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Exobiology and Complexity

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Article Outline

Glossary

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.

Cosmic evolution A grand synthesis of the many varied changes in the assembly and composition of radiation, matter, and life throughout the history of the Universe.

Cosmology The study of the structure, evolution, and destiny of the Universe.

Energy The ability to do work or to cause change.

Energy rate density The amount of energy flowing through a system per unit time per unit mass.

Evolution Any process of growth and change with time, including an accumulation of historical information; in its broadest sense, both developmental and generational change.

Exobiology The study of the origin, evolution, and distribution of past and present life in the Universe; also known as astrobiology or bioastronomy.

Thermodynamics The study of the macroscopic changes in the energy of a system, for which temperature is a central property.

Definition of the Subject

Recent research, guided by theoretical searches for unification as much as by compilation of huge new databases, suggests that complex systems throughout Nature are localized, temporary islands of ordered structures within vastly larger, disordered environments beyond those systems. All such complex systems – including, for example, stars, life, and society – can be shown to obey quantitatively the principles of non-equilibrium thermodynamics, and all can be modeled in a common, integral manner by analyzing the energy passing through those systems. The concept of energy flow 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 an agent of evolution broadly considered, thereby affecting, and to some extent unifying, all of physical, biological, and cultural evolution.

More specifically, non-equilibrium thermodynamics, especially the energy flows resulting from contrasting temporal behaviors of matter and radiation energy densities, can generally explain the cosmic environments needed for the emergence of increasingly ordered structures over time. Furthermore, a necessary (though perhaps not sufficient) condition for the natural flow of energy, and hence for the growth of complexity, is the expansion of the Universe itself. Among all of Nature's diverse systems, energy – acquired, stored, and expressed – is a principal driver of the rising complexity among galaxies, stars, planets and life-forms throughout the cosmos. Neither new science nor appeals to non-science are required to appreciate the outstanding hierarchy of evolutionary change, from atoms to galaxies, from cells to society.

One way to approach the topic of exobiology and complexity – also known as astrobiology or bioastronomy – is to place it within the grand context of cosmic evolution. This interdisciplinary subject seeks to combine all the natural sciences into a unified whole, thereby effectively creating a new scientific worldview for the 21st century. Evolution, broadly considered, has indeed become a powerful unifying concept in all of science. Life itself, including complex life, seems to be a natural, but not necessarily inevitable, result of the way things complexify in an expanding Universe.

Introduction

Cosmic evolution 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 many other complex systems, our Galaxy, our Sun, our Earth, and ourselves. The result is an inclusive evolutionary synthesis bridging a wide variety of scientific specialties – physics, astronomy, geology, chemistry, biology, and anthropology – a genuine scientific narrative of epic proportions extending from the beginning of time to the present, from big bang to humankind.

The general idea of evolution – change writ large – extends well beyond the subject of biology, granting it a powerful unifying potential in all of science. Unquestionably, change is widespread throughout all of Nature, much as the Greek philosopher Heraclitus asserted 25 centuries ago: "All flows … nothing stays". Yet questions remain: How realistic is the quest for interdisciplinary unification? Can we reconcile the observed constructiveness of cosmic evolution with the inherent destructiveness of thermodynamics? Specifically, how have the amazing examples of order all around us arisen from chaos – and how does all this fit into complexity science?

We especially seek to understand the origins of the many diverse structures spanning the Universe today, notably those characterized by the term "complexity" – a state of intricacy, complication, variety, or involvement, as in the interconnected parts of a system. (In this article, no definitional distinctions are made among the words "order", "form", and "complexity"; we address only a general understanding of an entire spectrum of structures often described by the intuitive usage of the term complexity.) Particularly intriguing is the increase of complexity over the course of time, indeed dramatically so (with some exceptions) within the past half-billion years since the Cambrian period on Earth. Perhaps some underlying principle, a general law, or an ongoing process does create, organize, and maintain all complex structures in the

Universe, enabling us to study Nature's many changes on uniform, common ground – in the same quantitative way and with the same mental tools, in other words "on the same page".

Both theory and experiment, as well as computer simulations, suggest affirmative answers to some of the above questions: Islands of ordered complexity – namely, open systems that are galaxies, stars, planets, and life-forms – are numerically more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All quantitatively agrees with the valued principles of thermodynamics, especially non-equilibrium thermodynamics. Furthermore, energy flows produced largely by the expanding cosmos do seem to be as universal a factor 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 affecting all of physical, biological, and cultural evolution, the combination of which constitutes cosmic evolution.

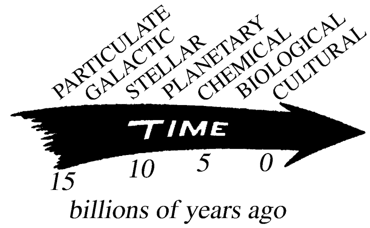
Therefore, a general outline for this article is:
Cosmic Evolution

- Subsets in time: physical evolution → biological evolution → cultural evolution.

Other researchers have addressed life and complexity in a cosmic setting, originally Chambers [16], who anonymously wrote a pre-Darwinian study of wide interdisciplinary insight, and notably Shapley [62], who pioneered a "cosmography" that classified all known structures according to increasing dimensions. Among others, Spencer [64] championed the idea of growing complexity in biological and cultural evolution, Henderson [31] regarded the whole evolutionary process, both physical and organic, as one and the same, Whitehead [72] sought to broaden scientific thinking with his "organic philosophy", von Bertalanffy [75] championed a systems theoretic approach to physical, biological, and social studies, and Sagan [57], Reeves [56], Jantsch [33] and Chaisson [7] widely advanced the concept of complex (intelligent) life within a cosmological framework.

Arrow of Time

Figure 1a sketches Nature's main historical epochs diagonally atop the so-called arrow of time [3]; these 7 epochs correspond to the major evolutionary phases comprising the whole of cosmic evolution [14]. Regardless of its shape or orientation, such an arrow symbolizes a *sequence* of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos in the early



