$\text{If } |f'(p)| < 1, \text{ then } p \text{ is an attractor (i.e., a sink)} \quad (20)$$

$$\text{If } |f'(p)| > 1, \text{ then } p \text{ is a repeller (i.e., a source)} \quad (21)$$

We also saw that if p is a *hyperbolic point* (i.e., a *saddle point*), then it is an *attractor* along one axis, a *repeller* along the other axis, and a *repeller* along all directions that do not line up with either axis.

We now seek to define *Lyapunov numbers* and *Lyapunov exponents* in such a way as to express the attracting and repelling properties of not just a fixed point, but of *an entire trajectory* (i.e., an *orbit*):

Let $f(x)$ be a map function of x . Let $\{x_1, x_2, x_3, \dots, x_n\}$ be an orbit under f whose initial position is x_1 . Next, calculate $|f'(x)|$ for (say) each of the first five points in this orbit. (Where $|f'(x)|$ varies by *direction*, we calculate the *largest* $|f'(x)|$ we can, since, as we have seen in the case of hyperbolic points, the repelling properties of a point tend to significantly dominate over its attracting properties.) Next, average the five $|f'(x)|$ values by calculating their *geometric mean*. (That is, multiply the five $|f'(x)|$ figures together and take their fifth root, as follows.)

$$(|f'(x_1)| |f'(x_2)| |f'(x_3)| |f'(x_4)| |f'(x_5)|)^{1/5} \quad (23)$$

Now, clearly formula 23 represents the geometrical-mean rate of divergence (or convergence) between orbit $\{x_1, x_2, x_3, x_4, x_5\}$ and its close neighboring orbits. Thus, to arrive at the *Lyapunov number* for orbit $\{x_1, x_2, x_3, \dots, x_n\}$ as n approaches infinity, all we have to do is to find the limit of formula 23 as n approaches infinity, if such a limit exists. (In formula 23, of course, $n = 5$.)

$$L(x_1) = \lim (|f'(x_1)| |f'(x_2)| \dots |f'(x_n)|)^{1/n} \text{ as } n \rightarrow \infty \quad (24)$$

where $L(x_1)$ is defined to be the *Lyapunov number* for the orbit of f starting at initial position x_1 .

From formula 24 it is clear that $L(x_1)$ cannot be a negative number. Also, if $L(x_1) > 1$ then orbits of f starting at initial positions that are *very close* to x_1 *diverge* from x_1 's orbit (on the average), while if $0 < L(x_1) < 1$ then such orbits, by contrast, *converge* towards x_1 's orbit (on the average). (Note also that, while the *rate* of such divergence or convergence is often exponential, this need not be the case.)

Instead of the *Lyapunov number* $L(x_1)$, mathematicians often prefer to specify the *Lyapunov exponent* $h(x_1)$, which is the logarithm of $L(x_1)$ with respect to

ON SYSTEMS

some arbitrary base (often e or 2). If we choose e as the base, then the *Lyapunov exponent* $h(x_1)$ is simply the natural logarithm of the *Lyapunov number* $L(x_1)$, so that:

$$h(x_1) = \ln L(x_1) \quad (25a)$$

Or, equivalently:

$$h(x_1) = \lim_{n \rightarrow \infty} (1/n) (\ln |f'(x_1)| + \ln |f'(x_2)| + \dots + \ln |f'(x_n)|) \quad (25b)$$

Notice that $h(x_1)$ exists if and only if $L(x_1)$ exists. Additionally, if $L(x_1) > 1$ (that is, nearby points on the average *diverge* from x_1 's orbit), then $h(x_1) > 0$ (i.e., the *Lyapunov exponent* is *positive*). But if $0 < L(x_1) < 1$ (that is, nearby points on the average *converge* towards x_1 's orbit), then $h(x_1) < 0$ (i.e., the *Lyapunov exponent* is *negative*).

Finally, note that if the orbit $\{x_1, x_2, x_3, \dots, x_n\}$ contains an x_i such that $f'(x_i) = 0$, then no limit for either $L(x_1)$ or $h(x_1)$ can be asymptotically approached, and both the *Lyapunov number* and the *Lyapunov exponent* are then undefined.¹⁸²

We are now in a position to mathematically specify what it means for an orbit to be *chaotic*. Let f be a map function of x and let $\{x_1, x_2, x_3, \dots\}$ be an orbit of x under f starting at initial position x_1 . Then this orbit is *chaotic* if and only if:

1. its *Lyapunov exponent* $h(x_1)$ is greater than zero, and
2. $\{x_1, x_2, x_3, \dots\}$ is not asymptotically periodic.¹⁸³

The phrase “not asymptotically periodic” means that the orbit does *not* end either in a *sink* or in a set of *periodic points* (i.e., a set of points that just keep repeating in a cycle). (As we mentioned earlier in connection with the “bowl game”, a *sink* can be thought of as a *periodic point* with a period of one.)

It is also important to note that, while the *idea* behind *Lyapunov numbers* and *Lyapunov exponents* is fairly straightforward, actually *calculating* them is often highly nontrivial. For example, if all you have is experimental data, then such a calculation is difficult-to-impossible.¹⁸⁴ Furthermore, even numerical simulation on a computer has its difficulties because the computer can only calculate a finite set of numbers to a finite number of decimal places. As the *Nonlinear FAQ* explains:

Strictly speaking, chaos cannot occur on computers because they deal with finite sets of numbers. Thus the initial condition is always precisely known, and computer experiments are perfectly predictable, in principle. In particular, because of the finite size, every trajectory computed will eventually have to repeat (and thus be eventually periodic). On the other

hand, computers can effectively simulate chaotic behavior for quite long times (just so long as the discreteness is not noticeable). In particular if one uses floating point numbers in double precision to iterate a map on the unit square, then there are about 10^{28} different points in the phase space, and one would expect the “typical” chaotic orbit to have a period of about 10^{14} .¹⁸⁵

Even some famous mathematical examples of chaos, such as the *Lorenz attractor*, have never been rigorously *proved* to satisfy the two required conditions for chaos (i.e., both a positive Lyapunov exponent and nonperiodicity).¹⁸⁶

The Ideal Gas

The fourth (and final) type of physical system in our “physical spectrum” is the *stochastic* system, and our dynamic example of this type of system is an *ideal gas* at equilibrium, considered at the molecular level. Recall that a *stochastic* physical system is *completely random* and contains no (or negligible) elements of order or determinism. Rather, *immanently objective absolute chance* reins completely supreme at the level of detail being considered. (From a *transcendent objective* point of view, of course, *all* physical systems are *deterministic* systems.)

As scientists have become more aware of the existence of *chaotic* systems in recent decades, they have increasingly come to realize that the *stochastic* system, like the *deterministic* system, is an extreme idealization which is seldom actually found in physical reality. In other words, virtually all *physically real* systems are either *tychistic* or *chaotic* from an *immanent* objective point-of-view. (An exception to this rule *may* be quantum mechanical systems, where observational limitations may forever limit us to a *sub-microscopic stochastic* description of physical reality that is encapsulated within a *macroscopic deterministic* description of that same reality.) Consequently, many physical systems that were formerly classified as *stochastic* have now been found to be *chaotic* instead.

For example, computer simulations of molecules of an *ideal gas* bouncing around inside an enclosure that contains certain elastic macroscopic obstacles at rest, such as partial walls or variously sized “billiard balls”, in some cases will result in the emergence of a surprising order, such as the preferential gathering of the ideal gas in one region of the enclosure rather than another!¹⁸⁷

In general, physical systems which closely approach the ideal of a *stochastic* system are characterized by a fantastically high number of degrees of freedom in the phase space – in other words, an extremely high number of elastically colliding-and-rebounding particles (of the order of magnitude of around 10^{23}).

ON SYSTEMS

With this many degrees of freedom, the concepts of *thermodynamics* come into play. We will therefore defer further discussion of *stochastic* systems until we get to our chapter on **Linear Thermodynamic Systems**.

Once Again, Irreversible Time T

At last we can give our promised account of how *irreversible time T* (“big” T) arises as a *constitutive characteristic* (a.k.a. “emergent property”) of physical systems even at the level of simple, conservative dynamic systems consisting of as few as *three* bodies that interact strongly and persistently: For, although the *laws* of dynamics involve only *reversible time t* (“little” t), which presents us with no new information that is not contained in the initial conditions plus the dynamic laws themselves, the existence of infinitely many moments of *absolute chance* during the chaotic behavior of the three-body system causes *irreversible time T* to become manifest as a fundamental *immanent* objective feature of reality.

We touched in passing on irreversible time T during our discussion of Figure 10 above, which generically shows the phase-space evolution of a Gibbs ensemble for a conservative, ergodic, chaotic system (such as the three-body gravitational system). There we noted that, while the *volume* of the Gibbs ensemble is conserved (by Liouville’s theorem for conservative systems), its *shape* becomes increasingly distorted, drawn out, and twisted over time, until eventually all points of equal total energy in the phase space are visited. This means that, from an *immanent* objective point-of-view, the three-body system is continually presenting us with *new, unique information* that we *cannot deduce* either from the initial conditions or from the gravitational dynamic laws themselves. Faced with such a situation, we pointed out that the only reasonable strategy for immanent beings such as ourselves to pursue is to make periodic observations of the system and to record particular, unique states of the system at various moments in time as best we can. This procedure enables us to periodically *reshape our Gibbs ensemble* so that it more-nearly approximates that unique point in phase space which represents the *transcendently* objective state of the system at a particular point in time. In other words, we must become *historians* in order to describe the gravitational three-body system adequately.

But while the above description accounts for the *fine grain* of irreversible time T , it does *not* account for the *single direction* of irreversible T . After all, it is conceivable that immanent objective time could have a very fine granularity (i.e., be characterized by unique, nondeducible information at infinitely many moments), yet still be *reversible*. What, then, is the specific source of T ’s *irreversibility*?

Imagine the two-step procedure that we, as immanent beings, would have to use to *temporally reverse* the three-body gravitational system:

1. We would have to *take precise observations* of the positions and momenta of the three bodies for a particular point in time.
2. We would then have to *apply force* to all three bodies in the exact magnitudes and directions required to temporally reverse the system.

The problem is that both our *initial observations* in step 1 and our *application of force* in step 2 would have to be carried out with *infinite precision*: Otherwise the “reversed” trajectories of the three bodies would soon diverge widely from the original forward trajectories due to “sensitivity to initial conditions”. More importantly, even if (by some miracle) we could accomplish steps 1 and 2 for some particular moment in time, we would still have to repeat this feat every time the three-body system encountered another one of its many *hyperbolic points* (*saddle points*) during its journey backwards in time.

In short, there is an infinite information barrier which ensures the irreversibility (as well as the fine granularity) of time T for every immanent being within the universe.

This association of the *irreversibility* of time T with an *infinite information barrier* is widely recognized, but this barrier is generally erroneously regarded as being established at the more-complex *thermodynamic* level, rather than at the level of *simple dynamic systems*, such as the three-body gravitational system. In our later chapter on **Linear Thermodynamic Systems** we will see that one of the definitions of the thermodynamic concept of *entropy* is “the negative of information” (or “the loss of information”), so that references in the thermodynamic literature to an “infinite negative-entropy barrier” are really equivalent to referring to an “infinite information barrier”. Yet even Ilya Prigogine and his colleagues do not appear to recognize the existence of irreversible time T as a fundamental constitutive characteristic (“emergent property”) at the level of simple conservative dynamic systems having relatively few degrees of freedom.

Constitutive Characteristics of Conservative Systems

In summary, we have established a surprising number of important *constitutive characteristics* (a.k.a. “emergent properties”) for simple, conservative dynamical systems having as few as *three* bodies that *strongly and persistently* interact. These include: *potential energy, fields, forces, tensive distances, absolute chance*, and *irreversible time T* . All of these *constitutive characteristics* are *immanently objective* properties of simple,

ON SYSTEMS

conservative dynamic systems such as the three-body gravitational system. In addition, potential energy, fields, forces, and tensive distances (but *not* absolute chance and *not* irreversible time *T*) are also *transcendently* objective characteristics of such systems. *None* of these constitutive characteristics can be explained or derived by reductionistically “summing up” properties of the *parts* of the system. (This is not to say, of course, that *summative characteristics*, such as the total number of parts of the system, the total mass of the system, the total volume of the system, and the total kinetic energy of all of the bodies within the system are not *also* important characteristics of conservative dynamic systems as well.)

In establishing the real existence of constitutive characteristics at the level of simple dynamic systems, it is *not* my intention to imply that *all* constitutive characteristics can be “reduced” to the level of simple dynamics: On the contrary, we will see that new constitutive characteristics continually appear at higher levels of physical organization (for example, *heat*, *pressure*, and *entropy* at the level of thermodynamics). But the fact that constitutive characteristics such as potential energy and irreversible time *do* appear at the level of simple dynamic systems decisively refutes the still-commonly-held reductionistic view that constitutive characteristics are always either reducible to summative characteristics, or are “merely subjective”.

Lastly, it is important to note that *all four* types of physical systems (*deterministic*, *tychistic*, *chaotic*, and *stochastic*) can be illustrated with some kind of simple, conservative dynamic system (with the possible exception of the *stochastic* system, which may require many millions of degrees of freedom in order to approach pure randomness). Moreover, the fact of *immanently objective absolute chance* within even simple nonlinear dynamic systems means that “doing science” in the future *cannot* just involve the discovery of new scientific laws (as important as the discovery of such laws will continue to be). Rather, the *particular branchings* at the *bifurcation points* (such as the *hyperbolic points*) of particular physical systems must also be modeled. This means that, to an increasing extent in the future, the mathematical numerical simulation itself will *be* the scientific model. (And where mathematical numerical simulation cannot be applied, verbal historical description will *be* the scientific model.)

Two Unfair Criticisms of Nonlinear Science

In this context, two different types of unfair criticism are often leveled at nonlinear science:

The first type of unfair criticism complains that nonlinear science hasn’t yielded any new deterministic, immutable laws that have everywhere-precise

solutions. This type of criticism is unfair because, as far back as the work of Henri Poincare, it has been proven that, in general, physical laws having everywhere-precise, deterministic solutions *simply do not exist* with respect to the many nonlinear physical phenomena that involve strong and persistent interaction between the parts of the system. It is therefore unreasonable to demand that nonlinear scientists discover such laws.

The second type of unfair criticism of nonlinear science is that it is just “playing around with computers”, because it never yields numerical simulations which *exactly* reproduce the physical phenomenon being studied: In other words, the critic is disappointed that, for example, a numerical simulation of biological evolution doesn’t ultimately yield a high-resolution image of *homo sapiens* striding majestically across the computer screen. This type of criticism is unfair because complex nonlinear phenomena can involve branching from *multi-millions* of bifurcation points at *many* of levels of hierarchical organization, *all* of these bifurcation points being *highly sensitive to initial conditions*. Under such circumstances it is unrealistic to expect that a specific numerical simulation will *exactly* match physical reality: Instead, the best we can hope for is that these numerical simulations will give us a better understanding of that physical reality.

Teleological Implications of Nonlinear Dynamic Systems

In our earlier section concerning teleological analogs to classical mechanical systems (which was the last section in our chapter on **Classical Mechanical Systems**) we presented enough information on *nonlinear* dynamic systems to refute those classical-mechanical teleological analogs (including *social-contract theory* and *deism*): Most issues with respect to the teleological implications of nonlinear dynamic systems were therefore dealt with in that earlier section.

However, we might briefly extend our earlier observations on *free-will* vs. *determinism* (which we originally presented in the context of classical-mechanical teleology) by noting that this was also a very “hot topic” during the Reformation period that immediately preceded the Enlightenment. During the Reformation period, however, *determinism* did not so much mean “determined by universal, immutable, impersonal natural laws” as it did “determined by the omnipotent will of God”. Indeed, a case can be made that the absolute *affirmation* of divine *predestination*, coupled with an absolute *rejection* of the reality of human *free-will*, is even more-fundamental to the classical Protestantism of Luther and Calvin than the oft-cited principles of *sola scriptura* (scripture alone) and *sola fides* (faith alone). For example, in the *Catholic Encyclopedia* article on “Calvinism” we read:

ON SYSTEMS

Luther had written that man's will is enslaved either to God or to Satan, but it is never free. Melancthon declaimed against the "impious dogma of free-will", adding that since all things happen by necessity according to Divine predestination, no room was left for it. This was truly the article by which the Reformation should stand or fall. God is sole agent. . . . Luther, contending with Erasmus, declares that "God by an unchangeable, eternal, infallible will, foresees purposes and effects all things. By this thunderbolt free-will is utterly destroyed."¹⁸⁸

By contrast the Catholic Church strove to achieve a balance between divine determinism and human free-will, with the Thomist school (favored by the Dominicans) emphasizing divine determinism and the Molinist school (favored by the Jesuits) emphasizing human free-will. Pope Clement VIII convened the Dominicans and the Jesuits to the *Congregatio de Auxiliis*, which was held in Rome from 1598-1607. There the two sides argued their respective positions *for nine years*! Finally Pope Paul V (on the advice of St. Francis de Sales) decided to permit *both* schools of thought, with the Jesuits forbidden to call the Dominicans Calvinists and the Dominicans forbidden to call the Jesuits Pelagians!¹⁸⁹

Now, clearly the distinction which we have drawn between *immanent* objective truth and *transcendent* objective truth in the *physical* realm suggests a corresponding distinction in the *teleological* realm: The fact of the existence of human free-will is an *immanently* true teleological fact (analogous to the *immanent* reality of absolute, constrained chance within the physical world). By contrast, the fact of moment-to-moment divine determinism is a *transcendently* true teleological fact (analogous to the *transcendent* reality of complete determinism in the physical world). This rather-simple observation seems to me to be the key to resolving this long-standing controversy.

Linear Thermodynamic Systems

Thermodynamic systems are systems that consist of millions-upon-millions of molecules. The order of magnitude of this “millions-upon-millions” is usually given as 6.02252×10^{23} , which is *Avogadro’s number* (roughly the number of molecules in one gram of hydrogen). A *mole* of any substance is the mass of that substance (usually expressed in grams) that contains Avogadro’s number of molecules.

If we were to regard a thermodynamic system to be merely a dynamic system with multi-millions of molecular parts, we would have to represent it in a dynamic phase-space having a number of dimensions (“degrees of freedom”) that is of the order of magnitude of *six times* Avogadro’s number (since each molecule would have to be represented by a three-dimensional vector for its *momentum* \mathbf{p} and a three-dimensional vector for its *position* \mathbf{q}). This is clearly a humanly overwhelming number of dimensions.

Instead, thermodynamic systems present themselves to us macroscopically at a *higher level of organization* that exists “above” the underlying dynamic level in such a way that additional *constitutive characteristics* (i.e., “emergent properties”) appear beyond those we have previously encountered. In our previous chapter on **Nonlinear Dynamic Systems** we discovered at the dynamic level such constitutive characteristics as *potential energy, fields, forces, absolute chance, and irreversible time T*. At the higher thermodynamic-level of organization we will discover additional constitutive characteristics, including *temperature, pressure, heat, internal energy, and entropy*. These additional thermodynamic constitutive characteristics cannot be merely “reduced” to the dynamic characteristics of molecules because they involve *configurational* aspects that are unique to the macroscopic thermodynamic level.

It is also important to note that many other interesting and highly complex levels of organization can appear between the molecular level and the macroscopic thermodynamic level, including the *chemical* organization and morphology of the molecules themselves and various *biological* levels of organization, such as supra-molecular structures, organelles, cells, tissues, organs, and so on. Nevertheless, if we consider just the three organizational levels represented by independent particles, three-or-more strongly & persistently interacting particles, and (finally) macroscopic thermodynamic systems consisting of over 10^{23} particles, perhaps we can begin to form an idea of how different hierarchical levels of physical organization are related.

In this chapter we will deal specifically with *linear* thermodynamic systems. This means that the mathematics used will be of the same type as is used to describe *classical mechanical systems*. (See the earlier chapter on **Classical Mechanical Systems** for a definition and discussion of *linear* differential

ON SYSTEMS

equations.) We will postpone our treatment of *nonlinear* thermodynamic systems until the following chapter on **Nonlinear Complex Physical Systems**.

Recall that in our previous chapters on **Classical Mechanical Systems** and **Nonlinear Dynamic Systems** we dealt almost exclusively with *conservative* systems involving only *conservative* forces. Here we repeat the definition(s) of *conservative* force which we gave in **Nonlinear Dynamic Systems**:

- A force is conservative if the work done by it on a body that moves between two points depends only on the position of those two points and not on the path followed. Equivalently, we may say that a force is conservative if the work done by the force on a body that moves through any round trip is zero. Or, again equivalently, a force is conservative if the body upon which the force acts has the same amount of kinetic energy at the end of the round trip as it had at the start (assuming that no other non-conservative forces act upon the body during the round trip).¹⁹⁰

As might be imagined, the definition(s) of *non-conservative* force are the exact opposite of the definition(s) of conservative force: The amount of work done by a *non-conservative* does *not* just depend on the starting and ending points, but rather *does* depend on the path followed. The amount of work done by a *non-conservative* force during a round trip is *not* zero. And, finally, the body upon which the *non-conservative* force acts does *not* have the same kinetic energy at the end of a round trip as it did at the beginning.

Recall, however, that we *did* briefly mention two dynamic examples where a *non-conservative* force was involved: namely, the *friction* version of the “bowl game” and the *friction* version of the oscillating pendulum. Both of these examples involved the *non-conservative* force of *friction*. In these examples frictional forces eventually brought the ball to rest at the bottom of the bowl and the oscillating pendulum to rest at the bottom of its swing. We also indicated that such *non-conservative* physical systems could therefore achieve true *asymptotic stability* rather than merely *orbital stability*, while conservative physical systems could achieve (at best) *only* orbital stability.

An obvious question arises concerning the state of these non-conservative systems when the ball has finally come to rest at the bottom of the bowl and the pendulum has finally come to rest at the bottom of its swing: *Where did the energy of these systems go to?* In dynamics only two kinds of energy are recognized: kinetic energy and potential energy. Yet the ultimate state of these two non-conservative systems clearly has *neither* of these kinds of energy (at least, not at the macroscopic level). The answer is that all of the energy of these systems has gone into *heat energy*. Frictional mechanical non-

conservative systems therefore exist at the borderline between *dynamics* and *thermodynamics*, and it will therefore be very useful for us to consider another example of such a frictional mechanical system in more detail.

The Block on the Table

Imagine a children's block resting on a large, empty kitchen table that is itself at rest near the surface of the earth. Suppose that initially the surfaces of the block and the table have been lubricated, so that the forces of friction between them are negligible. Suppose furthermore that *conservative* forces push the block around on the table and finally return it to the place from which it started. Then, in that case, we know that the net amount of *work* which these conservative forces have done on the block is *zero*, no matter what path the block has taken on its *round trip*.

Now, from equations 4b ($W = \Delta K$) and 6a ($\Delta K = -\Delta U$) in our chapter on **Nonlinear Dynamic Systems** we know that:

$$\Delta U = -W \quad (1)$$

where ΔU is the *change* in the *potential energy* of a conservative dynamic system and W is the *work done by* the system. (The work done *by* the system is regarded to be *positive*, while the work done *on* the system is regarded to be *negative*.)

If, instead, a conservative dynamic system undergoes only an *infinitesimal* change in its potential energy due to an *infinitesimal* amount of work done by the system, then we can write equation 1 in *differential form* as:

$$dU = -dW \quad (2)$$

For a *round trip* in a *conservative* dynamic system, we know that the total amount of work done is *zero*. We can now express this fact by the following equation:

$$\int dU = -\int dW = 0 \quad \text{for a round trip} \quad (3)$$

Equation 3 essentially expresses the *law of conservation of mechanical energy* in a different way.

But suppose that we remove the lubrication from the surfaces of the block and the table in this example. Now when the block is pushed around on the table and finally is returned to its original position, the *non-conservative* force of *kinetic friction* has been acting in equal and opposite directions on both the block and the table all the while the block was being moved. The magnitude of this force of kinetic friction is approximately independent of the area of contact between the block and the table, as well as being approximately

ON SYSTEMS

independent of the instantaneous velocity of the block relative to the table. However, the magnitude of this kinetic-friction force is *directly proportional* to the magnitude of the *normal force* acting on the block. The magnitude of this *normal force* is, in turn, equal to the *weight* of the block. (The *normal force* is that force, ultimately arising from the microscopic elastic deformation of the surfaces of the block and table in contact, which is *equal* and *opposite* to the force of gravity pressing down on the block.) The proportionality constant involved here is called the *coefficient of kinetic friction*, and it varies depending on the particular surfaces involved. The force law for *kinetic friction* is therefore as follows:

$$F_k = u_k N \quad (4)$$

where F_k is the magnitude of the force of kinetic friction, u_k is the coefficient of kinetic friction, and N is the magnitude of the normal force.¹⁹¹

That's the situation *dynamically*. However, *thermodynamically* the key point is that the amount of work done in pushing the block around on the table and returning it to its original position is *no longer zero* when the *non-conservative* force of friction is involved. Instead, some of the system's macroscopic *mechanical energy* becomes dissipated as *heat energy*. How much mechanical energy becomes dissipated as heat energy is dependent on the path the block takes, not just on the beginning and end point of the block's motion. *Non-conservative* systems therefore *violate* the law of conservation of *mechanical energy* (equation 3, above).

Fortunately, however, the constitutive characteristic *potential energy* (which emerges at the *dynamic* level) can be modified in order to conceptualize the related-but-different constitutive characteristic *total internal energy* (which emerges at the *thermodynamic* level). *Total internal energy*, like potential energy, is symbolized by the capital letter U . Also, like potential energy, its actual value must be defined relative to an arbitrary initial value U_0 . If Q is the amount of heat that enters the system, then it turns out that empirically the following equations (which are analogous to equations 1, 2, and 3 above for conservative systems) hold true for non-conservative *thermodynamic* systems:

$$\Delta U = Q - W \quad (5a)$$

$$dU = dQ - dW \quad (5b)$$

$$\int dU = \int dQ - \int dW = 0 \quad \text{for a cyclic process} \quad (5c)$$

where U is now the *total internal energy* of the system. (A *cyclic process* in this context is one that returns the system to its initial state.) Note also that, in this formulation, Q is *positive* for heat *entering* the system, while W is

positive for work done *by* the system. On the other hand, if heat energy *leaves* the system, then Q is *negative*. And if work is done *to* the system, then W is *negative*.¹⁹² (If we were to reverse the significance of positive and negative with respect to work W , we could easily change the negative sign in equation 5c to a positive sign.)

Equation 5c above is one mathematical statement of the *First Law of Thermodynamics*, also called the general *Law of Conservation of Energy*. This law may be expressed verbally as follows:

When a system undergoes a transformation of state, the algebraic sum of the different energy changes, heat exchanged, work done, etc., is independent of the manner of transformation. It depends only on the initial and final states of the transformation.¹⁹³

In other words, energy can only be *transformed* from one kind to another: It can never be created or destroyed. In the famous formulation of Rudolf Clausius:

Die Energie der Welt ist konstant. (The energy of the universe is constant.)¹⁹⁴

The formulation of the First Law of Thermodynamics in equation 5c can be extended to include additional algebraic terms for other kinds of energy, including electrical energy, magnetic energy, and so on. Furthermore, since Einstein demonstrated the equivalence of mass and energy in his famous formula $E=mc^2$ (where E is energy, m is mass, and c is the speed of light in a vacuum), even energy changes caused by the *flow of matter* into and out of the system due to *diffusion* or *chemical reactions* can also be included in the First Law of Thermodynamics.

The First Law of Thermodynamics can also be expressed as a *negative* (i.e., as an *impossibility*) with respect to the feasibility of a *perpetual-motion machine of the first kind*. In the words of Max Planck:

It is in no way possible, either by mechanical, thermal, or chemical, or other devices, to obtain perpetual motion, i.e., it is impossible to construct an engine which will work in a cycle and produce continuous work, or kinetic energy, from nothing.¹⁹⁵

To put it another way, because $\int dU = 0$ for a cyclic process, macroscopic kinetic energy can only be produced by *transforming* some other kind of energy into kinetic energy: It cannot be created *ex nihilo*.

Because any change in the value of total internal energy U depends only on the *state* of the system at the system's specified temporal starting and end points and not on the path taken by the system, U is called a *state variable*. By contrast, because both Q and W in non-conservative thermodynamic

ON SYSTEMS

systems represent energy changes and flows that *do* depend on the path the system takes, they are called *path variables*.

We will later discuss the First Law of Thermodynamics in more detail. But for now let's return to our example of the children's block resting on the kitchen table.

Imagine that we give a brief push to the block. If both the block and the table are lubricated so that they are essentially *frictionless*, then the block will move across the table at a *constant velocity* (so that it has a *constant kinetic energy* of $\frac{1}{2}mv^2$) until it finally falls off the edge of the table.

But if, by contrast, the block and the table are *not* lubricated, then the non-conservative force of *friction* acts on both the block and the table in equal and opposite directions in accordance with Newton's third law of motion. The result is that the block *decelerates* until it comes to rest on the table (if the table surface is large enough). Once the block has come to rest on the table, all of its original macroscopic *kinetic energy* has been converted into *heat energy*, which has been absorbed by both the block and the table in varying proportions.

But what is *heat energy*, anyway? As far back as the 1600s and 1700s British scientists such as Robert Boyle and Sir Isaac Newton correctly intuited that *heat* at the macroscopic thermodynamic level is usually correlated with the *microscopic agitative motion* of a given macroscopic body's component molecules. In other words, macroscopic *heat* is usually associated with *random microscopic molecular kinetic energy*, whether that kinetic energy be translational, rotational, or vibrational. However, a strongly competing French school of thermodynamic thought (which included such luminaries as Lavoisier, Fourier, Laplace, and even, for a time, Sadi Carnot) believed that, on the contrary, heat is an indestructible fluid-like substance which they called *caloric*. Only after the experiments of Benjamin Thompson (a.k.a. Count von Rumford) and later James Prescott Joule conclusively proved that mechanical energy can be transformed into heat and vice versa was the *caloric* theory of heat abandoned in favor of the *random molecular kinetic energy* theory of heat.¹⁹⁶

In passing, we should note that there are a few exceptions to the rule that macroscopic heat is associated with random molecular kinetic energy: For one thing, as heat is added to a macroscopic body, that body experiences *phase transitions* at certain points, first from a *solid state* to a *liquid state* and later from a *liquid state* to a *gaseous state*. During such *phase transitions* heat energy goes into loosening the bonds between the body's component molecules, rather than into directly increasing the kinetic energy of those molecules. Also, in certain situations, heat energy may exist as

electromagnetic radiation in “thermal equilibrium” with matter. Such radiation is called *heat radiation* or *thermal radiation*.¹⁹⁷ But, in general, the association between macroscopic *heat* and microscopic *random molecular kinetic energy* holds true.

If, now, we think dynamically about the process whereby friction slows the block down and brings it to a stop on the table (while at the same time heating up both the block and the table), we realize that kinetic energy has been *downshifted* from the macroscopic level to the microscopic level (which is another way of saying that the macroscopic kinetic energy has been *dissipated* into heat energy). In other words, instead of the block being slowed down and stopped by (say) hitting other blocks randomly at rest on the table, the block has been gradually slowed to a stop by transferring its kinetic energy to *many millions of molecules* (of the order of magnitude of 10^{23} molecules) existing near the contacting surfaces of the block and the table.

Clearly this process of the block coming to rest on the table due to friction is an *irreversible process* (from an *immanent objective* point-of-view), due to the considerations we advanced in our previous chapter on **Nonlinear Dynamic Systems**. In that chapter, you will recall, we proved that the *immanent objectivity* of irreversible time T at the level of dynamics is due to the *infinite information barrier* which prevents finite beings such as ourselves from successfully temporally reversing even simple nonlinear dynamic systems having as few as *three* strongly and persistently interacting bodies (for example, the famous three-body gravitational system). For exactly the same reasons we advanced in **Nonlinear Dynamic Systems**, the thermodynamic process of the block being slowed to rest by friction is likewise *irreversible* from an *immanent objective* point-of-view, since there is *no way* we could measure and record the momenta and trajectories of the multi-millions of affected molecules with an infinite precision and then give them all the perfect “shove” to reverse their motions precisely.

Of course, a transcendent being who *did* have such a precise knowledge of this particular physical system out to an infinite number of decimal places, together with the power to simultaneously change the momenta and trajectories of multi-millions of molecules with similar infinite precision *could* reverse this process. In that case what might we see? We might see the block start from rest on the table and gradually accelerate, until it hit our hand with the same magnitude of force that we originally released it with (just as if we were watching a movie in reverse)!

But although this *thermodynamic* “arrow of time” is ultimately based on the more-basic *dynamic* “arrow of time” we discussed in our chapter on **Nonlinear Dynamic Systems**, an important new element is added at the

ON SYSTEMS

thermodynamic level, namely, the inevitable tendency of an isolated thermodynamic system to move towards a state in which more and more of its total kinetic energy is *downshifted* (i.e., *dissipated*) into microscopic random molecular kinetic energy. This is often described as an inevitable *increase in disorder*, or an inevitable *increase in “entropy”*, within the isolated thermodynamic system.

Of course, thermodynamic processes *do* occur in which kinetic energy is *upshifted* from the *microscopic* to the *macroscopic* level (for example, when a heated gas expands inside a cylinder, thus driving a piston, which, in turn, helps to move an automobile). But the problem is that, while it is *easy* to *downshift* 100% of a given amount of *macroscopic* mechanical kinetic energy into *microscopic* kinetic energy (as we saw in the case of the unlubricated block being slowed to a complete stop on the unlubricated table), it is *impossible* to *upshift* 100% of a given amount of *microscopic* random kinetic energy (i.e., heat) into usable *macroscopic* mechanical kinetic energy.

This impossibility is expressed in the *negative* form of the *Second Law of Thermodynamics*, which says that it is impossible to construct a *perpetual-motion machine of the second kind*:

It is impossible to construct an engine which will work in a complete cycle and convert *all* the heat it absorbs from a [heat] reservoir into mechanical work.¹⁹⁸

The *positive* form of the *Second Law of Thermodynamics* postulates the existence of a new, emergent thermodynamic property which Rudolf Clausius named *entropy* (from the Greek word for “transformation”). The exact definition of the concept of entropy is highly nontrivial and even today is controversial, but for now we can simply state that entropy is the *negative of a certain kind of information* and is associated with *an increase in a certain kind of disorder*, namely, the *downshifting* of macroscopic kinetic energy (and other types of macroscopic energy) into random molecular kinetic energy (in other words, energy *dissipation*). Using this concept of entropy, we can then *positively* express the *Second Law of Thermodynamics* as follows:

The entropy of an isolated thermodynamic system (or of *any* thermodynamic system plus its environment) always increases to a maximum over time.

Now, it is important to stress that this *entropy* feature of the *thermodynamic* “arrow of time” is newly emergent at the thermodynamic level and is *not* a feature of irreversible time *T* at the *dynamic* level. To see this, consider again *Burrau’s problem*, which we discussed in our prior chapter on **Nonlinear Dynamic Systems**. Recall that in this particular version of the gravitational three-body problem, three masses of proportions 3:4:5 start out at rest in a

two-dimensional plane at the corners of a 3:4:5 right triangle. Starting from these very orderly initial conditions, the three bodies begin to attract each other. Soon the system goes through a very chaotic phase during which the three bodies orbit each other in a way that is immanently unpredictable and extremely sensitive to initial conditions. However, ultimately, the lightest of the three bodies is thrown off and moves away at a constant velocity, while the heavier two bodies orbit one another in perfectly deterministic classical Newtonian fashion. Clearly, then, this *dynamic* system (which is characterized by *irreversible dynamic time T*) evolves from an *orderly* state to a *disorderly* state, and then back again to an *orderly* state once more. In other words, *there is no entropic arrow of time at the fundamental level of dynamics!*

This means that the thermodynamic entropic “arrow of time” does *not* have the universal applicability often claimed for it, but rather *only* applies to thermodynamic systems having multi-millions of microscopic molecular components. It is not *the* “arrow of time”, as was claimed by Sir Arthur Stanley Eddington, nor do the concepts of entropy and the Second Law of Thermodynamics necessarily apply to the *universe-as-a-whole* (“die Welt”), as was claimed by Rudolf Clausius. (In fact, at the cosmological level of physical organization a much-more-natural “arrow of time” is provided by the cosmological expansion of the universe from the initial moment of the “big bang”.)

Entropy and the Second Law of Thermodynamics also do not apply to the relationship between macroscopic physical objects in our everyday experience, unless of course microscopic random molecular kinetic energy (i.e., *heat*) is somehow involved. This point was made in an article by Frank L. Lambert appropriately titled “Shuffled Cards, Messy Desks, and Disorderly Dorm Rooms – Examples of Entropy Increase? Nonsense!”¹⁹⁹ As Lambert puts it:

There is no more widespread error in chemistry and physics texts than the identification of thermodynamic entropy increase with a change in the pattern of a group of macro objects. The classic example is that of playing cards. Shuffling a new deck is widely said to result in an increase in entropy in the cards.

This erroneous impression is often extended to all kinds of things when they are changed from humanly designated order to what is commonly considered disorder: a group of marbles to scattered marbles, racked billiard balls to a broken rack, neat groups of papers on a desk to the more usual disarray. . .

. . . Chemically unchanged macro things do not spontaneously, by some innate tendency, leap or even slowly lurch toward visible disorder.²⁰⁰

ON SYSTEMS

Nor do entropy and the Second Law of Thermodynamics apply to biological levels of physical organization that are intermediate between the molecular and thermodynamic levels. These biological levels include polymers, supra-molecular structures, organelles, cells, tissues, organs, and biological organisms as-a-whole. In fact, a contrary tendency towards *increased macroscopic order* and *increased macroscopic complexity* has often been noted in the history of the evolution of life on earth. (This contrary tendency does not, of course, actually *violate* the Second Law of Thermodynamics at the thermodynamic physical level, since the earth is not an isolated thermodynamic system, but rather a system which continuously receives significant amounts of solar energy.)

Nevertheless, while not universal, entropy and the Second Law of Thermodynamics *do* apply to a wide range of phenomena in which energy is *downshifted* from the macroscopic to the microscopic molecular level, including not only heat generation, but also such phenomena as the diffusion of matter, the dissipation of electric charge, chemical reactions, and so on.

Some “Laws of Hierarchy”

So far we have already learned quite a few things about thermodynamics, even though we have considered only the “borderline-case” of frictional dynamic systems. Before we move on to purely thermodynamic cases, perhaps we might venture to formulate a few “laws of hierarchy” based on our consideration of the following three hierarchical levels of physical organization: the level of independent dynamic particles, the level of three-or-more strongly and persistently interacting particles, and, finally, the thermodynamic level consisting of bodies (or volumes) containing around 10^{23} component molecular particles.

The first such “law of hierarchy” may be expressed as follows:

- The definition of a *summative characteristic* is “passed up” hierarchical levels of organization *essentially unchanged*. Furthermore, in many (but not all) cases the value of a summative characteristic can simply be summed up the hierarchy.

Summative characteristics (a.k.a. “additive properties”) such as *mass* and *volume* obey the above law completely: Physical hierarchies are completely *reductionistic* with respect to such properties, so that (for example) the mass of a macroscopic body considered thermodynamically may, to very close approximation, be said to be “nothing but” the sum of the masses of its component molecules. (In thermodynamics *volume* is an especially important summative characteristic.)

By contrast, although the *definition* of the summative characteristic *kinetic energy* is passed unchanged up the physical hierarchy, and kinetic energy *is* additive within a given organizational level, we cannot actually sum kinetic energy from the molecular level of organization up to the macroscopic thermodynamic level, because most molecular kinetic energy is reclassified as the macroscopic emergent property of *heat energy* at the thermodynamic level. Furthermore, *heat energy* is *not* “nothing but” microscopic kinetic energy, because it also includes the energy associated with macroscopic thermodynamic phase transitions (melting, freezing, boiling, condensation, and so on), as well as thermal radiation.

Our second proposed “law of hierarchy” is:

- A *constitutive characteristic* (a.k.a. “emergent property”) arises at a particular level of physical organization and is associated with the configurational and structural aspects of systems *at that level of organization*. Although often related to the summative (and constitutive) characteristics of the system’s lower-level components, a constitutive characteristic can never be merely “reduced” to summative characteristics. Furthermore, a constitutive characteristic may be both *immanently objective* and *transcendently objective*, or it may be *immanently objective* only.

In our chapter on **Nonlinear Dynamic Systems** we discovered at the physical hierarchical level of three-or-more strongly and persistently interacting particles the following *irreducible* constitutive characteristics: *potential energy, fields, forces, tensive distances, absolute chance*, and *irreversible time T*. Of these six constitutive characteristics, we saw that both *absolute chance* and *irreversible time T* are *immanent* objective properties of the system but not *transcendent* objective properties, while the other four characteristics are both *immanently* and *transcendently* objective.

At the thermodynamic organizational level we have so far discovered the following *irreducible* newly-emergent constitutive characteristics: *heat, total internal energy, entropy*, and *irreversible thermodynamic time*. Soon we shall be dealing with additional specifically thermodynamic constitutive characteristics, such as *pressure* and *temperature*.

Here’s a third proposed “law of hierarchy”:

- A *constitutive characteristic* that arises at a lower hierarchical level *may* be “passed up” to a higher hierarchical level, but only if it is *transformed* to allow for the (often significant) differences between the configurational/structural features of the lower level and the configurational/structural features of the higher level.

ON SYSTEMS

For example, we have just seen that the constitutive characteristic *potential energy* (which arises at the dynamic level) must be transformed into the related-but-very-different constitutive characteristic *total internal energy* at the thermodynamic level in order to allow for the significant differences in configurational/structural features between the dynamic and thermodynamic levels respectively.

We have also seen that, when the constitutive characteristic *irreversible time* T is “passed up” from the dynamic to the thermodynamic level, it becomes transformed into irreversible *thermodynamic* time and acquires the additional specifically-thermodynamic constitutive property of *inevitable progression towards maximum entropy* (for an isolated thermodynamic system, or for *any* thermodynamic system plus its environment).

Now, of course, the above three “laws of hierarchy” do not constitute a complete theory of physical hierarchy, and much concerning the relationship between hierarchical levels of physical organization is poorly understood, especially where nonlinear physical processes are involved (as is the case in biology). But for now the above three laws at least provide us with a reasonable start. Moreover, we will propose additional “laws of hierarchy” later on in this book.

The Ideal, Reversible, Cyclic Heat Engine

The next thermodynamic example we need to consider is the *ideal, reversible, cyclic heat engine*, which was first studied in detail by the brilliant French military engineer Sadi Carnot (1796-1832). In essence, at its most abstract level, a *heat engine* simply absorbs heat energy from a *hot reservoir*, transforms some of that heat energy into mechanical work (via a heated gas expanding against a piston, or by other means), and expels any unused heat energy into a *cold reservoir*. It was Carnot’s brilliant insight that the maximum amount of work that could be obtained from a heat engine depended only on the temperatures of the hot reservoir and cold reservoir respectively and not on the particulars of how the heat engine was constructed.²⁰¹

Furthermore, Carnot showed that this ideal limit of efficiency for a given temperature t_1 for the hot reservoir and a given temperature t_2 for the cold reservoir could only be approached if the heat engine operated *very slowly* with only *minimal temperature gradients* occurring between the reservoirs and the heat engine, such that almost all of the change in the temperature of the system was due to a change in volume (for example, due to expansion of a gas pushing a piston) rather than to the flow of heat. At the theoretical limit of *infinite slowness*, Carnot showed that such a heat engine was *reversible*: In

the “forward” direction, heat flowing *from* the hot reservoir *to* the cold reservoir *through* the heat engine would cause the engine to do work on the environment, while in the “reverse” direction work done *on* the heat engine *by* the environment would cause heat to flow *from* the cold reservoir *to* the hot reservoir (like a refrigerator), with no net loss of energy or efficiency in either direction. Lastly, Carnot showed how an ideal, reversible heat engine could operate in a *cycle* by returning to its *initial state* after performing a certain amount work, so that it was ready to perform work again.²⁰²

Carnot’s results lend themselves to a straightforward application of the First Law of Thermodynamics (the Law of Conservation of Energy), which we discussed in our earlier section concerning ***The Block on the Table***: If Q_1 is the quantity of heat energy that flows *from* the hot reservoir *to* the ideal, reversible heat engine during one cycle, W is the amount of work done *by* the heat engine during that cycle, and Q_2 is the quantity of unused heat energy that flows *from* the heat engine *to* the cold reservoir during that same cycle, then the following equation holds, by virtue of the First Law of Thermodynamics:

$$W = Q_1 - Q_2 \quad (6) \text{ reversible}$$

In this context it makes sense to define the *efficiency* of the reversible heat engine (which we’ll symbolize by η) to be the ratio of the work done W and the initial heat supplied Q_1 . From this definition, together with equation 6 above, we can see that:

$$\eta = W / Q_1 \quad (7a) \text{ reversible}$$

$$\eta = (Q_1 - Q_2) / Q_1 \quad (7b) \text{ reversible}$$

$$\eta = 1 - Q_2 / Q_1 \quad (7c) \text{ reversible}$$

Although all ideal, reversible heat engines are maximally efficient *for a given* Q_1 and Q_2 , formula 7c above shows that an *absolute* maximum of efficiency of 1 (i.e., 100%) could only be achieved if $Q_2 = 0$, that is, if the heat engine actually succeeded in converting *all* of Q_1 into work W during the given cycle. But, as we noted earlier, the conversion of *all* of Q_1 into W would be a violation of the *Second* Law of Thermodynamics, one formulation of which says that it is impossible to “upshift” all of the *microscopic* kinetic energy (i.e., heat energy) in a thermodynamic system up to the level of *macroscopic* kinetic energy with 100% efficiency.²⁰³

Because both Q_1 and Q_2 are functions of the *temperatures* of the hot reservoir and cold reservoir respectively (*temperature* being a macroscopic, emergent measure of the *average microscopic molecular kinetic energy* within a given body, or region of a given body), Lord Kelvin (a.k.a. William Thomson,

ON SYSTEMS

1824-1907) realized that equation 7c above could be used to define an *absolute temperature scale* that did not depend on any particular material properties of the bodies whose temperature was being measured, but rather depended solely on the theoretical properties of an ideal, reversible heat engine. On this absolute temperature scale, called the *Kelvin scale*, a cold reservoir at zero degrees Kelvin (*absolute zero*) corresponds to a theoretical, ideal, reversible heat engine having an efficiency of 1 (that is, 100%), such that $Q_2 = 0$ and $T_2 = 0$, where T_2 is the temperature of the *cold* reservoir on the Kelvin scale. If, additionally, we define T_1 to be the temperature of the *hot* reservoir on the Kelvin scale, then equation 7c can be rewritten as follows:

$$\eta = 1 - Q_2 / Q_1 = 1 - T_2 / T_1 \quad (8a) \text{ reversible}$$

from which it is evident that (because $Q_2 / Q_1 = T_2 / T_1$):

$$Q_1 / T_1 = Q_2 / T_2 \quad (8b) \text{ reversible}$$

and

$$Q_1 / T_1 - Q_2 / T_2 = 0 \quad (8c) \text{ reversible}^{204}$$

Equation 8c above suggested to Rudolf Clausius (1822-1888) the existence of a new, emergent thermodynamic *state variable* which (as we noted earlier) he called *entropy* (symbolized by S). Clausius defined an infinitesimal *change* in entropy, dS , for an ideal, reversible heat engine to be:

$$dS = dQ / T \quad (9) \text{ reversible}$$

where dS is an infinitesimal change in entropy, dQ is an infinitesimal change in heat energy, and T is the temperature in degrees Kelvin. (It is assumed that both Q and dQ are *positive* for heat energy flowing *into* the heat engine and are *negative* for heat energy flowing *out from* the heat engine.)

Now, as we mentioned in our earlier discussion of total internal energy, the change in the value of a *state variable* depends only on the *state* of the system at the beginning and end of a system process and *not* on the path the system takes to get between the beginning and end. Also, recall that the net change in a *state variable* for a *round trip* is *zero*. By considering a composite of an infinite number of ideal Carnot heat-engine cycles that differed only by an infinitesimal amount of temperature dT , Clausius was able to show that:

$$\int dS = \int (dQ / T) = 0, \text{ for a round-trip cycle} \quad (10) \text{ reversible}$$

Now, because temperature gradients are assumed to be infinitesimal in an ideal, reversible heat engine, the temperature T of the heat engine and the reservoirs remains essentially constant while heat is being exchanged between them. Therefore the change in entropy for a given reversible flow of heat Q under these conditions may also be expressed as Q / T . Furthermore, because

entropy is a state variable, we know that for a single round-trip cycle of an ideal, reversible heat engine the sum of the change in entropy associated with the flow of heat *from* the hot reservoir *to* the heat engine and the change in entropy associated with the flow of heat *from* the heat engine *to* the cold reservoir must be zero:

$$Q_1 / T_1 + Q_2 / T_2 = 0, \text{ for a round-trip cycle} \quad (11) \text{ reversible}$$

This Clausius equation is identical to Lord Kelvin's equation 8c above, except that it contains a plus sign rather than a minus sign due to the fact that Q is here regarded to be a *signed* quantity. As *signed* quantities, Q_2 is regarded to be *negative* (because it represents heat flowing *out from* the heat engine), while Q_1 remains *positive* (because it represents heat flowing *into* the heat engine).²⁰⁵

Another point concerning entropy and heat engines: Because the flow of heat with respect to both the hot and cold reservoirs is the *negative* of the flow of heat with respect to the heat engine itself, *the change in the entropy of the environment is the negative of the change in entropy of the heat-engine* (at least in the case of an *ideal, reversible* heat engine). And, since the change in the entropy for one cycle of an ideal, reversible heat engine is *zero*, it is evident that the corresponding change in the entropy of the environment (i.e., the reservoirs) is also *zero*.²⁰⁶

The Non-Ideal, Irreversible Cyclic Heat Engine

So far we have been discussing only the *ideal, reversible* cyclic heat engine. But, as we mentioned earlier, the *ideal, reversible* heat engine works *infinitely slowly*, which is another way of saying that it *doesn't work at all* in the real physical world! Rather, all real heat engines instead involve *irreversible* thermodynamic processes to one degree or another. So the question arises, how can we modify the equations in the previous section to allow for these irreversible processes?

Essentially, for real *irreversible* heat engines, the magnitude of Q_2 (the amount of heat flowing *out* to the cold reservoir) is *higher* than would be the case for an ideal, *reversible* heat engine. There are a number of reasons for this:

- The irreversible heat engine is *less efficient* than the reversible heat engine, so that *less* of its incoming heat energy Q_1 is converted into work. Therefore proportionately *more* of its incoming heat energy flows *out* to the cold reservoir unused.

ON SYSTEMS

- There are *significant temperature gradients* between the irreversible heat engine and its reservoirs, so that extra heat spontaneously and irreversibly flows from the irreversible heat engine to the cold reservoir.
- *Frictional forces* between the mechanical parts of the irreversible heat engine irreversibly generate *internal* heat. This extra internally generated heat then must be expelled *out* to the cold reservoir, again making the magnitude of Q_2 correspondingly higher than would be the case for an ideal, reversible heat engine.

(It is important to remember, of course, that this *irreversibility* aspect of the physically real, irreversible heat engine emerges as an *immanent* objective property of the system, but is not a *transcendent* objective property of that system.)

In any event, let's begin by modifying equations 8a, 8b, and 8c above to apply to the real, *irreversible* heat engine, rather than to the ideal, reversible heat engine. We can easily do this by simply remembering that the magnitude of Q_2 is *higher* in the *irreversible* case than in the reversible case:

$$\eta = 1 - Q_2 / Q_1 < 1 - T_2 / T_1 \quad (12a) \text{ irreversible}$$

$$Q_1 / T_1 < Q_2 / T_2 \quad (12b) \text{ irreversible}$$

$$Q_1 / T_1 - Q_2 / T_2 < 0 \quad (12c) \text{ irreversible}$$

Now, from equation 11 above we know that if Q is regarded to be a *signed* quantity, so that Q_1 is *positive* and Q_2 is *negative*, then we can rewrite inequality 12c as:

$$Q_1 / T_1 + Q_2 / T_2 < 0, \text{ for a round-trip cycle} \quad (13) \text{ irreversible}$$

from which we may conclude that:

$$\int (dQ / T) < 0, \text{ for a round-trip cycle} \quad (14) \text{ irreversible}$$

This puts us at a “moment of decision” with respect to our earlier definition of the change in entropy: Either we continue to define the change in entropy as $dS = dQ / T$ (in which case entropy is no longer a state variable, since a round trip no longer sums the entropy changes to zero), or we continue to regard entropy as a state variable (in which case the entropy change has an undefined component and $dS > dQ / T$). Clausius made the latter choice, calling the undefined component the “uncompensated transformation” (*uncompensirte Verwandlung*). Therefore the following formulas hold for an *irreversible* heat engine:

$$dS > dQ / T \quad (15a) \text{ irreversible}$$

$$d_e S = dQ / T \quad (15b) \text{ irreversible}$$

$$dS = d_e S + d_i S \quad (15c) \text{ irreversible}$$

where $d_e S$ is the change in entropy of the system due to the *exchange* of heat between the system and its environment (i.e., the exchanges of heat between the heat engine and its reservoirs), and $d_i S$ is the change in entropy of the system due to *internal* irreversible processes within the system (such as the internal generation of frictional heat). From these formulas it is clear that $d_i S$ is Clausius's "uncompensated transformation". Later on we will extend $d_e S$ to include exchanges of other forms of energy (and even of matter) between the thermodynamic system and its environment.

It also turns out to be the case that, while $d_e S$ may be either *positive* or *negative* or *zero*, $d_i S$ can *only* be *positive* for any irreversible thermodynamic system in the real world that is not at equilibrium, whether that system be *isolated* (has no exchanges of energy or matter with its environment), *closed* (exchanges only energy with its environment), or *open* (exchanges both energy *and* matter with its environment). And this is true not only for every real thermodynamic system, but also for *every subsystem* of every real thermodynamic system. This always-positive value of $d_i S$ under all of these conditions constitutes the strongest and most-general statement of the Second Law of Thermodynamics.

Now, because we wish to continue to regard entropy to be a *state variable* for at least certain types of *irreversible* thermodynamic systems, the following holds true *for the system* where $\int d_e S < 0$:

$$\int dS = \int d_e S + \int d_i S = 0 \text{ for a round-trip cycle}$$

in the case where

$$\int d_e S = \int (dQ / T) < 0$$

(16) irreversible

However, we must also consider the entropy change *for the environment*. Because the flow of heat with respect to both the hot and cold reservoirs is the *negative* of the flow of heat with respect to the heat engine itself (as we noted earlier), we may rewrite formulas 13 and 14 *for the environment* as follows:

$$(-Q_1) / T_1 + (-Q_2) / T_2 > 0, \text{ round-trip, environment} \quad (17) \text{ irreversible}$$

therefore

$$\int (dQ / T) > 0, \text{ round-trip, environment} \quad (18) \text{ irreversible}$$

ON SYSTEMS

And while the *system* returns to its original thermodynamic state upon the completion of its round-trip cycle (so that $\int dS = 0$ for the *system*), the *environment* does *not* return to its original thermodynamic state, since the environment has been the net recipient of dissipated (“downshifted”) energy, in this case excess heat. Therefore formula 18 above suggests that $\int dS > 0$ for the *environment*, which makes the sum total of *all* entropy changes resulting from a cyclical, irreversible thermodynamic process always *greater than zero*, in spite of the fact that entropy may be a state variable *with respect to the system itself*.²⁰⁷ This, of course, leads us back to the positive formulation of the Second Law of Thermodynamics, which we stated earlier in connection with our section about ***The Block on the Table***:

The entropy of an isolated thermodynamic system (or of *any* thermodynamic system plus its environment) always increases to a maximum over time.

Of course, for all real, irreversible thermodynamic systems, $\int dS$ can be equal to zero for the system’s “round trip” only if $\int d_e S$ is *less than zero*, since $\int d_i S$ is *always greater than zero* for such systems. In particular, in the case of an *isolated* thermodynamic system which has *no* exchanges of energy or matter with its environment, so that $d_e S$ is zero, we have:

$$\int d_e S = 0, \int d_i S > 0, \int dS > 0, \text{ round-trip (19) isolated irreversible}$$

Clearly, then, in the case of an *isolated* irreversible thermodynamic system (as well as in cases where $\int d_e S > 0$), entropy is *not* a state variable.

As is the case with energy, we are usually interested in *changes* in entropy (dS) rather than in the actual value of S itself. However, S can be given a definite, objective value by means of the *Nernst heat theorem* (often called the *Third Law of Thermodynamics*), which states that *the entropy of any chemically homogeneous solid or liquid body approaches zero as its temperature approaches absolute zero degrees Kelvin*.²⁰⁸

$$S \rightarrow 0 \text{ as } T \rightarrow 0^\circ\text{K} \quad (20)$$

This makes sense in terms of our discussion in the section concerning ***The Block on the Table***, because there we associated the concept of *entropy* with the idea of the *dissipation* and *downshifting* of macroscopic energy to the level of molecular kinetic energy: Therefore, where such molecular kinetic energy vanishes and becomes zero, as it essentially does at absolute zero degrees Kelvin, we would expect entropy to vanish and become zero as well.

Thermodynamic Forces and Flows

Rudolf Clausius did not provide a way to directly calculate the always-positive internally generated “uncompensated transformation” $d_i S$. Consequently, in most treatments of classical thermodynamics, the entropy associated with an *irreversible* thermodynamic system can only be calculated by finding a corresponding infinitely-slow *reversible* thermodynamic system for which the net entropy change *can* be calculated.

It is the great merit of the modern *Brussels (Belgium) school* of thermodynamics, beginning with Theophile De Donder (1872-1957) and continuing with Ilya Prigogine and his followers, to have discovered how to calculate $d_i S$ directly. Essentially what they discovered is that $d_i S$ can be expressed as the sum of the products of *thermodynamic forces* and *thermodynamic flows*, so that:

$$d_i S = \sum F_k dX_k \geq 0 \quad \text{where } k = 1 \text{ to } n \quad (21)$$

Here F_k is one of a number of *thermodynamic forces* and dX_k is the corresponding resulting *thermodynamic flow* caused by that particular thermodynamic force. Equation 21 can also be rewritten to capture the rate of change (i.e. derivative) of $d_i S$ with respect to time:

$$d_i S/dt = \sum F_k (dX_k/dt) \geq 0 \quad \text{where } k = 1 \text{ to } n \quad (22a)$$

Now, if $J_k = dX_k/dt$ is defined to be a *thermodynamic flow per unit time* (that is, a *thermodynamic current*) and $P = d_i S/dt$ is defined to be the *rate at which internal entropy is produced per unit time*, then we may rewrite equation 22a as:

$$P = \sum F_k J_k \geq 0 \quad \text{where } k = 1 \text{ to } n \quad (22b)$$

To take an example, consider the case of an isolated thermodynamic system consisting of two blocks of iron, one *cold* and one *hot*, which are set right next to one another so that their faces are in firm contact. We know from experience and experiment that heat will spontaneously and irreversibly flow from the hot block of iron to the cold block of iron until both blocks are the same temperature. At that point this isolated thermodynamic system will be in *thermodynamic equilibrium* with respect to heat, and no further flow of heat will occur within the system.

In the above example the *thermodynamic force* F is the *temperature gradient*, which may be expressed by the following empirically derived formula:

$$F_{TG} = (1/T_{\text{cold}} - 1/T_{\text{hot}}) \quad (23)$$

where F_{TG} is the temperature gradient, T_{cold} is the temperature of the cold block of iron, and T_{hot} is the temperature of the hot block of iron.

ON SYSTEMS

The internal *thermodynamic flow* dX is the internal flow of heat dQ between the two iron blocks. The *heat current* $J_Q = dQ/dt$ is defined by Fourier's famous empirical law of *heat conduction*:

$$J_Q = \alpha (T_{\text{hot}} - T_{\text{cold}}) \quad (24)$$

where α is a positive *coefficient of heat conductivity* that varies depending on the material make-up of the two bodies involved.

Combining formulas 22b, 23, and 24 above, we may write:

$$P = F_{\text{TG}} J_Q = (1/T_{\text{cold}} - 1/T_{\text{hot}}) \alpha (T_{\text{hot}} - T_{\text{cold}}) \geq 0 \quad (25a)$$

$$P = \alpha (T_{\text{hot}} - T_{\text{cold}})^2 / (T_{\text{hot}} T_{\text{cold}}) \geq 0 \quad (25b)$$

From formula 25b it is clear that, because α , T_{hot} , and T_{cold} are all positive numbers, the value of P (i.e., the rate of internal entropy production) is *greater than zero* so long as T_{hot} is not equal to T_{cold} . However, as the difference between T_{hot} and T_{cold} approaches zero, P also approaches zero.

From formula 25b it is also evident that the rate of internal entropy production P is a quadratic function of the difference in temperature between the hot and cold blocks, $\Delta = (T_{\text{hot}} - T_{\text{cold}})$. Figure 23 shows two graphs of this situation:

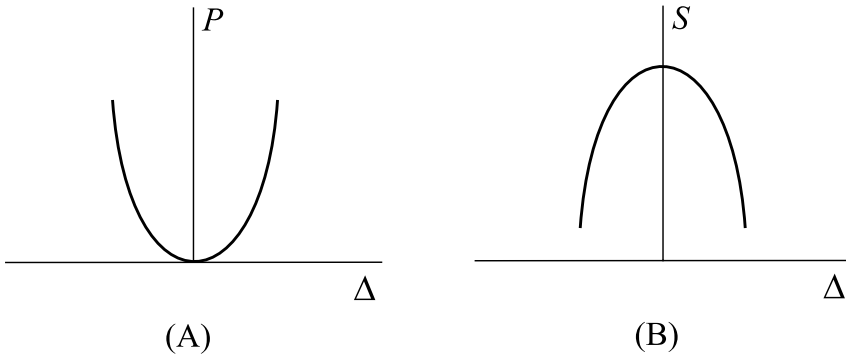


Figure 23 (after figure 3.10 on page 94 of Kondepudi and Prigogine)

In the first graph (A) the rate of internal entropy production P is shown as a function of Δ , while in the second graph (B) the total system entropy S is shown as a function of Δ . (In these graphs Δ is *negative* if the roles of the blocks are reversed, such that the hot block is the cold block and the cold block is the hot block. Also, because this two-iron-blocks system is assumed to be *isolated*, it follows that $d_e S = 0$, so that only $d_i S \geq 0$ contributes to the total system entropy S .)

From the graphs in Figure 23 it is clear that the total entropy S of an isolated thermodynamic system is at its *maximum* when the rate of entropy production P has slowed to *zero*. Furthermore, when S is at its maximum and P is at zero, then the isolated thermodynamic system is at *thermodynamic equilibrium* and no further thermodynamic changes can occur. We can see this because both figure 23 and formula 25b show that $P = 0$ if and only if $\Delta = (T_{\text{hot}} - T_{\text{cold}}) = 0$. But in that case both the temperature gradient F_{TG} and the heat current J_Q are *also* equal to zero by formulas 23 and 24, so that no further internal heat transfers can take place.²⁰⁹

At thermodynamic equilibrium the isolated thermodynamic system has ultimately suffered what is sometimes called a *heat death*, in accordance with the Second Law of Thermodynamics. It is also notable that this thermodynamic equilibrium of an isolated thermodynamic system is truly *asymptotically stable*, unlike the conservative dynamic systems that we primarily studied in our previous chapter on **Nonlinear Dynamic Systems**: (These conservative dynamic systems could only attain *orbital stability*, involving a continually active “swinging” about a mean.)

Finally, note that the isolated thermodynamic system is characterized by *unconditional equifinality*: No matter where the system starts out, it ultimately ends in a completely stable thermodynamic equilibrium. This thermodynamic equilibrium is therefore a *global attractor* for the isolated thermodynamic system. (We have seen this phenomenon of *unconditional equifinality* not only in this case of the two iron blocks, but also in the case of the friction versions of both the bowl game and the oscillating pendulum in our previous chapter on **Nonlinear Dynamic Systems**.)

So far we have considered only the thermodynamic force *temperature gradient* and its associated thermodynamic flow *heat current*. But, as formulas 21, 22a, and 22b above indicate, other thermodynamic force/flow pairs can also be important in evaluating both the internally produced change in entropy $d_i S \geq 0$ and the rate of internal entropy production $P \geq 0$ within a given thermodynamic physical system. These force/flow pairs include: *diffusion gradient* and *diffusion current* (i.e., *mass flux*), *electromotive force* and *ion current*, *hydrodynamic force* and *viscous flow*, and (finally) *chemical affinity* and the *velocity of chemical reaction*.²¹⁰

But how exactly do these *thermodynamic* forces differ from the *conservative dynamic* forces we examined in our earlier chapters?

As we saw in our chapter on **Nonlinear Dynamic Systems**, a *conservative dynamic* force gives a solid body *kinetic energy* by doing *work* on that body in accordance with the formula $W = \int F(q) dq$, where W , the *work*, is equal to the *kinetic energy* imparted to the body, $F(q)$ is the magnitude of the

ON SYSTEMS

conservative *force* as a function of position q , and dq is an infinitesimal change in position. This *conservative dynamic* formula is strongly reminiscent of the *thermodynamic* formula 21 above ($d_i S = \sum F_k dX_k \geq 0$), yet the *conservative dynamic* formula relates to *work* and *energy*, while the *thermodynamic* formula relates to *entropy*. Why is this?

The answer is that *thermodynamic* forces do not simply impart kinetic energy to a solid body. Instead, they result in *thermodynamic flows*. A *thermodynamic flow* is a thermodynamic process during which *macroscopic* energy or structure is irreversibly “downshifted” (i.e., *dissipated*) to the *microscopic* level: That is why the *larger* the magnitudes of the thermodynamic forces and flows within a given system, the *larger* is the increase in internal entropy $d_i S$ within that same system. (The *irreversibility* of this “downshifting”, or dissipation, is, of course, an *immanent objective* fact, but not a *transcendent objective* fact.)

Often a *thermodynamic flow* is a *vector* or *tensor* quantity and therefore has a spatially directional character, but sometimes it is a *scalar* quantity and therefore is *not* spatially directional (for example, the somewhat-misnamed *velocity of chemical reaction*).

Thermodynamic forces, like *conservative dynamic forces*, are *constitutive characteristics* (i.e., “emergent properties”) of physical systems taken as a whole. Both types of forces are intimately related to the *configurational* aspects of the entire physical system. The major difference between them is that *conservative dynamic forces* and potentials arise holistically at the physical level of *several* strongly and persistently interacting bodies, while *thermodynamic forces* and potentials arise holistically at the physical level of *millions-upon-millions* of strongly and persistently interacting particles (i.e., molecules).

It might here be objected that, while the molecules in solids and liquids may be said to interact “strongly and persistently”, the same cannot be said of the molecules which comprise *gases*. In fact, the random, colliding trajectories of molecules in a gas would seem to be an almost-perfect realization of a classical, linear, Newtonian “free-particle” system that has only *summative characteristics* (i.e., “additive properties”).

But while this is largely true at the *microscopic dynamic level*, at the *macroscopic thermodynamic level* holistic thermodynamic forces and potentials still manage to arise because of macroscopic structural considerations: For example, at the *microscopic* level millions-upon-millions of molecular collisions and rebounds are occurring every moment within a given volume of a gas. The forces involved in these collisions are immense, but their *duration* is extremely brief. These forces are therefore *not* “strong

and persistent” at the microscopic dynamical level, so the classical Newtonian “free-particle” model can still be validly applied to the system at that level. However, at the *macroscopic thermodynamic* level of physical organization these same forces of molecular collision add up and average out in such a way as to create the emergent thermodynamic force of *gas pressure* with respect to the gas’s containing walls. This gas pressure *does* represent a “strong and persistent” interaction *at the macroscopic thermodynamic level* between the gas and its containing walls.

In fact, if one side of the gas’s container is replaced by a piston, it turns out that the irreversible increase in internal system entropy as the expanding gas drives the piston can be written as:

$$d_i S = (p_{\text{gas}} - p_{\text{piston}}) / T \, dV \geq 0 \quad (26a)$$

$$P = d_i S / dt = (p_{\text{gas}} - p_{\text{piston}}) / T \, dV/dt \geq 0 \quad (26b)$$

where $d_i S$ is the internally generated change in system entropy, P is the rate of internal entropy production, p_{gas} is the pressure of the gas on the piston from *inside* the container, p_{piston} is the pressure acting on the piston from *outside* the container, T is the temperature in degrees Kelvin, dt is the time differential, and dV is the change in the volume of the container resulting from the expansion of the gas against the piston.

In this case the “thermodynamic force” is $(p_{\text{gas}} - p_{\text{piston}}) / T$ and the “thermodynamic flow” is dV/dt . Because $(p_{\text{gas}} - p_{\text{piston}})$ and dV always have the same sign (and T is always positive), both $d_i S$ and P are also always positive, except at *thermodynamic equilibrium*, where $(p_{\text{gas}} - p_{\text{piston}}) / T$, dV , $d_i S$, and P are all equal to zero and S is therefore at a *maximum*.²¹¹

The fact that the irreversible internally caused increase in entropy $d_i S$ for a thermodynamic system is always associated with the *dissipation* (“downshifting”) of energy or structure from the macroscopic thermodynamic level to the microscopic level is dramatically illustrated by the *Gibbs paradox*. Imagine a container containing two different gases which are separated by a removable divider into the left and right halves of the container, respectively. To make the situation clearer, imagine that the gas in the left half of the container is red in color, while the gas in the right half of the container is completely clear and transparent. When the removable barrier is taken away, the two gases irreversibly diffuse into one another until they thoroughly combine into a pink mixture, at which point the system is in thermodynamic equilibrium with respect to both diffusion gradients and diffusion currents (i.e., mass flux). Josiah Gibbs was able to demonstrate that, so long as there is at least *some* slight difference between the two gases, the entropy of the system *increases* to a maximum as a result of this diffusion

ON SYSTEMS

process. (The *degree* of difference between the gases is immaterial, so long as there is at least *some* small difference.) However, if the gases that start in the left and right halves of the container are *exactly the same*, then *no* increase in entropy results when the removable barrier is taken away and the gas molecules intermix, *even though the microscopic molecular mixing process is exactly the same in both cases*. (This is the *Gibbs paradox*.)²¹²

The *Gibbs paradox* becomes understandable once we realize that the difference between the two gases, however slight, creates a *macroscopic structure* which becomes *dissipated* (“downshifted”) as the thermodynamic process proceeds. Therefore entropy increases. On the other hand, if the gases are the *same*, then no such macroscopic structure exists just after the removable barrier is taken away, so there is no macroscopic structure to dissipate. Therefore entropy remains the same.

Another way of thinking about this would be to say that, as the two different gases begin to diffuse into one another, they each have a *macroscopic kinetic energy* with respect to each other taken as macroscopic wholes. As the intermixing process proceeds, however, this macroscopic kinetic energy becomes *dissipated* (“downshifted”) into random molecular kinetic energy until, finally, neither macroscopic kinetic energy nor macroscopic structure remain between the two gases. (Of course, the actual *magnitude* of this macroscopic kinetic energy of the gases taken-as-wholes is at all times *trivial* when compared to the magnitude of the microscopic molecular kinetic energy *within* the gases, so no measurable increase in heat energy results from this particular “downshifting” of macroscopic kinetic energy.)

Sometimes it is maintained that thermodynamic systems can be successfully dealt with in an *entirely reductionistic* manner by referring *only* to the summative properties of their component molecules. It is especially tempting to think this way when considering the thermodynamic properties of gases. But, as we saw above, even *gas pressure* is a constitutive characteristic (emergent property) at the macroscopic thermodynamic level. And when massive amounts of gases are involved (as, for example, in the atmosphere of the earth), both pressure gradients and temperature gradients (reflected in weather diagrams showing *isobars* and *isotherms*) assume complicated structures and forms that clearly involve macroscopic, holistic configurational aspects.

Boltzmann’s Formula

Of course, in the “simple” case of an “ideal” gas (which involves only random translational motions of its component molecules), *it is possible to*

give a *statistical* account of entropy at the microscopic level by using Ludwig Boltzmann's famous formula

$$S = k_B \ln W \quad (27)$$

where S is the total entropy, W is the number of possible microstates corresponding to the macrostate whose entropy is S , k_B is the Boltzmann constant, and “ln” is the natural log function: The *macroscopic* fact that one kind of gas is in the left half of a container, while another kind of gas is in the right half of a container, then corresponds to the *microscopic* fact of *statistical correlations* between the multi-millions of molecules comprising the two gases. These statistical correlations, in turn, affect the way in which W is counted. Furthermore, the Second Law of Thermodynamics may then be expressed at the microscopic level by saying that S increases irreversibly over time because W increases irreversibly over time. And W , in turn, increases irreversibly over time because *a higher W is always more probable than a lower W* (according to Boltzmann).

For example, if there are N_L gas molecules in the left half of a container and a different number N_R of gas molecules *of the same type* in the right half of a container, then W is given by the formula:

$$W = (N_L + N_R)! / (N_L! N_R!) \quad (28)$$

where ! is the factorial operator. ($N! = 1 \text{ times } 2 \text{ times } 3 \dots \text{ times } N$.) It can then be shown that, for formula 28, W is at a *maximum* when $N_L = N_R$. And since (according to Boltzmann's formula), when W is at a maximum, S is also at a maximum, we may therefore conclude that this isolated thermodynamic system has attained thermodynamic equilibrium when N_L equals N_R .²¹³

However, Boltzmann's thesis that a higher W always becomes more probable over time than a lower W merely because a higher W represents a higher number of *possible* microstates is an assumption that is open to serious question. Early on, for example, Boltzmann's teacher, Josef Loschmidt, presented Boltzmann with the “thought experiment” of an *instantaneous inversion of the velocity* of all of the molecules in a gas, performed by Maxwell's transcendent, fictional demon. In that case (as Boltzmann had to admit), entropy might very well *decrease* as the system returned to its original “less probable” state, in contradiction to Boltzmann's thesis.²¹⁴

In fact, it needs to be admitted that *all* attempts to “reduce” the irreversible temporal increase in thermodynamic entropy to “nothing but” particle dynamics (including even the attempts of Ilya Prigogine and his colleagues) have ultimately been failures. In our chapter on **Quantum Mechanical Systems** we quoted what Griffiths and Omnes wrote in their August 1999 article in *Physics Today*, and it is worth repeating that quotation here:

ON SYSTEMS

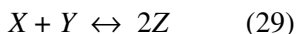
[T]he problem of showing that a system of [multi-millions of] classical particles will exhibit thermodynamic irreversibility, a typical macroscopic phenomenon, has not yet been settled to everyone's satisfaction, despite a continuing effort that goes back to Ludwig Boltzmann's work a century ago.²¹⁵

One key here is recognizing that *some* aspects of entropy (such as the “downshifting” aspect) are both immanently *and* transcendently objective, whereas *other* aspects of entropy (such as the “irreversibility” aspect) are immanently objective *only*.

Chemical Thermodynamics

Another great scientific contribution of Theophile De Donder, the founder of the Belgian school of thermodynamics, was the discovery of chemical *affinity* as the thermodynamic force that is responsible for driving chemical reactions (as well as many other phenomena) towards thermodynamic equilibrium. For De Donder, the idea of chemical *affinity* rested on the idea of a *chemical potential* and was related also to a corresponding thermodynamic flow which he called the *velocity of reaction*.

For example, consider a chemical system having the form:



Here one molecule of *X* combines with one molecule of *Y* to form two molecules of *Z*. Simultaneously the reverse reaction is also occurring (i.e., two molecules of *Z* decomposing into one molecule of *X* and one molecule of *Y*). If the rate of the *reverse* reaction is greater, then formula 29 proceeds irreversibly from *right* to *left*. If, on the contrary, the rate of the *forward* reaction is greater, then formula 29 instead proceeds irreversibly from *left* to *right*. Finally, if the rates of the forward and the reverse reactions become balanced and equal, then this chemical system has attained thermodynamic (and chemical) equilibrium, and internal system entropy is therefore at a maximum with respect to this chemical system (other things being equal).

Let N_x be the number of moles of chemical *X*, let N_y be the number of moles of chemical *Y*, and let N_z be the number of moles of chemical *Z*. Then dN_x is the *change* in the number of moles of chemical *X*, dN_y is the *change* in the number of moles of chemical *Y*, and dN_z is the *change* in the number of moles of chemical *Z*. Furthermore, each of these changes in the number of moles of the particular chemical is associated with a *chemical potential* (μ_x , μ_y , and μ_z , respectively). (Often the chemical potential of a chemical is directly proportional to the *concentration* of that chemical, but this is not always the case.)

In any event, De Donder proved that, in general, the following relation holds:

$$d_i S = -1/T \sum \mu_k dN_k \geq 0 \quad \text{for } k = 1 \text{ to } n \quad (30)$$

where $d_i S$ is the change in the internal entropy of the system, T is the temperature of the system, μ_k is the chemical potential of the various chemicals involved in the reaction ($k = 1$ to n), and dN_k is the change in the number of moles of the various chemicals involved in the reaction ($k = 1$ to n).

Furthermore, for the particular chemical reaction system shown in formula 29 above, the rates of change dN_x , dN_y , and dN_z are given by the following stoichiometric formula:

$$dN_x / (-1) = dN_y / (-1) = dN_z / 2 = d\xi \quad (31)$$

where $d\xi$ is the change in variable ξ , which De Donder called the *extent of reaction* (or the *degree of advancement* of the reaction) from left to right. The basic idea behind formula 31 is that the changes in the mole numbers of X , Y , and Z in the reaction system shown in formula 29 above are intimately related because in the forward reaction (for example) *one* molecule of X is lost and *one* molecule of Y is lost for every *two* molecules of Z that are gained. This means that (for the particular reaction system shown in formula 29) all three changes in mole numbers can be expressed in terms of the change in the *extent of reaction* as follows:

$$dN_x = -d\xi \quad (32a)$$

$$dN_y = -d\xi \quad (32b)$$

$$dN_z = 2d\xi \quad (32c)$$

Now, by substituting 32a, 32b, and 32c into formula 30 above, De Donder arrived at the following formula for a reaction such as that shown in formula 29:

$$d_i S = [(\mu_x + \mu_y - 2\mu_z) / T] d\xi \geq 0 \quad (33)$$

This, in turn, suggested to De Donder, that an overall thermodynamic force for the whole reaction could be defined by using the chemical potentials of the component chemicals. This thermodynamic force he called *affinity*, and he defined it as follows (for a chemical reaction system such as formula 29):

$$A \equiv (\mu_x + \mu_y - 2\mu_z) \quad (34)$$

Substituting this definition for affinity into formula 33, we obtain:

$$d_i S = (A / T) d\xi \geq 0 \quad (35)$$

ON SYSTEMS

Clearly the definition of affinity in formula 34 (which applies only to chemical reaction systems of the type shown in formula 29) can be extended to *any* chemical reaction system by means of a suitable formalism, thus making formula 35 perfectly general. Furthermore, if we differentiate formula 35 by time, we obtain:

$$d_1 S / dt = (A / T) d \xi / dt \geq 0 \quad (36a)$$

$$P = (A / T) v \geq 0 \quad (36b)$$

where $P = d_1 S / dt$ is the rate of internal entropy production due to the chemical reaction and $v = d \xi / dt$ is the rate of change in the extent of reaction, which De Donder named the *velocity of reaction*.

