Complexity: An Energetics Agenda

Energy as the Motor of Evolution

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1. INTRODUCTION

From galaxies to snowflakes, from stars and planets to life itself, modern science is weaving an intricate pattern describing all of natural history—a sweepingly inclusive view of the order and structure of every known class of object in our richly endowed Universe. Cosmic evolution—the heart of this broad scenario—is the study of the sum total of the many varied developmental and generational changes in the assembly and composition of radiation, matter, and life throughout all space and across all time. These are the physical, biological, and cultural changes that have produced, in turn and among other systems, our Galaxy, our Sun, our Earth, and ourselves. The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties—physics, astronomy, geology, chemistry, biology, and anthropology, among others—a genuine narrative of epic proportions extending from the beginning of time to the present, from big bang to humankind.

Our appreciation for evolution now extends well beyond the subject of biology; the concept of evolution, generally considered, has become a powerful unifying factor in all of science. Yet questions remain: How valid are the interdisciplinary continuities among Nature's many historical epochs, and how realistic is our quest for unification among them? Can we reconcile the observed constructiveness of cosmic evolution with the inherent destructiveness of thermodynamics? Is there a single driver of fundamental change writ large? We especially want to know more about the origins of the richly ordered and diverse structures spanning both the terrestrial and extraterrestrial Universe, notably those systems often characterized by the intuitive term "complexity"—a state of intricacy, complication, variety, or involvement, as in the interconnected parts of a system. Particularly intriguing is the rise of complexity over the course of time, indeed dramatically so within the past half-billion years since the end of the pre-Cambrian on Earth. Resembling a kind of neo-Platonism, perhaps some underlying principle, a unifying law, or an ongoing process does create, order, and maintain all structures in the Universe, enabling us to study everything on uniform, common ground—"on the same page," so to speak.

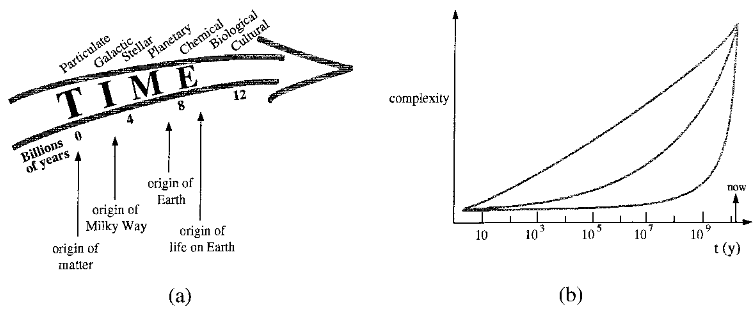
Recent research, guided by notions of beauty and symmetry and bolstered by vast new databases, suggests affirmative answers to some of these queries: Islands of ordered complexity—namely, open systems such as galaxies, stars, planets, and life forms—are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All can be shown to be in quantitative agreement with the principles of thermodynamics, especially nonequilibrium thermodynamics. Furthermore, flows of energy engendered largely by the expanding cosmos do seem to be as universal a process in the origin of structured systems as anything yet found in Nature. The optimization of such energy flows might well act as the motor of evolution broadly conceived, thereby orchestrating much of physical, biological, and cultural evolution [1].

2. ARROW OF TIME

Figure 1(a) shows an archetypal illustration of cosmic evolution, the "arrow of time." Regardless of its shape or orientation, such an arrow represents an intellectual guide to the *sequence* of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos in the early Universe to order more recently. That sequence, as determined by a large body of post-Renaissance data, accords well with the idea that a thread of change links the evolution of primal energy into elementary particles, the transformation of those particles into atoms, in turn of those atoms into galaxies and stars, and of stars into heavy elements, the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, and of intelligent life into the cultured and technological society that we now share. Despite the compartmentalization of today's academic science, evolution knows no disciplinary boundaries.

As such, the most familiar kind of evolution—biological evolution, or neo-Darwinism—is just one, albeit important, subset of a much broader evolutionary scheme encompassing more than mere life on Earth. In short, what Darwinian change does for plants and animals, cosmic evolution aspires to do for all things. And if Darwinism created an intellectual revolution by helping to free us from the notion that humans basically differ from other life forms on our planet, then cosmic evolution extends that revolution by treating matter on Earth and in our bodies no differently from that in the stars and galaxies beyond.

