

A unifying concept for astrobiology

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Abstract: Evolution, broadly construed, has become a powerful unifying concept in much of science – not only in the biological evolution of plants and animals, but also in the physical evolution of stars and planets, and the cultural evolution of society and its many varied products. This paper (1) explores the bulk structure and functioning of open, non-equilibrium, thermodynamic systems relevant to the interdisciplinary field of astrobiology, (2) places the astrobiological landscape into an even larger, cosmological context, (3) defines life, complexity and evolution writ large, (4) claims that life depends ultimately on the expansion of the Universe and the flow of energy derived therefrom and (5) proposes a quantitative metric to characterize the rise of complexity throughout all of natural history. That metric is neither information nor negentropy, for these inveterate yet qualitative terms cannot be quantified, nor even defined, to everyone's satisfaction in today's scientific community. Rather, the newly proposed metric is normalized energy flow, a revision of a long-cherished term – energy – that is physically intuitive, well defined and readily measurable. All ordered systems – from rocky planets and shining stars, to buzzing bees and redwood trees – can be best judged empirically and uniformly by gauging the amount of energy acquired, stored and expressed by those systems. Appeals to anthropism are unnecessary to appreciate the impressive hierarchy of the cosmic evolutionary narrative, including a technological civilization that now embraces an energetics agenda designed to better understand, and perhaps to unify, all the natural sciences.

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Introduction and caveats

This paper concerns the 'big picture', placing the newly emerging subject of astrobiology into a wider, cosmological perspective. It addresses few things specifically, but many things generally; the details are found elsewhere, notably in some of the references provided. It stresses especially the interface between physics and biology, and, in keeping with the charge presented at Windsor Castle, explores whether the origin and evolution of life is natural, inevitable or 'fine-tuned'.

Although the majority of those relatively few workers seeking unification in science today embrace aspects of quantum gravity – a grand synthesis of quantum mechanics and relativity theory considered by some a holy grail – other, less exotic roads toward unification exist. To be sure, when looking out the window, we see no elementary strings, no 11 dimensions and no multiple universes – principal features of currently fashionable efforts to merge the very big and the very small. Instead, we sense mainly, and especially when aided by technology, the very complex. We observe a single Universe of four dimensions, populated with, details aside, galaxies, stars, planets and life forms. Furthermore, a clear chronological trend among those objects displays a rise in complexity throughout all of natural history, and it is on the basis of that simple verity of growing complexity that I strive

to build a unifying, cosmic, evolutionary synthesis, from big bang to humankind (Chaisson 2001).

Not that this effort is new, only modern. Others have been down this path before, most originally perhaps the mid-19th-century encyclopedist Robert Chambers (1844), who anonymously penned a pre-Darwinian tract of wide interdisciplinary insight, and the mid-20th-century astronomer Harlow Shapley (1930), whose 'cosmography' classified all known structures by increasing size. The philosopher Herbert Spencer (1896) championed the notion of increasing complexity in biological evolution and the mathematician Alfred North Whitehead (1925) later sought to undergird these ideas with his 'organic philosophy'.

Two introductory caveats usefully preface this paper. First, given that I am a physicist with a penchant for quantifying even highly interdisciplinary subjects, I am often mistaken for a strict reductionist. But this impression would be wrong. And I am sometimes accused of trying, in particular, to reduce biology to physics. That impression would be very wrong. Rather, my research agenda attempts to broaden physics to include biology – namely, to treat life, like non-life, as a natural consequence of environmental changes that allow the emergence of increasingly ordered structures within an expanding, unequilibrated Universe. Like much else in Nature, ordered systems are characterized neither entirely by reductionism nor wholly by holism, any more than

by chance or necessity, or by randomness or determinism. Rather, events at work in the real world seem to be syntheses of dichotomies – uncertain chance mixes with strict determinism, as much as holistic networking integrates with reductive specialization – for Nature is clearly neither black nor white, but more like shades of grey throughout.

Secondly, appeals to the anthropic principle need not be embraced for broad understanding. The weak anthropic principle is hardly more than cosmic evolution at work, whereas the strong anthropic principle seems nothing more than teleology at play. Strong statements, to be sure. But, rather than believing in Providence or in multiple universes as ways to justify the values of some physical constants, I prefer to reason that, when the laws of science become sufficiently robust, we shall naturally understand why the physical constants have the values they do. It is much like in mathematics. Who would have thought, *a priori*, that the ratio of the circumference of a circle to its straight diameter would be 3.14159 ...? Such an odd number; why is it not 3, or 3.5, or even just 3.1, rather than such a peculiar number that runs on *ad infinitum*? We now understand enough mathematics to realize that this is simply the way geometry scales; there is nothing fine-tuned about a perfect circle that derives from the decidedly odd value of π . Circles exist as rounded curves perfectly closed upon themselves *because* π has the strange value it does. Likewise, ordered systems in Nature likely exist, including life, *because* the physical constants have such decidedly odd values.

Cosmic evolution and the arrow of time

Cosmic evolution is the study of the sum total of the many varied developmental and generative changes in the assembly and composition of radiation, matter and life throughout all space across all time. These are the physical, biological and cultural changes that have produced, in turn and among many other systems, our Galaxy, our Sun, our Earth and ourselves. Understanding this change *en masse* is tantamount to synthesizing a grand evolutionary scheme bridging a wide variety of disciplines – physics, astronomy, geology, chemistry, biology and anthropology, among others – thus forging a scientific narrative of epic proportions extending from the beginning of time to the present. (But not into the future, for this is natural *history*, and with contingency operative, predictability in evolution is much constrained.)