Comparing formulas 22a and 22b above with formulas 36a and 36b, it is easy to see that affinity divided by temperature (A / T) is the *thermodynamic force* driving the chemical reaction, while the velocity of reaction v is the *thermodynamic flow* (or *thermodynamic current*) which results from this thermodynamic force. As is the case with all thermodynamic forces and flows, both the affinity and the velocity of reaction become zero at thermodynamic (and chemical) equilibrium, which is also the point at which internal entropy is at a maximum (other things being equal).

A few other important facts about chemical affinity, as defined above: If the affinity is *greater* than zero, then the chemical reaction proceeds from left to right (i.e., in the *forward* direction). But if the affinity is *less* than zero, then the chemical reaction proceeds from right to left (i.e., in the *reverse* direction). Finally (as we just noted) if the affinity is *equal to* zero, then the chemical reaction is in an equilibrium state (that is, the reverse reaction exactly cancels out the forward reaction).

Another interesting “affinity fact”: If a complex chemical reaction can be decomposed into two or more *component* chemical reactions, then *the affinity of the net reaction is equal to the sum of the affinities of the component individual reactions*.²¹⁶

Theophile De Donder soon realized that formula 36b above could be easily extended to cover the case where several simultaneous (but quite separate) chemical reactions are occurring within the same closed system: In that case the rate of internal entropy production P would simply be the sum of the rate of production of entropy for the individual reactions taken separately, as follows:

$$P = \sum (A_k / T) v_k \geq 0 \quad \text{for } k = 1 \text{ to } n \quad (37)$$

where A_k and v_k are the affinities and velocities-of-reaction for the separate, simultaneous chemical reactions taken separately and T is (of course) the

temperature. (Note, however, that A_k and v_k are not truly summative properties because the simultaneous chemical reactions can strongly and persistently interact with one another, thus affecting the A_k and v_k values holistically.)

In the above case, it is also important to note that the *individual* simultaneous reactions *taken separately* do not have to have a positive-or-zero internal rate of entropy production P : Rather, all that is required is that the *total* internal entropy production for *all* of the reactions *taken together* are positive or zero. Such so-called *coupled affinities* are common in biological systems and are one of the ways in which a biological system can seem to defy the Second Law of Thermodynamics, by allowing *some* of its simultaneous biochemical reactions to proceed with a *negative* rate of internal entropy production, thus preserving and even *increasing* the level of macroscopic biological organization within the system.²¹⁷

Diffusion Thermodynamics

Chemical potentials and chemical affinities apply to far more than just chemical reactions in the strict sense. As Konopudi and Prigogine have written:

Other than heat conduction, *every* irreversible process – chemical reactions, diffusion, the influence of electric, magnetic, and gravitational fields, ionic conduction, dielectric relaxation, etc. – can be described in terms of suitable chemical potentials.²¹⁸

To take just one example of this, we will return again to our simple case of the diffusion of a gas of constant composition, but uneven concentration, from (say) the left half of a container to the right half of the same container until the concentration of the gas is the same throughout. Let N_L again be the number of moles of the gas in the left half of the container, while N_R is the number of moles of the gas in the right half of the container. Suppose further that $N_L > N_R$, so that the concentration of gas is higher in the left half of the container than in the right half. Naturally, the gas will diffuse from the left half of the container to the right half until thermodynamic equilibrium is achieved. How might we express this in terms of chemical potentials, affinity, and the extent of reaction?

To begin with, we can express this particular “chemical reaction” as follows:



meaning that moles of the gas can flow either to the left or to the right, depending on which side of the container has the higher concentration of gas. Next, we express the change in the “extent of reaction”:

$$-dN_L = dN_R = d\xi \quad (39)$$

meaning that the loss of a molecule (or mole) of the gas from the left half of the container is exactly matched by the gain of a molecule (or mole) of the gas in the right half of the container. It is also clear from our earlier discussion that affinity (in this case) can be defined as follows:

$$A \equiv (\mu_L - \mu_R) \quad (40)$$

In formula 40 the variable μ_L is the “chemical potential” associated with the *higher* concentration of the molecules in the *left* half of the container, while μ_R is the “chemical potential” associated with the *lower* concentration of the molecules in the *right* half of the container. Since, in the situation as described, the “reaction” proceeds from left to right (i.e., “forward”) as molecules of the gas diffuse from the left half of the container to the right half, it is to be expected that the affinity A will continue to be *positive* (since $\mu_L > \mu_R$) until thermodynamic equilibrium is achieved, at which point $\mu_L = \mu_R$ and $A = 0$.

The change in internal entropy for this simple diffusion example would be given by:

$$d_i S = [(\mu_L - \mu_R) / T] d\xi = (A / T) d\xi \geq 0 \quad (41)$$

while the corresponding rate of internal entropy production P would be given by:

$$P = [(\mu_L - \mu_R) / T] v = (A / T) v \geq 0 \quad (42)$$

Of course, if we started out with a higher concentration of molecules on the *right* side of the container rather than the *left*, then the gas would diffuse to the *left* rather than the *right* (i.e., the “reaction” would proceed in reverse). In that case the affinity would be *negative* rather than positive. But then the velocity of reaction v would *also* be negative, so that P would remain positive until equilibrium was reached, at which time P would become zero. (We should note, however, that the concept of *affinity*, being a scalar, cannot entirely replace the concept of a *concentration gradient*, which is a vector.)

Notice also that in all of the affinity examples we have so far presented, the change in mole quantity (for example, dN) is really the *internal* change in that mole quantity. In addition, there could be a change in mole quantity due to an exchange with the environment, which is *outside* the system. Such an exchange could, of course, result in a corresponding change in entropy that could be *negative* as well as positive and that could, in fact, completely offset the always-positive increase in the internal entropy of the system. (This is the case, for example, with all viable biological systems.)

Additionally, it is important to point out that even though, in the examples we have considered, the *chemical potential* of a particular chemical is closely identified with the *concentration* of that chemical per unit volume, this is not always necessarily the case. As Kondepudi and Prigogine have noted in connection with the phenomenon of diffusion:

The positivity of [entropy production], required by the Second Law, implies that particle transport is from a region of higher chemical potential to a region of lower chemical potential. . . In many situations this is a flow of a component from a higher concentration to a lower concentration. At equilibrium the concentrations become uniform. But this need not be so in every case. For example, when a liquid is in equilibrium with its vapor or when a gas reaches equilibrium in a gravitational field, the chemical potentials become uniform, not the concentrations. *The tendency of the thermodynamic forces that drive matter flow is to equalize the chemical potentials, not [necessarily] the concentrations.* [italics in original]²¹⁹

Linear Thermodynamic Forces and Flows

Recall now formula 22b above, which we reproduce for convenience below as formula 43:

$$P = \sum F_k J_k \geq 0 \quad \text{where } k = 1 \text{ to } n \quad (43)$$

This formula says that the rate of production of internal entropy P is the sum of the products of the respective thermodynamic forces and flows within the system, and furthermore says that P is always greater than or equal to zero. Unfortunately this formula tells us nothing about the quantitative relationship between the magnitudes of thermodynamic forces and the magnitudes of the resulting thermodynamic flows.

It turns out that, in general, thermodynamic flows are highly complicated *nonlinear* functions of the thermodynamic forces. However, *near equilibrium* thermodynamic flows are *linear* functions of these same thermodynamic forces. (This is the realm of *linear thermodynamics*, which is the subject of this chapter.) In the simplest near-equilibrium case, where only one thermodynamic flow and one thermodynamic force are involved, the following formula holds true:

$$J = LF \quad (44)$$

where J is the thermodynamic flow, F is the thermodynamic force, and L is a constant called the *phenomenological coefficient*. Following are some formulas for particular thermodynamic flows and thermodynamic forces that follow the pattern of formula 44 above:

- *Fourier's law of heat conduction:*

ON SYSTEMS

$$J_Q = -\kappa \nabla T(x) \quad (45a)$$

where J_Q is the flow of heat,
 $\nabla T(x)$ is the temperature gradient as a function of position x ,
 and κ is a heat conductivity constant for the particular material.

- *Fick's law of chemical diffusion:*

$$J_K = -D_K \nabla n_K(x) \quad (45b)$$

where J_K is the rate of diffusion (diffusion current) of compound K ,
 $\nabla n_K(x)$ is the concentration gradient of K as a function of position x ,
 and D_K is the diffusion coefficient of compound K .

- *Ohm's law of electrical conduction:*

$$I = V / R \quad (45c)$$

where I is the electric current,
 V is the voltage,
 and R is the (constant) electrical resistance.²²⁰

But what if more than one thermodynamic flow/force pair are simultaneously at work within the near-equilibrium system? In that case the thermodynamic flow/force relationships are still linear and still depend on the *phenomenological coefficients*, but the formula is a bit more complicated than formula 44 above:

$$J_k = \sum L_{kj} F_j \quad \text{where } k = 1 \text{ to } n \text{ and } j \text{ is summed from } 1 \text{ to } n \quad (46)$$

Notice that, in this case, each thermodynamic flow J_k is a linear function of not only its own corresponding thermodynamic force, but of all the other thermodynamic forces involved in the near-equilibrium system as well.

Kondepudi and Prigogine give some examples:

The thermoelectric effect is one such cross effect, in which a thermal gradient drives not only a heat flow but also an electrical current and vice versa. Another example is cross diffusion, in which a gradient in the concentration of one compound drives a diffusion current of another.²²¹

As other examples, there is the *Soret effect*, in which a heat gradient also drives a flow of matter, and the corresponding *Dufour effect*, in which a concentration gradient also drives a heat flow.

As might be expected, those linear phenomenological coefficients which correspond to a thermodynamic force that is directly paired with its corresponding thermodynamic flow, namely L_{kk} , are generally positive (with a positive force resulting in a positive flow). However, those phenomenological coefficients which correspond to a thermodynamic force's effect on a *non-corresponding* thermodynamic flow (L_{kj} where k is not equal to j) may be

either positive or negative. For example, in the cross-diffusion case mentioned above (where two compounds are diffusing into each other from opposite halves of a container), it is clear that the stronger the concentration gradient is for one compound, the more that gradient will *retard* the flow of the other compound, so that in that case L_{kj} will be negative.

Now, if we use formula 46 to substitute for J_k in formula 43 above, we can then express the rate of internal entropy production P for near-equilibrium systems solely as a function of the thermodynamic forces acting within the system:

$$P = \sum L_{jk} F_j F_k \geq 0 \quad \text{where } j = 1 \text{ to } n \text{ and } k = 1 \text{ to } n \quad (47)$$

In 1931 Lars Onsager (1903-1976), building on earlier conjectures by Lord Kelvin and others, demonstrated that a further remarkable constraint exists on the phenomenological coefficients in the linear regime. He proved that:

$$L_{kj} = L_{jk} \quad \text{for all } j \text{ and } k \quad (48)$$

These relations are called the *Onsager reciprocal relations*, and they essentially mean that if, for example, in a given near-equilibrium thermodynamic system a thermal gradient also drives a flow of electric current, then an electrical voltage within that same system will also drive a heat flow in exactly the same way and to exactly the same degree.²²²

A final important constraint on the coupling of thermodynamic forces and flows is Ilya Prigogine's *symmetry principle* (based on a similar principle discovered by Pierre Curie), which Prigogine and Kondepudi explain as follows:

[A] scalar thermodynamic force such as chemical affinity, which has the high symmetry of isotropy, cannot drive a heat current, which has lower symmetry because of its directionality. . . . Another way of stating this principle is that a scalar cause cannot produce a vectorial effect. . . . In general, irreversible processes of different tensorial character (scalars, vectors, and higher-order tensors) do not couple to each other. . .

Because of the symmetry principle, the [internal] entropy production due to scalar, vectorial, and tensorial processes should each be positive.²²³

Non-Equilibrium Linear Thermodynamics

So far the only time-independent (i.e., macroscopically unchanging) thermodynamic state we have discussed is thermodynamic equilibrium, where (for an isolated system) the rate of internal entropy production P is zero and total internal entropy S is at its maximum: Thermodynamic equilibrium is the *unconditionally equifinal* state to which all such isolated thermodynamic systems tend.

ON SYSTEMS

However, a thermodynamic system can also be maintained in a time-independent, macroscopically unchanging *non-equilibrium* state by means of a constant flow of energy and/or matter through the system. (Such a system is, then, of course, *not* isolated.)

Imagine an iron bar which is in firm contact with a hot reservoir on its left end and a cold reservoir on its right end. Imagine further that, external to this iron bar, the hot reservoir is kept at a constant temperature T_h and that no other thermodynamic forces, other than the resulting thermal gradient, are at work within the iron bar. In that case this thermodynamic system will evolve to a time-independent, macroscopically unchanging (i.e., “stationary”) *non-equilibrium* state in which the temperature of the cold reservoir on the right is a constant T_c and the flow of heat through the bar from left to right is a constant J_Q . This constant flow of heat J_Q through the system will then result in a constant positive rate of internal entropy production $P = d_i S/dt$ within the bar. (For purposes of this example we will regard the iron bar to be the “system” and the reservoirs to be the “environment”).

Now, because this thermodynamic system has evolved to a stationary thermodynamic state, we know that the overall rate of change in system entropy dS/dt must equal zero. We further know that the total dS/dt for this system must be the sum of the *internal* rate of entropy production $d_i S/dt$ plus the rate of change in system entropy due to entropy *exchanges* between the system and its environment $d_e S/dt$. From these facts it is clear that:

$$dS/dt = d_e S/dt + d_i S/dt = 0 \quad [\text{stationary non-equilibrium}] \quad (49a)$$

$$d_e S/dt = -d_i S/dt \quad [\text{stationary non-equilibrium}] \quad (49b)$$

But because $d_i S/dt$ is always necessarily *positive*, it follows from formula 49b that $d_e S/dt$ must necessarily be *negative* for the stationary non-equilibrium case. This, in turn, means that the amount of entropy flowing *into* the system from the *hot* reservoir is less than the amount of entropy flowing *out* of the system into the *cold* reservoir, so that the net change $d_e S$ is *negative*, from the system’s point-of-view. Furthermore, this difference $d_e S$ is exactly equal to the negative of $d_i S$, the change in entropy being internally produced by the system. Another way of putting this is that “[t]he non-equilibrium state is maintained through the exchange of negative entropy with the outside world; the system discards the entropy produced by the [internal] irreversible processes.”²²⁴

Several points need to be made here:

- First, in a stationary, linear non-equilibrium thermodynamic system the rate of internal entropy production $d_i S/dt$ never reaches zero, but it *does* reach and stay at a constant, positive nonzero value.

- Second, formulas 49a and 49b apply to *all* stationary non-equilibrium thermodynamic systems, not just the thermal system described explicitly above. For example, an industrial chemical process can be kept in a stationary non-equilibrium state by constantly supplying input chemicals and constantly removing the resulting chemical products. (In this case, instead of a constant flow of heat J_Q , a constant velocity of reaction J_v characterizes the stationary non-equilibrium state.)
- Third, while formulas 49a and 49b are perfectly general, the *pure constancy* of positive $d_i S/dt$ and negative $d_e S/dt$ is guaranteed only when the stationary non-equilibrium thermodynamic system is also *linear* and *near-equilibrium* (rather than *nonlinear* and *far-from-equilibrium*). By contrast, stable (“stationary”) *nonlinear, far-from-equilibrium* thermodynamic systems (such as biological systems) are characterized by far-more complex patterns of entropy flux and flow than pure, constant positive $d_i S/dt$ and pure, constant negative $d_e S/dt$.

So far we have considered mainly stationary, linear non-equilibrium thermodynamic systems involving only *one* thermodynamic force and *one* thermodynamic flow. But, as we saw earlier, in more-complex linear thermodynamic systems *several* thermodynamic forces and flows can be active at once, with any given thermodynamic flow being a linear function of *all* of the thermodynamic forces in play (i.e., $J_k = \sum L_{kj} F_j$, where $j = 1$ to n and $k = 1$ to n). This suggests the question: How do more-complex stationary, linear non-equilibrium thermodynamic systems behave?

It turns out that, in most cases, those thermodynamic flows which are directly associated with thermodynamic forces that are being *constrained from outside the system* ultimately produce a constant, positive, nonzero rate of internal entropy production $d_i S/dt$ (just as in the case of the simple stationary, linear, one-force-one-flow non-equilibrium systems that we have already discussed). By contrast, those portions of the internal entropy production $d_i S/dt$ produced by thermodynamic flows which are directly associated with thermodynamic forces that are *not* being constrained from outside the system ultimately fall to constant zero (just as in the case of simple isolated *equilibrium* thermodynamic systems). For this reason, more-complex, linear, non-equilibrium thermodynamic systems, taken as a whole, may be said to usually evolve to a stationary state of *constant minimum entropy production*, just as isolated thermodynamic systems evolve to a stationary state of *zero entropy production*. (The general formulation of this *Theorem of Minimum Entropy Production* is due to Ilya Prigogine, based on prior work by Lord Rayleigh and Lars Onsager.)

ON SYSTEMS

Kondepudi and Prigogine explain further:

[W]e have seen how different flows J_k , $k = 1, 2, \dots, n$, are coupled to the thermodynamic forces F_k . In such situations the system may be maintained away from equilibrium by constraining some forces F_k , $k = 1, 2, \dots, s$, to be at a fixed nonzero value, while leaving the remaining forces F_k , $k = s + 1, \dots, n$, free. In these cases, one often finds that the flows corresponding to the constrained forces reach a constant, $J_k = \text{constant}$, $k = 1, 2, \dots, s$, whereas the unconstrained forces adjust so as to make their corresponding flows zero, $J_k = 0$, $k = s + 1, \dots, n$. An example is thermal diffusion in which the stationary state corresponds to a zero matter flow and constant heat flow. . . In the linear regime, where the Onsager reciprocal relations are valid, all stationary states are characterized by the following general extremum principle. . . :

In the linear regime, the total [rate of internal] entropy production in a system subject to flow of energy and matter ($d_i S/dt$) . . . reaches a minimum value at the non-equilibrium stationary state.²²⁵

Figure 24, below, compares the evolution of an *isolated* thermodynamic system towards an *unconditionally* equifinal equilibrium state of zero entropy production with the evolution of a *linear non-equilibrium* thermodynamic system towards a stationary *conditionally* equifinal state of constant positive minimum entropy production (the *condition* being that at least some of the thermodynamic forces acting on the system are subject to constant *external* constraints):

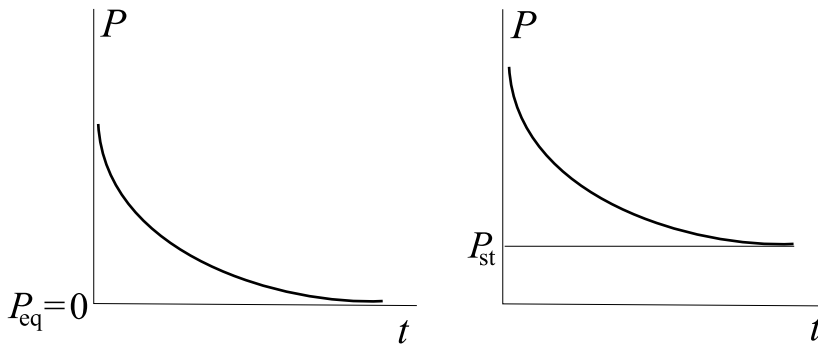


Figure 24 (after figure 17.5 on page 404 of Kondepudi and Prigogine)

In the above figure the vertical P axis represents the rate of internal entropy production $d_i S/dt$, while the horizontal t axis represents time.

In the following chapter on **Nonlinear Complex Physical Systems** we will consider the fascinating properties of *nonlinear far-from-equilibrium* thermodynamic systems, as well as other types of nonlinear complex physical

systems. Such *nonlinear far-from-equilibrium* thermodynamic systems are characterized by both external *and* internal conditional equifinality (unlike *linear near-equilibrium* stationary thermodynamic systems, which are characterized by *external* conditional equifinality only). Meanwhile, all that remains to be done in this chapter is to consider the teleological implications of the *linear* thermodynamic systems we have so far considered.

Teleological Implications of Linear Thermodynamic Systems

The *unconditionally* equifinal character of isolated thermodynamic systems – specifically, their universal tendency to evolve to a state of maximum entropy (“heat death”) – has exercised a powerful influence on the modern mind.

After all, isn’t the universe as-a-whole by definition an “isolated” thermodynamic system? And doesn’t the universe’s purported inevitable evolution to a state in which it consists of nothing but a “stochastic soup” of randomly colliding molecules demonstrate more clearly than anything else the teleological “meaninglessness and senselessness” of the universe? Merely mentioning the Second Law of Thermodynamics at an academic cocktail party will cause heads to nod in knowing, sad, cynical agreement concerning the ultimate futility of existence.

The discoverer of the twin concepts of entropy and the Second Law of Thermodynamics, Rudolf Clausius, explicitly applied them to the universe as-a-whole: “The entropy of the universe [*die Welt*] approaches a maximum”, he declared unequivocally.²²⁶ And the suicide of the great physicist Ludwig Boltzmann (1844-1906), whom we mentioned earlier in connection with his famous formula relating entropy S to the number of microstates W , is widely (though perhaps mythically) regarded as being due to his despair at the seemingly unrelenting purposelessness of a universe so cruelly subjected to the Second Law of Thermodynamics.

How can we reply to this? At the risk of sounding Pollyannaish, we must reply that “things are not as bad as they seem”. Things are not as bad as they seem because (as we have demonstrated earlier):

- The Second Law of Thermodynamics does *not* apply to all aspects of all physical systems, but only to relevant aspects of systems which are composed of multi-millions of microscopic parts. Many physical systems can also be usefully described without referring to their microscopic parts, including the universe-as-a-whole.
- The Second Law of Thermodynamics is not the only “arrow of time” that exists, and, in fact, the primary “arrow of time” associated with the universe-as-a-whole is the *cosmological* arrow resulting from the

ON SYSTEMS

universe's continual expansion since the "big bang", which we discussed in our chapter on general relativistic systems.

- The ultimate basis for *all* arrows of time is the *nonlinear dynamic* arrow, which (as we saw earlier in this chapter) does *not* entail any necessary or inevitable movement towards system-wide disorder.
- The seemingly-inevitable (and therefore depressing?) *irreversibility* of time is, from a nonlinear dynamic point-of-view, merely an epistemological artifact that is intimately related to the inability of finite beings such as ourselves *within* the universe to measure and/or control things to infinite precision. By contrast, the perfect transcendent God suffers no such limitations.
- Therefore, we must look to the perfect God who is *transcendent* (as well as immanent) for ultimate purpose and meaning: By contrast, no limited, finite teleological being having a complete physical analog within the physical universe (including the purely-immanent pantheistic God) can adequately supply such ultimate purpose and meaning.

In addition to isolated, *unconditionally* equifinal linear thermodynamic systems, which inevitably evolve to thermodynamic equilibrium ("heat death"), there is also the interesting case of *externally* constrained *conditionally* equifinal linear thermodynamic systems which *conditionally* evolve to a stationary attractor state of constant minimum entropy production. The relevant condition is, of course, that certain of the thermodynamic forces acting on the system must be constantly constrained from outside the system: If such outside conditional constraints cease to be effective, then the system inevitably evolves to an equilibrium heat death, just as in the case of the isolated system.

But note that, in the case of *linear* thermodynamic systems, any conditional constraint must be *external*: *Internally* the linear thermodynamic system continues to obey linear, deterministic laws, analogous to the linear, deterministic laws of classical Newtonian mechanics. By contrast, in the following chapter on **Nonlinear Complex Physical Systems** we will deal with hierarchical *nonlinear far-from-equilibrium* thermodynamic systems that also have *internal* macroscopic bifurcations and conditionalities. Here, at last, we will find a rich, hierarchical pattern of physical, internal, conditional equifinalities whose teleological analogs are the complex decisions, goals, and purposes of life itself.

Nonlinear Complex Physical Systems

What are *nonlinear complex physical systems*? First, let's consider the term *nonlinear*. As far back as our early chapter on **Classical Mechanical Systems** we discussed nonlinear mathematical functions and nonlinear systems in some detail (initially to contrast them with the linearity of classical mechanical systems). To very briefly summarize, in a *nonlinear* function the rate of change in the variables can be a higher power of (or a complex function of) the variables themselves. *Nonlinear* functions are required to describe *nonlinear* physical systems, which are any physical systems that are characterized by strong *and* persistent interactions between their parts and which therefore have emergent, constitutive properties (in other words, the vast majority of physical systems). Furthermore, the *physical* fact that nonlinear physical systems cannot be described only in terms of summative (additive) properties corresponds to the *mathematical* fact that nonlinear functions do *not* obey the *superposition principle*. In other words, it is *not* generally true of nonlinear functions that $f(x) + f(y) = f(x + y)$ or that $c f(x) = f(cx)$.

Next, let's consider the term *complex*. This term is more difficult to define than *nonlinear*, since it has a number of meanings, some of which are relevant in the present context and some of which are not. In one sense it may be said that *any* nonlinear system is complex, for the reasons stated in the previous paragraph. Therefore complexity in the present context partially derives from this nonlinearity of the physical systems being studied. In particular, we will find that in nonlinear systems in which an "autocatalytic" aspect ("the more of this, the *more* of this") is almost, but not quite, counterbalanced by an "autoinhibition" aspect ("the more of this, the *less* of this"), a high degree of system complexity may be expected to arise because of nonlinear mathematical considerations alone.

But, in addition, our earlier chapter on **Nonlinear Dynamic Systems** presented a "spectrum" of physical systems, ranging from *deterministic* to *tychistic* to *chaotic* to *stochastic*, which suggests a further relevant meaning of *complex* in the present context: What is suggested is that the *exact middle* of this spectrum (which we may describe as being at "the right edge of tychism" or alternatively as being at "the left edge of chaos") is the point at which maximally complex physical systems may be found. Work by Chris Langton, Stuart Kauffman, and others associated with the Santa Fe Institute suggest that systems which are maximally complex in this sense may represent an optimal balance between confirmation and novelty, from an information-processing point-of-view. (Recall that we introduced the terms *tychistic* and *tychism* to denote physical systems which are dominantly deterministic and ordered, but which contain significant immanently objective

ON SYSTEMS

elements of randomness and disorder, in contrast to *chaotic* systems which are dominantly disordered, but which contain significant elements of order.)

Piero Scaruffi describes Stuart Kauffman's insights with respect to this "[left] edge of chaos" as follows:

[Stuart Kauffman's] "candidate principle" states that organisms change their interactions in such a way as to reach the boundary between order and chaos. Examples include Per Bak's pile of sand (whose collapse under the weight of a new grain is unpredictable), any ecosystem (in which organisms live at the border between extinction and overpopulation), the price of a product (which is defined by supply and demand at the border of where nobody wants to buy it and where everybody wants to buy it). Evolution proceeds towards the [left] edge of chaos. Systems on the boundary between order and chaos have the flexibility to adapt rapidly and successfully.²²⁷

There is a further requirement in order for a physical system to qualify as "complex" in this present chapter: It must be composed of many parts (often multi-millions of parts), usually arranged in multiple layers of hierarchy. (We need to add this requirement because, as we saw in our chapter on **Nonlinear Dynamic Systems**, even systems consisting of only *three* strongly and persistently interacting bodies can be complex in the sense that they are nonlinear and fall within the tychistic/chaotic range of the physical spectrum, sometimes even at the *midpoint* of that range.)

In a sense, therefore, the physical systems we will be considering in this chapter combine nonlinearity, which we studied in detail in our **Nonlinear Dynamic Systems** chapter, with the hierarchical, emergent properties of systems consisting of multi-millions of parts, which we studied in our **Linear Thermodynamic Systems** chapter.

Finally, there is one important definition of "complexity" which does *not* capture the meaning intended here in this chapter, namely the definition of *algorithmic complexity* independently proposed around 1965 by the Soviet mathematician A. Kolmogorov and the American mathematician G. Chaitin. Nicolis and Prigogine explain:

The algorithmic complexity of a sequence of data is defined as the minimum length of a computational algorithm (measured, for instance, in number of bits if the algorithm is to be communicated to a digital computer) that would produce this sequence as output.

Is the algorithmic complexity just defined tantamount to the complexity observed in the physical sciences and biology? Consider a sequence *N* of data long expressed in binary form and displaying an overall regularity (e.g. 100 100 100 . . .). Clearly, the message contained in it can be considerably compressed. For instance, it could be transmitted to a

computer by the very simple algorithm “Print 100 ten [or one hundred, or one million] times”. The number of binary digits in such an algorithm is a small fraction of the number in the initial series, and as the series grows larger in size the algorithm size increases at a much slower rate. According to the definition, this therefore implies limited algorithmic complexity.²²⁸

Kolmogorov and Chaitin were able to show that the number of such “orderly” sequences of limited algorithmic complexity is very low compared to the total number of possible ways of arranging N binary digits. Therefore, the vast majority of sequences of N binary digits are incompressible and have *high* algorithmic complexity, according to the Kolmogorov/Chaitin algorithmic definition of complexity.

Such a definition would clearly tend to identify the *most-stochastic* systems as maximally complex on the “physical spectrum” that ranges from *deterministic* to *tychistic* to *chaotic* to *stochastic*. In other words, the Kolmogorov/Chaitin definition of algorithmic complexity would identify maximal complexity with the *far-right* edge of the physical spectrum, rather than with its *middle*. Again, Nicolis and Prigogine:

In reality, physico-chemical complexity must somehow be sandwiched between these two extremes [of low and high algorithmic complexity], and thus should not be fully identified with [high] algorithmic complexity.²²⁹

Later on in the same book, Nicolis and Prigogine indicate that the key reason for this is that “in addition to randomness . . . [the complexity of natural objects] . . . also involves some large-scale regularities.”²³⁰

Lastly, we need to consider the term *physical* in the title **Nonlinear Complex Physical Systems**: *Physical*, in the context of this present chapter, refers to the fact that we are here primarily dealing with *physical* (“bracket out the subject”) systems rather than *teleological* (“bracket out the object”) systems. Nevertheless, at the end of this chapter we will give some consideration to teleological systems that are *teleological analogs* of the physical systems described in the main part of the chapter (just as we considered similar teleological analogs to various types of physical systems in earlier chapters).

This chapter will be unique with respect to earlier chapters in this book in that it will use examples from a wide range of subject-matter, including nonlinear thermodynamics, biology, and sociology. The perspective of this chapter may therefore be loosely identified with that of *General Systems Theory*, which was first proposed by Ludwig von Bertalanffy in the late 1930s and 1940s. General Systems Theory is currently controversial in Anglo-American science for two reasons, one of which has no merit and the other of which does.

ON SYSTEMS

The meritless reason for rejecting General Systems Theory is the profound bias in Anglo-American science in favor of reductionism, linear solutions, and deterministic/stochastic models (resulting in the *downplaying* of chaotic models and the outright *rejecting* of tychistic models). This reason is meritless because, as we have seen, the vast majority of physical systems are nonlinear and therefore have emergent, constitutive properties, which automatically puts them somewhere within the tychistic/chaotic range of the physical spectrum.

By contrast, the objection to General Systems Theory that *does* have some merit claims that it merely identifies features that must be true of any physical system that properly requires description in terms of nonlinear equations or concepts, and that therefore General Systems Theory is really “about” nonlinear mathematics (coupled perhaps with superficial physical analogies), not about physical reality. Although von Bertalanffy has some good answers to this objection, this controversy is irrelevant for purposes of the present chapter: In other words, it is not necessary for the argument of this chapter to prove that a truly universal General Systems Theory as a viable “theory of everything” actually *exists*, or is even actually *possible*.

We should also note that in earlier chapters we have introduced (and often resolved) many topics and issues that are normally thought to arise only at the level of nonlinear complex physical systems. For example, our first chapter on **Classical Dynamic Systems** established the reality of *emergent, constitutive, holistic properties* (e.g., potential energy and force fields) at the level of simple dynamics, while our chapter on **Nonlinear Dynamic Systems** established the immanent-objective reality of *irreversible time* at the level of as few as *three* bodies that strongly and persistently interact. And, in our chapter on **Linear Thermodynamic Systems**, we have already proposed three “laws of hierarchy” that apply to all systems having many parts.

Furthermore, the mathematical concept of *phase space*, which we discussed in our chapter on **Nonlinear Dynamic Systems**, is fully applicable to nonlinear complex physical systems as well, except that we are not limited to the two dynamic variables *momentum* and *position*, but instead have a potentially wide-range of emergent, constitutive variables to choose from. In a similar fashion, we can easily build on other concepts that we introduced in **Nonlinear Dynamic Systems**, including *map functions, attractors, repellers, stable manifolds, unstable manifolds, chaos, Lyapunov numbers*, and *Lyapunov exponents*.

The Pitchfork Bifurcation

Our first “simple” example of a nonlinear complex physical system is the *pitchfork bifurcation*, taken from the book *Modern Thermodynamics* by Dilip Kondepudi and Ilya Prigogine.²³¹ In keeping with the General-System-Theory orientation of this chapter, this particular example will be taken as representative of a whole class of nonlinear complex physical systems, rather than as describing a particular physical system within a particular subject-matter area.

Figure 25, below, depicts the *pitchfork bifurcation*:

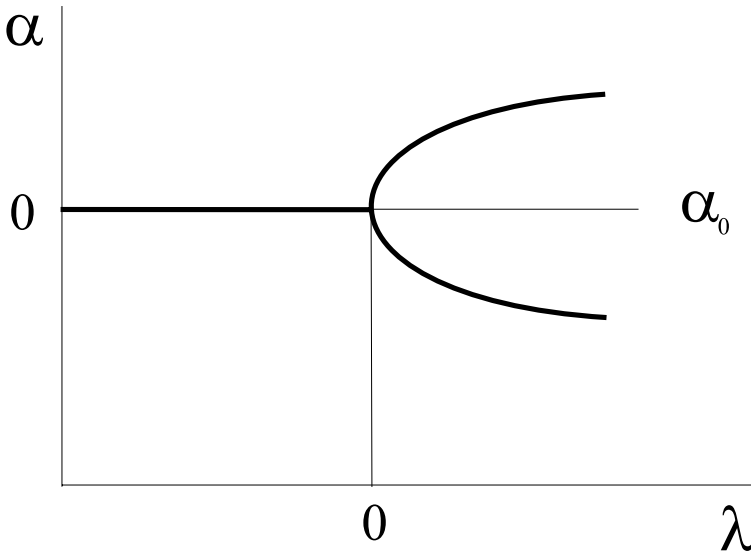


Figure 25 (after Figure 19.1 on page 429 of Kondepudi and Prigogine)

Consider the following nonlinear equation in the context of Figure 25:

$$d\alpha/dt = -\alpha^3 + \lambda\alpha \quad (1)$$

This equation is nonlinear with respect to the *internal* variable α because the rate of change in α with respect to time t , that is $d\alpha/dt$, is dependent on a higher power of α itself, namely α^3 . Furthermore the value of α is also dependent on the *external* variable λ , which we presume to be the “control variable” that is varied from outside the system in order to influence α . Now, as λ is varied from outside the system by increasing it from a negative value through zero and then up into the range of positive values, what happens to the “stationary solutions” of α (that is, those solutions of α for which $d\alpha/dt = 0$)? Starting from formula 1 above and setting $d\alpha/dt = 0$ we get:

$$0 = -\alpha^3 + \lambda\alpha \quad (2a)$$

$$\alpha^3 = \lambda\alpha \quad (2b)$$

$$\alpha^2 = \lambda \quad (2c)$$

$$\alpha = \pm \sqrt{\lambda} \text{ (or, also, } \alpha = 0 \text{ , as can be seen from 2a \& 2b)} \quad (2d)$$

Now, if we assume that, for physical reasons, α cannot be an imaginary number, it follows that, whenever the value of λ is *less than* zero, the *only possible* stationary solution of α is $\alpha = 0$, as is evident from Figure 25. However, if the value of λ becomes *greater than* zero, then there are *three* possible stationary solutions of α , as is also evident from Figure 25. Unfortunately only *two* of these stationary solutions are stable, namely $\alpha = \pm \sqrt{\lambda}$. By contrast, the stationary solution $\alpha = 0$ is *not* stable if λ is greater than 0. (The term “stable” in this context means that any small perturbation from the particular stationary solution of α decays, and the system falls back to that stationary solution, while “unstable” means that any such small perturbation from the stationary solution of α is magnified away from the stationary solution. The mathematical proof of these stability results is not difficult, but is tedious, so we will not give it here.)

The net result, as can be clearly seen in Figure 25, is that, as the control parameter λ is increased upwards from negative values and into the range of positive values, the value of the internal variable α *bifurcates* at $\lambda = 0$. That is, α begins to assume one of two possible stable values, either $+\sqrt{\lambda}$ or $-\sqrt{\lambda}$ (This particular kind of bifurcation is called a *pitchfork bifurcation*. Another kind of bifurcation is the *saddle-node bifurcation*, which we met in our chapter on **Nonlinear Dynamic Systems**.)

As Kondepudi and Prigogine note:

The bifurcation of new solutions at exactly the point where one solution loses its stability is not a coincidence. It is a general property of the solutions of nonlinear equations. (This general relation between bifurcation and stability of solutions of nonlinear equations can be explained using *topological degree theory*, which is beyond the scope of this discussion.)²³²

Now, the key point here is that it is a matter of *immanent-objective chance* which of the two possible paths the internal variable α begins to take as the external control parameter λ is increased above zero: This internal macroscopic system bifurcation therefore cannot be dismissed as being “merely subjective”. To be sure, such a bifurcation would not be observed by a transcendent being who had perfect knowledge of all variables and contingencies out to an infinite number of decimal places: For such a being, the system would remain absolutely determined, marred by no element of either macroscopic or microscopic chance. But science is done by imperfect

finite beings who exist *within* the universe they are studying, and for such beings phenomena such as macroscopic absolute chance and irreversible time are *immanent-objective* facts, as we proved in our chapter on **Nonlinear Dynamic Systems**.

In addition, even this present, relatively simple, example illustrates a characteristic feature of many nonlinear complex physical systems, namely, *internal conditional equifinality*. Recall from our previous chapter that a near-equilibrium *linear* thermodynamic system can be kept in a state of constant minimum entropy production through the application of suitable constant constraints from *outside* the system. We therefore described such a system as being characterized by *external* conditional equifinality: In other words, provided only that certain conditions were established *external* to the system, the system would attain an attractor state of minimum entropy production that was equifinal no matter where the system itself started from.

The present *nonlinear* example system is similar in that it is also subject to an *external* conditional constraint, namely, the value of the *external* control variable λ . However, this nonlinear system is *also* subject to an *internal* conditional constraint, namely, which of two possible paths the *internal* variable α will take as the value of the external variable λ passes upwards through zero. Once the system starts along one or the other of these paths, however, it proceeds in a deterministic manner that may be equifinal with respect to that particular path. I say “may be” because, in more-complex nonlinear situations, the system will probably once again arrive at a bifurcation point that is characterized by absolute immanent-objective chance, conditionally split at that point, proceed “deterministically” for a while, and so on. In fact this structure, consisting of many nested *internal conditional equifinalities*, is quite common in those nonlinear complex physical systems which we have named *tychistic* (i.e., those systems which are dominantly “deterministic”, but which contain significant elements of absolute immanent-objective chance).

Tychistic nonlinear complex physical systems are therefore often characterized by both *external and internal* conditional equifinality. (In our chapter on **Nonlinear Dynamic Systems** we saw that even simple *nonlinear dynamic* systems, such as the rotating pendulum, have this property as well, though in very primitive form.)

It is important to note, too, that although we have used the word “equifinality” in this context, there is *no* element of what we have earlier defined to be *teleology* in our present discussion: Rather, *everything* we have so far said involves only the proper scientific method of “bracketing out the

ON SYSTEMS

subject” (nuanced perhaps by the fact that we *have* had to distinguish immanent, imperfect beings from transcendent, perfect ones).

Nevertheless this physical, scientific fact of *internal conditional equifinality* within many tychistic nonlinear complex *physical* systems is obviously highly suggestive of interesting *teleological* systems that are *analogs* of those physical systems. For example, even with respect to the present pitchfork-bifurcation example it is very easy (and convincing) to make the teleological statement that the system *decided* to follow one of two possible paths in response to the upward change in the value of λ , and that thereafter the system pursued the *goal* represented by that path. (As we have noted earlier, teleological *decisions* are often analogous to instances of internal macroscopic *absolute chance* within the corresponding physical tychistic system.)

In fact, it is so easy to speak teleologically about nonlinear, tychistic, complex physical systems that we will adopt the convention for the rest of this book of putting words like “decided” and “goal” within quotation marks when we mean “the *physical* property that is the analog of the corresponding *teleological* property”. (Of course, at the end of this chapter we will also discuss in far more detail possible *teleological* analogs to nonlinear complex *physical* systems, just as was our practice at the end of prior chapters on the other types of physical systems.)

Benard Cells

Our next relatively “simple” example of a nonlinear complex physical system is the system of *Benard cells*, which were discovered by the French physicist Benard in 1900. *Benard cells* represent a particular physical system within the subject-matter of *nonlinear* thermodynamics. We will here discuss *Benard cells* descriptively, without any attempt to model them mathematically, basing our discussion on that of Nicolis and Prigogine.²³³

Imagine a very thin layer (only a few millimeters thick) of a fluid such as water trapped between two large, flat horizontal plates near the earth’s surface (and therefore subject to the earth’s gravity). Imagine further that these plates are at ordinary “room temperature” and that initially there is no difference in temperature between the two plates. Under such conditions the motions of the water molecules are purely random, the system is in a state of thermodynamic equilibrium, the rate of internal entropy production is zero, and the system’s entropy is at a maximum. (We discussed all of these concepts in our previous chapter on **Linear Thermodynamic Systems**).

Furthermore, clearly this type of system is *asymptotically stable*. For example, if you briefly touch your finger onto the bottom surface of the bottom plate, thus briefly raising its temperature at that spot, and then remove your finger, this local *perturbation* in temperature will quickly be dampened and evened out, and the system will retain no “memory” of this event whatsoever. Similarly, any minor *internal fluctuations* arising from within the system will also be suppressed.

Suppose now that we continually apply a small amount of heat to the bottom plate, so that we maintain a constant, small difference in temperature ΔT between the two plates. In that case heat flows from the bottom plate up through the thin layer of water to the top plate by means of *thermal conduction*. Because of this external constraint ΔT , the system’s rate of internal entropy production cannot fall to zero (as it does in the equilibrium case), but it *does* fall to the minimum value possible in accordance with the *theorem of minimum entropy production*, which we discussed in our previous chapter on **Linear Thermodynamic Systems**. In this *near-equilibrium* thermodynamic regime, thermodynamic flows are linear functions of the thermodynamic forces, and the only macroscopic differentiation that is observable in the water is a gradual, practically linear *decrease* in temperature and *increase* in density as we move from the bottom plate up to the top plate.

But now suppose that we drive the system even farther from thermodynamic equilibrium by increasing the amount of heat that we apply to the bottom plate, such that the ΔT difference between the temperatures of the two plates arrives at a critical value ΔT_c . At this critical value, the water molecules suddenly organize themselves into a set of vertically rotating convection cells, as is shown in Figure 26 on the following page. This is the thermodynamic regime of *thermal convection*, and these rotating convection cells are called *Benard cells*.

Bernard cells have some remarkable properties. In the first place, they form relatively *suddenly* and *globally* throughout the water layer when the critical value ΔT_c is reached. In the second place, they are created via a *holistic nonlinear process* in which a macroscopic continuum of random molecules suddenly becomes macroscopically structured and differentiated: What essentially happens is that a small amount of the *microscopic* kinetic energy of the individual water molecules becomes suddenly “upshifted” into the *macroscopic* kinetic energy of the bulk movements of the water that forms the convection cells. Ilya Prigogine and his followers call the (often sudden) appearance of such macroscopic structures *symmetry breaking*, a term which I find to be unnecessarily confusing. For what is actually “broken” is not

ON SYSTEMS

symmetry (except perhaps in a technical mathematical sense), but rather macroscopic *continuity*. I will therefore henceforth refer to this typical phenomenon of nonlinear processes as *macroscopic continuity breaking*, or *continuity breaking* for short. (Other writers on nonlinear complex physical systems use the term *phase transition* instead of *symmetry breaking* or *continuity breaking*.)

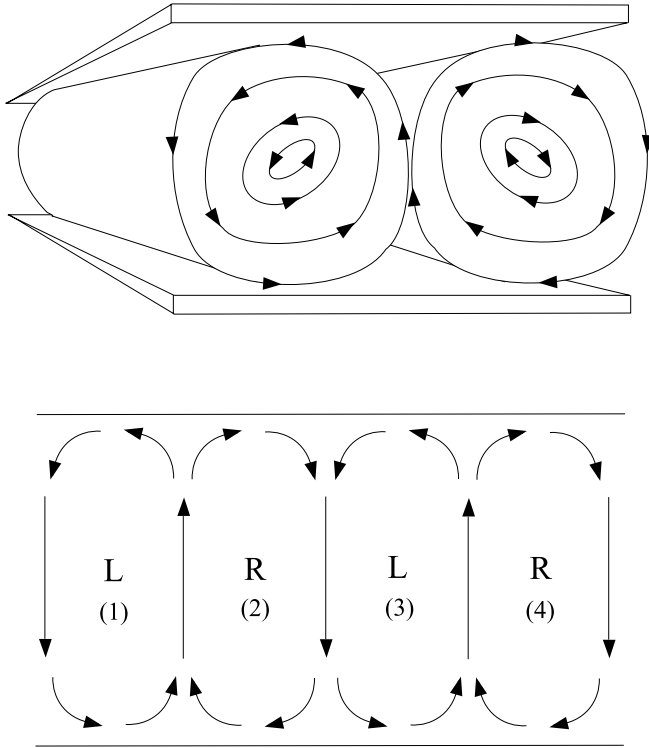


Figure 26 (after Figure 3 on page 11 of Nicolis and Prigogine)

Now this typical nonlinear phenomenon of relatively sudden *macroscopic continuity breaking* is clearly associated with a corresponding sudden (though perhaps small) *decrease in entropy* within the system: For if an *increase* in entropy involves the “downshifting” of macroscopic structure and kinetic energy to the microscopic level (as we established in our chapter on **Linear Thermodynamic Systems**), then clearly *macroscopic continuity breaking* is the *reverse* of this process, and therefore represents a *decrease* in system entropy. (That is one reason why physical systems that are dominantly characterized by tychistic nonlinear processes, such as Benard cells and biological systems, can seem to defy the second law of thermodynamics.)

There is another important aspect to *continuity breaking*, however: Notice in Figure 26 that neighboring Benard cells rotate in *opposite* directions. If Benard's experiment is repeated, it is found that about half the time the *odd*-numbered Benard cells rotate *clockwise* and the *even*-numbered Benard cells rotate *counterclockwise*, while the other half of the time the reverse is the case. Which scenario happens is purely a matter of immanent-objective absolute chance, just as was the case in our earlier pitchfork-bifurcation example. In fact, we may say that ΔT plays the same role in the Benard-cells example as the external control variable λ did in the pitchfork-bifurcation example. We may therefore also view the Benard-cells system as an example of macroscopic *temporal* continuity breaking (as well as macroscopic *spatial* continuity breaking), thus resulting in a system that has a *unique macroscopic history*.

Although, as we have stated, Benard cells do form relatively suddenly and holistically, the detailed *process* by which they arise is still of great interest. As is typical of nonlinear complex physical systems, Benard cells form through the amplification of small internal fluctuations. Nicolis and Prigogine explain:

Owing to thermal expansion the confined fluid layer becomes stratified, with the part close to the lower plate characterized by a lower density than the upper part. This gives rise to a continuous change in density, a gradient from low to high upward through the fluid that opposes the force of gravity. Imagine that [a] volume element [near the lower plate] is weakly displaced upward by a [fluctuation]. Being now in a colder – and hence denser – region, it will experience an upward Archimedes force that will tend to amplify the ascending movement further. If, on the other hand, a small droplet initially close to the upper plate is displaced downward, it will penetrate an environment of lower density, and the Archimedes force will tend to amplify the initial descent further. We see therefore that, in principle, the fluid can generate ascending and descending currents like those observed in the experiment. The reason these currents do not appear as soon as ΔT is not strictly zero is that the destabilizing effects are counteracted by the stabilizing effects of the viscosity of the fluid, which generates an internal friction opposing movement, as well as by thermal conduction, which tends to smear out the temperature difference between the displaced droplet and its environment. This explains the existence of a critical threshold ΔT_c , observed in the experiment.²³⁴

As ΔT approaches the critical threshold value ΔT_c , these internal fluctuations begin to become amplified, and proto-Benard cells characterized by some degree of macroscopic bulk movement begin to form. However, these proto-Benard cells are at first destroyed by the “old regime” of thermal conduction: Only when the critical threshold value ΔT_c is actually reached do the Benard cells suddenly establish themselves, such that the “new regime” of thermal convection at last replaces the “old regime” of thermal conduction. (Ilya

ON SYSTEMS

Prigogine describes this process of spatial and temporal continuity breaking as *order through fluctuations*.)

It is also significant that the force of gravitation, which is minute compared to the other forces acting on the water molecules, can be such a profoundly effective cause of the emergence of the Benard cells. This is so only because the system is extremely sensitive to minute forces and fluctuations at the critical threshold value ΔT_c (which corresponds to the *bifurcation point* in our pitchfork-bifurcation example). As Prigogine and Stengers put it:

[G]ravitation plays an essential role here and leads to a new structure in spite of the fact that the Benard cell may have a thickness of only a few millimeters. The effect of gravitation on such a thin layer would be negligible at equilibrium, but because of the non-equilibrium induced by the difference in temperature, macroscopic effects due to gravitation become visible even in this thin layer. Non-equilibrium magnifies the effect of gravitation.²³⁵

Now, this process of *continuity breaking* at the *macroscopic* level corresponds to the emergence of significant long-range *statistical correlations* between the molecules at the *microscopic* level. Again, Nicolis and Prigogine:

[B]eyond the threshold ΔT_c , everything happens as if each volume element [within the water] was watching the behavior of its neighbors and was taking it into account so as to play its own role adequately and to participate in the overall pattern. This suggests the existence of *correlations*, that is, statistically reproducible relations between distant parts of the system. . . [I]t is important to note the long-range character of these correlations as compared to the short range of the intermolecular forces. The characteristic space dimension of a Benard cell in usual laboratory conditions is in the millimeter range (10^{-1} centimeter), whereas the characteristic space scale of the intermolecular forces is in the angstrom range (10^{-8} centimeter). Intermolecular forces operate up to a distance equal to about one molecule; a single Benard cell comprises something like 10^{20} molecules. That this huge number of particles can [suddenly] behave in a coherent fashion, as in the case of convective flow, despite the random thermal motion of each of them, is one of the principal properties characterizing the emergence of complex behavior.²³⁶

What happens when ΔT increases well beyond the critical threshold value ΔT_c ? The answer is that ultimately a second critical threshold value $\Delta T'_c$ is crossed, the Benard cells break up, and a regime of *thermal turbulence* suddenly becomes dominant. In this turbulent regime macroscopic *disorder* becomes dominant over macroscopic *order*, but this macroscopic disorder does not entirely vanquish macroscopic order: In other words the system suddenly goes from being macroscopically *tychistic* to being macroscopically *chaotic*.

It is interesting to note that, as this Benard-cells system has been forced farther-and-farther from equilibrium because of the steady increase in ΔT , it has *macroscopically* traversed most of the way across our “physical spectrum” from *left-to-right*: *Macroscopically* this system is *deterministic* in the regime of thermal conduction, *tychistic* in the regime of thermal convection (where the Benard cells actually appear), and, finally, *chaotic* in the regime of thermal turbulence.

Meanwhile, at the *microscopic* level, from the point-of-view of the millions of individual component molecules, this same system has moved in the *opposite* direction from *right-to-left* across the “physical spectrum”: *Microscopically* the system is *stochastic* in the regime of thermal conduction (since virtually all of the kinetic energy of the molecules is random), *chaotic* in the regime of thermal convection (since a pattern of bulk movement is overlaid onto still-dominant random molecular motions), and *tychistic* in the regime of thermal turbulence (since by this time the kinetic energy of bulk movement has come to dominate random molecular kinetic energy).

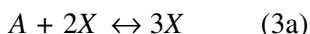
This suggests a fourth *law of hierarchy*, which we may tentatively add to the three laws of hierarchy that we presented in our previous chapter on **Linear Thermodynamic Systems**:

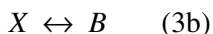
- Whenever a physical system, considered from the point-of-view of a *higher* level of hierarchical organization, moves from left-to-right across the “physical spectrum” (or vice-versa), then that same physical system, considered from the point-of-view of the *next lower* level of hierarchical organization, tends to move in the *opposite* direction across the “physical spectrum”. (This “physical spectrum” is, from left to right, *deterministic-tychistic-chaotic-stochastic*.)

That is why, for example, that an increase in freedom at a higher holistic organizational level is always paid for by a loss of freedom by the component parts (and vice-versa). (An exception to this fourth *law of hierarchy* is that class of discrete, purely theoretical physical systems called *cellular automata*, which always remain resolutely deterministic at their lowest hierarchical level.)

A Chemical Nonlinear Complex Physical System

Our next “simple” example of a nonlinear complex physical system is also taken from Nicolis and Prigogine.²³⁷ It is the abstract chemical system represented by the following two chemical reactions, taken together:





Reaction 3a (in the forward direction) shows that one molecule of A combines with 2 molecules of X to form 3 molecules of X . This reaction can also proceed in the reverse direction (as is indicated by the double-headed arrow). At chemical equilibrium the reaction rates of these forward and reverse reactions always exactly balance out, a chemical principle known as *the principle of detailed balance*.

Reaction 3b (in the forward direction) shows that one molecule of X is transformed into one molecule of B . Again, the principle of detailed balance applies at chemical equilibrium with respect to the reaction in the reverse direction.

Notice too that the forward-reaction part of reaction 3a (i.e., reading left-to-right) is an example of *autocatalysis*: The more of X we have, the *more* of X we get, i.e., “The more of this the *more* of this.” By contrast the forward-reaction part of reaction 3b is an example of “*autoinhibition*” in the broadest sense: The more of X we have, the *less* of X we get, i.e., “The more of this the *less* of this.” (Technically, true *autoinhibition* refers to the case where a chemical inhibits the production of its own catalyst and thereby inhibits the production of itself, but we will here very loosely use the term to also include the common case where the reaction, in the forward direction, consumes and destroys the chemical.) This fine counterbalancing between an *autocatalytic* process on the one hand with an “*autoinhibitory*” process on the other is characteristic of many tychistic nonlinear complex physical systems. (For example, in biology, the key autocatalytic process is *reproduction*, while the key “autoinhibitory” process is *death*.)

Of course, if the autocatalytic process and the autoinhibitory process were to *exactly* counteract one another, then they would completely cancel each other out, and nothing interesting would happen. However, if these two processes are slightly *offset*, so that they are not simply the exact reverse of one another, then tychistic nonlinear physical phenomena of extraordinary complexity can occur.

The nonlinear aspects of the chemical reactions shown in 3a plus 3b above become evident when we write the corresponding equations for the *rates of reaction*. Now, usually it is the case that the rate of a chemical reaction is directly proportional to the concentrations of the reactants *multiplied together*. This is so because the more concentrated the reactants, the more frequent are the collisions between the molecules and the more likely it therefore is that the reaction will actually occur. Assuming in the present case that this proportionality holds, we will use a , b , and x to represent the concentrations of chemicals A , B , and X respectively, and we will use k_1 , k_2 ,

k_3 , and k_4 to represent the reaction-rate proportionality constants, with the odd-numbered constants corresponding to the forward reactions, and the even-numbered constants corresponding to the reverse reactions. Such reaction-rate proportionality constants represent factors such as temperature, pressure, and the presence or absence of catalysts, all of which factors we will assume to be constant in this example. (A *catalyst* is a chemical that speeds up a chemical reaction without itself being consumed or produced by that chemical reaction.)

Since at chemical equilibrium *the principle of detailed balance* applies, so that the forward and reverse reactions of each reaction pair *taken individually* are exactly equal in reaction rate, the following reaction-rate equations are therefore each *individually* true for this system when it is at chemical equilibrium:

$$k_1 a x^2 = k_2 x^3 \quad (4a, \text{ which corresponds to the reactions in 3a})$$

$$k_3 x = k_4 b \quad (4b, \text{ which corresponds to the reactions in 3b})$$

We will also assume that we can control the concentrations a and b at will by continuously supplying and/or removing chemicals A and B from the system, so that concentration x is the only *dependent* variable in the system. The question then arises: What is the value of concentration x at chemical equilibrium (which we will call x_{eq}) for given values of a_{eq} , b_{eq} , k_1 , k_2 , k_3 , and k_4 ?

Assuming $x \neq 0$, $k_2 \neq 0$, and $k_3 \neq 0$, we can use ordinary algebra to solve the simultaneous equations 4a and 4b above by dividing them as necessary with x , k_2 , and k_3 . The result is:

$$x_{\text{eq}} = k_4 b_{\text{eq}} / k_3 = k_1 a_{\text{eq}} / k_2 \quad (5)$$

Notice that this is a single, unique, determined solution for x_{eq} .

Furthermore, by algebraically rearranging the second equality in equation 5, we can see that our choice of a and b is not entirely free, if we want the system to attain chemical equilibrium. For the required *ratio* of a and b at chemical equilibrium is determined by the reaction-rate proportionality constants taken together:

$$b_{\text{eq}} / a_{\text{eq}} = k_1 k_3 / k_2 k_4 \quad (6)$$

But what if this chemical reaction system is driven by external constraints to a stationary state that is *far-from-equilibrium* rather than *at* or *near equilibrium*? In that case the principle of detailed balance does *not* apply. Instead, all that is required is that the effect of the two forward reactions *taken together* be exactly balanced by the effect of the two reverse reactions

ON SYSTEMS

taken together. The resulting rate-of-reaction equation can be found by essentially *adding* equations 4a and 4b above as follows:

$$-k_2x^3 + k_1ax^2 = 0 \quad (7a, \text{corresponding to } 4a)$$

PLUS

$$-k_3x + k_4b = 0 \quad (7b, \text{corresponding to } 4b)$$

EQUALS

$$-k_2x^3 + k_1ax^2 - k_3x + k_4b = 0 \quad (7c)$$

Now, equation 7c is a cubic (i.e., *nonlinear*) equation in x that can have as many as *three* solutions for certain values of a and b (two of these solutions being stable, and one being unstable) !

As Nicolis and Prigogine put it:

[N]on-equilibrium reveals the potentialities hidden in the nonlinearities, potentialities that remain dormant at or near equilibrium.²³⁸

If we now define a control parameter μ that is a suitable combination of the constant reaction-rate proportionality constants k_1 , k_2 , k_3 , and k_4 and the independently variable concentrations a and b , then Figure 27, below, shows how the *dependent* concentration x (at its far-from-equilibrium stationary state) varies as the combined *independent* control variable μ is altered:

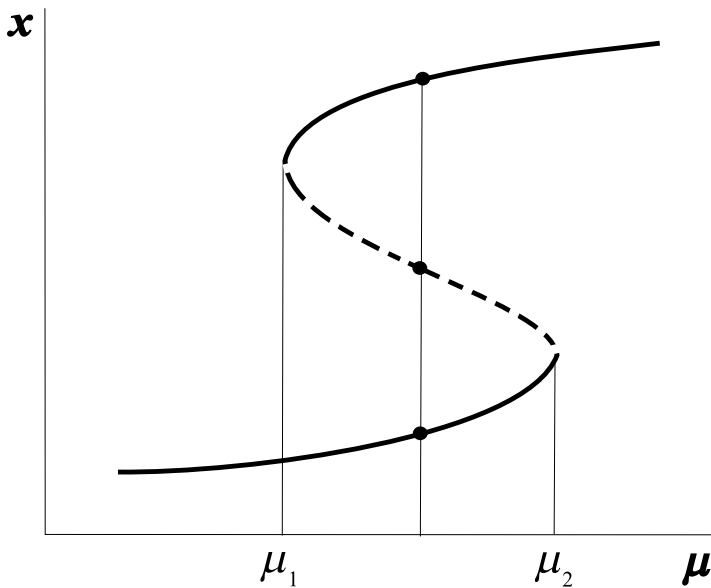


Figure 27 (after figure 75a on page 172 of Nicolis and Prigogine)

Notice that the graph in Figure 27 is S-shaped, as is often the case with cubic equations. Notice too that the middle portion of the graphed line is broken and dashed, indicating that these solutions for x are mathematically *unstable* in the sense that we defined in our pitchfork-bifurcation example. By contrast the solid portions of the graphed line (the upper and lower branches of the “S”) represent *stable* solutions of x .

Now, if we start with μ at a very low value, so that the value of x is on the lower branch of the “S”, and if we then slowly increase the value of μ , then the value of x moves slowly upward until μ reaches the value labeled as μ_2 in Figure 27. At that point the concentration of x jumps *suddenly upward*, and the system is instantly on the *upper* branch of the “S”. If, after μ has been increased above μ_2 , it is then slowly decreased below μ_2 , the value of x does *not* immediately jump back down to the lower branch of the “S”: Instead, the concentration x slowly goes down along the *upper* branch of the “S” until μ is taken down to the value μ_1 , at which point the concentration of x suddenly *drops downward* onto the lower branch of the “S”.

This example of a “simple” nonlinear chemical system illustrates three important features that are shared by many other nonlinear complex physical systems:

- Between the values μ_1 and μ_2 this system demonstrates the nonlinear phenomenon of *bistability*, since, for any given value of μ within this range, x can have one of *two* very different stable values.
- Which of these two stable values of x the system attains is entirely dependent on the *prior history* of the system, a scientific phenomenon known as *hysteresis*.²³⁹
- If that range of μ between μ_1 and μ_2 for which x is bistable is relatively narrow, then the control variable μ can act as a kind of *binary switch*, switching the system discontinuously between a high concentration of x and a low concentration of x . In this way nonlinear complex physical systems can store binary information.

Nonlinear complex physical systems that display some or all of the above three features include transistors, lasers, and biological membranes, as well as other nonlinear chemical systems.²⁴⁰

Memory and History in Nonlinear Chemical Systems

Figure 28, below, represents (at an abstract level) a more-complex nonlinear chemical system in which pitchfork bifurcations of the type depicted in Figure 25 are combined with hysteresis-related bistable transitions of the type depicted in Figure 27:

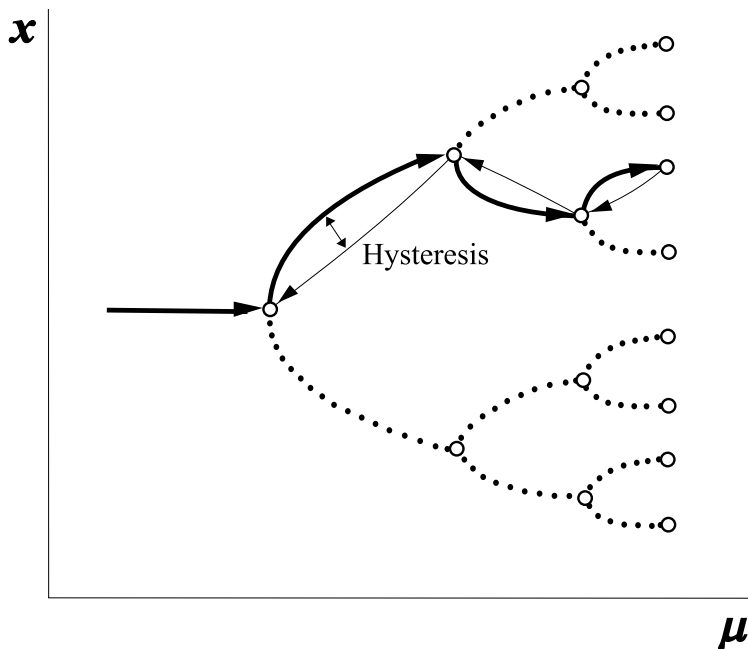


Figure 28 (after figure 12, on p. 49 of Jantsch's *Self-Organizing Universe*)

In Figure 28, the horizontal μ axis represents once again a suitable combination of *independent* constants and control variables that can affect the system, while the vertical x axis now represents a suitable combination of *dependent* variables (usually chemical concentrations) which are driven by μ in a nonlinear manner. The thick, solid curved arrows represent an actual path which this system might take through the branching system “choices” (i.e., the bifurcation points represented by the small circles) as the control variable μ is increased. By contrast the dotted curved lines represent the paths *not* taken by the system. As the system is driven farther and farther from chemical equilibrium (i.e., as μ is increased), each “choice” made by the system at a bifurcation point usually results in holistic macroscopic *continuity breaking* (both temporal and spatial), accompanied by a sudden momentary reduction in system entropy.

Especially interesting in Figure 28 are the thin straight arrows that *approximately* retrace in the opposite direction the forward path represented

by the thick, solid curved arrows: For if we identify a gradual, continuous *increase* in control variable μ as driving this chemical system *away* from equilibrium, then a subsequent gradual, continuous *decrease* in control variable μ may be said to represent a retreat back *towards* equilibrium. Amazingly, in that case (unless the system is strongly perturbed) the value of x will *approximately* retrace backwards its original forward path! (The reason the backwards retrace path will only *approximately* match the forward path is because of the effects of bistability and hysteresis, which we just discussed in regard to Figure 27.) As Erich Jantsch observed:

This implies a primitive, holistic *system memory* which appears already at the level of chemical reaction systems. The system “remembers” the initial conditions which made a particular development possible, the beginnings of each new structure in its evolution. We may say, the system is capable of *re-ligio*, the linking backward to its own origin. In linking backward, the system “relives” its own experience – not in separable details, but in a sequence of holistic . . . regimes.²⁴¹

Thus teleological analogs to nonlinear chemical systems include not only *decisions* and *goals*, but *memory* and re-lived *history* as well !

Another important point: Even though each “choice” made by the system as it moves from left to right in Figure 28 (i.e., *farther* from equilibrium) usually results in a relatively-sudden macroscopic continuity breaking, accompanied by an equally sudden *momentary decrease* in system entropy, the amount of entropy internally produced by the system on a *continuous* basis actually *increases* after each such temporary entropy drop, due to the intensification of internal chemical reactions as we move up to each successive level of the far-from-equilibrium regime. As Kondepudi and Prigogine put it:

Each new structural instability generally increases the . . . entropy production in the system because it increases the number of reactions. This is in contrast to . . . near-equilibrium systems . . . in which the entropy production tends to a minimum. Structural instability may progressively drive far-from-equilibrium systems to higher states of entropy production and higher states of order. . . [I]nstability, fluctuation, and evolution to organized states is a general non-equilibrium process whose most spectacular manifestation is the evolution of life.²⁴²

This suddenly-increased continuous internal entropy production (which usually accompanies the sudden emergence of the next-higher level of the nonlinear far-from-equilibrium regime) results in yet-more internal entropy that needs to be continuously *dissipated* out to the external environment in accordance with the process we explained in our chapter on **Linear Thermodynamic Systems**. That is why Ilya Prigogine and his colleagues call the macroscopic structures created by nonlinear far-from-equilibrium continuity-breaking *dissipative structures*.

ON SYSTEMS

Cellular Automata

For a considerable change of pace, our next example of a nonlinear complex physical system is British mathematician John Horton Conway's famous simulation called *Life*, which he developed in 1970. *Life* is a member of that class of discrete dynamic systems called *cellular automata* (or CA for short). *Life* is not a real physical system, but only an imagined one. Nevertheless it may be regarded to be loosely analogous to biological systems involving cellular reproduction and death.

Imagine a very large (theoretically infinite) flat plane that is marked by a fine (perhaps invisible) rectangular grid. Each square of this grid is one "cell" that can have one of two states, *on* or *off* (or, if you prefer, *alive* or *dead*), which we may represent by having an *on* cell marked with a round black dot and an *off* cell simply left blank. (In some cellular automata systems that are more-complex than *Life*, each cell can have more than just these two states.) Each such cell has eight immediate neighbors: four neighbors that are above, below, left, and right of it, and four neighbors that are diagonally closest to it.

We start the *Life* simulation with a plane that consists entirely of *off* cells, except for a small pattern of *on* and *off* cells in the center of the plane. (This small initial "seed pattern" of cells is the only thing that is allowed to vary in the standard *Life* simulation.) We then begin to evolve this seed pattern of *on* and *off* cells in accordance with the following three simple rules:

1. If a cell has exactly *two* neighbors, it *stays the same* (i.e., *on* if it is already on, *off* if it is already off).
2. If a cell has exactly *three* neighbors, it is *turned on* if it is presently off, or it *stays on* if it is already on.
3. If a cell has *any other number* of neighbors (i.e., zero, one, four, five, six, seven, or eight), it is *turned off* if it is presently on, or it *stays off* if it is already off.²⁴³

That's all! The application of these three simple rules is repeated for generation after generation for as long as you want, and the resulting patterns are observed. Doing this simulation on a personal computer is relatively easy, and you can try it yourself by using one of the many "freeware" and "shareware" *Life* programs that can be found on the internet.

Depending on what small seed pattern you start with, the results can be utterly astonishing: Intricately interacting "macroscopic" patterns often quickly establish themselves in highly complex "lifelike" ways. To take but one simple example, Figure 29, on the facing page, shows the evolution of a very common set of *Life* patterns that *Life* enthusiasts call a "glider":

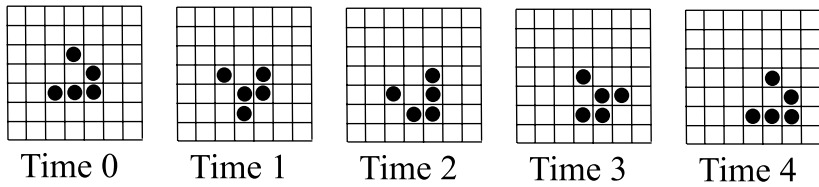


Figure 29 (after the figure on p. 30 of Poundstone's *The Recursive Universe*)

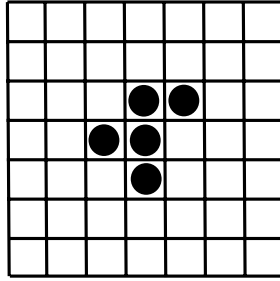
The grids labeled **Time 0** through **Time 4** in Figure 29 represent successive generations of the “glider” in the *Life* simulation. Notice that the pattern in **Time 4** is the same as the pattern in **Time 0**, except that it is shifted down and to the right. This sequence of **Time 0** through **Time 4** repeats itself over and over in subsequent *Life* generations, resulting in a single “macroscopic” glider *gestalt* that either creeps or sails diagonally across your computer screen, depending on how fast the computer presents the successive generations.

Many other such patterns-in-motion may appear and interact during a given run of the *Life* simulation. *Life* enthusiasts have given some of them whimsical, descriptive names, such as “spaceships”, “blinkers”, “traffic lights”, “glider guns” (which shoot out a continuous stream of “gliders”), and “eaters” (which eat and destroy any “gliders” unfortunate enough to run into them). No written description can do justice to the complexity of interaction of these *Life* patterns: You really do feel that you are watching some kind of strange and varied “macroscopic” life forms (comprised of “on” cells) interacting in surprising ways!

Any given run of *Life* eventually evolves to a relatively *steady state* consisting of various stable *unchanging* patterns (such as “blocks”, “beehives”, and “loafs”), plus various stable *repeating, oscillating* patterns (such as “blinkers”, “traffic lights”, and “pulsars”), all strewn randomly across the *Life* plane, together with “gliders” which have sailed off to infinity, never to interact again. This *steady state* is often reached relatively quickly. However, some initial seed patterns result in *Life* simulations that are exceptionally prolific and continue for many generations before achieving their *steady state*. For example, starting the *Life* simulation from the simple **R pentomino** seed pattern depicted in Figure 30 on the following page results in a *Life* simulation that continues for 1,103 generations before it finally settles down to a *steady state* consisting of eight “blocks”, four “beehives”, four “blinkers”, one “boat”, one “loaf”, and one “ship”, together with six “gliders” sailing off to infinity!²⁴⁴ During these 1,103 generations, hundreds

ON SYSTEMS

of these and other types of “macroscopic” *Life* “creatures” have been both created and destroyed!



R Pentomino

Figure 30 (after the figure on p. 33 of Poundstone’s *The Recursive Universe*)

Our wonder at how all of these *Life* “creatures” could have been created from nothing but the simple **R pentomino** seed pattern and the three simple *Life* rules faintly parallels our wonder at how all of the diversity of life on earth throughout history could have arisen from (and therefore been implicit within) earth’s simplest beginning life-forms.

But the *Life* simulation holds even more surprises if we consider that hierarchical level of organization immediately above what we have so-far called the “macroscopic”: For in 1982 Conway published a proof that, at that level, *Life* “creatures” can exist which are capable of *complete self-reproduction*! William Poundstone explains:

Conway’s proof is detailed. It is founded on the realization that the glider gun and many other *Life* objects can be constructed in glider collisions. Conway demonstrated that vast constellations of glider guns and eaters can produce and manipulate gliders to collide in just the right way to form a copy of the original constellation. Conway’s proof incorporates [John] Von Neumann’s reasoning about self-reproducing machines and machines that make machines more complex than themselves.²⁴⁵

Poundstone then goes on to describe Conway’s proof in some detail. Based on this proof, Conway himself has speculated that:

There are *Life* patterns which behave like self-replicating animals. . . It’s probable, given a large enough *Life* space, initially in a random state, that after a long time, intelligent self-replicating animals will emerge and populate some parts of the space.²⁴⁶

We are far from knowing exactly how and why reproducing, potentially intelligent macro-patterns in the *Life* space can emerge. But a closer examination of the three simple *Life* rules *does* reveal that, at the heart of all

of this complexity lies our (by now familiar) key concepts of *autocatalysis* (a.k.a. *reproduction*), “*autoinhibition*” (a.k.a. *death*), and *nonlinearity*. For the second *Life* rule (that a cell which is off and has exactly three immediate neighbors is turned *on* in the next generation) is clearly an *autocatalytic* rule (“the more of this the *more* of this”). By contrast, the third *Life* rule (that a cell which is on and has any number of neighbors *except* two or three is turned *off* in the next generation) is clearly an *autoinhibitory* rule (“the more of this the *less* of this”). As in our previous examples, the third *autoinhibitory* rule partially (but not completely) undoes the effects of the second *autocatalytic* rule. (The first *Life* rule, which states that a cell having two neighbors stays the same in the next generation, is neutral and is neither *autocatalytic* nor *autoinhibitory*.) It is also very interesting to note that in this case the *autoinhibitory* rule works “on both sides” of the *autocatalytic* rule: That is, a cell can “die” both because it has *too many* immediate neighbors, and because it has *too few*.

As far as the *nonlinearity* of *Life* is concerned, in 1992 Leon O. Chua and his colleagues proved that Conway’s *Life* could be successfully modeled as a *Cellular Nonlinear Network* (CNN). Furthermore, Chua demonstrated that the complex “macroscopic” emergent phenomena arising out of a given *Life* simulation were closely associated with the strength and nature of the “local activity” between the cells. (Chua’s “local activity” idea with respect to *discrete* cellular-automata systems evidently bears a relation to the idea of *strong* and *persistent* interaction between the parts of the *continuous* nonlinear physical systems which we have previously studied.) As Chua puts it:

[T]he *local activity* dogma . . . asserts that a homogeneous, non-conservative medium with symmetric boundary conditions cannot exhibit a heterogeneous static or dynamic pattern unless it is *locally active* in a precise sense.

Chua and his colleagues identify the “[left] edge of chaos” as a particularly fruitful subset of the local activity domain.²⁴⁷

Because of the nonlinearity of *Life* and other similar *discrete* cellular-automata (CA) systems, it is not surprising that such systems display many of the properties of the *continuous* nonlinear physical systems we have previously considered. As Gravner and Griffeath note:

Even the most basic parameterized families of CA systems exhibit a bewildering variety of phenomena: self-organization, meta-stability, turbulence, self-similarity, and so forth. From a mathematical point-of-view, cellular automata may rightly be viewed as the discrete counterparts to nonlinear partial differential equations. As such, they are able to emulate many aspects of the world around us, while at the same time being

ON SYSTEMS

particularly easy to implement on a computer. The downside is their resistance, for the most part, to traditional methods of deductive analysis.²⁴⁸

We can place *Life* within the context of other members of the family of cellular-automata (CA) systems by considering the basic features of all such systems:

- The *system space* of a CA system is the total collection of cells which comprise the system. For *Life* this is an infinite 2-dimensional plane of rectangularly arranged cells. Other cellular automata use an infinite 1-dimensional line of cells, or a set of cells arranged 1-dimensionally in a circle. It is also possible to have a 3-dimensional system space, but this is rarely done because of the extreme complexity of the resulting calculations.
- The *neighborhood* of each cell (often abbreviated as *nbhd*) is the set of those immediately-nearby cells which determine the next state of the cell. The nbhd always includes the cell itself. For *Life* this neighborhood is the so-called *Moore* nbhd, which is 2-dimensional and has 9 members (the cell itself, plus its 8 immediate neighbors, both rectangular and diagonal). Other possible neighborhoods include the *Von Neumann* nbhd, which is the same as the Moore nbhd, except it doesn't count the diagonal neighbors, so it has only 5 members. For cellular automata in 1-dimensional space, the nbhd can be defined as including the closest cell to a cell's left and the closest cell to a cell's right, or it can be defined as including the *two* closest cells to a cell's left and the *two* closest cells to a cell's right, and so on up to any number of "closest" cells. The number of cells in the nbhd of a given cellular automaton we will call *N*. (For *Life*, *N* = 9.)
- The *states* which a single cell can assume is also a distinguishing feature of CAs. For *Life* these states are *on* and *off* (also called *alive* and *dead*, or 1 and 0). Typically the *Life* cell is colored with a round black dot to mean "on" and is left empty to mean "off". While a *Life* cell has 2 states, the cell which John Von Neumann used for his cellular automaton had 29 states. One of the states of a CA can be designated as the *quiescent* state. In *Life* the quiescent state is the *off* state. The number of states which a cell can assume we will call *S*. (For *Life*, *S* = 2.)
- The *transition rule* of the CA, which says how the current states of the cells in a cell's nbhd determine the state of that cell in the next generation, is also an important feature of all CAs.