FIGURE 1



(a) This symbolic "arrow of time" highlights salient features of cosmic history, from its fiery origins some 14 billion years ago (at left) to the here and now of the present (at right). Labeled diagonally across the top are the major evolutionary phases that have produced, in turn, increasing amounts of order and complexity among all material systems: particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. Cosmic evolution encompasses all of these phases. Time is assumed to flow linearly and irreversibly, unfolding at a steady pace, much as other central tenets are assumed, such as the fixed character of physical law or the mathematical notion that $2 + 2 = 4$ everywhere. (b) Sketched here qualitatively is the rise of order, form, and structure typifying the evolution of *localized* material systems throughout the history of the Universe. This family of curves connotes the widespread, innate feeling that complexity of ordered structures has *generally* increased over the course of time. Whether this rise of complexity has been linear, exponential, or hyperbolic (as drawn here), current research aims to specify this curve, to characterize it quantitatively.

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Time's arrow implies no anthropocentrism; it is not pointing at us. The arrow merely provides a mental roadmap symbolically mapping the rise of increasingly complex structures, from spiral galaxies to rocky planets to reproductive beings. Nor does the arrow mean to imply that "lower," primitive life forms biologically changed directly into "higher," advanced organisms, any more than galaxies physically change into stars or stars into planets. Rather, with time, the environmental conditions suitable for spawning primitive life eventually changed into those favoring the emergence of more complex species; likewise, in the earlier Universe, environments ripe for galactic formation eventually gave way to conditions more conducive to stellar and planetary formation; now, at least on Earth, cultural evolution dominates. Change in surrounding environments usually precedes change in organized systems, and the resulting system changes have *generally* been toward greater amounts of order and complexity.

Figure 1(b) sketches the widespread impression that material assemblages have become more organized and complex, especially in relatively recent times. This family of curves refers to islands of complexity comprising systems per se—whether giant stars, buzzing bees, or urban centers—not their vastly, indeed increasingly, disorganized surroundings. A central task of complexity science aims to—or ought to—explain this temporal rise of organization. That is the objective of this paper.

3. NONEQUILIBRIUM THERMODYNAMICS

Cosmic evolution, as understood today, is governed largely by the laws of physics, particularly those of thermodynamics. Note the adjective "largely," for this is not an exercise in traditional reductionism; no attempt is made here to "reduce" biology to physics, rather to broaden physics to include biology. For of all the known principles of Nature, thermodynamics has perhaps the most to say about the concept of change—yet change dictated by a combination of chance and necessity, of randomness and determinism. Even so, the cosmic-evolutionary narrative is much too rich and diverse to be explained merely by equilibrium thermodynamics. All structures, whether galaxies, stars, planets, or life forms, are demonstrably open, nonequilibrated systems, with flows of energy in and out a central feature. And it is this energy, the so-called available, or "free" energy, that goes to work and helps build structures.

By utilizing energy order can be achieved, or at least the environmental conditions made conducive for the potential rise of order within open systems ripe for growth. Whether it's electricity powering a laser, sunlight shining on a plant, or food consumed by humans, energy flows do play a key role in the creation, ordering, maintenance, and fate of complex systems—all in quantitative accord with thermodynamics' celebrated second law. None of Nature's ordered structures, not even life, is a violation (nor even a circumvention) of this law. For both ordered systems as well as their surrounding environments, we find good agreement with modern, nonequilibrium thermodynamics. No new science is needed [1].

Championed decades ago by Bertalanffy [2] and later espoused by Schroedinger [3], the need for energy has come to be recognized as an essential feature, not only for biological systems such as plants and animals that process foodstuffs in the course of living, but also for physical systems such as stars and galaxies that convert gravitation potential into heat and light, indeed for social systems, too, such as cities that economize the inward flow of food and fuel and the outward flow of products and wastes. The analysis is much the same for any open system, provided we reason in broad, interdisciplinary terms.

