Order, Evolution, and Natural Law: Fundamental Relations in Complex System Theory

Rod Swenson  University of Connecticut, Storrs, Connecticut

I. BACKGROUND AND PREVIEW
A. Reductive Materialism and the Roots of the Modern Scientific World View

Following the virulent attacks on Aristotelian causality by Bacon and Descartes, the stunning success of Newtonian mechanics paved the way for the construction of a modern scientific enterprise, built (as Bacon claimed it should be [1]) almost entirely on efficient cause—on summativity, reversibility, and determinism. The reductive materialism of this “purposeless-particle” world view effectively eliminated all goals, purposes, intentions, or other end-directed behavior from the physical world [3,4], thus radically defining the ontological foundation and epistemological thrust of modern thinking. In contrast, the physics of Aristotle, the study of the “nature” of things which dominated scientific thinking for nearly two millennia before the mechanical world view took hold, was precisely the study of ends. Efficient causes, along with formal (the geometry, shape, or form of a thing or process) and material causes (the substrate from which a thing or process arises), were taken to be governed by the ends they served, or final cause. It was precisely the relation between these different kinds of cause and their interaction with respect to final cause that was understood as the subject of inquiry. Aristotelian physics was a physics of teleology, the study of nature as end-directed, and
thus Aristotle argued that "one only knows a thing when one knows why it is, its reason" [5].

The Aristotelian view of an active, end-directed physics sought to explicate the more general view of the Greeks that the order of the natural world emerged from chaos [6] in a process of perpetual transformation and flux, and this is precisely what was explicitly expurgated from the "dead" or static perspective of the mechanical view, which began its ascendancy in the seventeenth century. "Inquiry into final causes," said Bacon, "is sterile, and, like a virgin consecrated to God, produces nothing" ("Nam causarum finalium inquisitio sterilis est, et, tanquam virgo Deo consecrata, nihil parit" [6].) [7]. Boyle [8] exemplified the modern mechanical view when he compared the universe to the "ingenious clock of Strasburg-Cathedral," a comparison supported by his younger contemporary Newton. In contrast to the Greek view of flux and change, it was the immutability of nature that characterized the rise of the mechanical view: the stars, the sun, the earth, and life upon it with the exception of those portions cultivated by man (sic) were thought to be eternal [6]. The anthropocentricity of this privileged human position, which shows how deeply the pillars of the modern scientific edifice were set in a theological foundation, is obvious.

B. Self-Organization, Purposiveness, and Extraphysical Causes

It was no accident that the why of Aristotelian physics was reduced to merely descriptive how of modern physics [4,9]—that purposiveness, or other end-directed behavior was surgically removed from the discourse of physics: it kept the watchmaker, or master designer, intact outside the Newtonian machine. Humans were thus dualistically situated with mind somehow outside nature and body within, manipulating the clock toward divine ends [10]. Boyle's remark that it was precisely because the universe was like the clock of Strasburg-Cathedral that it must necessarily have an intelligent creator [8] make explicit the unique marriage of materialism and theology that characterized the rise of the mechanical world view.3 Although by conforming to the emotional requirements of the religious social ordering of the time (including the religious consciences of those doing the physics), this construction permitted stunning advances in physics, the price tag on the impoverished causal framework that this flawed materialism carried with it was an ontological dualism that has plagued future generations.4

By the middle of the nineteenth century the empirical facts were already more than sufficient to deny the view of an immutable nature. Kant's attack on the eternity of the solar system, made nearly a century before, was now widely accepted (although not the details of his theory). The solar system was now seen as something that had come into being [6] from within the context of the larger universe.
Figure 1  A glass of liquid at temperature $T'$ is placed in a room at a different temperature $T''$. The disequilibrium between them (the temperature difference) defines a field potential that, in accordance with the second law of thermodynamics, produces a flow of energy as heat $\Delta Q_k$ that acts as a drain to minimize the potential—to maximize the entropy. If $T'$ exceeds $T''$ as in (a), the flow is from the glass to the room $-\Delta Q_k^I = \Delta Q_k^II$, and if $T'$ is less than $T''$ as in (b), the flow is from the room to the glass $\Delta Q_k^I = -\Delta Q_k^II$. In both cases the flow continues until $T' = T''$ and the potential is minimized (the entropy maximized) as in (c), at which time all flows stop, $\Delta Q_k^I = \Delta Q_k^II = 0$.

In fact, entropy maximization is precisely a statement of final cause in the Aristotelian sense.9 “The entropy of the world,” said Clausius [20], “strives to a maximum.” “Nature prefers certain states,” said Planck [21], “and the measure of the
preference is Clusius' entropy. The full impact of this explicit recognition of an end-directed nature was deflected by the hegemony of the mechanical view perpetuated by the interpretation of the second law due to Boltzmann [22]. Following the work of Maxwell, who had modeled gas molecules as billiard balls, and in an effort to salvage the mechanical world view, Boltzmann reduced the second law to a stochastic collision function (to purposeless mechanical collisions or efficient cause). Since when a monatomic gas is confined to a box every collision will produce a change in the velocity and direction of each molecule, all nonequilibrium energy distributions or coherent velocity distributions—molecules moving at the same speed or in the same direction—will become increasingly dispersed and irregular, leading to a final state of maximum disorder. Boltzmann recognized this state as the state of maximum entropy, and thus claimed entropy maximization, hence the second law, was simply a law of probability, the statistical result of the random collisions of elementary particles. For this reason, a collection of molecules or "bodies" "moving at the same speed and in the same direction" said Boltzmann, "is the most infinitely improbable configuration of energy conceivable" [23]—and the second law became a law of disorder.