The general idea of evolution – change writ large – extends well beyond the subject of biology, granting it a powerful unifying potential throughout all of science. For if there is any common denominator among all structured systems in Nature, it is change – an oxymoronic ‘constant change’. Heraclitus of 25 centuries ago perhaps had the best idea ever when he argued that the world shows nothing permanent except change. Yet questions remain, among them: how valid are the apparent continuities connecting the many scientific disciplines, and how realistic is the quest for an interdisciplinary, evolutionary unification? Can we reconcile the observed constructiveness of cosmic evolution with the inherent

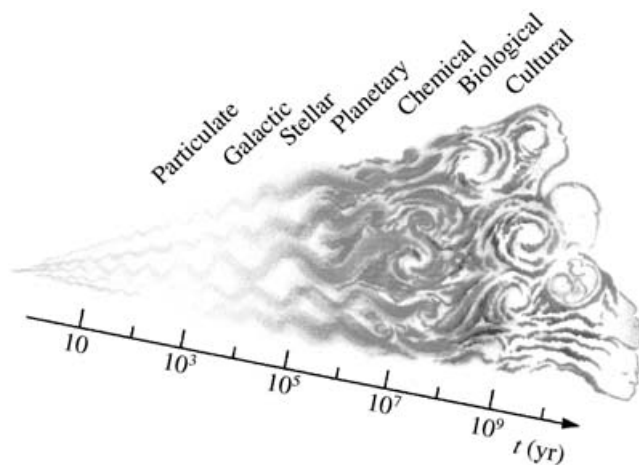


Fig. 1. This stylized arrow of time highlights salient features of cosmic history, from its fiery origins some 14 Ga (left) to the here and now of the present (right); consult Chaisson (1997) for a historical discussion of cosmic age. Labeled diagonally across the top are the major evolutionary phases 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 taken to flow steadily and irreversibly (and is identically drawn logarithmically for all figures here), much as we assume the fixed character of physical law or the mathematical result that $2 + 2 = 4$ everywhere.

destructiveness of thermodynamics? And despite the omnipresent changes virtually everywhere, are there fixed underlying principles – akin to a modern form of Platonism perhaps – that govern those myriad changes?

Fig. 1 shows Nature’s main historical epochs astride the so-called arrow of time. This is a highly simplified illustration, not drawn to scale and not pointing at us; it entails no anthropocentrism. The arrow archetypically symbolizes a *sequence* of events based on a large body of post-Renaissance data – a continuous thread of change, from simplicity to complexity, from inorganic to organic, from chaos in the early Universe to order more recently. Despite the high degree of specialization among the present-day academic sciences, evolution knows no disciplinary boundaries.

Accordingly, the most familiar kind of evolution – biological evolution, or neo-Darwinism – is just one, albeit important, subset of a much broader evolutionary scheme encompassing much 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 a revolution in understanding by helping to free us from the notion that humans basically differ from other life forms on our planet, then cosmic evolution extends that intellectual revolution by treating matter on Earth and in our bodies no differently from that in the stars and galaxies far beyond. The scenario of cosmic evolution is a decidedly materialistic proposition.

Given the predilection of the Windsor meeting sponsorship, it is worth stressing that anthropocentrism is neither

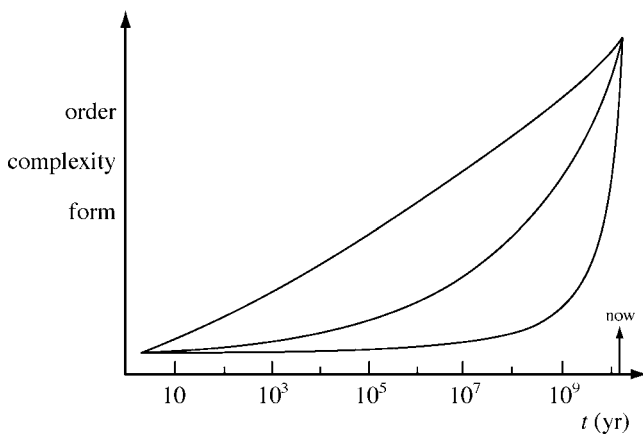


Fig. 2. Sketched here qualitatively is the rise of order, form and structure typifying the evolution of *localized* material systems throughout the history of the Universe. This family of curves connotes the widespread, innate feeling that the complexity of ordered structures has *generally* increased over the course of time. Whether the rise of complexity has been linear, exponential or otherwise (as drawn here), current research aims to specify this curve and to describe it quantitatively.

intended nor implied by the arrow of time – which is why some of us prefer to draw it (as done here) opening up in variety and diversity, rather than pointing anywhere other than toward the future. Humans are not the culmination of cosmic evolution, nor are we likely to be the only technologically competent beings that have (or will have) emerged in the organically rich Universe. The arrow merely provides a convenient symbol – an intellectual roadmap – artistically depicting a mixture of chance and necessity operating together while building increasingly complex structures from round stars to rocky planets to reproductive beings.

Nor does time's arrow mean to imply that 'lower', primitive life forms have biologically changed directly into 'higher', advanced organisms, any more than galaxies have physically changed into stars, or stars into planets. Rather, with time – much time – the environmental conditions suitable for spawning primitive life eventually changed to those favouring 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, for our local planetary environment has once more changed to foster greater, societal complexity. Change in surrounding environments usually precedes change in organized systems, and the resulting changes for those systems selected to endure have *generally* been toward greater amounts of order and complexity.