Figure 2 schematically diagrams, along the lines developed by Prigogine [4], the emergence of structure in the presence of energy flow. Physicists are familiar with the type of curves at the top; biologists more comfortable with those at bottom. Upon crossing certain energy thresholds that depend on a system's status, bifurcations can occur, fostering the emergence of whole new hierarchies of novel structures that display surprising amounts of coherent behavior. Such dissipative structures export some of their entropy (or expel some of their energy) into the external environment with which they interact. Accordingly, order is created and often maintained by routine absorption of substances rich in energy, followed by discharge of substances low in energy. This process, often misnamed, is not really *self*-ordering; it is ordering in the presence of energy. "Self-organization" reflects an essential tension between energy inflow and dissipative outflow; these systems do not function magically by themselves.

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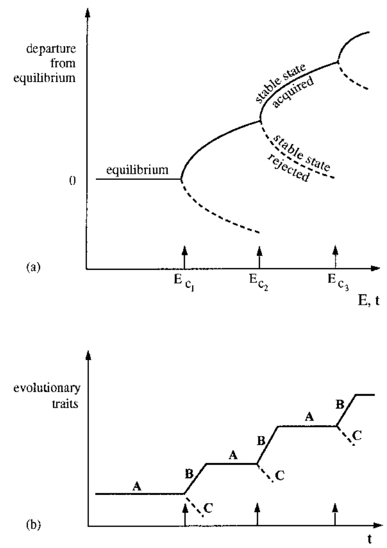
The onset of order from a state originally having none is relatively straightforward. Fluctuations—random deviations from some average, equilibrium value of, for example, density, temperature, or pressure—inevitably yet stochastically appear in any system having many degrees of freedom. Normally, as in equilibrium thermodynamics, such instabilities regress in time and disappear; they just come and go by chance, the statistical fluctuations diffusing as quickly as they arise. Even in isolated systems, such internal fluctuations can generate local, microscopic reductions in entropy, but the second law ensures that they will always balance out. Minute temperature fluctuations, for instance, are said to be thermally relaxed. Nor can open systems *near* equilibrium evolve spontaneously to new and interesting structures. But should those fluctuations become too great for an open system to damp, that system will then depart far from equilibrium and be forced to regroup. Such reorganization generates a "dynamic steady

FIGURE 2



(a) The extent to which open systems depart from equilibrium is drawn here as a function of both time and energy. The time axis makes clear that this is an historical, evolutionary process, whereas the parallel energy axis denotes the free energy flowing through an open system as a vital part of its being. At certain critical energies, labeled here E_c, the system can spontaneously change, or bifurcate, into new, nonequilibrium, dynamic steady states. Statistical fluctuations—that's chance—affect which fork the system selects—that's necessity—upon bifurcation (vertical arrows), namely which spatial structure is achieved. The process of change, as always, is an interplay of randomness and determinism; therefore the end result is inherently unpredictable, as with virtually all of evolution. (b) Events in evolutionary biology mimic those of the physical diagram in (a), although the results are richer in structural detail, system function, and energy flow. In phases marked A, species survive and persist until the environment changes (vertical arrows), after which further evolution occurs—along phase B toward renewed survival or phase C toward extinction. The upward rising graphs (drawn solid in both a and b) imply no progress, but they do suggest a *general trend* toward increasing complexity.

state," provided the amplified fluctuations are continuously driven and stabilized by the flow of energy from the surroundings—namely, provided the energy flow rate exceeds the thermal relaxation rate. Global, coherent cycling is often the result, because under these conditions the spontaneous creation of macroscopic structures dissipates energy more rapidly than the ensuing, and damaging, heat can damp the gradients and destroy those structures. Furthermore, because each successive reordering causes more complexity than the preceding one, such systems become even more susceptible to fluctuations. Complexity itself consequently creates the conditions for greater instability, which in turn provides an opportunity for greater reordering. The resulting phenomenon—termed "order through fluctuations"—is a distinctly evolutionary one, complete with feedback loops that can drive a system farther from equilibrium. But only in the presence of energy, for otherwise Nature abhors a gradient (and not just a vacuum). And as the energy consumption and resulting complexity accelerate, so does the evolutionary process—all of which put us into the realm of true thermo*dynamics*, the older, traditional subject of that name more properly labeled "thermostatics."

