Gradient Reduction Theory: Thermodynamics and the Purpose of Life

Dorion Sagan and Jessica Hope Whiteside

Abstract

We argue that nonequilibrium thermodynamics, informed by a general version of the second law that applies equally to open and closed systems, connects flow processes of life to nonlife in illuminating ways. Energy delocalizes or, in the words of Eric D. Schneider (see chapter 4 in this volume), "nature abhors a gradient." Investigating how this version of the second law informs the natural organization of complex flow systems, we rethink the teleological status of systems, such as organisms and Gaia, usually covertly or overtly endowed with "purpose" or "mind." Our conclusion is that teleology as found in purposeful organisms, including humans, derives from inanimate flow systems thermodynamically organized "to" (this is their function, their prebiotic physiology, and their materialistic purpose) reduce ambient gradients.

A Fourth Copernican Deconstruction

Although scientifically anchored, this chapter's aim is to sample the breadth of gradient-reduction (nonequilibrium thermodynamic) theory, especially as it applies to Gaia—that is, to Earth's surface considered as a global physiological system. Although lack of space prevents us from being able to present either a detailed description of the gradient-based or open-system thermodynamics on which this chapter is based, or the full range of philosophical implications of such a scientific perspective, we hope to hit on the major points (Schneider and Kay, 1994b; Sagan and Schneider, 2000).[1]

One can provisionally identify four scientific displacements or deconstructions of human's special place at the center of the cosmos;[2] the first three of these are (1) Copernicus's decentering of Earth, (2) Darwin's destruction of humanity's special place above the rest of the animals (a corollary of which is our microbial ancestry), and (3) the disproof of the vitalistic conceit that life is composed of any special stuff, associated both with Fredreich Woeller's 1828 synthesis of urea (an "organic compound") from ammonium cyanate (an "inorganic compund") and the details of nucleosynthesis—the production of the chemical elements of which life is made (carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, etc.) in nuclear reactions inside exploding supernovae (Gribbin and Gribbin, 2000).

A fourth deconstruction, we argue, is that life shares its basic process—of being end-directed toward gradient reduction in regions of energy flow—with other naturally complex, materially cycling systems. This fourth deconstruction is based on the philosophical repercussions of the realization that the second law of thermodynamics can be restated for open systems. The most famous descriptions of the second law are the classical, quantitative descriptions of the nineteenth century. They involve the tendency of entropy (originally heat divided by temperature, and later given a statistical formulation) to increase in isolated systems.

However, modern thermodynamics has realized that not all systems (life being the most spectacular example) head inevitably toward equilibrium. The most complex thermodynamic systems in the universe are open to their energetic surroundings. The second law absolutely does not contradict life's tendency to become more organized and regulated over evolutionary time because life is an open system dispersing waste as heat, entropy, and reacted gases into its surroundings. In fact, life, like other natural complex systems, seems not only to have as its most basic function (its natural "purpose") the laying to waste of ambient gradients. It also seems, by forming natural gradient-reducing "machines," positively to accelerate the efficiency with which organized environments are rendered disorganized in accord with the second law. Complex, growing, cyclical (and in the case of life, at least, self-regulating and reproducing), thermodynamic systems tend to be much better (quicker and more efficient) at reducing the gradients that sustain them than random particle interactions.

from: Schneider, S.H., Miller, J.R., Crist, E., and Boston, P.J. (eds.), 2004, Scientists Debate Gaia: The Next Century. MIT Press, Cambridge Massachusetts, p. 173-186.

Thus, despite the quantitative efficacy of entropy as a measure of energy's tendency to become lost in sealed systems, the second law must be stated in a more general and qualitative way that includes open systems. Restated to include open systems, the second law says that energy delocalizes—or, as Eric D. Schneider puts it, nature abhors a gradient. From this point of view life, not just in its matter but also in the essence of its evolutionary process, is a particular historically developed thermodynamic system whose trends from planetary expansion and prokaryotic metabolic innovation to increasingly efficient energy use and even the rise of animal intelligence are all in harmonious keeping with the second law mandate to reduce gradients.

This deconstruction, showing that life is an energetic process deeply related to certain other complexity-building processes, links life to nonlife, matter to mind, and purpose (in its manifold forms, ranging from function and physiology to human intentionality) to the unconscious thermodynamic "computations" of equilibrium-seeking systems, of which humanity (we make the materialistic assumption) is a long-evolved example. Although others have come to similar philosophical conclusions, they have done so on the basis of an entropy maximization law that is demonstrably incorrect.[3] Our aim thus is to show roughly some major philosophical implications of a nonequilibrium thermodynamics which displays purpose (a stumbling block for acceptance of geophysiology, or Gaia, criticized for being teleological) and yet is based on the energetics of nonliving, nonconscious systems. As Lovelock's Daisyworld models have shown (in rebutting such criticism), coordinated thermoregulatory behavior—mistaken for mind, purpose, or complexity requiring extended periods of natural selection—is a natural consequence of organismic growth within constraints (Watson and Lovelock, 1983).

In our view, this is a specific example of a general, thermodynamic phenomenon:[4] complex thermodynamic behavior can be taken (especially out of context) for purposeful behavior or consciousness because nature's thermodynamic systems, engulfed in the genetic systems of life, are at the root of the complex, intelligent-acting behaviors of life. Gaia arose in the recognition of thermodynamic atmospheric disequilibria; any "purposeful" or physiological behaviors displayed by the biosphere, a population of one, must be understood in terms of thermodynamics, not natural selection among competing variants. In short, our proposed fourth Copernican deconstruction goes beyond the stuff of life to the process of life, linking mind and matter, human purpose and purposeful-seeming planetary behavior to physiology and prephysiological gradient-reducing behaviors.