Now, for a given CA, how many *neighborhood configurations* can its nbhd assume? Since each cell can assume one of S possible states, and since the nbhd of each cell contains N cells, it is clear that the total number of possible configurations for the nbhd is S^N (because there are S ways to choose the state of the *first* cell in the nbhd, S ways to choose the state of the *second* cell in the nbhd, and so on). For *Life* the number of *neighborhood configurations* is $2^9 = 512$.

Another interesting question is: For a given CA, how many *possible* transition rules are there? Since each one of the S^N possible neighborhood configurations can determine the state of the cell in S possible ways, it follows that the number of *possible* transition rules for the CA is S raised to the power of S^N . For *Life* this means that its transition rule (which we broke down into three sub-rules for ease of comprehension) is one of 2^{512} *possible* transition rules. How big is 2^{512} ?

If every elementary particle in the universe were a supercomputer examining a trillion CA per second, starting at the Big Bang, by now only one part in 10^{44} would have been examined. Failing some fundamental advance in the physics of computation . . . we will never, Never, NEVER see all the possibilities.²⁴⁹

Clearly, we need all the help we can get in our search for transition rules that give “interesting” results for a wide range of initial seed patterns!

In our chapter on **Nonlinear Dynamic Systems** we described *phase space* as a space in which each point in the space represents the complete state of a system at a given point in time. For dynamic systems the number of dimensions for this phase space is equal to the number of particles in the system times six (since each particle is specified by a vector for position and a vector for momentum, and each such vector requires three numbers to specify it in 3-dimensional space.) Analogously, we may say that the *phase space* for a cellular automaton is the set of all possible *global configurations* of the cells in the system. For example, if the *system space* of a given CA consists of 128 cells arranged in a circle and the number of possible *cell states* is 2, then clearly there are 2^{128} possible *global configurations* of this CA *system space*, with each such *global configuration* representing one “point” in the CA *phase space*. (Of course, if the CA *system space* is an infinitely long line of cells or an infinite plane of cells, then the number of points in the CA *phase space* is also infinite.)

In 1984 Stephen Wolfram examined CAs having a 1-dimensional circular system space by starting from a random seed pattern. Studying the CA phase space of such systems, he demonstrated that the behavior of such cellular automata falls into four distinct classes, depending on the transition rule used.

ON SYSTEMS

Each of Wolfram's classes is loosely analogous to a classification on the "physical spectrum" that we discussed earlier:

1. Single-point attractors (roughly corresponding to the left side of *determinism*).
2. Periodic attractors (i.e., oscillators, roughly corresponding to the right side of *determinism*).
3. Coherent structures that propagate, grow, split apart, and recombine (corresponding to complex *tychistic* systems). Cellular automata in this class yield stable, periodic, and propagating structures that can persist over arbitrary lengths of time, and can include "extended transients" similar to the "gliders" in *Life*. In fact, CAs in this regime have by-far the longest-lasting "transients" and therefore take the highest number of generations to settle down to a relatively *steady state*. (However, note that not every randomly generated seed pattern produces this "tychistic" behavior for the given transition rule.)
4. Strange attractors (corresponding to *chaotic* systems).

(Wolfram actually labeled his classes I, II, III, and IV, and reversed the order of 3 and 4 relative to what we have presented above.)²⁵⁰

In 1990 Christopher Langton developed a parameter he called the *lambda parameter*, which gives a rough idea of the average probability that a CA cell will be alive in the next generation. More-precisely, if each CA cell has 2 possible states, then *lambda* is the ratio of the number of neighborhood configurations resulting in a live cell in the next generation (in accordance with the CA transition rule) to the total number of possible neighborhood configurations. Langton then showed that *lambda* generally *increases* as we go down Wolfram's list from CA class 1 to CA class 4 (i.e., as we move from left to right on the "physical spectrum").

Langton also showed that there is a "critical region" of *lambda* within which class 3 (i.e., complex tychistic) structures can exist. Furthermore, the width of this "critical region" shrinks sharply as the total number of possible neighborhood configurations increases.²⁵¹ We may therefore identify this "critical region" of *lambda* with the "right edge of tychism", with the "left edge of chaos", with the "center of the physical spectrum", and with maximum *complexity* (as we have defined the term).

Finally, Langton suggested that living creatures maintain themselves (for as long as they can) in a class 3 (complex tychistic) state by making use of the very long transients available within the "critical region" of *lambda*.²⁵²

Particularly surprising is Langton's finding (mentioned above) that the average probability of cell survival as measured by *lambda* may actually *increase* as we move from *complex tychistic* CA systems (class 3) to *chaotic* CA systems (class 4). If we take a hierarchical perspective, however, and regard the CA patterns at each level of hierarchical organization as the "cells" for the next level up, and we furthermore define a revised "*lambda*" to be the average probability of survival of *all* of these "cells" taken together (at whatever level), then it seems intuitively obvious that the existence of a *complex tychistic* regime of organization at *every* hierarchical level would maximize revised "*lambda*" as we have redefined it. This leads us to tentatively propose a fifth *law of hierarchy*:

- For any nonlinear, far-from-equilibrium hierarchical system, the average survival rate for all entities within the system (taken together from all hierarchical levels) tends to be maximized when a *complex tychistic* organizational regime prevails at *every* hierarchical level.

That is probably one reason why the evolution of life on earth has (with some reversals) tended to result in increasing complexity within the biosphere over time (though such neo-Darwinists as Stephen Jay Gould would strenuously deny even the *fact* of such increasing complexity).

Interestingly, taking the fourth *law of hierarchy* and the fifth *law of hierarchy* together suggests that nonlinear complex hierarchical physical systems will tend to move towards their complex tychistic optimum from alternately *opposite* directions as we move up and down their holistic hierarchical levels.

Another similarity between *discrete* nonlinear CA systems and the *continuous* nonlinear complex physical systems we have previously considered is that the emergence of CA pattern-entities such as "gliders", "blinkers", "eaters", and so on is clearly an example of "macroscopic" *continuity breaking*, and many of the properties of these CA pattern entities are therefore *emergent*, *constitutive* properties of the system. As Nicolis and Prigogine put it:

Could a [CA] network . . . give rise to global "computation" patterns as a function of time featuring some new, *emerging properties* not included in the initial "programmed" units? In principle, the answer to this question is yes. . . . An attractor corresponding to a self-organizing pattern emerging through a [continuity]-breaking instability necessarily endows the system with a collective property that transcends the properties of the individual subunits.²⁵³

Russell K. Standish explains this in a way that defines the key concept of *emergent properties* with particular clarity. He takes as his example the "glider" pattern in Conway's *Life* (our Figure 29), and proposes that two

ON SYSTEMS

“languages” exist to describe this pattern, namely the *macroscopic language* (or *macro-language*) and the *microscopic language* (or *micro-language*):

An emergent phenomenon is simply one that is described by the atomic concepts available in the *macro-language*, but cannot be so described in the *micro-language*. In the case of the glider in [Conway’s] Game of Life, any attempt at describing a glider would involve the CA transition table (naturally), but also the specific pattern of cell states that make up the glider. But which pattern? A glider can appear at any location within the CA, and may have one of four possible orientations. The [*micro-*] description cannot represent the fact that two gliders separated diagonally by one cell along each axis with the same orientation are temporally related. A glider, as an object-in-itself, is a pure *macro*-description object.

. . . Of considerable interest is, given a system specified in its micro-language, does it have emergent properties? There is no general procedure for answering this question. One has to construct a macro-description of the system. If this macro-description contains atomic concepts that are not simple compounds of micro-concepts, then one has emergent properties.²⁵⁴

In spite of the many similarities we have found between the “artificial” *discrete* cellular nonlinear networks (CNNs) and the “natural” *continuous* nonlinear complex physical systems which we actually experience in the “real world”, there is one very important way in which they differ: At their lowest level of micro-description, CNNs (i.e., CAs) are resolutely and completely *deterministic*. That is, for a given system space, neighborhood, set of possible cell states, transition rule, and initial seed pattern, *every* CA system always evolves in *exactly* the same way in *every* run of the computer. Moreover, it is theoretically possible (perhaps even easy) to stop any given CA run and reverse it back to its seed pattern. Therefore, the immanent-objective features of *absolute chance* and *temporal irreversibility* that characterize *continuous* nonlinear complex physical systems are simply not present in *discrete* CNNs.

However, if we were to imagine ourselves to be ignorant of the CA micro-language and if we were to be confined to experiencing a single run of the CA, then absolute chance and temporal irreversibility *would* for us become immanent-objective features of the macro-language for that CA, as the presence of both tychistic (class 3) macro-descriptions and chaotic (class 4) macro-descriptions for CA systems clearly demonstrates.

This strongly suggests that one reason that immanent-objective absolute chance and temporal irreversibility *do* characterize *continuous* nonlinear complex physical systems is that the lowest possible (presumably deterministic) level of micro-description for such systems is simply not available to us as finite intelligent beings existing *within* the physical world. Rather, the lowest level of micro-description we can *actually* attain is

microscopically *stochastic* (i.e., quantum theory). Nor (according to quantum theory) will we ever be able to control experimental conditions sufficiently to be able to rerun a given quantum-mechanical experiment deterministically: For us, therefore, the element of immanent-objective *absolute chance* at the quantum level is simply a fact that we must accept. Consequently, *absolute chance* and *temporal irreversibility* are also immanent-objective facts of the *macroscopic* physical universe that we must accept as well.

Teleological aside: We might speculate that our view of Conway's *Life* and other discrete CAs may be analogous to how God views our continuous physical universe: deterministic at its ultimately lowest and finest level, yet still "surprising" (and even "spontaneous") at its higher levels.

Molecular Biological Systems

Our next examples of nonlinear physical complexity are taken from the field of molecular biology. This area is far too vast for us to cover in detail within this limited section: The most we can do is to present convincing evidence that molecular biological systems are, in fact, *nonlinear complex physical systems* in the sense in which we have been using that term.

Recall that John Conway based his proof that high-level self-reproducing patterns could evolve in the *Life* system space on John Von Neumann's earlier proof of self-reproduction for his cellular automaton. Recall also that each cell in Von Neumann's automaton has 29 possible states (one of which is *off*), as opposed to *Life*'s 2 states, and that the neighborhood for Von Neumann's cellular automaton is the 5-cell Von Neumann nbhd, as opposed to *Life*'s 9-cell Moore nbhd. Von Neumann's theoretical self-reproducing cellular automaton consists of the following major "macroscopic" parts:

1. A *universal constructor* capable of constructing a wide variety of patterns, depending on the instructions given to it.
2. A *duplicator* that copies any instructions given to it.
3. A *supervisory unit* that
 - a. Passes a set of instructions (the *blueprint* [item 4 below]) to the *universal constructor*, which uses those instructions to manufacture a copy of the *universal constructor*, *duplicator*, and *supervisory unit*.
 - b. Passes this same *blueprint* to the *duplicator* for copying.

ON SYSTEMS

- c. Appends the resulting copy of the *blueprint* to the output of the *universal constructor*, while retaining a copy of these instructions for itself.
4. A *blueprint* that contains instructions for manufacturing the *universal constructor*, *duplicator*, and *supervisory unit* (but *not* itself).

(The essential reason that a *supervisory unit* is needed for this process of self-reproduction is that the *universal constructor* by itself is too “dumb” to realize that a copy of the blueprint must become a part of the final copy of the self-reproducing automaton.)²⁵⁵

Now, remarkably, molecular biological systems are similar to Von Neumann’s cellular automaton in a number of ways:

- #4, the *blueprint*, is similar to the *DNA-based chromosomes*, plus the *messenger RNA* that carries DNA’s blueprint “message” to other locations within the biological cell.
- #2, the *duplicator*, is similar to the enzyme *DNA polymerase*, which rapidly “unzips” the double-stranded DNA and thus enables it to reproduce. (Duplication also occurs when the enzyme *RNA polymerase* aids in the copying of DNA to messenger RNA.)
- #1, the *universal constructor*, is similar to the living cell’s *ribosomes*, which act like automated factories, producing a wide variety of proteins in accordance with the instructions delivered by the messenger RNA. If a needed material cannot be produced directly by the ribosomes (and this is true of DNA, RNA, ATP, phosphates, etc.), then the ribosomes instead produce protein enzymes (such as the DNA polymerase and RNA polymerase we just mentioned) to do the actual work of making the needed material.
- Finally, the role of #3, the *supervisory unit*, is played by protein enzymes that “turn on” and “turn off” the various biological functions.

As William Poundstone has expressed it:

The only basic difference between organic [reproduction] and Von Neumann’s reproduction is that Von Neumann arbitrarily pictured his machine as duplicating its blueprint after the machine itself had been duplicated. In living cells, duplication of DNA takes place early in the

replication process. The construction of the new cellular “machinery” is an ongoing process, continuing even after the cell has split in two.²⁵⁶

Before continuing, we must issue three cautions with respect to the above analogy between molecular biology and Von Neumann’s theoretical self-reproducing cellular automaton: *First*, the term “blueprint” suggests something that “looks like” the thing that will be produced from it, whereas in fact the “blueprints” for both Von Neumann’s theoretical self-reproducing automaton and for real self-reproducing biological cells consist of coded instructions that look nothing like what the “universal constructor” produces using them. *Second*, terms such as “machine” and “factory”, when applied to either Von Neumann’s automaton or to a biological cell, suggest a near-equilibrium machine that is merely “the sum of its parts”, whereas in fact each is, in its own way, a *nonlinear holistic organic system* with strongly & persistently interacting parts and (therefore) many important emergent, constitutive characteristics. *Third*, ribosomes only manufacture one class of important biochemical materials needed to make a copy of the full-functioning cell (i.e., the class of *proteins*), but do not, by themselves, actually construct the full copy of the cell. By contrast, Von Neumann’s *universal constructor* actually constructs the entire copy of the automaton (excepting only the *blueprint*, which is added by the *supervisory unit*).

This analogy between Von Neumann’s nonlinear, cellular, self-reproducing automaton and the inner workings of the biological cell is our *first* piece of evidence that molecular biological systems are *nonlinear complex physical systems*.

Our *second* piece of evidence that molecular biological systems are *nonlinear complex physical systems* is the elementary fact that they *reproduce* themselves (i.e., they are *autocatalytic* systems). Furthermore, this process of reproduction is offset (but not quite *completely* offset) by the process of *death* (i.e., they are also *autoinhibitory* systems in the very broad sense in which we have defined that term). As we have seen earlier, this very close “competition” between nearly-offsetting autocatalytic and autoinhibitory processes is one characteristic feature of many nonlinear complex physical systems, especially those that exist at the “right edge of tychism” (i.e., at the “left edge of chaos”).

Furthermore, molecular biological systems are not only *macroscopically* autocatalytic and autoinhibitory: The biochemical reactions which characterize their lower-level inner workings are autocatalytic and auto-inhibitory as well. Once more we turn to Prigogine and Stengers:

Although the effects of “nonlinear” [chemical] reactions . . . are comparatively rare in the inorganic world, molecular biology has

ON SYSTEMS

discovered that they are virtually the rule as far as living systems are concerned. Autocatalysis (the presence of X accelerates its own synthesis), autoinhibition (the presence of X blocks a catalyst needed to synthesize it), and crosscatalysis (two products belonging to two different reaction chains activate each other's synthesis) provide the classical regulation mechanism guaranteeing the metabolic function.

Let us emphasize an interesting difference. In the [relatively few] examples [of nonlinear chemical reactions] known in inorganic chemistry, the molecules involved are simple but the reaction mechanisms are complex. . . . On the contrary, in the many biological examples we have, the reaction scheme is [relatively] simple, but the molecules (proteins, nucleic acids, etc.) are highly complex and specific. This can hardly be an accident. Here we encounter an initial element marking the difference between physics and biology. Biological systems *have a past*. Their constitutive molecules are the result of an evolution.²⁵⁷

Although nonlinear *biochemical* reaction schemes may be “simple” in comparison to *non-organic* nonlinear chemical reactions, they are anything but “simple” when compared to any kind of *linear* chemical reactions.

Michael Behe, in his excellent book *Darwin's Black Box*, discusses in detail five nonlinear, complex biochemical systems: the cilium or flagellum (a “tail” which some cells possess that thrashes or spins, thus propelling the cell), the blood-clotting system, the chemical transport-system within each cell, the immune system, and (finally) the cell's energy-storage system. He demonstrates that *all* of these biochemical systems (and presumably many more) are *irreducibly complex*. Behe explains:

By *irreducibly complex* I mean a single system composed of . . . interacting parts that contribute to the basic function, wherein the removal of any one of the parts causes the system to effectively cease functioning. An irreducibly complex system cannot be produced directly (that is, by continuously improving the initial function, which continues to work by the same mechanism) by slight, successive modifications of a precursor system, because any precursor to an irreducibly complex system that is missing a part is by definition nonfunctional.²⁵⁸

From Behe's definition, it would seem that the *irreducible complexity* of biochemical systems is closely related to the fact that they are *nonlinear holistic* systems comprised of parts that interact strongly *and* persistently. This impression is confirmed when we look at the details of Behe's descriptions of his five chosen biochemical systems. For example, Behe's discussion of the blood-clotting system focuses on a dizzying “cascade” of biochemical reactions which clearly involve complex patterns of autocatalysis, autoinhibition, and crosscatalysis.²⁵⁹

Behe wishes to use his concept of *irreducible complexity* to show that nonlinear complex biochemical systems could not have arisen by the linear,

minute, step-by-step process of pure microscopic random mutations being selected individually for survival value by a purely deterministic macroscopic process of natural selection, as is envisioned by neo-Darwinism. In this he succeeds brilliantly!

However, instead of proceeding to propose a *nonlinear* theory of biological evolution (such as Robert F. de Haan's theory of *macrodevelopment*, which we will consider in part 2 of this book), Behe instead proposes the theory that life on earth was *intelligently designed*. Unfortunately this violates our criterion that, insofar as possible, a scientific theory must "bracket out" references to particular subjects, including any "intelligent designer". While it is certainly a solid, transcendent *teleological* theory of the origin and development of life on earth, we must unfortunately reject *intelligent design* as a *scientific* theory of biological evolution for purposes of our future discussion.

Instead, we will strongly affirm that *nonlinear* biological processes *are* capable of creating *irreducibly complex* biological systems without the need to invoke an intelligent designer because, via continuity-breaking, such nonlinear processes are capable of suddenly organizing relatively large regions of biological "space" in an all-at-once holistic manner. (A very simple non-biological example of this is the sudden, global emergence of Benard cells.) In other words, a *nonlinear* theory of evolution (such as the theory of *macrodevelopment*) does *not* require a linear, reductionistic, minute, step-by-step, mechanical, "trial and error" assembly-line process of the kind required by neo-Darwinism.

Furthermore, we have seen that the kinds of structures created by *nonlinear* continuity-breaking are often characterized by both external *and* internal conditional equifinality, which is why such structures often contain physical analogs to teleological entities such as "decisions", "goals", "purposes", "functions", and the like. This further suggests that pursuing the study of both molecular biology and evolution from a *nonlinear* perspective is the most fruitful way to proceed from a scientific point-of-view, even though (of course) we are at present far from being able to offer precise nonlinear explanations of most biological phenomena.

Now, quite apart from his important concept of *irreducible complexity*, Michael Behe has still more to teach us concerning the holistic nature of biomolecular systems: The appendix of his book *Darwin's Black Box*, titled "The Chemistry of Life", is an excellent "crash course" in molecular biology. There we learn that there are (at least) *four* levels of organization of each protein in a biological system:

ON SYSTEMS

- The *primary structure* of the protein is simply the linear sequence of *amino acids* which comprise the protein (“like beads on a string”). One single such linear structure (also called a *polypeptide*) may consist of hundreds, or even thousands, of amino acids.
- The *secondary structure* of the protein consists of the α -*helices* (i.e., spirals) and β -*pleated sheets* into which, typically, 40% to 50% of the protein’s amino acids are twisted or folded. (The rest of the amino acids form either turns connecting the α -*helices* and β -*pleated sheets*, or else form irregular structures.)
- The *tertiary structure* is the way in which these α -*helices*, β -*pleated sheets*, and irregular structures pack against each other to form (in most cases) a compact globular shape. Behe explains:

The driving force for the packing of the helices and sheets comes from the oily nature of many protein side chains. Just as oil separates from water to form a distinct layer, so the oily, hydrophobic side chains huddle together to form a water-free zone in the interior of the protein. . . . [H]owever, . . . some protein side chains are either polar or charged, and they want to stay in the water. The pattern of oily and polar side chains along the amino acid sequence, and the need for the protein to fold so that most of the hydrophobic groups are in the interior of the protein and most of the hydrophilic groups are on the exterior, provides the information that drives a specific protein to fold to a specific [tertiary] structure.²⁶⁰

- Finally, a *quaternary structure* may arise when several different tertiary structures stick together and act as one protein unit composed of several subunits.

Now, the key points here are: Each of the *higher* levels of biological organization mentioned above is composed of parts taken from the *next-lower* level of organization which are in *strong* and *persistent* interaction. Furthermore, specifically *biological* functions and properties *emerge* at the organizational levels of the *tertiary* and *quaternary* structures and can in no way be “reduced” to the primary-structure properties of the separate amino acids strung together in a linear fashion “like beads on a string”.

For example, the key protein *hemoglobin*, which carries oxygen in the blood throughout the body, is a quaternary structure comprised of four tertiary structures. *Only* the entire quaternary structure has oxygen-binding properties: Taken separately, the four component tertiary structures have *no* oxygen-binding properties whatsoever.²⁶¹ Similarly, proteins known as *enzymes*, which catalyze biochemical reactions, must be precisely shaped at

the tertiary or quaternary level in order to bind to their biochemical target and thus enhance that target's chemical reactivity. As Behe puts it:

If it is the job of . . . [an enzyme] to catalyze a chemical reaction, then the shape of the enzyme generally matches the shape of the chemical that is its target. When it binds, the enzyme has amino acids precisely positioned to cause a chemical reaction.²⁶²

The folding of enzymes and other proteins into their proper (and critical) tertiary and quaternary structures is a reliable biological process. However, because of the extreme complexity of the strong and persistent interactions between the “parts” of the protein (with “parts” being defined at multiple levels of hierarchical organization), it is extremely difficult (and may prove impossible) for biologists to model exactly why any given protein assumes its particular tertiary or quaternary shape. David Berlinski explains:

Within the cell, most proteins fold themselves into their proper configuration within seconds. Folding commences as the protein itself is being formed, the head of an amino-acid chain apparently knowing its own tail. Some proteins fold entirely on their own; others require molecular chaperones to block certain intermediate configurations and encourage others. Just how a protein manages to organize itself in space, using only the sequence of its own amino acids, remains a mystery, perhaps the deepest in computational biology.

Mathematicians and computer scientists have endeavored to develop powerful algorithms in order to predict the three-dimensional configuration of a given protein. The most successful of these algorithms gobble up the computer's time and waste prodigally its power. To little effect. Protein-folding remains a mystery.

Just recently, IBM announced the formation of a new division, intended to supply computational assistance to the biological community. A supercomputer named Blue Gene is under development. Operating at processing speeds 100 times faster than existing supercomputers, the monster will be dedicated largely to the problem of protein folding.²⁶³

As Berlinski mentions, some proteins require other “chaperone” proteins in order to properly fold into their correct biologically-effective three-dimensional shape. Particularly striking is the case of so-called “prions”, which are the infectious proteins that cause scrapie and mad cow disease: Prions act as “traitor” chaperones that go about re-folding normal brain proteins into a shape that matches their own. These anomalous re-folded proteins then re-fold still other normal brain proteins until the death of the infected host ultimately results. Note that DNA and/or RNA “genes” are not involved at all here, and the entire process occurs at a structural level well-above that of the linear “beads-on-string” primary-structure of the proteins!²⁶⁴

ON SYSTEMS

Similarly complex structural considerations apply to the non-protein components of living systems, such as *deoxyribonucleic acid (DNA)*, which we identified earlier as the main “blueprint” containing the information needed by a biological organism in order to reproduce. DNA is a long biochemical chain like the proteins, except that it consists (at the *primary-structure* level) of many millions of *nucleotides* (rather than amino acids) strung together “like beads on a string”. (Hence it is known as a *polynucleotide*.) Each individual *nucleotide* consists of the carbohydrate *deoxyribose*, with a *phosphate group* attached to one side and one of four *bases* attached to the other side. These four bases are: adenine, cytidine, guanine, and thymine (abbreviated A, C, G, and T, respectively). Only the difference in bases distinguishes one nucleotide from another.

In the early 1960s Nobel laureates Marshall Nirenberg, Severo Ochoa, H. Gobind Khorana, and their associates proved that biological systems use each group of three nucleotide bases (which they called *codons*) to code for the production of one amino acid needed by a protein. Michael Behe explains:

Since there are sixty-four possible combinations of four bases taken three at a time, there are more than enough permutations to code for all twenty amino acids. All possible three-base “codons” are used by the cell, so the genetic code is redundant, meaning that several different codons can designate the same amino acid. For example ACT, ACC, ACA, and ACG all code for the amino acid threonine. Most amino acids have two or more codons designating them; several, however, have only one. A total of sixty-one of the possible sixty-four codons designate amino acids; the remaining three are used as “stop” codons. When the decoding apparatus encounters one of these special signals, it halts its production of protein at that point.²⁶⁵

In addition to its *primary structure*, DNA (like the proteins) also has a *secondary structure*, which in this case is the famous *double-helix* discovered by Crick and Watson in the early 1950s. That is, DNA comes as a complementary pair of polynucleotides which are wound together to form a spiral such that base C on one strand is always matched by base G on the other, and base A on one strand is always matched with base T on the other. The enzyme *DNA-polymerase* “unzips” (i.e., separates) these two complementary strands, thus enabling the DNA to reproduce by having each separated strand attract its complementary nucleotide bases. This results in two identical double-helices where once there was one.

In addition, the enzyme *RNA-polymerase* (with the help of the enzyme *topoisomerase*) can *partially* unzip a *middle* section of the DNA double-helix, so that a polynucleotide of *messenger RNA* (coding for a specific protein) can be created by matching up nucleotide bases with one of the strands of the partially opened DNA double-helix. This messenger-RNA polynucleotide is then transported to a *ribosome*, which uses it as the

blueprint to actually manufacture the desired protein in accordance with the 3-base codon code discussed above. (RNA stands for *ribonucleic acid*. It is very similar to DNA, except that the central carbohydrate of each nucleotide is *ribose*, rather than deoxyribose, the base uracil (U) replaces DNA's base thymine (T) in RNA's genetic code, and RNA does *not* form a double-helix.)

Note, however, that the above scenario of a single DNA nucleotide (codon) sequence being translated into a single messenger-RNA sequence, and thence into a single protein amino-acid sequence is not the only possibility: Not infrequently a process of *alternative splicing* occurs. Barry Commoner explains:

The molecular events that accomplish [alternative splicing] are focused on a particular stage in the overall DNA-RNA-protein progression. It occurs when the DNA gene's nucleotide sequence is transferred to the next genetic carrier – messenger RNA. A specialized group of fifty to sixty proteins, together with five small molecules of RNA – known as a “spliceosome” – assembles at sites along the length of the messenger RNA, where it cuts apart various segments of the messenger RNA. Certain of these fragments are spliced together into a number of alternative combinations, which then have nucleotide sequences that differ from the gene's original one. These numerous, redesigned messenger RNAs govern the production of an equal number of proteins that differ in their amino acid sequence and hence in the inherited traits they engender. . .

Alternative splicing can have an extraordinary impact on gene/protein ratio. We now know that a single [DNA] gene originally believed to encode a single protein that occurs in the cells of the inner ear of chicks (and of humans) gives rise to 576 variant proteins, differing in their amino acid sequences. The current record for the number of different proteins produced from a single gene by alternative splicing is held by the fruit fly, in which one [DNA] gene generates up to 38,016 variant protein molecules. . .

. . . By rearranging the single [DNA] gene's nucleotide sequence into a multiplicity of new messenger RNA sequences, each of them different from the unspliced original, alternative splicing can be said to generate new genetic information. Certain of the spliceosome's proteins and RNA components have an affinity for particular sites and, binding to them, form an active catalyst that cuts the messenger RNA and then rejoins the resulting fragments. The spliceosome proteins thus contribute to the added genetic information that alternative splicing creates.²⁶⁶

In addition to its *primary* and *secondary structure*, DNA also has a “*tertiary structure*” like the proteins (although this specific term is generally not used in connection with DNA). What we will call the DNA's “*tertiary structure*” consists of the way in which the DNA double-helix is wrapped around small blobs of a class of proteins called *histones* at regular intervals along the length of the DNA's double-helix. At this higher “*tertiary*” level of organization we therefore also have “beads on a string”, but this time the

ON SYSTEMS

histone blobs are the “beads”, while the DNA double-helix is the “string”! In the assembling of this DNA “tertiary structure”, these histone “beads” take an active role in shaping the DNA. The final resulting DNA “tertiary structure” is called a *chromosome* in the biological literature.

Microbiologists used to think that this higher-level “tertiary structure” (i.e., the chromosome structure) of DNA was of no importance. Now, however, they realize that chromosome structure is vital in determining which regions (or “genes”) of the DNA double-helix are allowed to be active, and which are suppressed. Scientists at the Cold Spring Harbor Laboratory explain:

In the August 10 [2001] issue of *Science*, Cold Spring Harbor Laboratory researcher Shiv Grewal and his colleagues report that seemingly small differences between two varieties of histone have dramatic effects on chromosome structure and gene expression. They found that “silent” regions of chromosomes – where genes are kept “off” and DNA resists genetic recombination – contain one variety of histone H3. In contrast, the researchers found that “active” regions of chromosomes – where genes can easily be switched “on” and DNA can readily recombine – contain a slightly different variety of histone H3. Histone H3 in silent DNA had a “methyl” group attached to a particular lysine amino acid, #9. Histone H3 in active DNA had a methyl group attached to a different, nearby lysine amino acid, #4. . . .

David Allis (University of Virginia), Grewal’s colleague in this and another study published earlier this year in *Science*, has proposed that in addition to the now familiar genetic code of repeating As, Cs, Gs, and Ts in the sequence of DNA, a “histone code” exists in which differentially modified histone proteins can organize the genome into active and silent regions that can be stably inherited.

Indeed, working at the National Cancer Institute in 1996, Grewal and former Cold Spring Harbor Laboratory scientist Amar Klar showed that active and silent chromosomal states can be stably inherited through mitosis (cell division) and, remarkably, through meiosis (the production of gametes such as egg and sperm). In essence, Grewal and Klar found that the Mendelian inheritance of traits sometimes depends not only on the faithful replication of DNA sequences, but also on the transmission of “higher order” chromosome structure. . . . The scientists proposed a chromosome replication model in which both the DNA molecule plus higher order chromosome structure are duplicated.²⁶⁷

Differing methylation, affecting the expression of “genes”, is not only characteristic of the histones within the chromosome, but of the DNA itself: It has been discovered that one of the DNA bases, cytosine (C), comes in a second form, *methyalted* cytosine (abbreviated mC), and that the pattern of C and mC along the DNA double-helix is related to whether any particular region (or “gene”) of the DNA double-helix is switched “on” or “off”.

All of the factors relating to whether or not a given “gene” on the DNA double-helix is actually expressed or not (and, if so, what form that “gene” expression will take) are called *epigenetic* factors. Epigenetic factors are associated not only with the DNA’s “tertiary structure” (i.e., chromosome-structure), but ultimately with the multi-level structure of the biological organism taken as a whole. For this reason, *epigenetics* has put enormous strain on the reigning linear, reductionistic, mechanical paradigm within biology – a paradigm which has tended to focus only on the linear primary structure of DNA and on the ultimately reductionistic concept of a “gene”, simplistically identified as a region of the DNA that uniquely determines a single protein, which in turn is supposed to uniquely determine a single biological “trait”.

Richard C. Strohman, Professor Emeritus of Molecular and Cell Biology at the University of California, Berkeley, sees the following problems with this reigning linear, reductionistic biological paradigm:

- **Population Biology:** Complex traits are not accessible to linear genetic analysis.
- **Disease Natural History:** Most common diseases are not genetic.
- **Evolutionary Biology:** No relationship exists between genetic and morphological complexity.
- **Developmental Biology:** There are no genetic programs.
- **Molecular and Cell Biology:** Informational redundancy confounds linear genetics.²⁶⁸

Professor Strohman elaborates on the above points:

Genetic determinism in current biomedical technology is based on the general equation of uniqueness between genes and phenotype: Unique Genes – Unique Effects (unique phenotypes). . .

. . . Essentially, the unique relationship between genes and phenotypes is flawed because most complex phenotypes (including diseases) [do not] have a unique genetic basis. Rather the relationship between genome and phenome is characterized by great complexity involving interaction between many genes, gene products, and environmental signaling. This interaction may involve 10, 100, or 1,000 or more genes for any common disease like cancer or heart diseases. . . .

. . . Diseases determined at fertilization, as Thomas McKeown has made clear, *are* based on genetic abnormalities of one kind or another. Examples are sickle cell anemia, cystic fibrosis, and Duchenne muscular dystrophy. There are literally thousands of these diseases, but they occur within the human population at extremely low frequency and account for less than 2

ON SYSTEMS

percent of our total disease load. So, only 2 percent of the time does the 'bad gene causes disease' mechanism operate. . .

. . . [T]here is [an] absence of relationship between genetic and morphological complexity of species. Some closely related species cannot be seen by expert examination to be different (have different morphology), yet they show great variation in complexity at both the genetic and protein sequence levels. Somehow organisms are able to take vastly different genomes and construct nearly identical phenomes. This cannot be explained by a simple linear genetic paradigm. Equally puzzling, humans and chimps have a very different morphology, yet humans do not differ genetically from chimps by more than one to two percent. Somehow we are able to construct very different organisms from very similar genomes; this is currently not explained by genetic theory. . .

. . . [G]enetic determinism for complex traits has assumed the notion of 'gene programs' to help explain the causal linkage between genes and phenotype. But this assumption has been found to be without experimental verification. There are no genetic programs. There are only genes that encode for proteins. . . . Genes, for example, do not control developmental traits; they only contain information necessary for the synthesis of proteins used in development – in the assembly of the organism. The control for this assembly is not found in the DNA; it is elsewhere within the cell and it depends on a vast array of information coming from many sectors of the organism. This control corresponds to epigenetic regulation. Far from being controlled by simple, linear genetic causality, development is seen to rely on a complex, *nonlinear* [process]. . .

[Finally], informational redundancy in organisms, especially within cells, confounds the uniqueness equation because more than one gene can bring about the same result. The uniqueness equation completely fails, as there is informational redundancy not only at the gene level, but the epigenetic level as well. There are many examples in the current literature of experimental biology testifying to the ability of the organism to get along without what were thought to be crucial genes. The organism, when a gene is missing, finds other genes or finds new ways (epigenetic controls) to use vast numbers of remaining genes to produce the same or highly similar phenotypes.²⁶⁹

The limits of the reigning linear, reductionistic paradigm in biology were amusingly revealed by the hype surrounding the recent completion of the human genome project, the 1.5 billion dollar national project to map all of the "genes" in all of the 23 pairs of human chromosomes. This was certainly a notable scientific achievement. However, claims that "the secret of life" had now been "decoded" were clearly overblown, and even curious laymen could see that being able to read the order of (and group into "genes") the nucleotide bases A, C, G, and T within the human genome hardly constituted an adequate linear, reductionistic explanation of human life.

As if to emphasize this point, only around 30,000 human genes were actually found (about twice the number of genes possessed by a fruit fly, or by a nematode worm), far fewer than biologists expected. Biologists “spun” this unexpected fact by saying that it proved that we humans should be humble, since we are really “nothing but” animals, hardly more complex or interesting than a fly or a worm. Laymen rightly suspected, however, that all the small number of human genes really proved was that there is far more to understanding human life than simply invoking the reductionistic concept of a DNA “gene”.

A few scientists were even willing to acknowledge this. The famous Harvard paleontologist Stephen Jay Gould, writing in the *New York Times*, observed that, thanks to the human genome project, we may finally be liberated from the “harmful and simplistic idea” that each aspect of our being, “either physical or behavioral, may be ascribed to the action of a particular gene ‘for’ the trait in question”. The collapse of the doctrine of one gene equals one protein equals one trait, “and one direction of causal flow from basic codes to elaborate totality, marks the failure of reductionism for the complex system that we call biology. . . . Organisms must be explained as organisms, not as a summation of genes.”²⁷⁰

Our final piece of evidence for the *nonlinearity* of molecular biological systems is provided by the following striking instance of *continuity breaking*, namely, the fact of the one-sided *chirality* (i.e., asymmetrical “handedness”) of virtually all biological molecules, a fact which was discovered by Louis Pasteur in 1857. Kondepudi and Prigogine explain:

The chemistry of life as we know it is founded on a remarkable asymmetry. A molecule whose geometrical structure is not identical to its mirror image is said to possess *chirality*, or handedness. Mirror-image structures of a chiral molecule are called *enantiomers*. Just as we distinguish the left and the right hand, the two mirror-image structures are identified as L- and D-enantiomers (L for “levo” and D for “dextro”; R and S is another convention for identifying the two enantiomers). Amino acids, the building blocks of proteins, and deoxyribose in DNA are chiral molecules. From bacteria to man, nearly all amino acids that take part in the chemistry of life are L-amino acids . . . and the riboses in DNA and RNA are D-ribose As Francis Crick notes: “The first great unifying principle of biochemistry is that the key molecules have the same hand in all organisms.” That is all the more remarkable because chemical reactions show equal preference for the two mirror-image forms (except for very small differences due to parity-conserving electroweak interactions).²⁷¹

The exact origins of this striking continuity-breaking asymmetry are not known, but Kondepudi and Prigogine present convincing evidence that only within a *nonlinear far-from-equilibrium* biochemical system could such a global, chiral continuity-break arise:

ON SYSTEMS

First, we note that such an asymmetry can arise only under far-from-equilibrium conditions; at equilibrium the concentrations of the two enantiomers will be equal. The maintenance of this asymmetry requires constant catalytic production of the preferred enantiomer in the face of interconversion between enantiomers, called *racemization*. (Racemization drives the system to the equilibrium state in which the concentrations of the two enantiomers will become equal.) Second, following the paradigm of order through fluctuations, we [can] see how in systems with appropriate chiral autocatalysis, the thermodynamic branch, which contains equal amounts of L- and D-enantiomers, can become unstable. The instability is accompanied by the bifurcation of asymmetric states, or states of broken [continuity], in which one enantiomer dominates. Driven by random fluctuations, the system makes a transition to one of the two possible states.²⁷²

Morphogenesis

Of all of the examples of *continuity breaking* in nonlinear complex physical systems, the most awesome and spectacular is perhaps the process of *morphogenesis*, i.e., the process by which the embryo of a living organism transforms from being comprised of generic *stem cells* to being comprised of a set of increasingly specific cells organized regionally into biological *organs*, each organ having a separate, but coordinated, biological function. Clearly this is not a linear, reductionistic, assembly-line process, but rather a nonlinear, holistic process that is characterized by both *continuity-breaking* and *conditional equifinality*.

As is typical of many other tychistic nonlinear physical processes, the *conditions* involved in morphogenesis are both *external* and *internal*. *External* conditions include the maintenance of the embryo's temperature within a certain range, the supplying of the proper amount and kind of food to the embryo, etc. By contrast, *internal* conditions include all of the "decisions" which the embryo makes during its development, such as: the sex of the developing organism, which "traits" will be taken from the mother and which from the father, and so on.

Furthermore, the *equifinality* aspect of morphogenesis is shown by the fact that (as Hans Driesch discovered in the early 1900s) severely disturbing and rearranging some types of embryos at an *early* stage of their development does not affect the final outcome: The embryo still ultimately organizes itself in such a way as to develop normally.²⁷³ However, if the embryo is experimentally disturbed and rearranged at a *later* stage of its development, the embryo will *not* be able to recover and develop normally. This shows that *equifinality* is a key characteristic of morphogenesis, but that it is a *conditional equifinality* (in this case, *externally* conditional on *when* the

embryo is experimentally disturbed and rearranged). Prigogine and Stengers comment:

[W]hen we observe embryological development on film, we “see” jumps corresponding to radical reorganizations followed by periods of more “pacific” quantitative growth. There are, fortunately, few mistakes. . .

Many years ago embryologists introduced the concept of a morphogenetic field and put forward the hypothesis that the differentiation of a cell depends on its *position* in that field. But how does a cell “recognize” its position? One idea that is often debated is that of a “gradient” of a characteristic substance, of one or more “morphogens”. Such gradients could actually be produced by [continuity]-breaking instabilities in far-from-equilibrium conditions. Once it has been produced, a chemical gradient can provide each cell with a different chemical environment and thus induce each of them to synthesize a specific set of proteins. This model, which is now widely used, seems to be in agreement with experimental evidence. In particular, we may refer to [Stuart] Kauffman’s work on drosophila. A reaction-diffusion system is taken as responsible for the commitment to alternative development programs that appear to occur in different groups of cells in the early embryo. Each compartment would be specified by a unique combination of binary choices, each of these choices being the result of a spatial [continuity]-breaking bifurcation.²⁷⁴

The details of this awesome nonlinear process of morphogenesis are at present far beyond our ability to fully understand. But certainly one reason for the extreme complexity of morphogenesis is the fact that morphogenic processes are going on at a number of hierarchical levels simultaneously. Now, at any given *higher* hierarchical level, a nonlinear complex physical system is constantly presented with fluctuations emerging from the *next-lower* hierarchical level. Most of these fluctuations are suppressed (more accurately, *controlled*), but occasionally a fluctuation, or set of fluctuations, is amplified and becomes an instance of continuity-breaking at that next-higher level. Notice, however, that the only fluctuations which can “get through” from this next-lower hierarchical level (and therefore be processed at all at the next-higher hierarchical level) are those which have *not* been suppressed/controlled at that lower level and have therefore become lower-level *continuity breaks*. In other words, what emerges from the lower-level is a “randomness” which has *already* been *constrained* (or “filtered”). This suggests a sixth *law of hierarchy*, which we may tentatively add to the five laws of hierarchy which we have previously formulated:

- In nonlinear complex physical systems, *continuity breaks* at a lower hierarchical level become the *fluctuations* for the next-higher hierarchical level.

ON SYSTEMS

In other words, a “decision” made at a *lower* hierarchical level is generally *controlled* (or even suppressed) at the *next-higher* hierarchical level, but very occasionally it is instead *amplified* and *transformed*, becoming a “decision” at that *next-higher* hierarchical level as well. Erich Jantsch has expressed this aspect of morphogenesis very well:

Up to now, all attempts to find valid formulations for morphogenesis at each level are based at best on a view which considers the interaction of stochastic and deterministic factors from an angle of view pertaining to a single level only. . . All processes which impinge on this level from another level are considered as random. But what is the meaning of “randomness” in the context of multilevel evolution in which each level brings new ordering principles into play? How random is the fluctuation which is introduced into a system by one of its members or by an outsider if this individual is itself the product of a long evolutionary chain and of its own ontogeny? . . . Indeterminacy is the freedom available at each level which, however, cannot jump over the shadow of its own history. Evolution is the history of an unfolding complexity, not the history of [purely] random processes. Out of this fog emerge the contours of a world in which . . . much is indetermined and free within limits.²⁷⁵

The Basic Logistic Equation

Our next example illustrates two possible behaviors of nonlinear systems which we discussed in some detail in our earlier chapter on **Nonlinear Dynamic Systems**, but which we have not yet discussed in detail in this chapter on **Nonlinear Complex Physical Systems**. These two behaviors are *periodic behavior* (also known as *limit-cycle behavior*) and *chaotic behavior*. The example we will choose to illustrate these two behaviors is the nonlinear complex physical system that is defined by the well-known *logistic equation*.

Let $f(x)$ be a map function whose domain/range are the real numbers between 0 and 1. Let $\{x_1, x_2, x_3, x_4, \dots\}$ be the orbit of $f(x)$ starting at x_1 , which is a randomly selected initial value between 0 and 1. Furthermore, let this map function $f(x)$ be defined by the following equation:

$$x_{n+1} = r x_n (1 - x_n) \quad (8)$$

Equation 8 is one version of the basic *logistic equation*.

To give this logistic equation some biological meaning, let's say that x_n represents an organism's population within a simple ecosystem (expressed as a fraction of the total ecosystem *carrying capacity* of 1 for that organism) during the *current* generation, while x_{n+1} represents this population fraction of total *carrying capacity* during the *next* generation. The variable r represents the organism's *reproductive* rate, or fecundity rate (which is associated with such environmental factors as the availability of food, etc.). It is then easy to

see that the right side of equation 8 can be split into two parts: Factor $r x_n$ represents the *autocatalytic* part (“the more of x in the current generation, the more of x in the next generation”), while factor $(1 - x_n)$ represents the *autoinhibitory* part (“the more of x in the current generation, the less of x in the next generation”). Once again, as is typical for many nonlinear physical systems, autocatalysis and autoinhibition nearly offset one another – but not quite. Put in simplified biological terms, factor $r x_n$ is associated with the rate of *reproduction* for the organism, while factor $(1 - x_n)$ is associated with an increasing rate of *death* for the organism as the ecosystem reaches its carrying capacity for that particular organism.

Notice also that, taken separately, the factors $r x_n$ and $(1 - x_n)$ are *linear*. However, when multiplied together (as in equation 8), they equal $-r x_n^2 + r x_n$ thus making equation 8 a *nonlinear* (in this case *quadratic*) equation in x .

Let’s now try the following mathematical experiment: Let r assume continuous values from 1 up to 4. For each such value of r , let’s select a random initial seed value for x_1 between 0 and 1 and begin iterating the logistic equation. Ignore the first 100 iterations, then start plotting the orbit of x for that value of r . The result is shown in Figure 31, below:

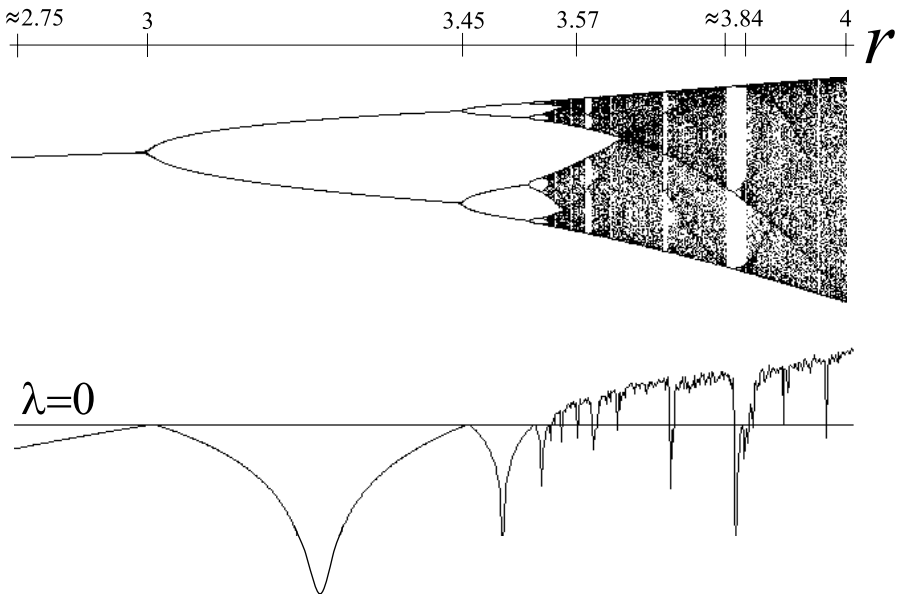


Figure 31 (based on the Dynamic Solver example file *liapunov.ds* and on figure 1.6 on page 19 of Alligood, Sauer, and Yorke)

The matching graph below the main graph in Figure 31 shows the *Lyapunov exponent* λ for the orbit of x associated with each value of r . (Values of this

ON SYSTEMS

Lyapunov exponent which are *above* the zero line indicate probable *chaotic* orbits of x , as we saw in our chapter on **Nonlinear Dynamic Systems**.)

Next, let's describe how the basic logistic equation (equation 8) behaves for each range of the value of r :

- For $r = 1$ (and for $0 \leq r < 1$), x stabilizes to a *sink* (i.e., an *attractor*) at $x = 0$. In other words, if the rate of reproduction r is 1 or less, the organism soon dies out. (This range of r is *not* shown in Figure 31.)
- For $1 < r < 3$ the value of x eventually stabilizes to a *sink* (i.e., an *attractor*) at a value of $x = (r - 1)/r$. In other words, for r within this range, the population level x settles to a constant value that is greater the greater the reproductive rate r itself is. The basic reason x stabilizes to a *sink* within this range of r is that the absolute value of the first derivative of the logistic equation at $x = (r - 1)/r$ is less than 1 within this range, i.e. $|f'(x)| < 1$ at $x = (r - 1)/r$. However, if $r > 3$, then the point $x = (r - 1)/r$ is no longer a sink, but rather becomes a *source* (i.e., a *repeller*), since then $|f'(x)| > 1$. (Note that only the small highest-portion of this range of r , between approximately 2.75 and 3, is shown in Figure 31.)
- For $3 < r < 3.45$ the orbit of x becomes a *periodic attractor* of period 2. In other words, x eventually settles into a state in which it jumps between two different x values on alternate iterations of the logistic equation, as can be clearly seen in Figure 31.
- For $3.45 < r < 3.57$ the orbit of x is a *periodic attractor* of ever-increasing periodicity: first 4, then 8, then 16, 32, 64, 128, etc. In other words, as r increases within this range, we get a *period-doubling cascade*, until, at around $r = 3.57$, *chaotic* behavior emerges. Such a *period-doubling cascade* is one common way in which *chaos* may be approached within a physical system.
- For $3.57 < r < 4$ the orbit of x generally “stabilizes” into an attracting *infinite* set of points known as a *chaotic attractor*. Remarkably, however, there are a few periodic “windows” within this range of r values. For example, within the range of r that is around 3.84 (i.e., $3.82 < r < 3.86$) a periodic attractor of period 3 emerges for a while. Such periodic “windows” within this logistic-equation chaos (which can be clearly seen as white, vertical bands in Figure 31) are strongly reminiscent of the “islands” of KAM curves within the “stochastic sea” of dynamic chaos, which we discussed in our earlier chapter on **Nonlinear Dynamic Systems**. Notice too that the value of the

corresponding *Lyapunov exponent* spikes strongly, but briefly, below zero during these periodic “windows” within the chaos.²⁷⁶

Some important observations:

First, we note that values such as 2.75, 3.45, 3.569, 3.82, 3.84, and 3.86 in the above discussion are only approximate values. (For example 3.45 is only an approximation for $1 + \sqrt{6}$.)

Second, we note that the point plotted on the graph in Figure 31 at $r = 3$ is known as a *bifurcation point* (as are similar points at $r = 3.45$, etc.), and the graph as-a-whole is known as a *bifurcation graph*. However, unlike in our earlier figures, these bifurcation points do *not* represent points at which the system branches to one of two possible behaviors. Instead, they are points at which the *periodicity* of the system radically changes. For example, at $r = 3$ the periodicity changes from 1 to 2, and the stable orbit of x starts to alternate between *two* values, while at $r = 3.45$ the periodicity changes from 2 to 4, and the stable orbit of x starts to alternate between *four* values, and so on. Notice also that at each bifurcation point the value of the Lyapunov exponent spikes briefly but strongly upward to zero (i.e., to the “edge of chaos”) and then sharply back down again when the next periodic regime is established. (The Lyapunov exponent is less than zero throughout each individual periodic regime, as might be expected.)

When an orbit of x settles down to cycle continuously between several periodic values, we have what is known as *limit-cycle behavior* within the system. Limit-cycle behavior is quite common within nonlinear complex physical systems. For example, the biological system of bacteria in a food medium in a Petri dish is (approximately) an example of a system governed by the logistic equation, and a regular, periodic, up-and-down rhythm in bacteria population has in fact often been observed within such systems. Another example of nonlinear limit-cycle behavior is that of *chemical clocks*, such as the famous *Belousov-Zhabotinski (BZ)* reaction in which a mixture of cerium sulfate, malonic acid, and potassium bromate (all dissolved in sulfuric acid) alternates sharply and regularly in a clock-like manner between being yellow-tinted and being colorless, with each stage lasting anywhere from several minutes down to a fraction of a minute.²⁷⁷

Biological rhythms of all kinds, superimposed on one another at all hierarchical levels, may also be regarded to be examples of limit-cycle behavior. Erich Jantsch writes:

The coupling of the endogenous rhythms of biological systems (i.e. the rhythms due to their own dynamics) with cosmic rhythms is an essential aspect of the co-evolution of life and its environment. . . . Circadian rhythms (meaning in literal translation “approximately of the period of

ON SYSTEMS

one day”) have, of course, to do with the alternation of day and night, light and darkness, which is of decisive importance for most life forms. Many basic activities of life are organized in circadian rhythms, ranging from biochemical processes within the cell and in the communication between cells to co-coordinated process systems in the organism as a whole.²⁷⁸

Perhaps the most personal example of nonlinear biological limit-cycle behavior is the beating of the human heart. An important feature of the human heartbeat (and of all other *nonlinear* periodic attractors) is their great stability in the face of perturbations, as compared to *linear*, near-equilibrium mechanical clocks, such as the ordinary pendulum. Nicolis and Prigogine explain:

An oscillator with which each of us is intimately familiar throughout our lives is the human heart. It beats more-or-less regularly at about 70 or 80 beats per minute for the average individual . . . Suppose now that because of some perturbation, the pattern of oscillation – the normal heart beat rhythm – is upset. Since the human system is subject to a great many perturbations every day, if the heart functioned as the pendulum does, fibrillation [the sudden inability to perform the complete set of muscular actions that constitute an entire heartbeat] could well have occurred in the embryo, before birth. But the heart is not like a pendulum, it does not “remember” the effect of a perturbation by permanently changing its pattern of oscillation; if no permanent damage has occurred and the cause of the perturbation is removed, the heart resumes its normal rhythm. This is true of any other reproducible phenomenon observed in nature, from circadian rhythms and the cell division cycle to the change in luminosity of variable stars, the cepheids. The fact that these and all other reproducible rhythmic phenomena observed in nature belong to the same realm as the oscillations in the BZ reagent shows the tremendous importance of irreversibility and dissipative systems.²⁷⁹

Let’s return now to physical systems that are defined by the logistic equation: We have seen that the predicted periodicity has actually been observed in bacteria populations growing in a food medium in a Petri dish. But what of chaotic behavior? It turns out that, for simple ecological systems that are defined by the logistic equation, the value of r never gets so high that the chaotic regime is reached. However, for more-complex ecologies, such as those that can be modeled using the nonlinear Lotka-Volterra predator-prey equations, there is some evidence that chaos *can* arise in ecological systems. In their article “Bifurcations and Chaos in Ecology: Lynx Returns Revisited”, Javier G.P. Gamarra and Ricard V. Sole write:

The most famous compilation of population data along time comes from the well-known two centuries [of] statistics of [the] Canadian lynx . . . fur trade compiled from the Hudson’s Bay Company archives. . . . Its meaning and interpretation have been a matter of controversy over the last fifty years. . . [M]ost of the theories found a ten-year cycle in lynx returns. . .

... [A]n alternative theoretical framework for the lynx case was developed by Gilpin (1973, 1979). Based on continuous Lotka-Volterra 3D equations, the model was able to display chaos. Further work, using the technique of attractor reconstruction (Takens 1981) showed that a three-dimensional system could be responsible for lynx fluctuations, suggesting that three variables (lynx, hare and vegetation) might be at play (Schaffer 1984, 1985). . .

... The introduction of [a] trapping effort as the “intervention variable” shows . . . that a period-doubling route to chaos might have acted over the system.²⁸⁰

To conclude our discussion of the basic logistic equation (equation 8, above), it is important to point out that, so long as the value of r is between 1 and 4 (exclusive), it does not matter which initial seed value of x we choose, provided only that this initial x is between 0 and 1 (exclusive): In all of these cases the orbit of x will eventually settle down to the periodic or chaotic attractor for r that is shown in the bifurcation diagram in Figure 31. However, if $r = 4$ then this is no longer the case: Instead, if $r = 4$, then the n th iteration of the logistic equation has 2^n fixed points, and the situation becomes even more complicated.²⁸¹

The General Logistic Equation

So far we have been discussing the basic logistic equation (equation 8), in which the “carrying capacity” of the system is regarded as fixed and is represented by the numeral 1. If, instead, we replace this numeral 1 with a new carrying-capacity parameter K , we get the following general version of the logistic equation:

$$x_{n+1} = r x_n (K - x_n) \quad (9)$$

In this context, ecologists like to talk about r -strategies versus K -strategies for survival. Prigogine and Stengers explain:

In this view, the typical evolution for a prey population will be the increase in the reproduction rate r . [By contrast,] the predator will evolve toward more effective ways of capturing its prey – that is, toward an [increase in] K . But this [increase in K], defined in a logistic frame, is liable to have consequences that go beyond the situations defined by logistic equations.

As Stephen J. Gould remarked, a K strategy implies individuals becoming more and more able to learn from experience and to store memories – that is, more-complex individuals with a longer period of maturation and apprenticeship. This in turn means individuals both more “valuable” – representing a larger biological investment – and characterized by a longer period of vulnerability. The development of “social” and “family” ties thus appears as a logical counterpart of the K strategy. From that point on, other factors, besides the mere number of individuals in the population,

ON SYSTEMS

become more and more relevant, and the logistic equation measuring success by the number of individuals becomes misleading. . .

. . . We cannot ask the same questions about a population of flies that reproduce and die by millions without apparently learning from or enlarging their experience and about a population of primates where each individual is an entanglement of its own experiences and the traditions of the populations in which he lives.²⁸²

As a specific example of a system in which the carrying capacity K varies as the system evolves, let's consider the following highly simplified model of a particular human society: Imagine a total human population of N people, each of whom can continuously "choose" either option α or option β . At any given time, which we'll call "the current time", X_α people out of the total population N have "chosen" and are living in accordance with option α , while X_β people out of the total population N have "chosen" and are living in accordance with option β . Furthermore, everyone in population N are considered always to have "chosen" (and therefore to be living in accordance with) either option α or β , so that it is always true that $X_\alpha + X_\beta = N$. (I have placed the words "choose" and "chosen" in quotation marks to indicate that we are here referring to that *physical* process which is the analog of the *teleological* process of *choosing* between options.)

In addition, we also define A_α and A_β to be the "attractiveness" of options α and β , respectively, at the current time. (Again, "attractiveness" is in quotes because it is the objective physical analog of the average subjective attractiveness of α and β with respect to the individuals in the whole population N at the current time.)

Nicolis and Prigogine now explain:

Clearly, the relative number of individuals wishing to switch to choice β will be proportional to the number of those having adopted some other choice, like α , multiplied by the relative attractiveness of β : $A_\beta/(A_\alpha + A_\beta)$. Similarly, those individuals wishing to leave choice β in favor of α will be proportional to X_β multiplied by the relative attractiveness of α : $A_\alpha/(A_\alpha + A_\beta)$.²⁸³

This suggests the following equation as a model for the rate of change in X_α over time t :

$$dX_\alpha/dt = r X_\alpha [X_\beta A_\alpha / (A_\alpha + A_\beta) - X_\alpha A_\beta / (A_\alpha + A_\beta)] \quad (10)$$

In this equation r represents the rate of recruitment per individual to choice α , while the expression between brackets indicates the number of X_β individuals currently wishing to switch to choice α , minus the number of X_α individuals currently wishing to switch to choice β . Multiplying r times X_α times the

bracketed expression gives us an approximate measure of the rate of change in X_α over time (i.e., dX_α/dt).

But, since, by hypothesis, $X_\alpha + X_\beta = N$ and therefore $X_\beta = N - X_\alpha$, we can substitute $N - X_\alpha$ for X_β in equation 10 and algebraically simplify, resulting in:

$$dX_\alpha/dt = r X_\alpha [N A_\alpha / (A_\alpha + A_\beta) - X_\alpha] \quad (11)$$

Comparing equation 11 to equation 9 we see that the only differences between the two equations are:

- Equation 11 is a *continuous* equation, whereas equation 9 is a *discrete* equation.
- The expression for the carrying capacity of the system in equation 9 is K . By contrast, in equation 11 the carrying capacity of the system is expressed by $N A_\alpha / (A_\alpha + A_\beta)$, which is the number of people who would want to switch to α at the present time if *everyone* was currently an X_β .

Nicolis and Prigogine continue their explanation:

[W]e see that the existence of options affects the carrying capacity of the system and makes it, through the dependence on the attractiveness on the X 's, a function of the instantaneous state.

The above discussion can easily be extended to an arbitrary number of choices. . . and to the more realistic situation in which the attractiveness of an option i depends on the particular population j envisioning this option. . .

[For example,] consider the development of an urban center as certain areas specialize in specific economic activities and as residential segregation produces neighborhoods differing in their living conditions and access to jobs and services. . .

. . . As the equations are highly nonlinear, it is expected that there will be several solution branches exhibiting a complicated set of bifurcation phenomena. Different initial conditions will place the system in different basins of attraction, thus switching on different evolutions, different histories. . .

Numerical solution of the equations of the model establish unequivocally the existence of a large number of solutions and of intricate bifurcation phenomena. Starting from a space in which variables are initially distributed at random, we observe the gradual emergence of an organized pattern with its own administrative and business centers, its industrial zones, its shopping centers, and its residential neighborhoods of varying qualities. In the absence of any massive disturbance the pattern remains stable indefinitely. This spontaneous [continuity] breaking is very similar to the formation of spatial structures in hydrodynamics and chemical kinetics . . .

ON SYSTEMS

. . . If a new activity is launched at a certain time, it [may] grow and stabilize. If the place is well chosen, it may even prevent the success of similar attempts made nearby at a later time. However, if the same activity is launched at a different time, it need not succeed; it may regress to zero and represent a total loss. This illustrates the dangers of short-term, narrow planning based on the direct extrapolation of past experience. Such static [linear, reductionistic] methods threaten society with fossilization or, in the long term, with collapse.²⁸⁴

In their book *Order Out of Chaos*, Ilya Prigogine and Isabelle Stengers describe nonlinear socio-economic models from a different, but complementary perspective:

A set of equations extending the logistic equations is constructed, starting from the basic supposition that populations tend to migrate as a function of local levels of economic activity, which thus define a kind of local “carrying capacity”, here reduced to an “employment” capacity. But the local population is also a potential consumer for locally produced goods. We have, in fact, a double positive feedback, called the “urban multiplier”, for local development: both the local population and the economic infrastructure produced by the already-attained level of economic activity accelerate the increase of this activity. But each local level of activity is also determined by competition with similar centers of activity located elsewhere. The sale of produced goods or services depends on the cost of transporting them to consumers and on the size of the “enterprise”. The expansion of each such enterprise depends on a demand that this expansion itself helps to create and for which it competes. Thus the respective growth of population and manufacturing or service activities is linked by strong feedback and nonlinearities.²⁸⁵

There are many other fascinating aspects of nonlinear complex physical systems (and the mathematics that can describe them) which we do not have time to go into in this short chapter. Interested readers are referred to discussions of such topics as: fractals,²⁸⁶ catastrophe theory,²⁸⁷ the Lorenz attractor,²⁸⁸ and the Rossler attractor²⁸⁹ in such books as *CHAOS: An Introduction to Dynamical Systems* by Kathleen Alligood, Tim Sauer, and James Yorke, *ORDER OUT OF CHAOS: Man’s New Dialogue with Nature* by Ilya Prigogine and Isabelle Stengers, and *THE SELF-ORGANIZING UNIVERSE: Scientific and Human Implications of the Emerging Paradigm of Evolution* by Erich Jantsch.

The Anglo-American Bias Against Nonlinear Science

From all that we have previously said it is clear that nonlinear science is the science of the future, if for no other reason than that the vast majority of scientific phenomena that we experience in our everyday lives are either tychistic or (more rarely) chaotic, rather than being deterministic or stochastic. Nevertheless, there exist strong philosophical biases *against*

nonlinear science and *in favor of* linear science, especially in Anglo-American countries, where the mechanical, reductionistic tone of Newtonian and neo-Darwinian thinking remain strong.

For example, we noted at the end of our chapter on **Nonlinear Dynamic Systems** that nonlinear science is often unfairly faulted for failing to provide accurate deterministic predictions of the future (or retrodictions of the past): At best (because of the immanent-objective fact of absolute chance) it can only provide numerical computer simulations that are *similar to* their real-world counterparts in some important respects. That is why nonlinear scientists are frequently accused of “just playing with computers” and why the prominent neo-Darwinist John Maynard Smith has attacked the artificial-life work of Chris Langton and Stuart Kauffman as being “basically a fact-free science”.²⁹⁰ That is also the reason for P. Hohenberg’s oft-quoted remark concerning Ilya Prigogine’s theory of nonlinear thermodynamics and dissipative structures: “I don’t know of a single phenomenon his theory has explained”, a remark made *after* Prigogine won the Nobel Prize in chemistry!

But consider this: Suppose (as a worst-case scenario) that the nonlinear scientific theories of Ilya Prigogine, Chris Langton, Stuart Kauffman, Erich Jantsch, etc. are *all* wrong. Even then, we have seen that the mere existence of strong *and* persistent interactions between *three* or more parts within a physical system is enough to *require* nonlinear equations to describe that system. This discovery by Henri Poincare during the late 1900s should *by itself* have been the death of the all-embracing linear, reductionistic program in Anglo-American science. That this linear, reductionistic program continues virtually unabated in Britain and America over 100 years later is a powerful testimony to the strength of ideology (as opposed to facts) in the formation and maintenance of scientific paradigms.

Many Anglo-American scientists have become especially uncomfortable with nonlinear science now that its focus has shifted from *chaos* to *complexity* (i.e., what we have termed *tychism*). For complex tychistic physical entities clearly are often characterized by external *and* internal conditional equifinality, strongly suggesting such teleological analogs as *decisions*, *goals*, *purposes*, and *functions*. Yet the prestige of scientists within secular Anglo-American society is closely tied with their presumed ability to deliver a teleologically “meaningless and senseless” universe as a *tabla rosa* on which the radically autonomous human individual can write his will unencumbered. Such, then, is their dilemma.

Interestingly, Anglo-American advocates of creationism, intelligent design, and vitalism are scarcely less hostile to nonlinear science than are the reductionists, since they basically agree with the reductionists that, physically,

ON SYSTEMS

life is “nothing but” an intricate, linear, near-equilibrium machine: They disagree with the reductionists only in wanting to super-add spiritual, metaphysical, or teleological causation to physical causation within the realm of science.

Seven Laws of Hierarchy

Of course, much work still needs to be done in order to develop compelling nonlinear scientific theories for many phenomena in nature, especially phenomena which arise in the biological sciences. In many ways nonlinear science is still in its infancy. Advances in nonlinear mathematics are also urgently needed, especially to deal with the problem of the interaction between nonlinearity and hierarchy in physical systems: We are still very far from having an adequate and comprehensive nonlinear theory of hierarchy. The importance of finding such a theory is reflected in Piero Scaruffi’s definition of a “living organism” (which follows similar definitions by Ludwig von Bertalanffy and others):

[A] living organism can be viewed as a *hierarchical* order of open [i.e., *nonlinear*] systems, where each level maintains its structure thanks to a continuous change of components at the next-lower level.²⁹¹

Throughout our chapters on **Linear Thermodynamic Systems** and **Nonlinear Complex Physical Systems** we have tentatively proposed six *laws of hierarchy*. Let’s restate them here without comment, and then see if we can add one more:

1. The definition of a *summative characteristic* is “passed up” hierarchical levels of organization *essentially unchanged*. Furthermore, in many (but not all) cases the value of a summative characteristic can simply be summed up the hierarchy.
2. A *constitutive characteristic* (a.k.a. “emergent property”) arises at a particular level of physical organization and is associated with the configurational and structural aspects of systems at that level of organization *taken as a whole*. Although often related to the summative (and constitutive) characteristics of the system’s components, a constitutive characteristic can never be merely “reduced” to summative characteristics. Furthermore, a constitutive characteristic may be both *immanently objective* and *transcendently objective*, or it may be *immanently objective* only.
3. A *constitutive characteristic* that arises at a lower hierarchical level may be “passed up” to a higher hierarchical level, but only if it is *transformed* to allow for the (often significant) differences between the

configurational/structural features of the higher level and the configurational/structural features of the lower level.

4. Whenever a physical system, considered from the point-of-view of a *higher* level of hierarchical organization, moves from left-to-right across the “physical spectrum” (or vice-versa), then that same physical system, considered from the point-of-view of the *next lower* level of hierarchical organization, tends to move in the *opposite* direction across the “physical spectrum”. (The “physical spectrum” is, from left to right, *deterministic-tychistic-chaotic-stochastic*.)
5. For any nonlinear, far-from-equilibrium hierarchical system, the average survival rate for all entities within the system (taken together from all hierarchical levels) tends to be maximized when a *complex tychistic* organizational regime prevails at *every* hierarchical level.
6. In nonlinear complex physical systems, *continuity breaks* at a lower hierarchical level become the *fluctuations* for the next-higher hierarchical level.

To these six laws of hierarchy let’s now add a seventh law, which Ludwig von Bertalanffy calls the *principle of progressive mechanization*:

7. Nonlinear complex physical systems tend to evolve in such a way that the relationship between the parts at any given holistic hierarchical level become increasingly *mechanically* hierarchical *within* that holistic hierarchical level.

Here, then, we must make a distinction between two kinds of hierarchy: All of our uses of the word *hierarchy* prior to this point refer to what we will here call *holistic hierarchy*. In a *holistic hierarchy* the higher level *completely includes* the next-lower level. For example, in the case of a corporation such as the General Electric Corporation, the corporation-level completely includes the departmental-level, which in turn completely includes the level of the individual employees. By contrast, a *mechanical hierarchy* exists entirely *within* a single level of a holistic hierarchy and consists of a *specialization* in the function of the parts, together with the establishment of a structure of *leading parts*, each of whose special functions strongly influence the workings of the parts which are below them in the mechanical hierarchy. With respect to our example of General Electric Corporation, a model of a *mechanical hierarchy* within the employee-level of the holistic hierarchy would be an *organization chart* showing Jack Welch as president of the corporation at the top of the pyramid, a number of vice-presidents immediately under him, a larger number of senior managers below them, a still-larger number of departmental managers below them, and so on. Each

ON SYSTEMS

vice-president has a more-specialized function than the president (e.g., information, sales, manufacturing, financial), and specialization increases as we move down through the lower levels of the mechanical hierarchy. (A similar mechanically hierarchical organization chart could, of course, be constructed using the departments within the departmental-level of the holistic hierarchy.)

We have chosen the term *mechanical hierarchy* because, to the extent that there is a *specialization* in the function of the parts, the whole can be viewed as “merely the sum of its parts”: Just add up the functions of the specialized parts taken separately and you have, to a large extent, defined the functions of the whole. In other words, to the extent that a given level within the holistic hierarchy is organized as a mechanical hierarchy, it may be regarded to be a *near-equilibrium machine* that is defined by linear laws.

This *principle of progressive mechanization* is especially evident in the realm of biology, as von Bertalanffy explains:

Organisms *are not* machines; but they can to a certain extent *become* machines, congeal into machines. Never completely, however; for a thoroughly mechanized organism would be incapable of reacting to the incessantly changing conditions of the outside world. The *principle of progressive mechanization* expresses the transition from undifferentiated wholeness to higher function, made possible by specialization and “division of labor”; this principle implies also loss of potentialities in the components and regulability in the whole.

Mechanization frequently leads to establishment of *leading parts*, that is, components dominating the behavior of the system. Such centers may exert “trigger causality”; i.e., in contradistinction to the principle, *causa aequat effectum*, a small change in a leading part may by way of *amplification mechanisms* cause large changes in the total system. In this way a [*mechanical*] *hierarchical order* of parts or processes may be established.²⁹²

Progress is possible only by subdivision of an initially unitary action into actions of specialized parts. This, however, means at the same time impoverishment, loss of performances still possible in the undetermined state. The more parts are specialized in a certain way, the more they are irreplaceable, and loss of parts may lead to the breakdown of the total system. To speak Aristotelian language, every evolution, by unfolding some potentiality, nips in the bud many other possibilities. We may find this in embryonic development as well as in phylogenetic specialization .

.²⁹³

Neglect of the principle of progressive mechanization and centralization has frequently led to pseudo-problems, because only the limiting cases of independent and summative elements, or else complete interaction of equivalent elements were recognized, not the biologically important intermediates.²⁹⁴

We may relate this *seventh* law of hierarchy to the *fourth* and *fifth* laws of hierarchy as follows: In accordance with the *fourth* law of hierarchy, *progressive mechanization* at a particular level within the holistic hierarchy represents a *leftward* shift on the “physical spectrum” (from tychism towards determinism) within that level. But this is the necessary price to be paid for an opposite *rightward* shift on the “physical spectrum” (from determinism towards tychism) at the *next-higher* holistic level. This rightward shift significantly enhances the flexibility and survivability of the entities at that next-higher holistic level. However, the overall increase in survival value resulting from progressive mechanization is limited by the *fifth* law of hierarchy, which states that the maximum survivability for *all* entities at *all* levels of the holistic hierarchy occurs when tychism prevails at *all* of these holistic levels. (This corresponds to von Bertalanffy’s observation, above, that the downside of mechanistic specialization is that it renders organisms vulnerable to a single point of failure.)

From this seventh law of hierarchy (the *principle of progressive mechanization*) it is clear that linear theories will continue to be important in this coming age of nonlinear science: In other words, linear, reductionistic theories (such as Richard Dawkins’ theory that organisms are robots driven deterministically by their genes) will continue to have value. What will no longer have value, however, is the *philosophy* of reductionism, according to which all nonlinear scientific theories are to be rejected, mocked, and annihilated.

In **PART 2: ON EVOLUTION** we will examine in detail one particular, but very important, instance of a radical conflict between a *linear* scientific theory (*neo-Darwinism*) and a *nonlinear* scientific theory (Robert F. DeHaan’s theory of *macrodevelopment*). Meanwhile, let’s consider briefly what the ubiquitous existence of nonlinear complex physical systems suggests with respect to teleological analogs.

Teleological Implications of Nonlinear Complex Systems

Many of the most interesting teleological systems that are analogous to nonlinear complex physical systems are those analogous to *biological* systems. The most obvious (and, in a sense, least controversial) is the *human self*, which is the teleological analog of the physical human body. The decisions, goals, moral actions, and thoughts which are such deep teleological characteristics of the human self undoubtedly have corresponding physical analogs with structures and events within the human body, which (like all biological organisms) is physically characterized by both external *and* internal conditional equifinality. (Of course, at present we are far from being

ON SYSTEMS

able to specify the exact nature of these physical structures and events.) That is why the simple distinction I have presented both in this book and in my previous book *WORLDVIEWS* between the scientific worldview (“bracket out the subject”) and the teleological worldview (“bracket out the object”) may be said to be the solution to the age-old philosophical “mind/body problem” (perhaps more accurately termed the “mind/brain problem”): The activities of mind and brain so miraculously correspond because, at bottom, they are *the same thing* viewed from radically different perspectives, namely, the teleological and the scientific.

We will deal in much greater detail with the teleological analogs to biological systems in the final chapter of **PART 2: ON EVOLUTION**. Meanwhile, however, we can make a few more-general observations concerning teleological systems that are analogous to nonlinear complex physical systems:

Experts in nonlinear science often refer to the nonlinear paradigm as being the paradigm of *self-organization*. In fact, Erich Jantsch actually titled his book *The Self-Organizing Universe*. In using the term *self-organization*, nonlinear scientists are referring to the fact that, overall, the teleological analog to a physically nonlinear universe is a teleological universe where beings at all levels of the holistic hierarchy organize themselves by making *decisions* according to *goals* (though, of course, this decision-making capability occurs with widely varying degrees of capability and sophistication). This clearly implies that *group subjectivity* is an essential feature of the teleological universe in which we live and that so-called “primitive peoples” were not so far wrong in believing in *animism*. I have dealt with the concept of *group subjectivity* in detail in my previous book *WORLDVIEWS*. In that book *group subjectivity* is shown to be one of the two pillars of teleological truth, the other pillar being *theism*.²⁹⁵

Of course, reductionists reject the self-organizing teleological paradigm because they wish to see the “radically autonomous” individual human being as the only kind of teleological self in the universe, and consequently they feel obligated to regard the rest of the universe to be teleologically “meaningless and senseless”, i.e., devoid of any other teleological beings, whether immanent or transcendent.

Vitalists, creationists, and believers in “intelligent design” as a *scientific* theory are equally hostile to the self-organizing paradigm. After all, if the universe actually teleologically organizes itself, then there is no need for a God to create and organize (i.e., *design*) the universe. Right?

Not necessarily. Here we have a problem that precisely parallels the problem of human free-will versus divine determinism, which we discussed briefly at

the end of our chapter on **Nonlinear Dynamic Systems**. There we wrote:

[C]learly the distinction which we have drawn between *immanent* objective truth and *transcendent* objective truth in the *physical* realm suggests a corresponding distinction in the *teleological* realm: The fact of the existence of human free-will is an *immanently* true teleological fact (analogous to the *immanent* reality of absolute, constrained chance within the physical world). By contrast, the fact of moment-to-moment divine determinism is a *transcendently* true teleological fact (analogous to the *transcendent* reality of complete determinism in the physical world).

Similarly we may say that the *self-organizing* aspect of the teleological world in which we live is an *immanent* teleological fact. By contrast, the fact that the universe is *created*, sustained, and completely determined from moment-to-moment by an omnipotent, transcendent God is a *transcendent* teleological fact.

One of the great benefits of this scientific paradigm of *tychistic nonlinearity* and its corresponding teleological paradigm of *self-organization* is that they enable us to transcend the controversy between *mechanism* and *vitalism*: On the one hand, we are not obligated to regard biological organisms to be merely linear, reductionistic, near-equilibrium machines. On the other hand, we are also not obligated to introduce teleological entities such as Hans Dreisch's *entelechy*, Henri Bergson's *elan vital*, or an implicit *intelligent designer* into science as purportedly scientific explanations.