Numerous such systems come to mind, and not only in the physical world of convection cells, river eddies, atmospheric storms, and even artificially made devices such as refrigerators and lasers among a whole host of similar examples of systems that experience coherent order when amply fed with sufficient energy. Biological systems, too, obey the rules of nonequilibrium thermodynamics, for we and our living relatives are demonstrable examples of dynamic steady states that emerge and flourish via energetically rich neo-Darwinism. As are Lamarckian-type cultural systems of more recent times, for energy again is the principal broker in the making of today's bricks and chips. The upshot is that life and its social inventions differ not in kind, but merely in degree—specifically, degree of complexity and energy use—among the myriad ordered systems evident in Nature.

4. STANDARD COSMOLOGY

The origin of Nature's many varied structures is closely synonymous with the origin of free energy. Time marches on, equilibrium fails, and free energy flows because of cosmic expansion [5,6], all of it typified by the run of density and temperature shown in Figure 3(a). Here, the essence of change is plotted on the largest scale—the truly big picture, or "standard model," of the whole Universe—so these curves pertain to nothing in particular, just everything in general. They track the main trends, minus the devilish details, of modern cosmology: the cooling and thinning of radiation and matter, largely based on observations of distant receding galaxies and of the microwave background radiation—all this change fundamentally driven by expansion of the Universe.

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Radiation completely ruled the early Universe. Life was then nonexistent and matter itself only a submicroscopic precipitate suspended in a glowing fireball of intense light, X-rays, and gamma rays. Structure of any sort had yet to emerge; the energy density of radiation was too great. If single protons captured single electrons to make hydrogen atoms, radiation was then so fierce as to destroy those atoms immediately. Prevailing conditions during the first few tens of millennia after the origin of time were uniform, symmetrical, equilibrated, and boring. We call it the Radiation Era.

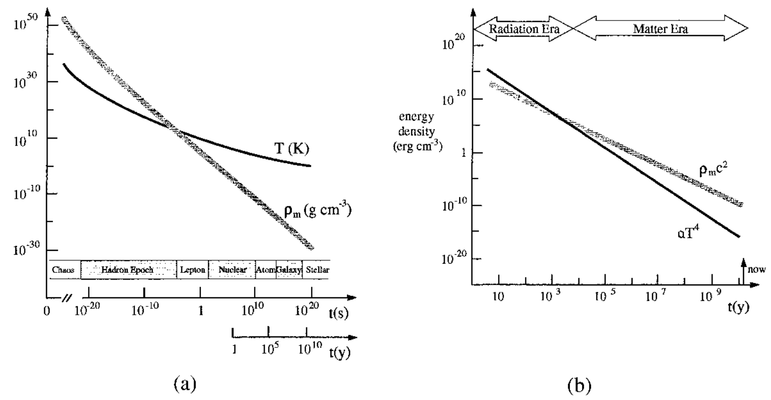
Eventually and inevitably, as depicted by Figure 3(b), the primacy of radiation gave way to matter. As the expanding Universe naturally cooled and thinned, charged particles assembled into neutral atoms, among the simplest of all structures; the energy density of matter began to dominate. This represents a change of first magnitude—perhaps the greatest change of all time—for it was as though an earlier, blinding fog had lifted; cosmic uniformity was punctured, its symmetry broken, its equilibrium spent. The Universe thereafter became transparent, as photons no longer scattered aimlessly and destructively. The bright Radiation Era gradually transformed into the darker Matter Era; it occurred about 300,000 years after the big bang, which is when the free energy began to flow.

More technically, although thermal and chemical (but not gravitational) entropy must have been maximized in the early Universe, hence complexity in the form of any structures then nonexistent, the start of the Matter Era saw the environmental conditions become more favorable for the potential growth of order, taken here as a "lack of disorder." At issue was timing: As density (ρ) decreased, the equilibrium reaction rates ($\propto \rho$) fell below the cosmic expansion rate ($\propto \rho^{1/2}$) and nonequilibrium states became possible. Thus we have a paradoxical yet significant result that, in an expanding Universe, both the disorder (i.e., net entropy) and the order (maximum possible entropy minus actual entropy at any given time) can increase simultaneously, the former globally and the latter locally [1].