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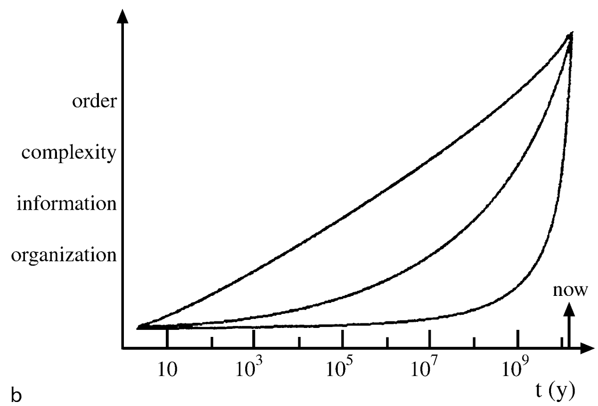


b

Exobiology and Complexity, Figure 1

a An arrow of time symbolically chronicles the principal epochs of cosmic history, from the beginning of the Universe ∼14 billion years ago (at left) to the present (at right). Labeled diagonally across the top are 7 major evolutionary phases (corresponding to the main historical epochs) that have produced, in turn, increasing amounts of order and complexity among all material systems: particulate, galactic, stellar, planetary, chemical, biological, and cultural. Cosmic evolution encompasses all of these phases, each of which represents a coarse temporal duration when the emergence of key systems flourished in Nature. Time is assumed to flow linearly and irreversibly, much as other basic tenets are presumed, including the fixed character of physical law and the idea that 2 + 2 = 4 everywhere. b Sketched here qualitatively is the rise of order, form, and complexity typifying the evolution of *localized* material structures throughout the history of the Universe. This family of curves depicts a widespread, innate feeling, and not a rigid proof, that the complexity of ordered structures has *generally* increased over the course of time. It is unknown if this rise of complexity has been linear, exponential, or even faster (as drawn here for the 3 curves); current research aims to specify this curve and to describe it quantitatively

Universe to order more recently. That sequence, as determined by a large body of post-Renaissance data, accords well with the idea that a chain of knowledge – a loose continuity along an impressive hierarchy of complexity – links, in turn:

- The evolution of primal energy into elementary particles and then atoms
- The evolution of those atoms into galaxies and stars
- The evolution of stars into heavy elements

- The evolution of those elements into the molecular building blocks of life
- The evolution of those molecules into life itself
- The evolution of advanced life forms into intelligence
- The evolution of intelligent life into a cultured and technological civilization.

Despite the extreme specialization of modern science, evolution marks no disciplinary boundaries; complexity science is a truly interdisciplinary topic. A more specific outline for this article is then:
Cosmic Evolution

- Subsets: physical evolution → biological evolution → cultural evolution
- Phases: particulate → galactic → stellar → planetary → chemical → biological → cultural.

Accordingly, the most familiar kind of evolution – biological evolution, or neo-Darwinism – is just one, albeit important, subset of a broader evolutionary scenario including much more than 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 anthropocentric belief that humans 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.

Note that time's arrow does not imply that primitive, "lower" life-forms have biologically changed directly into advanced, "higher" 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 simple life eventually changed into those favoring the biological origin and evolution of more complex species. Likewise, in the earlier Universe, the physical evolution of environments ripe for galactic formation eventually gave way more recently to conditions conducive to stellar and planetary formation. Now, at least on Earth, cultural evolution dominates, since our local planetary environment has once more changed to foster greater, societal complexity. Change in the 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 diverse order and complexity.

Anthropocentrism is neither intended nor implied by the arrow of time; the arrow is not pointing at humankind. Anthropic principles notwithstanding, no logic supports the idea that the Universe was conceived in order to produce specifically us. Humans are not the pinnacle or culmination of the cosmic-evolutionary scenario, nor are we likely to be the only technologically competent beings that have emerged in the organically rich Universe. The arrow merely provides a convenient symbol, artistically suggesting the building of increasingly complex structures, from spiral galaxies to rocky planets to thinking beings.

Figure 1b graphs the widespread impression that material systems have become more organized and complex, especially in relatively recent times. This family of curves graphs "islands" of complexity that comprise ordered systems per se – whether massive stars, colorful flowers, or busy urban centers – not their vastly, indeed increasingly disorganized surroundings. Modern science aims to explain this rise of complexity and to do so with accepted scientific principles and observational or experimental data.

Non-equilibrium Thermodynamics

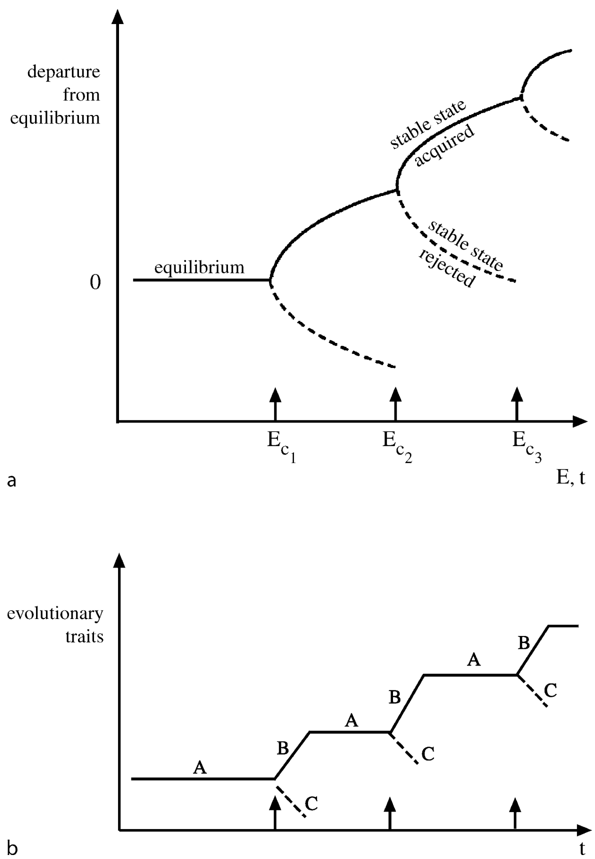
Cosmic evolution, as understood today, is governed largely by the laws of physics, particularly those of thermodynamics. However, this does not mean classical reductionism, for here we seek to model change guided by a combination of randomness and determinism, of chance and necessity. Nor does the cosmic-evolutionary narrative employ mere equilibrium thermodynamics – the kind most often used to explain closed systems isolated from their surroundings and having maximum entropy states. All structures observed in Nature, among them most notably galaxies, stars, planets, and life-forms, are demonstrably open, non-equilibrium systems, with flows of energy in and out being an important feature. And it is this energy, often called available, or "free" energy that helps to build structures [27,28,38,54,60,74].

By utilizing energy, order can be achieved temporarily, or at least the environmental conditions made conducive for the potential rise of order within open systems ripe for growth. Energy flow plays a vital role in the creation, maintenance, and fate of complex systems – all quantitatively in accord with the second law of thermodynamics, which demands an overall rise in disorder. None of Nature's ordered structures, not even life itself, is a violation (or even a circumvention) of the second law. Considering both any ordered system as well as its disordered surroundings, non-equilibrium thermodynamics shows that the net entropy of the system and its environment always increases. (Quantitative details for many such systems can be found in [10].)

Energy is now recognized as a key ingredient, not only for biological systems such as plants and animals, but also for physical systems such as stars and galaxies, indeed as well for social systems such as a city's inward flow of food and resources amidst its outward flow of products and wastes (Weber [69]; Dyke [21]). The analysis is much the same for all open systems, provided they are modeled in broad, interdisciplinary ways; energy flow seems indispensable for any system's origin and evolution.