Nature's Abhorrence of Gradients

Classical and statistical thermodynamics suffer from their characterization of the special (but experimentally easier to observe) case of isolated (energetically and materially sealed) systems as universal. Real complex systems, however, including those which potentially exhibit intelligence (e.g., humans) or a simulacrum of it (e.g., computers), inevitably tend to be open to, and to a large extent defined by, their material and energetic flows. Thus the tendency of improbable matter and energy distributions to settle to equilibrium in isolated containers—prematurely and perhaps egregiously universalized into the notion that the universe is inevitably headed toward cosmic standstill, or "heat death"—continues to impede understanding of the crucial ways in which energy flows organize complex systems. This situation is alleviated by Schneider's rephrasing of the second law (Schneider and Kay, 1989). Significantly, the notion that "nature abhors a gradient," as opposed to "entropy inevitably increases in isolated systems," applies to open systems—and focuses our attention on the flows that sustain and help organize them.

Complex systems (approaching and, in the case of the origins of life, apparently achieving selfhood) tend to appear spontaneously in nature under the influence of appropriate gradients when and where dynamic conditions permit. A gradient is a measurable difference across a distance of temperature (the classic thermodynamic gradient which runs heat engines), pressure, chemical concentration, or other variables. At the limit the difference may not be graded much, as in the clichéd difference between the something (air molecules) and nothing (their lack) of a vacuum, which nature is correctly said to abhor. There are also exploitable economic and mathematical gradients—for example, between rich and poor people, and between actual and probable distributions of playing cards (see below). The value of gradient reduction theory can be seen in its ability to illuminate many widely disparate energy-based systems, including those involving intelligent perceivers actively looking for gradients from which they can profit.[5]

From primordial differences gravitationally manifesting into the major distinction between stars and space (Chaisson, 2001) to temperature and pressure gradients within the protosolar nebula organizing the distribution of chemical elements and compounds (Harder, 2002), differences are exploited by complex systems, generating further differences; although we are acutely aware that a theory which explains everything explains nothing, the notion of difference seems pivotal not only scientifically in terms of measurement, but also in the philosophical realms of ontology and epistemology (e.g., Derrida, 1967; Bateson, 1979).[6]

That nature abhors a gradient restates thermodynamics' second law (Schneider and Kay, 1989; Sagan and Schneider, 2000). Differences in barometric pressure, for example, lead to hurricanes and tornadoes, complex and cyclical processes that dissipate such gradients and vanish when done. Although such gradient-driven, nonrandom, cyclically complex processes may be chemical, biological, and economic (as well as purely physical), their appearance is not assured merely by the existence of a gradient. Kinetic, chemical, and thermodynamic constraints—an appropriate infrastructure—must also be in place before they "pop into existence," exhibiting selflike recursive and teleomatic behaviors. Moreover, the pressure, temperature, electron potential, semiotic, or mathematical gradient must be "just right": if it is too steep, or not steep enough, no complex system will form. Finally, that complex behaviors "eat" gradients of a certain steepness, temporarily and cyclically reducing them (and thus the source of organization for the complex systems themselves), may be at the root of the cyclical (and fundamentally thermodynamic) processes of physiology.[7]

The Goldilocks Paradox and Perception

A tendency to misattribute mystifyingly "mindlike" factors to the emergence of complex systems sensitively reacting to gradients of only certain steepnesses and under certain constraints can be considered a kind of "Goldilocks Paradox"—the complex systems behave as if they recognize or "know" their external gradients (Sagan, 2000).[8] A similar situation, which Harold Morowitz refers to under the general rubric of immanent natural rules of "informatic" matter, and specifically as the nondynamical "noetic" character of the Pauli exclusion principle in quantum mechanics, leads to the know-how of particles to arrange themselves nonrandomly in the elements of the periodic table (Morowitz, 2002). Leaving aside questions of immanence versus transcendence and divinity, it is clear that complex systems in their sensitivity to external conditions may be confused with living and intelligent systems, both directly and by default in cases where complexity seems irreducible and thus explicable only by design. From electrically generated computer algorithms and Belousov-Zhabotinsky chemical clocks kept going by chemical gradients to globally regulating Gaia, kept alive by the solar gradient and its offshoot, the atmospheric redox gradient, complex systems are inevitably "fed" by physical potentials in their surroundings; they do not appear ex nihilo.

Although they span a huge range of complexity, the would-be mysterious systems that elicit awe and a rush toward overly complex explanations are not always particularly complex. If exposed to constraints, nature will fluidly "attempt" to reach equilibrium, sometimes giving the appearance of "choice" or "will," as in the case of a dusted streamer of warm air "seeking" the way out of a leaky house "in order to" come into equilibrium with the cooler air outdoors. Whether near equilibirum or far from equilibrium, such complex behaviors with their ability to mimic "mindfulness" inevitably occur within an environment demarcated by a gradient—a gradient whose existence may go undetected because, although necessary (if not sufficient) for the complex process, it lies just beyond the observer's frame of reference or focus of attention. Epistemologically, ontologically, and eschatologically, the gradient represents preexisting organization, a potential for energy and future activity which must be unlocked by intelligence or its reasonable simulacrum.

James Clerk Maxwell defined dissipated energy as "energy which we cannot lay hold of and direct at pleasure, such as the energy of the confused agitation of molecules which we call heat. Now, confusion, like the correlative term order, is not a property of material things in themselves, but only in relation to the mind which perceives them. . . . It is only to a being in the intermediate stage, who can lay hold of some forms of energy while others elude his grasp, that energy appears to be passing inevitably from the available to the dissipated state" (Nørrestranders, 1991, 21–22). We would be reluctant to interpret this comment by the inventor of Maxwell's demon to be a lapse into some sort of idealism or non-Cartesian mysticism; it rather seems to us to augur the ultimate necessity of dismantling, on the basis of gradients and their recognition, the wall separating mind (teleology) from body (mechanism).