The belief that from the standpoint of physics the production of order was "infinitely improbable" turned what Eddington [16] has called the most important scientific discovery of the nineteenth century (the second law) into the most serious roadblock yet to a nondualistic view of nature or comprehensive evolutionary theory. Physics, on this view, was not just passively disposed toward order as with the "dead" physics of the classical mechanical model, but now worked relentlessly against it. This not only reinforced the apparent justification for invoking extraphysical causes, but led theorists to speak about the various extraphysically endowed states (e.g., living systems) as "struggling against" or "paying a price" or "debt" to the laws of physics in order to "do business." Of course the problem of explaining the origin and operation of such extraphysical, purposive "debt-payers," or exactly what business they might be in (particularly in the odd sense of somehow having their existence now tied to a fight against the universal laws of nature) simply backs the theorist further into the dualistic corner [12].

Recent advances in the theory of nonequilibrium thermodynamics (the "second thermodynamics") have turned the Boltzmann conception precisely on its head, providing the basis for obliterating the untenable dualistic ontology that has hung like a great weight around the neck of the modern scientific enterprise from its beginning. The world is not reducible to the purposeless collisions of elementary particles—to a stochastic collision function or any other kind of linear, summative, aimless behavior—and this can be shown by simple and easily understood physical facts. In particular, order is no longer seen as infinitely improbable but inexorable under universal law; the world is now understood to be in the order production business, and it is the laws of physics that make it so. The rest of this tutorial sets forth the fundamental principles.
II. NATURAL SYMMETRY AND THE LAWS OF EVOLUTION

A. Evolution in Physics, Biology, and Culture

When we speak of evolution, or a theory of evolution, it is almost always taken to be Darwinism that we are talking about. But this fact is the result of decades of social construction. In truth Darwin never even used the word “evolution” in the first five editions of *The Origin* at all. This is not because the term “evolution” was not in use. It was widely popularized in the early and mid-1850s by Spencer, who defined it as the lawful and progressive production of order from disorder, which he said held uniformly from the physical (nonliving) to the living and the cultural (human social) [11, 12, 15, 24]. The fact of the matter is that Darwin did not use the word “evolution” for the reason that he never intended to address the general problem of evolution at all: his intention was simply to show that “species” were transformed over time as the result of natural selection (a particular facet of evolution).

When the term evolution was historically expropriated by the proponents of Darwinism, the idea of evolution became effectively reduced from a spontaneous process of universal ordering to the result of natural selection acting on a population of differentially replicating or reproducing entities competing for fixed resources. The consequences of this reduction, the decoupling of the living from the physical world, are why the notion that Darwinism “owns” evolution (cf. ref. 25) must be thoroughly rejected. In assuming the “struggle for life” to begin with and avoiding the directed and global nature of terrestrial evolution as a whole, Darwinism explicitly avoids addressing the material or physical origins of such goal-or end-directed behavior and simply dualistically smuggles it into a mechanical world of physics ad hoc from outside its theory (cf. Elliot [26]). Darwinism cannot, therefore, be expected to answer the deeper questions of evolution.

The same kind of smuggling occurs with respect to cultural ordering, where the problem of order production is avoided by the assumption that culture is simply the rational creation and production of (and for the good of) man (sic). Yet this dualist deduction, which is no more than a modern construction of the same old incongruent blend of materialism and miracles discussed above, absurdly assumes that humans preceded culture—that they evolved (or miraculously appeared full-blown) and then rationally invented it! Obvious logical impossibilities aside, this view is unequivocally denied by the evolutionary facts. Members of the genus *Australopithecus* with chimpanzee-sized brains used tools for more than 2 million years before the genus *Homo* even emerged. Thus cultural evolution began long before there were any humans at all: humans, including their intentional dynamics, were a production of it [10].
B. A Selection Principle Grounded in Physical Law

Because the "mechanics" of Darwinism are carefully defined in such a way so as to avoid addressing these fundamental problems of evolution, Darwinism excludes itself a priori from any possibility of ever solving them. Because on the Darwinian view, evolution is operationally reduced to the result of "natural selection" working on a population of replicating or reproducing entities showing heritable variation and competing for the same resource (a Malthusian population), Darwinism cannot address either the evolutionary origin of the replicating ordering it assumes or the directed nature of evolution as a whole [22]. That is, while the evolutionary record shows terrestrial evolution as a progressive global phenomenon (that the Earth system at its highest level has evolved, functions, and is evolving as a single global entity characterized by increasingly more highly ordered states), Darwinism cannot address or even recognize this global evolution (in fact denies it [27]) because there is no population of competing Earth systems on which natural selection can act: the global Earth system is a population of one.