5. THE RISE OF COMPLEXITY

Recall the task we set out to address: to quantify the rise of complex systems, ideally for all such systems in the same way, lest special effects prescribe some systems, not least perhaps life. But how shall we characterize complexity, a slippery term for many researchers? In biology alone, much as their inability to reach consensus on a definition of life, biologists cannot agree on a complexity metric. Some count nonjunk genome size [7], others employ morphology and flexibility of behavior [8], whereas still others chart numbers of cell types in organisms [9] or appeal to cellular specialization [10]. Each of these attributes of life is useful in qualitative ways, but they evade quantification and apply

FIGURE 3



(a) The essence of big-bang cosmology: A plot of the density (ρ) of matter and the temperature (T) of radiation, from near the origin of the Universe to the present. The thicker width of the density curve represents the range of uncertainty in total mass density, whose value depends on the (as yet unresolved issue of) "dark matter." By contrast, the cosmic background temperature is very accurately measured today, and its thin curve can be accurately extrapolated back into the early Universe. The startling possibility, recently discovered, that universal expansion might be accelerating should not much affect these curves to date. (b) The temporal behavior of both matter energy density (ρc^2) and radiation energy density (aT^4) illustrates perhaps the greatest change in history, where a is the radiation constant and c is the speed of light. Where the two curves intersect, neutral atoms began to form. By some 300,000 years, the Universe had changed greatly as thermal equilibrium and particle symmetry had broken, and the Radiation Era transformed into the Matter Era. A uniform, featureless state characterizing the early Universe thus naturally changed into one in which order and complexity were thereafter possible.

only to biological systems. Here, the goal is to push the envelope beyond mere words, indeed beyond biology.

Putting aside as unhelpful the idea of information content (of the Shannon-Weaver type, which is admittedly useful yet controversial in some contexts) and of negative entropy (or "negentropy," which Schroedinger [3] first adopted and then quickly abandoned), I prefer to embrace the quantity with greatest appeal to physical intuition—energy. Given that energy is the most universal currency known in the natural sciences, energy has a central role to play in any attempt to unify physical, biological, and cultural evolution. Not that energy has been overlooked in previous studies of Nature's many varied structures. Physicists [11, 12], biologists [13, 14], ecologists [15, 16], to cite but a few, have championed the cause of energy's organizational abilities. Even so, the quantity of choice cannot be just energy alone, for a star clearly has more energy than an amoeba, a galaxy much more than a single cell. Yet any living system

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is surely more complex than any inanimate object. Thus, absolute energies are not as telling as relative values, which depend on a system's size, composition, and efficiency. Nor are maximum energy principles or minimum entropy states likely relevant; rather, organizational complexity is mostly governed by the *optimum* use of energy—not too little as to starve a system, yet not too much as to destroy it.

To characterize complexity objectively—that is, to normalize all such ordered systems on that same page—I adopt a kind of energy density, much like the competing energy densities of radiation and matter that dictated events in the early Universe [Figure 3(b)]. Moreover, it is the *rate* at which free energy transits a complex system of given mass that seems most important. Hence, *free energy rate density*, symbolized by Φ_m, is an operational term whose meaning, measurement, and units (erg s^{-1} g^{-1}) are clearly understood.

Figure 4 plots a *sampling* of many findings, where free energy rate densities are graphed as horizontal histograms for various systems' evolutionary ages. As expected, plants ($\Phi_m \sim 10^3$ erg s^{-1} g^{-1}) are more complex than stars ($\sim$1) or planets ($\sim 10^2$); animals ($\sim 10^4$) and their brains ($\sim 10^5$) more complex yet; and society collectively ($\sim 10^6$) among the most complex of all known ordered systems. That is, although the total energy flowing through a star or planet is hugely larger than that through our human body or brain, the *specific* rate (per unit mass) is much larger for the latter. The modeled flow of normalized energy for a wide range of open systems, be they alive or not, closely resembles the intuitive rise in complexity implied by Figure 1(b). Complexity (as treated here energetically for localized structures) has in fact risen throughout the course of natural history, and at a rate at least exponential in more recent times [1, 17].

This is not to say, by any means, that galaxies per se evolved into stars, or stars into planets, or planets into life. Rather, this analysis suggests that galaxies gave rise to environments suited to utilize flows of energy for the birth and maturation of stars, that some stars spawned environments energetically conducive to the formation and maintenance of planets and that at least one planet fostered an energy-rich environment ripe for the origin and evolution of life. Cosmic evolution, to repeat, incorporates both developmental and generational change, spanning physical, biological, and cultural systems, across a wide and continuous hierarchy of complexity from big bang to humankind. And in an expanding, nonequilibrated Universe, energy is a natural underlying driver for the rise of that complexity.