Objections to and Defenses of the Gaia Hypothesis

The objections to and defenses of Gaia theory are instructive, as much for what they say about the research program of a physiological Earth as for the light they shed on the cultural history of ineluctably human science. Among the complexities to be reckoned with are that "the Gaia hypothesis," even in its strict scientific formulation, has undergone changes. Thus, for example, J. W. Kirchner (1991) identifies multiple versions of Gaia, from a "strong" version that "Earth is a living organism," which the analytic philosopher maintains is untestable (and likens to the Shakespearean line that "all the world is a stage") to weak versions which amount to a claim of coevolution of life and the environment, which he dismisses as true but already known and relatively trivial. This "divide and conquer" rhetorical ploy is reminiscent of Arthur Clarke's Law of Revolutionary New Ideas: "All revolutionary new ideas ... pass through three stages, which may be summed up by these reactions: 1. 'It's crazy—don't waste my time'; 2. 'It's possible, but it's not worth doing'; and 3. 'I always said it was a good idea'"(Clarke, 1972). In other words, Gaia in its strongest form—that Earth is an organism—is crazy, while in its weaker forms of environmental-organismic coupling it is trivial. If and when a stronger form becomes accepted, according to this trajectory it will be portrayed as unrevolutionary.

Biospheres and Closed (Ecosystemic) Versus Open (Organismic) Systems

However, even at this relatively superficial level of analytical philosophical rhetoric, an interesting defense can be, and was, made for the strong form. Assuming reproduction is the signal trait of organismhood, it was argued in the form of a thought experiment that the development of closed ecosystems would represent de facto reproduction of Gaia (Sagan, 1990). Since it is easy to imagine technologically enclosed biospheres—more advanced versions of Biosphere II, the failed human experiment in creating a giant enclosed ecosystem near Tucson, Arizona—separated from Earth on Mars, in orbit, or even in spacecraft, the organismic status of Gaia, taken as the planetary biota and its environment, was considered proven. Moreover, this thought experiment illuminated the "deep ecological" perspective that the global life-form was transhuman, since in any currently imaginable technological scenario, the only way for global life to reproduce would be by carting into space recycling systems including edible plants, waste-recycling bacteria and fungi, and living green matter from cyanobacteria to vegetables to produce oxygen and take in carbon dioxide. Humans and technology, in other words, while necessary for present global reproduction, are only part of the alleged "Gaian superorganism" (Kelly, 1995; Margulis and Sagan, 1997).

However, we now find this defense interesting more for its implication of humans as unknowing participants in a biology-like extraterrestrial expansion of Earth life—the "budding" or "sporulation" of Gaia, and our human involvement in this "strange brood"—than in the technical claim of Gaia as an organism. Thermodynamically, Gaia does not qualify as an organism because the global ecosystem is largely a closed rather than an isolated or open system. Open systems in thermodynamics, whether construed as near or far from equilibrium, include all actively living cells and organisms made of cells, and always enjoy an influx of materials; organisms require incoming sources of carbon, hydrogen, nitrogen, sulfur, phosphorus, and oxygen to maintain, grow, and reproduce their bodies.

Closed systems, of which Gaia is a good example, are (again, in thermodynamics) closed to material but open to energetic influx. In the case of the biosphere, including the deep, hot biosphere, energy is provided from above the terrestrial envelope in the form of sunlight and from below in the form of chemical gradients, such as the energetic difference between sulfide- and oxygen-feeding bacteria. As in ecosystems, or their desktop simulations—glass-enclosed ecospheres containing shrimp and algae once sold as novelties—the matter of the living Earth (except for occasional meteorites coming in and astronautic stuff going out) forms basically a closed system. At present, as technological humanity is finding out, there is limited room to grow: if there were room, we would not be faced with the ethical quandaries of territorial violence, eating other intelligent animals, and so on. Perhaps only if the biosphere did evolve sufficient ecotechnoscience to actively funnel matter into growth of viable miniature biospheres would we be justified in considering it an organism, *sensu stricto*. Until then it remains a superecosystem, a biosystem or biosphere with physiological properties whose origins must still be addressed.

Doolittle's Objection

Other interesting objections to and defenses of the Gaia hypothesis include those of the neo-Darwinists Richard Dawkins and W. Ford Doolittle. Doolittle, a

Canadian molecular biologist, in a paper titled "Is Nature Really Motherly?," ridiculed the notion that there might be a concerted network of interactions among diverse life-forms, thereby somehow ensuring global regulation of environmental variables (Doolittle, 1981). Note that, as in early objections to continental drift by plate tectonics, the phenomenon (global physiology, like continental drift) is dismissed because there seems to be no reasonable explanatory mechanism (Lovelock's cybernetic links among organisms being as unpalatable as plate tectonics). Doolittle spoke dismissively of a "secret consensus" among organisms, suggesting the absurdity of late-night committees of organisms coming together to discuss their common interests. Perhaps in tacit rebuttal Lovelock remarked that Gaia is no doting nanny but has all the sympathy for humanity of a microprocessor in the warhead of an intercontinental nuclear missile.

Cybernetics, the computer-based discipline inaugurated by Norbert Weiner (1948) to study the nature of control in organisms and machines, came to the fore in Lovelock's attempts to provide an acceptable scientific mechanism for the seeming miracle of global physiology. Cybernetic mechanisms, through positive and negative feedbacks, can amplify or attenuate trends automatically. Thus, what appeared to be intelligence and unified organismhood could accrue without any secret committees or personified collusions among presumably mindless organisms. There was neither an implicit motherliness to nature nor anything more mindful than could be found in computers.

Despite the expediency and versatility of cybernetics as the Gaian mechanism of choice, however, it may have been flawed. A thermodynamic analysis, for example, would distinguish sharply between the ideal case of a machine as an isolated system, inevitably coming to equilibrium in accord with the second law, and the real status of organisms as open systems, indefinitely postponing their tendency to return to an equilibrium state by making more of themselves. In other words, the machines and organisms conflated by cybernetics in its rush to understand control, contrasts rather dramatically with distinctions between classical thermodynamics based on a study of steam engines and nonequilibrium thermodynamics attempting to understand life.

The Cybernetic Turn and Abiotic Thermoregulation

We would also suggest that the recent turn in Gaia science away from cybernetics to natural selection (e.g., Lenton, 1998; Harding and Lovelock, 1996) represents a turn both toward a more orthodox (and thus scientifically and politically acceptable) explanatory principle and a turn away from cybernetics (spawned by control mechanisms in ballistic missiles), away from a too machine-focused science. Nonetheless—and we are not intelligent enough to say precisely how—we sense that cybernetic feedback behaviors, insofar as they exist in the natural world beyond the realm of human engineering, stem from autocatalytic networks feeding on gradients.