Fig. 2 sketches that widespread perception that material systems have become more organized and complex, especially in relatively recent times. This family of curves graphs islands of complexity comprising systems *per se* – whether massive stars, dainty flowers or urban centres – not their vastly, indeed increasingly, disorganized surroundings. In this paper, no definitional distinctions are made among the words

'order', 'form', 'complexity' and the like, appealing only to a general understanding of a whole host of diverse structures often described by the common usage of the term *complexity*: a state of intricacy, complication, variety or involvement, as in the interconnected parts of a system – a quality of having many interacting, different components. Particularly intriguing is the potentially dramatic rise of complexity (with some exceptions) within the past half-billion years since the end of the pre-Cambrian on Earth. Perhaps indeed resembling a modern form of Platonism, some underlying principle, a unifying law, or an ongoing process creates, orders and maintains all structures in the Universe, enabling us to study all such systems on a uniform, level ground – 'on the same page', to use a contemporary, if trite, phrase.

Thermodynamics and the expanding universe

The broadest view of the biggest picture for astrobiologists is the expanding Universe – a much tested 'standard model' based largely on a trilogy of observations of distant receding galaxies, microwave background radiation and light-element abundances. In such a dynamic cosmos, changing environmental conditions naturally and inevitably gave rise to the kind of energy that helped to drive change globally and locally. This is 'free energy', so-called because of its availability to build, maintain or destroy systems. It is the origin of free energy that is inevitable, not the resulting systems *per se*, which is why it is called 'available', or potential, energy freely capable of doing work. And in a Universe that obeys the standard model, time marches on and free energy flows because of cosmic expansion (Gold 1962; Layzer 1976).

Radiation completely ruled the early Universe, a period so intensely hot and dense that it can be simulated for only fleeting moments in the bowels of particle accelerators on Earth today. Life was then non-existent and matter itself only a submicroscopic precipitate suspended in a glowing fireball of high-frequency 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 again inevitably, as depicted in Fig. 3, the primacy of radiation gave way to matter. As the Universe naturally cooled and thinned owing to its expansion, charged particles assembled into neutral atoms, among the simplest of all structures; the energy density of matter had won the day. 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. The Universe thereafter became transparent, as photons no longer scattered aimlessly and destructively. The brilliant radiation era gradually transformed into the darker matter era and natural history became more interesting; it all happened nearly half a million years

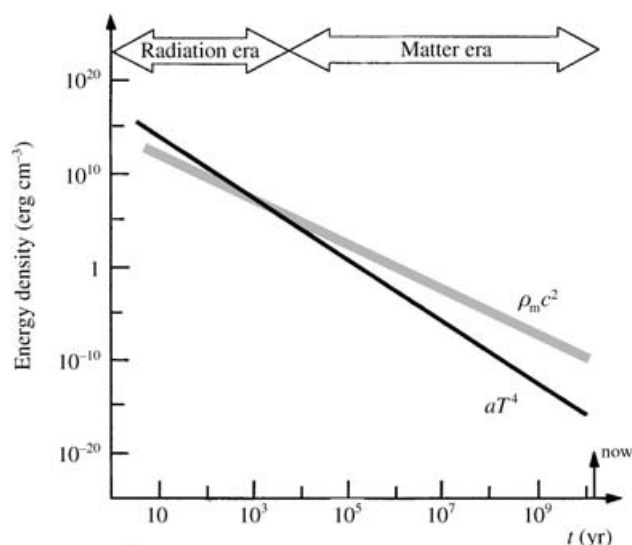


Fig. 3. The temporal behaviour of both matter energy density (ρc^2) and radiation energy density (aT^4) illustrates perhaps the greatest change in all of natural history. (The thicker width of one curve represents the range of uncertainty in total mass density, ρ , the value of which depends on the unknown amount of 'dark matter'; T is temperature and a is the radiation constant.) Where the two curves intersect, neutral atoms began to form; by $t \sim 10^5$ yr after the big bang the Universe had changed greatly as thermal equilibrium and particle symmetry had broken, and the radiation era had become the matter era. A uniform, featureless state portraying the early Universe was thus naturally transformed into one in which order and complexity were thereafter possible.

after the big bang, which is when the free energy began to flow. Change was a given, inducing gradients, forming systems and evolving structures, and the results, emergent over billions of years, included galaxies, stars, planets and life.

Now, some 14 billion years after the start of all things, a whole new era – the Life Era – has begun, at least locally. The onset of technologically intelligent life, on Earth and perhaps elsewhere, heralds a new era wherein life, in turn, has gradually begun to control matter, much as matter evolved earlier to control radiation. This second of two pre-eminent changes was not triggered by the origin of life *per se* several billion years ago, rather, it began with technically competent life that only recently allowed humanity to manipulate matter and energy, to alter genes and the terrestrial environment, and to tinker with evolution itself, thus signalling the start of the Life Era – all of which again entails no anthropocentric sentiment. We humans simply comprise the here and now in our cosmic-evolutionary story, having become agents of change quite unlike lower forms of life or other types of inanimate matter throughout the Universe.