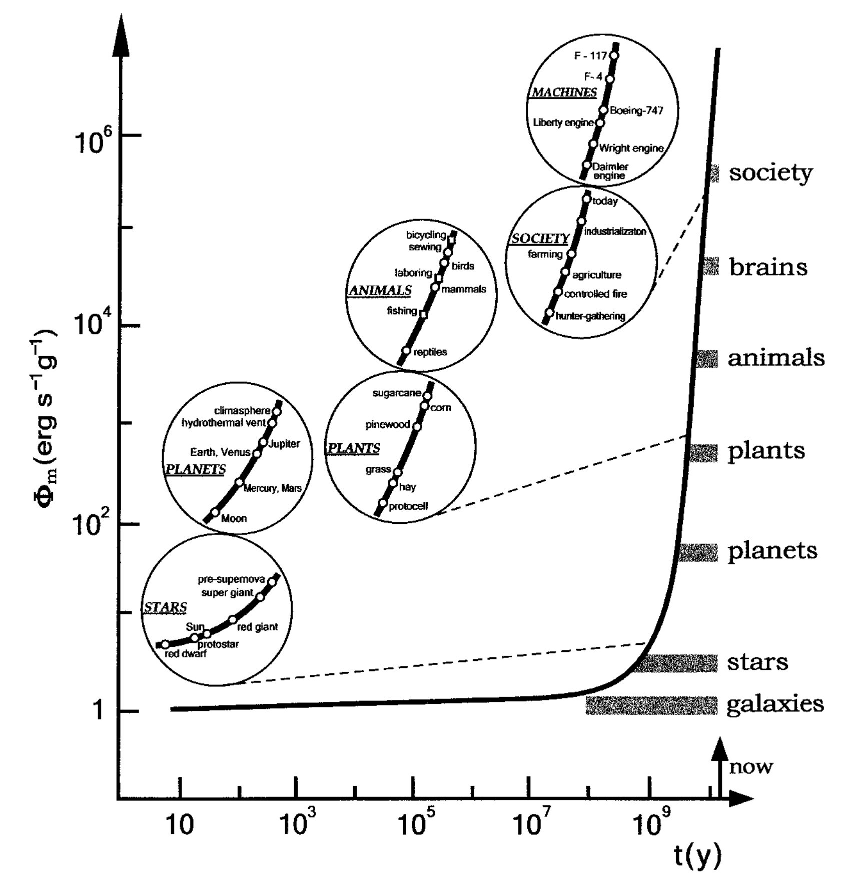
6. EVOLUTION, BROADLY CONSIDERED

The word *evolution* need not be the sole province of biology, its usefulness of value only to life scientists. Charles Darwin never used it as a noun, in fact only as a verb in the very last sentence of his 1859 classic, *On the Origin of Species* [18]. Nor need natural selection be the only cause of evolutionary change, past and present. Darwin surely embraced it, as we do today to describe much of biological change, but here too he cautioned us: "I am convinced that Natural Selection has been the main but not exclusive means of modification."

Actually, the term "selection" is itself a bit of a misnomer, for no known agent in Nature deliberately selects. Selection is not an active promoter of evolution as much as a passive pruning device to weed out the unfit. As such, selected objects are simply those that remain after all the poorly adapted or less fortunate ones have been removed from a population of such objects. A better term might be "nonrandom elimination" [19], for what we really seek to explain are the adverse circumstances responsible for the deletion of some members of a group. Accordingly, selection can be broadly taken to mean preferential interaction of an object with its environment, an acknowledged factor in the flow of resources into and out of any open system, and not just life forms. All systems are selected by their ability to utilize energy; and this energy—the ability to do work—is a "force," if there is any at all, in evolution. Liberally interpreted, selection does occur in the inanimate world, often providing a formative step in the production of order. A handful of cases will suffice to illustrate the increased use of energy density among a spectrum of systems in successive phases of cosmic evolution.

