Thermodynamics, Evolution, and Behavior

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It was Descartes's dualistic worldview that provided the metaphysical foundation for the subsequent success of Newtonian mechanics and the rise of modern science in the 17th century, and it was here at their modern origins as part of this dualistic worldview that psychology and physics were defined by their mutual exclusivity. According to Descartes, the world was divided into the active, striving, end-directed psychological part (the perceiving mind, thinking I, or Cartesian self) on the one hand, and the "dead" physical part on the other. The physical part of the world (matter, body), defined exhaustively by its extension in space and time, was seen to consist of reversible (without any inherent direction to time), qualityless particles governed by rigidly deterministic laws from which the striving, immaterial mind (without spatial or temporal dimension) was immune.

Arguing that the active, end-directed striving of living things in general (Descartes had limited the active part of the world to human minds) could not be adequately described or accounted for as part of a dead, reversible, mechanical world, Kant promoted a second major dualism, the dualism between physics and biology, or between the active striving of living things and their dead physical environments. The Cartesian-Kantian dualistic tradition was built into evolutionary theory with the ascendancy of Darwinism, in which physics was given no role to play and "organisms and environments were totally separated" (Lewontin, 1992, p. 108). The same Kantian argument for the "autonomy of biology" from physics based on the apparent incommensurability of physics with the active, end-directedness of living things has been used by leading proponents of Darwinism right up to recent times (e.g., Mayr, 1985).

In this century, Boltzmann's view (advanced during the last quarter of the 19th century) of the second law of thermodynamics as a law of disorder became the apparent physical basis for justifying the postulates of incommensurability, the first between psychology and physics and the second between biology and physics. With the physics of Newton the world consisted of passive particles that had to be ordered, but with Boltzmann's view the physical world was not just assumed to be "dead" or passive but also to be constantly working to destroy order. Given this view, it is "no surprise," in the words of Levins and Lewontin (1985, p. 19), "that evolutionists [came to] believe organic evolution to be the negation of physical evolution." As Ronald Fisher (1958, p. 39), one of the founders of neo-Darwinism, wrote about the apparent incommensurability between living things and their environments, between biology and physics, or, more particularly, between evolution and thermodynamics, "entropy changes lead to a progressive disorganization of the physical world . . . while evolutionary changes [produce] progressively higher organization."

Contrary to many of his contemporaries who simply accepted the postulates of incommensurability as given, Fisher wondered out loud about the unification of the two opposite directions apparently taken by evolution and thermodynamics under a deeper, more general principle. Although this did not happen in Fisher's lifetime, at the end of this century we can perform such a unification. It can now be shown that the active, end-directed, or intentional dynamics of living things, their reciprocal relation to their environments, and evolution as a general process of dynamically ordered things that actively work to bring more order into the world is the production of an active order-producing world following directly from natural law. For a fuller explanation of the ideas presented here the reader is particularly referred to Swenson (1991, 1992, 1995, 1997a, 1997b) and Swenson and Turvey (1991).

Evolutionary Ordering and the Limited Scope of Darwinian Theory

Although evolutionary theory as first articulated in the works of the Naturphilosophs and in the work of English scholars such as Chambers and Spencer, who first popularized the term *evolution,* were general theories of change in which physics, biology, and psychology were, in principle, commensurable parts of a universal law-based process, with the ascendancy of Darwinism the idea of evolution became progressively reduced in meaning. Today evolution and Darwinism are typically taken to be synonymous, and the "almost universally adopted definition of evolution is a change in gene frequencies" (Mayr, 1980, p. 12) following from natural selection. Whatever the internal differences there are between various sects of contemporary Darwinism, the core concept is that evolution is that which follows from natural selection (Depew & Weber, 1995). Natural selection is taken to be the fundamental explanation or true cause *(vera causa)* of evolution. In the final quarter of this century it has become widely recognized that an evolutionary theory so defined must itself, by definition, be fundamentally incomplete. It is not that any serious doubt has been cast on the fact of natural selection; it is that natural selection by itself is not sufficient for a comprehensive or robust evolutionary theory. In particular, natural selection cannot explain the active, end-directed striving of living things (the "fecundity principle"), nor can it address the fact of planetary evolution, a special case of the problem of the population of one.

The Fecundity Principle, or Biological Extremum

In the Darwinian view, evolution is taken to be the consequence of natural selection, but natural selection is itself the consequence of the active, end-directed striving—or intentional dynamics—of living things. Natural selection, said Darwin (1937, p. 152), follows from a population of replicating or reproducing entities with variation "striving to seize on every unoccupied or less well occupied space in the economy of nature." Because "every organic being" is "striving its utmost to increase, there is therefore the strongest possible power tending to make each site support as much life as possible" (p. 266). As Schweber (1985, p. 38) has written, paraphrasing Darwin, this says that nature "maximizes the amount of life per unit area" given the constraints. This makes up the content of the "fecundity principle" or "biological extremum," a principle stated in terms of a maximum or minimum, from which natural selection follows and on which it thus depends.