The "problem of the population of one," the problem of how order is selected from disorder, requires an evolutionary theory that accounts for the phenomenon of spontaneous order production, and this puts the question of purposive or end-directed physics directly back on the table [15]. In particular, it asks that what was dualistically removed from the physical world by the theological beliefs of the seventeenth century be returned to its rightful place [12]. The principle of parsimony suggests that if a world of purposeless mechanical particles (the Newtonian-Boltzmann narrative) needs miraculous makers to order it, then the physical world cannot be reducible to purposeless mechanical particles. That is, it suggests that such a description of the physical world is incomplete. More specifically, the spontaneous evolutionary ordering of the natural world suggests the operation of a physical selection principle (since if it does not require a population of replicating entities to act, the principle cannot be biological) that accounts for the production of ordered from disordered states. Competition in this case would thus be between ordered (or macro) and disordered (or micro) modes, and such a law would turn the Boltzmann conception precisely on its head. This is indeed the case and it will be shown below.

C. Unifying the Dynamics of the Material World: Energy Is Not a Measure of the Ability of a System to Do Work

The understanding of evolution or directed change requires a clear understanding of the first and second laws of thermodynamics and their particular relation to each other. Perhaps because it is counterintuitive to describe the dissipations of a system's potential for change by the increase of a quantity, or else because end
states are not as inductively obvious causes as simple cause-effect relations (efficient causes), many who take energy for granted have believed entropy to be difficult to understand. Since understanding either energy or entropy requires the understanding of both, such a belief simply indicates a misunderstanding of energy. In fact energy was not defined or understood historically until “entropy” (a word coined by Clausius [20] to sound like “energy” in order to stress the relation between the two) was also defined. It was the contribution of Clausius and Thomson to recognize that two quantities were operable in all real-world processes: one that was conserved (energy) and one that was not (entropy), and neither was intelligible without the other.

This misunderstanding is so deep that while energy is a common word even in everyday vocabulary, entropy is hardly known. Entropy is avoided altogether by ascribing all the properties of both entropy and energy to energy, although this is precisely the impossibility that lead to Clausius’ and Thomson’s important formulation of the two quantities to begin with. In particular (1) colloquialisms such as “consuming” or “producing” energy, (2) causal statements describing processes as being “driven by energy,” (3) apparently technical definitions of energy as “a measure of the ability of a system to do work,” or (4) popular admonitions about “trying to conserve energy” are either impossible or false; the first law of thermodynamics (the conservation law) says that energy is always conserved—it can never be destroyed (consumed) or created (produced); the quantity of the energy in any dynamical process is simply transformed from one configuration or form to another. For example, when fuel is used to run a car, the energy is not consumed but only transformed into other forms (e.g., heat in the air from gasoline in a tank). The same is seen with the liquid in the glass shown in Figure 1. If we build a box to enclose the glass and a portion of the air in the room so that no matter and energy can flow through the box’s walls, and if the temperature of the liquid is, say, warmer than that of the rest of the air in the box, a flow of heat will be produced from the glass to the air, but the total amount of energy in the box will remain unchanged.

What changes in both cases is not the quantity of energy, which is conserved, but its quality, which is not, and it is the entropy that is a measure of the quality of the energy and motivates the change. Thus it is legitimate in both cases to talk about the dissipation, consumption, or destruction of field potentials (or “availability”)—the production of entropy—but not about the consumption or destruction of energy. It is thus clearly seen from the case in Figure 1 that it is not the energy in the box that drives the process or provides a measure of the ability of the system to do work (produce a process): after the system has come to equilibrium and the process stops, the quantity of energy is precisely the same as it was when the liquid was warmer than the air and the process started. It is the extent to which the entropy is maximized relative to the equilibrium state, its distance from equilibrium, that determines the magnitude of the motive force or field potential. The
further the system from equilibrium, the greater the force. At equilibrium there are no field potentials, and there are no flows. This is precisely the meaning of Planck’s preference (see above). The conservation and interconvertibility of all forms of energy (the first law) shows the underlying unity of all natural processes (dynamics); entropy maximization (the second law) provides their motivation [3].

D. The First and Second Laws: Symmetry of the Laws of Physics Themselves

The preceding discussion set us up to make a fundamental point more explicit: the first and second laws of thermodynamics are not ordinary laws of physics; they sit above the ordinary laws as laws about laws expressing the dynamical symmetry of the laws of physics themselves [3,28]. The conservation principle described by the first law expresses the time-translation symmetry of the laws of physics, and the second law likewise expresses a symmetry that governs all other physical laws, but in a completely unique and powerful way. Whereas the first law is a law of equivalence, the symmetry expressed by the second law where nonequilibrium distributions of energy occur is a symmetry unfulfilled, and it is precisely this unfulfilled symmetry that underlies the preference of Planck as well as the striving of Clausius, and motivates and directs the dynamics or action of the natural world [3]. Evolution can now be understood and defined in a deeper way as symmetry on the way to making. The relation between the unfulfilled symmetry of the second law, of the motivation and production of self-organizing states—progressively higher order symmetries on the way to making—and the physical law that governs selection from micro to macro mode is the subject of the next section.