Figure 2, adapted from the work of Prigogine et al. [55] and Salk [58], graphically diagrams the emergence of structure in the presence of energy flow. Physicists relate to the type of curves drawn in part (a); biologists are more familiar with those in part (b). By crossing certain energy thresholds that depend on a system's status, bifurcations can occur, fostering the origin of whole new structures that display surprising amounts of coherent behavior. Such "dissipative" structures can export some of their entropy (or expel some of their energy) into their external environments. Accordingly, order is created and sustained 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. "Self-assembling" systems demonstrate an essential tension between energy inflow and dissipative outflow; such systems do no function magically by themselves.

The emergence of order from a condition where originally there was none (or less of it) is relatively straightforward [54,59]. 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 come and go by chance since the statistical fluctuations diffuse 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. Microscopic temperature fluctuations, for instance, are said to be thermally relaxed, and entropy remains maximized in such systems. Nor can an open system *near* equilibrium change spontaneously to new and interesting structures. But should those fluctuations become too great for an open system to damp, that system can then depart far from equilibrium and have a chance to reorganize. Such restructuring generates a "dynamic steady state", provided the amplified fluctuations are continuously driven and stabilized by a flow of energy from the surroundings – namely, provided the energy flow rate exceeds the thermal relaxation rate. Systematic, coherent cycling is often the result, since under these conditions the spontaneous creation of macroscopic structures dissipates



Exobiology and Complexity, Figure 2
a The departure of an open system from equilibrium is drawn here as a function of both time, *t*, and energy, E. The time axis makes clear that this is an historical, evolutionary process, whereas the parallel energy axis tracks free energy flowing through the open system as a vital part of that process. At certain critical energies, labeled here E_c, a system can spontaneously change, or bifurcate, into new, non-equilibrium, 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. Not all new systems survive (*solid curve*); some are rejected (*dashed curve*). The process, as always, is a mixture of randomness and determinism, therefore the end result is inherently unpredictable, as with all of evolution. b Events in evolutionary biology mimic those of the diagram in a, although the results here are richer in structural detail, system function, and energy flow. In phases marked A, a species survives and thus persists until the environment changes (*vertical arrows*), after which further evolution occurs – along phase B toward renewed survival or phase C toward extinction. Both upwardly rising graphs (drawn by *solid lines* for both parts of this figure) imply neither progress nor inevitability, but they do suggest a *general trend* toward increasing complexity with time – a trend that cannot be denied among organized systems observed throughout Nature

energy more rapidly than the ensuing, and damaging, heat can damp the gradients and destroy those structures. Furthermore, since each successive reordering often 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. Nothing is guaranteed; thermodynamics specifies what can happen, not what actually does happen. The resulting phenomenon – termed "order through fluctuations" – is a distinctly evolutionary one, complete with feedback loops that help drive some systems further from equilibrium. And as the energy consumption and resulting complexity accelerate, so does the evolutionary process. This is the realm of true thermo*dynamics*, the older, established subject of that name more properly labeled "thermostatics".

Numerous examples abound throughout Nature, and not just among physical systems, but for biological and social systems as well. Naturally occurring phenomena such as convection cells, river eddies, atmospheric storms, and even artificially made devices such as kitchen refrigerators and coherent lasers among an array of many physical systems that experience coherent order when amply fed with sufficient energy, all display enhanced order when energy flows exceed some threshold. Biological systems also obey the rules of non-equilibrium thermodynamics, for we and our living relatives are demonstrable examples of dynamic steady states that emerge and function via energetically enhanced neo-Darwinism (though biologists often worry that such statements aim to reduce biology to physics – whereas in reality physics is broadened to include biology.) As are Lamarckian-type cultural systems of more recent times also dynamic steady states, for among the bricks and chips that civilization has built, energy has been a principal driver (although, again, sociologists and anthropologists often loathe their subjects being treated thermodynamically). The result is that life and its cultural inventions differ not in kind, but merely in degree – specifically, degree of complexity – among numerous ordered systems evident in Nature.

Big-Bang Cosmology

The origin of Nature's many complex structures depends on the flow of free energy. And this, like the arrow of time itself, is a direct consequence of the expanding Universe – a much tested "standard cosmological model" based largely on three-fold observations of distant receding galaxies, microwave background radiation, and light-element abundances. Time marches on and free energies flow because the cosmos dynamically evolves – building, maintaining, and often destroying systems. Indeed, it is cosmic expansion, and probably nothing more, that has caused the entire Universe to depart from its initial state of thermodynamic equilibrium. (Thus, the free energies are inevitable, not the resulting systems per se – which is why it's called "available", or potential, energy freely *capable* of doing work.) The stark contrast between localized hot stars and the vast, cold interstellar space surrounding them now guarantees a state of non-equilibrium, a cosmic condition that has pertained for billions of years [26,40].

Matter

Although modern cosmology stipulates that matter only later emerged from the primordial radiation of the early Universe, it is pedagogically useful to quantify first the role of matter and thereafter the primacy of radiation. In this way, perhaps the greatest change in the history of the Universe – the transformation from radiation to matter – can be mathematically justified.

Imagine an arbitrary shell of mass, m, and radius, r, expanding isotropically with the Universe at a velocity, v, from some central point. The sphere within the shell is not necessarily meant to represent the entire Universe, only an extremely large gas cloud within it – in fact, larger than the extent of a typical galaxy supercluster ($\sim$50 Mpc across), which comprises the highest rank in the known hierarchy of matter assemblages in the Universe. Invoking the principle of energy conservation, we find the Friedmann–Lemaitre equation that describes a family of models for the Universe in bulk,

$$H^2 - \frac{8}{3}\pi G\rho_{\mathrm{m}} = -kR^{-2}\,.$$

Here, H is Hubble's constant (a measure of galaxy recession in the expanding Universe), G is the universal gravitational constant, ρ_{m} is the matter density, and k is a time-dependent curvature constant. R is a scale factor which relates the radius, r, at any time, t, in cosmic history to the current radius, r_0, at the present time – namely, $r = Rr_0$. Solutions to the above equation specify three general models for the Universe:

- The Universe is "open" (i. e., k negative) and thus recedes forevermore
- The Universe is "closed" (i. e., k positive), meaning it eventually stops and thereafter contracts to a point much like that from which it began
- The Universe is precisely balanced between the open and closed models, in which case it eternally expands

and never contracts (because it can never reach infinity).

Even if the Universe is, as now suspected, accelerating in its outward expansion, the effect of "dark energy" (that supposedly causes the acceleration) on stars and galaxies is minimal, and that on smaller structures like planets and their organized living systems is inconsequential; cosmic acceleration likely affects only the dynamics of the Universe on the largest scales and not those of organized systems that are controlled by local energies within it.