First, consider stars as an example of physical evolution. Growing complexity serves as an indicator of stellar evolution as stars' interiors naturally foster steeper thermal and elemental gradients during repeated cycles of nuclear fusion; more data are needed to describe the higher-temperature, gas-differentiated, onion-like layers as heavier elements fuse near the cores of aging

FIGURE 4



The rise in free energy rate density, Φ_m, plotted as histograms starting at those times when various open structures emerged in Nature, has been rapid in the last few billion years, much as expected from human intuition and Figure 1(b). The solid curve approximates the increase in normalized energy flows best characterizing the order, form, and structure for a wide range of systems throughout the history of the Universe. The circled insets show greater detail of further measurements or calculations of the free energy rate density for stars and planets, plants and animals, and societies and machines, each of them typifying physical, biological, and cultural evolution, respectively (Adapted from Chaisson [1, 17].).

stars. Stellar size, color, brightness, and composition all change, while progressing from protostars at "birth" ($\Phi_m \sim 0.5$ erg s^{-1} g^{-1}), to main-sequence stars at mature "mid-life" ($\sim$2), and to red giants near "death" ($\sim$100). Those parenthetical values are their respective energy rate densities, our newly devised complexity metric, plotted among other values in the circled inset at the bottom of Figure 4. At least as regards energy flow, matter circulation, and structural development while undergoing change, stars have much in common with life. None of which is to claim that stars are alive, a common misinterpretation of such an eclectic stance. Nor do stars evolve in the strict and limited biological sense. Yet close parallels are apparent, including system selection, simplified adaptation, and perhaps even a kind of reproduction among the stars, all of it reminiscent of the following Malthusian-inspired scenario.

Galactic clouds spawn clusters of stars, only a few of which (the more massive ones unlike the Sun) cause (via supernovae) other, subsequent populations of stars to emerge in turn, with each generation's offspring showing slight variations, especially among the heavy elements contained within. Waves of "sequential star formation" propagate through many such clouds like slow-motion chain reactions over eons of time—shocks from the death of old stars triggering the birth of new ones—neither any one type of star displaying a dramatic increase in number nor the process of regeneration ever being perfect. Those massive stars selected by Nature to endure the fires needed to produce heavy elements are in fact the very same stars that often create new populations of stars, thereby both gradually and episodically enriching the interstellar medium with greater elemental complexity on timescales measured in millions of millennia. As always, the necessary though perhaps not sufficient conditions for the growth of complexity depend on the environmental circumstances and on the availability of energy flows in such (here, galactic) environments. On and on, the cycles churn; build up, break down, change—a version of stellar "reproduction" minus any genes, inheritance, or overt function, for these are clearly the value-added qualities of biological evolution that go well beyond physical evolution.

Next, consider plants as an example of biological evolution. Here, we can trace the rise in complexity with evolution among plant life (as for myriad other life forms). And here natural selection—genuine neo-Darwinism—is clearly at work, making use of free energy rate densities well in excess of those for galaxies, stars, and planets. As shown in Figure 4 (middle circled inset), energy-flow diagnostics display an increase in complexity among various plants that locally and temporarily decrease entropy: Photosynthesis requires more normalized energy flow for pinewood ($\Phi_m \sim 3 \times 10^3$ erg s^{-1} g^{-1}) than for simple hay or grass ($\sim 5 \times 10^2$), and, in turn, still more energy for more efficient, highly cultivated corn ($\sim 6 \times 10^3$), among a host of other more organized woodstuffs. System functionality and genetic inheritance are factors, above and beyond mere system structure, which enhance order among animate systems that are clearly living compared to inanimate systems that are clearly not.

Onward across the bush of life (or the arrow of time)—cells, tissues, organs, organisms—we find much the same story unfolding. Cold-blooded reptiles ($\sim 10^4$) have Φ_m values higher than globally averaged plants ($\sim 10^3$), warm-blooded mammals typically more ($\sim 5 \times 10^4$); examining animal life with finer scale, sedentary humans ($\sim 2 \times 10^4$) have less Φ_m than for laboring humans ($\sim 6 \times 10^4$), which, in turn, have less than bicycling humans ($\sim 10^5$), and so on [20]. Starting with life's precursor molecules (the realm of chemical evolution) and all the way up to human brains exemplifying the most complex clump of matter known (neurological evolution), the same *general* trend characterizes plants and animals as for stars and planets: The greater the apparent complexity of the system, the greater the flow of free energy density through that system—either to build it, or to maintain it, or both.