III. MAXIMUM ENTROPY PRODUCTION AND THE PHYSICS OF ORDER

A. Thermodynamic Systems Produce Dynamics That Reduce Their Field Potentials at the Fastest Possible Rate Given the Constraints

Because classical thermodynamics was developed in the middle of the nineteenth century as a direct result of the effort to understand and improve the efficiency of the steam engine (see, e.g., ref. 8), the production of entropy was simply taken as a nuisance to contend with. Explicating self-organization or the production of order was not part of the agenda of the early thermodynamicists; they were dealing with machines already designed and constructed according to the plans of external creators (human engineers). Understanding, however, that the symmetry described by the second law is a symmetry that in its breaking provides the origin, and in its making the end of macroscopic change, is to see the cosmic origins of evolution itself: the fundamental breaking of symmetry (that which rendered the symmetry
unfulfilled) is the expansion of the universe and the disequilibrium it generates by its expansion. Herein lies the source of universal ordering.

While classical thermodynamics tells us that entropy is maximized at thermodynamic equilibrium, it tells us nothing about which path of action is selected out of those that are otherwise available to get there. Although the answer to this question is easy to demonstrate, its consequences are profound: it reveals a physical world that is not only end-directed but inherently opportunistic in obtaining its ends [3, 12, 15]. This flies in the face of the antiteological or purposeless view of the physical world passed down from the dualistic foundations of seventeenth-century science. Figure 2 shows an adiabatically sealed chamber (closed to the flow of energy) divided by an adiabatic wall into two equal compartments, each holding equal quantities of a monatomic gas such that the temperature of the first chamber is greater than the temperature of the second, $T_1 > T_2$, producing a field potential with force $F$. Although I and II are out of equilibrium with each other, if the constraints are left intact the system will remain the way it is and the entropy is maximized given the constraints. If, however, a section of the adiabatic seal is stripped off the dividing wall (Fig. 2a), a flow of energy in the form of heat (a drain or pathway) is immediately produced from I to II until the potential is mini-
mixed (the entropy is maximized), given the new constraints. The rate of entropy production, which can be taken as a measure of Planck’s preference, is given by

\[
\frac{dS}{dt} = \frac{dQ}{dt} \left( \frac{1}{T_1} - \frac{1}{T_2} \right)
\]

where \(dQ/dt\) and \((1/T_1 - 1/T_2)\) are the flow and fore, respectively.

Equation (1) shows immediately, ceteris paribus, that the rate of the entropy production is determined by the coefficient of conductivity of the wall. In Figure 2b a second portion of the adiabatic seal is stripped off, but the wall underneath is composed of a different material with a different coefficient of conductivity. It is easy to see that if the rate of 2 relative to the rate of 1 is sufficient to drain some quantity of the potential before 1 drains it all, then that quantity is automatically assigned to 2. If with different relative coefficients 2 can drain all the potential before 1 can drain any, the entire quantity is assigned to 2 and 1 gets none. If more drains are added (Fig. 2c), the behavior is precisely the same: regardless of the particulars of the system, not only will it produce the appropriate dynamics to minimize the potential, it will select the assembly of pathways or drains among those that are available (it will allocate its resources) to minimize the potential (maximize the entropy) at the fastest possible rate given the constraints [3,12,15].

**B. Order Produces Entropy Faster than Disorder**

This universal selection principle, the law of maximum entropy production [3,10,12,15,22,29,30], shows precisely why the world is in the order-production business—why order is spontaneously selected from disorder according to physical law (the selection principle sought in Section II.B): order produces entropy faster than disorder. Order is not improbable as Boltzmann alleged, but the inexorable product of natural law. With this single fact the dualistic edifice, built as it has been on a purposeless physical world, crumbles at its foundations. The physical world is not only end-directed but opportunistic in its end-directed behavior. The spontaneous production of order entails the transformation of field potential into the continuously coordinated or collective nonlinear ("circular") behavior of the previously disordered components, permitting the field to access a new dimension of dissipative space.

Whereas it has been understood for some time that such processes could occur as long as they produced enough entropy to compensate for their internal entropy reduction (see, e.g., refs. 31, 32), given Boltzmann’s claim concerning the “infinite improbability” of coordinated, ordered behavior, there was no causal account of why such discontinuous entropy reductions (“populations of one” in the language of Section II.B) should ubiquitously and progressively occur. The law of maximum entropy production at once makes this remarkably easy to understand. Local entropy reduction (order production) occurs precisely because it increases...
the rate of entropy production of the field from which it emerges. As a result of the circular relations that define them (where effects become causes) self-organizing systems in their entification bring a new causal agency into the world—a new formal cause in Aristotle’s terms. Such self-organizing systems are inherently self-amplifying sinks or drains for field potentials; the kinetic and potential energy carried in the circularity of their component relations gives them an internal (or “on-board”) potential with its own internal force that acts as an internal amplifier (see refs. 12, 15, and 22 for further discussion).

C. Studying the Generics in a “Simple” Physical System

Since the law of maximum entropy production is a level-independent law (invariant under transformations of scale) that acts on level-dependent substrates (material causes in Aristotle’s terms), the reductionist claim that dynamics can be reduced to the laws and particles at some elementary level is rejected. The order that emerges at each level is dependent on the components and their accessible lawful relations particular to that level, and these themselves are emergent. This shows why not only ecosystems and civilizations, for example, but global evolution as a whole must proceed in levels or stages—why the components of the cosmic cloud from which the solar system emerged had to have already come from the interior of a star to produce the substrate necessary for the emergence of replicative order (life) on Earth, why you had to have prokaryotes before you could have eukaryotes, agriculture before states, quantum mechanics before an electronic media or computer revolution. Because of its invariant level-independent nature, the generic aspects of this behavior can be studied with simple physical systems under laboratory conditions. One of the best is an experiment first devised by Henri Bénard [34,35] at the beginning of this century (although he did not know the remarkable scale invariance of the results at the time).