The simplest case ($k = 0$, also known as the Einstein–deSitter solution) leads to the critical density for closure,

$$\rho_{\mathrm{m,c}} = 3H^2/8\pi G ,$$

which, when evaluated for G and H (~70 km/s/Mpc), equals $\sim 10^{-29}$ g/cm^3. This is ~6 atoms in each cubic meter of space, or about a million times thinner than in the region between Earth and the Moon. Whether the actual current density, on average everywhere, is smaller or larger than this value, making the Universe open or closed, respectively, is currently unknown; there is too much uncertainty concerning "dark (non-baryonic) matter" that is implied, but not found yet needed, to gravitationally bind galaxies and their clusters. However, the above-noted acceleration of the Universe does imply that it is expanding ever faster, thereby giving it an open geometry that will recede toward infinity forevermore.

To follow the evolution of matter throughout cosmic history (up to the present), we appeal to the conservation of material particles in the huge sphere postulated above, $\rho_{\mathrm{m}} = \rho_{\mathrm{m},0} R^{-3}$, substitute into the special ($k = 0$) case of the Friedmann–Lemaitre equation, and manipulate,

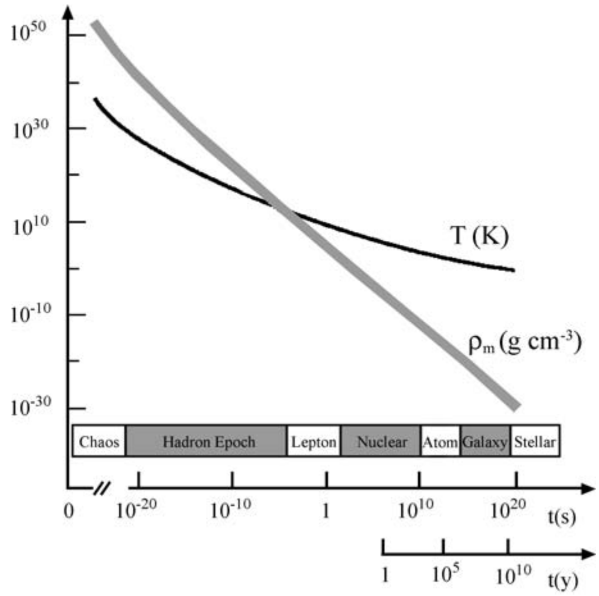
$$\int \mathrm{d}t = \left(\frac{8}{3}\pi G \rho_{\mathrm{m,c}}\right)^{-0.5} \int R^{0.5} \mathrm{d}R .$$

The result suggests that the Universe is $\sim 14 \times 10^9$ y old ($\pm\sim 10\%$). This equation additionally stipulates how the average matter density thins with time,

$$\rho_{\mathrm{m}} \approx 10^6 t^{-2} ,$$

where ρ_{m} is expressed in g/cm^3 and t in seconds.

Figure 3 plots this evolution of matter throughout all of universal history. This run of density, ρ_{m}, in standard, big-bang cosmology demonstrates the essence of change on the largest scales – the broadest view of the biggest picture. Here displayed in this one plot is the thermodynamic history of the whole Universe, so the curve for ρ_{m} in this figure (as well as the curve for T discussed in the next section) pertain to nothing in particular, just everything in general.



Exobiology and Complexity, Figure 3
Log-log plot of the density (ρ_{m}) of matter on average and the temperature (T) of radiation on average, over the course of all time, to date. The thick width of the density curve displays the range of uncertainty in total mass density, whose true value depends on the amount of "dark matter" in the Universe. By contrast, the cold cosmic background temperature is very accurately measured today (2.7 K), and its thin curve here is equally accurately extrapolated back into the hot, early Universe. Recent findings that cosmic expansion is accelerating should not much affect these curves

Radiation

The same analysis regarding matter can be applied to radiation in order to follow the change of temperature with time. Again, for the simplest $k = 0$ case,

$$H^2 = \frac{8\pi G \rho_{r,c}}{3R^4} ,$$

where ρ_r is the equivalent mass density of radiation. Here the R^4 term derives from the fact that radiation scales not only as the volume ($\alpha\ R^3$) but also by one additional factor of R because radiation (unlike matter) is also affected linearly by the Doppler shift. And noting that $\rho_r c^2 = \mathrm{a}T^4$, where a is the universal radiation constant for any blackbody emitter and T is the temperature of radiation, we find the temporal dependence of average temperature throughout all time (in seconds),

$$T \approx 10^{10} t^{-0.5} .$$

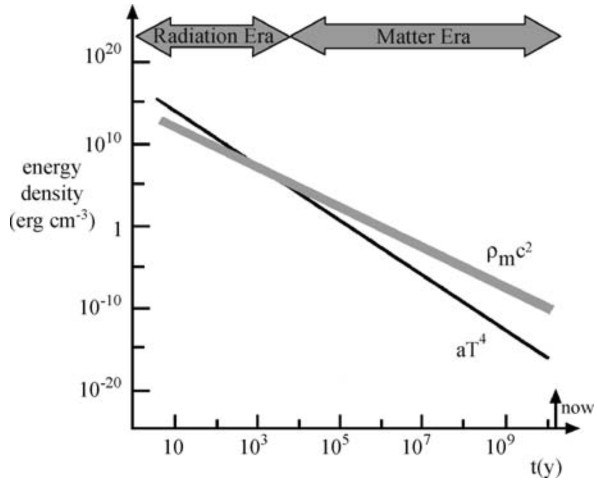
The universal radiation, having begun in a fiery expansion (popularly called the "big bang"), has now cooled to 2.7 K, the average value of the cosmic microwave background measured today by radio telescopes on the ground and satellites in orbit [2].

Figure 3 also plots this run of T versus t. Again, for emphasis, the two curves in this figure show the prime twin trends of big-bang cosmology: the cooling and thinning of radiation and matter, based largely on observations of the microwave background radiation and of the distant receding galaxies.

For the first few hundred millennia of the Universe, radiation reigned supreme over matter. Life was nonexistent and matter only a submicroscopic precipitate suspended in a glowing, chaotic fireball. All space was flooded with high-frequency photons, especially light, x-rays, and γ-rays, ensuring a non-structured, undifferentiated, (virtually) informationless, and highly uniform plasma. Matter and radiation were intimately coupled to each other – thermalized and equilibrated. Structure of any sort had yet to emerge; the energy density of radiation was too great. If single protons captured single electrons to form simple hydrogen atoms, the radiation was then so fierce as to destroy those atoms immediately. However, as the Universe expanded with time, the energy of radiation decreased faster than the energy equivalently contained in matter.