The problem is that if natural selection follows from, or depends on, the active striving of living things expressed by the fecundity principle, natural selection cannot explain this active striving—natural selection cannot explain or account for the sine qua non of the living. It must, in effect, by smuggled in ad hoc.

Darwin, who did not intend to address these issues with his theory, took the active properties of the living to have been "breathed into" dead matter by the Creator. The contemporary view has been that the active properties of the living came into the dead world of physics by an astronomically improbable "accident" that would only have to happen once (e.g., Dawkins, 1989). Given enough time, the argument goes, even an astronomically or infinitely improbable event can occur. Such an explanation, which is really no better than Darwin's, is unsatisfying for a number of reasons. For one thing such infinitely improbable "accidents" would have had to have happened not once but repeatedly to produce the evolutionary record we see. For another, the evolutionary record as it is now known shows that life arose on Earth and persisted not after some long period of lifeless time but as soon as the Earth was cool enough to keep the oceans from evaporating—as soon as it had the chance. This is the picture we now know of evolutionary ordering in general. Order typically arises as soon as it gets the chance, as soon as some constraint is removed or some minimal threshold reached; the urgency towards existence expressed in the fecundity principle is seen in the evolutionary record writ large, which is opposite on both counts with respect to the second law of thermodynamics as a law of disorder.

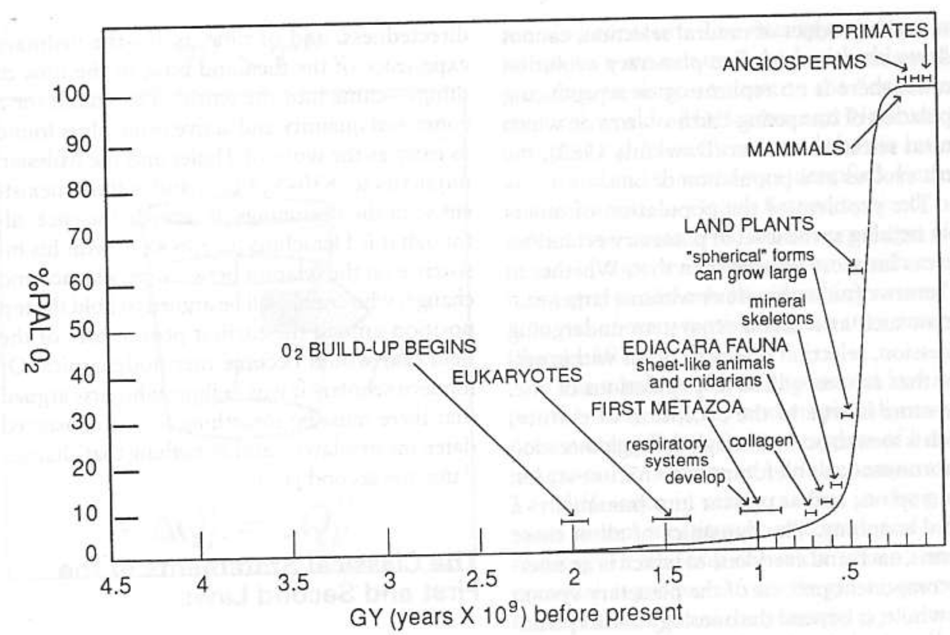

Figure 1. Buildup of atmospheric O_2 in geological time (PAL is present atmospheric level). From Swenson, (1989a), p. 71. Copyright © 1989 IEEE. Reprinted by permission.

The Problem of the Population of One

Life as a Planetary Process

One of the most important empirical facts recognized in recent decades is that the Earth at the planetary level evolves as a single global entity (e.g., Cloud, 1988; Margulis & Lovelock, 1974; Schwartzman, Shore, Volk & McMenamin, 1994; Swenson & Turvey, 1991; Vernadsky, 1986). The present oxygen rich atmosphere, put in place and maintained by life over geological time, is perhaps the most obvious prima facie evidence for the existence and persistence of the planetary entity. With the shift of the Earth's redox state from reducing to oxidative some 2 billion years ago, evolution undeniably became a coherent planetary process. Figure 1 shows the redox state shift and the increase in atmospheric oxygen over evolutionary time that followed until it reached its present atmospheric level. Figure 1 also shows the progressive emergence of more highly ordered forms as a function of increasing levels of atmospheric oxygen. Studies with shapes of things and their metabolic and respiration capacities (e.g., Runnegar, 1982) suggest that order (as noted before) seems to come into being as soon as minimal thresholds (in this case, oxygen) are reached. Both the progressive increase in atmospheric oxygen and the production of increasingly more highly ordered states constitute an accelerating departure of the global system from equilibrium, again (as Fisher noted) running opposite to that generally assumed to be the predicted direction for physical evolution according to the second law.