Finally, consider human society as an example of cultural evolution. Here, the cosmic-evolutionary narrative continues, with greater energy flows to account for the rise of our decidedly complex, far-from-equilibrium civilization—to the dismay of some anthropologists and economists, let alone sociologists, who often cringe at the notion of thermodynamic principles being used to model their subjects. As nonetheless noted in Figure 4 (top circled inset), we can trace several progressive stages for a variety of human-related cultural advances among our hominid ancestors: Quantitatively, that same energy rate density increases from hunter-gatherers of a million years ago ($\Phi_m \sim 10^4$), to agriculturists of several thousand years ago ($\sim 10^5$), to the early industrialists of some 200 years ago ($\sim 5 \times 10^5$). The import of rising energy expenditure per capita has reached a current high for today's well-lit (18-terrawatt) world in the energy-crazed United States with $\Phi_m \sim 3 \times 10^6$ erg s^{-1} g^{-1}, thus empowering our technologically "sophisticated" society well beyond the 2800 kilocalories that each of us typically consumes daily.

Machines, too, and not just computer chips, but also ordinary motors and engines that impel our fast-paced, 21st-century society, can be likewise cast in evolutionary terms—though here the mechanism is less Darwinian than Lamarckian, with its emphasis on accumulation of acquired traits. Either way, energy remains the driver. Aircraft engines, for example, display clear evolutionary trends as engineering improvement and customer selection over generations of products have made engines not only more powerful and efficient but also more intricate and complex, all the while utilizing enriched flow of energy density, from the Wright engine of the early 1900s ($\Phi_m \sim 10^6$ erg s^{-1} g^{-1}), to the Boeing-747 jumbo jet of the last few decades ($\sim 10^7$), to the F-117 stealth aircraft of the present ($\sim 10^8$). Automobiles, from the pioneering model-Ts ($\sim 10^5$) to today's gas-guzzling, gadget-rich SUVs ($\sim 10^6$), can be similarly analyzed [16], as can the vaunted silicon chips that accelerate the global economy [1]. Remarkably, even fine-scale evolution (and complexification) of the typical American passenger car can be traced over the past decades, made clear by growing horsepower-to-weight ratios provided by the U.S. Highway Traffic Safety Administration: $\Phi_m = 5.9 \times 10^5$ ergs s^{-1} g^{-1} in 1978, 6.8×10^5 in 1988, and 8.3×10^5 in 1998.

Humankind is now moving toward a time, possibly as soon as within a few generations, when we shall no longer be able to expect Earth to provide for us naturally the environmental conditions—especially per capita energy flow—needed for survival. Rather, society itself will have to increasingly engineer the very conditions of our own ecological existence. From the two, society and the biosphere, will likely emerge a socially controlled bioculture. Here the components will become ideas, artifacts, technology, and humans, among all other living organisms on Earth—the epitome (thus far) of complexity known anywhere in Nature. Indeed, we are perched at the dawn of a whole new cosmological era—the Life Era—wherein sentient, manipulative, energy-efficient beings truly become the agents of change.

7. CONCLUSION

This article has taken the liberty of using the word "evolution" in an intentionally provocative way, to capture ontological, ecological, and phylogenetic change on all spatial and temporal scales by means surely including, but not restricted to, natural selection. I have sought, within the grand context of cosmic evolution, general trends among Nature's myriad changes during an extremely long line of temporality, from big bang to humankind. And I have been especially alert for any processes—developmental or generative, gradual or punctual—in the universal environment that have allowed for, indeed potentially driven, evolution from time immemorial.

More than any other single factor, *and quantitatively so*, energy flow would seem to be a principal means whereby all of Nature's diverse systems naturally became increasingly complex in an expanding Universe, including not only galaxies, stars and planets, but also lives, brains and civilizations. One might prefer to embrace information content to describe and unify complex systems in the natural world, but until such time that information can be satisfactorily quantified, energy will remain a useful descriptor of complexity. Energy, specifically humankind's use of it wisely and optimally, will likely guide our fate along the future arrow of time, for we, too, are part of the cosmic-evolutionary scenario, an epic-class story of rich natural history for the new millennium.

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