To understand how changing environmental conditions can give rise to order and structure, consider the most cherished of all physical laws – the second law of thermodynamics. An acknowledged bias, the second law is the core of this physicist's psyche. Note the phrase 'can give rise', not necessarily does give rise; thermodynamics tells us not what

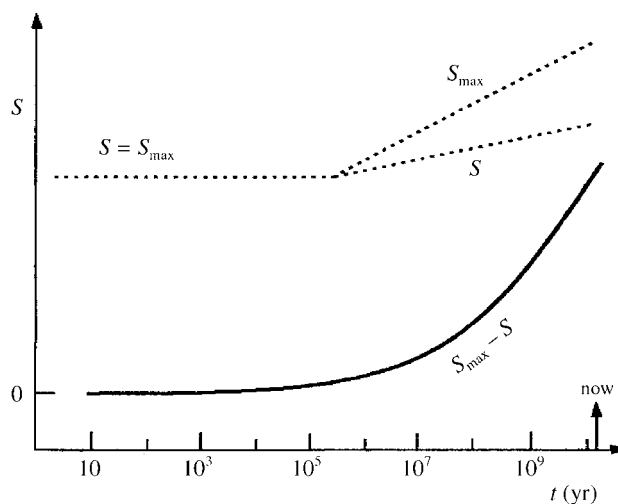


Fig. 4. In the expanding Universe, the actual entropy, S , increases less rapidly than the maximum possible entropy, S_{\max} , once the symmetry of equilibrium broke when matter and radiation decoupled at $t \sim 10^5$ yr. In contrast, in the early, equilibrated Universe, $S = S_{\max}$ for the prevailing conditions. The potential for the growth of order – operationally defined here as a lack of disorder ($S_{\max} - S$), and shown as the thick black curve – has increased ever since the start of the matter era. Accordingly, the expansion of the Universe can be judged as the ultimate source of free energy, promoting the evolution of everything in the cosmos. This potential rise of order compares well with the curves of Fig. 2 and provides a theoretical basis for the growth of system complexity.

does happen, only what *can* happen. Yet, looking back, our models do show clearly what did happen a few thousand centuries after the big bang: symmetry was broken and equilibrium destroyed. Gradients were established naturally owing to the expansion of the Universe, for thereafter the temperatures of matter and of radiation diverged with time.

Fig. 4 graphs the run of entropy, S , for a thermal gradient typical of a heat engine, here for the whole Universe. This is not a mechanical device running with idealized Newtonian precision, but a global engine capable of potentially doing work as locally emerging systems interact with their environments – especially those systems able to take advantage of increasing flows of free energy resulting from cosmic expansion and its naturally growing gradients. Although thermal and chemical (but not gravitational) entropy must have been maximized in the early Universe, hence complexity in the form of any structures was then non-existent, after decoupling the environmental conditions became favourable for the potential growth of order, taken here to be a 'lack of disorder'. At issue was timing: as the density (ρ) decreased, the equilibrium reaction rates ($\propto \rho$) fell below the cosmic expansion rate ($\propto \rho^{1/2}$) and non-equilibrium states froze in. 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. All the more interesting when

we compare the shape of this curve of potentially rising order ($S_{\max} - S$) with our earlier intuited sketch of rising complexity in Fig. 2.

Physics–biology interface

By itself, the second law of thermodynamics practically prohibits systems from changing spontaneously toward more ordered states. All things, when left alone, naturally and inevitably decay into chaotic, randomized, less ordered states. Isolated systems are defined by maximum entropy, equilibrium conditions and no environmental interactions. But these are not the systems of interest to astrobiologists. All real structures in Nature – whether galaxies, stars, planets or life forms – are demonstrably open, non-equilibrium systems, with flows of energy in and out being vital. And it is this energy freely available to do work that helps to build structures (von Bertalanffy 1932; Schrödinger 1944).

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 is electricity powering a laser, sunlight shining on a plant or humans feeding ourselves, energy does play a key role in the creation, maintenance and fate of complex systems – all quantitatively in accord with the celebrated second law. None of Nature’s ordered structures, not even life, is a violation (or even a circumvention) of the second law. Considering both a system of order as well as its surrounding environment, good agreement obtains with modern, non-equilibrium thermodynamics; no new science is needed.

The role that energy plays is now recognized as an essential feature, not only for the biological systems we know so well as plants and animals, but also for physical systems such as stars and galaxies, indeed for social systems too, such as the inward flow of food and fuel into a city and its outward flow of products and wastes. The analysis is much the same for any open system, provided we are willing to think in broad, interdisciplinary terms. All of which brings us to a proposed definition of *life*: an open, coherent spacetime structure kept far from thermodynamic equilibrium by a flow of energy through it – a carbon-based system operating in a water-based medium with higher forms metabolizing oxygen.