The controversy between mechanism and vitalism parallels similar, but much older, controversies concerning the relationship between *body* and *soul* within man. These anthropological controversies have taken many forms, but in essence the split is between those who see the physical human body as being mechanical, dead, and lifeless (in contrast to the human soul, which is seen as being purely teleological and life-filled), versus those who view the human soul as having a *close physical correlate* which is an intimate aspect of the human body itself. (Today, we may identify this *close physical correlate* with the *tychistic nonlinear* aspects of the physical human body.) The latter view (which I believe to be the correct one) is indirectly reflected in the following statement, taken from the recent *Catechism of the Catholic Church*:

The unity of soul and body is so profound that one has to consider the soul to be the “form” of the body: . . . [S]pirit and matter, in man, are not two natures united, but rather their union forms a single nature.²⁹⁶

The profound disagreement between the two opposing anthropological views sketched above played a major role in both the Christological controversies in the early Church and in the intense iconoclastic conflict that followed: Some early Church fathers, such as Origen and Eusebius, devalued the human body as being mere dead, mechanical, lifeless matter. Others, such as Cyril of

ON SYSTEMS

Alexandria and St. Maximus the Confessor, took a far more positive view of the human body. It is the latter view that ultimately (after great struggle) prevailed in Christian orthodoxy. As Bishop Christoph Schonborn (who edited the *Catechism of the Catholic Church*) wrote in his book *God's Human Face*:

Cyril differs from Origen and Eusebius mainly in his *anthropology*. In a nutshell, one might observe that Origen sees man as an incarnate soul, Cyril as “animated flesh”. The only item in Origen’s teaching explicitly rejected by Cyril is his doctrine of the dual creation [of body and soul]; for Cyril, the body was not added to the soul because of sin; rather, body and soul form one unity because they were created together.²⁹⁷

Origen and Eusebius were the spiritual precursors of the *iconoclasts* – those who, for over 100 years (from 726 - 843 A.D.), sought to destroy all physical Christian icons, condemning them as being completely unworthy to express the divine being. By contrast Cyril of Alexandria and St. Maximus the Confessor were the precursors of the ultimately triumphant *iconophiles* – those who believed that, because of the incarnation, physical Christian icons, especially icons of Jesus Christ, could actually represent “God’s human face”.

The triumph of the iconophiles (after much struggle) was ultimately a result of the fact that *salvation* in orthodox Christian theology means the salvation of soul *and* body as a holistic unity (finalized as the *resurrection* of both soul *and* body at the end of time), and that this salvation is *proximately* accomplished through the spiritual *and* physical incorporation of the believer into the Church as the Body of Christ via the real presence of Jesus, the *incarnate* Son of God, *transubstantiated* into the *physical* bread and wine which the believer consumes during the Eucharist.

More generally, the triumph of the iconophiles inspired confidence in the West that art could actually represent *truth*, as opposed to just being merely decorative, amusing, or pleasing. The Jewish literary critic George Steiner, in his 1989 book *Real Presences*, regards the twin concepts of *incarnation* and *transubstantiation* (which he views as “concepts utterly alien to either Judaic or Hellenic perspectives”) as being *the* defining concepts of Western civilization, both religious and secular:

At every significant point, Western philosophies of art and Western poetics draw their secular idiom from the substratum of Christological debate. Like no other event in our mental history, the postulate of God’s kenosis through Jesus and of the never-ending availability of the Savior in the wafer and wine of the Eucharist, conditions not only the development of Western art and rhetoric itself, but at a much deeper level, that of our understanding and reception of the truth of art.²⁹⁸

But iconoclasm was revived by the Protestant “reformers”, and from the Protestant revolt through the Enlightenment all the way up to current post-modernism we see an increasing despair and rejection of the possibility that art can actually represent truth. Here is Fr. Richard John Neuhaus, continuing to quote from George Steiner’s book *Real Presences*:

In fashionable critical theories of our day we witness “endeavors of the aesthetic to flee from incarnation”. “It is the old heresies which revive the models of absence, of negation or erasure, of the deferral of meaning in late-twentieth-century deconstruction. The counter-semantics of the deconstructionist, his refusal to ascribe a stable significance to the sign, are moves familiar to [an earlier iconoclastic] negative theology.” Heidegger’s poetics of “pure immanence” are but one more attempt “to liberate our experience of sense and form from the grip of the theophanic”. But, Steiner suggests, attempted flights from the reality of *Corpus Christi* will not carry the day. “Two millennia are only a brief moment.”²⁹⁹

Nevertheless, it is important to note in this context that the Christian idea of *eternal life* (which underlies the Christian concepts of incarnation, transubstantiation, and resurrection) is a completely *transcendent* idea – a *mysterium* which makes no sense within the confines of the *immanent* teleological universe that we are familiar with. For, as we noted earlier, *death*-almost-offsetting-reproduction is an *absolutely inherent* feature of all earthly biological life as we know it, including our own. (This is the principle of *autocatalysis* vs. *autoinhibition* which we found throughout our discussion of nonlinear complex physical systems.) That is why, from an *immanent* teleological point-of-view, the cynics are right that “sex and death” are at the root of our earthly life.

That is also why *prayer* and *faith* are required to even begin to intimate the nature of *eternal life*. But faith in *what*? Minimally:

- Faith in the existence of transcendent teleological beings who do not have direct, complete physical analogs within the physical universe as we know it (especially faith in the existence of an omnipotent, omniscient *transcendent God*, who alone gives ultimate meaning, purpose, and coherence to the teleological universe, both immanent and transcendent).
- Faith that at the “end of time” not only our own corruptible human bodies, but the physical embodiment of all earthly life during all time will be transformed into an incorruptible physicality which is at the farthest reaches of our human ability to even imagine.

For, as St. Paul wrote in his letter to the Romans:

ON SYSTEMS

[T]he creation waits with eager longing for the revealing of the sons of God; for the creation was subjected to futility, not of its own will but by the will of Him who subjected it in hope; because the creation itself will be set free from its bondage to decay and obtain the glorious liberty of the children of God. We know that the whole creation has been groaning in travail together until now; and not only the creation, but we ourselves who have the first fruits of the Spirit groan inwardly as we wait for adoption as sons, the redemption of our bodies.³⁰⁰

***PART 2:* ON EVOLUTION**

If you've gotten this far in the book, congratulations! You've just completed a "crash course" on the general types of physical systems dealt with in modern 21st century science, together with a brief evaluation of teleological systems that are analogs to those physical systems.

In **PART 2: ON EVOLUTION** we will apply what we have learned in **PART 1: ON SYSTEMS** to the particular scientific problem of *biological evolution*. We will first present a list of our basic assumptions. We will then present a brief description of the currently dominant theory of biological evolution, the essentially *linear* theory of *neo-Darwinism*. Next comes a brief description of Robert F. DeHaan's theory of *macrodevelopment* as a representative example of the kind of *nonlinear* theory of evolution which is required in the 21st century. Next we will consider, one at a time, each of the major facts of biological evolution, followed by an individual evaluation of how the respective theories of neo-Darwinism and macrodevelopment explain that particular fact (or fail to do so). A summary conclusion will follow. **PART 2** will then end with a special chapter on the teleological analogs suggested by the physical biosphere and its history.

Basic Assumptions

In a treatment this short on a subject as large and controversial as biological evolution it is important and necessary that, insofar as is possible, basic assumptions should be stated up front. They are:

- The reader has read **PART I** of this book (or, at a minimum, has read the previous chapter on **Nonlinear Complex Physical Systems**).
- Biological evolution is a *fact*, by which I mean that scientific evidence overwhelmingly shows that currently existing biological species are *in some sense* the “descendents” of previous biological species, and that the total assemblage of biological species has changed significantly and irreversibly over millions of years.
- Purportedly scientific theories such as creationism, vitalism, and “intelligent design” will not be considered as candidates for possible theories of biological evolution, on the grounds that they violate our earlier definition of science as a methodology that *brackets out the subject* as much as possible. Nevertheless we will quote frequently and appreciatively from the work of intelligent-design advocates such as Michael Behe, Jonathan Wells, and Phillip Johnson, since their critiques of the evolutionary theory of neo-Darwinism are usually “on-target”.
- *Ad hominem* attacks on those who hold to a differing theory of evolution than one’s own is never justified, nor is it ever justified to attempt to silence critics via intimidation and censorship. (Unfortunately this rule is frequently violated, especially by neo-Darwinists.)

Neo-Darwinism

Neo-Darwinism is the currently dominant, essentially *linear* theory of biological evolution. Neo-Darwinism builds on Charles Darwin's theory of evolution, as found especially in Darwin's famous book *On the Origin of the Species* (1st edition, 1859), but refines Darwin's theory through the use of the results of statistical *population genetics*, a field of study which was established by the Austrian monk and abbot Gregor Mendel (whose results became generally known only after 1900).

The basic principles of neo-Darwinism are often stated as follows:

1. Microscopic, *purely random* changes (such as mutations and copying errors) occur within the genetic code (*genotype*) of biological organisms, resulting in macroscopic variations in the physical characteristics (*phenotype*) of the individuals within the population of any given species. The vast majority of these purely random microscopic changes are harmful, but a very few are helpful in promoting the survival of the individual and therefore of the species of which that individual is a member.
2. Nature selects phenotypes by means of an essentially *deterministic* macroscopic process called *natural selection* (analogous to the artificial selection practiced by human breeders of plants and animals) according to the principle of the *survival of the fittest*: Those individuals of the species having phenotypes *favorable* to survival tend to produce offspring which carry the corresponding genotype on to the next generation. By contrast those individuals of the species having *unfavorable* phenotypes tend to die off before they can reproduce themselves. (This process of *natural selection* is often said to proceed by *trial-and-error*.)
3. By means of the above two basic principles, all of the various species (together with biological phyla, classes, families, etc.) comprising the biosphere have been created and transformed gradually, minutely, step-by-step throughout the earth's long history.

Now, a major problem with this formulation of neo-Darwinism lies in point 2. For it is evident that concepts such as *natural selection*, *survival of the fittest*, and *trial-and-error*, as stated, are really *teleological* concepts, rather than scientific concepts: Nature is being personified as a conscious being who *chooses* (i.e., selects) by trial-and-error which individuals of the species are to survive in accordance with a *goal* (i.e., fitness). If we can't re-cast neo-Darwinism into a scientific formulation (rather than a teleological

ON EVOLUTION

formulation), we will have to immediately reject it for the same reasons we previously rejected creationism, vitalism, and intelligent design.

Fortunately neo-Darwinists themselves have re-interpreted point 2 scientifically, as follows:

2. Different phenotypes among the individuals who comprise a species have statistically different rates of reproduction and statistically different rates of mortality. Phenotypes which have the *highest* rates of reproduction and/or the *lowest* rates of mortality tend to predominate within the species and pass their corresponding genotypes on to the next generation. Moreover, random microscopic changes to the genotype (as specified in point 1) constantly result in new macroscopic phenotypes which are then subjected to these same essentially deterministic processes of *differential reproduction* and *differential mortality*.

Notice in particular that in neo-Darwinism the element of objective, absolute *chance* is confined entirely to the *microscopic* world of the genotype, while *determinism* essentially rules in the *macroscopic* world of the phenotype in the form of the “iron law” of differential reproduction and differential mortality (“survival of the fittest”). In this respect neo-Darwinism somewhat resembles quantum theory, which (as we saw in a previous chapter) is characterized by objective randomness at the sub-microscopic level encapsulated within the deterministic Schrodinger wave function at the macroscopic level. Another similarity between the two theories is that neo-Darwinism and quantum theory both rely heavily on the mathematics of *statistics* in their formulation.

By confining themselves to the realms of the stochastic and the deterministic (found at the opposite extremes of the “physical spectrum”), neo-Darwinism and quantum theory both manage to avoid the messy nonlinearities which characterize the tychistic and chaotic portions of the “physical spectrum”. For this reason they both are able to remain essentially *linear* physical theories. That is also why contemporary neo-Darwinists such as Richard Dawkins can describe living organisms as being “nothing but” mechanical, linear, reductionistic robots (albeit highly complex robots) that are driven deterministically by their “selfish genes”.

Of course neo-Darwinists are not entirely unaware that the mathematics which describes *differential reproduction* versus *differential mortality* often results in nonlinearities: In the previous chapter on **Nonlinear Complex Physical Systems** we discussed in some detail the nonlinearities associated with the *logistic equation* (which is often used to model biological

populations), and we briefly mentioned the nonlinear *Lotka-Volterra predator-prey equations*. Nevertheless, neo-Darwinists almost always regard any elements of chance which happen to arise at the *macroscopic* level due to such nonlinearities to be “merely subjective”, an attitude which enables them to continue to view the macroscopic processes of differential reproduction and differential mortality as being *essentially* linear and deterministic. (As an exception to this generalization, the maverick neo-Darwinist Stephen Jay Gould *does* regard macroscopic absolute chance to objectively exist, but *not* within any meaningful context of external *and internal* conditional equifinality.)

Teleological aside: The confining of objective, absolute chance entirely to the *microscopic* level, thus allowing objective determinism to essentially rule the *macroscopic* level, enables neo-Darwinists to model the biosphere in such a way that *no teleologically “meaningful” analogs to anything in the biosphere are possible* (except for the weak “figure of speech” analog of nature “selecting” individuals and species for survival). This enables the neo-Darwinists (together with the quantum theorists) to present putatively conclusive proof that the universe is truly “meaningless and senseless” from a teleological point-of-view and that it is, in fact, a *teleological desert* in which the “radically autonomous” individual human self reigns supreme by default.

Neo-Darwinism is also kin to two other highly influential 19th century scientific theories: in geology, Charles Lyell’s theory of *uniformitarianism* (the doctrine that *all* major geological changes are the result of gradual rather than catastrophic processes), and in astronomy, the *steady-state* theory (the idea that the universe has always been essentially as it appears today), an idea long advocated by Fred Hoyle. All three of these theories (Darwinism, uniformitarianism, and steady-state theory) sought to tame the universe into a quasi-Newtonian framework by regarding the *macroscopic* universe to be essentially linear and deterministic, while confining chance entirely to the *microscopic* realm, where it could play a role analogous to “experimental error” within Newtonian physics.

In fact, Charles Lyell, who strongly influenced Darwin, actually believed that the dinosaurs could someday return and that all of the changes in the biosphere and in the geology of the earth over millions of years were merely “experimental errors” varying around a deterministic mean. In 1830 Lyell wrote:

Then might those genera of animals return, of which the memorials are preserved in the ancient rocks of our continents. The huge iguanodon might reappear in the woods, and the ichthyosaur in the sea, while the pterodactyl might flit again through the umbrageous groves of tree ferns.³⁰¹

ON EVOLUTION

Since the 1980s Lyell's doctrine of uniformitarianism has fallen into disrepute under the weight of contrary evidence, including conclusive proof that the channeled scablands in northeastern Washington were carved by a catastrophic flood originating from the glacial lake Missoula³⁰² and compelling geological evidence that at least some biological mass-extinctions (most famously, the extinction of the dinosaurs at the end of the Cretaceous period) were the result of world-wide catastrophic events, such as asteroid impacts.³⁰³ As a result, today the geological doctrine of uniformitarianism is presented as meaning little more than that "the laws of nature are the same today as in the past", a statement with which even the most hard-core young-earth creationist could agree.

Similarly, as we saw in our earlier chapter on Einstein's Theory of General Relativity, the astronomical *steady-state* theory has been vanquished by what Fred Hoyle contemptuously called the "big bang" theory, largely as a result of the discovery during the 1960s of the universal three-degree-Kelvin microwave background radiation. Thus, of the three major 19th century scientific theories proclaiming that *all* important change in the physical universe is "minute and gradual", only neo-Darwinism remains as entrenched orthodoxy.

In fairness we should note that, although the vast majority of neo-Darwinists are gradualists, some dissenting neo-Darwinists, notably paleontologists Stephen Jay Gould and Niles Eldredge, seek to explain the evidently irregular rhythm of evolution in the fossil record by means of the theory of *punctuated equilibrium*, which we will explain in later chapters. (Orthodox neo-Darwinists call the theory of punctuated equilibrium "punk-eek" or "evolution by jerks"!)

In the following chapters we will be examining in some detail how neo-Darwinism does or does not fit the facts of biology and paleontology as we know them. But even at this point it is evident that, while neo-Darwinism is *correct* in stressing the centrality of differential reproduction and differential mortality in biological evolution, it is *incorrect* in regarding these processes to be essentially deterministic and linear, rather than tychistic and nonlinear.

Macrodevelopment

The nonlinear David which we have chosen to oppose the linear Goliath of neo-Darwinism is Robert F. DeHaan's theory of *macrodevelopment*, which he first presented in three articles in 1996 and 1997.³⁰⁴ Our formulation of the theory of macrodevelopment will differ somewhat from DeHaan's due both to our incorporation of insights from our previous chapter on **Nonlinear Complex Physical Systems** and our incorporation of insights by John A. Davison and others concerning the significance of *semi-meiosis* and *polyploidy* in evolution.

In addition, our terminology differs from DeHaan's in that DeHaan uses the term "evolution" to essentially mean what we have called the *theory* of neo-Darwinism, while by contrast we are using the term "evolution" to denote the *fact* of transformation of life forms over millions of years. (In other words, for us, "evolution" is the *fact* which the respective *theories* of neo-Darwinism and macrodevelopment are competing to explain.) Furthermore, DeHaan is willing to concede that neo-Darwinian mechanisms play a role in the evolution of *species* (as opposed to higher taxonomic categories such as phyla and families), whereas we will view neo-Darwinian mechanisms as effective *only* in creating and preserving *varieties within* species. Finally, it is important to note that the theory of macrodevelopment which we are presenting here is highly tentative: The only thing we assert as certain is that some nonlinear theory similar to macrodevelopment will prove to be the correct scientific theory of evolution.

Here, then, are the basic principles of the theory of *macrodevelopment*, as we will be presenting it:

1. The evolution of life on earth over millions of years is essentially a *nonlinear* process which is analogous to the nonlinear process of embryonic development (*morphogenesis*) that we discussed in our previous chapter on **Nonlinear Complex Physical Systems**. In other words, the irreversible nonlinear *macrodevelopment* of the biosphere over millions of years parallels in important ways the irreversible nonlinear *microdevelopment* of the individual biological organism over its lifetime (especially during its embryonic stage).
2. One important parallel between macrodevelopment and microdevelopment is the manner in which the overall *body plans* of biological organisms (corresponding to the *phylum* taxon-level) appeared rapidly during the Cambrian era and the correspondingly rapid manner in which the overall *body plan* of the individual is generically established during morphogenesis. (That is why Robert F. DeHaan calls Cambrian animals *stem*

ON EVOLUTION

animals, analogous to the *stem cells* in the individual embryo.)

DeHaan explains:

Both individuals and phyletic lineages begin with a general body plan. The body plan is among the first structures to appear in the individual embryological development. The earliest and defining feature of the Cambrian animals was their basic body plan.

Both individuals and phyletic lineages develop very rapidly at the start. Early development in the embryo is extremely rapid. In human beings all systems and morphological features are in place in slightly more than three months after conception. The formation of body plans in the Cambrian [era] occurred with extreme rapidity, geologically speaking, paralleling the very rapid formation of the body plan early in individual embryonic development and growth.³⁰⁵

3. The parallels between macrodevelopment and microdevelopment are not confined to the embryonic stage, but extend to the entire span of the individual's life, from birth until death. Again, Robert F. DeHaan:

The entire life span of individual animals is a manifestation of development. All organisms start small and simple at conception, rise rapidly through the prenatal and juvenile stages, grow large and complex, reach a rounded maximum on many variables in maturity, decline in old age, and eventually die. The rise and subsequent decline is an invariant characteristic of lifelong individual development.

There is also an unvarying succession of changes in ancestral lineages, starting with a few, small, insignificant animals, that increase in size, complexity, population density, and on many other dimensions; reach a rounded maximum, and then decline to fewer, smaller, less robust groups. This orderly sequence is isomorphic to development in the individual life span. . . .

In short, the overall shape of individual development and the general shape of ancestral lineages are remarkably similar. The only major difference between them is the time scale: enormous for the historical lineages, insignificantly short for the individual organisms. The resemblance between large-scale sequences of [ancestral] changes covering millions of years and the sequence of changes in [the] early embryonic and lifelong development of individual organisms is quite astounding. It cannot be a meaningless coincidence that so many phyletic patterns of change in the fossil record are found to resemble patterns of development found in individual

organisms. These similarities are surely not trivial or merely coincidental. On the contrary, they point to a deep unity between the overarching historical processes, called macrodevelopment, and small-scale individual development. Patterns in the fossil record are sufficiently similar to [the] patterns in [the] development of individual organisms that those in the fossil record can provisionally be considered [to be] the results of development on a large historical scale.³⁰⁶

4. The evolution of the biosphere has proceeded via a long historical series of nonlinear “continuity-breaking” bifurcations. In each of these bifurcations a *single* instance of a *more-generic* taxon (i.e., kingdom, phylum, class, order, family, genus, or species) has split into *two* instances of taxa at the *next most-specific* level. As a result of this split, the more-generic ancestral taxon continues to exist only in the form of the generic features of the two more-specific taxa into which it has split. That is why the splitting of taxa in accordance with the process of macrodevelopment is a process of *symmetrical* splitting in which the “ancestor” taxon ceases to independently exist. (By contrast, neo-Darwinism proposes that new taxa *split off* from previous taxa, leaving the older ancestral taxon to continue to independently exist and evolve. Neo-Darwinian taxonomic splits are therefore inevitably *asymmetrical*, whether the version of neo-Darwinism is the phyletic gradualism of Darwin, the punctuated equilibrium of Niles Eldredge and Stephen Jay Gould, or even the “hopeful monster” theory of Richard Goldschmidt.) Two important points:

- When a more-generic taxon splits into two more-specific taxa, those more-specific taxa need not be at the next-most-specific *named* level. In other words, a phylum need not split into two classes, a class need not split into two orders, and so on. This is because there are far too many taxonomic levels to be able to actually name them all. Nevertheless the *direction* of the splits is always from the *generic* to the *specific*.
- The more-generic animals and plants of the past were not necessarily “blander” than the animals and plants of today: Contemporarily they may have had all of the particularity of today’s animals and plants. However, the traits comprising that exact particularity were irrevocably lost to the future as a result of the taxon-splitting process.

ON EVOLUTION

5. Each taxonomic bifurcation within the biosphere is a taxon-wide phenomenon of nonlinear “continuity breaking” that occurs holistically within one (or a few) generations: It does *not* occur gradually, minutely, and mechanically, as neo-Darwinism proposes, but rather *suddenly* and *holistically*, like the sudden holistic organization of Benard cells, or the sudden holistic reorganizations that occur periodically during the course of morphogenesis (both of which we discussed in our earlier chapter on **Nonlinear Complex Physical Systems**).
6. It is probably true that taxon-wide nonlinear bifurcations within the biosphere do not occur today. Nevertheless they were once a prominent feature of the biosphere’s past.
7. Genetic evidence strongly supports the macrodevelopment hypothesis (especially when we exclude the individualistic “hopeful monster” hypothesis, essentially because it requires taxonomic “splitting off”). This genetic evidence includes: *polyploidal speciation* events among contemporary plants; at least two major *tetraploid events* within the evolutionary history of vertebrates, one associated with the evolutionary emergence of jawless fish and the other associated with the evolutionary emergence of the four-limbed vertebrates, a.k.a. tetrapods (Susumu Ohno, 1970); the *structure of the differences between the DNA of closely-related species* (typically characterized by long, identical segments of DNA that are rearranged and/or “flipped” relative to one another, rather than differing by point mutations, as neo-Darwinism would suggest); and, finally, John A. Davison’s evidence for the involvement of *semi-meiosis* in the “origin of the species”. We will discuss all of these concepts and terms (which, we assume, are probably unfamiliar to you) in much more detail when we present the facts of evolution in the next chapter.
8. Neo-Darwinian mechanisms, described in the previous chapter, only succeed in changing the statistical distribution of phenotypes (i.e., *varieties*) *within* the species. This change in the statistical distribution of *intra-species* varieties occurs as a continuous process of adaptation to the environment. However, all such statistical changes are almost-instantly *reversible* if the environment reverts back to its former state. Therefore, calling such changes “microevolution” (as is often done) is a misnomer,

since true biological evolution (whether “micro” or “macro”) is an essentially *irreversible* process (Charles Lyell to the contrary).

9. Biological systems (including the biosphere as-a-whole) are highly complex, hierarchical, holistic, open, tychistic, nonlinear systems, rather than being the macroscopically deterministic and microscopically stochastic systems assumed by orthodox neo-Darwinism.

The above nine points express the essence of the theory of *macrodevelopment* as used in the discussion of the facts of evolution in the next chapter. Points 1 through 3 are essentially the same as Robert F. DeHaan’s original theory of macrodevelopment, while points 4 through 9 represent expansions of DeHaan’s original theory with which DeHaan himself may or may not agree.

DeHaan is careful to distinguish his theory of *macrodevelopment* from a theory which superficially seems to be similar, namely, the so-called *biogenic law*, popularly expressed as “ontogeny recapitulates phylogeny”:

[Macrodevelopment] is not a warmed-over version of the so-called biogenic law, popularized by the slogan “ontogeny recapitulates phylogeny”. This outmoded “law of recapitulation”, formulated by Ernst Haeckel (1834-1919), held that there is a one-to-one correspondence between phylogeny and ontogeny; that each organism in its development from zygote to adult repeats its phyletic history in condensed form, i.e., climbs its own family tree, so to speak. Raff described the biogenic law more technically as follows: “All animals should recapitulate their phylogenies in an abbreviated form during development, and developmental stages should reveal those histories.”

[Macrodevelopment], however, is not concerned with trying to find replications of exact stages of phyletic transformation in the development of individual organisms; rather, it focuses on generalized processes and patterns that are universal across all lineages.³⁰⁷

DeHaan also distinguishes his theory of *macrodevelopment* from an earlier theory called *orthogenesis*:

[Macrodevelopment] is distantly related to ideas that were held in the 1920s by several paleontologists. [Niles] Eldredge reported the situation as follows:

Paleontologists have had an abiding interest in long-term evolutionary trends that struck Cope and many others as linear or “rectilinear”. “Orthogenesis”, a term coined by Haacke (1893; fide Simpson 1944), describes a pattern of linear directional change in phylogeny, a pattern generally thought in pre-synthesis days to reflect internal evolutionary processes. This line of thinking, at least in paleontological circles, reached its culmination in the

ON EVOLUTION

work of vertebrate paleontologist Henry Fairfield Osborn, whose theory of orthogenesis (later called “aristogenesis”) saw linear evolutionary change arising from within organisms themselves, a mechanism, moreover, taking precedence over natural selection if not supplanting it altogether.

The general theory of [macrodevelopment] is an advance over the earlier ideas of “orthogenesis” and “aristogenesis” because it (1) is a multidimensional concept; it identifies many different kinds of long-term trends that are parallel to individual development, and because it (2) relates the process to real causal genetic mechanisms.³⁰⁸

We may expand on DeHaan’s remarks by noting that from Eldredge’s description it appears that orthogenesis was viewed as being a *linear*, mechanical (albeit internal) process, whereas by contrast macrodevelopment is an inherently holistic, *nonlinear* process.

In addition, we may distinguish the theory of macrodevelopment from the work being done on evolution by Stuart Kauffman and others at the Santa Fe Institute: Their work *does* contain a high awareness of the presence of nonlinearity in the biosphere. However, their work is also almost entirely confined to a statistical population-genetics approach, which has had the effect of enmeshing them in residual stochastic/deterministic neo-Darwinist assumptions.

Much closer to the theory of macrodevelopment (and, indeed, important confirmation of it) is recent work done by the famous mathematician Ian Stewart and his biologist collaborator Jack Cohen. It all started when Cohen asked Stewart about nonlinear “symmetry breaking” (i.e., what we are calling nonlinear “continuity breaking”). After Stewart replied, Cohen remarked: “Speciation – that’s symmetry breaking, isn’t it?” Ian Stewart explains what happened next:

First I thought he didn’t understand what I was talking about. Then I asked him what he meant. He said: If you’ve got one species, that’s a very symmetric situation, because all the animals are pretty much the same, but two species must be less symmetric.

We’ve written a few papers about this as a mathematical metaphor for speciation, modeling a species as identical organisms and worrying about the differences between individuals later on. These models turn out to include a general mathematical process, called *bifurcation*, where the state of the system changes quite dramatically, even though the system’s environment only changes a small amount.

The models produce some general predictions: the split happens very fast, on an evolutionary timescale, and the two new species ‘pull apart’ in opposite directions compared with the original. For instance, if the original species is a bird with a medium-sized beak, then the species splits into

one with a big beak and one with a small. The average size of beak doesn't change at all.

Until very recently, I'd have left that as a metaphor. . . [But now] we've got something to nail down and test, with experiments on bacteria, for example. It looks as if it's going to go beyond metaphor and into science.³⁰⁹

This Stewart/Cohen idea that a single nonlinear continuity-breaking speciation-event would result in a *symmetrical* split, such that the characteristics of the two "descendants" can be *averaged back* to the characteristics of the "ancestor", is a significant hypothesis: We will discuss it later as the *Stewart/Cohen hypothesis*.

The theory of macrodevelopment has even (to some extent) been anticipated by the noted critic of neo-Darwinism and advocate of intelligent design, Phillip E. Johnson, who writes:

Certain features, like the existence of natural groups and common "junk DNA" sequences, support an inference that there was some sort of process of development [of species] from some common source. We may call that process "common ancestry", but it does not necessarily follow that we are referring to the ordinary process of reproduction that we observe in today's world, where ancestors give birth to descendents very much like themselves. Normal reproduction is not known to produce radically new organs or organisms, and if it did so it would have to proceed one tiny step at a time. In fact there is a great deal of evidence that innovative transformations must have involved organisms doing something "different from what they ordinarily do".³¹⁰

Finally, we need to stress how limited is the present constituency for the theory of macrodevelopment, or indeed for any other *nonlinear* theory of biological evolution. Orthodox neo-Darwinists are thoroughly entrenched in the Anglo-American scientific establishment and have multi-millions of dollars (together with vast non-monetary resources) at their disposal. (Witness, as one small example, the recent 8-hour PBS series *Evolution*, which was financed by a reported *15-million dollar* donation from Microsoft co-founder Paul Allen.) Even believers in special creation and intelligent design have a not-insignificant constituency and, consequently, a not-insignificant monetary base.

By contrast there is virtually *no* political or scientific constituency for the theory of macrodevelopment (even though Robert F. DeHaan regards himself to be a part of the "intelligent design" movement). When I wrote to DeHaan in November of 2000 to inquire if he had completed any full-length book on macrodevelopment, he wrote back: "I completed a book-length MS on this subject several years ago and submitted a summary of it to every publisher I could find, both here and abroad. To no avail." In addition to his finished

ON EVOLUTION

unpublished book on the overall subject of macrodevelopment, DeHaan is currently working on a book on what he calls *phylogerontology*. This second book will deal in far greater detail with the analogies between the later stages in the life of individual organisms (as they move towards death) and the later stages in the life of taxonomic lineages.³¹¹

So how, then, will our nonlinear David (macrodevelopment) fare against the linear Goliath (neo-Darwinism)? To find out, we need to present, one-by-one, **The Ten Facts of Biological Evolution**, and then compare, for each of those ten facts, how neo-Darwinism and macrodevelopment explain that particular fact (or fail to do so).

The Ten Facts of Biological Evolution

1. Biological Nonlinearity and Holism

Biological systems are highly complex, hierarchical, holistic, open, tychistic, nonlinear physical systems, rather than being macroscopically deterministic and microscopically stochastic physical systems.

We have already demonstrated this first fact of biological evolution in our previous chapter on **Nonlinear Complex Physical Systems**. Clearly macrodevelopment is more consistent with this fact than is the competing theory of neo-Darwinism. For, while it is undoubtedly true that certain *aspects* of biological systems are linear and mechanical (particularly the aspect of mechanical hierarchical organization within a given holistic hierarchical level), it is also true that a theory, such as neo-Darwinism, which essentially acknowledges *only* the mechanical and stochastic aspects of the biosphere is likely to miss much that is of importance. By contrast the theory of macrodevelopment is free to fully acknowledge both the linear *and* nonlinear aspects of its subject-matter.

This first fact of evolution is therefore a strong point *against* the theory of neo-Darwinism and *in favor of* the theory of macrodevelopment.

2. Irreducible Complexity and Tychism

The nonlinearity of biological systems is essentially due to the fact that their many parts are characterized by strong *and* persistent interactions. That is why biological systems are, in the terminology of Michael Behe, *irreducibly complex* (the whole is more than the sum of its parts, the removal of a single part can completely destroy the functionality of the whole, and so on). Moreover, only nonlinear *tychistic* processes can create and sustain the physical analogs to those functions, purposes, goals, and decisions which are such prominent *teleological* features of biological life at all of its hierarchical levels. (That's because only nonlinear *tychistic* physical systems are characterized by both external *and* internal conditional equifinality.)

This second fact of biological evolution was also proved in our previous chapter on **Nonlinear Complex Physical Systems**. Because macrodevelopment is a tychistic nonlinear theory and therefore *can* explain the phenomenon of *irreducible complexity* in nature, while neo-Darwinism is a reductionistic linear theory which *denies* the existence of *irreducible complexity* in nature, this second fact of biological evolution is, again, a strong point *in favor of* macrodevelopment and *against* neo-Darwinism.

Neo-Darwinism claims that biological systems evolve gradually, linearly, mechanically, step-by-step as nature continually and deterministically “selects” the “fittest” phenotypes from among the various macroscopic

ON EVOLUTION

phenotypes that result from the purely random microscopic variations in the corresponding genotypes. But if the actual *functionality* of the biological system that is being constructed gradually and linearly along this temporal “assembly line” does not in fact appear at all until that particular biological system is essentially complete (because of the biological system’s holistic nature and *irreducible complexity*), then how does “nature” (without some kind of “advance knowledge”) know which *interim* phenotypes to select? The problem here is that “natural selection” must somehow “choose” *interim* phenotypes that have no *current* survival value and that, in fact, are probably severely inimical to the *current* survival of the biological system. Yet the linear mechanisms of neo-Darwinism provide no way for “natural selection” to successfully do this.

This basic problem with both Darwinism and neo-Darwinism was pointed out as long ago as 1871 by St. George Mivart in his book *On the Genesis of Species* in a chapter called “The Incompetency of ‘Natural Selection’ to Account for the Incipient Stages of Useful Structures”. Yet, neo-Darwinists have *still* not provided a successful reply to Mivart’s argument.

David Berlinski here describes further this neo-Darwinian dilemma:

“The belief that an organ so perfect as the eye,” Darwin wrote, “could have been formed by natural selection is enough to stagger anyone.” It is. The problem is obvious. “What good,” Stephen Jay Gould asked dramatically, “is 5 percent of an eye?” He termed this question “excellent”.

The question, retorted Oxford professor Richard Dawkins, the most prominent representative of the [orthodox neo-]Darwinians, “is not excellent at all”:

Vision that is 5 percent as good as yours or mine is very much worth having in comparison with no vision at all. And 6 percent is better than 5, 7 percent is better than 6, and so on up the gradual, continuous series.

But Dawkins, replied Phillip Johnson in turn, had carelessly assumed that 5 percent *of* an eye would see 5 percent *as well as* an eye, and that is an assumption for which there is little evidence.³¹²

To get out of this fix, neo-Darwinists sometimes point out that interim phenotypes may *also* relate to other completely different *currently useful* functionalities which “natural selection” can *currently* select for. While this is certainly true in some cases, it strains credulity to believe that this is the case for *all* of the multi-millions of gradualistic interim phenotypes required by orthodox neo-Darwinian theory.

Orthodox neo-Darwinists claim that biological organisms (which they say are only *seemingly* teleologically purposeful, but are *really* purely robotic and mechanistic) can easily be created by a neo-Darwinian process of “natural

selection” which is *fully deterministic* at the macroscopic level, acting on random mutations that are *purely stochastic* at the microscopic level. For example, Richard Dawkins, in his book *The Blind Watchmaker*, suggests a thought experiment in which a group of monkeys, each with his own typewriter, bangs out letters purely randomly, as they collectively attempt to generate the Shakespearean sentence “Methinks it is like a weasel”. David Berlinski describes the rest of Dawkins’ thought experiment as follows:

The Shakespearian target chosen by Dawkins – “Methinks it is like a weasel” – is a six word sentence containing 28 English letters (including the spaces). It occupies an isolated point in [phase] space of 10,000 million, million, million, million, million, million possibilities. . . .

Such are the fatal facts. The problem confronting the monkeys is, of course, a double one: they must, to be sure, find the right letters, but they cannot lose the right letters once they have found them. A random search in a [phase] space of this size is an exercise in irrelevance. This is something the monkeys appear to know. What more, then, is expected; what more required? *Cumulative* selection, Dawkins argues – the answer offered as well by Stephen Jay Gould, Manfred Eigen, and Daniel Dennett. The experiment now proceeds in stages. The monkeys type randomly. After a time, they are allowed to survey what they have typed in order to choose the result “which *however slightly* most resembles the target phrase”. It is a computer that in Dawkins’s experiment performs the crucial assessments . . . The process under way is one in which stray successes are spotted and then saved. This process is iterated and iterated again. Variations close to the target are conserved *because* they are close to the target. . . until, with the appearance of a miracle in progress, randomly derived sentences do begin to converge on the target sentence itself. . . .

The entire exercise is, however, an achievement in self-deception. A *target* phrase? Iterations that *most resemble* the target? . . . If things are sightless, how is the target represented, and how is the distance between randomly generated phrases and targets assessed? And by whom? . . . The mechanism of deliberate design, purged by Darwinian theory on the level of the organism, has reappeared in the description of natural selection itself, a vivid example of what Freud meant by the return of the repressed.³¹³

As Berlinski points out, all such neo-Darwinian “thought experiments” covertly introduce a conscious “selector” (supposedly analogous to nature as “natural selector”) who guides the experiment to its successful conclusion. In Dawkins’ case this “selector” is a computer that has been *programmed by a human being as an extension of that human being’s consciousness and will*. The “selector” selects in such a way that a *future goal* (such as the completion of the sentence “Methinks it is like a weasel”) will be arrived at. But neo-Darwinian deterministic/stochastic processes are fundamentally incapable of such a future orientation: Only nonlinear tychistic systems (such as are envisioned by macrodevelopment) can have the requisite future

ON EVOLUTION

orientation, by virtue of their temporal (and spatial) holism together with their external *and internal* conditional equifinality. Again, David Berlinski:

Favorable changes are one thing; changes that *will* be favorable, another. If the mechanism of Darwinian evolution is restricted to changes that are favorable at the time they are selected, I see no reason to suppose that it could produce any fancy structures whatsoever. If the mechanism is permitted to incorporate changes that are neutral at the time of selection, but will be favorable some time in the future, I see no reason to consider the process Darwinian.³¹⁴

The heart of the neo-Darwinist dilemma is therefore this: If the neo-Darwinist is serious about personifying nature as a conscious “natural selector”, then he must be equally serious in regarding macroscopic nature to be a nonlinear, holistic, tychistic system. But this contradicts one of neo-Darwinism’s fundamental postulates, namely, that macroscopically nature is essentially *linear, mechanical, and deterministic*. On the other hand, if the neo-Darwinist is serious in maintaining that the twin macroscopic natural processes of differential reproduction and differential mortality are essentially *linear and deterministic* in their sorting of the results of microscopic random genetic variations, then *personifying* these putatively deterministic processes as “natural selection” in order to imply a nonexistent future-orientation for them is illicit and is, in Berlinski’s words, “an achievement in self-deception”.

3. *Varieties versus Species*

Neo-Darwinian and Mendelian mechanisms are effective *only* in creating and sustaining intra-species varieties *within limits*: There is *no* evidence of a truly separate typological species or other taxon *ever* having been formed by these mechanisms. Furthermore, even with respect to intra-species varieties, there is good reason to believe that the source of variation is not purely microscopic and random.

The instances which neo-Darwinians present as evidence of “evolution in action today” are inevitably instances in which the statistical distribution of varieties within a species changes in response to an environmental change. Differential rates of reproduction and differential rates of mortality between intra-species varieties can certainly be described, and furthermore can be demonstrated to occur in accordance with the neo-Darwinian and Mendelian statistical laws of *population genetics*. The following three examples are the most-commonly cited:

- The resistance to antibiotics which bacteria inevitably develop.
- Kettlewell’s famous observations of “industrial melanism” in the peppered moth: When trees near Birmingham, England became

blackened due to industrial pollution, the survival of the dark (melanic) variety of peppered moth was favored due to the fact that it was better-hidden from predators while resting on the blackened trees, and consequently this dark variety grew to dominate the population of this species. But when the trees subsequently lightened in color due to local pollution-control measures, the survival of *lighter*-colored peppered moths was instead favored, and *they* became the dominant variety.³¹⁵

- The example of Darwin's finches in the Galapagos islands: In 1977 a severe drought caused the population of medium ground finches on Daphne Major (one of the Galapagos islands) to drop to 15% of its normal size. The husband/wife team of Peter and Rosemary Grant observed that the survivors of the drought had slightly larger bodies and slightly larger beaks than the finches who did not survive the drought. Noticing that the supply of small seeds was also drastically reduced by the drought, the Grants theorized that the larger beaks of the finch survivors enabled them to crack the tougher, larger seeds better than the finches with smaller beaks, thus enabling them to survive the drought. After the heavy rains which the weather phenomenon El Nino brought to Daphne Major during the winter of 1982-1983, the average beak size of the indigenous medium ground finches returned to its previous value.³¹⁶

Besides the above three examples, hundreds (or even thousands) more could be cited, as neo-Darwinists never tire of pointing out. But they all have this in common: They all have to do with changes in the statistical distribution of varieties *within* a species, rather than with the creation of *new* species. Such changes are often erroneously regarded as being examples of *microevolution*, but in fact they are not examples of evolution at all, as is evidenced by the relative ease with which all such changes in the distribution of varieties within a species can be *reversed* by simply reverting the environmental conditions back to their original state (e.g., the example just cited of the average beak size of Darwin's finches returning to its original value when the rains returned). *Evolution*, by contrast, is a *nonlinear* process that is therefore generally *irreversible* from an immanent-objective point-of-view (though, as we saw earlier, in a few cases nonlinear processes can *approximately* reverse themselves, if we ignore the significant effects of hysteresis.).

Furthermore, Darwin's basic thesis was that both species and higher taxon-levels within the biosphere were created and sustained by precisely the same

ON EVOLUTION

processes of mutation, copying-error, sexual recombination, and “natural selection” by which intra-species varieties are universally acknowledged to be created and sustained today. (This is Darwin’s version of Lyell’s “uniformitarian” principle.) Therefore, piling up examples in which mutation, copying-error, sexual recombination, and “natural selection” have been shown to create and promote intra-species varieties provides *no* evidence whatsoever for either Darwinism or neo-Darwinism: Such evidence is simply *irrelevant* in evaluating Darwin’s basic thesis.

The Biological Species Concept (BSC)

It is important to stress once again: *No* examples of new typological species (or other new taxa) being created by neo-Darwinian mechanisms has *ever* been found in nature. Why, then, do neo-Darwinists never tire of claiming that, on the contrary, *thousands-upon-thousands* of such examples exist? Essentially their strategy has been to redefine the concept of a *species* to include many kinds of *varieties* (i.e., subspecies), thus instantly turning evidence for the neo-Darwinian creation of *varieties* into evidence for the neo-Darwinian creation of *species*. To see this, we need to explore in more detail the definition of the word *species*.

We begin by noting that both a *strong* and a *weak* version of the *biological species concept (BSC)* exist. Richard Milton explains:

In biology there is a strong and a weak definition [of the BSC].

The strong definition (proposed by Dobzhansky) is, “That stage of evolutionary progress at which the once actually or potentially interbreeding array of forms becomes segregated into two or more arrays which are *physiologically incapable* of interbreeding.”

The weak definition (proposed by Ernst Mayr) is, “Groups of actually or potentially interbreeding natural populations which are *reproductively isolated* from other such groups.”

Notice that the strong definition is strong because it makes it unambiguously clear that one species *cannot* breed with another [in such a way as to produce fertile offspring, for essentially *genetic* (i.e., “*physiological*”) reasons].

[By contrast,] the weak definition is weak because it does not spell out the meaning of “reproductively isolated”. Does it mean “the two groups might [successfully] mate if they had the chance, but unfortunately are on opposite sides of the lake without a rowing boat”?

Virtually all of the so-called examples of speciation . . . offered by Darwinists are in reality examples of them exploiting the ambiguity of the weak definition of species to suggest that what are no more than subspecific varieties are actually different species.

For example, an old favorite that Darwinists often try to slip in by the back door is the idea that all the different breeds of dog are different species, when in fact all breeds of dog, from the tiny Chihuahua to the Great Dane, are all members of a single species, *Canis familiaris*, and are [genetically] capable of [successfully] interbreeding. . . .

“Speciation” in the Darwinian sense of one species gradually changing by selection into another has not been observed and no examples are known.³¹⁷

(Note that Dobzhansky may mean “*physiologically incapable of interbreeding*” to include differences in *size* and *shape*, as well as *genetic isolation*, but we will henceforth regard the term “strict BSC” to mean *genetic isolation only*.)

John A. Davison elaborates on the point made above that all dogs belong to the same species, if the “strict BSC” criterion is adopted:

In addition to the many working breeds [of dog], man has produced some bizarre creatures like the Chihuahua and the Dachshund, as well as giant animals like the Great Dane, the Mastiff, and the Saint Bernard. Great variations in color, coat quality, and even temperament have also been produced. These differences are due to the action of Mendelian genes segregating and recombining in sexual reproduction. The result is that the products are able to interbreed not only with each other but with the wolf as well. The hybrids are fertile, which is to say that they are not physiological hybrids at all, indicating that no real evolution has taken place. . . .

An even more impressive example of the failure of selection [to produce true speciation] is offered by the goldfish. Starting with the Asiatic carp *Carassius auratus*, the Chinese and Japanese have derived some strange creatures, such as those with telescopic eyes, some of which even gaze upward, as in the variety “celestial”. They have even produced forms which depart from the fundamental vertebrate character of possessing two pairs of lateral appendages, the pectoral and pelvic fins, corresponding to our arms and legs respectively. By duplicating the anal fin, they converted the fish to a potential hexapod! They also duplicated the caudal fin, a condition unknown in the natural world, and even suppressed the dorsal fin, a basic character in virtually all fishes. The variety “celestial” combines all of these features and is blind as well. [Yet] none of this has produced any semblance of speciation, and the animals are still Asiatic carp.

Why do these attempts fail? Apparently they fail because they represent the selection for individual mutant genes, from which one can draw the formal conclusion that such alterations may have little or nothing to do with the evolutionary process.³¹⁸

In contrast to this “strict BSC” definition of speciation, Ernst Mayr’s *weak* version of the BSC allows the following types of “reproductive isolation” to *automatically* create “speciation”: *differences in physiological size and shape* between intra-species varieties (such as the difference in size between

ON EVOLUTION

the Chihuahua and the Great Dane, mentioned above), the *temporal isolation* between varieties that prefer to breed at different times, the *behavioral or “cultural” preference* of one variety not to mate with another variety (e.g., because of different courtship and mating rituals), differences between varieties’ mate recognition systems, and even the mere fact that two varieties are *geographically isolated* from one another. The inclusion of *geographic isolation* among the means of *automatically* creating two different species is particularly useful to Mayr, since it makes his theory of *allopatric speciation* (i.e., species-creation via geographical isolation) *true by definition*, without need of further evidence! (This oft-noted fondness for nearly tautological “explanations” is perhaps why neo-Darwinists are so absolutely sure that their theory of evolution is the correct one.)

The strangeness of the “weak version” of the BSC can easily be seen if we try to apply it to our own species, *home sapiens*. For example, since for cultural and geographical reasons people of different races don’t often intermarry, we would have to classify the different human races as *different species* under Mayr’s weak version of the BSC. Even the mere fact that the European variety of *home sapiens* seldom crosses the ocean to mate with the American variety automatically makes Europeans and Americans *different species* according to the weak BSC. By using such a weak version of the BSC, the evidence for the neo-Darwinian theory of the “origin of the species” becomes instantly “overwhelming”!

As a specific practical instance of this problem, consider once again that classic “icon of evolution”, Darwin’s finches: Originally there were thought to be fourteen separate species of Darwin’s finches, in spite of the fact that the morphological differences between them (such as beak size) were quite small. When ornithologist David Lack visited the Galapagos islands in 1937, he tried to observe instances of one of these “species” pairing off with another, but he did not find a single case. He concluded that “Clearly hybridization between [these] species is rare, if not absent.” This provided seemingly-strong evidence that these fourteen “species” were true BSC species, and not merely intra-species varieties, and that “evolution in action” was really being observed in the Galapagos islands.³¹⁹

However, when Peter and Rosemary Grant studied Darwin’s finches in much more detail during the 1980s and early 1990s they found *many* instances in which different finch “species” mated, producing “hybrid” offspring that were even more fertile than the “non-hybrids”! As the Grants themselves came close to admitting in an article in *Science* magazine in 1992, this calls into serious question whether Darwin’s finches are, in fact, separate species at all: If “species” is strictly defined by the inability to interbreed, then, the Grants

concluded: “At the extreme, six species would be recognized in place of the current fourteen, and additional study might necessitate further reduction.”³²⁰ John A. Davison summarizes:

Darwin’s celebrated finches have all been placed in the genus (or subgenus) *Geospiza*. Since they are all extremely similar, it is not surprising to learn that they produce . . . fertile and genetically fit hybrids (Grant and Grant 1994). Thus, by a physiological criterion they are one species and, as with dogs and goldfish, no significant evolution has really taken place.³²¹

All of this is not to say, however, that *no* instances of true speciation are currently observed in nature. In fact, it has often been observed that a mode of speciation called *polyploidy*, in which the number of sets of chromosomes within the genome of a biological organism (usually a plant) suddenly changes (e.g., doubles), can create a new species *within one or two generations*! Later we will see that such speciation via *polyploidy* can be related to Robert F. deHaan’s theory of *macrodevelopment*.

Here we will just note that, in spite of the fact that speciation via *polyploidy* is the only form of true speciation that has ever actually been *observed* in nature, both neo-Darwinists and creationists dismiss polyploidal speciation as an unimportant “exception”: Neo-Darwinists don’t like it because it produces a new species within one or two generations by a non-Darwinian process that is clearly not “minute, gradual, and step-by-step”. Creationists don’t like it because it is clearly a physical, natural, observed method of speciation that does not proximately require the direct intervention of a divine Creator.

The Typological Species Concept (TSC)

A more basic definition of the word *species* than even the strong version of the biological species concept (BSC) is the *typological* definition of *species*, according to which *species* is the most-specific level of classification in a hierarchy of biological classification that includes as taxon-types (from most-general to most-specific): kingdom, phylum, class, order, family, genus, and species. This *typological species concept* (TSC) is the most-basic because it includes *all* biological organisms, including those that reproduce *asexually* as well as sexually, and including all biological organisms that have ever lived. By contrast even the strong version of the BSC is limited to sexually reproducing organisms who are living today (since there is no way to tell from the fossil record whether two similar, yet different, fossils represent different *varieties* or, by contrast, different *species* in accordance with BSC criteria, whether those criteria be strong or weak).

Nevertheless the *strong* version of the BSC is a useful *supplement* to the TSC (with respect to currently-living sexually-reproducing species) because it

ON EVOLUTION

clearly distinguishes between those biological differences which are easily *reversible* and sortable in accordance with sexual (i.e., Mendelian) population genetics and those biological differences which are essentially *irreversible* and beyond the capability of Mendelian genetics to modify. It is the *latter* kind of “strict BSC” biological differences which correlate closely with the defining characteristics of *typological* species (and, indeed, the other higher typological classifications of the organism as well), while the *former* kind of biological differences represent merely the characteristics of *varieties* within species.

Our observations in the previous paragraph hint at the strange nature of that “shotgun wedding” between Darwinism and Mendelian population genetics which the neo-Darwinist synthesis represents: While Darwin insisted that the process of sexual reproduction *can* generate new species, phyla, classes, and so on, Mendel insisted that it *cannot*. Lynn Margulis, the famous discoverer of the endosymbiotic relationship between the cell and the mitochondria which it contains, puts it this way:

Mendel, who developed the rules for genetic traits passing from one generation to another, made it very clear that, while those traits re-assort, they don't change over time. . . . *Species* of organisms, Mendel insisted, *don't* change through time. . . . The genes are simply shuffled around to come out in different combinations, but those same combinations generate exactly the same types. Mendel's observations are incontrovertible.³²²

Nevertheless, the idea that Mendelian sexual population genetics is the mechanism that drives the Darwinian “origin of the species” unaccountably remains as a permanent fixture of neo-Darwinian dogma.

The fact that all biological organisms, both present-day and those which emerged and became extinct in prehistoric times, can be sorted into a meaningful non-arbitrary typological hierarchy is (in an important sense) *the* fact of evolution which *any* theory of evolution must explain. Yet neo-Darwinians are, for the most part, philosophical *nominalists* who believe that all such biological typological hierarchies are “arbitrary” and “merely subjective”. That is why they can freely blur the distinction between varieties and species: To them the distinction is simply of no importance. It is highly ironic that the neo-Darwinists contemptuously dismiss this most-essential *fact* of biological evolution, while the creationists (who *do* acknowledge the reality of the biological typological hierarchy) do not.

To sum up this section, we may quote from the writings of two famous naturalists. First, the world-renowned horticulturist Luther Burbank:

I know from my experience that I can develop a plum half-an-inch long or one two-and-a-half inches long, with every possible length in between,

but I am willing to admit that it is hopeless to try to get a plum the size of a small pea, or one as big as a grapefruit. I have daisies on my farm little larger than my fingernail and some that measure six inches across, but I have none as big as a sunflower, and never expect to have. I have roses that bloom pretty steadily for six months in the year, but I have none that will bloom twelve, and I will not have. In short, there are limits to the developments possible [via Mendelian genetics]. . .³²³

Second, the famous French zoologist Pierre Grasse, editor of the 28-volume *Traite de Zoologie*:

The “evolution in action” of J. Huxley and other [neo-Darwinists] is simply the observation of demographic facts, local fluctuations of genotypes, geographical distributions. Often the species concerned have remained practically unchanged for hundreds of centuries! Fluctuation as a result of circumstances, with prior modification of the genome, does not imply evolution, and we have tangible proof of this in many panchronic species [i.e., living fossils that remain unchanged for millions of years]. . .³²⁴

Sources of Intra-Species Variation

Having shown that neo-Darwinist mechanisms are effective only in producing and sustaining intra-species *varieties* and not the species themselves, we can go further to show that even the producing and sustaining of these *varieties* is probably not entirely a neo-Darwinian process: For while there is solid evidence that neo-Darwinian “natural selection” (i.e., differential reproduction and differential mortality) *is* vital to the creation and sustenance of intra-species varieties, the neo-Darwinian postulate that the initial *source* of variation is always *purely microscopic* and *purely random* is questionable.

For example, it is evidently the case that the traits and genes which are sorted, repressed, and expressed by Mendelian sexual genetics are *not* purely random: Rather, they represent intra-species genotypes whose corresponding phenotypes have proved to be valuable to the species’ survival in the past. In fact it would seem to be the primary function of the Mendelian sexual process to preserve and redistribute such actually *or potentially* useful intra-species genotypes in a flexible (i.e., *reversible*) fashion. (Another function of sexuality may be seen in the redundancy between the two sets of chromosomes, which provides the organism with some protection from the effects of undesirable random mutations.)

Furthermore, there is considerable evidence that both sexual *and* asexual organisms have the ability to draw from a genetic “library” of pre-existing genotypes. For example, Stuart B. Levy, in his article titled “The Challenge of Antibiotic Resistance” in the March 1998 issue of *Scientific American*, wrote that:

ON EVOLUTION

Many bacteria possessed resistance genes even before commercial antibiotics came into use. Scientists do not know exactly why these genes evolved and were maintained.³²⁵

It is possible that this “library” may be stored in the so-called “pseudo-genes” and “junk DNA” which comprise such a vast majority of chromosomal DNA. It is also possible that *which* genotypes actually get “checked out” from this library depends on nonlinear epigenetic processes that are currently poorly understood. Once “checked out”, however, neo-Darwinian “natural selection” (differential reproduction and differential mortality) will act on the corresponding phenotypes to adjust the proportions of varieties within the species.

But what is the ultimate origin of the intra-species genotypes in this genetic “library”? They could, of course, ultimately be the results of purely random microscopic processes such as mutation and copying-error, as is claimed by the neo-Darwinists. On the other hand, there is evidence that they could also be created by a feedback from the realm of the phenotype back to the realm of the genotype. This is, of course, the process of “inheritance of acquired characteristics” first proposed by the French naturalist Jean-Baptiste Lamarck and supported even by Darwin himself in his theory of *pangenesis*. For neo-Darwinists, however, such a feedback is *streng verboten* because it would destroy the supposedly strict separation between the *essentially random* origin of the *microscopic* genotypes and the *essentially deterministic* “natural selection” of the corresponding *macroscopic* phenotypes.

Neo-Darwinians express their opposition to this heresy of *Lamarckism* by means of the rule called *Weismann’s barrier*, which states that genetic information can only flow *from* germ cells (i.e., sperm and egg cells) *to* somatic cells (i.e., body cells), but can *never* flow in the reverse direction from somatic cells to germ cells. Unfortunately for the neo-Darwinists there is now considerable evidence that Weismann’s barrier not only *can* be pierced, but frequently *has* been pierced as well.

First, there is overwhelming evidence of the inheritance of acquired characteristics in plants:

What about acquired inheritance in plants? Here there is *no* ‘Weismann Barrier’ separating the soma and the germline. Acquired somatic modifications in plants which are gene-based can in principle be propagated to progeny when the seed is formed from that part of the plant that developed the somatic mutation. . . Phenomena such as acquired inheritance of induced heavy metal tolerance can be routinely demonstrated. The flax plant has been particularly useful in demonstrating the role of environmental stress triggering inherited changes in plant genomes; and the validity of this conclusion is underlined by the pioneering

work by Nobel laureate Barbara McLintock on transposable genetic elements in maize.³²⁶

Second, Ted Steele and his associates have found considerable detailed evidence at the biochemical level of soma-to-germline feedback in the development of that part of the genotype “library” that relates to the *immune system*.³²⁷

Third, there are weaker and more speculative examples which are nonetheless intuitively compelling. One such example is cited by Steele, Lindley, and Blanden:

Animals such as the ostrich and the African warthog have large, prominent [calluses] on parts of the body (sternum, forelimbs, hindlimbs), apparently as a consequence of their resting or foraging habits. . . . [Calluses] can be found at all of those sites where the skin makes contact with the ground, the sternal callus being particularly large. . . . Callusing of this type can therefore be classed as an ‘acquired’ somatic adaptation. What is particularly interesting is that all those prominent natural calluses found in adult ostriches and warthogs are *already well-formed in the embryo* in the absence of friction or rubbing. This implies that these strategically located [calluses] are *germline encoded*.³²⁸

As Gordon Rattray Taylor and others have remarked, it is perhaps conceivable that a microscopic random mutation or copying-error could result in a phenotype of *generally* thickened skin which could then be favored by “natural selection”. But a random mutation to thicken the skin in *exactly* the places where the adult animal will sit or rub is almost inconceivably improbable. Neo-Darwinists such as Richard Dawkins scoff at such concerns, calling them the “argument from incredulity”. (Interestingly, only with respect to neo-Darwinism do “skeptics’ societies” seem to strongly prefer the “argument from *credulity*” to the “argument from incredulity”!)

Nevertheless, as Ted Steele and his co-workers admit, exactly *how* information concerning the specific “desired” locations of calluses on the body could be transmitted from somatic cells to germline cells is a total mystery, which is why such putative examples of Lamarckian processes remain speculative.

In any case, the question of whether neo-Darwinian processes, or on the contrary Lamarckian processes, are the ultimate source of the variations between intra-species genotypes is irrelevant to the question of the “origin of the species”, since both kinds of processes relate only to the creating and sustaining of intra-species *varieties*, not the creating and sustaining of *species*.

ON EVOLUTION

In summary, since we have shown that neo-Darwinian processes are *not* capable of creating true typological species, but only intra-species varieties, this third *fact of evolution* is clearly a strong point *against* the theory of neo-Darwinism and (by default) a strong point *in favor of* the theory of macrodevelopment.

4. *Strongly Uneven in Tempo*

Biological evolution is *strongly uneven in tempo*, marked by long periods of stasis punctuated by bursts of change: In other words, the fossil record clearly shows that true typological species tend to remain the same over many millions of years, and that both the creation and the extinction of species occur relatively suddenly within a geological time-frame. Moreover, this sudden creation and extinction of species tends to occur over a *relatively wide geographical area*, rather than being a slow, radiative process.

This fact of evolution was known even in Darwin's time, and he regarded it to be one of the most serious arguments against his theory – a theory which requires (of course) that newer species split off from older species gradually, step-by-step, over millions of years ("phyletic gradualism"). The only explanation Darwin could come up with to counter this fact of evolution was that the fossil record uncovered thus far was incomplete and that future paleontological research would uncover the many missing intermediates.

Unfortunately for the theory of neo-Darwinism, this proved not to be the case. As the prominent paleontologists Niles Eldredge and I. Tattersall wrote in their 1982 book *The Myths of Human Evolution*:

Paleontologists just were not seeing the expected changes in their fossils as they pursued them up through the rock record. . . . That individual kinds of fossils remain recognizably the same throughout the length of their occurrence in the fossil record had been known to paleontologists long before Darwin published his *Origin*. Darwin himself . . . prophesied that future generations of paleontologists would fill in these gaps by diligent search. . . . One hundred and twenty years of paleontological research later, it has become abundantly clear that the fossil record will not confirm this part of Darwin's predictions. Nor is the problem a miserly fossil record. The fossil record simply shows that this prediction is wrong.

The observation that species are amazingly conservative and static entities throughout long periods of time has all the qualities of the emperor's new clothes: everyone knew it but preferred to ignore it. Paleontologists, faced with a recalcitrant record obstinately refusing to yield Darwin's predicted pattern, simply looked the other way. . . .

Darwin's prediction of rampant, albeit gradual, change affecting all lineages through time is refuted. The record is there, and the record

speaks for tremendous anatomical conservatism. Change in the manner Darwin expected is just not found in the fossil record.³²⁹

The well-known paleontologist and naturalist Stephen Jay Gould put it this way in an article called “Evolution’s Erratic Pace”:

The history of most fossil species include two features particularly inconsistent with [phyletic] gradualism:

1. *Stasis* – most species exhibit no directional change during their tenure on earth. They appear in the fossil record looking much the same as when they disappear; morphological change is usually limited and directionless;
2. *Sudden appearance* – in any local area, a species does not arise gradually by the steady transformation of its ancestors; it appears all at once and ‘fully formed’.³³⁰

To take a “specific” example (pun intended), consider this instance, cited by Rebecca Teed:

Jackson and Cheetham (1994) made a detailed study of Caribbean bryozoa (all species in the genera *Metrarabdotos* and *Stylopoma*) and found that new species appeared “fully formed” and remained unchanged for 2.5 million to 16 million years ($p > .99$ for sixteen species and $p > .9$ for three species). They found “no evidence that intraspecific rates of morphological change can account for differences between species”.³³¹

And the 1994 study by Jackson and Cheetham which Teed cites is not atypical. Donald R. Prothero writes:

As paleontologists had known for over a century, most species are stable for millions of years, and change so rapidly that we rarely witness it in the fossil record. Of the hundreds of studies that have been reviewed elsewhere (Gould and Eldredge, 1977, 1986; Gould, 1992), a few stand out: Stanley (1992), Cheetham (1986) and Stanley and Yang (1987) examined all the available lineages of their respective groups (bryozoans and bivalves) through long intervals of time, using multivariate analysis of multiple character states. Both concluded that most of their species were static through millions of years, with rare but rapid episodes of speciation. Williamson (1981, 1985) examined the details of [the] evolution of mollusks in Lake Turkana, Kenya, and showed that there were multiple examples of rapid speciation and prolonged stasis, but no gradualism. Barnosky (1987) reviewed a great number of different lineages of mammals, from mammoths to shrews and rodents, that lived during the last two million years of the Ice Ages. He found a few examples of gradualism, but many more showed stasis and punctuation.

My own research (Prothero and Shubin, 1983; Prothero, 1992; Prothero, Heaton, and Stanley, in press) examined all the mammals with a reasonably complete record from the Eocene-Oligocene (about 30-35 million years ago) beds of the Big Badlands of South Dakota and related areas in Wyoming and Nebraska. This study not only sampled every available lineage without bias, but also had much better time control from magnetic

ON EVOLUTION

stratigraphy (Prothero and Swisher, 1992) and wider geographic coverage than the studies by Gingerich. . . With one exception (gradual dwarfing in the creodont *Miniochoerus*), we found that all of the Badlands mammals were static through millions of years, or speciated abruptly (if they changed at all). . . .

Most impressive are demonstrations of species stability *in spite of well documented environmental change*. The fluctuations of glacial-interglacial cycles during the last three million years of the Ice Ages are about as extreme a climactic change as our planet experiences. Yet studies from land mammals (White and Harris, 1977; Barnosky, 1987) to microscopic marine ostracodes (Cronin, 1985, 1987) document extreme stability in most species in spite of these changes. Rather than adapt to new environments, species migrate back and forth in response to them.

My own research on the Eocene-Oligocene transition about 34 million years ago (Prothero and Berggren, 1992) documents a similar phenomenon. Most of the mammals from the Badlands discussed above (Prothero and Shubin, 1983; Prothero, 1992) show remarkable stability over an interval of well-documented climactic stage.³³²

Thus, this fourth *fact of evolution* (i.e., unevenness in tempo) must also be regarded to be a strong point *against* the theory of neo-Darwinism.

But, in addition to being a point against neo-Darwinism, this fourth fact is also a point against creationism as well, if by “creationism” we mean the interpretation of the Biblical book of Genesis as a straightforward scientific theory. For Genesis literally requires that all of the biological species and higher-level taxa be created “in the beginning” within the span of a few days. Yet the fossil record clearly shows species, and even higher-level taxa, arising suddenly at a wide variety of times throughout the geological past, continuing for millions of years, and then disappearing as quickly as they arose. In other words, the problem is not that there are *no* ancestral taxons: Rather, the problem is that there are *too few* ancestral taxons spaced *too widely apart* to confirm neo-Darwinism.

What about the theory of *macrodevelopment*? Macrodevelopment fits this fourth fact of evolution “like a glove”. For, as we saw in our previous chapter on **Nonlinear Complex Physical Systems**, the development of the embryo of the biological individual is characterized by long periods of stasis and linear growth punctuated by short moments of nonlinear bifurcation and holistic transformation: This is *exactly* the same rhythm and pattern we see in the long history of the evolution of the biosphere! (Even the intense, relatively-short period of macrodevelopment of the phyla during the Cambrian era is paralleled by a similarly short, intense period of *bauplan* formation during the early stages of development of the individual biological embryo.) Not only that, but the fact that the sudden emergence of a species generally occurs *over a relatively wide geographical area* further confirms the holistic, nonlinear

nature of speciation, parallel to similar processes which occur during the morphogenesis of the individual biological embryo.

On “Punctuated Equilibrium”

But before leaving this point, we need to consider the major way in which the neo-Darwinists have tried to “explain away” this major disconfirmation of their theory: They have mainly tried to do this by extending Ernst Mayr’s concept of *allopatric speciation* (which we mentioned in our earlier discussion of the *third* “fact of evolution”) using ideas created by Niles Eldredge and Stephen Jay Gould under the heading of *punctuated equilibrium*.

Gould himself explains *punctuated equilibrium* in the following terms:

How does speciation occur? This is a perennial hot topic in evolutionary theory, but most biologists would subscribe to the “allopatric theory” (the debate centers on the admissibility of other modes; nearly everyone agrees that allopatric speciation is the most common mode). *Allopatric* means “in another place”. In the allopatric theory, popularized by Ernst Mayr, new species arise in *very small* populations that become isolated from their parental group at the *periphery* of the ancestral range. Speciation in these small isolates is *very rapid* by evolutionary standards – hundreds of thousands of years (a geological microsecond). Major evolutionary change may occur in these small, isolated populations. Favorable genetic variation can quickly spread through them. Moreover, natural selection tends to be intense in geographically marginal areas where the species barely maintains a foothold. In large central populations, on the other hand, favorable variations spread very slowly, and most change is steadfastly resisted by the well-adapted population. Small changes occur to meet the requirements of slowly altering climates, but major genetic reorganizations almost always take place in the small, peripherally isolated populations that form new species.

If evolution almost always occurs by rapid speciation in small, peripheral isolates – rather than by slow change in large central populations – then what should the fossil record look like? We are not likely to detect the event of speciation itself. It happens too fast, in too small a group, isolated too far from the ancestral range. We will first meet the new species as a fossil when it reinvades the ancestral range and becomes a large central population in its own right. During its recorded history in the fossil record, we should expect no major change. . . . [I]t . . . will appear “suddenly” in the fossil record and become extinct later with equal speed and little perceptible change in form.³³³

Now, the reason that Gould alleges that neo-Darwinian processes occur far more rapidly in small, peripheral populations is the so-called “founder effect”. Wesley Elsberry explains:

When a small sub-population is isolated from the rest of a population of a species, the particular set of variations in the sub-population is much

ON EVOLUTION

smaller than that in the remainder of the population. These variations, when in conjunction with suitable features of geographic locale, climate, and resources, can lead to rapid development of reproductive isolation from the ancestral population. The reduction in variation due to small sub-population size is known as the “founder effect”.³³⁴

Unfortunately for the neo-Darwinists, there are at least *two* major problems with this theory of *punctuated equilibrium*:

First, even though it *may* be true that the operation of neo-Darwinian processes (mutation, copying errors, genetic drift, sexual re-assortment, differential reproduction, differential mortality, increase in size & shape differences between varieties, increase in behavioral differences between varieties, changes in the varieties’ mate recognition systems, etc.) are significantly speeded up within small, peripheral populations, *all* of these neo-Darwinian processes are *still* the same processes which we demonstrated in evolutionary fact 3 above to be *incapable* of generating the strict, irreversible, *genetic* separation of species (the “strong” BSC): Rather, we showed in evolutionary fact 3 that the “major genetic reorganizations” (corresponding to the creation of *true* typological species and other taxa) which Gould speaks of above can *only* occur as the result of holistic, bifurcating, nonlinear processes, such as are seen *today* in the polyploid speciation of plants and *in the past* in the genetic evidence for major tetraploid events during vertebrate evolution (Susumu Ohno, 1970).

In some of his papers on punctuated equilibrium, Gould *has* mentioned one alleged factor in speciation that is *not* part of neo-Darwinian orthodoxy, namely the idea of a macro-mutation (saltation) in a developmental gene, causing radical changes in the phenotype of a single individual within a single generation. For example, in a 1980 paper Gould wrote:

Speciation is not always an extension of gradual, adaptive allelic substitution to greater effect, but may represent, as Goldschmidt argued, a different style of genetic change – rapid reorganization of the genome, perhaps nonadaptive.³³⁵

But Gould has always regarded such a scenario to be rare.

The main problem with Goldschmidt’s so-called “hopeful monster” scenario is, of course, the problem of passing such a radical random genetic change on to the next generation, together with the extremely long odds of such a macro-mutation producing a useful phenotype in the first place. (These same problems exist if we view such radical genetic reorganizations as *polyploidy* and Davison’s *semi-meiosis* in isolation as affecting only a single individual: That is why the theory of macrodevelopment regards such radical *individual* genetic transformations to be only sub-processes within the much-larger

process of *holistic taxon-wide* nonlinear bifurcation. We will discuss such issues in much more detail in our discussion of evolutionary fact 8, below.)

In any case, the *second* major problem with the theory of *punctuated equilibrium* is that it does not adequately explain why species should suddenly appear *across a wide geographical area*. In other words, the *radiation* of the new species from its small, peripheral location back out through its large “ancestral range” would often have to be extremely fast (a geological “instant”) in order to match the fossil evidence, but the theory of punctuated equilibrium gives no adequate reason as to why this radiation should commonly be so rapid, other than to point out that the ecological processes of dispersal and succession can occur very rapidly compared to the neo-Darwinian processes of species formation. But this sole reason given by the theory of punctuated equilibrium does *not* adequately explain why so many new species are “instantly” successful when they return to their large ancestral domain, rather than radiating back into that ancestral domain slowly and gradually. (By contrast, the theory of macrodevelopment holds that true typological species arise in a *holistic* manner as a result of a *taxon-wide split*, thus accounting for the instantly wide geographical distribution of the new species.)

On “Species Selection”

To end our discussion of this fourth *fact of evolution* (unevenness of tempo), it is interesting to note that recent paleontological theory is finally beginning to acknowledge the objective reality of true typological species and higher-level taxa, and to appreciate their holistic nature. Donald R. Prothero explains this relatively new phenomenon in his article on “Punctuated Equilibrium at Twenty” (1992):

The other major implication of the idea that species are static for millions of years is the implication for the *reality* of [typological] species. Traditionally, species were considered the sum of all of their component populations, and all processes (such as selection) operated on the level of [the] individual and populations. But if species are not just arbitrary slices of a continuum, but distinct entities with their own history of “birth” (speciation) and “death” (extinction), then perhaps species have characteristics that operate *on a hierarchical level above that of the genes, the individual, or the population*. This concept of *hierarchy* . . . has important implications for evolutionary biology (Gould and Eldredge, 1977; Gould, 1982a, 1982b; Vrba and Eldredge, 1984; Salthe, 1985; Eldredge, 1985b; Gould, 1985; Vrba and Gould, 1986).

Although glimmerings of this idea were present in the original 1972 Eldredge and Gould paper [on punctuated equilibrium], it first emerged explicitly in a brief paper by [Steven] Stanley (1975) followed by his

ON EVOLUTION

stimulating and controversial book *Macroevolution* (1979). Stanley called this concept “species selection”, and it was the basis for a new round of debates for over a decade. Since the original proposal, Elisabeth Vrba and Stephen Jay Gould (1986) have since argued that it should be called “species sorting”, since the process is not really analogous to natural selection on the level of individual populations.

In a nutshell, the argument postulates that species are real entities which have characteristics that are more than the sum of the characteristics of their component populations. When two or more species come into competition, the differential survival which sorts out the “winners” and “losers” may be due to these intrinsic species properties, rather than natural selection on individuals or populations.

For example, the tendency of a group to speciate rapidly or slowly is not a property of its component individuals. Organisms do not speciate, species do.³³⁶

In effect, the paleontologists who actually study the fossil evidence are coming very close to accepting (or, more accurately, discovering for themselves) that the nonlinear holistic theory of macrodevelopment is the correct theory of evolution. The self-appointed keepers of reductionistic neo-Darwinian orthodoxy are *not* amused. Again, Prothero:

Traditional neo-Darwinists have failed to see any difference between traditional natural selection and species sorting (Mayr, 1992; Hecht and Hoffman, 1986; Hoffman and Hecht, 1986; Hoffman, 1982, 1984, 1989, 1992). In reading the literature, it is clear that the debaters are talking past each other, since each has fundamentally different perceptions of the world. Traditional neo-Darwinists come from a reductionist viewpoint that cannot see species as entities, even after all the evidence that has accumulated. The opposing camp sees the world as hierarchically ordered, with each level having its own reality. As long as this fundamental difference in worldview underlies the argument, neither side will convince the other, even with the clearest possible examples.

More is at stake here than the reality of species, however. If species sorting is real, then the processes operating on the level of species (*macroevolutionary processes*) are not necessarily the same as those operating on the level of individuals and populations.³³⁷

No wonder orthodox neo-Darwinists (such as Mayr, Hecht, Hoffman, John Maynard Smith, George Williams, Daniel Dennett, Richard Dawkins, and Robert Wright) bitterly attack these renegade paleontologists (Eldredge, Gould, Prothero, Stanley, Salthe, and Vrba) as “accidental creationists”!³³⁸

5. *Strict Typological Hierarchy*

Virtually all multi-cellular biological organisms, both past and present, can be scientifically, objectively classified according to a strict typological hierarchy

in which all of the taxa are *monophyletic* groups. This is strong evidence that biological evolution proceeded by means of a process of *symmetrical* splits in which each *more-generic* “ancestor” taxon was entirely replaced by two *more-specific* “descendent” taxa. (Each such more-generic “ancestor” taxon *may* have had more-specific features, over and above its generic characteristics, but these more-specific features were not passed on to its “descendents”. Also, the two “descendent” taxa need not be at the next-lower *named* level in the hierarchy because there are always far more levels in the hierarchy than can be conveniently named.)

Typological hierarchies can themselves be classified into two types: those in which the boundaries between the taxa are indistinct and/or arbitrary (i.e., partially *subjective*), and those in which the boundaries between the taxa are clear and *objective*. (However, which hierarchical levels we actually give *names* to and what we *name* the individual taxa is, of course, arbitrary even in objective hierarchies.)

The *biological* taxonomic hierarchy is of the latter *objective* type, and the taxa within it are all *monophyletic* groups. A *monophyletic* group (also called a *clade*) consists of an “ancestor” taxon together with *all* taxa which are either immediate or more-distant “descendents” of that taxon. Figure 32, which can be found on the following page, depicts a simple nested hierarchy of monophyletic taxa. (Such a diagram is called a *cladogram*). In addition to the more-specific “leaf” taxa at the top (Amphibians, Reptiles, and Mammals), we see a more-generic taxon which we have called Amniotes (i.e., animals which produce watertight eggs) and a still-more-generic taxon which we have called Tetrapods (i.e., four-limbed creatures).

The numbers beside each node of the hierarchy in Figure 32 (such as 1, 1.2, 1.2.2, etc.) may be thought of as biological “version numbers”: The first digit in the number represents a set of characteristics (or traits) at the most-generic level, the second digit (after the first period) represents a set of traits at the next-most-generic level, and so on down to the most-specific level, which is represented by the last digit. A plus sign after the number means that this “ancestor” taxon *may* have had additional specific traits which were not passed on to its “descendents”.

Notice in Figure 32 that a hierarchy of monophyletic taxa is a hierarchy in which each nested group is clearly defined and separated, which is exactly what we find in nature with respect to virtually all multi-celled animals and plants. Notice also that, in a sense, the root “ancestor” of every monophyletic taxon “dies” when it splits into its two immediate “descendent” taxa, continuing to survive only in the generic aspects of its “descendents”. That is why monophyletic splits are *symmetrical* splits. (This is reflected in the Venn

ON EVOLUTION

diagram at the bottom of Figure 32 by showing the names *Amniotes* and *Tetrapods* in italics.)