In the Bénard experiment (Fig. 3) a viscous fluid is held in a circular container between a hot source (it is heated evenly from below) and a cold sink (it is exposed to the colder air above). As long as the disequilibrium (field potential) is maintained, the system works to drain it—produces entropy—by transferring heat from source to sink. In Figure 3a heat is transferred by the incoherent, uncorrelated collisions of the molecules (conduction). The smooth and uniform macroscopic symmetry of the fluid is maintained by the microscopic disorder of the component relations: each molecule undergoes billions of collisions per second, nonaverage fluctuations are immediately damped or “sank out,” and the entire fluid and its intrinsic spacetime dimensions are describable by mean free path distances and relaxation times. When the temperature of the source (hence the field force) is increased beyond a critical threshold, spontaneous order breaks the symmetry of the disordered regime as hundreds of millions of molecules exhibiting
Figure 3  (a) At $t_1$, heat is transferred from source to sink through the disordered, uncorrelated collisions of the molecules in a viscous fluid. (b) At $t_2$ when the field potential is increased above a critical minimum, spontaneous order emerges as hundreds of millions of molecules start moving coherently together, producing macroscopic dynamics with an intrinsic spacetime orders of magnitude greater than in the disordered regime (see text) (From Ref. 22).

Figure 4  The discontinuous increase in the efficiency of heat transport (ratio of field potential minimization) that occurs in an experiment similar to that shown in Figure 3 as a result of the transition from disorder to order. $k^*$ is heat transport in the disordered regime (similar to Fig. 3a), and $k^* + \sigma^*$ is heat transport in the ordered regime ($3.1 \times 10^{-4} H$ (cal/cm²/s)) plotted against field force $F$ [36]. (From "Engineering Initial Conditions in a Self-Producing Environment" by R. Swenson, in M. Rogers and N. Warren (eds.), A Delicate Balance: Techniques, Culture and Consequences, Institute of Electrical and Electronic Engineers, Los Angeles, 1990, P. 70. © 1989 IEEE. Reprinted by permission.)
Figure 5  Two self-organizing states are seen to emerge as populations of one right after
the critical threshold has been reached (prior to Fig. 3b). Other things being equal, their
existence is dependent only on the fact that the macro (ordered) mode drains the field poten-
tial (pulls resources into its own coherent dynamic) faster than the micro (disordered) mode
from which it emerges. There is no interaction between the two self-organizing states at this
stage (From Ref. 22).

highly coordinated behavior start moving collectively together. Figure 4 shows
the discontinuous increase in the rate of heat transport that results from the disor-
der-to-order transformation. The dissipation of field potentials (entropy produc-
tion) is a function of a field’s dissipative surfaces, which are dependent on its
spacetime extension; order-from-disorder transformations increase these dimen-
sions by orders of magnitude.18

Figure 5 shows a photograph of time slice in the Bénard experiment right after
the critical threshold has been crossed19; two self-organizing states (“cells”) are
seen to have already come into being as populations of one—initially each is an
individual case of micro-to-macro selection20 with no interaction going on be-
tween them. Moments later the entire fluid is inhabited with a full population of
self-organizing states (Fig. 3b). Each as a self-amplifying sink pulls resources into
its production (the spacetime extension of its dissipative surfaces) at the fastest
possible rate given the constraints, but now the constraints include those imposed
by competition with other individuals for the same resource; the action space of these originally uncorrelated cells becomes progressively deformed (constrained) as the entire volume of fluid within the contained acts selectively as a higher level entity to maximize the spacetime extension for the fluid as a whole, given the constraints. The attractor or time-independent state in this case—the symmetry that for the time-dependent behavior was on the way to making—is a highly regular and uniform array of hexagonal cells. There is not the space here to show additional photos of the remarkable evolutionary behavior that occurs in this simple fluid as it progresses toward this symmetry state (converges on its attractor), but I have published these elsewhere (see, e.g., refs. 12, 22, 30).

Two general kinds of selection may be distinguished in these evolutionary dynamics: external selection, which acts in the spontaneous production of order (the emergence and maintenance of a population of one) selecting macro (order) from micro (disorder); and internal selection, which chooses between the accessible microstates of the components and their possible relations from the population of many within that comprises the the population of one (self-organizing system). Darwinian selection is a special case of internal selection that occurs when the particular components are replicative components (when the self-organizing system is characterized by replicative ordering, e.g., the global Earth system as a whole).

Another important property of the generic behavior that falls out of the physics of self-organization or spontaneous ordering is spontaneous fission. Because the entropy production of any growing entity depends on the extension of its dissipative surfaces, and because surface increases as the square of the linear dimensions and volume increases as the cube, as an entity isometrically increases in size, the specific entropy production (entropy production per unit weight) progressively goes down although the total entropy production increases [10,12,27,30]—that is, the internal amplifier becomes progressively less efficient. Beyond a critical size, the system becomes unstable to spontaneous fission, by which the field further elaborates its surfaces and increases its transformation of resources or field potential. This behavior too is readily observed in the evolutionary dynamics of the Bénard fluid (for photos and further discussion see refs. 10, 22, 30, and for discussion with regard to bacterial cells and global evolution as a whole see refs. 29, 30).