Fig. 5 shows schematically the emergence of structure in the presence of energy flow. Physicists are familiar with the type of curves at the top, biologists are more at home with those at the bottom. Upon crossing certain energy thresholds that depend on the status of a system, bifurcations can occur, fostering the emergence of whole new hierarchies of novel structures that display surprising amounts of coherent behaviour (Prigogine *et al.* 1972). 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 consumption 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. So-called self-organized systems actually

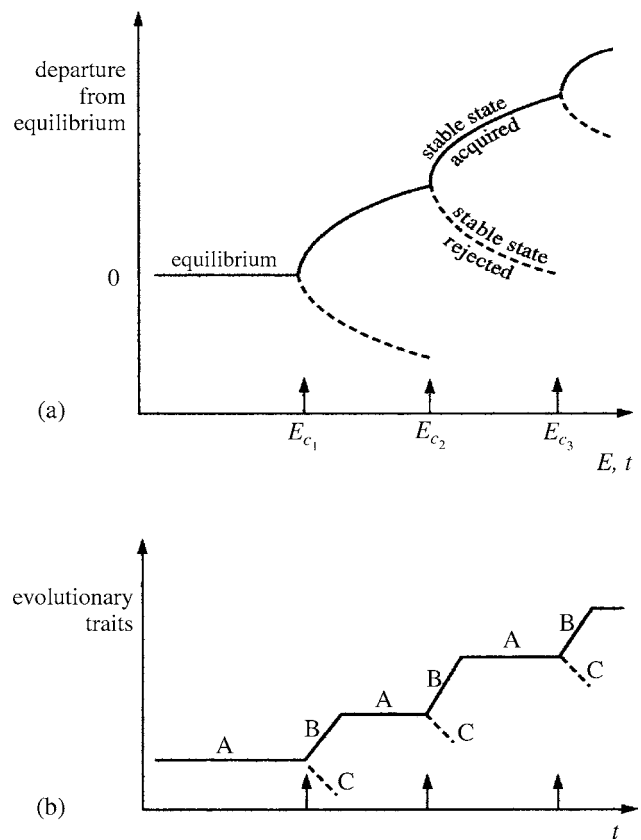


Fig. 5. (a) The extent to which open systems depart from equilibrium is drawn here as a function of both time and energy. The time axis makes clear that this is an historical, evolutionary process, whereas the parallel energy axis denotes the free energy flowing through an open system as a vital part of its being. At certain critical energies, labelled here as E_c , the system can spontaneously change, or bifurcate, into new, non-equilibrium, dynamic steady states. Statistical fluctuations – that is chance – affect which fork the system selects – that is necessity – upon bifurcation (vertical arrows), namely which spatial structure is achieved. (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 in solid for both parts of this figure) imply no progress, but they do suggest a *general trend* toward increasing complexity.

reflect an essential tension between energy inflow and dissipative outflow; these systems do not function magically by themselves.

The emergence of order from a condition where originally there was 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 natural 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 an isolated system, 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 an open system *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 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, since 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, since 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 drive the system further 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 puts us into the realm of true *thermodynamics*, the older, traditional subject of that name more properly labelled ‘thermostatics’.

Numerous such systems come to mind, and not only in the physical world. Among them, are naturally occurring phenomena such as convection cells, river eddies, atmospheric storms and even artificially made devices such as refrigerators and lasers among a whole host of physical systems that experience coherent order when amply fed with sufficient energy. Biological systems, too, obey the rules of non-equilibrium thermodynamics, for we and our living relatives are demonstrable examples of dynamic steady states that emerge and flourish via energetically rich events. As are Lamarckian-type cultural systems of more recent times, for among the bricks and chips we have built, energy has been the principal driver. The upshot is that life and its cultural inventions differ not in kind, but merely in degree – specifically, degree of complexity – among the myriad ordered systems evident in Nature.

Free energy rate density

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 do it, given the varied connotations that the word ‘complexity’ presents for many researchers? In biology alone, much as with their inability to reach consensus

on a definition of life, biologists cannot agree on a complexity metric. Some count non-junk genome size (Smith 1995), others employ morphology and flexibility of behaviour (Bonner 1988), while still others chart numbers of cell types in organisms (Kauffman 1993) or appeal to cellular specialization (McMahon & Bonner 1983). But as useful as each of these attributes of life may be qualitatively, they prove difficult to quantify in practical terms, nor do they apply to non-biological systems. I wish 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 Schrödinger 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 might reasonably be expected to have a central role 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 (e.g. Morrison 1964; Dyson 1979), biologists (Lotka 1922; Morowitz 1968) and ecologists (Odum 1988; Smil 1999), to name but several, have championed the cause of energy’s organizational abilities. Even so, the quantity of choice cannot be energy alone, for a star clearly has more energy than an amoeba, a galaxy much more than a single cell. Yet any living system is surely more complex than any inanimate object. Thus, absolute energies are not as telling as relative values, which depend on the size, composition and efficiency of a system. Nor are maximum energy principles or minimum entropy states likely to be relevant; rather, organizational complexity is more likely to be 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 changing events in the early Universe (Fig. 3). Moreover, it is the *rate* at which free energy transits a complex system of given mass that is most important, for all of Nature’s structures are open to their environments. Hence, the *free energy rate density*, symbolized by Φ_m , is an operational term the meaning, measurement and units of which are clearly understood.

Fig. 6 plots a *sampling* of many findings, where free energy rate densities are graphed as horizontal histograms for evolutionary ages of various systems. As expected, plants ($\Phi_m \sim 10^3 \text{ erg s}^{-1} \text{ g}^{-1}$) are more complex than stars (~ 1) or planets ($\sim 10^2$); humans ($\sim 10^4$) and their brains ($\sim 10^5$) are more complex yet; and society collectively ($\sim 10^6$) is 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. This modelled flow of normalized energy for a wide range of open systems, be they alive or not, closely resembles