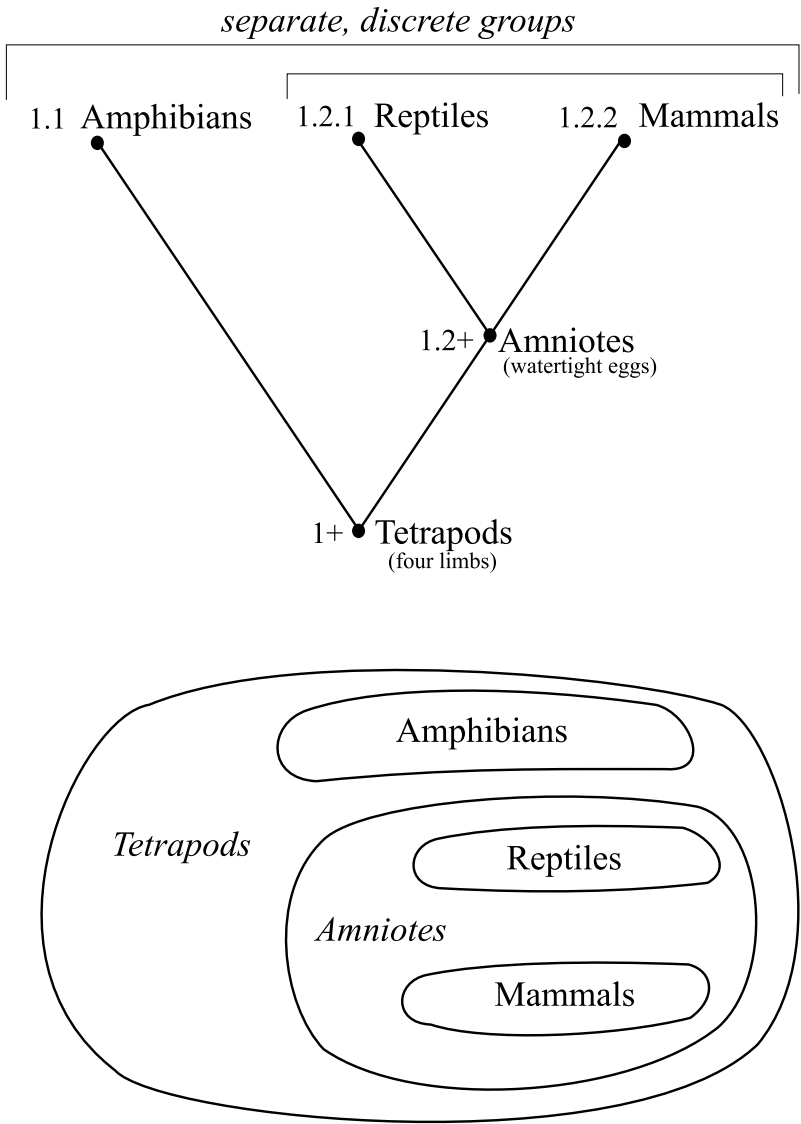


Figure 32 (*monophyletic* hierarchy = CORRECT hierarchy)

Finally, note that, in the foregoing paragraphs, the word “taxon” means both “the root ancestor taxon” and “the group consisting of the root ancestor taxon plus all of its descendent taxa”. (In the case of *monophyletic* taxa there is no real conflict between these two complementary meanings.)

The most-modern and by-far most-dominant contemporary biological system of classification is called *cladistics*. Cladistics uses *monophyletic* taxa exclusively, because that way of classifying multi-celled biological organisms fits the biological facts best. By contrast, the basic problem with older biological classification systems, such as so-called *evolutionary systematics* and the *Linnean system* (kingdom, phylum, class, order, family, genus, and species), is that they sometimes use *paraphyletic* taxa in addition to monophyletic taxa.

A *paraphyletic* taxon (like a monophyletic taxon) consists of a group of “descendent” taxa, together with all of their common “ancestors”, down to a root “ancestor” taxon. However, *unlike* the monophyletic taxon, in the *paraphyletic* taxon not all descendents of this root “ancestor” taxon are included in the group. Consequently a *paraphyletic* taxon tends to suggest that the group of descendents was initially formed by “splitting off” from the root “ancestor” taxon, which itself continues to exist much as it did before the split. That is why we say that the splits in a hierarchy of *paraphyletic* taxa are *asymmetrical* splits.

Figure 33, drawn on the following page, shows a *paraphyletic* version of the monophyletic hierarchy in Figure 32. It is important to note that Figure 33 is now known to be *incorrect*. However, Figure 33 *does* correspond to the textbook orthodoxy we were taught in school – namely, that the reptiles “split off” from the amphibians and that, later, the mammals “split off” from the reptiles.

Just as in Figure 32, the numbers in Figure 33 represent biological “version numbers”: The number 1 represents Amphibians, 1.1 represents Reptiles, and 1.1.1 represents Mammals. In Figure 33 the Mammals are a paraphyletic taxon because they are shown as descending from the Reptiles, who are themselves not part of the Mammal taxon group. Similarly, the *amniotes* (Reptiles plus Mammals) form a paraphyletic taxon because they are shown as descending from the Amphibians, who are not themselves part of the *amniotes* group. In other words, Figure 33 depicts the amniotes (actually, the Reptiles) as “splitting off” from the Amphibians: Later, the Mammals, in turn, are depicted as “splitting off” from the Reptiles.

The names *amniotes* and *tetrapods* do not appear in Figure 33 because, while both of these names could be regarded as naming paraphyletic taxa, no actual “ancestor” taxon corresponds to either of them in Figure 33. This is because the name of a *paraphyletic* taxon can only name the group, since there is really no corresponding actual, separate, unique “ancestor” taxon at the root of a paraphyletic taxon.

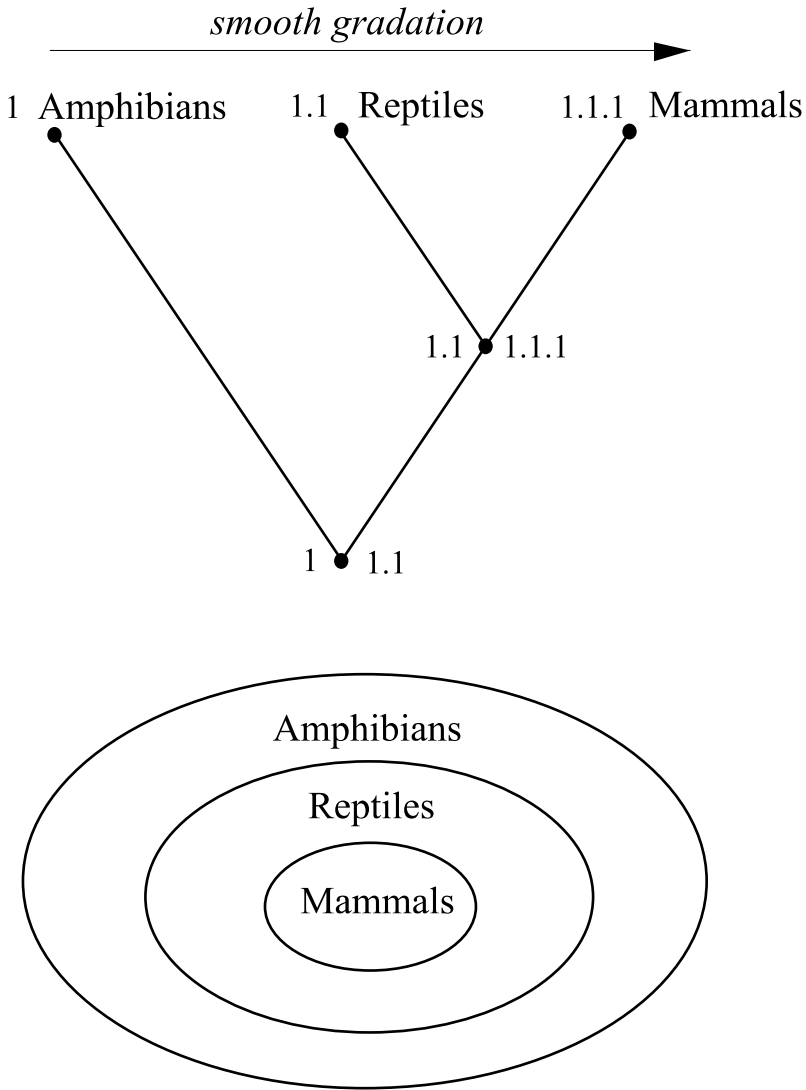


Figure 33 (*paraphyletic hierarchy = INCORRECT hierarchy*)

Notice also in Figure 33 that a hierarchy of paraphyletic taxa ultimately produces a smooth gradation of organisms at the current, contemporary “leaf” level. (This is represented by the horizontal series of version numbers 1, 1.1, and 1.1.1 at the top of Figure 33.) In other words, no clear, distinct hierarchy is visible at the current, contemporary level. Consequently, where

we draw the divisions between current biological organisms that have arisen from a *paraphyletic* hierarchy is, to a large degree, *subjective* and *arbitrary*. Because of this, notice, in particular, that the Reptiles in Figure 33 are a *transitional* taxon existing *between* Amphibians and Mammals. (But note, again, that Figure 33 is now known to be *incorrect*.)

A final way in which biological organisms can be grouped together is in a *polyphyletic* group. A *polyphyletic* group of organisms (unlike the monophyletic and paraphyletic groups) *cannot* be traced back to a common “ancestor”. Rather, a *polyphyletic* group of organisms is grouped together (in part, at least) on the basis of *analogous* traits, rather than *homologous* traits. *Analogous* traits are those which have evolved separately along lines of *parallel* evolution (also called *convergent* evolution). By contrast *homologous* traits are those which have evolved “vertically” up the evolutionary tree, such that they can be used as the basis for evolutionary classification. *No* systems of biological classification (neither the Linnean, the “evolutionary”, nor the cladistic) permit the use of *polyphyletic* taxa. (Probable examples of *polyphyletic* groupings include: the class of all flying vertebrates, the class of all warm-blooded animals, and the class of all swimming amniotes.)

Nevertheless, determining *which* biological traits are *analogous* and *which* biological traits are, on the contrary, *homologous* is often not easy! To make this determination as objective as possible, biological taxonomists (today called *cladists*) try to consider many separate traits, treating them statistically via computer analysis in order to avoid having any subjective preferences for “pet” traits. The cladists then select from the many possible monophyletic trees (i.e., cladograms) according to the criteria of parsimony and simplicity, together with a consideration of the fossil evidence. (At least they *should* consider the fossil evidence; they are sometimes remiss in that respect!) The American Museum of Natural History summarizes well the situation of contemporary cladistics:

Although cladistics provides us with the best current method of determining evolutionary relationships, it is not perfect. Contradictions among advanced features often suggest alternative evolutionary trees. In such cases, the cladogram consistent with the most features is chosen for the time being. True evolutionary relationships can never be definitively established, either by examining fossils or studying DNA. But we can get closer and closer to the actual sequence of evolution by testing hypotheses about relationships with as many features as possible.³³⁹

In spite of these uncertainties concerning the precise results of cladistic classification, cladists *are* sure that evolution proceeded according to the process suggested by cladistic *monophyletic* evolutionary relationships

ON EVOLUTION

(*symmetrical* splitting, Figure 32) rather than the process suggested by *paraphyletic* relationships (*asymmetrical* “splitting off”, Figure 33). How can they be so sure?

Evidence for Monophyletic Evolutionary Relationships

In the first place, closer examination of both living multi-celled biological organisms and the fossils of their extinct ancestors began to cast doubt on previously-assumed neat transitional evolutionary series, such as the series of amphibians-to-reptiles-to-mammals: Such a series would tend to suggest that reptiles should be *transitional* (i.e., “half-way”) between amphibians and mammals in their morphological characteristics (as is implied by Figure 33), whereas closer examination revealed that both reptiles and mammals are instead morphologically *equidistant* from amphibians (as is implied by Figure 32). As Michael Denton has written:

[I]t has always been traditionally considered that the morphology of the vertebrate heart and aortic arches in fish, lungfish, amphibians, reptiles, and mammals form a clear series. However, the sequence is very much a broken one, and it is doubtful to what extent it really gives evidence of being a sequence. Take one section of the traditional sequence: amphibian → reptile → mammal. There are many detailed aspects of the comparative anatomy which do not support it, for example, the aortic arches. The major vessel leaving the left ventricle in a reptile, which is the major vessel carrying aerated blood from the heart, is formed from the fourth right aortic arch, while in a mammal it is derived from the left aortic arch. Instead of arranging them in a sequence amphibian → reptile → mammal, we might just as easily arrange them circumferentially, with reptile and mammal equidistant from amphibians. . . .

But if there is some hint of a sequence in the case of the aortic arches, it is hopeless trying to arrange vertebrate egg cells, and the pattern of cell division in the earliest stages of embryology up to the formation of the blastula and beyond, into any sort of convincing sequence. In some ways, mammalian eggs are closer in their initial pattern of development to those of a frog [i.e., an amphibian] than to any reptile.³⁴⁰

Of course, classifying multi-celled biological organisms *morphologically* is non-quantitative, difficult, and often controversial: The “clincher” came when scientists began to *quantitatively* compare the differences between the sequences of amino acids in proteins that are common to many different species of multi-celled biological organisms. Michael Denton explains:

In the late 1950s it was found that the sequence of a particular protein, say, hemoglobin, was not fixed but varied considerably from species to species. The amino acid sequence of a protein from two different organisms can be readily compared by aligning the two sequences and counting the number of positions where the chains differ. . . . [T]he differences between two proteins can be quantified exactly, and the results of these

measurements can provide an entirely novel approach to measuring the differences between species. . .

It became increasingly apparent as more and more sequences accumulated that the differences between organisms at a molecular level corresponded to a large extent with their differences at a morphological level; and that all the classes traditionally identified by morphological criteria could also be detected by comparing their protein sequences. . .

However, as more protein sequences began to accumulate during the 1960s, it [also] became increasingly apparent that the molecules were not going to provide any evidence of sequential arrangements in nature, but were rather going to reaffirm . . . that the system of nature conforms fundamentally to a highly ordered hierarchic scheme. . . Moreover, the divisions turned out to be more mathematically perfect than even the most die-hard typologists would have predicted.³⁴¹

Michael Denton provides detailed and conclusive proof of this in his chapter titled “A Biochemical Echo of Typology” from his brilliant book *Evolution: A Theory in Crisis*.³⁴² For example, Denton cites information from the *Dayhoff Atlas of Protein Structure and Function* which shows clearly that the percent sequence divergence between the protein cytochrome C₂ in the bacterium *Rhodospirillum rubrum* and the corresponding cytochromes in *all* eukaryotic multi-celled organisms varies narrowly between 64% and 69%. (For example: humans 65%, rabbits 64%, ducks 64%, rattlesnakes 65%, bullfrogs 65%, tuna 65%, fruit flies 65%, and sunflowers 69%.) In other words, *all* contemporary eukaryotic multi-celled animals are typologically *equidistant* from the lowly bacteria, with no paraphyletic “transitional forms” bridging this gap! As Denton remarks:

Considering the enormous variation of eukaryotic species . . . and considering that eukaryotic cytochromes vary among themselves by up to about 45%, this must be considered one of the most astonishing findings of modern science.³⁴³

Furthermore, this clean, nested, monophyletic hierarchical pattern continues as we examine the more-specific taxonomic levels. For example, a comparison between the protein cytochrome C of the silk moth (an *insect*) and the corresponding cytochromes of the *vertebrates* reveals a relatively narrow variation of between 25% and 30% (horse 27%, pigeon 25%, turtle 26%, carp 25%, and lampreys 30%), which is strong evidence that there are no “transitional taxa” between insects and vertebrates.³⁴⁴ Or, again, the percentage difference between the cytochrome C in a carp (a *fish*) and the cytochrome C in the *tetrapods* varies quite narrowly between 13% and 14%: For the horse and the rabbit (both mammals) the variance is 13%, for the turtle (a reptile) it is also 13%, and for the bullfrog (an amphibian) the variance remains 13%. This, in turn, is strong evidence that amphibians are *not* “transitional” between fishes and reptiles (nor are reptiles “transitional”

ON EVOLUTION

between amphibians and mammals), and that the statements of neo-Darwinian textbook orthodoxy saying that “the amphibians *split off* from the fishes, the reptiles *split off* from the amphibians, and (finally) the mammals *split off* from the reptiles” are highly unlikely to be true!³⁴⁵

If we choose a different protein, for example, hemoglobin rather than cytochrome C, then the difference between the carp (a *fish*) and the *tetrapods* varies closely *around 50%* for hemoglobin, rather than *around 13%-14%* for cytochrome C. Nevertheless, the tetrapods all remain *equidistant* from the carp, whether we measure them using hemoglobin, cytochrome C, or some other protein!

Michael Denton continues:

[The tetrapods] can themselves be divided into two basic classes, by virtue of their molecular similarities. One class contains the amphibians, and the other the reptiles & mammals. Again the subdivision corresponds to that based on classical morphological grounds, but whichever species are taken for comparative purposes, the distance between amphibian species on the one hand and mammalian & reptilian species on the other is always the same. No amphibian species is midway between other amphibians and the reptiles & the mammals. Similarly, no reptilian or mammalian species is closer to amphibians than any of the others. . .

The classification system that is derived from these comparative molecular studies is a highly-ordered non-overlapping system composed entirely of groups within groups, of classes which are inclusive or exclusive of other classes. There is a total absence of partially inclusive or intermediate classes, and therefore none of the groups traditionally cited by [neo-Darwinian] biologists as intermediate gives even the slightest hint of a supposedly transitional character.³⁴⁶

Denton goes on to show that the molecular evidence supports the appropriateness of a similarly strict monophyletic hierarchy in the classification of the primates (monkeys, gibbons, apes, and man). Furthermore, subsequent work comparing the sequences of *nucleotides* in *RNA* for various species (rather than the sequences of *amino acids* in *proteins*) has given the same kind of results as those that we have described above.³⁴⁷

Ultimately, therefore, it is the *molecular* evidence which has “clinched” the case for a cladistic, monophyletic classification of multi-celled biological organisms (corresponding to the *symmetric* splitting shown in Figure 32), as opposed to the older classification systems (such as the “evolutionary” and the Linnean), which erroneously included paraphyletic groups in their hierarchies. (These erroneous paraphyletic groups correspond to the *asymmetrical* “splitting off” shown in Figure 33.)

Another complementary way of viewing this cladistic, monophyletic “tree” of taxa is to recognize that it has a self-similar *fractal* structure. In other words,

as we magnify our view of this genealogical “tree”, it continues to “look the same” at increasing levels of magnification. M.E.J. Newman and R.G. Palmer explain:

As long ago as 1922, it was noted that if one takes the taxonomic hierarchy of current organisms, counts the number of species n_s in each genus, and makes a histogram of the number of genera n_g for each value of n_s , then the resulting graph has a form which closely follows a power law (Willis 1922, Williams 1944):

$$n_g \text{ [is proportional to]} n_s^{-B}$$

[B, or beta, is a constant that varies for differing groups of organisms: For flowering plants it equals 1.5 ± 0.1 .]

Recently, Burlando (1990, 1993) has extended these results to higher taxa, showing that the number of genera per family, families per order, and so forth, also follow power laws, suggesting that the taxonomic tree has a *fractal* structure.³⁴⁸

As an aside, we might note that the fact that the monophyletic taxonomic “tree” has a *fractal* structure is *by itself* a strong argument that it was produced by *nonlinear* processes, such as macrodevelopment, rather than by neo-Darwinian linear processes.

Perhaps the most-important conclusion we can draw from this fact of the biological universality of monophyletic, fractal structure is that biological evolution must have proceeded historically from the *generic* to the *specific*, as is clearly shown in Figure 32. In other words, Figure 32 clearly reveals that the most-generic (least-specific) *tetrapods* appeared prior to the intermediate-generic (intermediate-specific) *amniotes*, which (in turn) appeared prior to the least-generic (most-specific) *amphibians*, *reptiles*, and *mammals*. This fact is confirmed not only by inferences from molecular biology and cladistics, but also by the fossil evidence: As we shall see in our discussion of the sixth *fact of evolution* (the fact of the “Cambrian explosion”), there is overwhelming fossil evidence that the generic body plans of *all* multi-celled biological organisms (i.e., the phylum-level taxa) appeared relatively quickly during the Cambrian era, with the more-specific taxa following later on in the approximate order of their specificity. In other words, all evidence shows that the more-specific the taxon, the later it appeared in evolutionary history. (This is not to deny, of course, that what we are calling *more-generic* “ancestors” may have had *more-specific* features that were irrevocably lost to their “descendents” as a result of the evolutionary process.)

As Richard Goldschmidt wrote (commenting on the fact that a phylum contains classes, a class contains orders, and so on with increasing specificity):

ON EVOLUTION

Can this mean anything but that the type of the phylum was evolved first and later separated into the types of classes, then into orders, and so on down the line? This natural, naïve interpretation of the existing hierarchy of forms actually agrees with the historical facts furnished in paleontology. The phyla existing today can be followed furthest back into remote geological time. Classes are a little younger, still younger are the orders, and so on until we come to the recent species which appear only in the latest geological epochs. Thus logic as well as historical fact tell us that the big categories exist first, and that in time they split in the form of the genealogical tree into lower and still lower categories.³⁴⁹

In contrast to the *correct* monophyletic tree shown in Figure 32, there is *no* clear historical movement from the generic to the specific in the *incorrect* paraphyletic tree shown in Figure 33: While, superficially, it may appear from Figure 33 that reptiles are “more generic” than mammals, and that amphibians are, in turn, “still more generic” than reptiles, neo-Darwinists would be the first to admit that these *apparent* differences in specificity between amphibians, reptiles, and mammals are purely subjective and arbitrary, depending on which traits of these multi-celled biological organisms we choose to look at.

Finally, we should note that the reason we have confined this discussion of taxonomy and cladistics to *multi-celled* biological organisms is that the taxonomy of *one-celled* organisms is far more complex than that of multi-celled organisms, due to the frequency of such phenomena as *horizontal gene transfers* and *endosymbiosis* in the one-celled realm. For this reason, it has recently been suggested that the “tree of life” is quite tangled at its one-celled base, and that consequently we may *never* be able to trace life back to a single archetypical cell.³⁵⁰

So, how do our two candidate theories of evolution (neo-Darwinism and macrodevelopment) fare in explaining this fifth fundamental *fact of evolution* (i.e., the fact of strict, monophyletic, typological hierarchy)?

The Neo-Darwinist Explanation

Considering neo-Darwinism first, it is important to note that *all* proposed neo-Darwinist evolutionary processes involve the “splitting off” of the newly-emergent taxon from the old taxon. For example, Darwin’s original theory of *phyletic gradualism* involves a continual “splitting off” of individuals into different phenotypes due to random mutations in their corresponding genotypes. “Natural selection” (i.e., differential reproduction and differential mortality) then determines which of these “split off” phenotypes will survive to become new varieties, species, and higher-level taxa. By contrast, in the *punctuated equilibrium* model of Eldredge and Gould, this “splitting off”

process occurs much less frequently, but speciation according to punctuated equilibrium still requires a small population to be *geographically* “split off” from the main population of the ancestor species. Even Goldschmidt’s “hopeful monster” scenario requires an *individual* to be “split off” from the main population of the ancestor species via a radical mutation or radical genetic reorganization of that individual. Yet, we have seen that *all* of the evidence supports the *symmetrical* “splitting” of taxa, as shown in Figure 32, rather than the *asymmetrical* “splitting off” of taxa depicted in Figure 33. In short, there is *no* evidence for the traditional neo-Darwinian story that amphibians “split off” from the fish, that reptiles then “split off” from the amphibians, and that, finally, the mammals “split off” from the reptiles. As Michael Denton puts it:

One of the most celebrated cases of [supposed] sequence is that of the vertebrate classes leading from the cyclostomes, through fish, amphibians, and reptiles to the mammals. While no [neo-Darwinian] has ever claimed that any of the living representatives of any vertebrate class is *directly* ancestral with respect to another vertebrate group, it is definitely *implied* that in terms of their general biology and overall morphology there are clear grounds for viewing the series as a natural phylogenetic sequence. .

[Y]et in terms of their biochemistry, none of the species deemed “intermediate”, “ancestral”, or “primitive” by generations of [neo-Darwinist] biologists, and alluded to as evidence of sequence in nature, shows any sign of their supposed intermediate status.³⁵¹

For that reason, there is also no scientific evidence for the philosophical *nominalism* of the neo-Darwinists: We have seen, on the contrary, that the hierarchical organization of multi-celled biological organisms into clearly-defined monophyletic “groups within groups” is simply a *scientific fact*.

What about the clear scientific evidence that more-generic taxa appeared *before* more-specific taxa during the history of life on earth? Neo-Darwinism can give no coherent explanation of this, fundamentally because it is a *linear* scientific theory whose primary mechanism, “natural selection”, causes the statistical distribution of phenotypes to track *any* environmental change, whether that particular environmental change happens to favor organisms with *more* specificity or *less* specificity. Furthermore, any such change in the statistical distribution of phenotypes is easily *reversible* if environmental conditions change back to their former state.

Consider, for example, Darwin’s own discussion of the only diagram that appears in his famous book, *The Origin of the Species*. Immediately prior to discussing this diagram, Darwin writes:

[I]n the general economy of any land, the more widely and perfectly the animals and plants are diversified for different habits of life, so will a greater number of individuals be capable of there supporting themselves.

ON EVOLUTION

A set of animals, with their organization but little diversified, could hardly compete with a set more perfectly diversified in structure. . .

. . . [W]e may, I think, assume that the modified descendants of any one species will succeed by so much the better as they become more diversified in structure . . .³⁵²

And a little later Darwin writes:

[A]s a general rule, the more diversified in structure the descendants from any one species can be rendered, the more places they will be able to seize on, and the more their modified progeny will be increased.³⁵³

These passages might suggest that Darwin believed that the evolution of taxa *from the generic to the specific* is favored by “natural selection”. Yet the full context of Darwin’s discussion of his diagram belies this:

Darwin’s diagram shows eleven species (which Darwin says are all members of *the same genus* “large in its own country”) marked *A* through *L* at the bottom of the diagram. A complex and diversified pattern of branches, forming a tree, extends up from species *A*, ultimately leading to eight species marked *a*¹⁴ through *m*¹⁴ as the “leaves” of this tree at the top of the diagram. A similar, but less “full” tree leads up from species *I* to six species marked *n*¹⁴ to *z*¹⁴, also at the top of the diagram. After a rather long and involved discussion, Darwin states:

[T]he six new species descended from (*I*), and the eight descended from (*A*), will have to be ranked as very distinct genera, or even as distinct sub-families.³⁵⁴

Now, the interesting thing is that if these two new groups of species are ranked as genera, then there has been *no* movement either from the generic to the specific *or* from the specific to the generic during the long course of evolution depicted in Darwin’s diagram! Rather, what has happened is that *one* genus containing eleven species has been replaced by *two* genera containing six and eight species, respectively, each such new genus being at the *same* level of specificity as the original genus. (In addition, species *F* continues in a straight line from the bottom up to the top of Darwin’s diagram, all of the original species *except* for *F* having become extinct).

On the other hand, if the two new groups of species at the top of Darwin’s diagram are ranked at the more-generic level of *sub-family*, then the historical movement of evolution depicted in the diagram is actually from the *specific* to the *generic* (since *one* genus turns into *two* sub-families)!

A few paragraphs later, Darwin further suggests that “[I]f, in our diagram, we suppose the amount of change represented by each successive group of diverging dotted lines to be very great”, then the two new groups of species “will form two distinct families, or even orders, according to the amount of

divergent modification supposed to be represented in the diagram. And the two new families, or orders, will have descended from two species of the original genus.”³⁵⁵

What Darwin is essentially proposing is that, as the varieties of biological organisms diversify via natural selection, they first give rise to species, then later group themselves into genera, still later into families, and (finally) into orders, so that the sequence of evolution historically proceeds from the *more-specific* taxa to the *more-generic* taxa. This in spite of the fact that the individual organisms *themselves* are all-the-while becoming increasingly diverse and specific! Quite apart from being a strange and confusing model, Darwin’s proposal flatly contradicts what we now know to be the truth: namely, that the more-generic taxa appeared *before* the less-generic taxa during the long course of evolutionary history.³⁵⁶

Now, even though neo-Darwinists can’t *explain* the scientific evidence represented by this vital fifth *fact of evolution* (i.e., strict monophyletic typological hierarchy, together with evolution’s progression from the generic to the specific), they nevertheless understandably feel strongly obligated to *explain* this evidence *away*. This *explaining-away* process began with Darwin himself in his book *The Origin of the Species*:

Darwin was well aware that the theory of evolution which he was proposing (i.e., biological varieties and species “splitting off” from one another numerous times via the processes of random microscopic variation and macroscopic “natural selection”) would necessarily create a smooth continuum of creatures such as that suggested in Figure 33 by the “version number” series 1, 1.1, 1.1.1 across the top of the figure. Why, then, (Darwin asked himself) is such a continuum not actually found in nature? The answer he suggested was that the *pattern of extinction* created by “natural selection” would be such as to cause “gaps” to occur in this continuous series. For example, if Reptiles were an *extinct* taxon (instead of a currently existing one), then the “version” number series at the top of Figure 33 would “jump” discontinuously from 1 to 1.1.1, rather than proceeding continuously from 1 to 1.1 to 1.1.1. Such a pattern of extinction might be expected to arise, Darwin theorized, if species became extinct principally due to intense competition with other closely-related species.

In discussing his own diagram in *The Origin of the Species*, Darwin makes it clear that it is principally the *extinction* of virtually all of the species *B* through *H* (which intervene between species *A* and *I* at the bottom of his diagram) that creates the separation between the two genera (or sub-families, or families, or orders) at the top of his diagram. He writes:

ON EVOLUTION

The intermediate species, also (and this is a very important consideration), which connected the original species (A) and (I), have all become, excepting (F), extinct, and have left no descendants. Hence the six new species descended from (I), and the eight descended from (A) will have to be ranked as very distinct genera, or even as distinct sub-families.³⁵⁷

Unfortunately, a very significant problem with Darwin's patterned-extinction hypothesis is that, while such extinctions might create an irregular *granularity* within the continuum of contemporary organisms (such that the contemporary biological "version numbers" might, for example, "jump" from 1 to 1.1.1 to 1.1.1.1.1 to 1.1.1.1.1.1.1.1.1, and so on), this pattern would *still* not duplicate the clear, monophyletic "nested hierarchy" pattern that actually occurs in nature (for example, the monophyletic "version number" series from 1 to 1.2.1 to 1.2.2 that occurs at the top of Figure 32). Darwin's patterned-extinction hypothesis therefore fails to "explain away" that formidable evidence against his theory which is represented by the fifth *fact of evolution*.

Furthermore, as we shall see in our discussion of the seventh *fact of evolution* (the fact of *taxonomic extinction*), paleontologists have found *no* evidence that Darwin's proposed process for biological extinction (namely, the supposedly intense competition for survival between closely-related species) is of any importance – and such a process may not, in fact, occur at all!

There is another far-more-elaborate hypothesis with which the neo-Darwinists have tried to "explain away", in particular, the overwhelming *biochemical* evidence against neo-Darwinism which we presented above. That hypothesis is the *molecular-clocks hypothesis*. According to the molecular-clocks hypothesis, the reason (for example) that the percentage difference between the cytochrome C in a carp (a fish) and the cytochrome C in all of the tetrapods varies quite narrowly between 13% and 14% is that the cytochrome C in all of the tetrapods has been subject to mutation at the same steady, minute, clock-like rate over the millions of years of geological time since the tetrapods "split off" from the fish. Furthermore, the reason the percentage difference between the hemoglobin in a carp (a fish) and the hemoglobin in all of the tetrapods varies narrowly around 50% (rather than 13% - 14%) is that the mutational "molecular clock" for hemoglobin ticks at a rate that is over three-times the rate of the "molecular clock" for cytochrome C (at least, with respect to the evolution of the tetrapods since they "split off" from the fish).

Applied to all of the many taxonomic groupings of multi-celled biological organisms and to all of the many families of proteins, this molecular-clocks hypothesis requires the existence of hundreds (and perhaps thousands) of separate molecular clocks, each keeping perfect, regular calendar time, yet each also ticking at a *different* constant rate that depends on *a*) the difference

between the taxonomic groups being measured and *b*) the family of proteins being measured.

According to neo-Darwinism, there are only two kinds of mutations which can gradually accumulate over time in a given protein of a given biological lineage: *neutral* mutations which are neither advantageous nor disadvantageous and which therefore accumulate via *genetic drift*, and (on the other hand) *advantageous* mutations which accumulate via “*natural selection*” (i.e., differential reproduction and differential mortality). By contrast, *disadvantageous* mutations can *never* accumulate, according to neo-Darwinism, because they are quickly weeded out by “natural selection”. That version of the molecular-clock hypothesis which says that the “ticks” of the molecular clocks are *neutral* mutations is called the *neutralist* hypothesis, while that version of the molecular-clock hypothesis which says that these “ticks” are *advantageous* mutations is called the *selectionist* hypothesis.

Taking first the *neutralist* hypothesis, we observe that the rate of *genetic drift* over time is directly related to and determined by the *mutation rate*, which for higher organisms has been estimated to be around 10^{-6} per gene per generation.³⁵⁸ Genetic drift is therefore expected to be much faster, in terms of *calendar* time, for organisms which reproduce quickly than for those which reproduce slowly. Michael Denton explains this problem for the *neutralist* hypothesis as follows:

A mouse may go through four to five generations in one year. The time taken by an elephant, a chimpanzee, or a man to reach maturity is about fourteen, seven, and ten years respectively. This means that at present the generation times of some mammalian species varies by a factor of nearly one hundred. Since the rodent order diverged from the primate, it is practically certain that the line leading to the mouse has undergone nearly one hundred times as many reproductive cycles as that leading to man. If mutation rates are approximately constant *per generation*, how then could [genetic] drift have generated equal [*calendar*] rates of genetic divergence in mice and men [relative, say, to the carp]? . . .

Only if the rate of mutation in homologous proteins in different organisms was, for some mysterious reason, adjusted so that it was constant with respect to absolute time would uniform rates of [genetic] drift occur.³⁵⁹

As W.J. Ewens has put it:

I note the well-known fact that the neutral theory predicts a constant rate of substitution per generation, whereas we appear to observe more a constant rate per year. In some of the species for which protein sequence comparisons have been made, there is a difference of one or even two orders of magnitude in generation time. It surely gets us nowhere simply to assume that the mutation rate adjusts itself in species of different generation time so that constant rates per year will arise.³⁶⁰

ON EVOLUTION

Michael Denton sums up the serious problems with the *neutralist* hypothesis as follows:

Unfortunately, all the evidence suggests that in different groups of organisms the mutation rate per unit of absolute time is vastly different, and this effectively excludes [genetic] drift as a mechanism for the generation of uniform rates of evolution. On top of this there is the additional difficulty of envisaging how [genetic] drift could have occurred at different rates in different genes to account for the different rates of evolution in different families of homologous proteins.³⁶¹

One way in which both neutralists *and* selectionists try to explain the fact that the mutational “molecular clocks” of differing families of homologous proteins “tick” at vastly different rates is the *functional constraint* theory. According to this theory, some proteins (such as histone 4) have relatively few gene sites at which a mutation would *not* be disadvantageous, due to “functional constraints”: Consequently, there are very few gene sites available for either neutral *or* advantageous mutations, and that is why the “molecular clock” of histone 4 is supposed to “tick” relatively slowly. By contrast, other proteins (such as the fibrinopeptides) are supposed to have far fewer “functional constraints”, which is why their “molecular clocks” are supposed to “tick” much more quickly. But, as Alan Wilson, an authority in this area, has pointed out:

...[W]e are not aware of direct experimental evidence showing rigorously that histone function is especially *sensitive* to amino acid substitution or that fibrinopeptide function is especially *insensitive* to amino acid substitution. Experimental studies would require that quantitative in vitro assays for the specific functions of histone 4 and fibrinopeptides be available. These have not been developed for histones, fibrinopeptides, or, indeed, most of the proteins whose evolutionary rates are listed.³⁶²

Furthermore, Michael Behe reports in a 1990 peer-reviewed article that experiments with yeast have shown that large parts of the histone molecule may be deleted without significantly affecting the viability of the organism. Behe writes:

[The experimental] results pose a profound dilemma for the molecular clock hypothesis: although the theory needs the postulate of functional constraints to explain the different degrees of divergence in protein classes, how can one speak of ‘functional constraints’ in histones when large portions of H2A, H2B, and H4 are dispensable for yeast viability? And if functional constraints do not govern the accumulation of mutations in histones, how can they be invoked with any confidence for other proteins?³⁶³

Michael Denton concludes:

Again, it is the sheer universality of the phenomenon – the necessity to believe that the functional constraints in *all* the members of a particular protein family, say *A*, in *all* diverse phylogenetic lines for *all* of hundreds of millions of years have remained precisely five times as stringent as those operating on the members of another protein family, say *B* – which fatally weakens the [functional constraints] theory.³⁶⁴

But what of the neo-Darwinist *selectionist* hypothesis as an alternative to the neo-Darwinist *neutralist* hypothesis? (Recall that the *selectionist* hypothesis states that the mutational “ticks” of the “molecular clocks” are *advantageous* mutations rather than neutral mutations.) Again, Michael Denton:

But if neutral drift gets us nowhere, selectionist explanations fare no better. It is very difficult to understand why all the members of a particular family of proteins, such as the hemoglobins or the cytochromes, should have suffered the same number of *advantageous* mutations since their common divergence.³⁶⁵

The serious problems with the *selectionist* hypothesis basically fall into two categories:

First is the current existence of “living fossils” such as the lungfish and the opossum, which have remained morphologically the same for tens (or even hundreds) of millions of years, yet which (in terms of their proteins) are just as equidistant from their ancestors as are “sister” species which have arisen much more recently and therefore have had a much-more diverse morphological history. As Denton remarks:

It is very difficult to understand why a protein [like hemoglobin] functioning in the basically unchanging physiological environment of the lungfish’s red [blood] cell should have undergone precisely the same number of beneficial mutations as a related protein evolving in a line subject to such global adaptational changes [as the lineage leading to man]. While selection at the morphological and molecular level may be relatively unlinked, it is surely inconceivable that they could be *absolutely* unrelated. . . .

Of course, the implausibility of selectionist explanations do not stop with the hemoglobins of a few living fossils. As in the case of uniform [genetic] drift, it is the sheer universality of the phenomenon – the necessity to believe that since their common divergence every single family of homologous proteins have suffered the same number of adaptive substitutions over the same period of time in *all* phylogenetic lines – which fatally weakens selectionist explanations.³⁶⁶

The *second* category of serious problems with the *selectionist* hypothesis relates to protein sequences which (so far as is known) have no other function than as “spacer” sequences, yet which have the *same* percent divergence with respect to ancestor species as do protein sequences which clearly are highly

ON EVOLUTION

functional (and therefore are supposedly strongly subject to “natural selection”). Denton gives this example:

A classic example of this are the two short amino acid sequences which are snipped out of the protein fibrinogen after it is activated during blood coagulation. These are known as fibrinopeptides *A* and *B*. As far as is known, neither of these two short peptides have any biological function, yet their percent sequence divergence in different mammalian groups conforms to the same ordered pattern as is found in all other proteins, i.e., the fibrinopeptides in all the members of any group are equally isolated from all the fibrinopeptide sequences found outside their group. . . .

. . . [S]electionist explanations [of this] . . . lead to absurd conclusions. Because the spacer sequences such as the fibrinopeptides exhibit the highest interspecies divergence of all proteins, if this is to be accounted for on purely selectionist grounds it is necessary to propose that they must have suffered adaptive changes very much more often than the hemoglobins or the cytochromes. In other words, they must have been under the intense scrutiny of natural selection. Not only must such sequences have suffered more adaptive changes than other proteins, but, in addition, these substitutions must have occurred regularly.³⁶⁷

Michael Denton sums up the serious problems with the neo-Darwinian “molecular clocks” hypothesis (in both its neutralist *and* selectionist flavors) as follows:

The difficulties associated with attempting to explain how a family of homologous proteins could have evolved at constant rates has created chaos in [neo-Darwinian] thought. The [neo-Darwinian] community has divided into two camps – those still adhering to the selectionist position, and those rejecting it in favor of the neutralist. The devastating aspect of this controversy is that *neither* side can adequately account for the [supposed] constancy in the rate of molecular evolution, yet each side fatally weakens the other. The selectionists wound the neutralist position by pointing to the disparity in the rates of mutation per unit time, while the neutralists destroy the selectionist position by showing how ludicrous it is to believe that selection would have caused equal rates of divergence in “junk” proteins or along phylogenetic lines as dissimilar as those of man and carp. . . .

Despite the fact that [there is] *no* convincing explanation of how random [neo-Darwinian] processes could have resulted in such an ordered pattern of diversity [as is found in molecular protein sequences], the idea of uniform rates of evolution is presented in the literature as if it were an empirical discovery. The hold of the [neo-Darwinian] paradigm is so powerful that an idea which is more like a principle of medieval astrology than a serious twentieth-century scientific theory has become a reality for [neo-Darwinian] biologists. . . .

What has been revealed as a result of the sequential comparisons of homologous proteins is an order as emphatic as that of the periodic table. Yet in the face of this extraordinary discovery the biological community

seems content to offer explanations which are no more than apologetic tautologies.³⁶⁸

Apropos Denton's reference to "medieval astrology", it is interesting to note that these neo-Darwinian "molecular clocks" are strongly reminiscent of the complex, nested epicycles which were multiplied in later Ptolemaic astronomy in order to be able to continue to place the earth firmly at the center of the solar system: These epicycles "worked" in the sense that they made the astronomical calculations come out "right", thus "saving" the Ptolemaic theory. But the epicycles were themselves so badly in need of explanation that the simpler Copernican theory placing the sun in the center of the solar system ultimately prevailed.³⁶⁹

Taking all of this evidence together, then, this fifth *fact of evolution* (i.e., the general conformance of the biosphere to a strict *monophyletic* typological hierarchy) is clearly a strong point *against* the theory of neo-Darwinism.

As a side note: How does *creationism* fare when confronted with this fifth *fact of evolution*? Creationism is actually *partially* confirmed by it: For over a hundred years creationists have maintained that the strict, monophyletic typological biological hierarchy is a scientific fact. And, over this same period, neo-Darwinists have inveighed against the sin of "essentialism" and have continually asserted that the apparent biological monophyletic hierarchy of "groups within groups" (shown in Figure 32) is a merely subjective, arbitrary illusion, and that instead the *paraphyletic*, smooth, continuous "splitting off" model depicted in Figure 33 is the correct one. It now turns out that on this point the creationists were right, and the neo-Darwinists were (and are) dead wrong.

However, this fifth evolutionary fact does not *entirely* confirm creationism. For creationists regard the typological biological hierarchy as existing solely within the "mind of God" when He created all biological organisms "in the beginning". Yet, clearly, the fossil evidence shows phyla appearing before classes, classes appearing before orders, orders before families, families before genera, and genera before species over the course of millions of years. In other words, the fact that the more-generic taxa have appeared before the more-specific taxa throughout evolutionary history is just as contrary to creationism as it is contrary to neo-Darwinism: True, all of the *phyla* appeared together during a relatively short period of time (i.e., the Cambrian era), but this is not enough to prove the creationist hypothesis that *all* biological taxa were created during a short period of time "in the beginning".

ON EVOLUTION

The Macrodevelopmental Explanation

What about the theory of *macrodevelopment* in relation to this fifth *fact of evolution*? Once again, macrodevelopment fits this fact “like a glove”: Figure 32’s depiction of the *symmetrical* splitting of each more-generic “ancestor” taxon into two more-specific “descendent” taxa (with the more-generic “ancestor” taxon then ceasing to independently exist) is *exactly* what the theory of macrodevelopment predicts. Furthermore, the appearance of the more-generic taxa *before* the more-specific taxa throughout evolutionary history is clearly analogous to the development of the individual biological embryo, where the early group of generic “stem cells” soon differentiates via nonlinear continuity-breaking to form increasingly more-specific groups of cells and organs.

This close analogy between *evolutionary* macrodevelopment and *individual* embryonic development is especially clear in Brian Foley’s description of the morphogenesis of mammals:

[V]ery early on in [the individual embryonic] development [of mammals], the cells that develop from the zygote [i.e., the egg cell] differentiate into three types. One type will make the skin and nerves, one type will make muscles and bone, and the third will make organs and blood. A bit later, the three types further differentiate into individual organs and tissues.

Such a method of development is called *hierarchical*, meaning “different levels”. Thus we can’t have skin without first having the zygote form the three basic types of cells and then the skin/nerve type further splitting into skin and nerve types, and then the skin type splitting further into hair follicles and sweat glands and other skin parts.³⁷⁰

What about the many serious problems surrounding the neo-Darwinian “molecular clocks” hypothesis? The theory of macrodevelopment deals with these problems in a manner precisely analogous to how the Copernican theory of astronomy dealt with the problem of Ptolemaic epicycles, i.e., by simply declaring that *there are no such things as molecular clocks*! Rather, the strict monophyletic hierarchical pattern of differences between homologous protein sequences within the biosphere was created as a byproduct of the same complex series of nonlinear continuity-breaking bifurcations that created the monophyletic biological taxon hierarchy itself. Since each such nonlinear bifurcation occurred quickly and holistically over the span of (at most) a few generations, macrodevelopment has no need to postulate the existence of hundreds (or thousands) of “molecular clocks” mysteriously ticking “slowly, minutely, gradually” at different linear calendar rates over millions of years!

In order to successfully account for the evidence of homologous protein-sequence differences, the theory of macrodevelopment requires that these

nonlinear continuity-breaking bifurcations within the biosphere obey the following law, which we shall tentatively propose as the *law of macrodevelopmental symmetry*:

- Any given instance of macrodevelopmental bifurcation must either:
 - a. Change exactly the same amino-acid sites on a given homologous protein on *each* side of the split (i.e., the homologous protein for each of the two “descendent” taxa is changed at *exactly* the same amino-acid sites), or
 - b. If the bifurcation *also* changes *additional* amino-acid sites on *one* side of the split, then subsequent bifurcations on the *other* side of the split tend to correct this imbalance by modifying those additional sites as well. (These subsequent bifurcations can *also* modify any *previously* modified amino-acid sites, but can *never* modify sites which were left untouched on *both* sides of the original bifurcation.)

Point *a* above corresponds to the *Stewart/Cohen hypothesis* mentioned earlier (i.e., that the traits of the two “descendent” species arising from a nonlinear continuity-breaking bifurcation will “average back” to the traits of the common “ancestor” species). However, point *b* goes beyond the Stewart/Cohen hypothesis to deal with the more-complicated case of nested bifurcations. (The fact that amino-acid sites which were completely untouched by the original bifurcation cannot be touched by subsequent bifurcations is closely related to the fact that a base of “generic” traits is passed unchanged from the “ancestor” taxon to *all* of its “descendent” taxa.)

Of course, any given instance of macrodevelopmental bifurcation can quickly affect *many* or even *all* of the relevant homologous proteins (via the DNA and RNA that templates these proteins), and it can affect each of those homologous proteins to a very different degree. (That’s why the difference between a carp and man with respect to hemoglobin is around 50%, while the difference between a carp and man with respect to cytochrome C is only around 13%-14%.)

Also, it is important to remember that macrodevelopmental bifurcations act not only suddenly, but also *holistically* (both spatially and temporally), so that these rapid and various changes in homologous protein sequences are really only byproducts of a sudden, global, taxon-wide process. Furthermore, the *temporal* aspect of this holism is why the subsequent nonlinear bifurcations seem to “know” that they can’t replace amino acids at sites that were left completely untouched by the original bifurcation.

ON EVOLUTION

To get an idea of how this *law of macrodevelopmental symmetry* works out in practice, consider Figure 34, below:

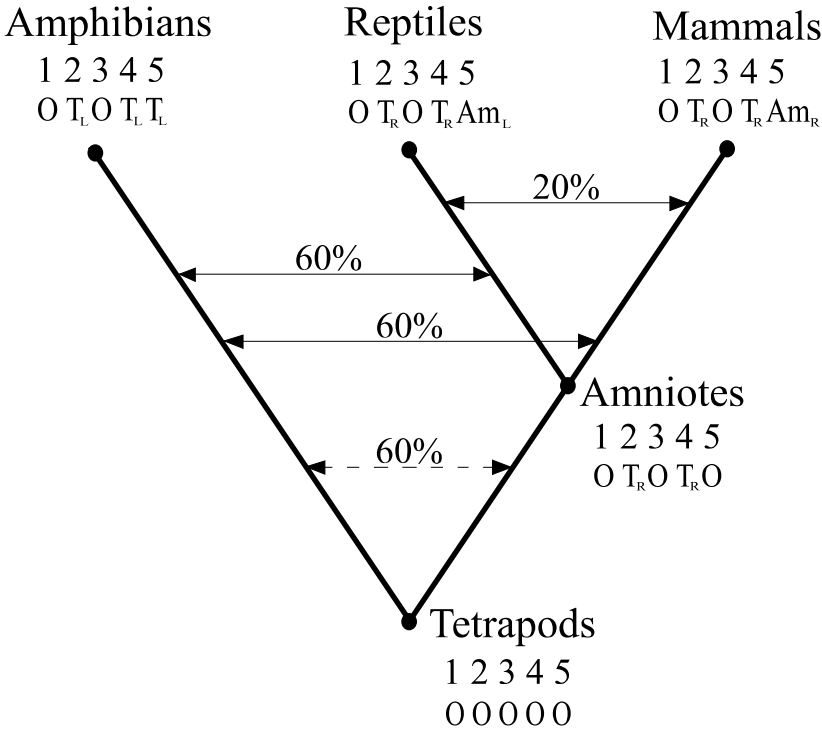


Figure 34

The basic structure of Figure 34 is based on Figure 32, except that under each node of the diagram are the numbers 1-through-5. Each number represents one position in an imaginary protein that has five amino-acid sites. (Of course, real proteins have hundreds, or even thousands, of such amino-acid sites.) Under each number 1-through-5 is a letter (or short sequence of letters) representing the amino-acid at that position.

For example, under all of the numbers 1-through-5 at the Tetrapods node is the letter **O**, which stands for “Original” (meaning, the original amino-acids occupying these five positions, before any bifurcations occur). Due to a nonlinear macrodevelopmental bifurcation, the Tetrapods “ancestor” taxon splits into the Amphibians “descendent” taxon on the left and the Amniotes “descendent” taxon on the right. As a result, *three* amino-acid sites (2, 4, and 5) under the Amphibians node show an amino-acid substitution, symbolized by **T_L** (meaning “the left side of the Tetrapods split”), while *two* amino-acid sites (2 and 4) under the Amniotes node also show an amino-acid substitution,

symbolized by T_R (meaning “the right side of the Tetrapods split”). The Tetrapods split, therefore, represents the kind of temporarily *unbalanced* split described in point *b* of the *law of macrodevelopmental symmetry*.

A subsequent nonlinear bifurcation of the Amniotes produces the Reptiles on the left and the Mammals on the right. As a result, both the Reptiles and the Mammals experience an amino-acid substitution at position 5. We call the Reptiles’ substitution at position 5 Am_L (meaning “the left side of the Amniotes split”), while the Mammals’ substitution at position 5 we call Am_R (meaning “the right side of the Amniotes split”). This Amniotes split therefore represents the kind of *balanced* split described in point *a* of the *law of macrodevelopmental symmetry*.

Now, notice that the Amphibians and the Amniotes differ in three out of five positions (2, 4, and 5), resulting in a protein sequence difference of 3/5, or 60%. (This is represented by the broken dimension line labeled as 60%. The dimension line is broken because we can’t directly measure this variance today.) The Reptiles and the Mammals also each differ from the Amphibians in three out of five positions (2, 4, and 5), again resulting in a protein sequence variation of 60%. (This is represented by the two solid dimension lines stretching from Amphibians to Reptiles and from Amphibians to Mammals, each respectively labeled as 60%.) Finally, the Reptiles and the Mammals differ from one another in only one position (position 5), resulting in a protein sequence variance of 1/5, or 20%, between Reptiles and Mammals. (This is represented by the solid dimension line stretching between the Reptiles and the Mammals that is labeled as 20%.) This general pattern of protein variance closely matches what we actually find in nature, with the Reptiles and Mammals being equally distant from the Amphibians in their own clearly-defined monophyletic group.

Notice also that the subsequent Amniotes split modifies position 5, which is the additional position that was modified on the *left* side of the original Tetrapods split. The Amniotes split therefore rectifies the failure of position 5 to be initially modified on the *right* side of the Tetrapods split. (In other words, the Amniotes split acts to restore the macrodevelopmental symmetrical balance.)

Furthermore, if the Am_L substitution for the Reptiles had occurred at position 3 (a position unmodified by *either* side of the Tetrapods split), rather than at position 5, then the protein sequence variance between Amphibians and Reptiles would have been 80%, as opposed to a Amphibian/Mammal variance of 60%, thus violating the actual evidence of the pattern of protein-sequence variation which we find in nature. Even if the Am_R substitution for the Mammals had *also* been at site 3 rather than at site 5, thus again rendering

ON EVOLUTION

the Reptiles and Mammals equidistant from the Amphibians (only with an equal variance of 80% rather than an equal variance of 60%), the variance between the Amphibians and the Amniotes (represented by the broken dimension line) would still remain at 60%. This would not, strictly speaking, violate the evidence of the pattern of protein sequence variation (since we can't *directly* measure the variance between the Amphibians and the Amniotes), but it *would* suggest that our current, most-recent situation is somehow unique and temporally privileged with respect to the past, and this does not seem at all likely.

(Note also that the fact that the Tetrapods split is *asymmetrical* in Figure 34 because it is unbalanced with respect to the number of amino-acid sites actually modified does *not* contradict the fact that the Tetrapods split is *symmetrical* in Figure 32, since all that is required for "symmetry" in Figure 32 is for the two "descendents" to be clearly different from the original Tetrapod "ancestor".)

We may therefore tentatively propose that the above *law of macrodevelopmental symmetry* expresses both the *necessary* and *sufficient* conditions for macrodevelopmental, nonlinear, continuity-breaking bifurcations to produce the pattern of homologous protein differences between taxa that we actually find in nature.

Now, we have seen that evolutionary macrodevelopment is evidently an "unfolding" process from the generic to the specific, just as is the case for individual embryonic development. Can we say anything else about this "unfolding" process?

Because there is some evidence that RNA (and hence, presumably, DNA) follow the same pattern of monophyletic hierarchical grouping as the homologous proteins, and because DNA, via messenger RNA, has been shown to provide a template for the creation of proteins, it might be proposed that this macrodevelopmental "unfolding" of the biosphere via nonlinear continuity-breaking bifurcations is *genetically programmed*. This is essentially what Robert F. DeHaan himself proposes:

According to the developmental perspective, the central [genetic] library was highly organized, with its information divided and subdivided into sections. Thus the phyletic germ line of each stem animal was differentiated and segregated into suites or modules of genetic programs along with their controlling regions. As a given phyletic germ line unfolded after the Cambrian explosion, it produced a lineage whose long journey through geologic time was shaped like a step-pyramid in Egypt, descending in step-wise fashion from the topmost stem animal into ever-lower, more-specific, and widening categories of lineage. That is, the control was hierarchical. The body plan of the stem animal at the top constrained the offspring in the next-lower category, the second-lower category controlled

all those below it, etc. These progressively descending, more-specific steps are called taxonomic levels of lineage that help scientists classify animals and plants. The phyletic germ line continued to be differentiated and segregated and expressed in this fashion, descending ever more-specifically through classes, order, families, genera, clear down to species, at which point the last programs of the lineal germ line were completely played out. This [macrodevelopmental] process resulted in the multiplicity of species found in the present time, numbering by some estimates, from 5 million to 50 million, but which have not produced any new, higher-level organisms.

The above scenario suggests further that the phyletic germ line may have originated, perhaps as sets of highly-ordered genes, such as the Hox genes, tucked away in relatively simple, undifferentiated, Precambrian proto-animals.³⁷¹

While I do think that Robert F. DeHaan is *essentially* correct, I believe that he here overstresses the role of *genetic programming* in this process. Rather, it seems to me much more likely that the nonlinear continuity-breaking bifurcations of macrodevelopment were *holistic* processes in which *cell-level epigenetic factors* and *macroscopic factors* (such as the “decisions” of biological taxa and individuals to respond to their environment in specific ways) significantly affected precisely how the biosphere has “unfolded”.

The major problem with DeHaan’s view as stated is that it appears to require that *all* of the information necessary to construct *all* of the biological organisms in the biosphere for *all* time were contained within the DNA of the first “relatively simple, undifferentiated, Precambrian proto-animals”. While it is, indeed, possible that this huge amount of information could arise out of the quantum depths of primitive DNA, or alternatively could arise as a result of the “unmasking” of existing DNA genes (see our later discussion of the ninth *fact of evolution*, concerning *metamorphosis*), it seems to me far more likely that this huge amount of information at least partially arose as a result of multi-millions of “decisions” at all biological levels over millions of years being “fed back” holistically into DNA, epigenetic storage, and even into macroscopic biological storage (e.g., into macroscopic organs such as the brain).

This holistic viewpoint (a kind of “super-Lamarckism”!), as opposed to the pure-genetic-programming viewpoint, is suggested, for example, by the fact that genes and homologies don’t always coincide. As Gavin de Beer wrote in 1971: “Because homology implies community of descent from . . . a common ancestor, it might be thought that genetics would provide the key to the problem of homology. This is where the worst shock of all is encountered. . . [because] characters controlled by identical genes are not necessarily homologous . . . [and] homologous structures need not be controlled by identical genes.” De Beer concluded that “the inheritance of homologous

ON EVOLUTION

structures from a common ancestor . . . cannot be ascribed to identity of genes.”³⁷²

Other factors pointing to this kind of “super-Lamarckian” holism include: *a*) cases where different proteins are read off the *same* stretch of DNA by *frame-shifting* the reading, *b*) cases where the *alternative splicing* of messenger RNA causes the same DNA “gene” to “encode” for hundreds (or even thousands) of different proteins,³⁷³ *c*) the fact that there are often far fewer genes than proteins, and *d*) the fact that homologous proteins are not, by themselves, “traits”, but only the building-blocks of “traits”.

Even with respect to the development of the individual embryo, it is now recognized that epigenetic factors are of the utmost importance, and that the embryo itself holistically “decides” such important things as the sex of the organism and which other traits the organism will take from which parent. (In other words, even the development of the individual embryo is not deterministically “programmed” by its genes.)

Taking all of these observations together, this fifth *fact of evolution* (i.e., strict monophyletic typology), like the first four *facts of evolution*, is clearly a strong point *in favor* of the theory of macrodevelopment.

6. The “Cambrian Explosion”

We have already mentioned the relatively sudden emergence of virtually all of the major phyla during the Cambrian era (around 530 million years ago) and how this fact of the “Cambrian explosion” parallels the relatively rapid development of the individual biological embryo at the beginning of morphogenesis. Furthermore, we have already indicated several ways in which this fact of the Cambrian explosion *disconfirms* the theory of neo-Darwinism (e.g., the Cambrian explosion’s *non-gradualism*, and the fact that the emergence of the early *generic* Cambrian taxa clearly preceded the emergence of the later *specific* taxa).

Robert F. DeHaan’s article, “Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment”,³⁷⁴ has been called “the flagship article on macrodevelopment”. In this path-breaking article DeHaan lists *twelve paradoxes in neo-Darwinism* that are generated by the facts surrounding the Cambrian explosion. Some of these paradoxes we have discussed previously, and some we will deal with in more detail later on. Nevertheless, DeHaan has provided a great service in summarizing all twelve in a concise and powerful manner. We will therefore arrange our discussion of this sixth *fact of evolution* (i.e., the fact of the Cambrian explosion) differently than our discussion of the previous five *facts of evolution*: Instead of presenting the

particular fact of evolution first and then separately discussing how the theories of neo-Darwinism and macrodevelopment measure up, we will instead present each of DeHann's twelve Cambrian *sub-facts* in turn, followed by the *paradox* which that sub-fact presents to neo-Darwinism, and, finally, [in brackets], how macrodevelopment resolves that particular "paradoxical fact".

What follows is a very long quotation from Robert F. DeHaan's article "Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment" (with paragraphs occasionally rearranged), interspersed with my comments in brackets that give the macrodevelopmental solution to each particular paradox. (The reader is strongly encouraged to read DeHaan's brilliant, original article in full in order to get all of his supporting evidence, especially his footnotes to the work of paleontology experts.) Here we go:

The pattern of paradoxes begins with the Cambrian explosion that occurred about 530 million years ago. The explosion refers to the outburst of complex, higher animals. The event is unique in the history of life on this planet; nothing like it happened before or since. . . . [Stephen Jay] Gould summarized the explosion as follows:

The Cambrian explosion is the key event in the history of multicellular animal life. The more we study the episode, the more we are impressed by its uniqueness and of its determining effect on the subsequent pattern of life's history. These basic anatomies that arose during the Cambrian explosion have dominated life ever since, with no major additions. The pattern of life's history has followed from the origins and successes of this great initiating episode.³⁷⁵

The sheer magnitude of the Cambrian explosion is difficult to appreciate. Consider the following summary of observations that suggests its scope and complexity. In what may be considered . . . a geological instant . . . approximately 50 animals with . . . body plans that were . . . novel, . . . disparate, . . . complex, and . . . of stable modern design . . . appeared roughly synchronously in the Lower Cambrian. Each descriptive adjective or phrase [in the previous sentence] suggests a paradox in Darwinian theory.

Paradoxical fact #1: *Rapid origin of Cambrian animals.* Stem animals of the Cambrian came into existence with rapid speed in a geological instant. The rapidity of their formation has recently been confirmed. It is now judged that the Cambrian explosion lasted at most 10 million years, and as little as 5 million, beginning 530 million years ago. [J.W.] Valentine estimated that for brachiopods the time may have been well under 5 million years, probably under 1 million years, and perhaps significantly less in some cases. He even hinted at a time span of only "hundreds of thousands of years or less." . . .

The paradox. Darwinian mechanisms work slowly and gradually, requiring extensive periods of geological time to bring about change. It is difficult to see how gradualistic natural selection, even punctuated

ON EVOLUTION

equilibrium, could have been a significant causal factor in the extremely rapid formation of body plans in the Cambrian explosion.

[The solution. *Nonlinear macrodevelopmental processes can work rapidly and holistically. Moreover, the rapid development of body plans during the Cambrian era is precisely analogous to the rapid development of general cell types and structures in the individual biological embryo during the early stages of morphogenesis.]*

Paradoxical fact #2: *Body plan.* The body plan of the stem animals is the central, most significant biological structure formed in the Cambrian explosion. The body plan - also called Bauplan, phylum, and class - refers to the most fundamental morphological and structural characteristics of the stem animals of the Cambrian. It refers to the basic architecture which defines the lineages founded by the stem animals; it is shared in common by all the subsequent descendants of the lineage. This is one of the most fundamental designs in the organic world. . . . Characteristics of the body plan are thus used to classify large groups of animals (phyla) founded by the stem animals of the Cambrian.

The paradox. *Animal lineages started with body plans at the highest taxonomic level of phyla. This observation challenges a central tenet of Darwinian theory, namely, that evolution starts at the lowest level, with varieties and species, and works upward into higher taxa. Some [neo-Darwinian] authors have countered this paradox with the dubious argument that higher taxonomic categories are artificial and unrelated to real events in the organic world. Such authors and others, however, freely use these same taxonomic categories when it suits their purposes and where the use of them does not challenge [neo-Darwinian] theory. The paradoxical evidence remains firm: Animal lineages originated as phyletic body plans of Cambrian animals, not as varieties and species.*

[The solution. *Macrodevelopmental processes produce biological taxa in a temporal direction that proceeds from the generic to the specific. Analogously, individual embryonic developmental processes produce biological organs in a temporal direction that proceeds from the generic to the specific.]*

Paradoxical fact #3: *Fifty body plans.* This is a staggering number of biological inventions. The variety of unique animal forms in the Cambrian is astounding, especially when compared with the relative uninventiveness and lack of diversity of the long previous Precambrian period.

The paradox. *This flood of unique body plans further calls into question natural selection as the agent of change in the Cambrian. The probability of random mutations supplying the genetic variability for so many unique and novel animals seems remote, even though small initial genetic changes may result in large genetic morphological outcomes. There is no evidence, moreover, that environmental factors could select for so many unique forms.*

[The solution. *Because macrodevelopment can act quickly and holistically, the large number of body plans produced nearly simultaneously during the Cambrian era presents no problems.]*

Paradoxical fact #4: *Novel body plans.* Cambrian animals have few known or confirmed morphological antecedents from the earlier Precambrian period. This is an extraordinary discontinuity. It is estimated that only 5 percent or less of them show validated evidence of Precambrian parentage.

Whether Cambrian animals had Precambrian ancestors that were too small, too flimsy, and unmineralized to leave fossils has yet to be demonstrated, and is being actively debated. Two alternative positions have been put forth. The first is that the fossil evidence of a Cambrian explosion should be taken at face value, that the animals indeed developed almost instantaneously, sans Precambrian antecedents; and the second, that Cambrian animals have a long but *invisible* Precambrian history. Since it is unlikely that Cambrian animals sprang into existence without any antecedents whatsoever, it is probable that some precursors may eventually be found. This would not detract from the discontinuity between Precambrian and Cambrian biota.

***The paradox.** A morphological discontinuity between Cambrian animals and the Precambrian biota is strongly implied by the paucity of confirmed, architectural antecedents. This hiatus challenges the principle of continuity of all life forms, a major doctrine of [neo-Darwinian] theory.*

[The solution. Since macrodevelopment relies on holistic, nonlinear, continuity-breaking bifurcations to create taxa, a long, linear history of life-forms continuously leading up to the Cambrian-era phyla is not required by the theory.]

Paradoxical fact #5: *Disparate body plans.* With few exceptions, the body plans of the Cambrian animals were architecturally different from each other and were novel and discontinuous from the Precambrian fauna. [Stephen Jay] Gould used the new term, disparity, to designate the immense chasms separating most body plans from each other; whereas he used the conventional term, diversity, to indicate the minuscule differences among species. Early in the Cambrian, phyletic disparity was high; species diversity was low. . .

That there were few, if any, intermediary architectural forms is the primary conclusion supported by the fossil record, and should be held unless it is contradicted by newly discovered, confirmed intermediate forms.

***The paradox.** The disparity and inconvertibility among the body plans of the Cambrian stem animals further challenges the essential [neo-Darwinian] principle of continuity of all life forms. This principle is difficult to maintain in the face of morphological discontinuities among many of the Cambrian stem animals themselves, to say nothing of the probable hiatus between the Cambrian and Precambrian biota.*

[The solution. Again, since macrodevelopment relies on holistic, nonlinear, continuity-breaking bifurcations to create taxa, significant discontinuities between taxa created over a geologically short period of time are to be expected, especially since these Cambrian bifurcations were working at the most-generic level.]

ON EVOLUTION

Paradoxical fact #6: *Dearth of species.* There were many body plans or phyla but few species in the early Cambrian. Specific diversity was low. The higher taxonomic forms were present, but the lower forms, the species, were largely absent. This observation is most astounding and of profound significance.

The paradox. [Stephen Jay] Gould called the observed dearth of species a central paradox of early life. Many more species than phyla should have appeared, since a fundamental principle of Darwinian theory is that a large group of higher animals (phylum) has its origin in a long train of species. The paradox, however, lies not with early life, but with the incorrect [neo-Darwinian] interpretation of it. Again, the logical conclusion is that ancestral lineages did not begin with varieties and species.

[*The solution.* Dearth of species is exactly what one would expect if the animals of the Cambrian were, in fact, generic “stem animals”, as is maintained by the theory of macrodevelopment.]

Paradoxical fact #7: *Synchronous appearance of body plans.* The fact that this large cohort of animals appeared approximately synchronously within roughly a 5-10 million year period deepens the mystery of the Cambrian explosion. Few Cambrian animals are the confirmed antecedent of another.

The paradox. The probability seems extremely low that natural selection could fully account for the synchronous appearance of 50 or so disparate body plans, in such a short time, in an environment presumably approximately common to all, as shown by the Burgess Shale. The synchronous appearance of Cambrian body plans is paradoxical to the Darwinian concept of natural selection.

[*The solution.* A rapid burst of major, nonlinear, continuity-breaking bifurcations occurring during this early Cambrian stage of the biosphere's macrodevelopment (analogous to what happens in the early stage of individual embryonic development) would account for this paradoxical fact.]

Paradoxical fact #8: *Stability of body plans.* The body plans of the Cambrian stem animals that survived are extremely stable. They have remained essentially unchanged for more than 500 million years, to the present time, with no modernization or upgrading (but with some reconfiguring of sea-urchin body plans.) The Cambrian body plans exist today in our modern phyla and appear in an early embryonic stage in all members of a given phylum. Every descendant of the Cambrian stem animals shares in common the stable body plan of the original stem animal.

The paradox. Change is practically synonymous with evolution, according to some [neo-Darwinian] authors. Yet the unchangeableness of body plans challenges this meaning. If body plans had been formed by natural selection, why would they not have continued to evolve over the past 530 million years? Yet they did not. This suggests that some other process has been at work to form and maintain the stability of phyletic body plans.

[The solution. This “other process” is macrodevelopment, which has been “unfolding” the biosphere for over 500 million years in accordance with a temporal pattern that proceeds from the more-generic to the more-specific.]

Paradoxical fact #9: *Top-down direction of change in phyla.* One of the most important phyletic patterns in the fossil record is the general-to-specific, or top-down, direction of change or modification in phyletic lineages. General, or higher taxonomic levels (phyla, classes, orders), of a given phyletic lineage appeared in the fossil record before specific, lower-level taxa (families, genera, species). Abundant fossil data from the Cambrian and later periods support the generalization that with few exceptions the order of appearance in the history of phyletic lineages works from general to specific taxa, from phyla clear down to species. Erwin, [Valentine, and Sepkoski have] stated [that] the fossil record suggests that the major pulse of diversification of phyla occurs before that of classes, classes before that of orders, orders before that of families, [and that] most higher taxa were built from the top down, rather than from the bottom up.³⁷⁶ This top-down pattern is also found in trilobites, amphibians, reptiles, mammals, and in birds.

[Neo-Darwinist] writers such as Simpson and Mayr acknowledged that higher taxonomic forms appeared before lower forms in the fossil record, but went on to deny the biological reality of higher taxonomic categories. Their position is beginning to crumble, however, under the undeniable biological reality of the body plans of the Cambrian animals, which are considered the equivalent of phyla. The paradox remains. Phyletic lineages develop from the top down, not from the bottom up.

The paradox. *The top-down direction of phyletic change clearly challenges the central concept of Darwinian evolution, namely, that evolution proceeds from the bottom up. Darwinian theory holds that varieties become species, which are modified until they can be considered genera, which become families, etc., through the process of natural selection. This doctrine was introduced by Darwin through his only diagram in **Origin of Species**, and has since been held without exception by [neo-Darwinian] authors since his day.*

[The solution. *The theory of macrodevelopment, unlike the theory of neo-Darwinism, correctly predicts the top-down direction of phyletic change which we actually find in nature.]*

Paradoxical fact #10: *The rise and fall of ancestral lineages.* Evidence from the fossil record demonstrates that ancestral lineages . . . rise to a maximum on many dimensions, such as size, complexity, population density, and [then] eventually decline on these and other variables. This pattern of increase to a maximum followed by decline is found in fishes, amphibians, reptiles and in many other lineages. For example, brachiopods declined systematically; as did corals. The decrease is especially significant. [J.Z.]Young, for instance, said, that mammals are at present at their peak of development, [and] perhaps they are already declining.³⁷⁷ The decline of lineages is supported by paleontological, biological evidence, and by

ON EVOLUTION

the logic that if a lineage increases, it must eventually decline. The fact remains: Decline is as ubiquitous as increase in phyletic lineages.

The paradox. *The paradox is this: If increase in size, complexity, etc., in a lineage is adaptive, as [neo-Darwinists] hold, how can later decrease in these dimensions also be adaptive? Decline itself is rarely adaptive. It is not regularly correlated with changes in the environment. The paradoxical decline in lineages is explained away by major [neo-Darwinist] authors who hold that declining lineages are actually adapting to their environment. Of course! Declining lineages continue to adapt as best they can, even to the very end. But let that not hide the fact that they do decline, and that decline in lineages is paradoxical to Darwinian theory.*

[The solution. *The rise and decline of ancestral lineages within the biosphere parallels the rise and decline of biological individuals. Although we have hitherto focused on the analogy between the biosphere and the embryo, in fact the biological individual continues his development after birth (only on a much slower time scale) as he moves from childhood to youth to adulthood to old age and, eventually, to death. The theory of macrodevelopment therefore provides a clear framework for the study of this phenomenon with respect to ancestral lineages. DeHaan calls the study of the decline of ancestral lineages “phylogerontology”.]*

Paradoxical fact #11: *Finality of body plans.* The body plans of the Cambrian constitute the first and last manifestation of such an unprecedented scale of biological inventiveness on earth. After the Cambrian explosion not a single new, major group or phylum of animals has come into existence. This is especially significant in view of the relative openness of the environment after the great Permian extinction, 250 million years ago, which exterminated up to 80 percent of marine species, leaving the environment about as empty as it had been at the Vendian-Cambrian boundary. Dry land, moreover, was a whole new habitat, a completely novel, vast, and varied ecological niche. Yet no new phyla-level body plans developed when vertebrates and invertebrates invaded it 300-360 million years ago. In spite of this open invitation for innovation, no new classes or phyla appeared. Indeed, the history of life since the Cambrian shows a dramatic loss of major groups of animals that originated in the Cambrian explosion.

The paradox. *The finality of Cambrian body plans is inexplicable in [neo-Darwinian] terms. If [natural selection] is the creative force in the organic world, why have no new body plans evolved? . . .*

[The solution. *Because macrodevelopment is inherently a nonlinear, irreversible process that acts on the biosphere as-a-whole, no repetition of the initial “Cambrian explosion” of most-generic biological taxa would be expected to occur at any later time.]*

Paradoxical fact #12: *Multiplicity of species since the Permian.* A further astounding fact is that species have multiplied almost beyond count, starting 250 million years or so ago, and accelerating in the last 65 million years to the present. . . .

***The paradox.** If species are the evolutionary precursors of higher-level taxa, and such a deluge of them has been occurring throughout the recent past, why have no new higher taxa been formed? With so many species emerging, this should be the age of new higher taxa. The reason it is not is that species evolve into other species, rarely if ever into higher-level taxa. The present age is thus the age of new species. Rather than being the start-up mechanism for new major groups of animals, natural selection and speciation may more realistically be seen as the closeout process of phyletic lineages. They put the finishing touches on ancestral lineages. This obviously goes against the thrust of Darwinian [theory].*

*[**The solution.** The theory of macrodevelopment accurately predicts that any new taxa appearing today would be at the most-specific taxonomic level only, i.e., at the level of the species. Moreover, the vast majority of new kinds of biological organisms appearing today are, in fact, merely new varieties (and are therefore “species” only in the loose BSC sense), not truly new typological species in the strict BSC sense.]*

Here ends our very long quotation from Robert F. DeHaan’s seminal article “Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment” (*PSCF* 48:180, 1996). Again, the reader is urged to study for himself this path-breaking article (which is extensively footnoted to the paleontological literature).

Wrapping up DeHaan’s twelve “paradoxical facts of evolution” as *sub-facts* within our sixth *fact of evolution* (i.e., the fact of the Cambrian explosion), it is clear that this *sixth* fact is (once more) a strong point *against* the theory of neo-Darwinism and *in favor* of the theory of macrodevelopment.

7. Taxonomic Extinction

The “Phanerozoic era” is the name which paleontologists give to the entire geological period from the start of the Cambrian era, about 540 million years ago (i.e., 540 My), all the way to the present. During this huge time frame, not only have many millions of species (and lesser numbers of higher-level taxa) appeared, but an almost-equal number have vanished and become extinct. Why? This is one of the most controversial questions in all of paleontology, largely due to the fact that the fossil record, together with geological data, is virtually the only evidence available to answer this question. Here are just a few of the problems encountered when evaluating this fossil evidence:

- The accurate dating of fossils is difficult. Radioactive isotopes used to estimate fossil dates on a geological time scale have poor resolution.

ON EVOLUTION

- Prehistoric environmental disturbances can upset strata deposition processes, thus giving rise to periods when the fossil record is poor.
- Marine organisms are much better preserved than land-dwelling organisms, because deposition processes are more uniform and reliable under water than on land.³⁷⁸
- If the number of specimens of a taxon are *few*, the chance of finding a specimen near the taxon's extinction date is slim, resulting in an estimate of the date of extinction that is *too early*. For the same reason, the estimate of the *origination* date for that taxon will tend to be *too late*. These effects are called the “Signor Lipps” effect, and (humorously) the “Lipps Signor” effect, respectively.
- Researchers usually record the origination and extinction of taxa to the nearest geological stage. The Phanerozoic era is divided into 77 such stages, but they are of uneven length, ranging from 1 My to 20 My, with a mean length of 7.3 My. Consequently a single large burst of extinction during a short stage will give an anomalously high rate of extinction relative to the same burst occurring during a long stage.
- It is quite common for paleontologists to assign a *different* species name to the *same* kinds of specimens found before and after a major stage boundary, thus resulting in both a false species “extinction” and a false species “origination”.
- The “pull of the recent” problem refers to the fact that the fossil record is better-preserved within more-recent strata than within older strata, thus biasing the more-recent strata towards the appearance of greater taxonomic diversity.
- The “monograph effect” refers to an apparent burst in taxa origination resulting from the zealous work of one researcher (or group of researchers) who happen to be especially interested in one particular group of biological organisms.
- The “Lagerstätten effect” refers to a similar apparent burst of taxa origination when a particularly fossil-rich site is first explored and added to the database.
- Many, indeed most, of the taxonomic groups actually used by paleontologists in the past to classify fossils were *paraphyletic*, rather than *monophyletic*. (You will recall from our previous

discussion that the most-modern and accurate system of biological classification, *cladistics*, requires the use of only *monophyletic* taxonomic groupings.) This undoubtedly causes a possibly-significant distortion in counts for both the origination and the extinction of higher-level taxonomic groups.³⁷⁹

Because of all of these uncertainties, it is common to find so-called *Lazarus taxa* – that is, taxa which have seemingly become extinct, as far as the ancient fossil record is concerned, but which re-appear in the more-recent fossil record, long after their reputed demise.³⁸⁰

In addition, there is the problem of separating true extinction from *pseudo-extinction*. Two types of *pseudo-extinction* may be distinguished:

- a. *Paraphyletic pseudo-extinction*. For example, dinosaurs are obviously extinct, but older paleontology regarded birds, which are currently living organisms, to have “split off” from the dinosaurs millions of years ago. Therefore, dinosaurs were said to be only *pseudo-extinct*, not truly extinct.³⁸¹ Since modern taxonomy (i.e., cladistics) rejects the validity of paraphyletic grouping, it would be best if the concept of paraphyletic pseudo-extinction were retired as well.
- b. *Monophyletic pseudo-extinction*. From Figure 32, it is clear that monophyletic grouping requires that an “ancestor” taxon split symmetrically into two “descendent” taxa. The “ancestor” taxon then *ceases to exist*, except in the generic features of its two “descendent” taxa. (We have also considered the possibility that the “ancestor” taxon had additional, specific traits that were forever-lost to subsequent evolution due to its split.) This kind of *monophyletic pseudo-extinction* must be relatively common, given the biological fact of strict, monophyletic typological hierarchy.

A survey of various mathematical models of taxonomic extinction by Newman and Palmer show that, because of the many problems mentioned above, the same imperfect fossil data can be made to fit a *power-law* curve, an *exponential-curve*, or even a *linear* curve. Ludwig von Bertalanffy’s warning in another context is therefore relevant here as well:

It is a mathematical rule of thumb that almost every curve can be approximated if three or more free parameters are permitted – i.e., if an equation contains three or more constants that cannot be verified otherwise.
...