The Problem for Darwinian Theory

The fact that the evolution and persistence of all the higher-ordered living states that have been the typical objects of evolutionary study (e.g., sexually reproducing animals) are dependent on a rich and steady supply of atmospheric oxygen makes them dependent upon the prior evolution and persistence of life at the planetary level for their existence. More precisely, they are internal productions of the larger planetary process, or in Vernadsky's (1986, p. 489) words, they are regular "functions" of the biosphere. This suggests that the study of evolution at the planetary level is the study of the most fundamental entity of terrestrial evolution without an understanding of which all the other living things that are effectively component productions will never be understood. Yet this poses a major problem for Darwinian theory because the planetary system as a whole cannot, by definition, be considered a unit of Darwinian evolution (Maynard-Smith, 1988). Darwinian theory, which defines evolution as the product of natural selection, cannot address or even recognize planetary evolution because there is no replicating or reproducing population of competing Earth systems on which natural selection can act (Dawkins, 1982); the Earth evolves as a population of one.

The problem of the population of one is most striking at the level of planetary evolution, but it is far more general than that. Whether in the rumen of an herbivore or within a larger ecosystem such as a forest ecosystem undergoing succession, selection is seen to occur within systems that are recognized as populations of one. The same is true in the evolution of culture, which is seen to occur through the agglomeration of autonomous chiefdoms into nation-states, into empires, and at present into (minimally) a global economy. The dynamics of all of these systems, each and every one of which is an internal component process of the planetary system as a whole, is beyond the ontology and explanatory framework of evolution following from natural selection. Natural selection is seen to be a process internal to the evolution of a population of one, and it cannot explain the systems to which it is internal. This suggests the need for a physical selection principle, since if selection is not between replicating or reproducing entities it cannot, by definition, be biological—a principle that would account for the selection of macro (ordered) from micro (disordered) modes, that would account for spontaneously ordered systems, and from which the fecundity principle could be derived.

The First and Second Laws of Thermodynamics

The first and second laws of thermodynamics are not ordinary laws of physics. Because the first law, the law of energy conservation, in effect unifies all real-world processes, it is a law on which all other laws depend. In more technical terms, it expresses the time-translation symmetry of the laws of physics themselves. Eddington (1929) has argued that the second law holds the supreme position among all the laws of nature because it not only governs the ordinary laws of physics but the first law as well. If the first law expresses the underlying symmetry principle of the natural world (that which remains the same), the second law expresses the broken symmetry (that which changes). It is with the second law that a basic nomological understanding of end-directedness, and of time itself—the ordinary experience of the then and now, of the flow of things—came into the world. The search for a conserved quantity and active principle is found as early as the work of Thales and the Milesian physicists (c. 630–524 B.C.) and is thus coexistent with the beginnings of recorded science, although it is Heraclitus (c. 536 B.C.), with his insistence on the relation between persistence and change, who could well be argued to hold the top position among the earliest progenitors of the field that would become thermodynamics. Of modern scholars it was Leibniz who first argued that there must be something that is conserved (later, the first law)—and something that changes (later, the second law).

The Classical Statements of the First and Second Laws

Following the work of Davy and Rumford, the first law was first formulated by Mayer, then Joule, and later Helmoholtz in the first half of the 19th century, with various demonstrations of the equivalence of heat and other forms of energy. The law was completed in this century with Einstein's demonstration that matter is also a form of energy. The first law says that (1) all real-world processes consist of transformations of one form of energy into another and that (2) the total amount of energy in all real-world transformations always remains the same or is conserved. Among the many profound implications of the first law is the impossibility of Cartesian dualism and all its descendent variants, which entail the interaction of a world split into one part governed by a conservation principle and the other not.

The first law was not fully understood until the second law was formulated by Clausius and Thomson in the 1850s. Some 25 years earlier Carnot had observed that like the fall of a stream that turns a mill wheel, the "fall" of heat from higher to lower temperatures motivates a steam engine. That this work showed an irreversible destruction of "motive force," or the potential for producing change, suggested to Clausius and Thomson that either the first law was false—energy was not conserved—or energy was not the motive force for change. Recognizing that the active principle and the conserved quantity could not be the same, they realized that there were two laws at work and showed their relation. Clausius coined the word