For example, Bénard-Rayleigh convection cells—hexagonal structures that appear on the surfaces of substances such as spermaceti (a waxy solid from whales), silicone, and sulfur hexafluoride gas that are exposed to temperature gradients within a certain steepness range (and that range only)—may exhibit thermoregulatory behaviors (Koschmieder, 1993). The phase transition from disordered conduction of heat to organized convection occurs at certain nondimensional numbers. At this critical point, associated with the difference in temperatures between the top and bottom of the liquids, heat transfer suddenly becomes more efficient: the system's convectional complexity, accelerating the rate of heat loss, appears to readjust itself to dissipate the gradient more effectively. The appearance of more efficient convection when the temperature below is raised, indicates an ability of the inanimate system "to cool itself." Do we see here a thermoregulatory mechanism that owes nothing to life (let alone natural selection)—a thermoregulatory system homologous to Gaia's alleged temperature control of the planet, which shows multiple signs of cooling itself for hundreds of millions of years in the face of increasing luminosity from the sun?

Dawkins's Objection and Daisyworld

The British zoologist Richard Dawkins, a staunch neo-Darwinist and defender of evolutionary theory against what he sees as religious or pseudoscientific threats, objected to Gaia on the grounds that a physiological Earth might be plausibly postulated only if it could have evolved, like animals, by natural selection (Dawkins, 1982). But since, Dawkins reasoned, there is only one living planet, it could not in principle have evolved by natural selection, which by definition requires competition among variants. If, Dawkins further suggested, Earth was but one of many living planets, some of which had not survived, competing in our solar system—if this solar system were "littered" with imperfectly physiological planets—then, he allowed, there would be the possibility of a physiological planet.

As with Doolittle, and earlier objectors to now-accepted plate tectonics, we see the failure of logic and seeming common sense when confronted with a phenomenon that has no obvious mechanism. The situation is analogous to a spectator witnessing a magician make a coin completely disappear and disavowing the mystery because he is not privy to the method. Of all the objections to Gaia, Dawkins's is at once the most interesting and the most cavalierly symptomatic of the limitations of reductionist science.

If the suggestion above of a protophysiological thermoregulatory Bénard cell in the total absence of life and complex chemistry—let alone reproduction, genetics, or natural selection—is not enough, many more examples can be adduced. The putative ancestor of life, if considered the first single cell, also cannot, any more than the present biosphere, be explained cogently by natural selection: in both cases the complex phenomenon is selflike, even a self, yet a population of one. Other cyclical selflike systems appear in the neighborhood of gradients, increasing our suspicion that all selves may not owe their existence to natural selection.

For example, hurricanes (often given first names) appear from gradients; their complexity and cyclicity have nothing to do with natural selection and everything to do with the formation of locally improbable gradients whose "job," in thermodynamic terms, is to destroy a preexisting improbability. "Whirlpool"—that is its name—is a permanent cycling eddy downstream of Niagara Falls. And chemical clocks, such as Belousov-Zhabotinski reactions, show intricate and unexpected patterns that grope toward individuality and selfhood as they reduce electron potential gradients. Although they do not reproduce, and therefore do not produce variants which can be naturally selected, they do grow and they do show complexity which, if observed out of context, would no doubt seem mysterious and unexpected.

Lovelock's response to Dawkins was to show how a model of a planet, consisting only of daisies of light and dark hue, would, with very simple biological assumption of growth (no natural selection!), thermoregulate a planet exposed to increasing luminosity from its sun (Watson and Lovelock, 1983). The albedo of light daisies growing in clumps tended to reflect light, thereby cooling the planet when it got too hot; the albedo of the dark daisies tended to absorb heat when the sun was proportionately less luminous. Together the daisies raised planetary temperature by absorbing more radiation in the sun's early years (stars are thought to become more luminous as they age) and reflecting more when the star might have overheated the planet. Because the clumps of daisies died when it got too hot or too cold, the thermoregulatory effect was not perfect, but operated only within a certain temperature range.

One can glean how the perfectly credible biological assumption of growth within a certain temperature range translates into thermoregulation, homeostasis, or homeorrhesis at a planetary scale. Ultimately, we would argue, it is the growth properties of the daisies—analogous if not homologous to Bénard-style complexity, appearing only within the window of a certain steepness of gradient—that confers the complex "physiological" phenomenon of thermoregulation on the planet. It is a phenomenon that Dawkins must dismiss because it seems to him, as it does to Doolittle, too mysterious to be explained by natural selection, which cannot be operating either on the lone planet or on the nonreproducing daisies. Parenthetically, one might argue, because such concerted planetary behavior, in the absence of natural selection, seems to call forth references to mystical directing powers, that Daisy World satisfies the Turing Test—a computer program that, in retrospect anyway, mimics the behavior of a teleological entity, either conscious or physiological, whose behavior is in fact a simple extrapolation of the growth properties of daisies—at least as far as Dawkins is concerned.

In real life, Gaian global cooling has been postulated to involve coccolith algae that grow in sunlight and emit sulfur gases that serve as condensation nuclei for raindrops depriving the algae of sunlight—a negative means of planetary "air-conditioning." Perhaps more obvious, if less studied, is the role of evapotranspiration: clouds appear regularly over rain forests exposed to high incident radiation. In this way areas such as Amazonia, with highly evolved ecosystems, cool themselves and reduce the gradient between hot sun and 2.7 Kelvin space. Life, as Lovelock has repeated, likes it cool—and cooling at the planetary surface via tree-produced cloud cover necessarily entails dissipation of heat farther out. The situation is symmetrical to a room heated up by a refrigerator. The sun is like the plug: if we were unaware of it, the cooling of the magic icebox would indeed be miraculous.