The consequence is that curve-fitting may be an indoor sport and useful for purposes of interpolation and extrapolation. However, approximation

ON EVOLUTION

of empirical data is not a verification of particular mathematical expressions used. We can speak of verification and of equations representing a theory only if (1) the parameters occurring can be confirmed by independent experiment; and if (2) predictions of yet unobserved facts can be derived from the theory.³⁸²

Because of the above considerations, anything said in the text below (or anywhere else for that matter) concerning the facts surrounding biological taxonomic extinction should be taken with the large proverbial “grain of salt”.

Mass Extinctions

The main part of Figure 35, below, shows the *extinction rate* in families per million years (My) for marine organisms as a function of time, while the inset in Figure 35 shows the comparable *origination rate* in families per My for marine organisms. This data is taken from Sepkoski’s 1992 database. (Sepkoski’s database, together with Benton’s 1993 database, is the most-often-cited attempt to gather biological taxonomic extinction/origination information in one place.)

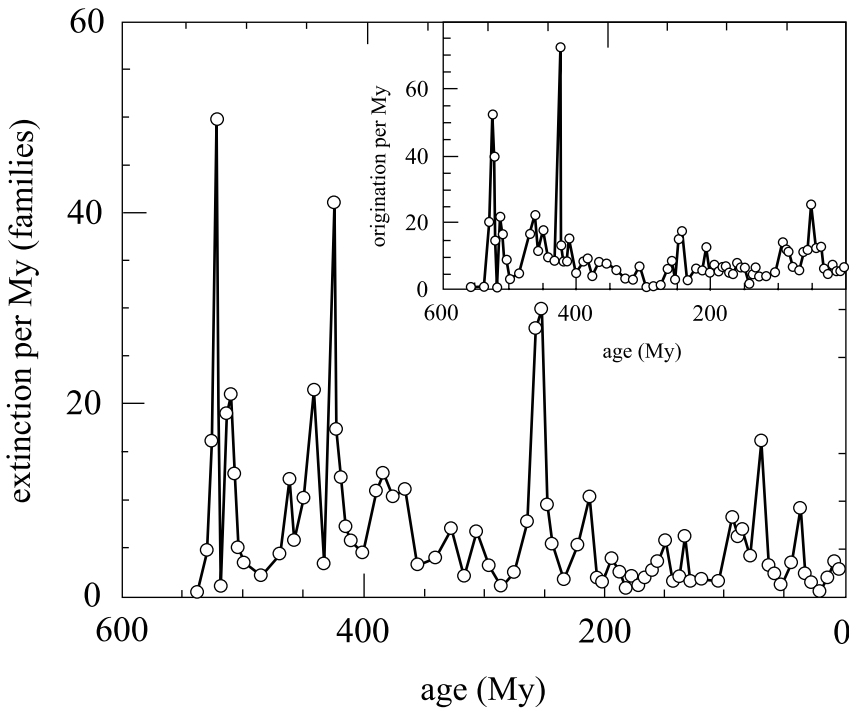


Figure 35 (after figure 1 on page 4 of Newman and Sibani)

Notice that, rising above the *background-level* of extinctions and originations, are a number of sharp peaks of *mass extinctions* and “*mass originations*”. If we (somewhat arbitrarily) select those mass extinction/ origination events that are associated with rates of over 15 families per My (million years), we can put them in the table shown in Figure 36, below:

Event	Age (My)	Extinct per My	Originated per My
<i>Cambrian explosion 1</i>	<i>530</i>	<i>50</i>	<i>53</i>
<i>Cambrian explosion 2</i>	<i>510</i>	<i>21</i>	<i>21</i>
mid-Ordovician expansion	460	12	23
end-Ordovician extinction	440	21	17
Silurian expansion	425	41	74
late-Permian extinction	260 / 240	29	15
end-Cretaceous extinction	65 / 50	17	25

Figure 36

Mass extinction/origination events (for marine families) that have rates of over 15 families per My (read off Figure 35). Where two ages are given, the first represents the extinction date, while the second represents the origination date. (My stands for “million years”).

Italic rows represent possible mass monophyletic pseudo extinctions at taxonomic levels higher than the family level.

Regular rows represent possible mass monophyletic pseudo extinctions at the family level.

Bold rows represent probable true mass extinction events having abiotic causes.

First, notice that these mass extinction/origination events are either *simultaneous*, or the origination peak appears about 15-20 My *after* the extinction peak: In *no* case does the origination peak significantly precede the extinction peak. This turns out to be generally true of background extinction events as well: Rarely (if ever) does the appearance of new taxa drive other

ON EVOLUTION

taxa (including parental and close-sibling taxa) to extinction via direct competition. As Niles Eldredge wrote in *The Miner's Canary*:

Further evolution, we will see time after time, often seems spurred on by the prior elimination of what came before: Extinction often has provided the very circumstances, some of the very preconditions, necessary for further evolution to occur. But the reverse is simply not the case: Newly emerged descendents do *not*, as the overwhelming rule, routinely cause the extinction (through direct competition) of their evolutionary forebears. If anything, it is quite the reverse: . . . [I]t is the well-entrenched species that in all likelihood stamp out fledgling new species that are not ecologically different enough from the parental species to gain a foothold. If . . . it does happen that descendent species occasionally outcompete parental species – unto the point of driving them to extinction – it is a minor process contributing to background rather than mass extinction.³⁸³

Second, notice that the rows in regular type (not *italics* and not **bold**) in Figure 36 (i.e., the mid-Ordovician expansion and the Silurian expansion) represent simultaneous peaks of extinction and origination in which the rate of family *origination* per million-years is roughly *double* the rate of family *extinction* per million years. This pattern of two families gained for every one family lost suggests that these rows *may* represent events of mass monophyletic pseudo-extinction at the family taxonomic level. This tentative hypothesis is strengthened when we consider that the age of the mid-Ordovician expansion (460 My) and the age of the Silurian expansion (425 My) correspond to times when the number of biological families rose to a near-maximum prior to the great late-Permian extinction. (The number of families rose to 500 at the 460 My age, and rose even-higher to 520 million families at the 425 My age).³⁸⁴

Third, notice that the rows in *italics* type in Figure 36 (i.e., *Cambrian explosion 1* and *Cambrian explosion 2*) represent simultaneous peaks of extinction and origination in which the *origination* rates for families are either *equal to* or *slightly higher than* the *extinction* rates for families. Because many paleontologists doubt that the Cambrian era was really a time of true mass-extinction (they dismiss these peaks as “sampling errors”³⁸⁵), and because we know from the sixth *fact of evolution* discussed above that the Cambrian era *was* an era of intense creation of taxa at a *higher* level than the family (i.e., phyla, classes, orders), we may hypothesize that *Cambrian explosion 1* and *Cambrian explosion 2* represent events of *mass monophyletic pseudo-extinction at taxonomic levels higher than the family*. (Note that the total number of families during the Cambrian era was only 125, compared to the much-higher figures of 500 and 520 respectively attained during the later Ordovician and Silurian periods.)

Finally, note that the remaining rows, in **bold** type in Figure 36 (i.e., the **end-Ordovician extinction**, **late Permian extinction**, and the **end-Cretaceous extinction**), probably represent true mass extinction events that have abiotic causes. This is particularly likely to be true in the cases of the **late Permian extinction** and the **end-Cretaceous extinction**: For in both of these cases the origination peak occurs *later* than the corresponding extinction peak by 15-20 million years. These later origination peaks may therefore consist disproportionately of “Lazarus taxa” that drastically fell in numbers to levels too small to be reliably fossilized, only to make a strong comeback 15-20 million years later. Or they may be due to a relatively sudden rise in the temperature of the biosphere back to normal levels, thus triggering a corresponding burst of nonlinear taxon-creating bifurcations.

It is now generally agreed that the proximate abiotic cause of the **end-Cretaceous extinction** was the impact of a 10-kilometer-wide asteroid at Chixculub, in the Yucatan Peninsula of Mexico, 65 million years ago. This asteroid struck the earth at an angle of from 20 to 30 degrees, creating a 180 km diameter crater and sending ground-hugging vaporous fireballs shooting across North America. Whether due to the burning up of the forests, or to particulate matter from the crater being shot up into the upper atmosphere, the resulting world-wide blockage of the sun’s rays resulted in a radical cooling throughout the entire biosphere, bringing about 70% of the earth’s species (including the dinosaurs) to extinction. As Trevor Palmer tells the story:

The breakthrough came when a paper claiming to provide evidence was published in *Science* in 1980. The Cretaceous-Tertiary boundary [a.k.a. the KT boundary] in limestone formations throughout the world is marked by a thin clay layer, just a centimeter or so in thickness, and the paleontologist Walter Alvarez of Berkeley had invited his father, the Nobel Prize-winning physicist, Luis Alvarez, to help him investigate this layer at Gubbio in Italy. The significant finding was a high concentration of the noble metal, iridium, normally almost completely absent from the earth’s crust. Similar results were then found at the Cretaceous-Tertiary [KT] boundary in Denmark and New Zealand. Iridium in such high concentrations could only have come from space, or from the earth’s core, released by volcanic activity, and there were no obvious indications of the latter at the sites in question. Hence the Alvarez group proposed that the Cretaceous extinctions had been caused by the impact of a 10 km asteroid, the resulting explosion scattering iridium-rich dust from the bolide around the world.³⁸⁶

Initially this proposal brought scorn and ridicule from paleontologists schooled in the doctrine of uniformitarianism, which they inherited from Lyell and Darwin: After all, the doctrine of uniformitarianism had just been resoundingly confirmed by the recent success of the theory of continental drift

ON EVOLUTION

– the theory that the continents have drifted “slowly, minutely, and gradually” with respect to one another over millions of years. Didn’t the success of the continental-drift theory *prove* the uniformitarian contention of Lyell and Darwin that *all* major large-scale geological and biological changes are “slow, minute, and gradual”?

At first paleontologists tried to tar the Alvarezes with the same insinuations of religious motivation and young-earth creationism that Lyell and Darwin had so successfully (and unfairly) aimed at the work of Georges Cuvier over a hundred years previously. For example, paleontologist L.B. Halstead wrote in 1981:

The asteroid or giant meteor explanation has the great popular appeal of high drama and curiously coincided with the release of a ‘disaster’ film on the same theme. Such theories are certainly an advance on invoking the wrath of a Deity but not very much.³⁸⁷

But the evidence in favor of the Alvarezes’ theory just kept piling up: By the end of 1983, *over 50 sites* had been found showing high iridium levels at the KT boundary:

Other evidence of impact, including tektites (glass spheres), shocked quartz grains, diamonds, and stishovite (a form of silica), which have been found at known impact craters, were also identified in the boundary clay (Raup, 1986; Hallam, 1989; Gehrels, 1994; Glen, 1994).³⁸⁸

Finally, the discovery of the 180 km crater at Chixiculub in 1990 at last swayed dominant paleontological opinion in the direction of the Alvarez asteroid theory.

With the success of the Alvarez asteroid theory in explaining the **end-Cretaceous extinction**, paleontologists began to consider asteroid and comet impacts as (at least partial) explanations for other mass extinctions. For example, the impact of a large comet has been suggested as at least a contributing cause of the **late-Permian extinction**. As Figures 35 and 36 show, the **late-Permian extinction** occurred around 260 million years ago. It was the largest mass-extinction event of all time, killing around 95% of marine species and 70% of land-dwelling species.³⁸⁹ The number of biological families precipitously dropped from around 375 to around 225.³⁹⁰ Recovery did not occur until 20 million years later, which corresponds to the sharp increase in the rate of family origination at age 240 My, as shown in Figures 35 and 36. This pattern is very similar to the pattern for the **end-Cretaceous extinction**, except on a grander scale.

Yet even paleontologists (such as Niles Eldredge) who remain skeptical of asteroid, meteor, and comet impacts as *general* explanations for mass extinctions agree that *one* abiotic cause almost-always figures most

prominently in true mass extinctions, and that is *a significant drop in temperature throughout the biosphere* (whether that temperature drop be due to asteroid/meteor/comet impacts, geological causes, or other climatic causes). As Eldredge has written:

There is no doubt that, in our survey of major extinction events of the past, temperature change, particularly temperature drop, seems to emerge time after time as the underlying culprit, a theme most persistently and completely pursued by paleobiologist Steven M. Stanley during the 1980s.³⁹¹

Notice too that it is global temperature *drops*, *not* global temperature *increases*, which generally are associated with true mass extinctions. In this connection a distant analogy suggests itself between evolutionary “retreat” as a result of temperature-drop-caused extinction and the “retreat” of certain bifurcating nonlinear chemical systems to prior states, when forced to drop back closer to equilibrium as a result of (for example) a drop in the rate of energy entering the system. (See Figure 28, together with its associated discussion.) For opposite reasons, the return of normal temperatures and rates of energy input to the biosphere about 15-20 My later might be expected cause a “flowering” of nonlinear taxon-creating bifurcations. (This may also be why the earth’s tropical regions are characterized by extremely high species diversity.)

A probable example of a temperature-drop-caused mass extinction *not* related to an asteroid, meteor, or comet impact is the **end-Ordovician extinction** shown in Figures 35 and 36 as occurring at age 440 My. Niles Eldredge expresses well the primary difference between the **end-Ordovician extinction** and the much “sharper” and sudden **late-Permian extinction** and **end-Cretaceous extinction** which we have just discussed:

According to paleontologist Patrick J. Brenchley (in articles written in 1989 and 1990), some 22 percent of known marine families became extinct [during the **end-Ordovician extinction**]. Statistically, as Brenchley says, this Upper Ordovician event qualifies as a mass extinction. In some groups, apparently more than 50 percent of the included species became extinct. Yet it is obvious to even the most casual observer that, from an ecological point-of-view, the Ordovician-Silurian boundary was hardly the point of major ecological revolution that some of the later extinctions – [**late-Permian**] and [**end-Cretaceous**], especially – would prove to be. Though 22 percent of Upper Ordovician families did, rather abruptly, disappear, larger-scale taxa were not affected, and the repopulating of ecosystems in the early Silurian was achieved with organisms that bear a direct resemblance to their Ordovician progenitors.³⁹²

The main cause of this **end-Ordovician extinction** was probably a global drop in temperature related to continental drift. Ricard V. Sole and Mark Newman explain:

ON EVOLUTION

The immediate cause of the [**end-Ordovician extinction**] appears to have been the continental drift of a significant land mass into the south polar region, causing a global temperature drop, glaciation, and consequent lowering of the sea level, which destroyed species habitats around the continental shelves. The sea level rose again with the end of the glacial interval about a million years later and caused a second burst of extinction.³⁹³

In addition to the **end-Ordovician extinction**, **late-Permian extinction**, and **end-Cretaceous extinction**, which we have just discussed, paleontologists generally list the late-Devonian extinction and end-Triassic extinction as rounding out the “big five” list of true mass extinctions.³⁹⁴ These latter two mass extinctions are poorly understood, and they “flew below our radar” because they did not result in rates of extinction or origination exceeding 15 families per My in Figures 35 and 36. For that reason, we will not be discussing them in any detail.

In our discussion of the *logistic equation* in the previous chapter on **Nonlinear Complex Physical Systems**, we noted that Gamarra and Sole have presented evidence that a possible period-doubling route to chaos in the ecological system involving the Canadian lynx may have resulted from human efforts to trap the lynx. Could such a nonlinear, chaotic “ecological collapse” be a significant cause of extinctions in the distant past? Mainline paleontologists such as Niles Eldredge do not think so. In *The Miner’s Canary* Eldredge writes:

... [I]s there any evidence that the very factors of biotic interaction that appear to hold communities together also can lead to the sudden crash of the system?

The answer appears to be “no”. Ecosystem collapse, the very essence of the extinction process, may well hinge in some instances on keystone species – species, for example, at the base of the energy (food) chain. But there is no evidence that ongoing interactions between species ever get sufficiently out of whack or taken to extremes that exceed some tolerable limit such that component species are driven to extinction – that is, until *Homo sapiens* arrived on the scene. . .

... There appear to be no seeds of massive self-destruction arising from biological interactions themselves.³⁹⁵

Before moving on to the subject of *background* extinctions (as opposed to *mass* extinctions), there is one more aspect of mass extinctions (actually, relatively small-sized “mass” extinctions) worth noting: In 1984 Raup and Sepkoski published a paper suggesting that the smaller-sized “mass” extinction events seen during the most-recent 250 My occur at regular, fixed intervals, with a period of around 26 My. Some researchers then suggested that the sun may have a companion star (dubbed *Nemesis*) or a large unknown planet (dubbed *Planet X*) whose passing every 26 My through the

hypothetical Oort cloud of comets might dislodge many comets, increasing the chance that the earth might be hit by one or more of them at 26 My intervals.³⁹⁶ However, Patterson and Smith (1987, 1989) have presented evidence that this 26 My period may be an artifact of noise, introduced by poor taxonomic classification, and Stanley (1990) has suggested that it may be the result of delayed recovery following larger mass-extinction events.³⁹⁷ The debate on this alleged 26 My periodicity continues.

Background Extinctions

Background extinctions are those biological taxonomic extinctions that have gone on all the time in the background, independent of the “catastrophes” of mass extinction. Determining the exact nature and causes of background extinctions is as difficult as determining the exact nature and causes of mass extinctions, though it can be said that (almost by definition) background extinctions have *biotic* rather than *abiotic* causes. In other words, background extinctions are related mainly to the ongoing dynamics of the biosphere, rather to exterior (often catastrophic) causes from the realms of climatology, geology, and astronomy. In spite of the uncertain evidence, paleontologists have discovered a few empirical “rules of thumb” with respect to background extinctions:

The *first* such rule-of-thumb, which we discussed earlier (citing Eldredge’s *The Miner’s Canary*, pp. 57-58), is that rarely (if ever) does the emergence of a new species (or other taxon) drive a previously-existing species (or taxon) to extinction as a result of direct competition. In other words, (contrary to Darwin) intense competition in the “struggle for survival” between closely-related species is *not* a major cause of extinction, whether the mode of extinction be mass extinction or background extinction.

A *second* rule-of-thumb with respect to background extinctions was stated by George Gaylord Simpson in his classic book *Tempo and Mode in Evolution* (1944): “[L]iability to extinction tends to be directly proportional to the rate of evolution [of the taxon].”³⁹⁸ In other words, the faster a taxon evolves, the faster it tends to die out and become extinct. We will call this important rule-of-thumb *Simpson’s rule*.

A *third* rule-of-thumb for background extinctions was discovered by Leigh Van Valen in 1973. This rule states that *the probability of extinction per unit time for any given taxon is independent of the age of the taxon*. (This is equivalent to saying that the probability of a given taxon surviving for a certain length of time t decays exponentially with t ,³⁹⁹ and it is also equivalent to saying that any given taxon is *equally* likely to become extinct in its “youth” as it is in its “old age”.) Furthermore, the exact figure for this probability of extinction per unit time depends on which higher-level taxon

ON EVOLUTION

the particular more-specific taxon is properly grouped under. (In other words, the exact figure is different for mammals than for reptiles, and so on.)⁴⁰⁰ This result is now known as *van Valen's law*.

For example, Figure 37, below, shows the number of genera of mammals surviving out of an initial group of 1,585 over a period of 36 My:

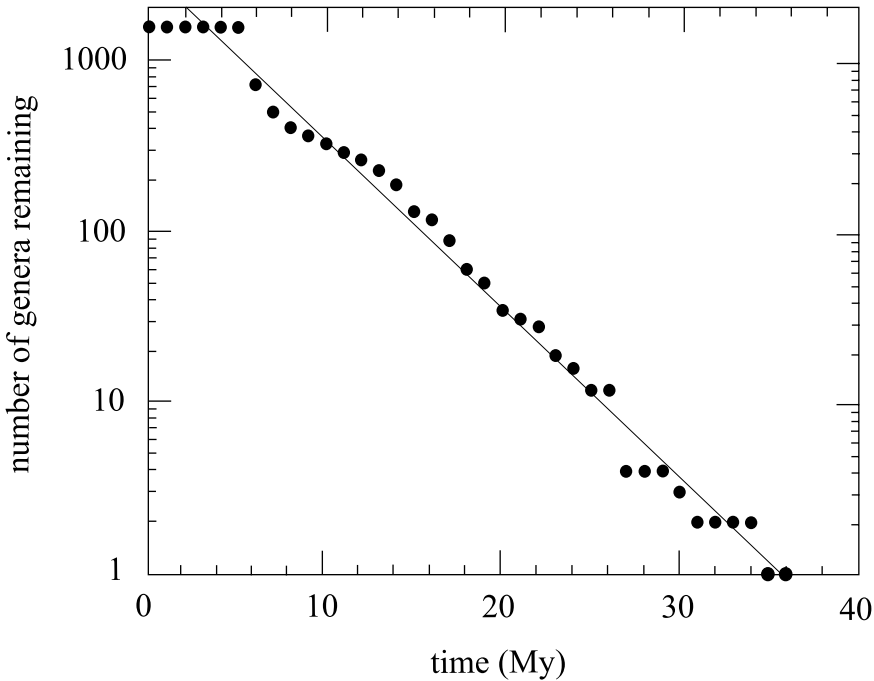


Figure 37 (based on Figure 13 on page 15 of Newman and Palmer. Shows “the number of genera of mammals surviving out of an initial group of 1585, over a period of 36 My. The dotted line is the best fit exponentials, and has a time constant of 4.41 ± 0.08 My. After van Valen, 1973.”)

Note that the x-axis of Figure 37 is a *linear* scale of time in My, while the y-axis is a *logarithmic* scale of the number of genera remaining as time passes. As you can see, the data approximately form a straight line. This kind of graph is called a *survivorship curve*, and van Valen found that this particular type of straight, semi-logarithmic survivorship curve applies to many other groups of taxa besides mammals, the only difference being that the slope of the line (i.e., the exact probability of extinction per unit time) differs for different groups.

For comparison, Figure 38, below, shows three types of survivorship curves found in biological studies of the lifespans of contemporary *individual* biological organisms:

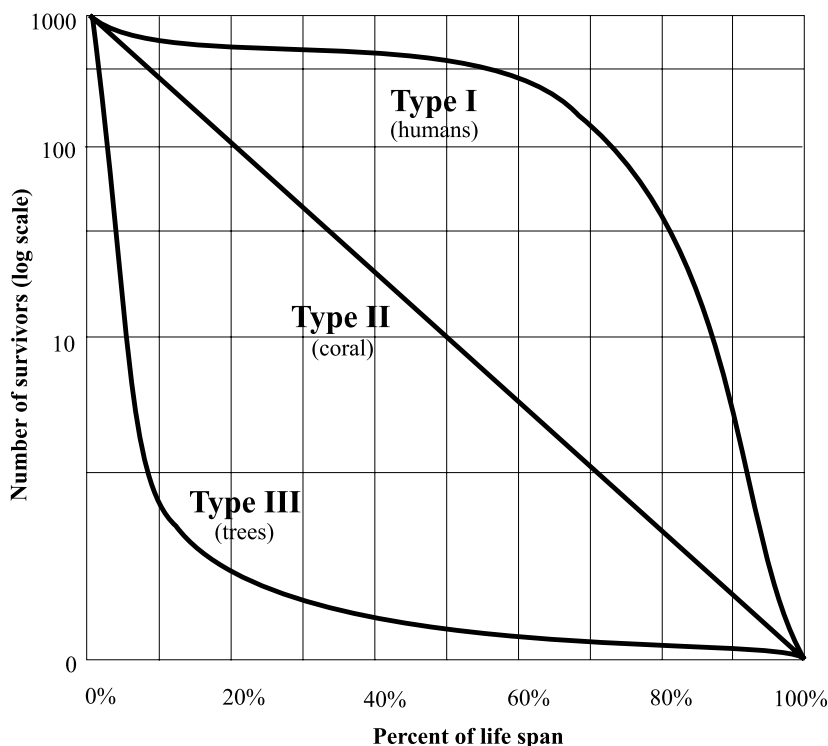


Figure 38 (after figure in “Survivorship Curves” <<http://bioinquiry.boil.vt.edu/bioinquiry/Cheetah/cheetachpaid/cheetahhtmls/popsurvivor.html>>, copyright 1999 by Arthur L. Buikema, Jr. and John Wiley and Sons, Inc.)

Note that van Valen’s survivorship curves for taxa are the “straight-line” **Type II**: That is, the probability of biological *taxa* extinction over time is the same in “youth” as in “old age”. (Contemporary biological *individuals* for which this equal-rate-of-mortality-over-time rule is true include: coral, squirrels, honey bees, and many reptiles, all of which have **Type II** survivorship curves.)

By contrast, the **Type I** survivorship curve shown in Figure 38 is for a kind of biological individual whose lifespan is characterized by a *low probability of death in youth, but a rapidly increasing probability of death in old age*. (This kind of survivorship curve is especially characteristic of *human* individuals, which is why the cost of life insurance is significantly higher if purchased later in life.)

ON EVOLUTION

The other contrasting type of survivorship curve depicted in Figure 38 is the **Type III** survivorship curve. This **Type III** survivorship curve is characteristic of biological individuals that have a *high probability of death in youth*, but a *lower and lower probability of death in old age*. (Biological individuals typically having a **Type III** survivorship curve include: trees, plants, oysters, and sea urchins.)⁴⁰¹

Van Valen's law has been criticized on several grounds: One criticism is that it fails to include the effects of mass extinctions. (David Raup has tried to generalize van Valen's law to allow for mass extinctions.) But van Valen never intended his law to cover mass extinctions, so this criticism is hardly fair. Raup has also criticized van Valen's law on mathematical grounds, claiming that it cannot be true at more than one taxonomic level at a time.⁴⁰² Yet, overall, van Valen's law has held up fairly well. As Niles Eldredge put it in his book *The Miner's Canary*:

Van Valen has had his critics, both of his interpretation and of his very data on which he based his Law of Constant Extinction in the early 1970s.

Yet there is more than a kernel of truth to Van Valen's patterns. There is most definitely a ticking of the extinction clock that indeed may be fairly regular over long spans of time within groups such as, say, trilobites, dinosaurs, and hominids (our own lineage).⁴⁰³

A *fourth* rule-of-thumb concerning background extinctions was discovered by Newman and Sibani in 1998. It is based on rather technical mathematical and statistical considerations, so we will just state it, rather than present any detailed evidence for it: The *rule of Newman and Sibani* states that, with respect to *background* extinctions, "the origination rate for families must be equal to the extinction rate [for families] at all times to within about one family per million years", and that "a similar result pertains for genera or any other taxonomic subdivision".⁴⁰⁴

A *fifth* rule-of-thumb that is (at least) *related* to background extinctions is the *increasing diversity of species* throughout the entire 540 My or so of the Phanerozoic era. As Newman and Palmer put it:

[O]n longer timescales, the diversity of species on the planet appears to have been increasing, as organisms discover for the first time ways to exploit new habitats or resources. . . [O]ne must be careful . . . because of the apparent diversity increase caused by the "pull of the recent". However, current thinking mostly reflects the view that there is a genuine diversity increase towards recent times associated with the expansion of life into new domains.⁴⁰⁵

The *sixth* (and final) rule-of-thumb concerning background extinctions is also possibly just an artifact of the "pull of the recent" in fossil discoveries, and

that is an apparent slow decline in the rate of extinction throughout the Phanerozoic era. This sixth rule is stated by Newman and Sibani as follows:

The fractional (or percentage) extinction rate should decline over time at all taxonomic levels, but it cannot decline faster than [the reciprocal of time t]. This prediction is in good agreement with the fossil record, within the statistical errors in the data.⁴⁰⁶

Our last topic concerning background extinctions comes under the always-interesting heading of a “possible fact”, namely the “possible fact” of background extinction due to “evolutionary overshoot” or “evolutionary momentum”. One famous instance is the Irish elk, shown in Figure 39, below:

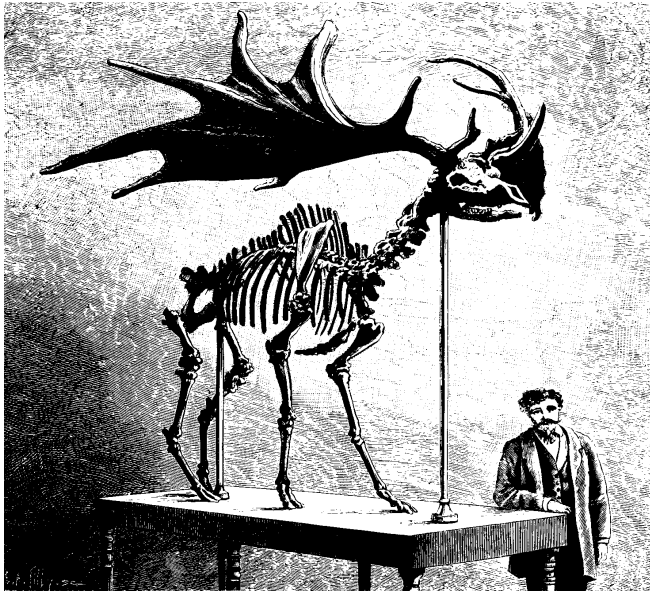


Figure 39 (from page 28 of Taylor, *The Great Evolution Mystery*)

The Irish elk’s antlers (it is speculated) evolved to become so large as to actually cause the extinction of that species. Gordon Rattray Taylor explains:

The classic example here is the Irish elk, *Cervus megaloceros*, which is neither Irish nor an elk, but is a Siberian deer. Its antlers were gigantic: twelve feet across and weighing nearly a quarter of a ton. As the Cambridge zoologist G.S. Carter writes: ‘But the enormous size of the antlers of the [Irish] elk makes it difficult to believe that they were evolved by the processes of natural selection. At this size they must have interfered seriously with the activity of the animal, and therefore, one would have thought, have been disadvantageous and removed by [natural] selection.’ One would, indeed.

ON EVOLUTION

Walter Modell, who has made the study of antlers his special interest, says: 'The antler is a strange and uneconomic experiment, extremely costly to its possessors in many ways, and it seems destined eventually to disappear.' Which suggests that the real mystery is why antlers appeared at all, leave alone why they sometimes became so huge.⁴⁰⁷

Another famous example is the *Smilodon*, whose two upper tusks evolved to be so long as to impede access to its mouth (and thus, it is said, contributed to its extinction).⁴⁰⁸

And, then, there is the oyster known as *Gryphaea*. Again, Gordon Rattray Taylor:

The shell of this mollusk began to coil early in its evolutionary history and this coiling was closely studied in the 1920s by A.E. Trueman, who took advantage of the fact that an unusually long series of fossil oysters was available. In the earliest forms the coiling amounts to a mere ten degrees or so, but it steadily increases and culminates in an impressive 540 degrees, or one and a half turns. At this point the oyster begins to have difficulty in opening its valves, and coiling cannot proceed further without it perishing of hunger. . .

. . . Nor is *Gryphaea* a unique instance. There are mollusks, living on coral reefs, the shells of which have become so thickened that they can barely open enough to admit the plankton on which they feed. The only reasonable view is that evolutionary trends sometimes acquire a momentum which carries them forward long past the point at which natural selection should have eliminated them.⁴⁰⁹

Needless to say, the neo-Darwinians violently disagree with this assessment. After discussing such cases for nine pages in his classic book *Tempo and Mode in Evolution*, neo-Darwinist George Gaylord Simpson declares magisterially:

There is no good evidence that a trend has ever continued by momentum beyond a point of advantageous or selectively neutral modification or has ever been the direct cause of extinction.⁴¹⁰

The famous neo-Darwinist paleontologist Niles Eldredge agrees: "Natural selection, after all, could not fashion an anatomical design that would sow the seeds of an organism's own destruction", and Eldredge goes on to attack this idea of extinction-via-overshoot as being a politically incorrect instance of "blaming the victim".⁴¹¹

Yet even Simpson admits that "[momentum effects] may be secondary causes of extinction to the extent that all tend to reduce the capacity of the population to react to changing conditions."⁴¹²

(As an aside, we may note that sometimes instances of "evolutionary momentum" were said to be the result of "racial senescence", i.e., defects related to the affected taxon's "old age" phase, but there really is no

necessary connection between the ideas of “evolutionary momentum” and “racial senescence”).

Here ends our presentation of the facts surrounding biological taxonomic extinction. How do the theories of neo-Darwinism and macrodevelopment measure up against these evolutionary facts? Let’s consider first the theory of neo-Darwinism:

The Neo-Darwinist Explanation

The first thing to note is that the rise of *neo-catastrophism* (e.g., asteroid/meteor/comet impacts) as an accepted contemporary explanation of at least *some* of the global mass extinctions in the geological past is a tremendous blow against the ironclad doctrines of *uniformitarianism* and *gradualism* advocated by Charles Lyell in geology and Charles Darwin in biology. Both men were adept at ridiculing catastrophist thinking as putatively religious and superstitious, and in presenting uniformitarianism and gradualism as inherently more “rational” and “scientific” – this in spite of the fact that, even by the 1850s, much evidence of catastrophism had been discovered in the fossil record. As Phillip E. Johnson has written:

. . . Darwin insisted that Cuvier’s theory of periodic catastrophes had been thoroughly discredited and that, on the contrary, “there is reason to believe that the complete extinction of the species . . . is generally a slower process than their production.” That judgment was based entirely on theoretical grounds, rather than on fossil evidence. In fact, the only evidence Darwin cited in the relevant passage was the extermination of the ammonites (ancient mollusks) at the end of the Cretaceous, which he acknowledged to have been “wonderfully sudden”. According to Darwin, the struggle for existence is so finely tuned that “the merest trifle would often give the victory of one organic being over another. Nevertheless so profound is our ignorance, and so high our presumption, that we marvel when we hear of the extinction of an organic being: and as we do not see the cause we invoke cataclysms to desolate the world. . .” In short, Darwinian ideology maintained that earlier geologists had attributed extinctions to catastrophes not because that was a reasonable interpretation of the fossil evidence, but because they were ignorant of the higher law of natural selection.⁴¹³

Another curious fact, which we pointed out above, is that true mass extinctions (whether caused by asteroid/meteor/comet impacts or not) generally were associated with *a significant drop in temperature throughout the biosphere*. If the theory of neo-Darwinism were correct, one would expect that such mass extinctions would *also* be associated with sudden, significant *increases* in temperature throughout biosphere as well, since the *direction* of temperature change should not have mattered if “failure to adapt to environmental changes” was all that was involved in these extinctions.

ON EVOLUTION

Even more damaging to the neo-Darwinian position is the fact (also discussed above) that Darwin's proposed mechanism of intense competition between closely-related species (the newer species driving out the older and less fit) as *the* primary cause of biological extinctions has been proved to be (instead) a very minor cause of extinctions, if indeed it happens at all:

Recall from our discussion of the fifth *fact of evolution* (i.e., the fact of strict typological hierarchy) that Darwin originally proposed this intense-competition mechanism to try to account for the contemporary discontinuity (i.e., "gaps") between existing taxa today. (Otherwise, the continual "splitting off" of species required by gradualistic Darwinism would be expected to result in a smooth sequence of continuously graded species.) Darwin's theory as to the cause of biological extinctions (and its intimate connection with his theory of "natural selection") is summarized by these two quotations, taken from Darwin's book *The Origin of the Species*:

. . .[A]s new species in the course of time are formed through natural selection, others will become rarer and rarer, and finally extinct. The forms which stand in closest competition with those undergoing modification and improvement will naturally suffer most. . . Consequently, each new variety or species, during the process of its formation, will generally press hardest on its nearest kindred, and tend to exterminate them.⁴¹⁴

As natural selection acts solely by the preservation of profitable modifications, each new form will tend in a fully stocked country to take the place of, and finally to exterminate, its own less improved parent or other less favored forms with which it comes into competition. Thus extinction and natural selection will, as we have seen, go hand in hand. Hence, if we look at each species as descended from some other unknown form, both the parent and all the transitional varieties will have been exterminated by the very process of formation and perfection of the new form.⁴¹⁵

Yet recall our earlier quotation from the prominent neo-Darwinist paleontologist Niles Eldredge in his book *The Miner's Canary*, wherein he admitted that:

Newly emerged descendents do not, as the overwhelming rule, routinely cause the extinction (through direct competition) of their evolutionary forebears. If . . . it does happen that descendent species occasionally outcompete parental species – unto the point of driving them to extinction – it is a minor process contributing to background rather than mass extinction.⁴¹⁶

Phillip E. Johnson summarizes the situation as follows:

Scientific thinking about extinctions has strayed far from the Darwinian principles that still define orthodoxy in the life sciences as a whole. According to [prominent paleontologist David M. Raup], the Darwinian

theory that extinctions result from the slow and steady effects of biological competition is “appealing, and has been learned by generations of biology students.” Nevertheless, “its verification from actual field data is negligible.” . . .

. . . There is no hard evidence that any observable extinctions were caused by competition from closely related species. Raup notes that evolutionary biologists long emphasized competition as a cause of extinctions because the explanation “seemed self-evident”, but when they actually tried to test the effect of competition the results were negative. The only reason for attributing extinctions to Darwinian competition remains the theory itself.⁴¹⁷

Nevertheless, this near-complete absence of evidence for Darwin’s theory of biological extinctions has not prevented neo-Darwinist paleontologists such as Niles Eldredge and David Raup from swearing their complete loyalty to neo-Darwinism. David Raup explains:

Natural selection remains the only viable, naturalistic explanation we have for sophisticated adaptations like wings and eyes. We would not be here without natural selection. Extinction by bad luck [i.e., extinction caused by asteroids, meteors, comets, and other catastrophes] merely adds another element to the evolutionary process, operating at the level [of] species, families, and classes, rather than the level of local breeding populations of single species.⁴¹⁸

But the problem with this disclaimer is that Darwin’s theory of extinctions is intimately connected with his theory of “natural selection”, as Darwin himself makes clear in our earlier quotations. Not to put too fine a point on it, if Darwin’s theory of biological extinctions is false (and the paleontological evidence clearly shows that it *is* false) then there is no way for Darwin’s proposed mechanism of “natural selection” to actually “select” species for survival. As Phillip E. Johnson says:

. . . Darwin’s theory of survival of the fittest and extinction of the less fit are the same thing, not two separable processes. Does natural selection produce variation only *within* the local breeding populations of single species? Then it doesn’t produce new species – much less new families and classes, or innovations like wings and eyes. Does natural selection continue to produce creative effects *beyond* the species boundary? Then it does so by selecting the less fit species for increasing rarity and eventual extinction, just as Darwin said. A natural selection that only creates and never destroys is a logical impossibility, because it wouldn’t be doing any selecting.⁴¹⁹

Now, if Darwin’s theory of extinctions is basically wrong (and paleontologists admit that this is so), what explanation do neo-Darwinist paleontologists *themselves* put forth for background taxonomic extinctions? The answer is that they either deny the existence or importance of background

ON EVOLUTION

extinctions (as David Raup does in his book *Extinction: Bad Genes or Bad Luck?*), or they rely on vague statements to the effect that background extinctions occur because species “fail to adapt quickly enough to their environment”. As Gordon Rattray Taylor puts it:

The stock view is that organisms fail to adapt sufficiently fast to changing circumstances. [George Gaylord] Simpson says, for instance, that the lag between ‘environmental demand and evolutionary response’ is ‘the usual or universal cause of extinction’.⁴²⁰

This sounds reasonable, except that the actual facts conform to what we have called *Simpson’s rule* (our *second* “rule-of-thumb” concerning the facts about background extinctions), which states that the faster a species evolves, the faster it tends to *die out and become extinct*! Again, Taylor:

The curious thing is that Simpson doesn’t seem to see the complete contradictions in what he says. He starts by asserting that extinction comes from not evolving fast enough; then he shows that it is precisely the fast evolvers which die out. Since the second proposition is known to be true, it must be the first which is faulty. And in that case the theory of natural selection stands in serious need of revision.⁴²¹

So far we have seen that our first two empirical “rules-of-thumb” with respect to background extinctions constitute strong evidence *against* neo-Darwinism. What of the last four “rules-of-thumb” (beginning with number three)? Do they provide evidence for, or against, neo-Darwinism?

Recall that our *third* “rule-of-thumb” concerning background extinctions is *van Valen’s law*, which states that *the probability of extinction per unit time for any given taxon is independent of the age of that taxon*. In other words, the rate of extinction for any given taxon is (in general) the same in its “youth” as in its “old age”, and the survivorship curve for taxa is therefore **Type II** (i.e., a straight line on a semi-log scale).

But, if neo-Darwinism were true, one would instead expect the survivorship curves of taxa to be **Type III** (i.e., a bowl-shaped curve in which the extinction rate during the taxon’s “old age” is far lower than during the taxon’s “youth”). The reason is that, according to neo-Darwinism, “old age” taxa would in general be expected to be the “fittest”, having survived a higher number of evolutionary challenges in a higher number of differing environments throughout their lifetimes: Consequently their rate of background extinction per unit time should be far *lower* than in the case of the untried, vulnerable “youthful” taxa. But this is not the case, and this is a serious point *against* neo-Darwinism. (A less serious point against neo-Darwinism is that it provides no explanation as to why the rate of extinction, and therefore the slope of the **Type II** line, should differ in a regular fashion between differing groups of biological organisms.)

Recall that our *fourth* “rule-of-thumb” with respect to background extinctions was the *rule of Newman and Sibani*, which states that “the origination rate for families must be equal to the extinction rate [for families] at all times to within about one family per million years”, and that “a similar result pertains for genera or any other taxonomic subdivision”.⁴²² Neo-Darwinism provides no good reason why this should be so. On the other hand, this fourth rule probably does not contradict neo-Darwinism directly.

Similarly, our *fifth* “rule-of-thumb” re background extinctions, namely, the *increasing diversity of species* throughout the entire 540 My or so of the Phanerozoic era, also cannot be explained by neo-Darwinism. This is essentially because neo-Darwinism is a *linear* theory of *reversible* processes, and therefore cannot really explain any historical trend whatsoever (except, perhaps, increasingly better adaptation to a specific environment), in spite of Darwin’s bald assertion that “[a] set of animals, with their organization but little diversified, could hardly compete with a set more perfectly diversified in structure.”⁴²³ Instead, as George Gaylord Simpson points out, in the long run it is the *less* specialized (“diversified”) taxa which tend to outlast the *more* specialized (“diversified”) taxa, contrary to Darwin’s assertion. (Simpson calls this “the rule of the survival of the relatively unspecialized”.⁴²⁴) So, once again, we have an evidential point that is either contrary to the theory of neo-Darwinism, or is neutral with respect to that theory.

Recall that our *sixth* (and final) rule-of-thumb concerning background extinctions is an apparent slow decline in the rate of background extinctions for all taxonomic levels throughout the entire 540 My of the Phanerozoic era. Here, at last, we seem to have a point that actually *favors* neo-Darwinism, since it appears that, on the average, taxa at all levels have gradually adapted better-and-better to their environment, thus gradually reducing their extinction rate per unit time (just as neo-Darwinism predicts). However, our enthusiasm for this piece of evidence must be tempered by acknowledging that *a*) this rule-of-thumb may just be the result of the “pull of the recent” in cataloging fossil data, *b*) paleontologists have shown that Darwin’s theory of extinctions (which is intimately connected to his theory of “natural selection”) is false, and *c*) we have shown that the other five “rules of thumb” with respect to background extinctions are either strong evidence *against* neo-Darwinism, or are neutral with respect to neo-Darwinism.

The last piece of evidence with respect to background extinctions which we need to consider in relation to neo-Darwinism is the “possible fact” of “evolutionary momentum” (also called “evolutionary overshoot”) as a cause of such extinctions. Obviously, if “evolutionary momentum” occurs, then “natural selection” is not as sensitive a mechanism as Darwin claimed, even if

ON EVOLUTION

extinction does eventually result. Furthermore, the “possible fact” of “evolutionary momentum” strongly suggests that nonlinear macrodevelopment may play an important role in evolution, and this is something that neo-Darwinians are determined to deny at all costs. After reviewing the evidence, George Gaylord Simpson suggests three neo-Darwinian “natural selection” explanations for the “possible fact” of “evolutionary momentum”:

Apparent momentum effects may be produced under the influence of [natural] selection in a variety of ways; among them are: selection on juveniles or young adults favoring characters disadvantageous to old adults; shifting of the optimum to a previous point faster than the population’s genetic structure can follow; [and] simultaneous selection on correlated characters such that the optimum for the two together is reached after one has passed its separate optimum.⁴²⁵

Simpson’s detailed arguments on this subject are often quite convoluted, as the following passage on the Irish elk (depicted in our Figure 39, above) shows:

A final possibility is that the progress of a structure beyond its optimum really occurred, but that it was caused by genetic or heterogenic linkage of this structure with another that had not reached its optimum. Then the true selection value is not the expression of one alone, but the two together. The genetic optimum is reached when the advantageous development of one, which has passed its phenotypic optimum, just balances the advantageous development of the other, which has not reached its phenotypic optimum . . . Such a phenomenon provides an elegant and sufficient explanation for many supposed momentum effects, including another classic “proof”, the Irish [elk], in which the antlers became so large that they had probably passed the optimum size. If this group had strong positive heterogony of antler size against body size, as it seems to have had and as its ally *Cervus elaphus* demonstrably has (Huxley 1932), then the increase in body size automatically produced a disproportionate increase in antler size. The condition reached was that at which the disadvantage of further increase in antler size balanced the advantage of further body increase. Here, again, postulation of a true momentum effect is quite unnecessary . . . Extinction would not follow automatically, because the point reached between the two phenotypic optima is the evolutionary optimum; but, again, there is no real evidence that the supposed momentum effect did cause extinction. It could readily be a contributing factor, because a group that suffers evil that good may come, that necessarily acquires a disadvantage to obtain an advantage, is likely to be less successful in any intensification of the struggle.⁴²⁶

Involved arguments of this type span nine pages, but ultimately succeed only in convincing the reader that Simpson is straining to “explain away” the “possible fact” of “evolutionary momentum”, which continues to be a serious embarrassment to the theory of neo-Darwinism. As Gordon Rattray Taylor points out:

The official explanation for the gigantic horns of the [Irish] elk is advanced by Professor George Gaylord Simpson. Horn size is correlated with body size, he maintains. In combat with other males for access to females, the bigger animal will usually win. Horns are secondary sexual characteristics and are used in combat. Consequently, large horns are preserved. But the fact is, when deer [or elk] fight seriously they fight with their feet. In antler fights, the antlers often become locked, and both animals die. Antlers are thus a disadvantage to the species.⁴²⁷

To summarize: It is clear that the facts surrounding biological taxonomic extinction (which facts, taken together, constitute our seventh *fact of evolution*) represent serious and significant evidence *against* the theory of neo-Darwinism, when this evidence is taken as a whole.

What, now, of the theory of macrodevelopment? Does it fare any better in the face of the facts of evolutionary extinction?

The Macrodevelopmental Explanation

In the first place, the theory of macrodevelopment is consistent both with “gradualistic” processes *and* with “catastrophic” processes. (In fact, an alternative way of looking at the sometimes-sudden transitions in nonlinear functions is Rene Thom’s *catastrophe theory*.) So, the rise of *neo-catastrophism* in contemporary paleontology and geology is not a crisis for the nonlinear theory of macrodevelopment, as it is for the gradualistic, linear theory of neo-Darwinism.

Secondly, the fact that *mass extinctions* (whether caused by asteroid/meteor/comet impacts or not) generally were associated with a significant *drop* in temperature throughout the biosphere (and *not* with a sudden or significant *rise* in temperature) is fully consistent with macrodevelopment, since macrodevelopment conceives of the biosphere to be a holistic, nonlinear, far-from-equilibrium system, and such far-from-equilibrium systems require a constant input of energy in order to sustain themselves. Consequently, if the energy input into a far-from-equilibrium system falters, then a collapse or retreat of that system is to be expected: That is why we earlier suggested that an analogy exists between evolutionary “retreat” as a result of temperature-drop-caused extinction and the retreat of certain bifurcating nonlinear chemical systems to prior states, when forced to drop back closer to equilibrium as a result of a drop in the rate of heat (or other energy) entering the system. (See Figure 28.)

By contrast, a sudden *increase* in the rate of energy going into the biosphere (conceived of as a macrodevelopmental far-from-equilibrium system) would be expected to result, not in a sudden increase in *extinctions* (as neo-

ON EVOLUTION

Darwinism would predict), but rather in a sudden increase in the *origination rate* for species and other taxa. (For the same reason, as we indicated earlier, the very high rate of solar energy input into tropical ecosystems is probably why they have such a high species diversity.)

Turning, now, to our six empirical “rules of thumb” of *background extinctions*:

With respect to the *first* such rule-of-thumb (that rarely, if ever, does the emergence of a new species drive a previously-existing species to extinction as a result of direct competition), we may say that this fact does not present macrodevelopment with the serious problem it presents to neo-Darwinism. Of course, the theory of macrodevelopment does *not* deny the fact of biological competition, but it *does* put biological competition into a nonlinear, holistic context, such that it simply does not function in the way that neo-Darwinism erroneously predicts.

With respect to the *second* rule-of-thumb, *Simpson’s rule* (that the faster a taxon evolves, the faster it tends to die out and become extinct), we may view this rule to be explainable by the theory of macrodevelopment by means of an analogy to the development of biological *individuals*: For, in general, the faster a biological *individual* develops, the sooner it reaches the end of its natural lifespan and dies. Similarly, the faster a biological *taxon* evolves (i.e., *macrodevelops*), the sooner *it* reaches the end of *its* natural lifespan and becomes extinct.

With respect to our *third* rule-of-thumb concerning background extinctions, *van Valen’s law* (that the probability of extinction per unit time for any given taxon is independent of the age of the taxon, so that the rate of extinction for the taxon is the same in its “youth” as in its “old age” and its survivorship curve is therefore always **Type II**), we begin by noting that the theory of macrodevelopment is compatible with *all* of the various types of survivorship curves (**Type I**, **Type II**, and **Type III**), since biological *individuals* exist for all three types, as is shown in Figure 38. (By contrast, we have seen that neo-Darwinism is compatible *only* with a **Type III** survivorship curve, and therefore contradicts the empirical evidence of *van Valen’s law*.)

Furthermore, macrodevelopment can explain the fact that the rate of extinction (i.e., the slope of the line in the **Type II** van Valen curve) differs for differing groups of taxa by using an analogy with the *rate of mortality* for biological *individuals* as grouped by species: Just as biological *individuals* (as grouped by species) have differing *rates of mortality* and differing natural lifespans, so biological *taxa* (as grouped under *higher-level* taxa) have differing *rates of extinction* and differing natural lifespans.

One idea in macrodevelopmental theory that is *not* entirely consistent with *van Valen's law* is the idea that taxa developmentally *decline* in “old age”. This idea was expressed as “racial senescence” by past paleontologists, and is today expressed as “phylogerontology” by Robert F. DeHaan. But if this were true, then one would expect that the rate of extinction for “old age” taxa would be significantly *higher* than the rate of extinction for “youthful” taxa. In other words, one would expect that background taxonomic extinction would follow a hill-shaped **Type I** survivorship curve (like that of human individuals), rather than the straight-line **Type II** survivorship curve which it actually follows. (It is still quite possible, of course, that taxa may “age” in such a way that the *causes* of extinction change as they proceed from “youth” to “old age”, even though the *rate* of extinction does not.)

With respect to our *fourth* rule-of-thumb, the *rule of Newman and Sibani* (which states that “the origination rate for families must be equal to the extinction rate [for families] at all times to within about one family per million years”, and that “a similar result pertains for genera or any other taxonomic subdivision”.⁴²⁸), we may view this as further positive evidence for the theory of macrodevelopment, since macrodevelopment requires that the biosphere be a hierarchy of “open systems” whose structure is maintained in a more-or-less “steady state” by a continuous near-equal balance of degeneration and regeneration of taxa at their various taxonomic levels, as energy flows through the system. The *rule of Newman and Sibani* automatically follows from this state of affairs. As Ludwig von Bertalanffy has written:

Living systems are maintained in a more or less rapid exchange, degeneration and regeneration, catabolism and anabolism of their components. The living organism is a hierarchical order of open systems. . . . As a general rule, turnover rates are the faster the smaller the components envisaged.⁴²⁹

With respect to our *fifth* rule-of-thumb (the *increasing diversity of species* throughout the entire 540 My or so of the Phanerozoic era), again we have evidence in favor of the theory of macrodevelopment: For the entire movement of the development of an individual embryo is from the generic to the increasingly specific, with temporally increasing diversity at all levels, but particularly at the most-specific levels. By analogy, therefore, the increasing diversity of species does *not* occur because more-specialized groups of animals are more competitive and hence live longer than less-specialized groups (as Darwin erroneously maintained), but rather because the temporal movement from the generic to the increasingly specific and increasingly diverse is a central thrust of the macrodevelopmental process, taken as a whole.

ON EVOLUTION

Finally, with respect to the *sixth* rule-of-thumb concerning background extinctions, namely, the apparent slow decline in the rate of background extinctions for all taxonomic levels throughout the entire 540 My of the Phanerozoic era, we may perhaps speculate that, as the biosphere's macro-embryonic period approaches its end, an *increase* in stability and a *decrease* in extinction rate at all taxonomic levels might be expected.

The last piece of evidence with respect to background extinctions which we need to consider in relation to the theory of macrodevelopment is the "possible fact" of "evolutionary overshoot" (illustrated by the picture of the Irish elk in Figure 39). The theory of macrodevelopment not only has no problem with these instances of "evolutionary overshoot": It actually predicts that they will occur! This is because macrodevelopmental theory regards the biosphere to be a nonlinear, far-from-equilibrium "open system" (or, more accurately, a hierarchy of such open systems), and "overshoot" is a quite common characteristic of nonlinear open systems in general and of biological systems in particular. Again we turn to Ludwig von Bertalanffy:

Closed systems generally tend toward equilibrium states in an asymptotic approach. In contrast, in open systems, false start and overshoot may occur . . . In other terms: If we find overshoot or false start – as is the case in many physiological phenomena – we may expect this to be a process in an open system with certain predictable [nonlinear] mathematical characteristics.⁴³⁰

Taking all of this evidence together, it is clear that the facts surrounding biological taxonomic extinction (which facts, taken together, constitute the seventh *fact-of-evolution*) are strong evidence *in favor of* the theory of macrodevelopment and *against* the theory of neo-Darwinism.

8. *The Genetic Evidence of Evolution*

In our third *fact of evolution*, discussed above, we demonstrated that neo-Darwinian and Mendelian mechanisms are effective *only* in creating and sustaining intra-species varieties *within limits*, and that such mechanisms have *never* produced true typological species or higher-level typological taxa. For this reason, if we were to compare the difference between the genomes of two varieties (subspecies) *within* a single, true typological species to the difference between the genomes of two *separate* (but closely related) typological species, we would expect the nature of those differences to be radically different in the two cases. This is, in fact, what we would find, as was pointed out as long ago as 1940 by the famous geneticist Richard Goldschmidt in his great book *The Material Basis for Evolution*.⁴³¹

Essentially, we would find that the variance between the genomes of the two *intra-species varieties* is (in general) characterized by differences in the *individual genes* (or, more accurately, in the *alleles* of those genes) at various points along their corresponding chromosomes (as would be expected where neo-Darwinian and Mendelian processes are at work). By contrast, the difference between the genomes of the two closely-related *typological species* would (again, in general) be characterized by differences in the overall *chromosome patterns* of the two species: In other words, the *individual DNA genes* of the two typological species would be very similar, but long segments of their chromosomes would be *rearranged* relative to one another by means of such processes as chromosome *fission*, *fusion*, *inversion*, *translocation*, and *duplication*. John A. Davison explains:

There are several kinds of chromosome rearrangements. Two chromosomes can fuse together to form one, or a chromosome can dissociate to form two. Two breaks can occur along a chromosome, with the broken fragment undergoing a 180-degree rotation before reattaching. There are two types of such inversions, depending upon where in the chromosome they occur. Each chromosome has somewhere along its length a place where the spindle fibers attach during mitosis [division of body cells] and meiosis [production of sex cells]. This structure, called the centromere, contains DNA and, like the chromosome, is also self-replicating. If the centromere is within the inverted segment, it is called a pericentric inversion. If the inversion does not include the centromere, it is termed a paracentric inversion. Another type of restructuring is reciprocal translocation in which two different chromosomes exchange parts. Other types of [chromosome] changes include duplications and deficiencies. Alterations can also occur in the number and position of nucleolar organizers as well as changes in the chromosome ends, or telomeres.⁴³²

As a specific example, Davison cites the higher primates:

Of special interest are the chromosomes of the order Primates to which we belong. We are fortunate in having three close relatives with which comparisons can be made: the chimpanzee, the gorilla, and the orangutan. The higher primates are also interesting because they are among the most recent evolutionary products and accordingly their karyotypes [i.e., the chromosomal makeup of their cells] are likely to have retained their original configurations.

In 1982 Yunis and Prakish published a paper entitled “The Origin of Man: A Chromosomal Pictorial Legacy” [*Science*, 215: 1525-1530] in which the karyotypes of man, chimpanzee, gorilla, and orangutan are compared. . . The karyotypes are remarkably similar, providing convincing evidence that we are all four related. . . The differences that can be recognized are largely structural rearrangements. For example, the three apes have 48 chromosomes, while we have 46. This has apparently resulted from the fusion of two . . . chromosomes to form a single human chromosome (chromosome 2). Some of the differences consist of paracentric and pericentric inversions of homologous chromosome

ON EVOLUTION

segments, as well as variations in heterochromatin. As examples, chromosomes 4, 5, 9, and 12 of man and chimpanzee each differ by a pericentric inversion. Certain chromosomes exhibit reciprocal translocations. Other differences include alterations in chromosome ends, or telomeres, as well as variations in the position of nucleolar organizers. . . .

The important point is that the differences which are evident are precisely of the sort that [Richard] Goldschmidt described: namely, the restructuring of existing genetic information. . .

Also, there are very small differences in both DNA and protein composition between ourselves and our living relatives . . . , further supporting the view that conventional (point) mutations may be of little or no significance in the evolutionary process. . .

The four higher primates, man (*Homo*), Chimpanzee (*Pan*), Gorilla (*Gorilla*), and Orangutan (*Pongo*) are all in separate genera. How can they be gradually transformed one into the other when the very differences which they so strikingly exhibit (chromosome reorganizations) by definition have no conceivably gradual or intermediate states? The restructuring of a chromosome, like pregnancy, is an all-or-none event!¹⁴³³

Davison also points out a very interesting fact with respect to the differences between the genomes of these Primate species: While the homologous sex-related X chromosomes differ very little between these Primate species, the homologous sex-related *male-determining* Y chromosomes *do* vary significantly, a fact which at least *suggests* that these species were *not* created via sexual reproduction, but rather that sexual reproduction was *re-established* for each species *after* the speciation event that created the species.

Another interesting fact: While the individual DNA genes of closely-related true typological species are often quite similar, the sequencing of their *proteins* can sometimes diverge widely. For example, it is estimated that the sequencing of 40% of human proteins are completely unique to the human species. (However, “more than 90% of the domains [i.e., protein structural sub-units] that can be identified in human proteins are also present in fruit fly and worm proteins, although they have been shuffled to create nearly twice as many different arrangements in humans.”⁴³⁴) This clearly suggests that proteins are produced by a far more holistic and complex process than simply “reading off” the linear sequence of a DNA gene.

All of this raises, of course, an important question: If sexual reproduction and individual point-mutations cannot create a typological species, what process (at the genetic level) *does*? This is, of course, a highly controversial question. However, John A. Davison of the University of Vermont (who we’ve cited so far) presents excellent evidence that one such process is what he calls *semi-meiosis*:

Semi-Meiosis

We begin by explaining that the *gametes* (sex cells, both ovum and sperm) in multi-celled organisms usually contain the *haploid* number of chromosomes. (This haploid set of chromosomes is the set of chromosomes containing the minimum, basic genetic information necessary to specify the organism.) By contrast, the *somatic* cells (regular body cells) in multi-celled organisms generally contain the *diploid* number of chromosomes (i.e., twice the haploid number), with one haploid set coming from each parent. Other types of *ploidy* are possible, however: If n is the *haploid* number of chromosomes, then $2n$ is the *diploid* number, $4n$ is the *tetraploid* number, and in general any number of chromosomes above $2n$ is an instance of *polyploidy*. (Recall, for example, from our discussion of the third *fact of evolution* that contemporary plants often speciate by means of *polyploidy*, and consequently plant cells are often *polyploid*.) John A. Davison now explains the basis of his *semi-meiotic hypothesis*:

In all diploid animals and plants the chromosomes occur in pairs. One member of each pair comes from one parent, the other from the other parent. Thus, each egg or sperm must have only one of each kind of chromosome, a condition known as *haploidy*. The process by which this reduction takes place is known as *meiosis*, or *chromosome reduction*. . . If one were to imagine the simplest way that chromosome reduction could take place, it might be as follows: The chromosomes would align in pairs and a single [cell] division would take the chromosome number from diploid to haploid. Not a single living creature undergoes meiosis in this way. Instead, each chromosome is duplicated, taking the chromosome number from diploid to tetraploid. Then, while they are in alignment, a very important step occurs: Breaks occur in some of the chromosomes, and exchanges occur between the original pairs of chromosomes, a phenomenon known as *crossing over*. Following this event, the chromosomes [and the cell which contains them] undergo the *first meiotic division*, returning the chromosome number from tetraploid to diploid [and producing two diploid cells]. The way in which this division occurs is critical to an understanding of the evolutionary process. The two originally identical chromosomes (known as *sister strands*) always remain together. Note that this first meiotic division is a perfectly valid form of diploid reproduction, and forms the basis for what I have called the *semi-meiotic hypothesis* for organic evolution (Davison, 1984, 1993). And, since meiosis involves two steps, it is mandatory that the first meiotic division must have evolved prior to the second, and accordingly can be considered a primitive and pre-sexual form of diploid reproduction.⁴³⁵

After the *first* meiotic division, what generally happens is that the two diploid cells each divide again (the *second* meiotic division), forming four haploid gamete cells and thus completing the process of meiosis in a normal way. However, in Davison's version of the *semi-meiotic hypothesis*, he presumes

ON EVOLUTION

that one of the two diploid cells winds up with two sister strands that have *not* undergone crossovers, inversions, etc., while the other diploid cell winds up with two sister strands that *have* undergone these types of chromosomal rearrangements. One of these two diploid cells is then rejected, leaving the other to develop as if it were a fertilized egg. If the chromosomally rearranged cell is rejected, a normal (but *homozygous*) individual of the same species is born. However, if the *other* cell is rejected, the chromosomally re-arranged cell may instead develop into an individual of a new species.⁴³⁶ (This corresponds to Schindewolf's theory, accepted by both Richard Goldschmidt and John A. Davison, that "the first bird hatched from a reptilian egg".⁴³⁷)

One major problem which I see with Davison's *semi-meiotic hypothesis*, as it stands, is that it involves the same kind of asymmetrical "splitting off" of one species from another as is found in both neo-Darwinism and in Richard Goldschmidt's "hopeful monster" theory: As we saw in our discussion of the fifth *fact of evolution*, the taxonomic facts of evolution *require* that biological organisms be arranged in *monophyletic* groups, which strongly suggests that evolutionary splits must occur *symmetrically*, with one more-generic "ancestor" taxon giving rise to two more-specific "descendent" taxa and simultaneously vanishing as an independent entity in the process.

Consequently, I propose a variation on Davison's semi-meiotic hypothesis, which I will call the *taxon-wide semi-meiotic twins hypothesis*. Under this hypothesis, chromosomal re-arrangements occur during the tetraploid stage which affect *both* sets of sister strands. Consequently *both* of the diploid cells resulting from the first meiotic division represent different "descendent" taxa, and each of these "descendent" taxa is more-specific than the original more-generic taxon. In addition, *both* of the diploid cells then behave as if they were fertilized eggs, and the "ancestor" mother gives birth to *twins*, one of each more-specific taxa. Finally, this event occurs for *every* birth within the "ancestor" taxon, thus resulting in the symmetrical evolutionary taxon-splitting which we actually find in nature and furthermore resulting in the pseudo-extinction of the "ancestor" taxon as an independent entity.

(Obviously, from this perspective, the chromosomal re-arrangements involved here are merely secondary effects of a much larger, more-holistic taxon-wide process, rather than occurring by mere chance at the level of the biological individual.)

Now, I freely admit that this *taxon-wide semi-meiotic twins hypothesis* sounds "rather incredible"! (Davison himself, in a personal communication to the author, says that this *twins hypothesis* "cannot be reconciled with known cytogenetic events".) But I truly believe that we are in a "Sherlock Holmes" situation in which, having eliminated the impossible, whatever remains

(however improbable) must be the truth. Nevertheless, I do not *insist* that the taxon-wide semi-meiotic twins hypothesis must be correct: Other macrodevelopmental hypotheses are also possible, such as *geographical* (i.e., *positional*) hypotheses in which the “ancestor” taxon splits into two “descendent” taxa by geographical region. But I have no idea how such alternative macrodevelopmental processes would look at the genetic level. (Notice, incidentally, that paleontology might be able to provide evidence for or against *geographical* taxon-splitting versus *non-geographical* taxon-splitting.)

More generally, it is also important to note that the distinction which Goldschmidt and Davison make between *intra*-species differences as essentially being caused by point mutations and allele substitutions in individual genes, versus *inter*-species differences as essentially being caused by global chromosomal re-arrangements (such as semi-meiosis), also explains the easy *reversibility* of the proportions of *intra*-species varieties via neo-Darwinist and Mendelian processes, versus the essential *irreversibility* (from an immanent objective point-of-view) which characterizes true nonlinear typological taxonomic evolution. John A. Davison elaborates on this point:

Point mutations (base pair substitutions) of individual genes are reversible, and that alone indicates that such changes do not play a significant role in evolution. By way of contrast, consider an inversion: If such a change should occur, the probability of it being reversed is virtually zero, since the chromosome would have to break in exactly the same two places in order for it to return to its original configuration. A similar argument applies to the improbable reversibility of chromosome fusion, dissociation, or reciprocal translocation. Furthermore, these structural changes are all-or-none events which have no intermediate states and cannot possibly be regarded as gradual. Accordingly, one might anticipate that these effects might be quite dramatic, although unpredictable. Incidentally, this perspective also offers an explanation for the absence of transitional forms in the fossil record.⁴³⁸

These observations are echoed in the work of geneticist Richard Goldschmidt (whom Davison cites appreciatively). For example, in Goldschmidt’s 1940 book *The Material Basis for Evolution* he quotes from a 1923 article by J.C. Willis as follows:

The small [point] mutations that are all that the Mendelian school [i.e., the neo-Darwinists] will allow are obviously in the highest degree unlikely to give rise to mutual intersterility, such as so commonly characterizes specific differences, and if they were to be accumulated it is difficult to see where the sterility would come in, for each would seem as likely to be fertile with its successor as with its predecessor – A with B, B with C, C with D, and so on. But let a big step, say, from A to M . . . be taken, and one would feel inclined to expect mutual intersterility as a matter of course.

ON EVOLUTION

If so large a difference as having, or not having, endosperm, few or indefinite stamens, etc., etc., can occur, as it does occur, over and over again between genera which are obviously closely allied, we are evidently simply making difficulties for ourselves by supposing such differences to be gradually acquired.⁴³⁹

(Furthermore, as we saw in our discussion of the seventh *fact of evolution*, concerning extinction, there is no credible evidence for Darwin's proposal that gaps such as that between A and M were, in general, caused by the extinction of closely-related species that were supposedly in intense competition.)

Later on in *The Material Basis of Evolution* Goldschmidt himself writes:

A complicated change of intrachromosomal pattern may occur instantaneously or in a few consecutive steps, and, if it leads at all to a stable condition, may at once produce the new reaction system, the species. Thus all the difficulties in the way of a slow, step-by-step selective accumulation of innumerable mutants vanish, difficulties which appear when we get away from generalities and try to apply the neo-Darwinian explanation to concrete cases.⁴⁴⁰

Ploidy Change

But as useful as these semi-meiotic and chromosomal-rearrangement hypotheses are in explaining evolution at the genetic level, it is clear that another important factor that cannot be ignored is *ploidy change*: Recall that the only true typological speciation that we observe today is due to *ploidy change* in plants (up to tetraploid, hexaploid, and even higher ploidy), which can result in a new species within one or two generations. Recall also that in 1970 Susumu Ohno found genetic evidence of at least two major *tetraploidization* events within the evolutionary history of vertebrates, one associated with the evolutionary emergence of jawless fish and the other associated with the evolutionary emergence of the four-limbed vertebrates, a.k.a. tetrapods. Here is a discussion of Ohno's discoveries in more detail:

In 1970, Susumu Ohno proposed that vertebrates arose as a result of two tetraploidization (gene duplication) events. These events were speculated to have occurred (1) after the first primitive chordates arose (~500 My) and (2) about the time that the tetrapods (four-limbed vertebrates) arose (~375 My). Several pieces of evidence support the tetraploidization theory. Genome sizes (amount of DNA per haploid cell) of organisms from various vertebrate and chordate taxa revealed a pattern of two genome duplication events during vertebrate evolution: one prior to the evolution of the jawless fish and one before the evolution of the tetrapods. Although this is generally true, DNA content is only a very rough measure of gene number. In addition, however, the observation that the gene loci for the alpha- and beta- chains of human hemoglobin were located on different chromosomes

suggested that tetraploidization must have been the mechanism responsible for vertebrate evolution. . . .

More evidence for the tetraploidization hypothesis came from the location of four human aldolase genes. The aldolase genes are found on separate chromosomes. . . [T]wo tetraploidization events are the most parsimonious explanation for the origins of these four aldolase genes.⁴⁴¹

Some researchers have suggested that an *increase* in ploidy might accompany a typological evolutionary event that required significant changes to body plan (e.g., the change to a four-limbed structure), while a *decrease* in ploidy during subsequent evolutionary events would act to eliminate unnecessary genetic redundancy.

We may therefore tentatively extend our *taxon-wide semi-meiotic twins hypothesis* to include *tetraploidy*, as follows: If, on a taxon-wide basis, not even the *first* meiotic division occurred after chromosome duplication and reorganization, the result might be a *tetraploid egg*, representing a new *tetraploid taxon*. If this egg developed to maturity (again on a taxon-wide basis), then the diploid “ancestor” taxon would disappear as an independent entity and *one* tetraploid “descendent” taxon would arise instead of the usual *two* diploid “descendents”, as all mothers belonging to the old diploid taxon gave birth to children belonging to the new tetraploid taxon. (Although exceptional, this would still be a *symmetrical* evolutionary event, and would therefore not disturb the *monophyletic* taxonomic structure of the biosphere.) During a subsequent evolutionary event this tetraploid taxon could then become the “ancestor” of *two* diploid “descendent” taxa (yet again on a taxon-wide basis), with each set of two “descendent” eggs being produced by a simple reduction of the tetraploid cell to the diploid state during the first meiotic division. (In all of these semi-meiotic and polyploidal scenarios, ordinary sexual reproduction would presumably be re-established soon after the evolutionary event, in order to confine *intra-taxon* biological changes within a defined and reversible range.)

Here are some other interesting facts about *polyploidy*:

First, polyploidal taxa are striking examples of the importance of holistic epigenetic factors in biology, in contrast to the reductionistic view that linear DNA sequences of “genes” are determinative. As Philip Hieter and Tony Griffiths have written:

Cells differing only by their ploidy are identical in terms of DNA sequence information and relative gene dosage, and yet are often quite different in terms of physiology, morphology, and behavior. . . A report by Galitski *et al.* . . [shows] that yeast (*Saccharomyces cerevisiae*) with different ploidies had different patterns of gene expression. Their findings provide definitive

ON EVOLUTION

evidence for a ploidy-driven mechanism of gene regulation that may be important in a variety of biological states.⁴⁴²

Second, it is of great interest from the perspective of the theory of macrodevelopment that changes in ploidy are often found during the development of the biological *individual*, as well as during the macrodevelopment of biological *taxa*. Again, Hieter and Griffiths:

Changes in ploidy during cell differentiation appear to be important in [individual] development. Almost all plants and animals generate specific sub-populations of polyploid cells by endoreduplication cycles (DNA replication in the absence of cell division) during tissue-specific differentiation. For example, the ploidy of megakaryocytes (the cells that produce blood platelets) ranges from 16n to 64n; that of cardiomyocytes (heart muscle cells) from 4n to 8n; and that of hepatocytes (liver cells) from 2n to 8n. . . . [Furthermore,] many cancer cells are polyploid, raising the still unresolved issue of whether an [uncontrolled] increase in ploidy contributes to, or is a consequence of, tumor development.⁴⁴³

Third, although polyploid speciation is most common today among contemporary plants, polyploid species can also be found among contemporary animals:

Polyploidy has been observed in some insects, fish, and amphibians. There are several polyploid species of insects, including: earwigs, stick insects, mantises, crickets, and mole-crickets. Families of insects typically range up to hexaploid levels. . . . Many species of fish have a wide range of chromosome numbers, likely the result of polyploid evolution. Similarly, diploid ancestors have been found to tetra-, hexa-, and octaploid amphibians and fishes; they tend to differ in mating call, reproductive season, and geographical distribution. . . . In fact, some groups such as salmonid fish and certain amphibians have clearly evolved by doubling or tripling their ploidy In known cases in animals, polyploidy is low level, meaning it is typically triploid or tetraploid.⁴⁴⁴

In 1999 a tetraploid *mammal* was even discovered, the red viscacha rat (*Tympanoctomys barrerae* Octodonidae)!⁴⁴⁵

Closely related to polyploidy is the phenomenon of *polyteny*, in which the duplicated chromosomes do not retain their individual identity, but instead remain in precise alignment, thus forming “giant” chromosomes.⁴⁴⁶ Also closely related to polyploidy is a phenomenon which Arnold H. Sparrow and Anne F. Nauman have called *cryptopolyploidy*, which results in chromosomes doubling in *size* rather than in *number*. Sparrow and Nauman, in their article “Evolution of Genome Size by DNA Doublings” in the May 7, 1976 issue of *Science*, present convincing statistical evidence that *genome doubling* (whether that genome doubling occurs via polyploidy, cryptopolyploidy, polyteny, or some other process) is an important historical, nonreversible feature of the evolution of the biosphere:

These data demonstrate the apparent existence of exponential periodicity over eight orders of magnitude, leading us to suggest an evolutionary continuity of doublings of a basic ancestral genome (of about 300 nucleotides), these doublings being independent of both chromosome number and ploidy level. This proposed continuity encompasses most major life forms, and is generally concomitant with increasing evolutionary complexity . . .⁴⁴⁷

Here ends our basic discussion of the eighth *fact of evolution*, the genetic evidence of biological evolution.

Theoretical Explanations

How do the various *theories* of evolution fit the genetic *evidence* of evolution? We begin with the theory of *neo-Darwinism*:

It is clear from the genetic evidence presented above that a true typological evolution event (e.g., a true speciation event) is always accompanied by *chromosomal rearrangement*, *chromosomal multiplication*, and/or *chromosomal reduction*, and that point-substitutions of alleles (i.e., individual gene variations) play little or no role in such events. For this reason, the following statements, contained in the current “Statement on Teaching Evolution” of the National Association of Biology Teachers, are obviously completely false:

. . . [E]volution can be defined as any change in the frequency of alleles within a gene pool from one generation to the next. . . .

Recent findings from the advancing field of molecular genetics . . . collectively provide indisputable demonstration of the theory of evolution [i.e., the theory of neo-Darwinism]⁴⁴⁸

In short, this eighth *fact of evolution* is very strong evidence *against* the theory of neo-Darwinism, the National Association of Biology Teachers to the contrary.

What about the theory of *young-earth creationism*? Because the genetic evidence *is* indicative of taxonomic ancestor-descendent relationships in the broad sense of the words “ancestor” and “descendent”, and because the fossil record clearly shows major changes in both the distribution and kinds of biological taxa over vast stretches of geological time, we must reject young-earth creationism as well.

There is, however, a theory which we must give more serious consideration to – a theory I will call *individualistic saltationism*. According to individualistic saltationism, evolution *does* proceed at the genetic level by means of the relatively sudden, “all at once” processes of chromosomal rearrangement, multiplication, and/or reduction that we described above. However, such

ON EVOLUTION

sudden processes (or *saltations*) are regarded as occurring only at the level of the biological *individual* and *not* simultaneously on a *taxon-wide* basis. Richard Goldschmidt gave the colorful name “hopeful monster” to the unusual biological individual that is produced by such an individualistic saltation – an individual who is presumed both to survive and to found a new taxon.⁴⁴⁹

Strong supporters of individualistic saltationism have included not only Richard Goldschmidt, but also Otto Schindewolf and Leo Berg. John A. Davison is a contemporary supporter of individualistic saltationism, although Davison is also aware of the strong parallels between individual biological development and evolutionary macrodevelopment.⁴⁵⁰ Finally, as we saw earlier, even the “maverick” neo-Darwinist paleontologist Stephen Jay Gould has proposed individualistic saltationism as an *occasional* evolutionary mechanism.

Yet, in spite of the fact that, intuitively, instances of *individual* saltation would seem to be far more probable than instances of *taxon-wide* saltation, there are two serious problems with individualistic saltationism as a theory of evolution:

The *first* problem has long been pointed out by orthodox, gradualistic neo-Darwinists, and that is the problem of how the “hopeful monster” could hope to reproduce: If we start with a male “hopeful monster”, where do we get a female “hopeful monstress”? If, on the other hand (as is far more probable), we start with a female “hopeful monstress”, where do we get a male “hopeful monster”? It does no good to suggest that the “hopeful monster” might mate in the ordinary sexual manner with a normal “un-monster”, because the concept of sexual reproductive isolation is inseparable from the concept of true typological speciation for those species that sexually reproduce. As the prominent neo-Darwinian biologist Ernst Mayr has written:

The occurrence of genetic monstrosities by mutation . . . is well substantiated, but they are such evident freaks that these monsters can be designated only as “hopeless”. . . The finding of a suitable mate for the “hopeless monster” and the establishment of reproductive isolation from the normal members of the parental population seem to me insurmountable difficulties.⁴⁵¹

The *second* serious problem with the theory of individualistic saltationism is that, like the theory of neo-Darwinism, it presumes that new taxa “split off” asymmetrically from old taxa. But, as we have seen, such asymmetrical “splitting off” is inconsistent with the *monophyletic* biological taxonomy that we actually find in nature.

Having eliminated the impossible, whatever remains, however improbable, must be the truth (per Sir Arthur Conan Doyle's famous fictional creation, Sherlock Holmes!). And what remains is the theory of *macrodevelopment*, according to which a nonlinear *symmetrical* taxon-wide split creates two more-specific taxa from one more-generic taxon, which then ceases to independently exist. This taxon-wide split is accompanied, at the genetic level, by simultaneous taxon-wide chromosomal rearrangements, multiplications, and/or reductions, with ordinary sexual reproduction being re-established only subsequent to the taxon-splitting event.