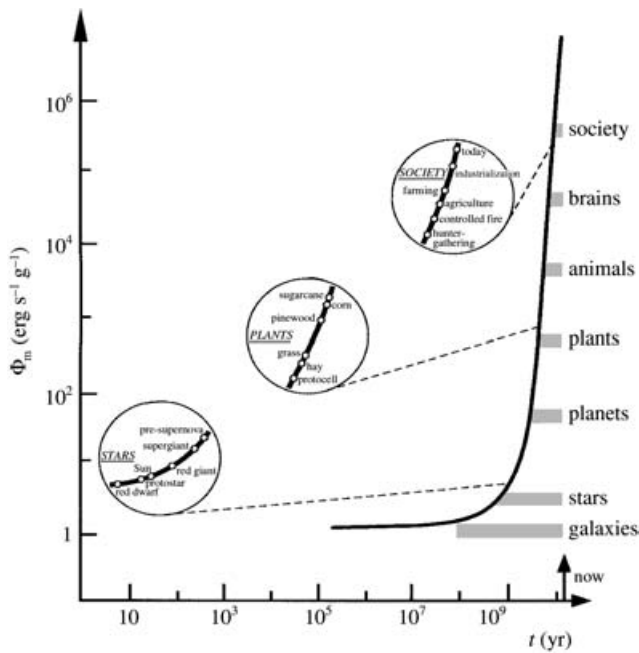


Fig. 6. The rise of free energy rate density, Φ_m , plotted as histograms starting at those times when various open structures emerged in Nature, has been rapid in the last few billion years, much as expected from both subjective intuition (Fig. 2) and objective thermodynamics (Fig. 4). The solid curve approximates the increase in normalized energy flows best characterizing the order, form and structure for a 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 three representative systems – stars, plants and society – typifying physical, biological and cultural evolution, respectively. Many more Φ_m measures are found in Chaisson (2001).

the intuitive rise in complexity drawn in Fig. 2; it also mimics the potential rise of order in the thermodynamic analysis of Fig. 4. Complexity (at least as treated here energetically for localized structures) has in fact risen throughout natural history, and quantitatively so, indeed at a rate faster than exponential in more recent times (Chaisson 1998, 2000; for details of energy computations and modelling, consult Chaisson 2001).

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

Evolution, broadly construed

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*. Nor need natural selection be the only cause of evolutionary change, past and present. Darwin stressed it, as we surely do today to describe much of biological evolution, 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 misnomer, for no known agent in Nature deliberately selects. Selection is not an active ‘force’ or 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 ‘non-random elimination’, a phrase long championed by one of the leading evolutionists of the 20th century, Ernst Mayr (1997). 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 any object with its environment – a more liberal interpretation that also helps widen our view of evolution.

Selection is a factor in the flow of resources into and out of all open systems, not just life forms. 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. Broadly considered, 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 can serve as an indicator of stellar evolution as the interiors of stars naturally develop steeper thermal and chemical gradients during successive cycles of nuclear fusion; more data are needed to describe their differentiated, onion-like layers of fused heavy elements as stars age. Stellar size, colour, brightness and composition all change, while progressing from protostars at ‘birth’ ($\Phi_m \sim 0.5 \text{ ergs s}^{-1} \text{ g}^{-1}$), to main-sequence stars at mature ‘mid-life’ (~ 2) and to red giants near ‘death’ (~ 100). Those parenthetical values are their increased energy rate densities, our newly devised complexity metric, plotted among other values in the bottom circled inset of Fig. 6. At least as regards energy flow, matter circulation and structural maintenance 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; most biologists would say that stars *develop*. Yet close parallels are apparent, including selection, 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 the offspring of each generation showing slight variations, especially among the heavy elements contained within. Waves of 'sequential star formation' (Elmegreen & Lada 1977) 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 kind 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 cycle churns; build up, break down, change – a kind of stellar 'reproduction' minus any genes, inheritance or overt function, for these are 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 of galaxies, stars and planets. As shown in Fig. 6 (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 ($\Phi_m \sim 3 \times 10^3 \text{ ergs s}^{-1} \text{ g}^{-1}$), 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 (Halacy 1977). 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 and 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 a finer scale, sedentary humans ($\sim 2 \times 10^4$) have less Φ_m than for labouring humans ($\sim 6 \times 10^4$), which, in turn, have less than bicycling humans ($\sim 10^5$), and so on (Hammond & Diamond 1997). Starting with the precursor molecules of life (the realm of chemical evolution) and all the way to human brains exemplifying the most complex clump of animate 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 Fig. 6 (top circled inset), we can trace some of the ordered stages, namely energy consumption, for a variety of human-related cultural advances among our hominid ancestors. Quantitatively, that same energy rate density increases from hunter-gatherers of a few million years ago ($\Phi_m \sim 10^4 \text{ ergs s}^{-1} \text{ g}^{-1}$), 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 importance of rising energy expenditure per capita has been recognized by cultural historians (White 1959; Brown 1976), reaching a current high in today's well-lit (18 TW) world in the energy-crazed United States with $\Phi_m \sim 3 \times 10^6 \text{ ergs s}^{-1} \text{ g}^{-1}$, thus empowering our technologically 'sophisticated' society well beyond the 2800 kcal that each of us 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 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 underlying 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 ($\Phi_m \sim 10^6 \text{ ergs s}^{-1} \text{ g}^{-1}$), 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 analysed (Smil 1999), and even fine-scale evolution of the typical American passenger car over the past two decades made clear by growing horsepower-to-weight ratios provided by the US Highway Traffic Safety Administration: $\Phi_m = 5.9 \times 10^5 \text{ ergs s}^{-1} \text{ g}^{-1}$ in 1978, 6.8×10^5 in 1988 and 8.3×10^5 in 1998.