The Biological Anthropic Principle

A final objection to the Gaia hypothesis of which we are aware was made in passing by Stephen Jay Gould at a colloquium. Asked about the peculiar habitability of the Earth going by the name of the Gaia hypothesis, Gould replied that, were we not gifted with a supportive environment, we would not be around to marvel at the question of the fine tuning of the environment. He added that if the colloquium were attended not by humans but by octopi, the question might be raised as to the basis of our near-miraculous possession of eight lovely arms.[9] Gould's response was consistent with his view of contingency in evolution: that if it were "replayed"—if the genetic deck of speciation were reshuffled, one might say—the chances of humans reevolving, or of intelligence reappearing, would be nil. Gould's dismissal of the Gaia hypothesis can also be seen as a biological version of the anthropic principle in physics, the weak version of which says that were the universe not so perfectly suited for the evolution and emergence of conscious life, conscious life would not be present to marvel at it.

Again, looking at Gaia as a magic trick, this seems to be the equivalent of accepting as trivially not in need of explanation a feat of surpassing improbability. Doolittle agrees: "If the fitness of the terrestrial environment is accidental, then is Lovelock not right in saying that for life to have survived to reach the stage of self-awareness 'is as unlikely as to survive unscathed a drive blindfold through rush-hour traffic?' I think he is right; the prolonged survival of life is an event of extraordinary low probability. It is however an event which is a prerequisite for the existence of Jim Lovelock and thus for the formation of the Gaia hypothesis.... Surely if a large enough number of blindfold drivers launched themselves into rush-hour traffic, one would survive, and surely he, unaware of the existence of his less fortunate colleagues, would suggest that something other than good luck was on his side" (Barlow, 1992, p. 33).

What we wish to stress, however, is not so much the improbability of Gaia as its natural appearance as a gradient-breaking structure from the improbable gradients of space. Gaia need not be one of many failed systems but, rather, a low-entropy gradient reducer fomenting external chaos in tune with the second law as it builds up internal complexity and history, "concentrating" improbability.

Nonequilbrium Thermodynamics and Extending the Second Law

A better way of understanding global physiology (and other examples of apparently inexplicable complexity or intelligent design) may be to return Gaia to its roots in nonequilibrium thermodynamics. Thermodynamics is notoriously confounding, in part because its conclusions of a universal tendency toward equilibration seem to contradict complexity and evolution, and in part because the mathematical equations for thermodynamic and information theory entropy, in addition to using the same term, are formally similar. There are many formulations of the second law, but the basic idea was formalized by Sadi Carnot in his miliatrily motivated attempts to improve steam power to battle the British navy and industry. Carnot pointed out that it was not simply the temperature of the steam-producing boiler that made pistons pump hard and fast in an engine, but rather the difference between the temperatures of its hot boiler and cooler radiator. "The production of heat is not sufficient to give birth to the impelling power. It is necessary that there should be cold; without it, the heat would be useless" (Guillen, 1995, p. 179).

The second law of thermodynamics, later understood in Boltzmann's statistical mechanics as matter's tendency to drift into states of increasing probability—there are more ways, for example, for cream particles in your coffee to be mixed with coffee than there are for them to be separated—linked Newtonian mechanics to the phenomenological observations of inexorable loss, decay, forgetting—thus producing, in Eddington's words, "the arrow of time" (Blum, 1968, pp. 5–6). Although this derivation is itself problematic—in infinite time even very unusual arrangements would be repeated an infinite number of times—it preceded evolutionary theory's equal, if opposite, linear time-based view of the cosmos. However, in thermodynamics the projected end of the cosmos was one of spent embers, with no energy left available for work, the "heat death" of the universe.

Thermodynamic Biology and the Purpose of Life

The rectification of the second law's degradation with life's complex maintenance and evolution was broached by Schrödinger, and major contributions to the physics of biology were made by Lotka, Vernadsky, Prigogine, Odum, Lovelock, Morowitz, Wicken, and Schneider. Morowitz, for example, in what is sometimes described as "a fourth law" of thermodynamics, argues that "In the steady state systems, the flow of energy through the system from a source to a sink will lead to at least one cycle in the system" (1979, p. 33). It is crucial to realize that the second law generalized the move to equilibrium in isolated systems, taking a very contrived and artificial experimental condition and applying it far beyond its ken.

In fact, we now see that stars, Bénard cells, Taylor vortices (which occur in counterrotating pairs as a result of rotational pressure gradients), whirlpools, dust devils, hurricanes, chemical clocks, and other nonliving selflike systems crop up spontaneously and grow (like the daisies of Daisy World) in response to ambient gradients.

Earth is cooler than a simple interpolation between Mars and Venus (whose atmospheres are "reacted-out" mixtures of mostly carbon dioxide) would suggest: Gaia itself is a giant gradient-reducing system. Wicken argues that "Thermodynamics is, above all, the science of spontaneous process, the 'go' of things. Approaching evolution thermodynamically allows us to bring the 'lifeness' of life into the legitimacy of physical process ... the emergence and the evolution of life are phenomena causally connected with the Second Law" (Wicken, 1987, p. 5). The genetic mechanisms of replication and reproduction provide, in Wicken's view, "stable vehicles of degradation" for ambient gradients to be reduced. At the same time, the randomizing effects of the second law inevitably disturb the copying process of the chemical Rube Goldberg machines which are living things, taking available energy from their environment and using it (up) not only to maintain and grow their structure, but also to seek out new gradients upon which their existence as selves, as forms depending on a whirling flux of materials, inevitably depends. Evolution, in this view, is second not only to selfhood but also to thermodynamic processes conferring metastability in the coherent areas of matter-degrading ambient gradients. These open systems are low-entropy and highly organized—indeed, organisms—within their frame because they are helping to randomize the surroundings outside their open bodies.

Which brings us to the precipice, or rather foothill, of the great and scientifically frightening edifice of teleology. Why is life? What is its purpose? The reader familiar with the literature of Gaia, or research funding for geophysiological studies within biology, will discern that the link to teleology has long been a thorn in the side of Gaia studies. But thermodynamics suggests a way around this impasse. Organisms as cells and bodies have a natural physiology: they exist "to" break down gradients in much the same way that lungs exist "to" take in air or the heart exists "to" pump blood. Indeed, the future orientation of beings whose genetic makeup presumably evolved piggyback on imperfectly reproducing vehicles of gradient degradation becomes naturalistic in a Gaian-thermodynamic view.