The evolutionary dynamics of the estimated 200-fold increase in the hominid population during the Paleolithic era is another example of the same process. The increase occurred not through a corresponding increase in the size of these ancestral villages or settlements, but through the proliferation by fissioning of their number—from something like 1500 at the beginning of the Paleolithic to some 75,000 or so at the end [37]. They grew to a certain size and divided. The work of Carneiro [37,38], demonstrating the universality (law-governed nature) of this evolutionary behavior in his study of the fissioning of autonomous villages, illustrates well the idea of level-independent laws acting on level-dependent sub-
strates. In the Bénard example, local fluctuations (inhomogeneities) resulting from molecular collisions are damped when the field conditions are below the critical threshold, and the same is the case in the fissioning of autonomous villages: when a village is below a critical size, social interactions that can be thought of as fluctuations or deviations from the mean (e.g., adultery, theft, disharmonious acts of witchcraft) are damped. Conversely, when the village exceeds a critical size, these same fluctuations are amplified to macroscopic proportions and fissioning occurs.

IV. BIOLOGY AND CULTURE: HOOKING DISSIPATIVE DYNAMICS ONTO KINEMATIC FIELDS

A. Captives of Local Gradients

The emergence of replicative ordering on Earth occurred extremely rapidly in geological time after the planet had cooled sufficiently to permit it. Given the mechanism it supplied for accessing otherwise inaccessible dimensions of dissipative space—new drains or sinks for the solar potential—this is no wonder. Discussions of entropy production maximization and evolution on Earth as a global system are provided elsewhere [10,12,29,30]. In this extremely brief section the intention is to introduce the functional and generalized mechanical properties that emerged with the living from the nonliving and the cultural from the noncultural, the emergent substrates on which the level-independent evolutionary laws of physics have progressively proceeded to act.

Despite the remarkable level-independent behavior we have already discussed, if the self-organizing living are compared to the self-organizing nonliving, a striking difference is immediately apparent: the nonliving are captives of their local gradients, while the living are not. That is, in the case of systems like tornadoes, dust devils, and the Bénard cells we have looked at above, if we remove the local field potential (e.g., turn off the heat in the Bénard experiment), the systems "die." This is not the case with even the simplest living systems such as bacteria. When their local potentials are removed or dissipated (when they run out of food), their activity often increases [12,40].

B. Replicative Ordering: Accessing Higher Order Dissipative Space with Perception and Action

The dynamics of the living systems are coordinated with respect to information specified by kinematic fields [41,42] that permits them to "skate across" local gradients and access higher dimensions of dissipative space through the production of higher order dissipative dynamics [3,12,40]. That is, whereas in nonliving systems the dynamics are governed by local field potentials (with dimensions of
mass, length, and time, viz., “mass-based” fields), the dynamics of the living are governed by nonlocal potentials linked together through observables with dimensions of length and time (kinematic or information fields). Self-organizing systems carry internal potentials (“on-board” potentials) in the kinetic and potential energy embodied in their constitutive relations, and the living hook this potential onto kinematic invariants to search out discontinuously situated potentials (resources). Bacteria, for example, are able to move away from harmful substances and find desirable resources, not only by perceiving the molecules they directly consume, but by perceiving and acting with respect to molecular gradients that allow them to discover the molecules they do consume (potentials they dissipate) and avoid those that are harmful—that provide them information about higher order field potentials.

This ability to act independently with respect to local potentials, and thus the facility to access higher order dissipative space, is the hallmark of the replicative order that characterizes the living. Replicative ordering requires a particular set of internal nonholonomic or rate-independent constraints as part of its constitutive relations [43]; they are discrete, linear, and rate-independent relative to rest of the cell dynamics, and their constitutive relations meet a minimal condition of “semantic closure” with the rate-dependent dynamics [44] that permits their “reading” and “writing.” Examples include gene sequences (harnessed by cell dynamics) and the words on this page (harnessed by cultural dynamics). Their capacity for meaning is derived from the relative thermodynamic arbitrariness of the sequences; for example, the order of the letters in the words on this page can be changed without thermodynamical consequences relative to the rate at which the words are written and read [36]. It is precisely as a result of this arbitrariness that replicative ordering is able to produce perceiving-acting systems that in their ability to behave arbitrarily with respect to local potentials are able to coordinate their dynamics with respect to higher order observables that specify higher order dimensions of dissipative space [3,12,40].

C. Second-Order Kinematics and the Rise of Culture

Learning is induced by problems, and from the physical point of view the global problem is the disequilibrium at the geo-cosmic interface [30]. Evolution on Earth can be seen as an epistemic process by which the global system as a whole learns to extend its dissipative surfaces so as to reduce the geo-cosmic potential at the fastest possible rate, given the constraints [29,30]. The ascendancy of replicative order is thus seen to be coextensive with the progressive emergence of perceiving-acting cycles, able to access higher order dissipative space by hooking new levels of dissipative dynamics to new observables. With the production of language in the emergence of culture came a qualitatively new form of replicative
order that can be called "second-order kinematics" [12] or flows about flows.
(where slow flow, e.g., as in the words on this page, can be treated as no flow, or
pure nonholonomic geometry). Second-order kinematics provided a new creative
substrate which, as the emergence of life had done before, opened the door to the
accelerated expansion of otherwise inaccessible dimensions of dissipative space.
The explosion in mass communication and globalization going on at present is a
new phase of matter that is precisely the latest (hypertrophied) version of this
same evolutionary order-building behavior that started in terms of terrestrial evol-
ution some 4 billion years ago on the Archean Earth.