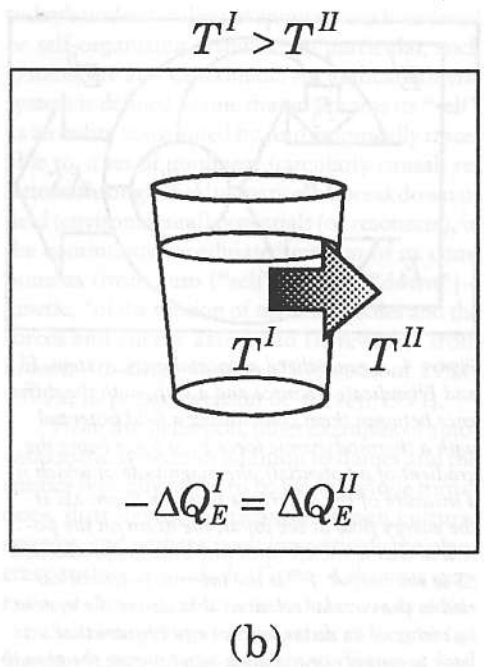

Figure 2. A glass of liquid at temperature T^I is placed in a room at temperature T^{II} so that $T^I > T^{II}$. The disequilibrium produces a field potential that spontaneously drives a flow of energy in the form of heat from the glass to the room in order to drain the potential until it is minimized (the entropy is maximized), at which time thermodynamic equilibrium is reached and all flows stop. The expression refers to the conservation of energy in that the flow from the glass equals the flow of heat into the room. From Swenson (1991), p. 45. Copyright © 1991 Intersystems Publications. Adapted by permission.

entropy[1] to refer to the dissipated potential, and the second law states that all natural processes proceed in order to maximize the entropy (or equivalently, minimize or dissipate the potential),[2] while energy, at the same time, is entirely conserved. The balance equation of the second law, expressed as $\Delta S > 0$, says that in real-world processes entropy always increases.

In Clausius's (1865, p. 400) words, the two laws thus became: "The energy of the world remains constant. The entropy of the world strives to a maximum." And with this understanding, in sharp contrast to the "dead" mechanical world of Descartes and Newton, the nomological basis for a world that is instead active and end-directed was identified. Entropy maximization, as Planck first recognized, provides a final cause (in Aristotle's typology) of all natural processes—"the end to which everything strives and which everything serves" or "the end of every motive or generative process" (Bunge, 1979, p. 32).

The active nature of the second law is intuitively easy to grasp and empirically easy to demonstrate. Figure 2 shows a glass of hot liquid placed in a room at a cooler temperature. The difference in temperatures in the glass-room system constitutes a potential, and a flow of energy in the form of heat, a "drain" on the potential, is produced from the glass (source) to the room (sink) until the potential is minimized (the entropy is maximized) and the liquid and the room are at the same temperature. At this point, all flows and thus all entropy production stops ($\Delta S=0$) and the system is at thermodynamic equilibrium.

The same principle applies to any system in which any form of energy is out of equilibrium with its surroundings; a potential exists that the world acts spontaneously to minimize. In addition to the temperature difference shown in Figure 2, Figure 3 shows some other examples of potentials.

The Second Law as a Law of Disorder

The active, macroscopic nature of the second law presented a profound blow to the mechanical worldview that Boltzmann attempted to save by reducing the second law to the stochastic collisions of mechanical particles: a law of probability. Modeling gas molecules as colliding billiard balls, Maxwell had shown that nonequilibrium

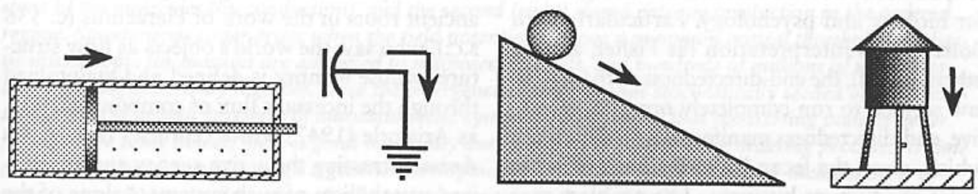

Figure 3. Further examples of potentials that follow from nonequilibrium distributions of energy. Whenever energy (in whatever form) is out of equilibrium with its surroundings, a potential exists for producing change.

velocity distributions (groups of molecules moving at the same speed and in the same direction) would become increasingly disordered with each collision, leading to a final state of macroscopic uniformity and maximum microscopic disorder. Boltzmann recognized this state as the state of maximum entropy. Given this, he argued, the second law was simply the result of the fact that in a world of mechanically colliding particles, disordered states are the most probable. There are so many more possible disordered states than ordered ones that a system will almost always be found either in the state of maximum disorder—the macrostate with the greatest number of accessible microstates, such as a gas in a box at equilibrium—or moving towards it. A dynamically ordered state, in which molecules move "at the same speed and in the same direction . . . is the most improbable case conceivable . . . an infinitely improbable configuration of energy" (Boltzmann, 1974, p. 20).