Organisms are, in Kantian language, "natural purposes" (Wicken, 1987) whose means are wrapped up with their ends in functional closure, autocatalytic chemical organization, and energetic and material openness to the environment. Humans have proliferated relative to other primates in large part due to a combination of neural plasticity (Skoyles and Sagan, 2002) and complex social relations (mediated by language) whose net result is a much enhanced ability to identify and deploy the food and other gradients necessary to move agricultural and technical civilization into the material evolutionary form which is humanity. Despite civilization and classical music, a disproportionate amount of waking human life is devoted to thoughts and activities revolving around the procuring of food, the finding of mates, and the making of money—activities necessary to maintain and perpetuate a particular form of genetically undergirded gradient-reducing organization.

Other species obey the same thermodynamic imperative arguably behind the processes of life's origination, growth (increase in biomass), reproduction, increase in respiration, energy efficiency, number and types of taxa (biodiversity), rates of circulation of elements, numbers of elements involved in biological circulation, and increase in intelligence (which identifies new gradients to be exploited and means of escaping the pollution which inevitably and thermodynamically accompanies rapid growth). The thermodynamic imperative or arrow thus points ahead, if not specifically in the direction of humanity; the teleology exists, but is prosaic. We thus are partially in accord with Ernst Mayr (1982), who distinguishes between the second law as teleomatic, the evolved physiology of animals as teleonomic, and conscious awareness as teleological. We see the teleological (so defined) as an outgrowth of the teleomatic; we would disagree, however, with the notion that the second law's status as law with regard to life is no different from the law of gravity.

The second law's character appears (at least proximately) to be more foundational to living teleology, and indeed provides the impetus for resisting the effects of gravitation in flight and motility by gathering, via biochemistry, energies from the environmental surround. The material purpose of life is to degrade the solar gradient (and perhaps this is connected with any "higher" purpose it may have). The tendency to retreat into ideational realms of mathematical or religious "ultimate reality" (e.g., ideas of heaven) during hard times may also reflect a thermodynamic tendency—the panbiological tendency to "shut down" (thus preserving a given gradient-reducing material form); in neurally plastic humans, this tendency may manifest itself in a relative foregrounding of previously imaginary realms and a correlated willingness to die for the social collective. Thus a thermodynamically based teleology, while at first glance seemingly allied to scientifically taboo thoughts of religious purpose, in fact maintains a materialism more uncompromising than Cartesian dualism—which would, perhaps for ultimately practical reasons, bracket all purpose and free will, fencing it off with divine authority in a "humans-only" realm.

This fourth Copernican deconstruction, refusing to consider special human mindlike computational and perceptive processes, allies the conscious teleology we perceive in ourselves to the nonliving realm of complex thermodynamic processes. Here we can discern that part of the sociopolitical problem with science's reception of Gaia has been the perceived vitalism of the hypothesis. But in a thoroughgoing thermodynamic worldview, inanimate matter already displays teleological behavior, precisely that of "seeking" gradients to come to equilibrium: the "teleological" behavior of a biosphere, acting as if it "knew" its surrounding environment by sensing and reacting to it, thus becomes a moot argument against the existence of Gaia or Gaia-like processes.

The Processes Themselves

And yet, our consciousness, our perception, may be at least in part an elaboration of such equilibrium-seeking, distorted by our need to feed on available gradients to maintain ourselves (or our relatives, associates, or children) as stable vehicles of degradation. Here we would have to disagree with the "candidate fourth laws" put forth by Stuart Kauffman (2000), who argues the need for a thermodynamic explanation of biology and technology. But the complexity of biology and technology, so dependent on energy and so productive of waste and pollution, is directly related to their status as nonequilibrium vehicles of degradation. Why invent a complex fourth law (and, moreover, one which applies disproportionately to life and technology) when the second law—a law which, as we stress, was originally based on the special case of isolated rather than the general case of open systems—can simply be extended?

Here we must accede both to Occam's razor and the connecting spirit of Darwinian evolution to chose a simpler, more general principle over a more complex and ad hoc one. As Nobel laureate Stephen Weinberg said, science rests on the discovery "of simple but impersonal principles."[10] We nominate Schneider's extension of the second law into a gradient-destroying tendency as such a principle. We see no reason why "explanations" of complexity should, instead of simplifying, apprentice themselves to the complexity of the phenomena they purport to explain. On the other hand, the iteration of the entire universe from simple, mindlike (computer algorithmic) rules by Stephen Wolfram (2002) seems to us to err in the opposite direction, and to commit the original thermodynamic sin of generalizing a highly specific situation (now computers, then the behavior of energetic systems in closed adiabatic containers) and applying it precipitously to the entire universe. The mathematician-philosopher Edmond Husserl, in founding phenomenology, advocated a "return to the things themselves." Similarly, those who study complex processes should return to "the processes themselves"—only a subset of which appear on computer screens.

Life and Nonlife

Gradient-based thermodynamics links life to nonlife, and linguistic, conscious human teleology to inanimate purpose in nature. Because complex material processes arise and persist to degrade gradients, and because thinking organisms represent a genetic example of such a process, there is a natural link between the behavior of matter (gradient reduction) and of mind (gradient perception). Gradient reduction theory thus would seem to further science's historical trajectory of linking us to the rest of the physical universe. If we are not at the center of the universe, if the atoms of our bodies are not special but common star stuff, our information- and energy-handling abilities also have a cosmic context. Taylor vortices jump to new states dependent upon their past history—they show a fledgling memory.

Parsimony suggests our animate purpose has roots in thermodynamic teleology. If this is the case, then the prosaic purpose of life can be understood. Our desires for food, sex, power, and money reflect us as open selves connected to growing nexuses involved in gradient destruction. The ability to perceive new gradients must have conferred huge evolutionary advantages, selecting for intelligence. A blackjack player counting cards recognizes statistically unlikely preponderances of high cards and aces, and puts his money down in larger bets in the hope that the numerical playing card gradient will reduce itself, as is its statistical wont (Griffin, 1999). Arbitrageurs buy cheap in one place and sell dear in another, selecting for global communications and means of commodity transfer.