To confirm this statement, compare the energy densities of radiation and matter, and especially how these two quantities have change over time. First convert the matter density derived earlier to an equivalent energy density by invoking the Einsteinian mass (m)-energy (E) relation, $E = mc^2$ – that is, by multiplying the above equation for ρ_m by c^2. Now, $\sim 14 \times 10^9$ y after the big bang, $\rho_{m,0}c^2 \approx 10^{-9}$ erg/cm^3, whereas $aT_0^4 \approx 4 \times 10^{-13}$ erg/cm^3; thus currently, $\rho_{m,0}c^2 > aT_0^4$ by several orders of magnitude, proving that matter is now in firm control (gravitationally) of cosmic changes, despite the Universe still being flooded today with long-wavelength radiation. However, given that $\rho_m c^2$ scales as R^{-3} and aT^4 scales as R^{-4}, there must have been a time in the past when $\rho_m c^2 = aT^4$, and an even earlier time when $\rho_m c^2 < aT^4$. Manipulation of the above equations shows that these two energy densities crossed at $t \approx 10^4$ y, well less than a million years after the big bang. Figure 4 is a graphical representation of this paragraph.

This crossover represents a preeminent change in all of cosmic history. The event, $\rho_m c^2 = aT^4$, separates the *Radiation Era* from the *Matter Era*, and designates the time ($\sim 10^4$ y) when the Universe gradually began to become transparent. Thermal equilibrium was destroyed and symmetry broken, causing the radiative fireball and disorganized matter to decouple; it was as though a fog had lifted. Photons, previously scattered aimlessly and destructively



Exobiology and Complexity, Figure 4
The temporal behavior of both matter energy density ($\rho_m c^2$) and radiation energy density (aT^4) illustrates perhaps the greatest change in all of natural history. Where the two curves intersect, neutral atoms began to form; by $t \approx 10^5$ y after the big bang the Radiation Era had changed into the Matter Era. A uniform, featureless state describing the early Universe was thus naturally transformed into one in which order and complexity were thereafter possible

by subatomic material particles (especially free electrons) in the expanding, hot, opaque plasma of the Radiation Era, were no longer so affected once the electrons were bound into atoms of the Matter Era. This crucial and dramatic change was over by $\sim 4 \times 10^5$ y, when the last remnants of the early ionized plasma state had finally transformed into neutral matter. The 2.7-K microwave radiation reaching Earth today is a relic of this critical phase transition, having streamed unimpeded (except for being greatly redshifted, $z \sim 10^3$) across space and time for most of the age of the Universe, granting a "view" of this grandest of all evolutionary events that occurred long ago.

With the onset of the Matter Era, matter literally began dominating radiation. Natural history became more interesting, for then structures could begin to form. The results of inevitable change, induced gradients, energy flows, and evolved systems, over billions of years and minus the details, are galaxies, stars, planets, and life-forms, one byproduct of which is intelligence – at least on Earth. And this, in turn, has anthropogenically changed nearly everything on our planet.

Life

Now ~ 14 billion years after the beginning of space and time, the *Life Era* has begun, at least locally on Earth (and possibly at many other places in the Universe). Here, the emergence of technologically intelligent life heralds a whole new era wherein life has gradually begun to dominate matter. This second of two great transformations was not caused by the origin of life per se several billion years ago; rather, it is technologically advanced life that differs significantly from primitive life and from other types of clustered inanimate matter scattered throughout the Universe. This is not an anthropocentric statement; we differ because we are the only species capable of knowing our past and worrying about our future, the only one able to control matter (albeit locally), much as matter evolved to control radiation long ago. Intelligent life on Earth is literally taking matter into its own hands – manipulating matter and energy, altering genes and terrestrial environments, indeed potentially changing evolution itself.

Some central questions before us are these: What caused the changes amid a wide spectrum of ordered structures throughout cosmic history and how has complexity increased with time? Have humans actually become the agents of change on Earth, able to tinker with both matter and energy, including now modifying genes and environments more than they affect us? How did the neural network within our human brains acquire the sophistication needed to fashion societies, weapons, cathedrals, philosophies, etc? In short, what caused us to become sentient enough to contemplate our complex selves?

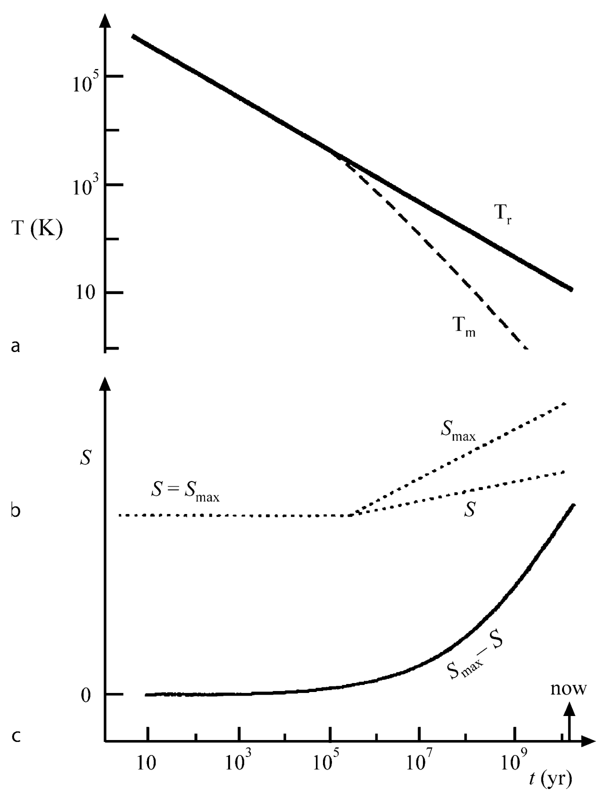
Measuring Complexity

To appreciate the crux of the historical appearance of structured matter and life, we return to the greater cosmic environment and to some of the thermodynamic issues raised earlier. In brief, when the Universe broke its symmetry a few thousand centuries after the big bang, equilibrium was also destroyed. Temperature gradients were thereafter established naturally owing to the expansion of the cosmos. And that meant free energy began flowing, in fact increasingly so as the temperatures of matter and radiation diverged with time. These are the environmental conditions that are favorable for the potential growth of order, form, and complexity.

Cosmic Environment for the Growth of Complexity

When matter and radiation were still equilibrated in the Radiation Era, only a single temperature is needed to describe the thermal history of the Universe; the absence of any thermal gradients imply (virtually) zero information content, or zero macroscopic order, in the early Universe. However, once the Matter Era began, the gas-energy equilibrium was destroyed and a single temperature is insufficient to specify the bulk evolution of the cosmos. Since the random motions of the H and He atoms failed to keep pace with the rate of general expansion of the atoms away from one another [40], the matter cooled faster, $T_{\mathrm{m}} \approx 6 \times 10^{16} t^{-1}$, than the radiation, $T_r \approx 10^{10} t^{-0.5}$. Figure 5a displays this thermal gradient, which has grown wider since $t \approx 10^5$ y.