Although Boltzmann himself acknowledged that his hypothesis of the second law had only been demonstrated for the case of a gas in a box near equilibrium, the science of his time was dominated by linear, near-equilibrium, or equilibrium thinking, and his hypothesis became widely accepted. What we understand today, in effect, is that the world is not a linear, near-equilibrium system like a gas in a box, but is instead nonlinear and far from equilibrium, and that neither the second law nor the world itself is reducible to a stochastic collision function. As the next section outlines, we now can see that spontaneous ordering, rather than being infinitely improbable, is the expected consequence of physical law.

The Law of Maximum Entropy Production, or Why the World Is in the Order-Production Business

Active, end-directed behavior was introduced nomologically into the world with the second law, but it did not at all seem to be the right kind for biology and psychology. Particularly with Boltzmann's interpretation (as Fisher, among others, noted), the end-directedness of the second law seemed to run completely opposite the active, end-directedness manifested by living things which, given the fecundity principle, are in the order-production business. The problem was partly put aside in the middle of this century when Bertalanffy (e.g., 1952, p. 145) showed

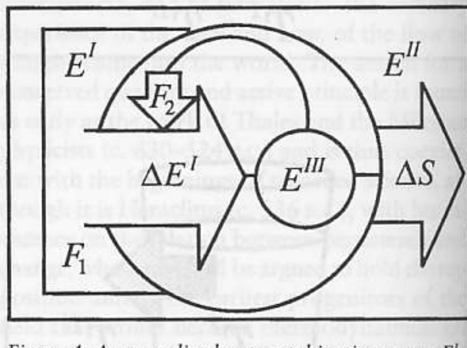

Figure 4. A generalized autocatakinetic system. E^I and E^{II} indicate a source and a sink, with the difference between them constituting a field potential with a thermodynamic force F_1 (a force being the gradient of a potential), the magnitude of which is a measure of the difference between them. ΔE^I is the energy flow at the input, the drain on the potential that is transformed into entropy production ΔS at the output. E^{III} is the internal potential carried in the circular relations that define the system by virtue of its distance from equilibrium that acts back to amplify or maintain input during the growth or nongrowth phases, respectively, with an internal force F_2. From Swenson (1989b), p. 191. Copyright© 1989 Pergamon. Adapted by permission.

that "spontaneous order . . . can appear in [open] systems" (systems with energy flows running through them) by virtue of their ability to build their order by dissipating potentials in their environments. Along the same lines and pointing to the balance equation of the second law, Schrödinger (1945) popularized the idea of living things as streams of order that like flames, are permitted to exist away from equilibrium because they feed off "negentropy" (potentials) in their environments. These ideas were further popularized by Prigogine (e.g., 1978), who called such systems "dissipative structures."

Self-Organizing Systems Are Autocatakinetic

The comparison of living things to flames has ancient roots in the work of Heraclitus (c. 536 B.C.), who saw the world's objects as flow structures whose identity is defined and maintained through the incessant flux of components. Fire, as Aristotle (1947) wrote centuries later in *De Anima*, stressing the active agency and generalized metabolism of such systems, "alone of the primary elements is observed to feed and increase itself" (p. 182). These ideas are at the root of today's understanding of spontaneously ordered or self-organizing systems.[3] In particular, such systems are autocatakinetic. An autocatakinetic system is defined as one that maintains its "self" as an entity constituted by, and empirically traceable to, a set of nonlinear (circularly causal) relations through the dissipation or breakdown of field (environmental) potentials (or resources), in the continuous coordinated motion of its components (from auto ["self"] + cata ["down"] + kinetic, "of the motion of material bodies and the forces and energy associated therewith," from *kinein*, "to cause to move") (Swenson, 1991, 1997a, in press; Swenson & Turvey, 1991).

From this definition, other examples of autocatakinetic systems in addition to flames and the entities typically taken to be living include tornadoes, dust devils, hurricanes, human cultural systems, and perhaps most interestingly the planetary system as a whole. Figure 4 shows a generalized drawing of an autocatakinetic system.

Schrödinger's point was that as long as living things, like all autocatakinetic systems, produce entropy at a sufficient rate to compensate for their own internal ordering, then the balance equation of the second law would not be violated. According to this view, living things were "permitted" to exist—as it became popular to say—as long as they "paid their entropy debt." This works for the classical statement of the second law per Clausius and Thomson, but according to Boltzmann's view such "debt payers" are still infinitely improbable. Living things—and a fortiori, evolution as a planetary process as a whole—are still infinitely improbable states struggling against the laws of physics; the urgency towards existence captured in the fecundity principle and in planetary evolution as a whole as suggested by Figure 1, where order arises as soon as it gets the chance, is entirely anomalous in this view with respect to universal law.