Indeed, commodification itself, the transformation of a desired and expensive luxury into a cheap and available product (and sometimes necessity), may be understood as a reduction in supply-demand gradients. The belief systems of societies, whose members feel kinship on the basis of interpretations and signs, and which battle each other, sometimes to the death, for access to resources, are perhaps also open to fruitful analyses in terms of gradient reduction theory. Gradient-based thermodynamics shows much promise for a variety of fields, including economics, evolutionary theory, ecology, and, of course, further Gaia studies, which began in James Lovelock's recognition of chemical atmospheric disequilibria.

Acknowledgments

The authors would like to thank Eric D. Schneider for inspiration and discussions, and acknowledge support from an NSF Graduate Research Fellowship to JHW. This is Lamont-Dohesty Earth observatory contribution number 6562.

Notes

1. A more complete discussion of some of the topics discussed here will be available in Eric D. Schneider and Dorion Sagan, *Energy Flow*, forthcoming, University of Chicago Press.

2. Copernican heliocentrism and vitalism's demise are arrayed with Darwinian evolution in a preliminary series of major scientific deconstructions in Margulis et al. (2002).

3. For example, Rod Swenson (1997), recognizing the inanimate basis, in thermodynamic behavior, of what has too readily been linked anthropocentrically with life and cognition, contrasts "Descartes' dualistic world [which] provided the metaphysical foundation for the subsequent success of Newtonian mechanics and the rise of modern science in the seventeenth century [but which defined] psychology and physics ... by their mutual exclusivity" with the energetically based "active, end-directed, or intentional dynamics of living things," errs in promulgating a "Law of Maximum Entropy Production." (pp. 217, 221–225). Entropy is neither maximized nor easy to measure in many complex open systems.

4. The natural computing functions of cycling thermodynamic systems unconsciously "seeking" equilibrium (but instead forming highly complex processes when their foundational gradients are maintained) may be the most interesting (if not elsewhere mentioned) example of complexity theorist Stephen Wolfram's (2002) claim of a universal equivalence of computing abilities among natural systems which are not "obviously simple." We would argue, however, that computer algorithms, far from generating real-world structures, let alone the second law of thermodynamics, represent a subset of natural energetic equilibrium-seeking processes (Sagan and Whiteside, 2002).

5. Computer technology consultant Peter Bennet's (1998) story "Jamie the Prospector" is about a financial wizard who uses a computerized trading system that instantaneously identifies disparities among stocks, commodities, bonds, and currencies. Jamie's computer system translates the price disparities into a three-dimensional cyber landscape over which Jamie flies in virtual reality; by using a joystick, he levels the hilly regions, which represent gradients. On the eve of the new millennium, the Far East shuts down its financial exchanges to avoid mishaps due to the projected year 2000 computer glitch. A great hilly region appears, which Jamie quickly levels, pocketing hundreds of millions of dollars in a matter of minutes.

6. Derrida's (seen but not heard) use of the term *différance*, as well as the importance of similar differences in Heidegger, Wittgenstein, Bohm, and others, can be found in the web article *Tracing the Notion of Difference* at http://tyrone.differnet.com/experience/append.htm.

7. Gradients are necessary but not sufficient for complex teleological, teleonomic, or teleomatic behaviors (Lenton and Lovelock, 2000).

8. The "just rightness" of the steepness of gradients, leading to the sensitive appearance of complex behaviors only under certain conditions, can be (and has been) mistakenly assumed to mean that human-style conscious awareness must be in the vicinity (Sagan, 2000).

9. The comment was made at a colloquium organized by Richard Lewontin at Harvard University in the early 1980s.

10. Weinberg's "simple but impersonal principle" statement is from his lecture at the nineteenth annual Key West Literary Seminar, Science & Literature: Narratives of Discovery, January 11–14, 2001.

References

Barlow, C. C., ed. 1992. *From Gaia to Selfish Genes: Selected Writings in the Life Sciences.* MIT Press, Cambridge, MA.

Baross, J. A., and S. E. Hoffman. 1985. Submarine hydrothermal vents and associated gradient environment as sites for the origin and evolution of life. *Origins of Life*, 15:327–345.

Bataille, G. 1988. *The Accursed Share: An Essay on General Economy.* vol. 1, *Consumption*, Robert Hurley, trans. Zone Books, New York.

Bateson, G. 1979. *Mind and Nature: A Necessary Unity.* Dutton, New York.

Bennet, P. 1998. Imprint: random thoughts and working papers (Global Business Network), 2:1–11.

Blum, H. F. 1968. *Time's Arrow and Evolution.* Princeton University Press, Princeton, NJ.

Chaisson, E. 2001. *Cosmic Evolution: The Rise of Complexity in Nature.* Harvard University Press, Cambridge, MA.

Clarke, A. C. 1972. *Report on Planet Three and Other Speculations.* http://public.logica.com/~stepneys/cyc/l/law.htm.

Corliss, J. B. 2001. *Life Is a Strange Attractor: The Emergence of Life in Archaean Submarine Hot Springs.* http://www.syslab.ceu.hu/corliss/Origin_of_Life_Intro.html.

Dawkins, R. 1982. *The Extended Phenotype.* W. H. Freeman, San Francisco.

Derrida, J. 1980 [1967]. *L'Écriture et la Différance: Writing and Difference,* Alan Bass, trans. University of Chicago Press, Chicago.

Doolittle, W. F. 1981. Is nature really motherly? *CoEvolution Quarterly,* 29:58–63.

Gribbin, J., with M. Gribbin. 2000. *Stardust: Supernovae and Life—the Cosmic Connection.* Yale University Press, New Haven, CT.

Griffin, P. 1999. *The Theory of Blackjack,* 6th ed. Huntington Press, Las Vegas.

Guillen, M. 1995. *Five Equations That Changed the World: The Power and Poetry of Mathematics.* Hyperion, New York.

Harder, B. 2002. Water for the rock: Did Earth's oceans come from the heavens? *Science News,* 161:184.