Such a thermal gradient is the clear signature of a heat engine, and it is this ever-widening gradient that has enabled matter, in the main, to "build things" increasingly complex. Theoretically at least, the environmental conditions after 10^5 y naturally allowed a rise in "negentropy" [60] or "information content" [61] – both factors



Exobiology and Complexity, Figure 5
a In the expanding Universe, the temperatures of matter and radiation separated once these quantities became fully decoupled at ~10^5 y. Since that time, the Universe has been in a non-equilibrium state. b S increases less rapidly than $S_{\max}$, once the symmetry of equilibrium broke when matter and radiation decoupled at ~10^5 y. By contrast, in the early, equilibrated Universe, $S = S_{\max}$ for the prevailing conditions. c The potential for the growth of order, $S_{\max} - S$, has increased ever since the start of the Matter Era. This potential rise of order compares well with the subjectively drawn curves of Fig. 1b, thus providing a theoretical basis for the growth of system complexity

qualitatively synonymous with the term "complexity" [42]. But, as noted below, in practice both such terms are overly vague and subject to interpretation [5,73], so we resort here to a more conventional use of entropy, as agreed upon by most thermodynamicists. The important point – without getting lost in dubious semantics or contentious definitions – is that such non-equilibrium states are suitable, indeed apparently necessary, for the emergence of order, thus it can be reasoned that *cosmic expansion itself is the prime mover for the gradual construction of a hierarchy of structures throughout the Universe*.

Figure 5b plots the run of entropy, S, for a thermal gradient typical of a heat engine, but here graphed for the whole Universe. This is a 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 then nonexistent, after decoupling the environmental conditions became favorable for the potential growth of order, taken here to mean a "lack of disorder." At issue was timing: As ρ decreased, the equilibrium reaction rates ($\alpha\rho$) fell below the cosmic expansion rate ($\alpha\rho^{1/2}$) 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 comparing the shape of this curve of potentially rising order, $S_{max} - S$ in Fig. 5c, with our earlier intuited sketch of rising complexity in Fig. 1b [12,25,41].

Free Energy Rate Density

Theory aside, have the many diverse real structures known to exist in the Universe displayed this sort of progressive increase in order during the course of time? The answer is generally yes. At issue again is how to best characterize complexity numerically, given the varied connotations that this term presents for many researchers [46,47]. In biology alone, much as their inability to reach consensus on a definition of life, biologists cannot agree on a complexity metric. Some count non-junk genome size [66], others employ structural morphology or behavioral flexibility [4], while still others chart numbers of cell types in organisms [36] or appeal to cellular specialization [49]. All these attributes of life have qualitative usefulness, yet all are hard to quantify in practical terms; nor do they apply to non-living things. If progress is to be made assessing a wide spectrum of complex systems in Nature, our analysis must extend beyond mere words, indeed beyond biology.

Putting aside as unhelpful (in the sense that it is too ambiguous and controversial) the above-noted concept of information content [32,34] as well as the concept of negative entropy (or negentropy, which Schroedinger [60] first adopted but then quickly abandoned), we return to the quantity with greatest appeal to physical intuition – energy. Given that energy – the ability to do work or to cause change – is the most universal currency known in the natural sciences, it might reasonably be expected to have a central role in any attempted unification of physical, biological, and cultural evolution.

Energy does act as an underlying, universal driver like no other in all of modern science. Whether living or non-living, dynamical systems need flows of energy to endure. If stars don't convert gravitational potential into heat and light, they would collapse; if plants don't photosynthesize sunlight, they would shrivel and decay; if humans don't eat, we too would die. Likewise, society's fuel is energy: Resources come in and wastes go out, all the while civilization goes about its daily business.

Not that energy has been ignored in previous studies of systems' origin and assembly. Physicists (e. g., Morrison [52] and Dyson [22]), biologists (Lotka [44]; Morowitz [51]; Fox [24]), and ecologists (Odum [53], Ulanowitz [68], and Smil [63]), to cite only a few researchers, have noted energy's organizational abilities. But 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 suitable as normalized values, which depend on a system's size, composition, and efficiency. Nor are maximum energy principles or minimum entropy states [43] likely relevant; rather, organizational complexity is more likely governed by the *optimum* use of energy – not too little as to starve a system, yet not too much as to destroy it.

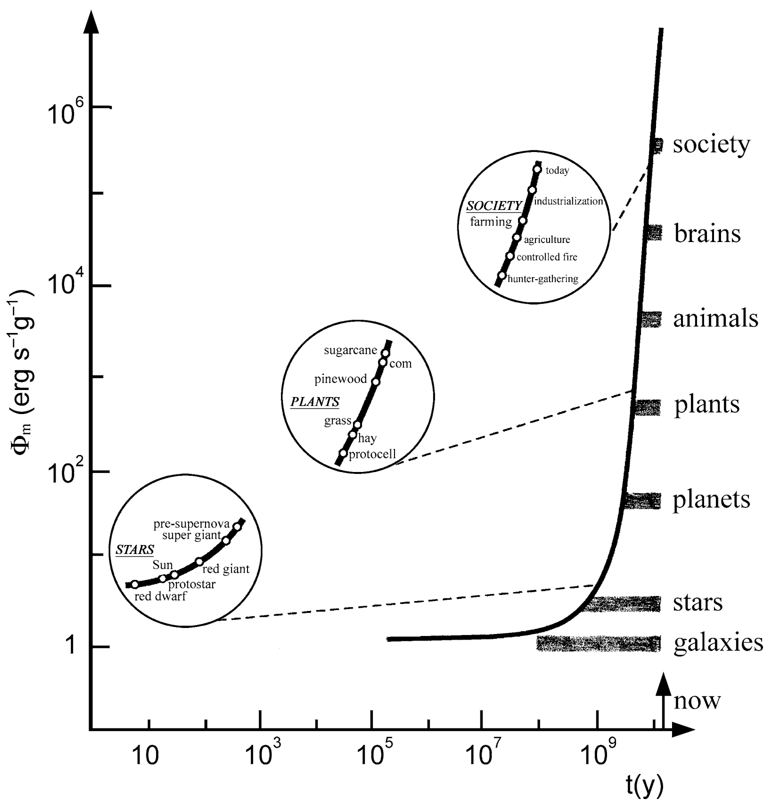
To characterize complexity objectively – that is, to normalize all such ordered systems on the same, level page – a kind of energy density is useful, much like the competing energy densities of radiation and matter that dictated changing events in the earlier Universe (Fig. 4). In fact, for a proper treatment of the thermodynamics of non-equilibrium open systems, it is the *rate* at which free energy flows through such systems of given mass that is most practical. Hence, *free energy rate density*, symbolized by Φ_m, is an operational term whose meaning, measurement, and units are clearly understood. In this way, neither new science nor appeals to nonscience are needed to justify the impressive hierarchy of the cosmic-evolutionary story, from stars to plants to society.