V. CONCLUSION

While a fuller exposition is not possible here, it is hoped that the reader has been
able to grasp the profound shift in the underlying assumptions regarding the na-
ture of evolutionary ordering that has resulted from a new understanding of some
deceptively simple physical facts. Rather than being static or purposeless, the evol-
utionary dynamics of the natural world are now seen to be creative and purposive;
the world is in the order-production business, and this can now be understood as a
spontaneous search for symmetry in terms of natural law. Clearly this has pro-
found epistemological and ontological consequences—consequences for under-
standing the nature of our own nondualistic being in an evolutionary (global
order-producing) becoming (see refs. 10, 45 for further discussion). It is most im-
portant to emphasize the rejection of reductionism and micromechanistic deter-
minism that the new and expanded physics provides; physics is no longer con-
strued as being reducible to a single level of "elementary" particles. Instead,
level-independent law acts on level-dependent substrates, which are themselves
emergent; level-dependent behavior is coordinated and defined by the ecological
dynamics particular to a given level and not reducible to any other. Creative beha-
vor comes into the world at the discontinuities where new levels of order arise;
it is here that the critical region of our evolutionary praxis resides.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of the Center for the Ecological
Study of Perception and Action (CESPA) during the time this chapter was com-
pleted, and valuable interactions with Claudia Carello, R. Cameiro, Gail R. Fleis-
chaker, H. H. Pattee, R. E. Shaw, and M. T. Turvey.

FOOTNOTES

1. "Efficient causes" are taken to be the local or proximate cause of change or mechanical
agency, as in the "impressed forces" of Newton [2]. "Summativity" means that the su-
perposition principle, as it is known in physics, holds, namely that the combined effect of a number of mechanical causes acting on a population of bodies or particles equals the sum of their effects acting independently from one another; "determinism" means that if the positions and velocities of all the bodies or particles in a system are known for any one time, all future and past states can be derived; and "reversibility" means there is no preferred direction of change, that nothing forbids reversing the signs of the equations of motion.

2. To the Greeks, physics ("phasis" or "physis") meant "nature," where the nature of a thing or process in the Aristotelian sense is the end it serves or for which it exists [1, p. 214].

3. That the physical description of the world provided by Newtonian mechanics was radically incomplete would not have been denied by Newton. Does not the world "being properly ordered," asked Newton, show the existence of an "intelligent ... incorporeal Being?" [11] (see also refs. 12, 13).

4. Descartes, the sine qua non of dualistic philosophers, said the world was divided into the physical world or "extension" and the nonphysical world, which was "thought" or "soul," the thinking "I." While the physical world on this view was subject to deterministic mechanical laws, the nonphysical world was not. Creativity, intentionality, purposiveness, and choice were all brought into the mechanical world from the outside through the thinking "I" and its immortal connection to God.

5. Invoking extraphysical causes to explicate the natural world, as the dualist does, has played a fundamental role in the construction of world views necessary for the production of social order. Galileo's assistant (a monk) in Brecht's Galileo understands this well: he tries to get Galileo to suppress his work confirming the Copernican heliocentric view of the universe, pointing to the effect it would have on the peasantry who draw their strength for their "miserable lives," he says, "from the Bible texts they hear on Sunday. They have been told that God relies upon them and that the pageant of the world has been written around them." [14].

6. Engels [6, p. 155] in similar fashion characterized Newton as a "an inductive ass" and as a "plagiarizer and corrupter." Russell [1, p. 602] further generalizes his remarks about Darwin when he says that "most men who have won fame for their ideas" are not original thinkers: "As a rule, the man who first thinks of a new idea is so much ahead of his time everyone thinks he is silly, so that he remains obscure and soon forgotten. Then, gradually, the world becomes ready for the idea, and the man who proclaims it at the fortunate moment gets all the credit."

7. In fact Malthus had already claimed that the "struggle for existence" (his term) was a general property of the "animal and vegetable kingdoms" when he applied it to human social systems. Malthus's "struggle for life" appears in the full title of Darwin's Origin as the "struggle for life," Darwin got from Spencer the term "survival of the fittest," which he said was better than his own term "natural selection" (see refs. 12, 15).

8. Since entropy is a measure of a system's energy unavailable for producing macroscopic processes ("work"), the opposite (variously called "negentropy" [17], of "free energy") can also be called the "availability," a term introduced by Carnot [18]. Entropy maximization is thus equivalent to availability minimization or the minimization of field potentials, or to put it another way, all natural processes proceed so as to extremize avail-
ability degradation or dissipation (cf. Gaggioli and Scholten [19]) or extremize field potential minimization [12,15].

9. The "end to which everything strives and which everything serves" [2], or in Aristotle's own words, "the end of every motive or generative process" [2].

10. Nor is the word not found in any of the 21 chapters of The Descent of Man [11,24] (see refs. 12, 15 for further discussion).