Humankind is now moving towards 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, artefacts, 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 onset of the Life Era, wherein sentient, manipulative beings truly become the agents of change.

Discussion at Windsor Castle

In this paper I take the liberty of using the word ‘evolution’ in an intentionally provocative way, to capture ontological, ecological and phylogenetical 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. I have been especially alert to any changes – developmental or generative, gradual or punctual – in the universal environment that might have allowed for, indeed driven, evolution from time immemorial. And I have argued that, 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.

Not everyone at the Windsor meeting embraced these ideas. Thoughtful criticisms were offered, leading to spirited discussion late into the evening. Of all the issues raised, the most contentious concerned that of information, especially my dismissal of it. I did so by claiming that the concept of information has had a muddled history, full of dubious semantics, ambivalent connotations and subjective interpretations (Wicken 1987; Brooks & Wiley 1988; Marijuan *et al.* 1996). Especially tricky is *meaningful* information, the value of information, and the kind of information. Shall we use Shannon information, or algorithmic information, or perhaps raw information? Does information need to be interpreted and understood for it to exist, or can it be garbled (in which case, message or not, the telephone company still charges for the data string)? Furthermore, no one has yet shown quantitatively, commonly, and on a single page, that information content rises epochally for physical, biological and cultural systems. And while I, too, feel that some day some kind of information will have some role in the cosmic-evolutionary narrative, I also suspect that we shall eventually come to recognize information as another form of energy – energy acquired, energy stored and energy expressed.

Regardless of the term used to characterize complexity, as here with free energy rate density, we ought to find intriguing any plot of a single quantity applicable to all systems and extending across all history. Even if I had proposed a wholly new term – let us say the quantity ‘ulfy’ with units of ‘strickenbaums’ – one should take note of any analysis uniformly treating all known systems that results in a portentous increase of that term throughout natural history. But I did not introduce a new term to describe complexity. I intentionally embraced a mere revision of an old one. In this way, neither new science nor appeals to non-science are invoked to justify the impressive hierarchy hallmarking the scenario of cosmic evolution.

Actually, the free energy rate density is hardly even a revised quantity, as many specialists often use this term without calling it thus. The metric, Φ_m , is familiar to astronomers as the luminosity-to-mass ratio, to physicists as the power density, to geologists as the specific radiant flux, to biologists as the specific metabolic rate and to engineers as the power-to-mass ratio. The free energy rate density is central to many varied subjects; all the more reason to embrace its interdisciplinary character and to use it in our search for unity across the spectrum of the natural sciences (Chaisson 2000, 2001, 2003).

Attendees also quickly noted that some of their favourite systems seemed missing along the curve of rising complexity in Fig. 6. Physicists asked about supernovae, biologists fussed about microbes and hummingbirds, and just about everyone wondered about computer chips – all of which, at face value, have high values of Φ_m . Supernovae, as well as bombs, flames and many other explosive events do have large energy throughput ($\Phi_m > 10^6$), but they do not belong on this curve; pre-supernovae are plotted there, representing an advanced stage of stellar evolution, but supernovae *per se* are destructive events and thus more typical of a retreat toward simplicity than an advance in complexity. Examples abound of other systems changing from complexity to simplicity, including bats moving back into caves over generations and thus gradually losing their eyesight as well as civilizations collapsing internally or externally and thus resorting to social chaos, but these are exceptions and not the rule in our study of the undeniable general trend of rising complexity in Nature.

As for microbes, they are indeed highly metabolic per unit mass, resulting in Φ_m values as much as 10^6 ergs $s^{-1} g^{-1}$, a million times greater than the Sun on whose light they feed. These respiring bacteria most surely do belong in our analysis, for the microbial world is an essential, ubiquitous part of the biosphere (Margulis & Sagan 1986). So why do microbes process so much normalized energy, sometimes higher than many other clearly more complex life forms, including human beings? The answer is that they are often so highly metabolic only when environmental resources warrant; few of them respire continuously. Measured rates are often quoted for peak periods of high reproductivity. By contrast, more than three-quarters of all soil bacteria are virtually dormant and thus have Φ_m values orders of magnitude less when eking out a living in nutrient poor environments. Much like the Komodo Dragon that can consume up to 80 percent of its body weight at one meal, yet not need another meal for a month, its time-averaged metabolic rate is much less than its maximum rate while eating; likewise, when all microbial rates are time-weighted, we find the average values for microbes to range in the thousands of ergs $s^{-1} g^{-1}$, as expected for systems of intermediate complexity.

As is much the case for the birds (and the bees), which are well known to have high specific metabolic rates ($\sim 3 \times 10^4$) during periods of peak activity, such as when earnestly foraging for food for their nestlings. That the smallest animals have the highest such rates is often taken (West *et al.* 1999)

as an explanation of their frequent eating habits (hummingbirds ingest up to half their body mass daily), extreme levels of activity (bumbees flap their wings up to 160 times per second) and relatively short lifespans (a few years typically, given the heavy toll on their metabolic functions); those are operational tasks, namely, function, not structure. Given that they operate normally in a three-dimensional aerial environment effectively solving advanced problems in spatial geometry, materials science, aeronautical engineering, molecular biochemistry and social stratification, then perhaps birds should have large values of Φ_m . That birds, while airborne, have values higher than for resting humans should not surprise us since we ourselves have not yet solved the art of flying, a decidedly complex task. By contrast, when bicycling vigorously or sewing intricately, our specific metabolic rates do exceed even those of birds in flight, for they cannot ride bicycles or thread needles. What is more, when we do fly, aided by aircraft we have built, machine values of Φ_m are indeed higher ($\sim 10^7$) than for even the most impressively ingesting hummingbirds.