We have proposed, above, the *taxon-wide semi-meiotic twins hypothesis*, as modified to account for possible *tetraploidy*, as one possible theory of how microscopic evolutionary genetic processes are related to macroscopic macrodevelopmental processes. (Other scenarios involving symmetrical taxon-wide splitting *by geographical region* are also possible, even though the corresponding evolutionary genetic processes are at present unknown.)

Additionally, the fact that *ploidy change* plays a significant role in the development of the biological individual, as well as in the macrodevelopment of the biosphere as-a-whole, is further strong evidence in favor of the macrodevelopmental theory of evolution.

Once again, therefore, macrodevelopment fits the evidence “like a glove”, and the eighth *fact of evolution*, like those before it, must likewise be regarded as strong evidence *in favor of* the theory of macrodevelopment.

We will now discuss the ninth and tenth *facts of evolution* much more briefly than the previous eight facts:

9. *Metamorphosis (and Parallel Evolution)*

The ninth *fact of evolution*, the fact of *metamorphosis*, refers to phenomena such as the transformation of a caterpillar into a butterfly or a tadpole into a frog. The differences between the pre- and post- metamorphosis organisms are not merely matters of shape, but of profound physiological differences.

The problem this poses for neo-Darwinism is summarized by Gordon Rattray Taylor in his book *The Great Evolution Mystery*:

Can there really be an evolutionary advantage in constructing one sort of organism and then throwing it away and starting again?⁴⁵²

On the other hand, the fact of metamorphosis is a point *in favor of* the theory of macrodevelopment because it shows that the genome of a single individual organism can contain enough information to construct (or help to construct)

ON EVOLUTION

at least two complete, very different body plans. So, why not more body plans? Again, Taylor:

There is an evident parallel between the transformation of tadpole to frog and the transformation of fish to amphibian [or, more-accurately, the transformation of a fish-like “ancestor” taxon into the “descendent” amphibian taxon and the “descendent” fish taxon]. . . . Is it possible that the fish carries or carried a battery of genes specifying ‘amphibian’ in a suppressed state and that these were suddenly activated? And similarly for other major evolutionary advances? If so, a great many puzzling facts suddenly fall into place.

It becomes easy to understand why twelve mammalian lines began to exhibit similar characteristics. All were carrying the same, or similar, sets of masked genes which began to be activated about the same time, perhaps because they were triggered by the same environmental circumstances. All instances of *parallel evolution* become understandable.

We have seen that molelike creatures, almost indistinguishable anatomically, developed independently in Asia and in South America. Is it not easier to believe that they did so by the unmasking, in similar situations, of similar genes than to suppose that the same group of mutations occurred twice, in different places, by pure chance? And when we are asked to believe that it occurred four times, as with the anteaters, credulity fails.

Again, the concept [of gene masking and unmasking] enables us to understand why so few intermediate forms are found. If the transformation occurred very rapidly, not necessarily in a single generation but at least rapidly on the evolutionary scale, the chance of transitional forms encountering the geological conditions necessary for preservation would be enormously reduced.

When the mammals decided to return to a marine existence in the form of dolphins and whales, the fact that they developed flippers very like those of ichthyosaurus, which existed in the Mesozoic [era] long before, is explicable as a new unmasking of the genes which had in the interim been suppressed. . .

Such cases must mean one of two things, either fatal to the concept of a slow accumulation of variations. Either the same mutations occur repeatedly (in which case they can hardly be due to chance), or the genes are there all the time, but are unmasked in appropriate circumstances.⁴⁵³

Taylor’s theory of *masking* and *unmasking of genes* can be brought into alignment with the fact of chromosomal rearrangement, multiplication, and/or reduction during true typological speciation (which we demonstrated in our discussion of the eighth *fact of evolution* above) by noting that all such chromosomal rearrangements, multiplications, and/or reductions are inevitably associated with changes in *gene expression*, rather than changes in *gene content*: Chromosomal *rearrangements* would be expected to change the

holistic pattern of histones and methylation that epigenetically regulate gene expression (leaving the actual DNA genes themselves unchanged), while changes in *ploidy* (i.e., chromosomal *multiplications* or *reductions*) have also been shown to regulate gene expression (while leaving actual gene content unchanged) by processes that are not entirely understood:

Galitski, Saldanha, Styles, Lander, and Fink, in their 1999 article in the journal *Science* entitled “Ploidy Regulation of Gene Expression” suggest several ways in which this ploidy-related regulation of gene expression may occur, including: sensing gene dosage, sensing total DNA content, transient pairing of homologous chromosomes (which “has been implicated in transvection, dominant position-effect variegation, and gene silencing, all of which involve alterations in gene expression”), and, finally, changes in the import and nuclear concentration of regulatory proteins, due to increased (or decreased) nuclear size and correspondingly decreased (or increased) nuclear surface/volume ratio.⁴⁵⁴

In any case, we must conclude that this ninth *fact of evolution*, namely, the fact of *metamorphosis* (together with *parallel evolution*), is again a strong point *against* neo-Darwinism and *in favor* of macrodevelopment.

10. The “Possible Fact” of Pre-Adaptation

Our final *fact of evolution*, fact number 10, is the “possible fact” of true *pre-adaptation*, which we define to be the appearance of a biological feature during the course of evolution *before* it was actually needed, where that feature has no plausible function *contemporaneous* with its appearance. As Gordon Rattray Taylor remarks: “If this really happens, it completely explodes the theory of natural selection and we need no further evidence to undermine it. What we would need is a new theory.”⁴⁵⁵ For this reason neo-Darwinists are at pains to deny that pre-adaptation in this sense ever occurs. What really occurs, they say, is that (in Taylor’s words) “a feature evolved for one purpose turns out to be useful for another”. But if we use the term “pre-adaptation” in *that* sense, as Taylor points out, “you end up by including everything: all adaptation is [then] pre-adaptation, since a feature can’t be selected until it is there”.

By contrast, evidence for possible *true* pre-adaptations include (again, in the words of Gordon Rattray Taylor):

- “the change in the fins of fishes, from a form supported by rays to one stiffened by a system of bones resembling those later found in the limbs of animals”. (Neo-Darwinists explain this

ON EVOLUTION

away by saying that fish became trapped in rock pools and then evolved so as to be able to walk back to the ocean.)

- “the appearance of feathers on the [non-flying] archaeopteryx, seemingly fully developed”. (Neo-Darwinists explain this away by saying that feathers originally evolved for warmth, not flight.)⁴⁵⁶

Taylor continues:

But I would like to tell you here of a much more clear-cut instance of ‘pre-adaptation’ which is extremely difficult to explain away.

There are a number of species of frogs which have discovered how to climb trees . . . One of the greatest experts of the biology of the amphibians who ever lived was G. Kingsley Noble, the explorer. He died in 1940. With his colleague M.E. Jaekle he studied these frogs in the late ‘twenties. On close examination, they noticed that the structure of their feet was quite unusual; the fingers were longer and there was an extra segment of cartilage. Under the microscope, differences in cell shape and arrangement, the distribution of skin glands, and the arrangement of connective fibers were found. The cartilage pad gave the frogs a better grip on the tree – a sort of built-in climber’s boot. A classical piece of adaptation, you might say, for ground-dwelling frogs do not possess these features.

But where the story becomes puzzling is that there are also a few lines of ground-dwelling frogs which never climb trees which do also have these adaptations. Noble and Jaekle were quite clear in their minds that these were not frogs which had recently abandoned tree-climbing. They seemed more like frogs which were getting ready to be climbers. ‘The conclusion seems obvious that the tree-climbing apparatus developed before the frogs began to climb trees,’ they commented. In fact they went further and said: ‘A detailed analysis of the many “marvelous adaptations” in the amphibians will reveal, we believe, that *in most cases* the modification arose before the function.’ (The italics are mine, for the statement would raise hackles on most biologists.) As one of them has said, ‘I personally doubt the truth of the statement as expressed. But when I reflect that G. Kingsley Noble was one of the greatest experts on the biology of the amphibians who ever lived, I do pause.’⁴⁵⁷

Again, Taylor:

To say, as [neo-Darwinist] Douglas Futuyama does (he works at the State University of New York at Stony Brook), that the Australian rhea was “pre-adapted” to slaughter sheep, when they were introduced into Australia, because it had a slashing great beak, is like saying that the human hand is pre-adapted to hold knives and forks. It is pathetic to trot out instances of this kind and then imagine that the real problems I have described have been satisfactorily dealt with.⁴⁵⁸

If *true* pre-adaptation *did* in fact occur during the history of evolution, then neo-Darwinism is powerless to explain it, since (according to neo-Darwinism)

evolution is a *linear* process in which small, minute changes in genotypes must *first* arise at the microscopic level by pure chance, with the resulting macroscopic phenotypes being *afterwards* “naturally selected” in a quasi-deterministic fashion for *current* survival value only: Such a neo-Darwinian process would make impossible (or, at least extremely unlikely) the appearance of *any* fully-formed macroscopic phenotype having only *future* usefulness in the “struggle for survival”.

By contrast, instances of *true* pre-adaptation in evolutionary history would present no problem for the theory of macrodevelopment, since that theory regards the evolution of the biosphere (like the development of the biological individual) to be a tychistic *nonlinear* process, and tychistic nonlinear processes commonly are characterized by both external *and* internal conditional equifinality, such that the “decisions” and “purposes” associated with *earlier* events and features of the system often make sense only in the light of *later* events and features of that same nonlinear system. (For example, the emergence of arms and legs in the individual human embryo is obviously a true “pre-adaptation” within individual development, since such arms and legs are evidently of little or no use to the embryo itself within its watery, confined environment.)

Another way of saying this is that nonlinear tychistic systems (such as the individual biological embryo and the biosphere) are characterized not only by *spatial* holism, but by *temporal* holism as well.

For all of these reasons, instances of *true* evolutionary pre-adaptation, *if* in fact they could be conclusively proved to occur, would constitute strong evidence *against* the theory of neo-Darwinism and *in favor of* the theory of macrodevelopment.

Summary of the Evolutionary Evidence

Here ends our discussion of the ten *facts of evolution*. Overall, how did the dominant evolutionary theory of *neo-Darwinism* (“Goliath”) fare against Robert F. DeHaan’s upstart theory of *macrodevelopment* (“David”)? The answer can be simply stated:

The evidence *for* Darwin’s theory of evolution and its subsequent Mendelian population-genetics enhancement (i.e., neo-Darwinism) is practically *nil*, while the evidence *against* Darwinism and neo-Darwinism is *overwhelming*: Contrary to the central claim of Darwin and the neo-Darwinists, true typological species and higher biological taxa were *not* produced and sustained by the very same sexual, Mendelian, and point-mutational processes that produce and sustain sub-species varieties today. While Darwin deserves enormous credit for proving the *fact* of evolution in his great work *The Origin of the Species*, it is long past time for it to be admitted that Darwin’s *theory* of evolution is an utter failure.

By contrast, Robert F. DeHaan’s theory of macrodevelopment is strongly supported by the empirical, scientific evidence of evolution: If the theory of macrodevelopment is *not* true, then some tychistic *nonlinear* theory similar to it *is* true. (Simplistic *linear*, reductionistic theories, like orthodox neo-Darwinism, are just no longer credible in explaining biological phenomena in the 21st century.)

Given the overwhelming nature of the empirical evidence *against* neo-Darwinism, why has neo-Darwinism continued to completely dominate both scientific and popular thinking about biological evolution, over thirty years after its 19th century, linear “companion theories” in geology and astronomy (i.e., Lyell’s uniformitarianism and Hoyle’s steady-state theory) finally “bit the dust” under the weight of contrary empirical evidence? In other words, what accounts for the continued strong attraction of neo-Darwinism, not only for scientists, but also for the legal profession, the media, and most other members of the intellectual elite, in spite of the overwhelming empirical evidence against the theory? Something more than mere nostalgia for “that ol’ time science” is clearly going on here.

Even Thomas Kuhn’s famous observations on the resistance and inflexibility of “normal science” in the face of many “anomalies” seems inadequate to explain this enormous staying-power of neo-Darwinism: After all, for neo-Darwinism, *virtually all* of the empirical evolutionary evidence has *always* consisted of “anomalies” that could not be explained by the theory, but rather had to be “explained away”!⁴⁵⁹

Many years ago, Ludwig von Bertalanffy hinted at both this problem and its solution when he said, concerning neo-Darwinism:

I think the fact that a theory so vague, so insufficiently verifiable . . . has become dogma can only be explained on sociological grounds.⁴⁶⁰

More recently, David Berlinski hinted at something similar when he wrote:

The defense of Darwin's theory by [orthodox neo-Darwinian] writers like [Daniel] Dennett or [Richard] Dawkins is at least in part a calculated *political* act – a statement about who is to control the ideologies of the democratic state.⁴⁶¹

In the following chapter, concerning the teleological implications of the various theories of biological evolution, we will contend that neo-Darwinism is perceived by most of the Anglo-American intellectual elites as being *the* most critical underpinning of that secular teleological worldview (deriving originally from the Enlightenment) whose “ultimate concern” is the putatively *radically autonomous human individual*, rather than any “so-called” transcendent God. Furthermore, the maintenance of that secular worldview is regarded by these elites to be so important, politically, that the overwhelming scientific evidence *against* the theory of neo-Darwinism *must* be either “explained away”, ignored, or (if necessary) suppressed.

Teleological Implications

The contrast between the teleological implications of the theory of neo-Darwinism, on the one hand, and the teleological implications of the theory of macrodevelopment, on the other, could not be greater:

The theory of neo-Darwinism (at least, as popularly presented to the public) presents the biosphere as being *microscopically* stochastic (because of random point-mutations), while also being *macroscopically* linear, mechanistic, and quasi-deterministic (because of the “iron law” of “natural selection”). As we pointed out earlier, neo-Darwinism is, in this respect, somewhat similar to quantum theory, which constrains *sub-microscopic* quantum randomness within the *macroscopic* linear, deterministic Schrodinger wave-function.

Because of this, *the biosphere has no real teleology*, according to neo-Darwinism. Instead, the biosphere is an empty, meaningless, purposeless *teleological desert*, in which the will of the *radically autonomous individual human being* shines like a beacon into utter darkness. (In the post-modern version of contemporary thought, this *teleological desert* even includes and overwhelms the individual human being, since neo-Darwinism provides no convincing analogical scientific reason why human beings should be exceptionally excluded from the utter emptiness of this teleological desert.)

That is why the National Association of Biology Teachers, in its “Statement on Teaching Evolution”, confidently declares that “natural selection” (by which they mean *evolution*) “has no specific direction or goal, including survival of a species.”⁴⁶² That is also why Miller and Levine, in their popular textbook *Biology*, declare with equal certainty that “. . . evolution works without either plan or purpose.”⁴⁶³

By contrast, the theory of macrodevelopment presents the biosphere as being a highly complex hierarchy of tychistic *nonlinear* systems, characterized at every level by both external *and* internal conditional equifinality.

Analogically, therefore, teleological meaning and purpose permeate the biosphere at all of its hierarchical levels, from the smallest living cell all the way up to the level of the biosphere as a whole. In my earlier book *WORLDVIEWS*, I named this teleological state of affairs *group subjectivity*, and I identified it as one of the two pillars of teleological (e.g., ethical, aesthetic, religious) truth, the other pillar being *theism*. (Note, however, that the theory of macrodevelopment does not *directly* imply theistic “design”, since all of the hierarchical “group subjects” within the biosphere may *also* be said to have *proximately* and *immanently* arisen via highly-complex far-from-equilibrium processes of “self-organization”, corresponding to countless numbers of “decisions” at all hierarchical levels of the biosphere.)

ON EVOLUTION

Of particular interest in this context are the teleological views of Stephen Jay Gould, who is foremost among the “heretical” neo-Darwinist paleontologists whom orthodox neo-Darwinians accuse of being “accidental creationists”. Gould, unlike orthodox neo-Darwinians such as Richard Dawkins, Daniel Dennett, and John Maynard Smith, is highly aware of the nonlinear nature of biological processes, as is shown in the following passage from his writings:

In terms of building materials, a new entity may contain nothing beyond its constituent parts, each one of fully known composition and operation. But if, in forming the new entity, these constituent parts interact in a “nonlinear” fashion – that is, if the combined action of any two parts in the new entity yields something other than the sum of the effect of part one acting alone plus the effect of part two acting alone – then the new entity exhibits “emergent” properties that cannot be explained by the simple summation of the parts in question. Any new entity that has emergent properties – and I can’t imagine anything very complex without such features – cannot, in principle, be explained by (reduced to) the structure and function of its building blocks.

Please note that this definition of “emergence” includes no statement about the mystical, the ineffable, the unknowable, the spiritual, or the like – although the confusion of such a humdrum concept as nonlinearity with this familiar hit parade has long acted as the chief impediment to scientific understanding and acceptance of such a straightforward and commonsensical phenomenon. When I argue that the behavior of a particular mammal can’t be explained by its genes, or even as the simple sum of its genes plus its environment of upbringing, I am not saying that behavior can’t be approached or understood scientifically. I am merely pointing out that any full understanding must consider the organism at its own level, as a product of massively nonlinear interaction among genes and environments.⁴⁶⁴

Nevertheless, because the vast majority of scientific work on nonlinear physical systems (excepting, perhaps, general relativity) has hitherto concentrated on *chaotic* systems rather than *tychistic* systems (which is why I had to create/adapt the name “tychistic” for the latter), Gould goes on to regard the biosphere to be essentially a *chaotic* system! This is reflected, for example, in Gould’s famous concept of the *spandrel*, which is (in effect) a phenotype that arises out of a moment (or moments) of objectively real *macroscopic* chance and which is currently non-adaptive, but which may prove to be useful later on.⁴⁶⁵ It is also especially reflected in Gould’s frequent insistence that biological evolution is a “random walk” that is not characterized by “progress” in *any* sense of the word, including even “progress” in the direction of increasing complexity (the fossil record, the phenomenon of repeated genome doubling throughout evolutionary history, and the emergence of man to the contrary):

There is no progress in evolution. The fact of evolutionary change through time doesn't represent progress as we know it. Progress is not inevitable. . . We are not marching toward some greater thing.⁴⁶⁶

These views enable Gould to reconcile his *scientific* knowledge that the biosphere is, in fact, a complex multi-layered nonlinear physical system with the analogical *teleological* result which secular society expects of him, namely, that the biosphere is truly purposeless and meaningless – indeed, is *even more* purposeless and meaningless than the orthodox neo-Darwinians say it is, since for Gould the pervasive randomness and chaos is not only microscopic, but also occurs objectively at the *macroscopic* level as well. (What Gould *fails* to acknowledge, of course, is that these instances of *macroscopic* randomness occur within a tychistic context of external *and* internal conditional equifinality, and thus they have teleological analogs to those countless meaningful and purposeful *decisions* that are being made all the time by the multi-leveled “group subjects” who comprise the biosphere.)

Man's Place in the Biosphere

The significant differences between the teleological implications of neo-Darwinism and macrodevelopment, respectively, are also evident in how they view man's place within the biosphere.

For the neo-Darwinist, man is of no more teleological importance or significance than any other species. As we saw in our earlier chapter on **Nonlinear Complex Physical Systems**, neo-Darwinists revel in the fact that the human genome has only about twice the number of genes as a fruit fly or a nematode worm: For them this proves that man is (at most) twice as teleologically important as fly or a worm. Acknowledging this “fact” they regard to be an act of appropriate humility. In this context, the neo-Darwinist paleontologist George Gaylord Simpson, in his book *The Meaning of Evolution*, made the following famous statement, which is frequently cited by neo-Darwinists: “Man is the result of a purposeless and natural process that did not have him in mind.”⁴⁶⁷

By contrast, the teleological analog to the theory of macrodevelopment strongly suggests that the place of man within the biosphere may very well be of extreme teleological importance: For if the evolution of the biosphere is truly analogous to the development of the individual embryo, and if true typological speciation no longer occurs today (with the exception of small-scale polyploidal speciation among plants), and if Robert Broom and John A. Davison are correct in asserting that not a single new genus has appeared in the last two million years and that the last genus to appear was *Homo* and the last species to appear was *Homo sapiens*,⁴⁶⁸ then it may very well be the case

ON EVOLUTION

that the emergence of mankind and human society is truly the *goal* towards which the macrodevelopment of the biosphere has been aiming all along (just as the fully-formed biological individual is the evident *goal* towards which the development of the embryo aims). If this is the case, then we may say (at least) that the emergence of mankind is of great teleological importance to that “group subject” which is the teleological analog of the biosphere as-a-whole.

Seen from this point-of-view, the neo-Darwinists’ insistence that, teleologically, man is little more important than a fly or a worm, looks not like humility, but on the contrary like an evasion of responsibility. And please note that we can confidently say this *even without any reference to theism whatsoever* (since even *pantheism* requires a reference to that “group subject” which is the teleological analog of the physical *universe-as-a-whole*, rather than merely to the “group subject” of the biosphere).

Atheism, Theism, and Theodicy

Yet we cannot, from this point on in our discussion of evolutionary teleology, continue to ignore issues of theism versus atheism with respect to the biosphere, if for no other reason than the fact that most (though not all) neo-Darwinists regard atheism to be a central tenet of any proper consideration of the biosphere from a teleological point-of-view, and they frequently insinuate this opinion even within their putatively purely scientific writings. A few examples of this, among many that could be cited, are as follows:

- Richard Dawkins, writing in *The Blind Watchmaker*, a popular book promoting neo-Darwinism: “Darwin made it possible to be an intellectually fulfilled atheist.”⁴⁶⁹
- David Hull, writing in a hostile review of Johnson’s *Darwin on Trial* that was published in the prestigious scientific journal *Nature*:

What kind of God can one infer from the sort of phenomena epitomized by the species of Darwin’s Galapagos Islands? The evolutionary process is rife with happenstance, contingency, incredible waste, death, pain and horror. . . The God of the Galapagos is careless, wasteful, indifferent, almost diabolical. He is certainly not the sort of God to whom anyone would be inclined to pray.⁴⁷⁰

- D.J. Futuyma, writing in a popular neo-Darwinist textbook on evolution, *Evolutionary Biology*:

By coupling undirected, purposeless variation to the blind, uncaring process of natural selection, Darwin made

theological or spiritual explanations of the life processes superfluous. Together with Marx's materialistic theory of history and Freud's attribution of human behavior to influences over which we have little control, Darwin's theory of evolution was a crucial plank in the platform of mechanism and materialism – of much of science, in short – that has since been the stage of most Western thought.⁴⁷¹

- The National Association of Biology Teachers, writing in the 1995 version of the “Statement on Teaching Evolution” (The italicized words *unsupervised* and *impersonal* in the following quotation were reluctantly deleted from subsequent versions of this statement, since those words made the quotation too *obviously* atheistic relative to the Association's pretence of being neutral with respect to religion):

The diversity of life on earth is the outcome of evolution: an *unsupervised, impersonal*, unpredictable, and natural process of temporal descent with genetic modification that is affected by natural selection, chance, historical contingencies, and changing environments. [*italics mine*]

- The prominent “heretical” neo-Darwinian paleontologist Steven Jay Gould:

Before Darwin we thought that a benevolent God had created us. . . No intervening spirit watches lovingly over the affairs of nature (though Newton's clock-winding god might have set up the machinery at the beginning of time and then let it run). No vital forces propel evolutionary change. And whatever we think of God, his existence is not manifest in the products of nature.

What alternative does Gould propose to taking God as our “ultimate concern” (Paul Tillich's phrase)? Naturally, like most other neo-Darwinists, he accepts the Enlightenment idea that our proper “ultimate concern” is our own *radically autonomous individual human selves*. Writing in his famous book *Wonderful Life*, Gould says:

We are the offspring of history, and must establish our own paths in this most diverse and interesting of conceivable universes – one indifferent to our suffering, and therefore offering us maximum freedom to thrive, or to fail, in our own chosen way.⁴⁷²

One of the reasons that most neo-Darwinists are absolutely sure that a good, transcendent God was *not* involved with the creation and evolution of the biosphere is suggested by David Hull in his comment above concerning the “happenstance, contingency, incredible waste, death, pain and horror” that can be found in nature. In this context, neo-Darwinists continually point out the many “imperfections” in nature, such as the purportedly defective design of the panda's pseudo-thumb, or the inverted way in which the retina attaches

ON EVOLUTION

to the eye in vertebrates. Creationists have sometimes countered these arguments by saying that these designs in nature aren't so bad after all.

But the real answer to neo-Darwinist arguments along this line is to note that theists, while certainly holding that "in the beginning, God created the heavens and the earth", have also in general *never* claimed that the created universe is *perfect*. For example, according to Christianity, the created universe is, in fact radically *imperfect*, i.e., "fallen": While neo-Darwinist David Hull says that the god of nature is "almost diabolical", Christians go all the way and explicitly identify Satan as the proximate "ruler of this world"!

Furthermore, as we noted in the teleological discussion at the end of our previous chapter on **Nonlinear Complex Physical Systems**, there is the overwhelming fact that *death*, inherently and intimately counterbalancing biological reproduction at all levels, is an *absolutely essential* feature of the biosphere: Compared with this "defect" of the *pervasiveness of death*, possible design problems with the panda's thumb seem like decidedly small potatoes!

All of this does, of course, raise the problem of *theodicy* ("If God is both all-good and all-powerful, then why is the universe created by Him in such a wicked, sorry, and imperfect state, and why is death so pervasive in this world?", etc.). Theologians have wrestled with, and given answers to, this question for many centuries: The fact that most neo-Darwinists apparently regard the problem of theodicy to be a simple "showstopper" for theism doesn't say very much for the philosophical depth of their atheism, and this immediately renders suspect their oft-implied judgment that God's non-existence is simply an evident scientific fact.

By contrast, what are the teleological implications of the theory of macrodevelopment with respect to theism and theodicy? Interestingly, macrodevelopment recognizes "imperfections" in nature that neo-Darwinism doesn't even acknowledge, such as evolutionary "overshoot", yet overall it is more compatible with theism than neo-Darwinism, if for no other reason than the simple fact that it views the biosphere as being *teleologically rich*, while neo-Darwinism instead regards the biosphere to be *teleologically impoverished*.

In any case, the teleological analog to macrodevelopment (while not *directly* implying theism) *does* reveal human individuals to be embedded within a biosphere-as-group-subject that has purposes and goals on a grand scale across hundreds of millions of years, and this teleological fact *by itself* automatically throws into doubt the fundamental Enlightenment dogma of the supposed "radical autonomy of the human individual".

Nevertheless, theists should beware of *proximately* identifying these purposes and goals of the biosphere with the will of God, and they should beware of this precisely because of the biosphere's aforementioned "imperfections" (especially the intimate pervasiveness of death throughout the biosphere at all levels). In other words, to what extent the purposes and goals of the biosphere *proximately* correspond with the purposes and goals of God, and to what extent they correspond, say, to the purposes and goals of Satan is a very interesting theological question. (Of course, theists also attribute *all* purposes and goals, even Satan's, to the *ultimate* will of an all-good and all-powerful God, and this gets us back to the deep questions of theodicy.)

Theists should especially beware of theories of "theistic evolution", such as that of the famous Jesuit paleontologist Teilhard de Chardin, in which the evolution of the biosphere is regarded to be marching majestically and naturally towards some perfect teleological "Omega point". Teilhard defines this Omega point to be "a harmonized collectivity of consciousness, equivalent to a kind of superconsciousness", and he writes, in his famous book *The Phenomenon of Man*:

Is evolution a theory, a system, or a hypothesis? It is much more – it is a general postulate to which all theories, all hypotheses, all systems must henceforth bow and which they must satisfy in order to be thinkable and true. Evolution is a light which illuminates all facts, a trajectory which all lines of thought must follow – that is what evolution is.⁴⁷³

Phillip E. Johnson aptly summarizes Teilhard's Omega-point theory by saying: "[For Teilhard,] evolution is, in short, the God we must worship. It is taking us to heaven . . ." ⁴⁷⁴

The essential problem with Teilhard's views is that they imply the *proximate* identification of God's will with both the evolution of the biosphere and the evolution of the physical universe as-a-whole. Unfortunately (as we pointed out in the teleological section of our chapter on **General Relativistic Systems**) the possible teleological analogs to the physical universe as-a-whole are unremittingly dismal, since the universe is pervaded with death (like the earthly biosphere it contains) and furthermore seems destined to either expand forever into nothingness, expand and contract endlessly, or be dissolved into nearly-pure randomness because of a thermodynamic heat death. In short, the physical universe's possible teleological analogs do *not* suggest that the universe is moving naturally and inevitably to a perfect "Omega point"!

In contrast to Teilhard, therefore, most theists correctly realize that, ultimately, only a *transcendent* God, acting from beyond the confines of physical time and space, could both *create* the physical universe and give it a satisfactory teleological meaning and goal. Moreover this creation of the

ON EVOLUTION

physical universe by a transcendent God is a basic teleological postulate of most theism and does not depend in any way on scientific theories, which (after all) can only *directly* imply the teleological existence of *immanent* subjects and group subjects, *not* transcendent ones. (The atheistic belief that a teleological subject can *only* exist if it has a complete, direct analog within the physical universe is, of course, a philosophical assumption, not a scientific fact.)

Ethics and Morality

Turning away, now, from the teleological issues surrounding atheism vs. theism, we next inquire concerning the implications of the teleological analogs of neo-Darwinism and macrodevelopment with respect to *ethics* and *morality*. From what we have previously said, it is clear that neo-Darwinists generally believe that their theory (by virtue of its implied *teleological minimalism*) strongly supports the Enlightenment doctrine that ethics and morality are ultimately founded on *the will of the radically autonomous human individual*, acting either alone or in concert with other such human individuals. By contrast, the theory of macrodevelopment (by virtue of its hierarchical, tychistic nonlinearity) teleologically implies the existence of many levels of *group subjects* within the biosphere and within human society. The existence of these group subjects, in turn, *indirectly* suggests the existence of a transcendent God (to give this hierarchy of group subjects ultimate teleological coherence and meaning, and to act as the ultimate foundation of ethics, morality, and the natural law). The teleological analog to macrodevelopment therefore suggests that the human individual owes ethical and moral duties to both God and to the group subjects of which he is a part (including family, church, country, and even to the biosphere), rather than being ethically and morally free to simply please his own “radically autonomous” self.

Throughout my previous book, *WORLDVIEWS*, I argued *in favor of* group subjectivity and theism and *against* the Enlightenment doctrine of the radical autonomy of the human individual, so there is no point in repeating these arguments here. However, it does seem appropriate to here consider a few of the *specific* moral implications of neo-Darwinism, since they were pointed out by Darwin himself in his book *Descent of Man*, which he published after his more-famous *Origin of the Species*.

In *Descent of Man*, Darwin (like Hobbes, Locke, and Rousseau before him) rejects the idea of a God-given natural moral law. Instead, he sees morality and ethics as contingently evolving throughout history via the principles of

natural selection and survival of the fittest. He therefore regarded *Descent of Man* to be (in part, at least) a natural history of morality.⁴⁷⁵

For Darwin, those public policies and moral beliefs are good which promote the survival of the fittest humans via natural selection (aided where necessary by artificial selection, that is, *eugenics*), while those policies and beliefs which do not are evil. Darwin therefore saw no problem in taking his erroneous scientific theory of species/subspecies extinctions (i.e., that species/subspecies become extinct principally due to *intense competition* with other *closely-related* species/subspecies) and applying that theory of extinctions to the relationships both between the various human races (such as the Caucasian, Negro, Mongoloid) and between other human subgroups (such as the healthy vs. the sick, the intelligent vs. the unintelligent, and so on). Thus, Darwin writes in *Descent of Man*:

The civilized races of man [i.e., the Caucasian race] will almost certainly exterminate and replace throughout the world the savage races [i.e., the non-Caucasian races]. At the same time the anthropomorphous apes . . . will no doubt be exterminated. The break will then be rendered wider, for it will intervene between man in a more civilized state, as we may hope . . . the Caucasian, and some ape as low as baboon, instead of as at present between the Negro or Australian and the gorilla.⁴⁷⁶

Again, from Darwin's *Descent of Man*:

We civilized men . . . do our utmost to check the process of elimination; we build asylums for the imbecile, the maimed, and the sick; we institute poor laws; and our medical men exert their utmost skill to save the life of everyone to the last moment. . . Thus the weak members of civilized societies propagate their kind. No one who has attended to the breeding of domestic animals will doubt that this must be highly injurious to the race of man. It is surprising how soon a want of care, or care wrongly directed, leads to the degeneration of a domestic race; but excepting in the case of man himself, hardly anyone is so ignorant as to allow his worst animals to breed. . .

. . . Man, like every other animal, has no doubt advanced to his present high condition through a struggle for existence, and if he is to advance still higher he must remain subject to a severe struggle.⁴⁷⁷

Darwin was vague as to how forcefully this program of eugenics should be applied, saying only that "All do good service who aid towards this end."⁴⁷⁸

As Benjamin Wiker comments in his article "Darwin and the Descent of Morality":

Although many today would shudder at Darwin's racism, we must concede that Darwin's conclusions were correctly drawn from his evolutionary principles. If [neo-Darwinism] is true, and the races themselves are the result of the struggle to survive, then how could intellectual and moral qualities *not* be diversely acquired by different races?

ON EVOLUTION

As for the survival of the fittest, contemporary liberals have attempted to separate Darwin from Social Darwinism, but Darwin's own words advocating severe struggle show us quite clearly that he was the first Social Darwinist.⁴⁷⁹

Darwin was not alone in drawing racist and eugenic teleological conclusions from his theory of evolution: In fact, up until World War II, the eugenics movement was strong wherever belief in Darwinism was strong, as it was among the "progressive" elites. (Ultimately, of course, it was the practices and policies of the Nazis, who were strongly influenced by Ernst Haeckel's earlier unification of Darwinism with the German pagan "Volk" mythology, which finally discredited racism and eugenics, not any putative "advances" in Darwinian or neo-Darwinian scientific theory.) To take just one example out of many, George William Hunter's high-school biology textbook *A Civic Biology*, which was the textbook John Scopes used to teach Darwin's theory of evolution in Dayton, Tennessee in 1925, thus setting the stage for the famous Scopes "Monkey Trial", is also pervasively racist and eugenic. After describing the Caucasian race as "the highest type of all", Hunter goes on to cite the Jukes family as an example of why human eugenics should be aggressively practiced. As described by Benjamin Wiker, here is more of what Hunter had to say in *A Civic Biology*:

For support, Hunter trotted out the notoriously bad breeders, the Jukes family, the matriarch of whom had "a feeble-minded son from whom there have been to the present time 480 descendents", of which "33 were sexually immoral, 24 confirmed drunkards, 3 epileptics, and 143 feeble-minded".

The eugenic moral was clear. "Hundreds of families such as those [Jukes] described above exist today, spreading disease, immorality, and crime to all parts of the country. The cost to society of such families is very severe. Just as certain animals or plants become parasitic on other plants and animals, these families have become parasitic on society. They not only do harm to others by corrupting, stealing, or spreading disease, but they are actually protected and cared for by the state out of public money. Largely for them the poor house and the asylum exist. They take from society, but they give nothing in return. They are true parasites."

Hunter then declared that "If such people were lower animals, we would probably kill them off to prevent them from spreading. Humanity will not allow this, but we do have the remedy of separating the sexes in asylums or other places and in various ways preventing intermarriage and the possibilities of perpetuating such a low and degenerate race."

All this from the . . . book John Scopes used to teach biology, Hunter's *A Civic Biology*.⁴⁸⁰

It is well worth remembering this the next time you view *Inherit the Wind*, or read accounts of the Scopes trial that portray it as a simple conflict between

the supposed religious ignorance, intolerance, and bigotry of the creationists versus the supposed sweet, scientific light of reason of the Darwinists.

IDT, BWT, and SOT

Although we excluded the Intelligent Design Thesis (IDT for short) at the outset of our scientific discussion of evolution on the methodological grounds that “the design inference” is ultimately a *teleological* explanation for evolution, rather than a *scientific* explanation for evolution (since we previously defined *teleological* to mean “bracket out the object” and *scientific* to mean “bracket out the subject”, and any “designer”, whether immanent or transcendent, is clearly acting as a *subject* when he designs), this does *not* mean that the IDT is not a significant thesis with respect to the relationship of teleology (especially theism) to science (especially biology).

As prominent IDT advocate Stephen C. Meyer pointed out in his article “DNA and Other Designs”,⁴⁸¹ the older argument for the existence of God based on the design of the biosphere relied on analogies between biological organisms and artifacts designed by humans. But the English philosopher David Hume made a significant attack on these analogies by pointing out that significant *differences* also exist between biological organisms and human artifacts. (As we have seen in our earlier discussion, these differences principally arise because human artifacts are typically machine-like, near-equilibrium, and therefore “linear”, while living biological organisms always exist far-from-equilibrium and are tychistically nonlinear.) By contrast, the new arguments by IDT theorists for the intelligent design of the biosphere are based on *information theory*, which is generally regarded to be a serious, technical, “hard” science.

But as we noted earlier in this book, there are some serious problems in regarding concepts such as *measurement*, *signal*, and *information* to be purely scientific concepts. These problems can ultimately be traced to the fact that, for example, the concept of *measurement* is intimately connected with the concept of a *measurer*. (In other words, a measurement is meaningless unless you specify, at least as to *type* of subject, *who* did the measuring and under what conditions.) Similarly, a *signal* requires the specification of not one, but *two* subjects – the sender and the receiver – in order to be meaningful. (In other words, a signal is always a signal *from* some particular subject *to* some other particular subject, both of which must be specified in some way *as conscious subjects*, rather than as objects.) Finally, the concept of *information* requires the specification of at least *one*, and often *two* subjects: Information must be created, sent, received, stored, and (especially) *known* by some particular subject or subjects whose characteristics *as subject*

ON EVOLUTION

rather than as object must be specified, at least with respect to the *type* of subject. In other words, *information* is meaningful only with respect to a particular *class of subjects*, who must be specified. (For this reason, “ $2 + 2 = 4$ ” is *not* “information” with respect to my dog Ransom, and an advanced, highly-technical mathematical work on information-theory would not be “information” with respect to myself!) All three of these concepts (*measurement*, *signal*, and *information*), then, to one degree or another, violate the scientific methodological principle “bracket out the subject”.

Earlier in this book we saw the enormous problems that have resulted in quantum theory from the attempt to incorporate the concept of a *measurement* into the theory. And we also noted that, later in life, Einstein was particularly bothered by the existence of the concept of a *signal* within his Theory of Relativity. (These problems with *measurement* and *signal* also derive from the *irreversibility* of time which they imply, which contradicts the *reversibility* of time presumed by quantum mechanics and special relativity respectively.)

On the other hand, while concepts such as *information*, *measurement*, and *signal* are not, in a pure sense, scientific, they are not purely teleological either. That is why we put them into the separate category of *epistemological* concepts. *Epistemology* is the study of the *border* (or *interface*) between the subject and the object, and it raises such questions as “How do subjects know what they know?” and “Under what conditions may knowledge and information be said to be reliable?” While not strictly scientific, epistemology is clearly an important and valid area of scholarly study that can be approached mathematically via information theory.

This distinction which I am drawing between *epistemology* and *science* is admittedly not always clear, as is shown by the fact that we have had to distinguish between the universe as viewed by imperfect, immanent subjects and the universe as it would be viewed by a perfect, transcendent subject, in order to make certain *scientific* concepts clear. We have even slipped into using the term *information* (without quotation marks!) in some of our preceding *scientific* discussions. Nevertheless, the distinction between epistemology and science remains an important one, even though precisely where we “draw the line” between them is, to some extent, a matter of interpretation and semantics.

Stephen C. Meyer expresses the essence of the modern information formulation of the Intelligent Design Thesis (IDT) as follows:

The design argument from the information in DNA does not depend upon [the kind of analogical reasoning critiqued by David Hume,] since it does not depend upon claims of similarity. . . [T]he coding regions of DNA

have the very same property of “specified complexity” or “information content” that computer codes and linguistic texts do. Though DNA does not possess all the properties of natural languages or “semantic information” – i.e., information that is subjectively “meaningful” to human agents – it does have precisely those properties that jointly implicate an antecedent intelligence.

As William A. Dembski has shown in his recent book *The Design Inference* (1998), systems or sequences that have the joint properties of “high complexity and specification” invariably result from intelligent causes, not chance or physical-chemical necessity. Complex sequences are those that exhibit an irregular and improbable arrangement that defies expression by a simple rule or algorithm. A specification, on the other hand, is a match or correspondence between a physical system or sequence and a set of independent functional requirements or constraints. As it turns out, the base sequences in the coding regions of DNA are both highly complex and specified. The sequences of bases in DNA are highly irregular, non-repetitive, and improbable – therefore, complex. Moreover, the coding regions of DNA exhibit sequential arrangements of bases that are necessary (within certain fine tolerances) to produce functional proteins – that is, they are highly specified with respect to the independent requirements of protein function and protein synthesis. Thus, as nearly all molecular biologists now realize, the coding regions of DNA possess a high “information content” – where “information content” in a biological context means precisely “complexity and specificity”. . .

. . . Because we know intelligent agents can (and do) produce complex and functionally specified sequences of symbols and arrangements of matter (i.e., information content), intelligent agency qualifies as a sufficient causal explanation for the origin of this effect. Since, in addition, naturalistic scenarios have proven universally inadequate for explaining the origin of information content, mind or creative intelligence now stands as the best and only entity with the causal power to produce this feature of living systems.⁴⁸²

Let’s let William A. Dembski (whom Meyer cited in the above quotation) continue the argument for the Intelligent Design Thesis (IDT):

[T]his debate [is] over whether life exhibits nothing more than the outcome of fully naturalistic purposeless material processes [i.e., physical processes that are either microscopically stochastic and macroscopically deterministic, or alternatively are nonlinearly chaotic], or whether life [instead] exhibits the purposeful activity of an intelligent agent, usually called a designer, who in creating life has impressed on it the clear marks of intelligence. Phillip Johnson has dubbed the first view the Blind Watchmaker Thesis (BWT). We’ll call the second view the Intelligent Design Thesis (IDT). BWT and IDT are mutually exclusive and exhaust all possibilities. . . .

Although design theorists take the question *Which is correct, BWT or IDT?* as a perfectly legitimate question concerning facts of the natural world, it is not treated as a legitimate question by the Darwinist

ON EVOLUTION

establishment. According to the Darwinist establishment BWT poses a “scientific” question whereas IDT poses a “religious” question. Thus, as far as the Darwinist establishment is concerned, IDT is a non-starter. Yes, BWT and IDT taken together may be mutually exclusive and exhaustive, but BWT is the only viable scientific option. IDT must therefore be ruled out of court from the start. . . .

It is here that we come to the heart of the design theorists’ critique of Darwinism. Logically, BWT and IDT are real possibilities. What’s more, as mutually exclusive and exhaustive possibilities, one of these theses has to be correct. (I’m sorry, but at this level of discourse the law of the excluded middle definitely holds.) The Darwinist establishment has so defined science that BWT alone can constitute an appropriate scientific answer to the question *How did life originate and develop?* Nevertheless, when Stephen J. Gould, Michael Ruse, Richard Dawkins, George Gaylord Simpson, and their many disciples assert the truth of BWT, they purport that BWT is the conclusion of a scientific argument based on empirical evidence. But of course it is nothing of the sort. The empirical evidence is in fact weak. . . .

The view that science must be restricted solely to purposeless, naturalistic, material processes . . . has a name. It’s called *methodological naturalism*. So long as methodological naturalism sets the ground rules for how the game of science is played, IDT has no chance in Hades. . . .

Okay, since BWT is so poorly supported empirically and since the scientific community is telling us that IDT isn’t science, what’s wrong with a simple profession of ignorance? . . . [The problem with a simple profession of ignorance is that,] as philosophers of science Thomas Kuhn and Larry Laudan have pointed out, for scientific paradigms to shift, there has to be a new paradigm in place ready to be shifted into. . . If you’re going to reject a reigning paradigm, you have to have a new improved paradigm with which to replace it. BWT is the reigning paradigm. But what alternative is there to BWT? Logically, the only alternative is IDT. But IDT isn’t part of science. This is a case of Hobson’s choice. There’s no pleading ignorance and no shifting away because [for neo-Darwinists] BWT is the only game in town.⁴⁸³

Arguments of this kind by Stephen C. Meyer, William A. Dembski, and other intelligent-design theorists make an important contribution in helping us to define the proper relationship between the fields of teleology, epistemology, and science. Nevertheless, these arguments for the IDT can be critiqued on the following grounds:

On the positive side, IDT theorists are to be commended for pointing out that biologists’ frequent use of the term *information* in connection with DNA (e.g., in describing the DNA sequence as a *code*) introduces, if not teleology, at least epistemology, into their purportedly scientific discussions. In other words, if biologists are going to talk about DNA as containing *information*, they had better be prepared to say both *for whom* it is information and *from*

whom that information has come. Also positive are the great contributions made by the IDT theorists' detailed, often mathematical, studies of the nature of information and its relationship to the concept of *intelligent design*.

But, on the negative side, it must be observed that when the intelligent-design theorists present the Blind Watchmaker Thesis (BWT) and the Intelligent Design Thesis (IDT) as mutually exclusive and exhaustive possibilities, they are presenting a false dichotomy that ignores a thesis which has the potential to resolve the conflict between the BWT and the IDT, namely what I will call the Self-Organization Thesis (SOT):

Naturalistic scientific explanations of the biosphere imply that the teleological analog of the biosphere is purposeless and teleologically meaningless (i.e., the BWT) *only if* the biosphere is regarded *either* to be the result of microscopically stochastic and macroscopically deterministic processes (as in Richard Dawkins' orthodox neo-Darwinism) *or* to be the result of *chaotic* nonlinear processes (as in Stephen Jay Gould's heretical neo-Darwinism). If, on the other hand, the biosphere is the result of *tychistic* nonlinear processes (that is, nonlinear processes in which order dominates over disorder, thus creating a hierarchy of entities that are characterized by both external *and* internal conditional equifinality at all hierarchical levels, up to and including the level of the biosphere as-a-whole), then the teleological analog to the biosphere is seen to be an inclusive hierarchy of countless *group subjects* that make decisions, have goals & purposes, and so on. In such a case, we may regard the biosphere, from an *immanent* teleological point-of-view, to be the result of *self-organization*, where we take the term *self* quite seriously, rather than merely metaphorically. (This is not to say, of course, that a cell has the *same* level of consciousness as a human being, but it does have *some* level of consciousness.) It is this thesis that I am calling the Self-Organization Thesis (SOT).

Now, it is clear that the SOT, while continuing to be closely tied to the naturalistic and scientific, nevertheless implies that the biosphere is rich in teleological purpose and meaning at all levels, quite contrary to the BWT. It is also clear that, if the SOT is true, then so-called "primitive peoples" were not so far wrong in believing in *animism*. We now intend to show that the SOT can bridge the seemingly-unbridgeable gap between the BWT and the IDT:

We begin by noting that the *legitimate* concerns of BWT theorists include:

- The desire to have a theory of evolution that is as empirically, scientifically verified as possible.

ON EVOLUTION

- The desire to preserve methodological naturalism in science (i.e., the desire to “bracket out the subject” as much as possible).
- In some cases, the desire to maintain a philosophy of *complete metaphysical naturalism*, which we define to be the belief that *only* the “bracket out the subject” statements of *science* can be true, *never* the “bracket out the object” statements of *teleology*. (Those who claim to be believers in complete metaphysical naturalism should, of course, remain entirely silent on issues of morality, ethics, law, aesthetics, and theology. The fact that they seldom do calls into serious question their true commitment to *complete* metaphysical naturalism.)

By contrast, the *illegitimate* concerns of BWT theorists include:

- The desire to use science to conclusively prove that God doesn’t exist (or, at least, if He exists He is Deistic and therefore remote, uninvolved in the present universe, and irrelevant).
- The desire to use science to conclusively prove the secular Enlightenment doctrine that our ultimate concern should be the radical autonomy of the human individual.

(These two latter concerns of the BWT theorists are *illegitimate* because science, with its “bracket out the subject” methodology, has no means whatsoever of directly deciding such teleological subject-related questions.)

By abandoning the BWT and accepting the SOT instead, current BWT theorists can satisfy their *legitimate* concerns, though not their *illegitimate* ones: For example, since the SOT is associated with the evolutionary theory of *macrodevelopment*, which has overwhelming empirical support, while the BWT is associated with the evolutionary theory of *neo-Darwinism*, which has practically none, switching from the BWT to the SOT would give the BWT theorists the empirically solid scientific theory of evolution that they currently lack. In fact, the SOT (as expressed in the theory of macrodevelopment) may be viewed as being the new paradigm of evolution which will replace the old BWT (as expressed in the theory of neo-Darwinism). Notice also that acceptance of the SOT would only require that current BWT theorists accept the fact that the biosphere is composed of many tychistic, complex structures that are characterized by both external *and* internal conditional equifinality: The SOT does *not* require the belief that these structures of external/internal conditional equifinality have real (as opposed to merely metaphorical) teleological analogs to decisions, goals, subjects, and so on. Therefore, acceptance of the SOT would allow former BWT theorists to preserve

methodological naturalism in science and even to remain *complete* metaphysical naturalists, if they so desire.

Notice, however, that the SOT does *not* give strong analogical support either for atheism or for the Enlightenment doctrine of the radical autonomy of the human individual, so BWT theorists would have to abandon these *illegitimate* concerns in order to accept the SOT: Their unwillingness to do so is undoubtedly one of the main reasons (in addition to habit, inertia, and the linear bias of Anglo-American science) that they continue to support the evolutionary theory of neo-Darwinism and continue to attack and persecute its opponents, despite the existence of overwhelming contrary, disconfirming, scientific, empirical evidence.

IDT theorists are in a better position with respect to the SOT than are the BWT theorists, since they do not have to abandon the IDT in order to accept the SOT: Instead, they just have to realize that the SOT is correct with respect to *immanent* scientific/teleological truth, while the IDT is correct with respect to *transcendent* scientific/teleological truth. This is so because the SOT relates *physically* to moments of chance that are *immanently* objective with respect to imperfect, immanent beings who can measure only out to a *finite* number of decimal places, and relates *teleologically* to the *decisions* (made by immanent subjects) that *analogically correspond* to those physical moments of chance. By contrast the IDT relates *physically* to God's *transcendently deterministic* view of the physical universe out to an *infinite* number of decimal places, and relates *teleologically* to God's corresponding omniscient, all-determining will and creative power, which "intelligently designs" the universe from beyond its immanent confines. (As we noted earlier, this distinction between an *immanent* point-of-view and a *transcendent* point-of-view is frequently of importance in scientific, philosophical, and theological discussions, for example, in the discussion of the problem of theodicy, or in the discussion of the problem of human "free-will" vs. divine "pre-destination".)

The *legitimate* concerns of IDT theorists include:

- The desire to reveal the overwhelming *lack* of scientific evidence for neo-Darwinism.
- The desire to confirm the "common sense" view of most human beings that the biosphere is teleologically meaningful and purposeful.
- The desire to account for the presence of complex *information* in DNA "code".
- The desire to affirm that the biosphere was created and designed by a transcendent, good God.

ON EVOLUTION

By contrast, the *illegitimate* concerns of IDT theorists include:

- The desire to eliminate methodological naturalism from science, so that teleological, subject-related “supernatural” causes could also be considered from *within* “hard” science.
- The explicit or implicit desire to have theism acknowledged as being *scientifically* true, since “science is the only universally valid form of knowledge within our culture”.⁴⁸⁴

(These latter two desires of the IDT theorists are *illegitimate* because their satisfaction would obliterate the very useful distinctions that can be made between scientific “bracket out the subject” truth and teleological “bracket out the object” truth: If teleological truth is not respected in our culture and is regarded as being “merely subjective”, then the solution is to re-discover and promote the *universal* subjective bases of teleological truth, namely *group subjectivity* and *theism*, rather than to try to “wedge” teleology into science.)

By supplementing the IDT with the SOT, current IDT theorists can satisfy their *legitimate* concerns, though not their *illegitimate* ones: For example, the SOT (as defined here) affirms the evolutionary theory of macrodevelopment, and rejects the evolutionary theory of neo-Darwinism as being completely contrary to the scientific, empirical evidence; the SOT is therefore consistent with the desire of IDT theorists to discredit neo-Darwinism. Also, the SOT views the physical biosphere as having rich teleological analogs; therefore the SOT confirms the “common-sense” view that the biosphere is teleologically meaningful and purposeful, just as IDT theorists desire. Furthermore, the SOT *immanently* accounts for the information in the DNA “code” as the product of holistic, tychistic, nonlinear processes which teleologically correspond to countless “decisions” being made by group subjects existing at all hierarchical levels of the biosphere; it is these group subjects which, from an *immanent* point-of-view, create, transmit, store, and read the information that exists not only in the linear DNA sequences, but holistically at all levels of the biosphere. (This immanent SOT explanation is, of course, *not* inconsistent with the IDT explanation that, from a *transcendent* point-of-view, God is the ultimate creator and source of the information in the biosphere.) Finally, the SOT does not *directly* prove that the biosphere was created and designed by a transcendent, good God. However, the SOT *does* present a biosphere that is so rich in group subjects and teleology that the affirmation of the existence of a transcendent, good God is likely to be soon seen as necessary in order to provide that biosphere with ultimate teleological coherence, meaning, and purpose.

However, note that the SOT does *not* satisfy the two *illegitimate* concerns of the IDT theorists: The SOT does *not* require that teleology be “wedged” into “hard” science, nor does it require that the existence of God be affirmed from *within* science itself. IDT theorists would therefore have to give up these two *illegitimate* goals in order to affirm the SOT as a supplement to the IDT. Whether or not they will ultimately do this is an open question, but so far IDT theorists have proved to be nearly as hostile to the SOT as the BWT theorists.

For the most part this hostility has been expressed in the form of the same casual, contemptuous brush-offs that the neo-Darwinian BWT theorists usually give to the SOT. For example, Phillip E. Johnson, in his book *Darwin on Trial*, devotes just a couple of paragraphs to citing and quoting from a 1990 article in *Science* that essentially condemned SOT models as an irrelevant playing around with computers, and at the end of *Darwin on Trial* Johnson presents an image of the SOT people manning a few high-tech lifeboats in a last, desperate (but ultimately futile) attempt to save naturalistic science.⁴⁸⁵ Michael Behe, in his book *Darwin's Black Box*, devotes a few pages to doing a brief “hatchet job” on the SOT, finally concluding that “complexity theory [i.e., the SOT] began as a mathematical concept to describe the behavior of some computer programs, and its proponents have not yet succeeded in connecting it to real life”.⁴⁸⁶

The most serious (though still weak) attempt that I have found on the part of an IDT theorist to actually refute (rather than simply dismiss) the SOT can be found in Stephen C. Meyer's previously-quoted article “DNA and Other Designs”. Meyer argues as follows:

Ironically, perhaps the most prominent early advocate of self-organization, Dean Kenyon, has now explicitly repudiated such theories as both incompatible with empirical findings and theoretically incoherent.

The empirical difficulties that attend self-organizational scenarios can be illustrated by examining a DNA molecule. . . . There are bonds, for example, between the sugar and the phosphate molecules that form the two twisting backbones of the DNA molecule. There are bonds fixing individual (nucleotide) bases to the sugar-phosphate backbones on each side of the molecule. Notice that there are no chemical bonds between the bases that run along the spine of the helix. Yet it is precisely along this axis of the molecule that the genetic instructions in DNA are encoded.

Further, just as magnetic letters can be combined and recombined in any way to form various sequences on a metal surface, so too can each of the four bases A, T, G, and C attach to any site on the DNA backbone with equal facility, making all sequences equally probable (or improbable). The same type of chemical bond occurs between the bases and the backbone regardless of which base attaches. All four bases are acceptable; none is preferred. In other words, differential bonding affinities do not account for the sequencing of the bases. Because these same facts hold for RNA

ON EVOLUTION

molecules, researchers who speculate that life began in an “RNA world” have also failed to solve the sequencing problem – i.e., the problem of explaining how information present in all functioning RNA molecules could have arisen in the first place.

For those who want to explain the origin of life as the result of self-organizing properties intrinsic to the material constituents of living systems, these rather elementary facts of molecular biology have devastating implications. The most logical place to look for self-organizing properties to explain the origin of genetic information is in the constituent parts of the molecules carrying that information. But biochemistry and molecular biology make clear that the forces of attraction between the constituents in DNA, RNA, and protein do not explain the sequence specificity of these large information-bearing biomolecules.

Significantly, information theorists insist that there is a good reason for this. If chemical affinities between the constituents in the DNA message text determined the arrangement of the text, such affinities would dramatically diminish the capacity of DNA to carry information. . . .

. . . Bonding affinities, to the extent they exist, mitigate against the maximization of information. They cannot, therefore, be used to explain the origin of information. . . .

The tendency to confuse the qualitative distinction between “order” and “information” has characterized self-organizational research efforts and calls into question the relevance of such work to the origin of life. Self-organizational theorists explain well what doesn’t need explaining. What needs explaining is not the origin of order . . . , but the origin of *information* – the highly improbable, aperiodic, and yet specified sequences that make biological function possible.

. . . Systems that are characterized by both specificity and complexity (what information theorists call “specified complexity”) have “information content”. Since such systems have the qualitative feature of aperiodicity or complexity, they are qualitatively distinguishable from systems characterized by simple periodic order. Thus, attempts to explain the origin of order have no relevance to discussions of the origin of information content.⁴⁸⁷

Meyer’s attack on the Self-Organizational Thesis (SOT) can be refuted as follows:

1. Vague attacks on the SOT as “incompatible with empirical findings and theoretically incoherent” amount to name-calling and are unworthy of refutation.
2. The fact that the forces of chemical bonding within the DNA molecule do not determine the order of the nucleotides along the DNA spine only means that the order of those nucleotides was specified (from a *scientific* point-of-view) by physical, holistic, nonlinear tychistic processes operating at an organizational level

higher than that of the DNA molecule itself. This fact, therefore, *in no way* refutes the SOT.

3. Meyer's accusation that SOT theorists are only studying "order" and not "information" is puzzling. It's true that, from a scientific perspective, SOT theorists are not *directly* studying "information", but that is only because they recognize that "information" is an *epistemological* concept and not a *scientific* concept. However, in addition to the presence of *order*, SOT theorists most definitely *do* recognize the equally important presence of significant *novelty* and microscopic & macroscopic *chance* within biological systems: That is why the SOT definition of *complexity* (whose epistemological analog is "information content") locates maximum complexity (and therefore maximum "information content") in the exact middle of what we have called "the physical spectrum", i.e., at the right edge of tychism and the left edge of chaos (rather than at the far right edge of stochastic randomness, as is done in the *algorithmic* definition of complexity).

Hopefully an increase in both the quantity and quality of the dialog between IDT and SOT theorists will help to clear up these kinds of misunderstandings in the future. One hopeful sign that this is beginning to happen is the cordial debate/dialog that occurred on November 13, 2001 at the University of New Mexico in Albuquerque NM between William Dembski (representing the IDT) and Stuart Kauffman (representing the SOT).⁴⁸⁸

To conclude, if you are an IDT theorist who continues to wish to regard the SOT as your mortal enemy, rather than as your friend, please consider carefully your answers to the following questions:

- From a *transcendent* point-of-view, God is the creator (i.e., the "sender") of the information stored in biological DNA. But who is the *receiver*? Is DNA just a "scratch pad" where God stores information he wants to remember later? Or is the *receiver* the biological individual specified by his DNA? But if this biological individual (whether human or nonhuman, at whatever hierarchical biological level) is a *receiver* of this information, then must he not also be regarded as an *immanent subject* (or "group subject") within the biosphere? And, then, don't we need the SOT to account for such *immanent subjects*?
- How do you deal with the problem of *theodicy*? If the biosphere was created by a perfect transcendent God, then why is it pervaded by death and many other lesser imperfections? Wouldn't acceptance of the SOT as complementary to the IDT

ON EVOLUTION

help to answer this question along the same lines as theologians have traditionally used to answer such questions as “How can there be both human free-will and divine pre-destination?” and “Why did God leave human beings free to decide for what is evil?”

For unless we embrace the Self Organization Thesis and the theory of macrodevelopment as the means to transcend this seemingly interminable strife between the creationist/IDT paradigm (“that ol’ time religion”) and the neo-Darwinist/BWT paradigm (“that ‘ol time science”), we will all be condemned to “inherit the wind”!

APPENDIX

On Proportionalism / Consequentialism

What is *proportionalism / consequentialism*? As used in this APPENDIX, proportionalism / consequentialism refers to all of those ethical theories which say that moral rules or laws, such as the ten commandments or the fundamental principles of natural law, are *guidelines* only: that is, they need not always be followed in every circumstance. Rather, according to proportionalism / consequentialism, in order to ultimately determine what is right or wrong in a particular situation, the ethical agent must, first, try to predict the probable *consequences* of the various courses of action open to him and then, second, evaluate the *proportionality* between good and bad in these various sets of consequences. The agent should then choose the *action* which will result in consequences containing the highest proportion of good to bad. (This *action* will *not* always be in accordance with traditional moral laws, such as the ten commandments or the natural law.) Sometimes such ethical theories are called *situation ethics*. Informal belief in this type of ethics is undoubtedly centuries old, but it has gained great currency over the past 30 years in the Western academic world, where it has been defended with detailed technical arguments.

Here is a hypothetical example often used to illustrate proportionalist / consequentialist ethics: Imagine that we are living in America in early Colonial days. A group of settlers is hiding in their cellar from a band of Indians. If the Indians discover the unarmed settlers, they will kill them all. A baby is among the settlers, in the arms of its mother. The baby begins to cry. If the Indians hear the baby, they will discover the settlers and kill them. Should the mother smother the baby to death to stop its crying? Believers in traditional ethics would say “no” because this would violate the fifth commandment (“Thou shalt not kill”) and would also violate the natural law. By contrast proportionalists and consequentialists would say that, since *only* the baby will die if it is smothered to death, whereas *all* the settlers will die if it is not killed, killing the baby would probably be the right thing to do.

With respect to the fifth commandment, proportionalist / consequentialist ethics is sometimes called *lifeboat ethics*, because the hypothetical examples used to justify breaking that commandment often involve a group of people in a lifeboat with resources so critically limited that (it is alleged) one of these people must be thrown overboard (or killed & eaten, etc.) so that all of the others may be saved.

What’s wrong with proportionalism / consequentialism, and what does it have to do with *science*? The *fundamental error* of proportionalism / consequentialism is its assumption that the moral agent can *accurately predict* (or at least can assign reliable statistical probabilities to) all of the consequences of his possible moral actions: Furthermore, it is assumed that

he can do this even within the high-pressure time frame of minimal reliable information in which most critical moral decisions must be made. Yet, from a purely *scientific* point-of-view, it can be said that the moral agent (or rather the physical body that *corresponds to* the moral agent in scientific discourse) is a far-from-equilibrium structure (i.e., a nonlinear tychistic system) interacting with other far-from-equilibrium structures in a highly-complex, radically nondeterministic way. By contrast, all of the hypothetical cases used to “prove” proportionalism / consequentialism are chock-full of *deterministic* assumptions. (The Indians will *definitely* kill all the settlers if they discover them, the baby *must* be smothered to death in order to quiet it, and so on) As the great Russian novelist Leo Tolstoy, author of *War and Peace*, has written:

Such devices, and the deductions from them, only prove that there are men who know that it is not well to lie, to steal, or kill but are still so unwilling that people should cease to do these things that they use all their mental powers to invent excuses for such conduct. . . .

“*Fais ce que dois, advienne que pourra*” — “Do what’s right, come what may” — is an expression of profound wisdom. We can each know indubitably what we ought to do, but what results will follow from our actions we none of us either do or can know. . .

[A]ll the horrors which fill the annals of history and of our own times came, and come, from this one thing: namely, that people will believe they really foresee speculative future results of actions.⁴⁸⁹

The Eastern religious tradition (especially as expressed in the *Bhagavad Gita* and practiced by Gandhi) is in complete agreement with Tolstoy that *nonattachment to results* is essential to right ethical action. By contrast proportionalists / consequentialists are *intensely* attached to the results (i.e., the *consequences*) of their actions.

Furthermore, the tradition of the Catholic Church agrees with Tolstoy and Gandhi on this point. As Pope John Paul II wrote in his famous encyclical *The Splendor of Truth (Veritatis Splendor)*:

The weighing of the goods and evils foreseeable as the consequence of an action is not an adequate method for determining whether the choice of that concrete kind of behavior is “according to its species,” or “in itself”, morally good or bad, licit or illicit. The foreseeable consequences are part of the circumstances of the act, which, while capable of lessening the gravity of an evil act, nonetheless cannot alter its moral species. (*Veritatis Splendor*, § 77)

Here, then, we have the unusual situation that a commonly held moral and ethical theory (proportionalism / consequentialism) can be refuted solely on *scientific* grounds, namely, the fact that the physical analogs to the moral agents and moral circumstances involved are complex, nonlinear,

nondeterministic physical systems, rather than *deterministic* physical systems.

It is important to note, too, that this fatal problem with proportionalism / consequentialism cannot be resolved by attempting to do a *statistical analysis* of the *probabilities* of various possible outcomes of a given moral choice, since statistical methods are generally only useful when dealing with stochastic/deterministic systems, and not when dealing with integrated, holistic, hierarchical nonlinear systems: That's because such hierarchical nonlinear systems are generally too *structurally complex* for their behavior to be adequately described and predicted by statistical methods. (Of course, statistical studies abound in the "soft" social sciences, but such studies are notoriously unreliable as predictors of the future behavior of social systems.)

Analogous problems exist with political promises such as "Elect me, and I will control world population", or "Elect me, and I will control the earth's climate", or even "Elect me, and I will control the national economy for your good": Only in a culture in which the universe is predominantly conceived of as being linear and deterministic, rather than nonlinear and tychistic/chaotic, could such political claims ever be taken seriously. (This fact has important implications for the teaching of science in a democratic society.)

Although many of the scholarly errors of proportionalism / consequentialism are associated with the political left and are of recent origin, there is one such error which is associated with the political right and is of ancient and traditional origin, and that is the *just-war theory*: For traditional just-war theory clearly justifies war under certain circumstances on grounds that are explicitly proportionalist / consequentialist. This constitutes a serious problem for traditional natural-law theory which we will have to deal with in the third and final book of this trilogy series, *HUMAN SOCIETY*.

On Miracles

How can a belief in miracles be justified in the face of the findings of modern science? First, we should recognize that the problem of justifying such essentially teleological/religious ideas as free-will and miracles was much more difficult in the 19th century. For then science was almost-exclusively Newtonian and deterministic in outlook: Confronted with a universe that was supposedly determined by rigid scientific laws, coupled with a particular set of initial conditions, it was hard to see where individual human persons might intervene in that universe with their free-will, let alone where God might find room to squeeze in a miracle or two!

Today, however, science regards chance to be an *irreducible* aspect of physical reality. This was first shown to be the case in the subatomic realm in the form of the *Heisenberg Uncertainty Principle*, which (as we saw in our chapter on **Quantum Mechanical Systems**) essentially states that both the position and momentum of an individual sub-atomic particle cannot be simultaneously observed: Either we can determine the position, but not the momentum, or we can determine the momentum, but not the position.⁴⁹⁰ Subsequently, *chaos theory* showed that an irreducible element of randomness exists in many *macroscopic* phenomena as well (to take a common example, in the temporal pattern of falling drops from a dripping faucet).

Particularly important in this context (as we saw) is Nobel Prize winner Ilya Prigogine's theory of the *far-from-equilibrium structure*, which is also characterized by *macroscopic* indeterminacy. As we noted earlier, the behavior of such a far-from-equilibrium structure follows a somewhat predictable pattern for a time; but then a *bifurcation point* is encountered, from which point one of two behavior patterns will emerge. *Which* of these behavior patterns emerges is a matter of *immanently objective chance*, from the point-of-view of science.⁴⁹¹ (Such *bifurcation points* are, as we have seen, the physical analogs of teleological *decision points* arising from the action of *free-will*.)

So, in this context, what is a miracle, anyway? *A miracle is a surprising, wonderful, and marvelous action of God.*

Often it has also been thought appropriate to specify that this action of God must *violate known scientific laws* in order to qualify as a miracle, but this proviso really adds nothing to the above definition and, in fact, results in the exclusion from the definition of "miracle" of many events that most religious believers would regard to be miracles. For example, in the healing miracles of Jesus it is often unclear what "known scientific laws" are being violated by the miracle: For, unlike classical Newtonian physics, medicine and biology are not governed by a set of fixed, deterministic, immutable laws, whose violation would be self-evident. The same may also be said of Jesus' miracles

involving meteorology (“Who then is this, that even wind and sea obey him?” Mark 4:41, RSV). Nevertheless, Christian believers still regard Jesus’ healings (and his calming of the wind and sea) to be *surprising, wonderful, and marvelous actions of God*, and therefore as *miracles*.

Of course, even if a given miracle does not violate any specific known law of nature, it often *can* be said to be scientifically *improbable*. But this scientific improbability is not evidence against the truth of the miracle: such improbability is, rather, the scientific correlative of the *surprise, wonder, and marvel* which are of the essence in defining the miraculous in religious terms. And, in any case, scientifically improbable never means scientifically *impossible*. Furthermore, as we have seen, most physical systems in our common experience are *nonlinear complex physical systems*, and in all such systems “improbabilities” abound, which is why they inherently have an *historical* character and are not deterministically predictable.

Another problem with restricting miracles to *violations of known scientific laws* is that it makes the miraculous entirely relative to the progress of science: As science progresses and scientific laws are modified (or new scientific laws are discovered), presumably fewer and fewer events are expected to be regarded as miraculous. But this is just another variant on the erroneous secular belief that the set of entities to which the *teleological/religious method* should be applied ought to correspondingly *shrink* as the set of entities to which the *scientific method* is applied *expands*. (This is sometimes called the “God of the gaps” point-of-view.)

This perspective is reflected in Rene Girard’s offhand comment that “Men tend to see a miracle in everything they don’t understand.”⁴⁹² This sounds plausible at first glance, but in fact does not correspond at all to the way most people view what they don’t understand: Some such things they see as annoyances, some as profound puzzles, some they just shrug off as of no importance, and so on. Only in very extraordinary cases will people regard what they don’t understand to be a *miracle*.

Now, at what moments are we most deeply aware of another’s personality? Is it not when that person does something *surprising*? Whether this surprise is *positive* (like the unexpected gift of a box of candy) or is *negative* (like being suddenly threatened with a knife), the other’s personality is most strongly revealed when the action arising out of the other’s free-will is a *surprise* to the one experiencing it.

Where a person experiences a *surprising* action of God that he finds to be *positive*, he will tend to call that action of God a *miracle* – and the more surprising and positive that action of God is, the more *miraculous* he will regard it to be. (Sometimes, as in the miracle of the cock crow in the story of

Peter's denial, the surprise is *negative* rather than *positive*, but it is nevertheless *deeply revelatory*.)

So, then, as we have seen, *a miracle is a surprising, wonderful, and marvelous action of God*. It therefore may also be said to be (among other things) a *decision point* at which God's transcendent free-will *acts*.

Consequently, for all of the reasons expressed above, a miracle no more contradicts the findings of modern science than does any other action arising out of free-will, whether that action be God's or anyone else's: The only difference is that God's actions are those of an omniscient, omnipotent *transcendent* person (which actions, from an *immanent* point-of-view, may *also* involve the actions of *immanent* subjects).

BIBLIOGRAPHY

- “Can computers simulate chaos?”, *Nonlinear FAQ* <[http://amath.colorado.edu/appm/faculty/jdm/faq-\[2\].html](http://amath.colorado.edu/appm/faculty/jdm/faq-[2].html)>.
- “Cellular Automaton Basics” <<http://classes.yale.edu/99-00/math190a/CABasics.html>>.
- “Mechanics”, concise version of *Microsoft Encarta Encyclopedia* (©1997-2000), <<http://encarta.msn.com/>>.
- “Predicting Cellular Automaton Behavior” <<http://classes.yale.edu/99-00/math190a/Langton.html>>.
- “Quantum Mechanics”, *The Concise Columbia Electronic Encyclopedia*, 3rd ed., 1994.
- “The Missoula Floods Controversy”, Oregon Public Broadcasting <<http://www.opb.org/ofg/1001/missoula/theory.htm>>.
- “The Particle Zoo”, *Physics FAQ* (1995) <http://www.public.iastate.edu/~physics/sci.physics/faq/particle_zoo.html>.
- “Vertebrate Genome Evolution and Evidence for Tetraploidization” <http://www.bu.edu/aldolase/aldolase/mol_evol/genevol.html>.
- Albro. “How Many Worlds?” <<http://www.seanet.com/~ksbrown/albro23.htm>>.
- Alligood, Kathleen T., Tim D. Sauer, and James A. Yorke. *CHAOS: An Introduction to Dynamical Systems* (New York: Springer-Verlag, 1997).
- Alvarez, Walter. *T. Rex and the Crater of Doom* (New York: Vintage Books, 1998).
- American Museum of Natural History. “Understanding Cladistics” <http://www.amnh.org/Exhibition/Fossil_Halls/cladistics.html>.
- Avnet, Jeremy. “Theory of Cellular Automata” <<http://www.theory.org/complexity/cdpt/html/node4.html>, June 6, 2000>.
- Barrow, John D., and Frank J. Tipler. *The Anthropic Cosmological Principle* (New York: Oxford University Press, 1986), p. 677.
- Barry, William. “Calvinism”, *The Catholic Encyclopedia*, Vol III (1908) <<http://www.newadventorg/cathen/03198a.htm>>.
- Becak, M.L., and W. Becak. “Evolution by polyploidy in Amphibians: new insights”, *Cytogenet Cell Genet* 80:28-33.
- Behe, Michael. “Histone deletion mutants challenge the molecular clock hypothesis”, *Trends in Biochemical Science*, 15:374-376 (October 1990).

BIBLIOGRAPHY

- Behe, Michael. *Darwin's Black Box* (New York: Simon & Schuster, 1996).
- Bell, J. "On the Einstein Podolsky Rosen paradox", *Physics* 1 #3, 195 (1964)
- Bell, J.S. *Speakable and Unspeakable in Quantum Mechanics*, Cambridge U.P., Cambridge, England (1987).
- Berlinski, David. "The Deniable Darwin", *Commentary*, vol. 101, no. 6.(June 1996).
- Berlinski, David. Reply to letters critical of his essay "The Deniable Darwin" that had appeared in the June 1996 issue of *Commentary* magazine. Both these critical letters and Berlinski's reply appear in the September 1996 issue of *Commentary* <[http:// www.commentarymagazine.com/ 9609/ letters.html](http://www.commentarymagazine.com/9609/letters.html)>.
- Berlinski, David. "What Brings a World into Being?", *Commentary* (April 2001).
- Bethell, Tom. "A Map to Nowhere: The genome isn't a code , and we can't read it" in *The American Spectator* (April 17, 2001).
- Blanton, John. "Does Bell's inequality principle rule out local theories of quantum mechanics?", *Physics FAQ*, 8/31/93 <[http:// www.public.iastate.edu/ ~physics/ sci.physics/ faq/ bells_inequality.html](http://www.public.iastate.edu/~physics/sci.physics/faq/bells_inequality.html)>.
- Bohm, David. *Wholeness and the Implicate Order* (London: Routledge & Kegan Paul 1980).
- Bohr, Niels. "Discussion with Einstein on Epistemological Problems in Atomic Physics", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969),
- Brent, Joseph. *Charles Sanders Peirce: A Life*, rev. & enlarged ed. (Bloomington and Indianapolis: Indiana University Press, 1993 & 1998).
- Briggs, John, and F. David Peat. *Looking Glass Universe: The Emerging Science of Wholeness* (New York: Cornerstone Library 1984).
- Budnik, Paul. "Is QM a complete theory?" <[http:// www.mtnmath.com/ faq/ meas-qm-5.html](http://www.mtnmath.com/faq/meas-qm-5.html)> (1995).
- Buikema, Jr., Arthur L. "Survivorship Curves", *Bioinquiry* (John Wiley and Sons, 1999) <[http:// bioinquiry.boil.vt.edu/ bioinquiry/ Cheetah/ cheetachpaid/ cheetahhtmls/ popsurvivor.html](http://bioinquiry.boil.vt.edu/bioinquiry/Cheetah/cheetachpaid/cheetahhtmls/popsurvivor.html)>.
- Burbank, Luther. *Partner of Nature* (1939).

- Catechism of the Catholic Church*, 2nd ed. (Liberia Editrice Vaticana, 1997), 365.
- Chua, Leon O. *CNN: A PARADIGM FOR COMPLEXITY* (World Scientific Series on Nonlinear Science, Series A, Vol. 31, 1998).
- Clausius, R. *Ann Phys.*, Vol. 125 (1865), p. 353.
- Cold Spring Laboratory Press Release August 9, 2001* <<http://www.arn.org/docs2/news/histonecode81001.htm>>.
- Commoner, Barry. "UNRAVELING THE DNA MYTH: The Spurious Foundation of Genetic Engineering", *Harper's Magazine* (February 2002).
- Conway, John, Elwyn Berlekemp, and Richard Guy. *Winning Ways (for Your Mathematical Plays)* (New York: Academic Press, 1982).
- Cramer, J.G. *Phys. Rev. D.* 22, 362 (1980).
- Darwin, Charles. *Descent of Man*.
- Darwin, Charles. *The Origin of the Species*.
- Davison, John A. "Semi-meiosis as an evolutionary mechanism", *J. Theor. Biol.* 111:725-735 (1984).
- Davison, John A. "An Evolutionary Manifesto: A New Hypothesis for Organic Change" (July 15, 2000) <<http://moose.uvm.edu/~jcdavison/Davison-manifesto.html>>.
- Davison, John A. "Evolution as a self-limiting process" <<http://www.uvm.edu/~jcdavison/dpaper.html>>.
- Dawkins, Richard. *The Blind Watchmaker* (1986).
- de Beer, Gavin. *Homology: An Unsolved Problem* (London: Oxford University Press, 1971).
- de Broglie, Louis. "A General Survey of the Scientific Work of Albert Einstein", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969).
- de Chardin, Teilhard. *The Phenomenon of Man* (1959).
- DeHaan, Robert F. "A Brief Critique of Evolution from the Developmental Perspective" (October 7, 1997) <<http://www.macrodevelopment.org/critiq.html>>.
- DeHaan, Robert F. "Introduction to the Phylo-Developmental Framework" (May 11, 1997) <<http://www.macrodevelopment.org/concept.html>>.