11. The term was originally used by Swiss performanceist Bonnet, who used it to mean the "unfolding of an embryo" [24], but it was Spencer who reintroduced the term, redefined it, and first put forth a comprehensive theory of evolution.

12. Simply the determination of what will exist between more than one possible mode or pattern of behavior that could otherwise drain the same potential with no "end-in-view" or "end-in-mind" implied.

13. Both matter and energy can be taken to be conserved (cannot be created or destroyed) on Earth. In stars, however, which are maintained by nuclear reactions in which matter and energy are interconverted according to Einstein's $E = mc^2$, then it is matter-energy that is conserved.

14. This excellent term used by Kugler and Turvey [31] for living systems is applicable to all self-organizing systems (see also my more extended discussion of "internal force" and "internal amplifier" with figures [12,15,22]).

15. At the risk of sponsoring unnecessary confusion for those who have not heard of Prigogine's theorem of minimum entropy production, which was erroneously thought to apply to order-producing systems, but to dispel confusion for those who have, a brief comment is in order (for more detail see ref. 22). The less technical reader is well-advised to simply ignore the theorem, since it makes no contribution whatsoever to the question of spontaneous ordering. It states that for a system extremely close to equilibrium with more than one force (potential) driving flows (and thus producing entropy), if one force is maintained constant but the others are allowed to dissipate, the entropy production will decrease until it reaches a minimum (relative to its earlier states) in the steady state. This statement is completely unsurprising. Since close to equilibrium the flows are a linear function of the forces, the flows will necessarily decrease as the forces dissipate until only the one force held constant remains. This tells us only that the flows are linearly dependent on the forces in the near-equilibrium regime (a fact well known since Onsager) and that potentials are spontaneously minimized—the second law. It does not tell us which flows or paths to equilibrium are selected, given these facts. The answer to that question (the one addressed in this text) is: the pathways or flows, given the constraints, that get it to equilibrium or minimize the potentials the fastest. This is the principle that accounts for ordering.

16. Following Bénard, Lord Rayleigh conducted convective experiments in containers in which the upper surface was sealed. Sometimes these two are conflated in the literature (the latter being called a Bénard convection or sometimes a Bénard-Rayleigh convection). The reader is referred to my earlier work [22] where both are illustrated and discussed in more detail than is possible here.

17. The mean free path is the average distance and the mean relaxation time the average time elapsed between interactions or collisions.
18. In the case of the Bénard experiment from of the order of $10^{-9}$ cm and $10^{-15}$ second to centimeters and seconds. The colossal magnitude of this new dynamical scale for a molecule in the fluid is equivalent to distances many times greater than the circumference of Earth and time scales greater than 4.6 billion years (the age of Earth) to humans.

19. The lawful nature of order production is seen clearly by the fact that every time the critical threshold is crossed, order inexorably emerges. The critical threshold is precisely the minimum field potential that can support the higher dissipation rate of the ordered state. This same opportunism, from the rise of replicative order and the rise of civilizations to the acceleration of global ordering today, is seen clearly in the evolutionary record as a whole (see refs. 10, 29, 30).

20. In this case competition is between conduction (disorder or micro) versus convection (ordered or macro).

21. Given the limits of space, I have chosen not to show this final state, which is quite well known and easily available. Usually it is only the final state that is shown, thus missing the whole directed time-dependent behavior, which is the behavior of interest with respect to evolutionary ordering.

22. The production of replicative order is order production that entails component production by replication (the system may or may not replicate or reproduce itself); for example, a cell illustrates replicative order that is also replicated, while the Earth system as a whole exhibits replicative ordering but is not itself replicated (at least not yet).

23. Villages have some minimum population at which they are viable (e.g., for the Yanomamö this is about 40–50). The critical threshold for fissioning is then necessarily 80+ [37]. I have discussed this issue of “minimal cell size” with regard to bacterial fission elsewhere [30].

24. Not only in the instance of fissioning, but with regard to the evolutionary dynamics of spontaneous order production in general, Carneiro's [38,39] elegant circumscription theory for the order and rise of the state, which tracks the lawful relations (the universality) observed in the individual and separate instances of the emergence of civilization (order) from previously autonomous (disordered or uncorrelated relative to each other) villages, reveals the operation of the same level-independent laws [12,22,30]. Circumscription, just as in the container holding the liquid in the Bénard case, limits the rate of horizontal dissipation, so the field elaborates vertically through order production. The operation of external and internal selection is vividly played out in Carneiro’s work and is seen to be one of the most characteristic level-independent dynamic invariants of global evolution as a whole.

25. Holonomic constraints are constraints that remove degrees of freedom in velocity and configuration space that do not require material instantiation (e.g., laws), and non-holonomic constraints are constraints that remove degrees of freedom in velocity space but must be materially instantiated to do so.

26. For example, the difference in the amount of entropy produced in writing or printing two alternate phrases (even if they have completely contradictory meanings) is inconsequential with regard to which one gets written, and the amount of ATP required to replicate DNA is the same regardless of the particular sequence.
REFERENCES


Cybernetics and Applied Systems

edited by Constantin Virgil Negoita

Hunter College
City University of New York
New York, New York

Marcel Dekker, Inc.
New York • Basel • Hong Kong