Note that this complexity metric is not an original term; free energy rate density is a mere revision of an old one. Moreover, for years the same term has been labeled differently by specialized researchers: 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. Free energy rate density is central to many varied subjects; all the more reason to use it to build a true interdisciplinary subject and to use it in search of unity across the spectrum of all the natural sciences [8,9,10,11].

Exobiology and Complexity, Table 1
Free energy rate densities for several representative systems

System	Duration (10^6 y)	Φ_m (erg/s/g)
Galaxy (Milky Way)	12,000	0.5
Star (main-sequence Sun)	10,000	2
Planet (Earth's climasphere)	5000	75
Plant (Earth's biosphere)	3000	900
Animal (hominid body)	10	20,000
Brain (human cranium)	1	150,000
Society (modern culture)	0	500,000

Table 1 lists values of Φ_m, in units of erg/sec/g, for seven representative systems (and their specific, computed cases in parentheses). Also listed is the duration, in millions of years, for each type of structure, dating back to their origins in the observational record. Clearly, Φ_m



Exobiology and Complexity, Figure 6
Increase in free energy rate density, Φ_m, plotted as *horizontal histograms* when various open structures prospered in Nature, has been especially rapid in the last few billion years, much as expected from subjective intuition (Fig. 1b) and objective thermodynamics (Fig. 5c). The *drawn curve* approximates the increase in normalized energy flows characterizing 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 free energy rate density for three representative systems – stars, plants, and society – typifying physical, biological, and cultural evolution, respectively. The *data in those circled insets* are discussed in Sect. "Complexity and Evolution, Broadly Considered". (Adapted from [9,10])

has increased as more intricately ordered systems have emerged throughout cosmic history, and dramatically so in relatively recent times.

The modeled flow of energy through a wide variety of open systems, alive or not, resembles the intuitive rise in complexity implied by Fig. 1b; it also mimics the potential rise of order in the above thermodynamic analysis of Fig. 5c. Complexity (at least as treated here energetically for localized structures) has indeed quantitatively increased over the course of natural history, and at a rate faster than exponential in more recent times ([9,11,13]; for details of energy computations and modeling, consult [10]).

Figure 6 plots the results listed in Table 1, where the Φ_m values are graphed as horizontal histograms for various systems' evolutionary durations to date. As expected:

- Stars and planets have small energy rate densities, $\Phi_m = 1\text{–}10^2$ erg/s/g
- Plants and animals have larger energy rate densities, $10^3\text{–}10^5$ erg/s/g
- Human societies have the largest known energy rate densities, $\sim 10^6$ erg/s/g.

Note that, although the total energy flowing through a star or planet is much greater than that through our individual bodies or brains, the *specific* rate (per unit mass) is larger for the latter – in fact, roughly a million times greater Φ_m for the human body than for the Sun.

This is not to say, by any means, that galaxies evolved into stars, or stars into planets, or planets into life. Rather, this analysis contends that galaxies gave rise to environments suited to the birth of stars, that some stars spawned environments conducive to the formation of planets, and that countless planets likely fostered environments ripe for the origin of life. Cosmic evolution, to repeat, incorporates both developmental and generational change.

Nor do these evolutionary phases, or historical durations, have well-determined start and stop times – or stop times necessarily at all. The horizontal histograms of Fig. 6 serve to stress that each of these phases once begun did not end; stars and galaxies, for example, first emerged in the earlier Universe, as also implied by the diagonal phases atop the arrow of time in Fig. 1a, but both such system types continue on presently originating, developing, and evolving, as do plants and animals that emerged much later. As depicted by those histograms yet unlike customary geological periods that do have set time intervals, currently all evolutionary phases noted in Figs. 1 and 6 operate simultaneously and indefinitely.

We thus arrive at a comprehensible reconciliation of the evident destructiveness of thermodynamics with the observed constructiveness of cosmic evolution. The sources and sinks of such energy flows passing through complex yet disparate entities such as stars, plants, and civilization all relate back to the time of thermal decoupling in the early Universe, when the conditions naturally emerged for the origin and evolution of order and organization.

Complexity and Evolution, Broadly Considered

Evolution should not be the sole province of biology, nor should its utility be of value only to life scientists. Darwin [19] never used the word "evolution" as a noun, in fact only once as a verb in the very last sentence of his classic book, *On the Origin of Species*. Nor need the principle of natural selection be the only mechanism of evolutionary change, past or present.

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 change as much as a passive mechanism that weeds out the unfit. As such, selected systems are simply those that remain after all the poorly adapted or less fortunate ones have been removed from a population of such systems. A better term might be "non-random elimination" [48]. What we really aim to explain are the adverse circumstances responsible for the deletion of some members of a group. Accordingly, selection can be generally taken to mean favorable interaction of any system with its environment – a more liberal interpretation that also helps widen the concept of evolution.

Selection works alongside the flow of resources into and out of all open systems, not just life-forms. Ordered systems are selected partly for their ability to utilize energy; and this energy is the "force", if there is any at all, in evolution. Broadly considered, selection occurs in the inanimate world as well as among animate objects, often providing a formative step in the production of order. It is energy flow and natural selection that together, working in tandem, underlie the "self" -assembly sketched in Fig. 2 – the former driving initial systems beyond equilibrium, the latter aiding the emergence of higher order in those systems that survive.

A handful of cases will suffice, among many others so documented [14], to illustrate the action of this energy-selection duo among a spectrum of increasingly ordered systems in successive phases of cosmic evolution:

- Red-giant stars are more complex than main-sequence stars
- Eukaryotes are more complex than prokaryotes
- Plants are more complex than protists
- Animals are more complex than plants
- Mammals are more complex than reptiles

- Brains are more complex than bodies
- Industrial society is more complex than hunter-gatherers.

Whether physical evolution of galaxies, stars and planets, or biological evolution of plants and animals on Earth, or cultural evolution of our technological civilization, a rather remarkable ranking order is apparent among all known organized structures. Stars, life, and society, all share a significant, common conclusion: Basic differences, both within and among these categories, are in degree, not in kind – namely, in degree of complexity arising from ongoing cosmic evolution. To justify this, consider below in greater detail each of the three major subsets of cosmic evolution noted in Sect. "Introduction".