Harding, S. P., and J. E. Lovelock. 1996. Exploiter mediated coexistence and frequency-dependent selection in a geophysiological model. *Journal of Theoretical Biology,* 182:109–116.

Kauffman, S. A. 2000. *Investigations.* Oxford University Press, Oxford.

Kelly, K. 1995. *Out of Control: The New Biology of Machines, Social Systems and the Economic World.* Perseus Press.

Kirchner, J. W. 1991. The Gaia hypotheses: Are they testable? Are they useful? In *Scientists on Gaia,* S. H. Schneider and P. J. Boston, eds. MIT Press, Cambridge, MA.

Kirchner, W. H. 1993. Acoustical communication in honey bees. *Apidologie,* 24(3): 297–307.

Koschmieder, E. L. 1993. *Bénard Cells and Taylor Vortices.* Cambridge University Press, Cambridge.

Lenton, T. M., and J. E. Lovelock. 2000. Daisyworld is Darwinian: Constraints on adaptation are important for planetary self-regulation. *Journal of Theoretical Biology,* 206:109–114.

Lenton, T. M. 1998. Gaia and natural selection. *Nature,* 394:439.

Lovelock, J. E. 1979. *Gaia: A New Look at Life on Earth.* Oxford University Press, Oxford.

Lovelock, J. E. 1991. *Healing Gaia.* Harmony Books, New York.

Margulis, L., and D. Sagan. 1997a. *Slanted Truths: Essays on Gaia, Evolution and Symbiosis.* Copernicus Books, New York.

Margulis, L., and D. Sagan. 1997b. *Microcosmos: Four Billion Years of Microbial Evolution.* Berkeley: University of California Press.

Margulis, L., D. Sagan, and J. H. Whiteside. 2002. From cells to cities: The evolution of composite individuality—early life leaves its record in the rocks. *Kosmos: Review of the Alexander von Humboldt Foundation,* July:23–24.

Mayr, E. 1982. *The Growth of Biological Thought.* Harvard University Press, Cambridge, MA.

Morowitz, H. 2002. *The Emergence of Everything: How the World Became Complex.* Oxford University Press, New York.

Morowitz, H. J. 1979. *Energy Flow in Biology: Biological Organization as a Problem in Thermal Physics.* Ox Bow Press, Woodbridge, CT.

Nørrestranders, T. 1991. *The User Illusion: Cutting Consciousness Down to Size,* Jonathan Sydenham, trans., pp. 21–22. Viking, New York, 1991.

Russel, M. J., A. J. Hall, A. G. Cairns-Smith, and P. S. Braterman. 1998. Submarine hot springs and the origins of life. *Nature* 336:117.

Sagan, D. 1990. *Biospheres: Reproducing Planet Earth.* Bantam, New York.

Sagan, D. 1992. Metametazoa: Biology and multiplicity. In *Incorporations (Zone 6; Fragments for a History of the Human Body),* Jonathan Crary and Sanford Kwinter, eds., pp. 362–385. New York, Zone Books.

Sagan, D. 2000. The Goldilocks paradox: Thermodynamics and Gaia. In *Abstracts Guide, 2nd Chapman Conference on the Gaia Hypothesis.* American Geophysical Union, Valencia, Spain, June 19–23. American Geophysical Union, Washington, DC.

Sagan, D., and L. Margulis. 1991. Gaia: A "good four-letter word." *Gaia* magazine, 3:4–6.

Sagan, D., and L. Margulis. 1993. Gaia hypothesis. In *McGraw-Hill Yearbook of Science & Technology 1993.* McGraw-Hill, New York.

Sagan, D., and E. D. Schneider. 2000. The pleasures of change. In *The Forces of Change: A New View of Nature,* pp. 115–126. National Geographic Society, Washington, DC.

Sagan, D., and J. Whiteside. 2002. A skeptical view of the "sciences of complexity." *Swift* (online newsletter of the James Randi Educational Foundation), http://www.randi.org/jr/011802.html, January 18, 2002; http://www.randi.org/jr/012502.html, January 25, 2002; and http://www.randi.org/jr/022202.html, February 22, 2002.

Schneider, E. D., and J. J. Kay. 1989. Nature abhors a gradient. In *Proceedings of the 33rd Annual Meeting of the International Society for the System Sciences,* P. W. J. Ledington, ed., vol. 3, pp. 19–23. International Society for the System Sciences, Edinburgh.

Schneider, E. D., and J. J. Kay. 1994a. Life as a manifestation of the second law of thermodynamics. *Mathematical Computer Modeling,* 19:25–48.

Schneider, E. D., and J. J. Kay. 1994b. Complexity and thermodynamics: Towards a new ecology. *Futures,* 26:626–647.

Schwartzman, D. 1999. *Life, Temperature, and the Earth.* Columbia University Press, New York.

Schopf, J. W., ed. 1992. *Major Events in the History of Life.* Jones and Bartlett, Boston.

Shock, E. L. 1990. Geochemical constraints on the origin of organic compounds in hydrothermal systems. *Origins of Life,* 20:331–367.

Skoyles, J., and D. Sagan. 2002. *Up from Dragons: The Evolution of Human Intelligence*. McGraw-Hill, New York.

Smolin, L. 1997. *The Life of the Cosmos*. Oxford University Press, New York.

Swenson, R. 1997. Thermodynamics, evolution, and behavior. In *The Encyclopedia of Comparative Psychology*, G. Greenberg and M. Haraway, eds. Garland, New York.

Von Frisch, K. 1967. *The Dance Language and Orientation of Bees*. Harvard University Press, Cambridge, MA.

Watson, A. J., and J. E. Lovelock. 1983. Biological homeostasis of the global environment: The parable of Daisyworld. *Tellus*, 35B, 284.

Wicken, J. 1987. *Evolution, Thermodynamics and Information: Extending the Darwinian Program*. Oxford University Press, New York.

Wiener, N. 1961 [1948]. *Cybernetics or Control and Communication in the Animal and the Machine*. MIT Press, Cambridge, MA.

Wolfram, S. 2002. *A New Kind of Science*. Wolfram Media, Champaign, IL.