Spontaneous Ordering in a Simple Physical System: Order Production With a Probability of One

In fact it is not just life that seems to go against the second law as a law of disorder, Boltzmann's hypothesis is easily and repeatedly falsified with simple physical experiments. Figure 5 shows two time slices in the now well-known Bénard

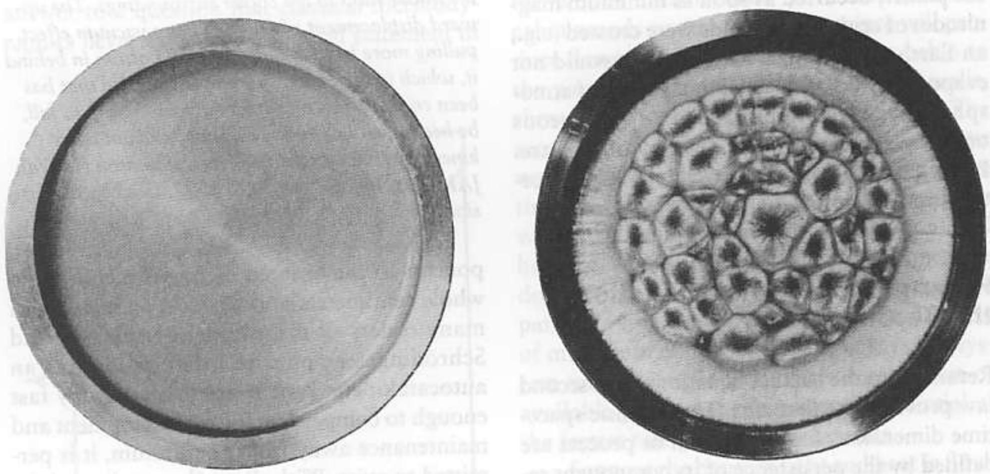

Figure 5. Two time slices from the Bénard experiment. The first time slice (left) shows the homogeneous or disordered "Boltzmann regime," in which entropy is produced by heat flow from the disordered collisions of the molecules (by conduction); and the second (right) shows entropy production in the ordered regime. Spontaneous order arises when the field potential is above a minimum critical threshold, stochastic microscopic fluctuations are amplified to macroscopic levels, and hundreds of millions of molecules begin moving coherently together. Since the emergence of order is thus stochastically seeded at the microscopic level (a generic property of autocatakinetic systems, which means that the starting point is never precisely the same twice), there is great variability during the early stages of the ordering process. As time goes on, the system goes through a generic developmental process of selection, which includes such dynamics as spontaneous fissioning of cells and competitive exclusion until the system reaches a final state of regularly arrayed hexagonal cells (not shown). From Swenson (1989b), p. 192. Copyright © 1989 by Pergamon. Reprinted by permission.

experiment, which consists of a viscous liquid held in a circular dish between a uniform heat source below and the cooler temperature of the air above. The difference in temperatures constitutes a potential (or thermodynamic force F), the magnitude of which is determined by the extent of the difference. When F is below a critical threshold, the system is in the disordered or linear "Boltzmann regime," and a flow of heat is produced from source to sink as a result of the disordered collisions of the molecules and the macroscopic state appears smooth and homogeneous (see left). As soon as F is increased beyond a critical threshold, however, the symmetry of the disordered regime is broken and order spontaneously emerges as hundreds of millions of molecules begin moving collectively together (see right).

According to Boltzmann's hypothesis of the second law, such states are infinitely improbable, but here, on the contrary, order emerges with a probability of one, that is, every time F is increased above the critical threshold. What is the critical threshold? It is simply the minimum value of F that will support the ordered state. Just as the empirical record suggests that life on Earth, the global ordering of the planet, occurred as soon as minimum magnitudes of critical thresholds were crossed (e.g., an Earth cool enough so its oceans would not evaporate or as soon as minimal levels of atmospheric oxygen were reached), spontaneous ordering occurs as soon as it gets the chance. But what is the physical basis for such opportunistic ordering?

Return to the Balance Equation of the Second Law

Returning to the balance equation of the second law provides the first clue. The intrinsic space-time dimensions for any system or process are defined by the persistence of its component relations. Since in the disordered regime there are no component relations persisting over greater distances or longer times than the distances and times between collisions, it is easy to see that the production of order from disorder thus increases the space-time dimensions of a system. In the Bénard case, for example, the intrinsic space-time dimensions of the disordered regime are on the order of 8^{-10} cms and 10^{-15} s, respectively. In stark contrast, the new space-time level defined by the coordinated motion of the components in the ordered regime is measured in whole centimeters and seconds, an increase of many orders of magnitude. Bertalanffy and Schrödinger emphasized that as long as an autocatakinetic system produces entropy fast enough to compensate for its development and maintenance away from equilibrium, it is permitted to exist. With the understanding of the relation between intrinsic space-time dimensions and order production we can get a physical understanding of how this works.