No strong distinctions are made here among Φ_m values for members of the animal kingdom, except to note that they are nearly all within a factor of ten of one another, nestled nicely between those for photosynthesizing plants on the one hand and central nervous systems on the other. The results are broadly consistent with measured specific metabolic rates scaling inversely with body mass, $M^{-1/4}$, among a wide variety of animal species (Kleiber 1961). And animals in the main and in keeping with Fig. 6 fit well within the trend for many of the major evolutionary stages of life: eukaryotic cells are more complex than prokaryotic ones, plants more complex than protists, animals more complex than plants, mammals more complex than reptiles, and so on. Whether stars, life or society, the salient point seems much the same: the basic differences, both within and among these categories, are of degree, not of kind.

Regarding computer chips, semiconductor technology is surely included in our analysis, in addition to many other recent cultural inventions requiring energy (Chaisson 2001). Technological gadgets, under the Lamarckian pressure of dealer competition and customer selection, do in fact show increases in Φ_m values with product improvement over the years. Not only can the cultural evolution of machines be traced and their Φ_m values computed as noted above for engines, but similar advances can also be tracked for silicon-based devices now inundating our global economy. 'Moore's law', specifying the doubling of the number of transistors on a single microprocessor every 18 months, can also be cast into energy rate density terms, with values of Φ_m currently reaching 10^{10} ergs $s^{-1} g^{-1}$, an immense *density* caused mostly by chip miniaturization despite reduced power consumption. Further undermining any lingering anthropocentrism, we should not find it surprising that many of these cultural devices do have complexity measures comparable to, and sometimes greater than, biological systems, including brains. Technology often does things that we cannot do alone, and usually faster too, which is why society continues to

embrace technology, despite its pitfalls, to aid our senses and improve our lives. While that hardly makes present-day microelectronic machines more intelligent than us, it probably does make some of them more complex, especially given their extraordinarily functional data-processing speeds.

Nor should we find it surprising that a single quantity such as Φ_m applies to all ordered systems, as several Windsor attendees doubted, given that some systems are affected by gravity and others practically not. Thermodynamics applies to all such systems universally, whether massive enough like stars to be subject to gravity, or less so as for life forms that are largely governed by electromagnetism. Energy flow is a common feature of every open, non-equilibrium system, and it is heartening not only that one such quantity is uniformly applicable but also that it seems to map so well the rise of complexity, whether systems are gravitationally bound or not. For a star, we compute energy flowing through it, as gravitational potential energy during the act of star formation is converted into radiation released by the mature star; high-grade energy in the form of gravitational and nuclear events produce greater (thermal and elemental) organization, yet only at the expense of its environment into which the star emits low-grade light copious in entropy. Likewise, for a plant we compute energy flowing through it, as captured solar energy during the act of photosynthesis converts H_2O and CO_2 into nourishing carbohydrates; here, the previous low-grade disordering sunlight becomes, in a relative sense, a higher-grade ordering form of energy compared to the even lower-grade (infrared) energy re-emitted by Earth. Either way, gravity is not the measure of order and complexity, energy is; Φ_m is the fuel of evolution, fostering some systems to assimilate increased power densities while driving others to extinction. Gravitational force in physics, natural selection in biology and technological innovation in culture are all examples of diversified actions that can give rise to accelerated rates of change at locales much, much smaller than the Universe *per se* – such as the islands of order called stars, life and civilization itself.

And what if the Universe itself is actually accelerating, as recent observations purport to show? Such a runaway, open Universe hardly obviates the above analysis, for, if anything, the cosmic-evolutionary story would only get richer, quicker. With future time, an accelerating Universe would create steeper gradients, more energy flow and at least the potential (with $S_{max} - S$ growing faster, in Fig. 4) for even greater complexity among ordered structures. To what end, contingent science cannot say. The evolutionary process, as always, is an interplay of chance and necessity, the end result being inherently unpredictable. The curve of rising Φ_m would likely ramp up to ever higher values, and more rapidly so, albeit temporarily, as such a Universe raced out toward its ultimate fate – which, quite naturally, inevitably and soberingly, would likely be a highly disordered and fully entropic state characterizing, alas, the equilibrated 'heat death' of the only Universe we know.

Conclusion

Recent research, guided by the ongoing search for unification as much as by the empirical wealth of huge new databases, suggests that structured systems – whether stars, life or society – are localized, temporary islands of ordered complexity in a vast sea of increasingly disordered environments beyond those systems. All such open systems can be shown to agree quantitatively with the principles of non-equilibrium thermodynamics, and all can be treated in a common, integral manner by rating the energy passing through those systems. Furthermore, the concept of energy flow, naturally caused and still driven by the expanding cosmos, does seem to be as universal a process as anything yet found in Nature for the origin, maintenance and evolution of ordered, complex systems. The optimization of such energy flows acts as the motor of evolution broadly construed, thereby affecting, and to some extent unifying, all of physical, biological and cultural evolution. Life, in particular, seems to be a natural, but necessarily neither inevitable nor finely tuned, result of the way things change. Specifically, humankind's use of energy 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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