BIBLIOGRAPHY

- DeHaan, Robert F. "Paradoxes in Darwinian Theory Resolved by a Theory of Macro-Development", *PSCF* 48 (September 1996): 180.
- Dembski, William A. "What every theologian should know about creation, evolution, and design" <[http:// www.leaderu.com/ offices/ dembski/ docs/ bd-theologn.html](http://www.leaderu.com/offices/dembski/docs/bd-theologn.html)>, last updated October 19, 1998.
- Denton, Michael. *Evolution: A Theory in Crisis* (Chevy Chase, MD: Adler & Adler, 1986).
- DeWitt, B.S., and N. Graham. *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1973). Includes Everett's original 1957 paper.
- Doolittle, W. Ford. "Uprooting the Tree of Life", *Scientific American* (February 2000), pp. 90-95.
- Easterbrook, Gregg. "What Came Before Creation?", *U.S. News & World Report*, 7/20/98.
- Einstein, A., B. Podolsky, and N. Rosen. "Can quantum-mechanical description of physical reality be considered complete?" *Physical Review* 41:777 (May 15, 1935).
- Einstein, Albert. "Autobiographical Notes", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court, 1969)
- Einstein, Albert. "Quantuenmechanik und Wirklichkeit", *Dialectica*, vol. 2, pp. 320-324.
- Einstein, Albert. "Reply to Criticisms", *Albert Einstein: Philosopher-Scientist*, Vol. 2, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1970) pp. 681-2.
- Einstein, Albert. 1921 lecture at King's College, London, England <[http:// members.tripod.com/~Chernobill/einstein/ae_prgrx.htm](http://members.tripod.com/~Chernobill/einstein/ae_prgrx.htm)>.
- Eldredge, N., and I. Tattersall. *The Myths of Human Evolution* (New York: Columbia University Press, 1982).
- Eldredge, Niles. *Evolutionary Macrodynamics* (New York: Mcgraw, 1989).
- Eldredge, Niles. *The Miner's Canary: Unravelling the Mysteries of Extinction* (New York: Prentice Hall Press, 1991).
- Elsberry, Wesley. "Punctuated Equilibria" <[http:// www.talkorigins.org/ faqs/ punc-eq.html](http://www.talkorigins.org/faqs/punc-eq.html)> (Feb 4, 1996).
- Engle, Phillip L. *WORLDVIEWS* (Philadelphia: Xlibris Press, 2000)

- Erwin, D., J. Valentine, and J. Sepkoski. "A Comparative Study of Diversification Events", *Evolution*, vol. 41, p. 1183 (1988).
- Ewens, W.J. "Comments on Dr. Kimura's Paper", *Genetics Supplement*, *Genetics* (1973) 73:36-8, p. 36.
- Foley, Brian. "Re: Genetic Code and Phenotype" (10/7/1996), *The MAD Scientist Network: Genetics* <<http://madsci.wustl.edu/posts/archives/dec96/834904210.Ge.r.html>>.
- Franson. "Bell's Theorem and Delayed Determinism", *Physical Review D*, pgs. 2529-2532, Vol. 31, No. 10, May 1985.
- Futuyama, D.J., *Evolutionary Biology* (Sunderland MA: Sinauer Associates Inc., 1986).
- Galitski, Timothy, Alok J. Saldanha, Cora A. Styles, Eric S. Lander, and Gerald R. Fink. "Ploidy Regulation of Gene Expression", *Science* 285:251-254 (July 9, 1999).
- Gallardo, Bickham, Honeycutt, Ojeda, and Kohler, "Discovery of Tetraploidy in a Mammal", *Nature* 401:341 (Sept. 23, 1999).
- Gamarra, Javier G.P., and Ricard V. Sole. "Bifurcations and Chaos in Ecology: Lynx Returns Revisited" <<http://www.santafe.edu/sfi/publications/Abstracts/99-10-067abs.html>>.
- Garbutt, K. "Polyploidy" <<http://www.as.wvu.edu/~jgarbutt/Papers2/Poly1.html>>.
- Gardner, Martin. "WAP, SAP, PAP, and FAP", in *The New York Review of Books*, 23 (May 8, 1986), No. 8 (1986), pp. 22-25.
- Gell-Mann, M., J.B. Hartle. *Complexity, Entropy and the Physics of Information*, W. Zurek ed. (Reading, Pennsylvania: Addison Wesley, 1990), p. 425.
- Gibbs, Phil. "What is Occam's Razor?", *Physics FAQ* (7/23/97) <<http://www.public.iastate.edu/~physics/sci.physics/faq/occam.html>>.
- Girard, Rene. *The Scapegoat*, trans. Yvonne Freccero (Baltimore: The Johns Hopkins University Press, 1986).
- Goldschmidt, Richard. *The Material Basis of Evolution* (New Haven: Yale University Press, 1940).
- Gould, Stephen Jay. "Bushes and Ladders", *Ever Since Darwin: Reflections in Natural History* (New York: W.W. Norton & Company, 1977), pp. 61-62.

BIBLIOGRAPHY

- Gould, Stephen Jay. "Evolution: The Pleasures of Pluralism", *New York Review of Books* (June 26, 1997).
- Gould, Stephen Jay. "Evolution's Erratic Pace", *Natural History* vol. 86, May 1977.
- Gould, Stephen Jay. "Of Tongue Worms, Velvet Worms, and Water Bears", *Natural History* 104: 15 (1995).
- Gould, Steven Jay. "In Gratuitous Battle", *Civilization Magazine* (November 1998) <http://www.jamesmoody.4biz.net/drmoody/civ_mag_gould.html>.
- Gould, Steven Jay. "The Pattern of Life's History", *The Third Culture*, Chapter 2 <<http://www.edge.org/documents/ThirdCulture/i-Ch.2.html>>.
- Gould, Steven Jay. "The Spandrels of San Marco and the Panglossian Paradigm; A Critique of the Adeptationist Program" (1978).
- Grant, V. *Plant Speciation* (New York: Columbia University Press, 1981).
- Grasse, Pierre. *Evolution of Living Organisms* (1977).
- Gravner and Griffeath, *CA Growth: Introduction* <http://psoup.math.wisc.edu/extras/rl_shapes/page1a.html>.
- Griffiths, R. J. *Stat. Phys.* 36: 219 (1984).
- Griffiths, Richard B., and Roland Omnes. "Consistent Histories and Quantum Measurements", *Physics Today*, August 1999, Part 1.
- Halstead, L.B. *Dinosaurs* (Poole: Blandford Press, 1981).
- Hawking, Stephen W. *A Brief History of Time* (New York: Bantam Books, 1996).
- Hieter, Philip, and Tony Griffiths. "Ploidy - More is More or Less", *Science* 285:210 (July 9, 1999).
- Horgan, John. "From Complexity to Perplexity" in *Scientific American* (June 1995).
- Ilya Prigogine Center at <<http://order.ph.utexas.edu/research/threebody3.html>>.
- Infeld, Leopold. "On the Structure of Our Universe", in *Albert Einstein: Philosopher-Scientist*, vol. 2, ed. Paul Arthur Schlipp, 3rd ed. (LaSalle IL: Open Court, 1970).

- Jackson, J.B.C., and A.H. Cheetham. "Phylogeny reconstruction and the tempo of speciation in cheilostome Bryozoa", *Paleobiology*, vol. 20 (1994), pp. 407-423.
- Jantsch, Eric. *The Self-Organizing Universe* (Oxford: Pergamon Press, 1980).
- Johnson, Phillip E. "Dembski and Kauffman Square off in New Mexico", *Weekly Wedge Update*, November 19, 2001 <[http:// www.arn.org/ docs/ pjweekly/ pj_weekly_011119.htm](http://www.arn.org/docs/pjweekly/pj_weekly_011119.htm)>.
- Johnson, Phillip E. "God and Evolution: An Exchange", *First Things* (June 1993) <[http:// www.firstthings.com/ ftissues/ ft9306/ Johnson.html](http://www.firstthings.com/ftissues/ft9306/Johnson.html)>.
- Johnson, Phillip E. "The Extinction of Darwinism", *The Atlantic* (February 1992) <[http:// www.arn.org/ docs/ Johnson/ raup.htm](http://www.arn.org/docs/Johnson/raup.htm)>.
- Johnson, Phillip E. "The Religion of the Blind Watchmaker" <[http:// www.arn.org/ docs/ Johnson/ watchmkr.htm](http://www.arn.org/docs/Johnson/watchmkr.htm)>.
- Johnson, Phillip E. *Darwin on Trial* (Downers Grove IL: Intervarsity Press, 1993).
- Jones, Douglas S. "The Many-Worlds Interpretation of Quantum Mechanics" (1997-99) <[http:// www.station1.net/ douglasjones/ many.htm](http://www.station1.net/douglasjones/many.htm)>.
- Kauffman, S.A., R.M. Shymko, and K. Trabert. "Control of Sequential Compartment Formation in *Drosophila*", *Science*, Vol. 199 (1978), pp. 259-69.
- Kimball, J. "Endoreplication" <[http:// www.ultranet.com/ ~jkimball/ Biology/ Pages/ E/ Endoreplication.html](http://www.ultranet.com/~jkimball/Biology/Pages/E/Endoreplication.html)>.
- Kondepudi, Dilip, and Ilya Prigogine. *MODERN THERMODYNAMICS: From Heat Engines to Dissipative Structures* (New York: John Wiley & Sons, 1998).
- Kuhn, Thomas. *The Structure of Scientific Revolutions* (2nd ed., 1970).
- Lambert, Frank L. "Shuffled Cards, Messy Desks, and Disorderly Dorm Rooms – Examples of Entropy Increase? Nonsense!", *Journal of Chemical Education*, 76: 1385 (1999), as found on the internet at <[http:// chemed.chem.wisc.edu/ Journal/ Issues/ 1999/ Oct/ abs1385.html](http://chemed.chem.wisc.edu/Journal/Issues/1999/Oct/abs1385.html)>.
- Laskar, J. "A numerical experiment on the chaotic behaviour of the solar system", *Nature* 338: 237-8 (1989).
- Lengauer, C., K. Kinzler, and B.H. Vogelstein. *Nature* 396:643 (1998).

BIBLIOGRAPHY

- Levy, Stuart B. "The Challenge of Antibiotic Resistance", *Scientific American* (March 1998), p. 35.
- Lipkin, Richard. *Science News Online* (May 25, 1996).
- MacIntyre, Alasdair. *After Virtue*, 2nd Edition (Notre Dame, Indiana: University of Notre Dame Press, 1984 [first edition 1981]).
- Margulis, Lynn. "Gaia Is a Tough Bitch", chapter 7 of *The Third Culture: Beyond the Scientific Revolution*, ed. John Brockman (New York: Simon & Schuster, 1995).
- Marx, E. "Relativistic Covariance and the Interpretation of Quantum Mechanics", *Physics Essays* 9: 282; 1996.
- Mayr, Ernst. *Population, Species, and Evolution* (Cambridge, Mass.: Belknap Press, 1970).
- Meyer, Stephen C. "DNA and Other Designs", *First Things* 102:30-38 (April 2000).
- Miller and Levine, *Biology* (Prentice Hall, 1995).
- Milton, Richard. "Darwin's Finches" <[http:// www.alternativescience.com / darwin's-finches.htm](http://www.alternativescience.com/darwin's-finches.htm), November 22, 1999>.
- Milton, Richard. "Speciation?" <[http:// www.alternativescience.com / speciation.htm](http://www.alternativescience.com/speciation.htm), November 22, 1999>.
- Monroe, Christopher. "A 'Schrodinger cat' superposition state of an atom", *Science*, vol. 272, p. 1131.
- National Association of Biology Teachers, "Statement on Teaching Evolution" <[http:// www.nabt.org/ sub/ position_statements/ evolution.asp](http://www.nabt.org/sub/position_statements/evolution.asp)>, as of December 21, 2001.
- Neuhaus, Richard John. "The End of Endings", *First Things* (September 2001).
- Newman, M.E.J., and Paolo Sibani. "Extinction, diversity and survivorship of taxa in the fossil record" (Santa Fe Institute 1998, working paper: final paper *Proc. R. Soc. London B* 266, 1593-1600.).
- Newman, M.E.J., and R.G. Palmer, "Models of Extinction: A Review" <[http:// www.phy.duke.edu/ ~palmer/ papers/ extinction99.pdf](http://www.phy.duke.edu/~palmer/papers/extinction99.pdf)>.
- Nicolis, Gregoire, and Ilya Prigogine. *Exploring Complexity: An Introduction* (New York: W.H. Freeman and Company, 1989).
- Ohno, S. *Evolution by Gene Duplication* (Heidelberg: Springer, 1970).

- Ohno, S., U. Wolf, and N. Atkin (1986). "Evolution from fish to mammals by gene duplication", *Hereditas* 59:169-187.
- Omnes, R. *J. Stat. Phys.* 53: 893 (1988).
- Palmer, Trevor. "The Fall and Rise of Catastrophism" (based on a lecture given at Nottingham Trent University on April 25, 1996) <<http://www.maths.ntu.ac.uk/~lsstaff/fallc.htm>>.
- Peirce, Charles S. "The Doctrine of Necessity Examined", *The Monist* 2 (April 1892): 334.
- Peirce, Charles S. "The Law of Mind", *The Monist* 2 (July 1892): 533-59.
- Physical Review Letters* 49 #2, 91 (12 July 1982), and 49 #25, 1804 (20 Dec 1982).
- Planck, Max. *Treatise on Thermodynamics*, 3rd ed. (New York: Dover Press, 1945).
- Pohle, J. "Controversies on Grace", *The Catholic Encyclopedia*, Vol VI (1909) <<http://www.newadvent.org/cathen/06710a.htm>>.
- Poincare, Henri. *New Methods of Celestial Mechanics*, ed. G. Goroff (American Institute of Physics, 1993).
- Poundstone, William. *The Recursive Universe: Cosmic Complexity and the Limits of Scientific Knowledge* (Chicago: Contemporary Books Inc., 1985).
- Prigogine, Ilya, and Isabelle Stengers. *Order Out of Chaos: Man's New Dialogue with Nature* (Toronto: Bantam Books, 1984).
- Prigogine, Ilya. *The End of Certainty: Time, Chaos, and the New Laws of Nature* (New York: The Free Press, 1996 & 1997).
- Prothero, Donald R. "Punctuated Equilibrium at Twenty: A Paleontological Perspective", *Skeptic*, vol. 1, no. 3. Fall 1992, pp. 38-47.
- Rae, Alistaire. *Quantum Mechanics*, 3rd ed.
- Raup, David M. *Extinction: Bad Genes or Bad Luck?* (Norton, 1991).
- Reichenbach, Hans. "The Philosophical Significance of the Theory of Relativity", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969).
- Resnick, Robert, and David Halliday. *Physics*, Part I (New York: John Wiley & Sons, Inc., 1966).

BIBLIOGRAPHY

- Ridley, Mark, ed. *The Darwin Reader* (New York, London: W.W. Norton & Company, 1987).
- Robertson, H.P. "Geometry as a Branch of Physics", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court, 1969).
- Ross, Hugh . "Design and the Anthropic Principle" <[http:// www.reasons.org/resources/papers/ design.html](http://www.reasons.org/resources/papers/design.html)>.
- Royzman, I., and T. L. Orr-Weaver. *Genes Cells* 3:767 (1998).
- Scaruffi, Piero. "Thinking about Thought" <[http:// www.thymos.com/ tat/emergenc.html](http://www.thymos.com/tat/emergenc.html)> (1998).
- Schindewolf, O.H. *Paleontologie, Entwicklungslehre and Genetik* (Berlin: Borntrager, 1936).
- Schonborn, Christoph. *God's Human Face*, trans. Lothar Krauth (San Francisco: Ignatius Press, 1994), p. 92.
- Schrodinger, E. "Die gegenwartige Situation in der Quantenmechanik", *Naturwissenschaften* 23: 807-812, 823-823, 844-849 (1935). English translation: John D. Trimmer, *Proceedings of the American Philosophical Society*, 124: 323-38 (1980), reprinted in *Quantum Theory and Measurement*, p. 152 (1983).
- Simpson, George Gaylord. *The Meaning of Evolution*, rev. ed. (New Haven: Yale University Press, 1967).
- Simpson, George Gaylord. *Tempo and Mode in Evolution* (New York: Columbia University Press, 1944).
- Sole, Richard V., and Mark Newman. "Patterns of Extinction and Biodiversity in the Fossil Record", *Encyclopedia of Global Environmental Change* (Wiley, 2000) <[http:// www.santafe.edu/ sfi/publications/ Abstracts/ 99-12-079abs.html](http://www.santafe.edu/sfi/publications/Abstracts/99-12-079abs.html)>.
- Sparrow, Arnold H., and Anne F. Nauman. "Evolution of Genome Size by DNA Doublings", *Science* 192:524-529 (May 7, 1976).
- Sprott, J.C. "Numerical Calculation of Largest Lyapunov Exponent" <[http:// sprott.physics.wisc.edu/ chaos/ lyapexp.htm](http://sprott.physics.wisc.edu/chaos/lyapexp.htm)> (1997-1998).
- Standish, Russell K. "On Complexity and Emergence" <[http:// parallel.hpc.unsw.edu.au/ rks](http://parallel.hpc.unsw.edu.au/rks) , February 26, 2001>.

- Steele, Edward J., Robyn A. Lindley, and Robert V. Blanden. *Lamarck's Signature: How Retrogenes Are Changing Darwin's Natural Selection Paradigm* (Reading, MA: Perseus Books, 1998).
- Strohman, Richard C. "Towards an Epigenetic Biology & Medicine", *Network* (May 15, 1996) <[http:// www.cmhc.com/ perspectives/ articles/ art05963.htm](http://www.cmhc.com/perspectives/articles/art05963.htm)>.
- Sussman, G.J., and J. Wisdom, "Chaotic evolution of the solar system", *Science* 257: 56-62 (1992).
- Taylor, Gordon Rattray. *The Great Evolution Mystery* (London: Secker & Warburg, 1982).
- Teed, Rebecca. "The Phyletic Gradualism - Punctuated Equilibrium Debate" <[http:// lrc.geo.umn.edu/ people/ teed/ papers/ macroev.html](http://lrc.geo.umn.edu/people/teed/papers/macroev.html)>, May 12, 1995.
- Tolan, D., J. Niclas, B. Bruce, and R. Lebo. "Evolutionary Implications of the Human Aldolase-A, -B, -C, and Pseudogene Chromosome Locations", *Am. J. Hum. Genet.* 41:907-924 (1987).
- Tolstoy, Leo. Letter to the American international lawyer Ernest Howard Crosby, in *Tolstoy on Civil Disobedience and Nonviolence* (New York: Bergman/Signet/New American Library, 1967).
- Van Valen, Leigh. "A New Evolutionary Law", *Evolutionary Theory* 1:1-30 (1973).
- von Bertalanffy, Ludwig. *General System Theory: Foundations, Development, Applications*, rev. ed. (New York: George Braziller, 1968).
- von Bertalanffy, Ludwig. *Perspectives on General Systems Theory: Scientific-Philosophical Studies* (New York: George Braziller, 1975).
- von Bertalanffy, Ludwig. *The Problems of Life* (New York: Watts, 1952).
- Watson, Joe. *Physics 16: Lecture 2* <[http:// cmtw.harvard.edu / Courses / Phys16 / 12_latex / 12_latex.html](http://cmtw.harvard.edu/Courses/Phys16/12_latex/12_latex.html)> 1994.
- Webster's New World Dictionary of American English*, Third College Edition (Cleveland & New York, Webster's New World, 1988).
- Wells, Jonathan. *Icons of Evolution* (Washington D.C.: Regnery Publishing Inc., 2000).
- Wheeler, John Archibald. "Bohr, Einstein, and the Strange Lesson of the Quantum," in *Mind in Nature*, ed. Richard Q. Elvee (New York: Harper and Row, 1981).

BIBLIOGRAPHY

- Whitfield, John. "Magical Numbers in Nature" (an interview with Ian Stewart), *Nature: Science Update* (October 28, 2001) <<http://www.nature.com/nsu/011018/011018-3.html>>.
- Wiker, Benjamin. "Darwin and the Descent of Morality", *First Things* 117:10-13 (November 2001).
- Wiker, Benjamin. "Facts to the Wind: Reviewing *Monkey Trial*, a PBS Documentary", in *National Online Review* (February 16, 2002).
- Willis, J.C. "The origin of species by large, rather than by gradual change and by Guppy's method of differentiation", *Ann. Bot.* 37:605-628 (1923).
- Wilson, A.C., S.S. Carlson, and T.J. White. "Biochemical Evolution" *Am. Rev. Biochem* (1977) 46:573-639.
- Wright, Robert. "The Accidental Creationist: Why Stephen Jay Gould Is bad for evolution", *The New Yorker*, December 13, 1999.
- Young, J. Z. *The Life of Vertebrates*, 3rd ed. (Oxford: Clarendon, 1981).
- Zaslavsky, George M. "Chaotic Dynamics and the Origin of Statistical Laws", *Physics Today* (August 1999, Part 1), p. 42.

END NOTES

¹ Ludwig von Bertalanffy, *General System Theory: Foundations, Development, Applications*, rev. ed. (New York: George Braziller, 1968).

² To learn more about the subject matter of classical mechanics, see any standard textbook, such as: Robert Resnick and David Halliday, *Physics*, Part I (New York: John Wiley & Sons, Inc., 1966).

³ Bertalanffy, *General System Theory*, pp. 54-5.

⁴ Ludwig von Bertalanffy, *Perspectives on General Systems Theory: Scientific-Philosophical Studies* (New York: George Braziller, 1975), p. 150.

⁵ Bertalanffy, *General Systems Theory*, p. 54.

⁶ Bertalanffy, *Perspectives on General Systems Theory*, p. 150.

⁷ Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature* (Toronto: Bantam Books, 1984), p. 72.

⁸ Thanks to my son, Jonathan Steven Engle, for providing this example!

⁹ Thanks again to Jon Engle!

¹⁰ Bertalanffy, *General System Theory*, p. 20.

¹¹ Prigogine and Stengers, p. 73.

¹² Prigogine and Stengers, p. 61.

¹³ Prigogine and Stengers, pp. 70-1.

¹⁴ Prigogine and Stengers, p. 71.

¹⁵ Prigogine and Stengers, p. 71.

¹⁶ Prigogine and Stengers, pp. 71-2.

¹⁷ Ilya Prigogine, *The End of Certainty: Time, Chaos, and the New Laws of Nature* (New York: The Free Press, 1996 & 1997), pp. 38-40, citing Henri Poincare, *New Methods of Celestial Mechanics*, ed. G. Goroff (American Institute of Physics, 1993).

¹⁸ Cited by Prigogine and Stengers, p. 27.

¹⁹ Cited by Prigogine and Stengers, p. 27.

²⁰ Cited by Prigogine and Stengers, p. 30.

²¹ Cf. Robert Nisbet, *The Quest for Community* (San Francisco, California: ICS Press, 1990), pp. 117-118. [First published by Oxford University Press in 1953.]

END NOTES

- ²² Alasdair MacIntyre, *After Virtue*, 2nd Edition (Notre Dame, Indiana: University of Notre Dame Press, 1984 [first edition 1981]).
- ²³ Prigogine and Stengers, p. 1.
- ²⁴ *Webster's New World Dictionary of American English*, Third College Edition (Cleveland & New York, Webster's New World, 1988).
- ²⁵ Prigogine and Stengers, p 52.
- ²⁶ Prigogine and Stengers, pp. 75-77.
- ²⁷ Prigogine and Stengers, p. 270.
- ²⁸ Prigogine, pp 38-40.
- ²⁹ Albert Einstein, "Autobiographical Notes", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court, 1969), p. 53.
- ³⁰ Joe Watson, *Physics 16: Lecture 2* <http://cmtw.harvard.edu/Courses/Phys16/12_latex/12_latex.html> 1994
- ³¹ Joe Watson, *Physics 16: Lecture 2*.
- ³² Hans Reichenbach, "The Philosophical Significance of the Theory of Relativity", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969) p. 289.
- ³³ Albert Einstein, 1921 lecture at King's College, London, England <http://members.tripod.com/~Chernobill/einstein/ae_prgrx.htm>.
- ³⁴ Albert Einstein, 1921 lecture at King's College, London, England.
- ³⁵ For an excellent summary of non-Euclidean geometries, see H.P. Robertson, "Geometry as a Branch of Physics", *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court, 1969), pp. 313-332.
- ³⁶ Einstein, "Autobiographical Notes", pp. 19-21.
- ³⁷ Einstein, "Autobiographical Notes", p. 25.
- ³⁸ Einstein, "Autobiographical Notes", pp. 27-29.
- ³⁹ Einstein, "Autobiographical Notes", pp. 35-37.
- ⁴⁰ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/Einstein/EinsteinEquations.html>>
- ⁴¹ Einstein, "Autobiographical Notes", pp. 77-79.
- ⁴² Einstein, "Autobiographical Notes", p. 89.

- ⁴³ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/Einstein/EinsteinEquations.html>>
- ⁴⁴ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/NumCrunchers2.html>>
- ⁴⁵ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/EinsteinTest.html>>
- ⁴⁶ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/GravWaves.html>>
- ⁴⁷ <<http://www.ncsa.uiuc.edu/Cyberia/NumRel/BlackHoleAnat.html>>
- ⁴⁸ Stephen W. Hawking, *A Brief History of Time* (New York: Bantam Books, 1996).
- ⁴⁹ Leopold Infeld, "On the Structure of Our Universe", in *Albert Einstein: Philosopher–Scientist*, vol. 2, ed. Paul Arthur Schlipp, 3rd ed. (LaSalle IL: Open Court, 1970), p. 477.
- ⁵⁰ Infeld, p. 479.
- ⁵¹ Infeld, pp. 480-485.
- ⁵² <<http://www.public.iastate.edu/~physics/faq/hubble.html>>
- ⁵³ <<http://map.gsfc.nasa.gov/html/lamba.html>>
- ⁵⁴ Infeld, pp. 488-492.
- ⁵⁵ Infeld, p. 492.
- ⁵⁶ Gregg Easterbrook, "What Came Before Creation?", *U.S. News & World Report*, 7/20/98.
- ⁵⁷ <<http://map.gsfc.nasa.gov/html/geometry.html>> (12/16/99)
- ⁵⁸ <<http://map.gsfc.nasa.gov/html/geometry.html>> (12/16/99)
- ⁵⁹ Eric Jantsch, *The Self-Organizing Universe* (Oxford: Pergamon Press, 1980), pp. 115-120.
- ⁶⁰ Jantsch, pp. 91-92.
- ⁶¹ <<http://www.pbs.org/faithandreason/intro/cosmo-body.html>>
- ⁶² Gregg Easterbrook, "What Came Before Creation?" *U.S. News & World Report*, 7/20/98.
- ⁶³ <<http://www.pbs.org/faithandreason/intro/cosmotime-body.html>>
- ⁶⁴ Stephen Hawking, *A Brief History of Time* (New York: Bantam Books, 1996).
- ⁶⁵ Gregg Easterbrook, "What Came Before Creation?" *U.S. News & World Report*, 7/20/98.

END NOTES

⁶⁶ Louis de Broglie, “A General Survey of the Scientific Work of Albert Einstein”, *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969), p. 124.

⁶⁷ quoted in Niels Bohr, “Discussion with Einstein on Epistemological Problems in Atomic Physics”, *Albert Einstein: Philosopher-Scientist*, vol. 1, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1969), p. 205.

⁶⁸ Einstein, “Autobiographical Notes”, pp. 45-47.

⁶⁹ “Quantum Mechanics”, *The Concise Columbia Electronic Encyclopedia*, 3rd ed., 1994.

⁷⁰ John Briggs and F. David Peat, *Looking Glass Universe: The Emerging Science of Wholeness* (New York: Cornerstone Library 1984), p. 46.

⁷¹ “Quantum Mechanics”, *The Concise Columbia Electronic Encyclopedia*, 3rd ed., 1994.

⁷² “The Particle Zoo”, *Physics FAQ* (1995) <[http:// www.public.iastate.edu / ~physics /sci.physics /faq /particle_zoo.html](http://www.public.iastate.edu/~physics/sci.physics/faq/particle_zoo.html)>.

⁷³ Briggs and Peat, p. 140.

⁷⁴ J.G. Cramer, *Phys. Rev. D.* 22, 362 (1980).

⁷⁵ E. Marx, “Relativistic Covariance and the Interpretation of Quantum Mechanics”, *Physics Essays* 9: 282; 1996.

⁷⁶ Biggs and Peat, pp. 46-47.

⁷⁷ See, for example, David Bohm, *Wholeness and the Implicate Order* (London: Routledge & Kegan Paul 1980), pp. 65-110.

⁷⁸ Prigogine and Stengers, pp. 220-221.

⁷⁹ Bohm, p. 66.

⁸⁰ Prigogine and Stengers, p. 223.

⁸¹ Prigogine and Stengers, p. 223.

⁸² J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, Cambridge U.P., Cambridge, England (1987), as cited by Richard B. Griffiths and Roland Omnès in “Consistent Histories and Quantum Measurements”, *Physics Today*, August 1999, Part 1, p 26.

⁸³ <[http:// www.public.iastate.edu/ ~physics/ sci.physics/ faq/ open_questions.html](http://www.public.iastate.edu/~physics/sci.physics/faq/open_questions.html)>.

- ⁸⁴ Richard Lipkin, *Science News Online* (May 25, 1996), citing Christopher Monroe, “A ‘Schrodinger cat’ superposition state of an atom”, *Science*, vol. 272, p. 1131.
- ⁸⁵ E. Schrodinger, “Die gegenwartige Situation in der Quantenmechanik”, *Naturwissenschaften* 23: 807-812, 823-823, 844-849 (1935). English translation: John D. Trimmer, *Proceedings of the American Philosophical Society*, 124: 323-38 (1980), reprinted in *Quantum Theory and Measurement*, p. 152 (1983).
- ⁸⁶ Richard B. Griffiths and Roland Omnes, “Consistent Histories and Quantum Measurements”, *Physics Today*, August 1999, Part 1, p 26.
- ⁸⁷ Griffiths and Omnes, p. 29.
- ⁸⁸ Bohr, pp. 209-210, 221-223.
- ⁸⁹ Bohr, p. 223.
- ⁹⁰ Briggs and Peat, p. 177.
- ⁹¹ Ilya Prigogine, pp. 150-1.
- ⁹² Griffiths and Omnes, p. 31.
- ⁹³ Based on the figure in Griffiths and Omnes, p. 27.
- ⁹⁴ Griffiths and Omnes, p. 27.
- ⁹⁵ Griffiths and Omnes, p. 29.
- ⁹⁶ Griffiths and Omnes, pp. 28-9.
- ⁹⁷ R. Griffiths, *J. Stat. Phys.* 36: 219 (1984), R. Omnes, *J. Stat. Phys.* 53: 893 (1988), M. Gell-Mann, J.B. Hartle, in *Complexity, Entropy and the Physics of Information*, W. Zurek ed. (Reading, Pennsylvania: Addison Wesley, 1990), p. 425.
- ⁹⁸ Griffiths and Omnes, p. 31.
- ⁹⁹ Briggs and Peat, p. 52.
- ¹⁰⁰ Griffith and Omnes, p. 31.
- ¹⁰¹ A. Einstein, B. Podolsky, N. Rosen, “Can quantum-mechanical description of physical reality be considered complete?” *Physical Review* 41:777 (May 15, 1935).
- ¹⁰² Briggs and Peat, pp. 71-72.
- ¹⁰³ Bohr, p. 233, quoting from his earlier paper in *Phys. Rev.*, 48: 696 (1935).

END NOTES

- ¹⁰⁴ Albert Einstein, “Reply to Criticisms”, *Albert Einstein: Philosopher-Scientist*, Vol. 2, ed. Paul Arthur Schilpp, 3rd ed. (LaSalle IL: Open Court 1970) pp. 681-2.
- ¹⁰⁵ Bohr, pp. 237-8.
- ¹⁰⁶ Einstein, “Reply to Criticisms”, p. 682.
- ¹⁰⁷ Albert Einstein, “Quantuenmechanik und Wirklichkeit”, *Dialectica*, vol. 2, pp. 320-324.
- ¹⁰⁸ Briggs and Peat, p. 73 and pp. 96-97. Also (in much more detail), Bohm, pp. 70-1, 79-81.
- ¹⁰⁹ J. Bell, “On the Einstein Podolsky Rosen paradox”, *Physics* 1 #3, 195 (1964)
- ¹¹⁰ John Blanton, “Does Bell’s inequality principle rule out local theories of quantum mechanics?”, *Physics FAQ*, 8/31/93 <[http:// www.public.iastate.edu/~physics/ sci.physics/ faq/ bells_inequality.html](http://www.public.iastate.edu/~physics/sci.physics/faq/bells_inequality.html)>.
- ¹¹¹ *Physical Review Letters* 49 #2, 91 (12 July 1982), and 49 #25, 1804 (20 Dec 1982).
- ¹¹² Franson, “Bell’s Theorem and Delayed Determinism”, *Physical Review D*, pgs. 2529-2532, Vol. 31, No. 10, May 1985.
- ¹¹³ Blanton, *Physics FAQ*, 8/31/93.
- ¹¹⁴ B.S. DeWitt and N. Graham, *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1973). Includes Everett’s original 1957 paper.
- ¹¹⁵ Phil Gibbs, “What is Occam’s Razor?”, *Physics FAQ* (7/23/97) <[http:// www.public.iastate.edu/~physics/ sci.physics/ faq/ occam.html](http://www.public.iastate.edu/~physics/sci.physics/faq/occam.html)>.
- ¹¹⁶ Alistaire Rae, *Quantum Mechanics*, 3rd ed.
- ¹¹⁷ Albrow, “How Many Worlds?” <[http:// www.seanet.com/~ksbrown/ albro23.htm](http://www.seanet.com/~ksbrown/albro23.htm)>.
- ¹¹⁸ Douglas S. Jones, “The Many-Worlds Interpretation of Quantum Mechanics” (1997-99) <[http:// www.station1.net/ douglasjones/ many.htm](http://www.station1.net/douglasjones/many.htm)>.
- ¹¹⁹ Douglas S. Jones, “The Many-Worlds Interpretation of Quantum Mechanics” (1997-99) <[http:// www.station1.net/ douglasjones/ many.htm](http://www.station1.net/douglasjones/many.htm)>.
- ¹²⁰ Briggs and Peat, pp. 111-12.
- ¹²¹ Bohm, p. 151.
- ¹²² Briggs and Peat, pp. 137-144.

- ¹²³ Prigogine, p. 131. See also the website page of the Ilya Prigogine Center at <[http:// order.ph.utexas.edu/ research/three body3.html](http://order.ph.utexas.edu/research/threebody3.html)>.
- ¹²⁴ Paul Budnik, "Is QM a complete theory?" <[http:// www.mtnmath.com/faq/ meas-qm-5.html](http://www.mtnmath.com/faq/meas-qm-5.html)> (1995).
- ¹²⁵ Bohr, p. 223.
- ¹²⁶ Bohr, p. 223.
- ¹²⁷ John Archibald Wheeler, "Bohr, Einstein, and the Strange Lesson of the Quantum," in *Mind in Nature*, ed. Richard Q. Elvee (New York: Harper and Row, 1981), p. 18.
- ¹²⁸ John D. Barrow and Frank J. Tipler, *The Anthropic Cosmological Principle* (New York: Oxford University Press, 1986), p. 677.
- ¹²⁹ Barrow and Tipler, pp. 677, 682.
- ¹³⁰ Hugh Ross, "Design and the Anthropic Principle" <[http:// www.reasons.org/ resources/ papers/ design.html](http://www.reasons.org/resources/papers/design.html)>.
- ¹³¹ Martin Gardner, "WAP, SAP, PAP, and FAP", in *The New York Review of Books*, 23 (May 8, 1986), No. 8 (1986), pp. 22-25.
- ¹³² "Mechanics", concise version of *Microsoft Encarta Encyclopedia* (©1997-2000), <[http:// encarta.msn.com/](http://encarta.msn.com/)>
- ¹³³ Robert Resnick and David Halliday, *Physics*, Part I (New York: John Wiley & Sons, Inc., 1966), p. 92.
- ¹³⁴ Resnick and Halliday, p. 93.
- ¹³⁵ Einstein, "Autobiographical Notes", pp. 35-37.
- ¹³⁶ Resnick and Halliday, pp. 132 - 138.
- ¹³⁷ Resnick and Halliday, p. 142.
- ¹³⁸ Resnick and Halliday, p. 143.
- ¹³⁹ Resnick and Halliday, pp.150-154.
- ¹⁴⁰ Resnick and Halliday, pp. 151-152.
- ¹⁴¹ Resnick and Halliday, p. 408.
- ¹⁴² Resnick and Halliday, p. 158.
- ¹⁴³ Gregoire Nicolis and Ilya Prigogine, *Exploring Complexity: An Introduction* (New York: W.H. Freeman and Company, 1989), p. 50.
- ¹⁴⁴ Resnick and Halliday, pp. 156-7.

END NOTES

- ¹⁴⁵ Resnick and Halliday, pp. 191-3.
- ¹⁴⁶ Nicolis and Prigogine, pp. 46-48.
- ¹⁴⁷ Prigogine, p. 111.
- ¹⁴⁸ Nicolis and Prigogine, pp. 47-48.
- ¹⁴⁹ Einstein, "Reply to Criticisms", pp. 687-8.
- ¹⁵⁰ Prigogine and Stengers, p. 259.
- ¹⁵¹ Kathleen T. Alligood, Tim D. Sauer, and James A. Yorke, *CHAOS: An Introduction to Dynamical Systems* (New York: Springer-Verlag, 1997), pp. 5, 78, 79.
- ¹⁵² Alligood, Sauer, and Yorke, pp. 9-10.
- ¹⁵³ Prigogine, p. 38.
- ¹⁵⁴ Prigogine, pp. 31-32.
- ¹⁵⁵ Prigogine, pp. 105-6.
- ¹⁵⁶ Charles S. Peirce, "The Doctrine of Necessity Examined" *The Monist* 2 (April 1892): 334, and Charles S. Peirce, "The Law of Mind", *The Monist* 2 (July 1892): 533-59, as cited in Joseph Brent's *Charles Sanders Peirce: A Life*, rev. & enlarged ed. (Bloomington and Indianapolis: Indiana University Press, 1993 & 1998), pp. 208-9.
- ¹⁵⁷ Prigogine, pp. 9-10.
- ¹⁵⁸ Alligood, Sauer, and Yorke, p. 106. (See also pp. 10 and 78.)
- ¹⁵⁹ Alligood, Sauer, and Yorke, p. 78.
- ¹⁶⁰ Alligood, Sauer, and Yorke, p. 87. (See also pp. 85-86.)
- ¹⁶¹ Alligood, Sauer, and Yorke, pp. 409-410.
- ¹⁶² Alligood, Sauer, and Yorke, p. 85.
- ¹⁶³ Prigogine and Stengers, p. 247.
- ¹⁶⁴ Prigogine, p. 33.
- ¹⁶⁵ Nicolis and Prigogine, p. 85.
- ¹⁶⁶ Prigogine and Stengers, p. 249.
- ¹⁶⁷ Prigogine, p. 34.
- ¹⁶⁸ Prigogine and Stengers, p. 265.
- ¹⁶⁹ Prigogine and Stengers, p. 267.

- ¹⁷⁰ Nicolis and Prigogine, pp. 48-9.
- ¹⁷¹ Nicolis and Prigogine, p. 93 and p. 271.
- ¹⁷² G.J. Sussman and J. Wisdom, "Chaotic evolution of the solar system", *Science* 257: 56-62 (1992), and J. Laskar, "A numerical experiment on the chaotic behaviour of the solar system", *Nature* 338: 237-8 (1989), as cited on pp. 99-101 of Alligood, Sauer, and Yorke.
- ¹⁷³ Nicolis and Prigogine, p. 116-117.
- ¹⁷⁴ Nicolis and Prigogine, pp. 90-91.
- ¹⁷⁵ Nicolis and Prigogine, p. 91.
- ¹⁷⁶ Nicolis and Prigogine, pp. 272-3.
- ¹⁷⁷ George M. Zaslavsky, "Chaotic Dynamics and the Origin of Statistical Laws", *Physics Today* (August 1999, Part 1), p. 42.
- ¹⁷⁸ Prigogine, p. 39.
- ¹⁷⁹ Prigogine, p. 40.
- ¹⁸⁰ Nicolis and Prigogine, p. 118.
- ¹⁸¹ Nicolis and Prigogine, p. 120.
- ¹⁸² Alligood, Sauer, and Yorke, pp. 106-108.
- ¹⁸³ Alligood, Sauer, and Yorke, p.110.
- ¹⁸⁴ J.C. Sprott, "Numerical Calculation of Largest Lyapunov Exponent" <<http://sprott.physics.wisc.edu/chaos/lyapexp.htm>> (1997-1998).
- ¹⁸⁵ [2.13] "Can computers simulate chaos?", *Nonlinear FAQ* <[http://amath.colorado.edu/appm/faculty/jdm/faq-\[2\].html](http://amath.colorado.edu/appm/faculty/jdm/faq-[2].html)>.
- ¹⁸⁶ Alligood, Sauer, and Yorke, p. 366.
- ¹⁸⁷ Zaslavsky, p. 44.
- ¹⁸⁸ William Barry, "Calvinism", *The Catholic Encyclopedia*, Vol III (1908) <<http://www.newadventorg/cathen/03198a.htm>>.
- ¹⁸⁹ J. Pohle, "Controversies on Grace", *The Catholic Encyclopedia*, Vol VI (1909) <<http://www.newadvent.org/cathen/06710a.htm>>.
- ¹⁹⁰ Resnick and Halliday, pp.150-154.
- ¹⁹¹ Resnick and Halliday, pp. 109-114.
- ¹⁹² Resnick and Halliday, pp. 560-561.

END NOTES

¹⁹³ Dilip Kondepudi and Ilya Prigogine, *MODERN THERMODYNAMICS: From Heat Engines to Dissipative Structures* (New York: John Wiley & Sons, 1998), p. 37.

¹⁹⁴ R. Clausius, *Ann Phys.*, Vol. 125 (1865), p. 353, as cited by Prigogine and Stengers, p. 119.

¹⁹⁵ Max Planck, *Treatise on Thermodynamics*, 3rd ed. (New York: Dover Press, 1945), as cited by Kondepudi and Prigogine, p. 39.

¹⁹⁶ Kondepudi and Prigogine, pp. 32-33.

¹⁹⁷ Kondepudi and Prigogine, p. 34.

¹⁹⁸ Kondepudi and Prigogine, p. 83.

¹⁹⁹ Frank L. Lambert, "Shuffled Cards, Messy Desks, and Disorderly Dorm Rooms – Examples of Entropy Increase? Nonsense!", *Journal of Chemical Education*, 76: 1385 (1999), as found on the internet at <<http://chemed.chem.wisc.edu/Journal/Issues/1999/Oct/abs1385.html>>.

²⁰⁰ Lambert, p. 1385.

²⁰¹ Kondepudi and Prigogine, pp. 68 ff.

²⁰² Kondepudi and Prigogine, pp. 69-70.

²⁰³ Kondepudi and Prigogine, p. 72.

²⁰⁴ Kondepudi and Prigogine, pp. 76-77.

²⁰⁵ Kondepudi and Prigogine, pp. 78-81; Resnick and Halliday, p. 633.

²⁰⁶ Kondepudi and Prigogine, pp. 80-81.

²⁰⁷ Kondepudi and Prigogine, pp. 81-83, 90.

²⁰⁸ Kondepudi and Prigogine, pp. 90-91.

²⁰⁹ Kondepudi and Prigogine, pp. 93-94.

²¹⁰ Kondepudi and Prigogine, p. 346; Nicolis and Prigogine, p. 64.

²¹¹ Kondepudi and Prigogine, pp. 94-95.

²¹² Kondepudi and Prigogine, pp. 156-7.

²¹³ Kondepudi and Prigogine, pp. 91-92.

²¹⁴ Prigogine and Stengers, pp. 244-246.

²¹⁵ Griffiths and Omnes, p. 31.

²¹⁶ Kondepudi and Prigogine, pp. 106 - 113.

- ²¹⁷ Kondepudi and Prigogine, p. 113.
- ²¹⁸ Kondepudi and Prigogine, p. 136.
- ²¹⁹ Kondepudi and Prigogine, pp. 113 - 115, 269 - 270.
- ²²⁰ Kondepudi and Prigogine, pp. 351-2.
- ²²¹ Kondepudi and Prigogine, p. 351.
- ²²² Kondepudi and Prigogine, pp. 353-4.
- ²²³ Kondepudi and Prigogine, pp. 357-8.
- ²²⁴ Kondepudi and Prigogine, p. 387.
- ²²⁵ Kondepudi and Prigogine, p. 393.
- ²²⁶ Kondepudi and Prigogine, p. 84.
- ²²⁷ Piero Scaruffi, "Thinking about Thought" <[http:// www.thymos.com/ tat/ emergenc.html](http://www.thymos.com/tat/emergenc.html)> (1998).
- ²²⁸ Nicolis and Prigogine, p. 27.
- ²²⁹ Nicolis and Prigogine, p. 28.
- ²³⁰ Nicolis and Prigogine, p. 192.
- ²³¹ Kondepudi and Prigogine, pp. 428-431.
- ²³² Kondepudi and Prigogine, p. 430.
- ²³³ Nicolis and Prigogine, pp. 8-15.
- ²³⁴ Nicolis and Prigogine, pp. 11-12.
- ²³⁵ Prigogine and Stengers, p. 163.
- ²³⁶ Nicolis and Prigogine, p. 13.
- ²³⁷ Nicolis and Prigogine, pp. 59-60, 171-173.
- ²³⁸ Nicolis and Prigogine, p. 60.
- ²³⁹ Nicolis and Prigogine, p. 24.
- ²⁴⁰ Prigogine and Stengers, p. 166.
- ²⁴¹ Jantsch, *The Self-Organizing Universe*, p. 49.
- ²⁴² Kondepudi and Prigogine, pp. 451-2.
- ²⁴³ William Poundstone, *The Recursive Universe: Cosmic Complexity and the Limits of Scientific Knowledge* (Chicago: Contemporary Books Inc., 1985), p. 26.

END NOTES

²⁴⁴ Poundstone, pp. 35-6.

²⁴⁵ Poundstone, pp. 196-7.

²⁴⁶ John Conway, Elwyn Berlekemp, and Richard Guy, *Winning Ways (for Your Mathematical Plays)* (New York: Academic Press, 1982), as cited by Poundstone, p.196.

²⁴⁷ Leon O. Chua, *CNN: A PARADIGM FOR COMPLEXITY* (World Scientific Series on Nonlinear Science, Series A, Vol. 31, 1998).

²⁴⁸ Gravner and Griffeath, *CA Growth: Introduction* <<http://psoup.math.wisc.edu/extras/rlshapes/page1a.html>>.

²⁴⁹ “Cellular Automaton Basics” <<http://classes.yale.edu/99-00/math190a/CABasics.html>>.

²⁵⁰ Jeremy Avnet, “Theory of Cellular Automata” <<http://www.theory.org/complexity/cdpt/html/node4.html>, June 6, 2000>.

²⁵¹ “Predicting Cellular Automaton Behavior” <<http://classes.yale.edu/99-00/math190a/Langton.html>>.

²⁵² “Predicting Cellular Automaton Behavior” <<http://classes.yale.edu/99-00/math190a/Langton.html>>.

²⁵³ Nicolis and Prigogine, pp. 140-141.

²⁵⁴ Russell K. Standish, “On Complexity and Emergence” <<http://parallel.hpc.unsw.edu.au/rks>, February 26, 2001>, p. 4.

²⁵⁵ Poundstone, pp. 185-189.

²⁵⁶ Poundstone, p. 190.

²⁵⁷ Prigogine and Stengers, p. 153.

²⁵⁸ Michael Behe, *Darwin's Black Box* (New York: Simon & Schuster, 1996), p. 39.

²⁵⁹ Behe, pp. 81-85.

²⁶⁰ Behe, pp. 264-5.

²⁶¹ Behe, p. 265.

²⁶² Behe, p. 53.

²⁶³ David Berlinski, “What Brings a World into Being?”, *Commentary* (April 2001).

²⁶⁴ Barry Commoner, “UNRAVELING THE DNA MYTH: The Spurious Foundation of Genetic Engineering”, *Harper's Magazine* (February 2002).

- ²⁶⁵ Behe, p. 269.
- ²⁶⁶ Barry Commoner, "UNRAVELING THE DNA MYTH: The Spurious Foundation of Genetic Engineering", *Harper's Magazine* (February 2002).
- ²⁶⁷ *Cold Spring Laboratory Press Release August 9, 2001* <<http://www.arn.org/docs2/news/histonecode81001.htm>>.
- ²⁶⁸ Richard C. Strohmman, "Towards an Epigenetic Biology & Medicine", *Network* (May 15, 1996) <<http://www.cmhc.com/perspectives/articles/art05963.htm>>.
- ²⁶⁹ Richard C. Strohmman, "Towards an Epigenetic Biology & Medicine".
- ²⁷⁰ Quoted by Tom Bethell in "A Map to Nowhere: The genome isn't a code , and we can't read it" in *The American Spectator* (April 17, 2001).
- ²⁷¹ Kondepudi and Prigogine, p. 431.
- ²⁷² Kondepudi and Prigogine, p. 432.
- ²⁷³ Prigogine and Stengers, p. 171.
- ²⁷⁴ Prigogine and Stengers, pp. 171-2, citing S.A. Kauffman, R.M. Shymko, and K. Trabert, "Control of Sequential Compartment Formation in *Drosophila*", *Science*, Vol. 199 (1978), pp. 259-69.
- ²⁷⁵ Jantsch, pp. 229-30.
- ²⁷⁶ Alligood, Sauer, and Yorke, pp.17-21.
- ²⁷⁷ Nicolis and Prigogine, pp 18-21.
- ²⁷⁸ Jantsch, p. 213.
- ²⁷⁹ Nicolis and Prigogine, pp. 20-21.
- ²⁸⁰ Javier G.P. Gamarra and Ricard V. Sole, "Bifurcations and Chaos in Ecology: Lynx Returns Revisited" <<http://www.santafe.edu/sfi/publications/Abstracts/99-10-067abs.html>>, pp. 3, 11.
- ²⁸¹ Alligood, Sauer, and Yorke, pp. 21-24.
- ²⁸² Prigogine and Stengers, pp. 204-5.
- ²⁸³ Nicolis and Prigogine, p. 239.
- ²⁸⁴ Nicolis and Prigogine, pp. 239-242.
- ²⁸⁵ Prigogine and Stengers, p. 197.
- ²⁸⁶ Alligood, Sauer, and Yorke, pp. 149-191.
- ²⁸⁷ Jantsch, pp. 43, 45, 57f., 148.

END NOTES

²⁸⁸ Alligood, Sauer, and Yorke, pp. 359-365.

²⁸⁹ Alligood, Sauer, and Yorke, pp. 370-375.

²⁹⁰ John Horgan, "From Complexity to Perplexity" in *Scientific American* (June 1995).

²⁹¹ Piero Scaruffi, "Thinking about Thought" <[http:// www.thymos.com/ tat/emergenc.html](http://www.thymos.com/tat/emergenc.html), 1998>.

²⁹² Ludwig von Bertalanffy, *General System Theory*, p. 213.

²⁹³ Ludwig von Bertalanffy, *General System Theory*, p. 70.

²⁹⁴ Ludwig von Bertalanffy, *General System Theory*, p. 73.

²⁹⁵ Phillip L. Engle, *WORLDVIEWS* (Philadelphia: Xlibris Press, 2000). (Oddly enough, Erich Jantsch actually manages to spin his philosophy of the *self-organizing universe* into an *individualistic* philosophy!)

²⁹⁶ *Catechism of the Catholic Church*, 2nd ed. (Liberia Editrice Vaticana, 1997), 365.

²⁹⁷ Christoph Schonborn, *God's Human Face*, trans. Lothar Krauth (San Francisco: Ignatius Press, 1994), p. 92.

²⁹⁸ Cited by Richard John Neuhaus in "The End of Endings", *First Things* (September 2001).

²⁹⁹ Richard John Neuhaus, "The End of Endings", *First Things* (September 2001).

³⁰⁰ Romans 8:19-23 (Revised Standard Version).

³⁰¹ Quoted by Trevor Palmer in "The Fall and Rise of Catastrophism" (based on a lecture given at Nottingham Trent University on April 25, 1996) <[http:// www.maths.ntu.ac.uk/ lsstaff/ fallc.htm](http://www.maths.ntu.ac.uk/~lsstaff/fallc.htm)>.

³⁰² "The Missoula Floods Controversy", Oregon Public Broadcasting <[http:// www.opb.org/ ofg/ 1001/ missoula/ theory.htm](http://www.opb.org/ofg/1001/missoula/theory.htm)>.

³⁰³ Walter Alvarez, *T. Rex and the Crater of Doom* (New York: Vintage Books, 1998).

³⁰⁴ Robert F. DeHaan, "Paradoxes in Darwinian Theory Resolved by a Theory of Macro-Development", *PSCF* 48 (September 1996): 180, "Introduction to the Phylo-Developmental Framework" (May 11, 1997) <[http:// www.macrodevelopment.org/ concept.html](http://www.macrodevelopment.org/concept.html)>, and "A Brief Critique of Evolution from the Developmental Perspective" (October 7, 1997) <[http:// www.macrodevelopment.org/ critiq.html](http://www.macrodevelopment.org/critiq.html)>.

- ³⁰⁵ Robert F. DeHaan, "Paradoxes in Darwinian Theory Resolved by a Theory of Macro-Development", *PSCF* 48 (September 1996): 180.
- ³⁰⁶ Robert F. DeHaan, "Paradoxes in Darwinian Theory Resolved by a Theory of Macro-Development", *PSCF* 48 (September 1996): 180.
- ³⁰⁷ Robert F. DeHaan, "Introduction to the Phylo-Developmental Framework" (May 11, 1997) <[http:// www.macrodevelopment.org/ concept.html](http://www.macrodevelopment.org/concept.html)>.
- ³⁰⁸ Robert F. DeHaan, "Introduction to the Phylo-Developmental Framework" (May 11, 1997) <[http:// www.macrodevelopment.org/ concept.html](http://www.macrodevelopment.org/concept.html)>, citing Niles Eldredge, *Evolutionary Macrodynamics* (New York: McGraw, 1989), p. 4.
- ³⁰⁹ John Whitfield, "Magical Numbers in Nature" (an interview with Ian Stewart), *Nature: Science Update* (October 28, 2001) <[http:// www.nature.com/ nsu/011018/ 011018-3.html](http://www.nature.com/nsu/011018/011018-3.html)>.
- ³¹⁰ Phillip E. Johnson, "God and Evolution: An Exchange", *First Things* (June 1993) <[http:// www.firstthings.com/ ftissues/ ft9306/ Johnson.html](http://www.firstthings.com/ftissues/ft9306/Johnson.html)>.
- ³¹¹ Robert F. DeHaan, personal communication to the author via email on November 27, 2000.
- ³¹² David Berlinski, "The Deniable Darwin", *Commentary*, vol. 101 no. 6 (June 1996).
- ³¹³ Berlinski, citing Richard Dawkins' book *The Blind Watchmaker*.
- ³¹⁴ David Berlinski, *Commentary* (September 1996): Reply to critics of his June 1996 article in *Commentary*, "The Deniable Darwin".
- ³¹⁵ Actually, the peppered-moth evidence is quite a bit more nuanced and complicated than this: See Jonathan Wells, *Icons of Evolution* (Washington D.C.: Regnery Publishing Inc., 2000), pp. 137- 158.
- ³¹⁶ Wells, pp. 159-176.
- ³¹⁷ Richard Milton, "Speciation?" <[http:// www.alternativescience.com / speciation.htm](http://www.alternativescience.com/speciation.htm), November 22, 1999>.
- ³¹⁸ John A. Davison, "An Evolutionary Manifesto: A New Hypothesis for Organic Change" (July 15, 2000) <[http:// moose.uvm.edu/ ~jcdavison/ Davison-manifesto.html](http://moose.uvm.edu/~jcdavison/Davison-manifesto.html)>.
- ³¹⁹ Richard Milton, "Darwin's Finches" <[http:// www.alternativescience.com / darwin's-finches.htm](http://www.alternativescience.com/darwin's-finches.htm), November 22, 1999>.
- ³²⁰ Cited by Wells, pp. 172-3.
- ³²¹ Davison, "An Evolutionary Manifesto".

END NOTES

- ³²² Lynn Margulis, “Gaia Is a Tough Bitch”, chapter 7 of *The Third Culture: Beyond the Scientific Revolution*, ed. John Brockman (New York: Simon & Schuster, 1995).
- ³²³ Luther Burbank, *Partner of Nature* (1939), p. 92, as cited in John A. Davison, “An Evolutionary Manifesto: A New Hypothesis for Organic Change” (July 15, 2000) <[http:// moose.uvm.edu/ ~jdavison/ davison-manifesto.html](http://moose.uvm.edu/~jdavison/davison-manifesto.html)>.
- ³²⁴ Pierre Grasse, *Evolution of Living Organisms* (1977), p. 130, as cited in Phillip E. Johnson, *Darwin on Trial* (Downers Grove IL: Intervarsity Press, 1993), p. 27.
- ³²⁵ Stuart B. Levy, “The Challenge of Antibiotic Resistance”, *Scientific American* (March 1998), p. 35.
- ³²⁶ Edward J. Steele, Robyn A. Lindley, and Robert V. Blanden, *Lamarck’s Signature: How Retrogenes Are Changing Darwin’s Natural Selection Paradigm* (Reading, MA: Perseus Books, 1998), p. 196.
- ³²⁷ Steele, Lindley, and Blanden, pp. 163-186.
- ³²⁸ Steele, Lindley, and Blanden, p. 191.
- ³²⁹ N. Eldredge and I. Tattersall, *The Myths of Human Evolution* (New York: Columbia University Press, 1982), pp. 45-46, 48.
- ³³⁰ Stephen Jay Gould, “Evolution’s Erratic Pace”, *Natural History* vol. 86, May 1977.
- ³³¹ J.B.C. Jackson and A.H. Cheetham, “Phylogeny reconstruction and the tempo of speciation in cheilostome Bryozoa”, *Paleobiology*, vol. 20 (1994), pp. 407-423, as cited by Rebecca Teed in “The Phyletic Gradualism – Punctuated Equilibrium Debate” <[http:// lrc.geo.umn.edu/ people/ teed/ papers/ macroev.html](http://lrc.geo.umn.edu/people/teed/papers/macroev.html)>, May 12, 1995.
- ³³² Donald R. Prothero, “Punctuated Equilibrium at Twenty: A Paleontological Perspective”, *Skeptic*, vol. 1, no. 3. Fall 1992, pp. 38-47.
- ³³³ Stephen Jay Gould, “Bushes and Ladders”, *Ever Since Darwin: Reflections in Natural History* (New York: W.W. Norton & Company, 1977), pp. 61-62.
- ³³⁴ Wesley Elsberry, “Punctuated Equilibria” <[http:// www.talkorigins.org/ faqs/ punc-eq.html](http://www.talkorigins.org/faqs/punc-eq.html)> (Feb 4, 1996).
- ³³⁵ Stephen Jay Gould, “Evolution: The Pleasures of Pluralism”, *New York Review of Books* (June 26, 1997), quoting from his own earlier 1980 paper.

³³⁶ Prothero, pp. 38-47.

³³⁷ Prothero, pp. 38-47.

³³⁸ For example, see Robert Wright, "The Accidental Creationist: Why Stephen Jay Gould Is bad for evolution", *The New Yorker*, December 13, 1999.

³³⁹ American Museum of Natural History, "Understanding Cladistics" <http://www.amnh.org/Exhibition/Fossil_Halls/cladistics.html>.

³⁴⁰ Michael Denton, *Evolution: A Theory in Crisis* (Chevy Chase, MD: Adler & Adler, 1986), pp. 111-113.

³⁴¹ Denton, pp. 275-278.

³⁴² Denton, pp. 274-307.

³⁴³ Denton, pp. 280-281.

³⁴⁴ Denton, p. 282.

³⁴⁵ Denton, p. 285.

³⁴⁶ Denton, pp. 285-286.

³⁴⁷ Denton, pp. 287-288.

³⁴⁸ M.E.J. Newman and R.G. Palmer, "Models of Extinction: A Review" <<http://www.phy.duke.edu/~palmer/papers/extinction99.pdf>>, p. 12, section 2.3.1.

³⁴⁹ Richard Goldschmidt, *The Material Basis of Evolution* (New Haven: Yale University Press, 1940), as cited by Gordon Rattray Taylor in *The Great Evolution Mystery* (London: Secker & Warburg, 1982), p. 162.

³⁵⁰ W. Ford Doolittle, "Uprooting the Tree of Life", *Scientific American* (February 2000), pp. 90-95.

³⁵¹ Denton, pp. 292-293.

³⁵² *The Darwin Reader*, ed. Mark Ridley (New York, London: W.W. Norton & Company, 1987), p. 97.

³⁵³ *The Darwin Reader*, p. 100.

³⁵⁴ *The Darwin Reader*, p. 103.

³⁵⁵ *The Darwin Reader*, p. 104.

³⁵⁶ Many others in the creationist movement and intelligent-design movement, such as Jonathan Wells and even Robert F. DeHaan, have made similar

END NOTES

observations. (See, for example, Wells' chapter on "Darwin's Tree of Life" in his book *Icons of Evolution*, pp. 29-58.)

³⁵⁷ *The Darwin Reader*, p. 103.

³⁵⁸ Denton, p. 297.

³⁵⁹ Denton, pp. 297-8.

³⁶⁰ W.J. Ewens, "Comments on Dr. Kimura's Paper", *Genetics Supplement*, *Genetics* (1973) 73:36-8, p. 36, as cited by Denton, p. 298.

³⁶¹ Denton, pp. 298-299.

³⁶² A.C. Wilson, S.S. Carlson, and T.J. White, "Biochemical Evolution" *Am. Rev. Biochem* (1977) 46:573-639, p. 611, as cited by Denton, p. 300.

³⁶³ Michael Behe, "Histone deletion mutants challenge the molecular clock hypothesis", *Trends in Biochemical Science*, 15:374-376 (October 1990), p. 375.

³⁶⁴ Denton, p. 301.

³⁶⁵ Denton, p. 301.

³⁶⁶ Denton, pp. 303-304.

³⁶⁷ Denton, pp. 304-305.

³⁶⁸ Denton, pp. 305 ff.

³⁶⁹ Denton, pp. 348-349.

³⁷⁰ Brian Foley, "Re: Genetic Code and Phenotype" (10/7/1996), *The MAD Scientist Network: Genetics* <<http://madsci.wustl.edu/posts/archives/dec96/834904210.Ge.r.html>>.

³⁷¹ Robert F. DeHaan, "Introduction to the Phylo-Developmental Framework" (May 11, 1997) <<http://www.macrodevelopment.org/concept.html>>.

³⁷² Gavin de Beer, *Homology: An Unsolved Problem* (London: Oxford University Press, 1971), pp. 15-16, as cited by Jonathan Wells, *Icons of Evolution*, p. 73.

³⁷³ Barry Commoner, "UNRAVELING THE DNA MYTH: The Spurious Foundation of Genetic Engineering", *Harper's Magazine* (February 2002).

³⁷⁴ Robert F. DeHaan, "Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment", *PSCF* 48:180 (September 1996).

³⁷⁵ Stephen Jay Gould, "Of Tongue Worms, Velvet Worms, and Water Bears", *Natural History* 104: 15 (1995), as cited by Robert F. DeHaan in "Paradoxes

in Darwinian Theory Resolved by a Theory of Macrodevelopment”, *PSCF* 48: 180 (September 1996).

³⁷⁶ D. Erwin, J. Valentine, and J. Sepkoski, “A Comparative Study of Diversification Events”, *Evolution*, vol. 41, p. 1183 (1988), as cited by DeHaan, “Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment”, *PSCF* 48: 180 (September 1996).

³⁷⁷ J. Z. Young, *The Life of Vertebrates*, 3rd ed. (Oxford: Clarendon, 1981), p. 577, as cited by Robert F. DeHaan in “Paradoxes in Darwinian Theory Resolved by a Theory of Macrodevelopment”, *PSCF* 48: 180 (September 1996).

³⁷⁸ Richard V. Sole and Mark Newman, “Patterns of Extinction and Biodiversity in the Fossil Record”, *Encyclopedia of Global Environmental Change* (Wiley, 2000) <<http://www.santafe.edu/sfi/publications/Abstracts/99-12-079abs.html>>.

³⁷⁹ Newman and Palmer, pp. 4-5, 12.

³⁸⁰ Niles Eldredge, *The Miner’s Canary: Unravelling the Mysteries of Extinction* (New York: Prentice Hall Press, 1991), pp. 93-5.

³⁸¹ Newman and Palmer, pp. 11-12.

³⁸² Von Bertalanffy, *General System Theory*, p. 172.

³⁸³ Niles Eldredge, *The Miner’s Canary*, pp. 57-58.

³⁸⁴ M.E.J. Newman and Paolo Sibani, “Extinction, diversity and survivorship of taxa in the fossil record” (Santa Fe Institute 1998, working paper: final paper *Proc. R. Soc. London B* 266, 1593-1600.), read off Figure 2 (data from Sepkoski, 1992).

³⁸⁵ Newman and Palmer, p. 6.

³⁸⁶ Trevor Palmer, “The Fall and Rise of Catastrophism”.

³⁸⁷ L.B. Halstead, *Dinosaurs* (Poole: Blandford Press, 1981), as cited by Trevor Palmer.

³⁸⁸ Trevor Palmer, “The Fall and Rise of Catastrophism”.

³⁸⁹ Sole and Newman, p. 3.

³⁹⁰ Read off Figure 2, p. 5 of Newman and Sabani.

³⁹¹ Niles Eldredge, *The Miner’s Canary*, p. 128.

³⁹² Niles Eldredge, *The Miner’s Canary*, pp. 80-81.

³⁹³ Sole and Newman, p. 2.

END NOTES

- ³⁹⁴ Sole and Newman, p. 2.
- ³⁹⁵ Niles Eldredge, *The Miner's Canary*, pp. 148-149.
- ³⁹⁶ Niles Eldredge, *The Miner's Canary*, pp. 137-138.
- ³⁹⁷ Newman and Palmer, pp. 8-9.
- ³⁹⁸ George Gaylord Simpson, *Tempo and Mode in Evolution* (New York: Columbia University Press, 1944), p. 143.
- ³⁹⁹ Newman and Palmer, p. 14.
- ⁴⁰⁰ Leigh Van Valen, "A New Evolutionary Law", *Evolutionary Theory* 1:1-30 (1973).
- ⁴⁰¹ Arthur L. Buikema, Jr. , "Survivorship Curves", *Bioinquiry* (John Wiley and Sons, 1999) <[http:// bioinquiry.boil.vt.edu/ bioinquiry/ Cheetah/ cheetachpaid/ cheetahhtmls/ popsurvivor.html](http://bioinquiry.boil.vt.edu/bioinquiry/Cheetah/cheetachpaid/cheetahhtmls/popsurvivor.html)>.
- ⁴⁰² Newman and Palmer, p. 15.
- ⁴⁰³ Niles Eldredge, *The Miner's Canary*, pp. 59-60.
- ⁴⁰⁴ Newman and Sibani, p. 2.
- ⁴⁰⁵ Newman and Palmer, p. 10.
- ⁴⁰⁶ Newman and Sibani, p. 15.
- ⁴⁰⁷ Gordon Rattray Taylor, *The Great Evolution Mystery* (London: Secker & Warburg, 1982), p. 27.
- ⁴⁰⁸ Taylor, p. 124.
- ⁴⁰⁹ Taylor, p. 29.
- ⁴¹⁰ Simpson, *Tempo and Mode in Evolution*, p. 178.
- ⁴¹¹ Eldredge, *The Miner's Canary*.
- ⁴¹² Simpson, *Tempo and Mode in Evolution*, pp. 178-179.
- ⁴¹³ Phillip E. Johnson, "The Extinction of Darwinism", *The Atlantic* (February 1992) <[http:// www.arn.org/ docs/ Johnson/ raup.htm](http://www.arn.org/docs/Johnson/raup.htm)>.
- ⁴¹⁴ *The Darwin Reader*, p. 93.
- ⁴¹⁵ Charles Darwin, *The Origin of the Species*, as cited by Phillip E. Johnson in his article "The Extinction of Darwinism".
- ⁴¹⁶ Niles Eldredge, *The Miner's Canary*, pp. 57-58.

- ⁴¹⁷ Phillip E. Johnson, "The Extinction of Darwinism", citing David M. Raup's book *Extinction: Bad Genes or Bad Luck?* (Norton, 1991).
- ⁴¹⁸ David M. Raup *Extinction: Bad Genes or Bad Luck* (Norton, 1991), as quoted by Phillip E. Johnson in his article "The Extinction of Darwinism".
- ⁴¹⁹ Phillip E. Johnson, "The Extinction of Darwinism".
- ⁴²⁰ Taylor, p. 86.
- ⁴²¹ Taylor, p. 88.
- ⁴²² Newman and Sibani, p. 2.
- ⁴²³ *The Darwin Reader*, p. 97.
- ⁴²⁴ Simpson, *Tempo and Mode in Evolution*, p. 143.
- ⁴²⁵ Simpson, *Tempo and Mode in Evolution*, p. 178.
- ⁴²⁶ Simpson, *Tempo and Mode in Evolution*, p. 177.
- ⁴²⁷ Taylor, p. 27.
- ⁴²⁸ Newman and Sibani, p. 2.
- ⁴²⁹ Von Bertalanffy, *General System Theory*, pp. 159-160.
- ⁴³⁰ Von Bertalanffy, *General System Theory*, p. 160.
- ⁴³¹ Richard Goldschmidt, *The Material Basis of Evolution* (New Haven: Yale University Press, 1940).
- ⁴³² Davison, "An Evolutionary Manifesto".
- ⁴³³ Davison, "An Evolutionary Manifesto"
- ⁴³⁴ Gerald M. Rubin, "Comparing Species", *Nature* 409:820-821 (February 15, 2001), p. 820.
- ⁴³⁵ John A. Davison, "Evolution as a self-limiting process" <<http://www.uvm.edu/~jdavison/dpaper.html>>. See also John A. Davison, "Semi-meiosis as an evolutionary mechanism", *J. Theor. Biol.* 111:725-735 (1984).
- ⁴³⁶ Davison, "An Evolutionary Manifesto".
- ⁴³⁷ Goldschmidt, p. 395, citing O.H. Schindewolf, *Paleontologie, Entwicklungslehre and Genetik* (Berlin: Borntrager, 1936), pp. 108ff.
- ⁴³⁸ Davison, "An Evolutionary Manifesto".
- ⁴³⁹ J.C. Willis, "The origin of species by large, rather than by gradual change and by Guppy's method of differentiation", *Ann. Bot.* 37:605-628 (1923), as cited by Goldschmidt, p. 212.

END NOTES

⁴⁴⁰ Goldschmidt, p. 244.

⁴⁴¹ “Vertebrate Genome Evolution and Evidence for Tetraploidization” <http://www.bu.edu/aldolase/aldolase/mol_evol/genevol.html>, citing S. Ohno *Evolution by Gene Duplication* (Heidelberg: Springer, 1970), and S. Ohno, U. Wolf, and N. Atkin (1986), “Evolution from fish to mammals by gene duplication”, *Hereditas* 59:169-187, and, finally, citing D. Tolan, J. Niclas, B. Bruce, and R. Lebo (1987), “Evolutionary Implications of the Human Aldolase-A, -B, -C, and Pseudogene Chromosome Locations”, *Am. J. Hum. Genet.* 41:907-924.

⁴⁴² Philip Hieter and Tony Griffiths, “Ploidy – More is More or Less”, *Science* 285:210 (July 9, 1999), citing T. Galitski *et al* in the same issue, p. 251.

⁴⁴³ Hieter and Griffiths, p. 210, citing I. Rozyman and T. L. Orr-Weaver, *Genes Cells* 3:767 (1998) and C. Lengauer, K. Kinzler, and B.H. Vogelstein, *Nature* 396:643 (1998).

⁴⁴⁴ K. Garbutt, “Polyploidy” <<http://www.as.wvu.edu/~jgarbutt/Papers2/Poly1.html>>, citing M.L. Becak and W. Becak, “Evolution by polyploidy in Amphibians: new insights”, *Cytogenet Cell Genet* 80:28-33 and V. Grant, *Plant Speciation* (New York: Columbia University Press, 1981).

⁴⁴⁵ Gallardo, Bickham, Honeycutt, Ojeda, and Kohler, “Discovery of Tetraploidy in a Mammal”, *Nature* 401:341 (Sept. 23, 1999).

⁴⁴⁶ J. Kimball, “Endoreplication” <<http://www.ultranet.com/~jkimball/Biology/Pages/E/Endoreplication.html>>.

⁴⁴⁷ Arnold H. Sparrow and Anne F. Nauman, “Evolution of Genome Size by DNA Doublings”, *Science* 192:524-529 (May 7, 1976), p. 528.

⁴⁴⁸ National Association of Biology Teachers, “Statement on Teaching Evolution” <http://www.nabt.org/sub/position_statements/evolution.asp>, as of December 21, 2001.

⁴⁴⁹ Goldschmidt, pp. 390-393.

⁴⁵⁰ Davison, “An Evolutionary Manifesto”.

⁴⁵¹ Ernst Mayr, *Population, Species, and Evolution* (Cambridge, Mass.: Belknap Press, 1970), p. 235.

⁴⁵² Taylor, p. 177.

⁴⁵³ Taylor, pp. 180-182.

- ⁴⁵⁴ Timothy Galitski, Alok J. Saldanha, Cora A. Styles, Eric S. Lander, and Gerald R. Fink, "Ploidy Regulation of Gene Expression", *Science* 285:251-254 (July 9, 1999), p. 253.
- ⁴⁵⁵ Taylor, p. 135.
- ⁴⁵⁶ Taylor, p. 135.
- ⁴⁵⁷ Taylor, p. 136.
- ⁴⁵⁸ Taylor, p. 137.
- ⁴⁵⁹ Thomas Kuhn, *The Structure of Scientific Revolutions* (2nd ed., 1970).
- ⁴⁶⁰ Taylor, p. 233, quoting from Ludwig von Bertalanffy, *The Problems of Life* (New York: Watts, 1952).
- ⁴⁶¹ David Berlinski, replying to letters critical of his essay "The Deniable Darwin" in *Commentary* magazine. Both these letters and Berlinski's reply appear in the September 1996 issue of *Commentary* <<http://www.commentarymagazine.com/9609/letters.html>>.
- ⁴⁶² National Association of Biology Teachers, "Statement on Teaching Evolution" <http://www.nabt.org/sub/position_statements/evolution.asp>, as of December 21, 2001.
- ⁴⁶³ Miller and Levine, *Biology* (Prentice Hall, 1995), p. 658.
- ⁴⁶⁴ Steven Jay Gould, "In Gratuitous Battle", *Civilization Magazine* (November 1998) <http://www.jamesmoody.4biz.net/drmoody/civ_mag_gould.html>.
- ⁴⁶⁵ Steven Jay Gould, "The Spandrels of San Marco and the Panglossian Paradigm; A Critique of the Adeptationist Program" (1978).
- ⁴⁶⁶ Steven Jay Gould, "The Pattern of Life's History", *The Third Culture*, Chapter 2 <<http://www.edge.org/documents/ThirdCulture/i-Ch.2.html>>.
- ⁴⁶⁷ George Gaylord Simpson, *The Meaning of Evolution*, rev. ed. (New Haven: Yale University Press, 1967), p. 345.
- ⁴⁶⁸ Davison, "An Evolutionary Manifesto".
- ⁴⁶⁹ Richard Dawkins, *The Blind Watchmaker* (1986), as cited by Phillip E. Johnson in *Darwin on Trial*, p. 9.
- ⁴⁷⁰ David Hull, reviewing Phillip E. Johnson's book *Darwin on Trial* in the scientific journal *Nature*, as cited by Phillip E. Johnson in "The Religion of the Blind Watchmaker" <<http://www.arn.org/docs/Johnson/watchmkr.htm>>.

END NOTES

- ⁴⁷¹ D.J. Futuyama, *Evolutionary Biology* (Sunderland MA: Sinauer Associates Inc., 1986), p. 2.
- ⁴⁷² Steven Jay Gould, *Wonderful Life*, as cited by Phillip E. Johnson in “The Religion of the Blind Watchmaker” <[http:// www.arn.org/ docs/ Johnson/ watchmkr.htm](http://www.arn.org/docs/Johnson/watchmkr.htm)>.
- ⁴⁷³ Teilhard de Chardin, *The Phenomenon of Man* (1959), as quoted by Phillip E. Johnson in *Darwin on Trial*, p. 132.
- ⁴⁷⁴ Phillip E. Johnson, *Darwin on Trial*, p. 132.
- ⁴⁷⁵ Benjamin Wiker, “Darwin and the Descent of Morality”, *First Things* 117:10-13 (November 2001).
- ⁴⁷⁶ Charles Darwin, *Descent of Man*, as quoted by Wiker.
- ⁴⁷⁷ Charles Darwin, *Descent of Man*, as quoted by Wiker.
- ⁴⁷⁸ Charles Darwin, *Descent of Man*, as quoted by Wiker.
- ⁴⁷⁹ Benjamin Wiker, “Darwin and the Descent of Morality”, *First Things* 117:10-13 (November 2001).
- ⁴⁸⁰ Benjamin Wiker, “Facts to the Wind: Reviewing *Monkey Trial*, a PBS Documentary”, in *National Online Review* (February 16, 2002).
- ⁴⁸¹ Stephen C. Meyer, “DNA and Other Designs”, *First Things* 102:30-38 (April 2000).
- ⁴⁸² Stephen C. Meyer, “DNA and Other Designs”, *First Things* 102:30-38 (April 2000).
- ⁴⁸³ William A. Dembski, “What every theologian should know about creation, evolution, and design” <[http:// www.leaderu.com/ offices/ dembski/ docs/bd-theologn.html](http://www.leaderu.com/offices/dembski/docs/bd-theologn.html)>, last updated October 19, 1998.
- ⁴⁸⁴ Dembski, citing Phillip E. Johnson.
- ⁴⁸⁵ Johnson, *Darwin on Trial*, pp. 109-110, 169-170.
- ⁴⁸⁶ Behe, *Darwin's Black Box*, pp.189-192.
- ⁴⁸⁷ Stephen C. Meyer, “DNA and Other Designs”, *First Things* 102:30-38 (April 2000).
- ⁴⁸⁸ Phillip E. Johnson, “Dembski and Kauffman Square off in New Mexico”, *Weekly Wedge Update*, November 19, 2001 <[http:// www.arn.org/ docs/ pjweekly/ pj_weekly_011119.htm](http://www.arn.org/docs/pjweekly/pj_weekly_011119.htm)>.

⁴⁸⁹ Leo Tolstoy, letter to the American international lawyer Ernest Howard Crosby, in *Tolstoy on Civil Disobedience and Nonviolence* (New York: Bergman/Signet/New American Library, 1967).

⁴⁹⁰ Prigogine and Stengers, pp. 222ff.

⁴⁹¹ Prigogine and Stengers, pp. 222ff.

⁴⁹² Rene Girard, *The Scapegoat*, trans. Yvonne Freccero (Baltimore: The Johns Hopkins University Press, 1986), p. 160.