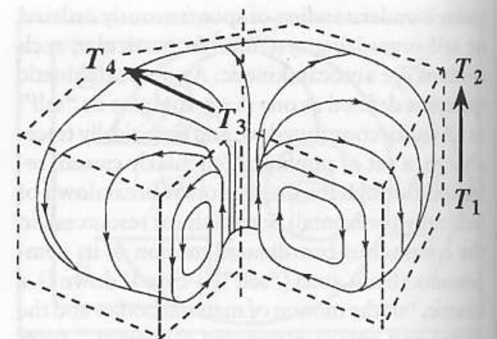

Figure 6. The autocatakinetic flow of the fluid constituting a Bénard cell is shown by the small arrows. T_1 —> T_2 the heat gradient between the heat source below and the sink above, constitutes the potential that motivates the flow. Because density varies inversely with temperature, there is also a density gradient from bottom to top giving groups of molecules ("parcels") that are displaced upwards by stochastic collisions an upward buoyant force. If the potential is above the minimum threshold, parcels will move upward at a faster rate than their excess heat can be dissipated to their surroundings. At the same time such an upward flow of heat will increase the temperature of the upper surface directly above it, creating a surface tension gradient T_3 —> T_4 which will act to further amplify the upward flow by pulling the hotter fluid to the cooler surroundings. The upward displacement of fluid creates a vacuum effect, pulling more heated fluid from the bottom in behind it, which in turn makes room for the fluid that has been cooled by its movement across the top to fall, be heated, and carry the cycle on; and autocatakinesis has been established. From Swenson (1997a). JAI Press, Inc. Copyright © 1997. Used by permission.

Figure 6 is a schematic drawing of the generalized pattern of flow that defines the new space-time level in the ordered regime of the Bénard experiment. It shows the ordered flow moving hot fluid up from the bottom through the center, across the top surface where it is cooled by the air, and down the sides where it pulls in more potential as it moves across the bottom and then rises through the center again as the cycle repeats. Figure 7 shows the dramatic increase in entropy production that occurs with the switch to the ordered regime, and this is just what we would expect from the balance equation of the second law. Ordered flow must function to increase the rate of entropy production of the system plus environment—must pull in sufficient resources and dissipate them—to satisfy the balance equation. In other words, ordered flow must be more efficient at dissipating potentials than disordered flow, and we see how this works in a simple physical system. The fact that ordered flow is more efficient at minimizing potentials brings us to the final piece in the puzzle.

The Law of Maximum Entropy Production

The puzzle's crucial final piece—which provides the nomological basis for spontaneous order production and for dissolving the postulates of incommensurability between physics and psychology and between physics and biology (between thermodynamics and evolution)—is the answer to a question that classical thermodynamics never asked. The classical statement of

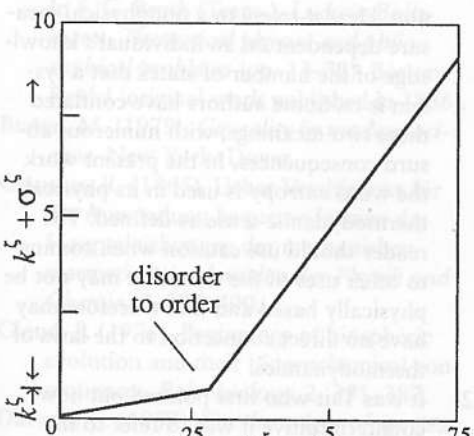

Figure 7. The discontinuous increase in the rate of heat transport that follows from the disorder-to-order transition in a simple fluid experiment. The rate of heat transport in the disordered regime is given by k^{ξ}, and $k^{\xi} + \sigma^{\xi}$ is the heat transport in the ordered regime [$3.1 \times 10^{-4}H(cal \times cm^{-2} \times sec^{-1})$]. From Swenson (1989a), p. 70. Copyright © 1989 IEEE. Reprinted by permission.

the second law says that entropy will be maximized, or potentials minimized, but it does not ask or answer the question of which of the available paths a system will take to accomplish this end. The answer to the question is that the system will select the path or assembly of paths, out of otherwise available paths, that minimize the potential or maximize the entropy at the fastest rate given the constraints. This is a statement of the law of maximum entropy production, the physical selection principle that provides the nomological explanation (as will be seen below) for why the world is in the order-production business (Swenson, 1988, 1991, 1992, 1997a, 1997b, in press; Swenson & Turvey, 1991). Note that the law of maximum entropy production is in addition to the second law. The second law says only that entropy is maximized, whereas the law of maximum entropy production says it is maximized—potentials minimized—at the fastest rate given the constraints. Like the active nature of the second law, the law of maximum entropy production is intuitively easy to grasp and empirically easy to demonstrate.

Consider the case of the warm mountain cabin sitting in cold, snow-covered woods. The difference in temperature between the cabin and the woods constitutes a potential, and the cabin-woods system as a consequence will produce flows of energy as heat from the cabin to the woods (by conduction through the walls, through the crack under the door, etc.). The second law says that if the fire in the wood stove warming the cabin goes out, then at some future time the temperature of the cabin and the woods will be the same and the potential will have been minimized. What the second law does not say is which paths out of available paths the system will select to do this. The law of maximum entropy production says the system will select the assembly of paths out of available paths that minimize the potential at the fastest rate given the constraints.

Suppose the house is tight and heat is flowing to the outside primarily by conduction through the walls. Imagine now opening a window or a door, which amounts to removing a constraint on the rate of dissipation. What we know intuitively, and can confirm by experiment, is that whenever a constraint is removed and a new path or drain is provided that increases the rate at which the potential is minimized, the system will seize the opportunity. In addition, since the opened window, for example, will not instantaneously drain all the potential, some will still be allocated to conduction through the walls. Each path will drain all that it can, the fastest procuring the greatest amount of potential, with what is left going to the slower paths. The point is that no matter what the specific conditions, or the number of paths or drains, the system will automatically select the assembly of paths from among those otherwise available in order to get the system to the final state (to minimize or drain the potential) at the fastest rate given the constraints. This is the essence of the law of maximum entropy production.

Given what has already been discussed, the reader may have already leaped to the correct conclusion. If the world selects those dynamics that minimize potentials at the fastest rate given the constraints, and if ordered flow is more efficient at reducing potentials than disordered flow, then the world will select order whenever it gets the chance; the world is in the order-production business because ordered flow produces entropy faster than disordered flow (Swenson, 1988, 1991, 1992, 1997a; Swenson & Turvey, 1991), and this means the world can be expected to produce as much order as it can. Autocatakinetic systems are self-amplifying sinks that, by pulling potentials or resources into their own self-production, extend the space-time dimensions and thus the dissipative surfaces of the fields from which they emerge, and thereby increase the dissipative rate.

Conclusion

The postulates of incommensurability built into the foundations of modern science and reinforced by the view that the second law of thermodynamics was a law of disorder have produced what Lakatos (1970) has called a "degenerative problem shift." A research program, paradigm, or worldview becomes degenerative when its core postulates are, in balance, more negative than positive with respect to an expanded understanding of the natural world. The postulates of incommensurability have left the most fundamental aspects of biology and psychology—in particular the active, end-directed nature of living things and their relation to their environments (at the largest terrestrial scale, the self-organizing planetary system as a whole)—unexplained and unapproachable.

Ecological psychologists (e.g., Gibson, 1986), arguing that living things and their environments must be seen as single systems, have historically rejected the postulates of incommensurability and instead have adopted living thing/environment mutuality or reciprocity as a basic postulate. The law of maximum entropy production, when coupled with the balance equation of the second law and the general process of autocatakinesis, shows how this postulate can be directly derived. New insights into the relation between thermodynamics and evolutionary theory thus provide a rich new context for understanding the active, end-directedness of living things and for grounding biology and, a fortiori, psychology in a commensurable context of universal law. Rather than being infinitely improbable "debt payers" struggling against the laws of physics in a "dead" world collapsing toward equilibrium and disorder, living things and their active, end-directed striving or intentional dynamics can now be seen as productions of an active order-producing world following directly from natural law.

Notes

1. Since its coinage by Clausius to refer to the dissipated potential in a system, the word *entropy* has been used to refer to numerous other measures that are not at all equivalent. One example is the use of the word in information theory by Shannon. Here it refers to a nonphysical measure dependent on an individual's knowledge of the number of states that a system is in. Some authors have conflated these two meanings, with numerous absurd consequences. In the present work the word *entropy* is used in its physical thermodynamic sense as defined. The reader should use caution when coming to other uses of the term that may not be physically based and that therefore may have no direct connection to the laws of thermodynamics.
2. It was Tait who first pointed out how counterintuitive it was to refer to the dissipative potential of a system as a quantity that increased, and he proposed reversing the sign so that it would be possible to talk about entropy (as the potential for change) being minimized. Maxwell picked up on this, but it never caught on. Because the idea of entropy increase is often hard to conceive, in this text I will often use "minimize the poten-

tial" in addition to or instead of "maximize the entropy." They should be taken as equivalent expressions.

3. The word *self-organizing* (used here synonymously with "spontaneously ordered") is another word like entropy that is currently used to describe a whole variety of systems that are quite different from one another and that should not be conflated. The term *autocatakinetic* is particularly useful to make the distinction between "real world" self-organizing systems as defined and what might be more appropriately called "programmed self-organizing systems," to refer to various types of rule-based systems that are run on computers and that are not autocatakinetic. All rule-based systems are ultimately internal productions of autocatakinetic systems, but the reverse is not true.

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