Physical Evolution

Stars are good examples of physical evolution. Growing complexity can serve as an indicator of stellar aging – a developmental process – allowing stars to be judged as their interiors undergo cycles of nuclear fusion that result in greater thermal and chemical gradients. More data are needed to describe the increasingly differentiated, onion-like layers of fused heavy elements within highly evolved stars; more energy also flows per unit mass. Stellar size, color, brightness, and composition all change while passing on up the hierarchy of complexity for all stars, each stage using more free energy rate density:

- From protostars at "birth" ($\Phi_m \approx 0.5$ erg/s/g)
- To main-sequence stars at "mid-life" (~ 2)
- To red-giant stars in "old age" ($\sim 10^2$),
- To pre-supernovae near "death" ($\sim 5 \times 10^2$).

Those parenthetical values are the stars' increased energy rate densities, plotted among other values in the lower circled inset of Fig. 6. At least as regards energy flow, material resources, and structural integrity while experiencing change, stars have much in common with life. This is not to say that stars are alive, which is an occasional misinterpretation of such a broad statement. Nor do stars evolve in the strict and limited biological sense; most researchers would agree that stars *develop*. Yet close parallels are apparent among stars, including selection, adaptation, and perhaps even a kind of stellar reproduction – a generational process – 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) enable 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" [23] propagate through many such clouds like slow-motion chain reactions over eons of time – shock waves 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 fusion needed to produce heavy elements are in fact the very same stars that often produce shocks to create new populations of stars, thereby both episodically and gradually 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. All of which is reminiscent of stellar "evolution", minus any genes, inheritance, or overt function, for these are the value-added qualities of biological evolution that go well beyond physical evolution.

Continuing on and throughout the physical evolutionary subset of cosmic evolution, a *general* trend prevails, at least as pertains to Earth's environment that set the stage for life:

- Young rocky planets have greater Φ_m (~ 10 erg/s/g) than normal stars and galaxies (~ 1)
- Hydrothermal vents on at least one of those planets have more (~ 50)
- Planetary climaspheres, such as Earth's ocean-air interface, have even more (~ 100).

Note that some physical systems seem to be exceptions to the above findings, but upon closer inspection they are not exceptional at all. For example, that supernovae have very high values of Φ_m ($\gg 10^6$ erg/s/g) does not violate our complexity metric. The reason is that supernovae are not organized systems, in fact just the opposite; as excellent examples of totally disorganized explosions of massive stars, they have too much energy flow that is well outside the optimal range for stars, and thus we should not expect to properly plot chaotic supernovae among other clearly ordered systems in Fig. 6. Pre-supernovae are noted there, representing an advanced stage of stellar evolution and growing complexity prior to explosion, but supernovae themselves are destructive events more typical of retreat from complexity toward simplicity. Likewise, bombs, flames, and many other damaging events do have large energy throughput yet do not belong on this curve, thus do not partake of a general trend toward rising complexity in Nature.

Biological Evolution

Plants are good examples of biological evolution. Here, we trace increasing complexity among plant life on Earth where neo-Darwinism is clearly at work, making use of free energy rate densities well higher than those for galaxies, stars, and planets. As shown in the middle circled inset of Fig. 6, energy-flow diagnostics display a definite increase in complexity among various plants that locally and temporarily decrease entropy. The most dominant process in Earth's biosphere – photosynthesis – well illustrates that complexity hierarchy [29]:

- From simple hay or grass ($\Phi_m \approx 5 \times 10^2$ erg/s/g)
- To inefficient pinewood ($\sim 3 \times 10^3$)
- To more efficient corn ($\sim 6 \times 10^3$)
- To well cultivated sugarcane ($\sim 10^4$).

System functionality and genetic inheritance are two factors, above and beyond mere system structure, which help to enhance order among animate systems that are clearly living compared to inanimate systems that are clearly not. Unsurprisingly, more complex life-forms require the acquisition of more energy per unit mass per unit time for their well being.

Energy flows through plants as captured solar energy during the act of photosynthesis converts H_2O and CO_2 into nourishing carbohydrates; 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. Likewise, as regards previously discussed physical evolution, energy flows through stars as gravitational potential energy during the act of star formation converts into radiation released by mature stars; high-grade energy produced by gravitational and nuclear events yield greater (thermal and elemental) organization, yet only at the expense of their environments into which stars emit low-grade light abundant in entropy. Either way, energy is a fuel for evolution, fostering some systems to utilize increased power densities while driving others to destruction and extinction.

Onward across the bush of life (or the arrow of time) – cells, tissues, organs, organisms – much the same metric holds for animals (all in units of erg/s/g):

- Cold-blooded reptiles have greater Φ_m ($\sim 10^4$) than globally averaged plants ($\sim 10^3$)
- Warm-blooded mammals typically have more ($\sim 5 \times 10^4$)
- Some birds, during complex flight, can achieve even more ($\sim 7 \times 10^4$).

Human life itself can also be examined on finer scale to show how energy usage continues upward (per unit mass) for more complex tasks [30,63]:

- Laboring humans have greater Φ_m ($\sim 6 \times 10^4$) than sedentary humans ($\sim 2 \times 10^4$)
- Vigorously bicycling and intricately sewing humans have more ($\sim 10^5$)
- Thinking human brains themselves have even more ($\sim 2 \times 10^5$).

Starting with life's precursor molecules (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 the complexity of plants and animals as for stars and planets: The greater the perceived 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.

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, confined 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 [37,70]. Suffice it to say that animals in the main and in accord with Fig. 6 fit well within the complexity trends for the major evolutionary stages of life and for the intermediate phases of cosmic evolution.

Note, however, as for some non-living systems above, a minority of living systems seem exceptional, their values of Φ_m somewhat out of bounds among other equally advanced biological systems. Occasional life-forms also display retreat from complexity, such as some bats that move deeper into caves over generations and thus gradually lose their eyesight, or snakes and whales that eventually lost legs over time. Exceptions, real and apparent, to any rule will likely occur in a biosphere so rich in numbers and diversity as ours on Earth. For example, respiring bacteria are problematic at face value, having Φ_m values as much as 10^6 erg/s/g [45], thus comparable to higher forms of life. But microbes are so highly metabolic only when environmental resources warrant; none 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 while eking out a living in nutrient-poor environments. When all microbial rates are time-weighted, microbes' average values range in the thousands of erg/s/g, as expected for systems of intermediate complexity. Likewise and to note just one other seemingly exceptional animal, the Komodo Dragon can consume 80% of its body weight at one meal, yet not need another meal for a month – however, its time-averaged metabolic rate is much less than its maximum rate while eating.

Birds are another case in point, as they are well known to have high specific metabolic rates ($\sim 3 \times 10^4$ erg/s/g) during periods of peak activity, such as when earnestly foraging for food for their nestlings. But, once again, upon closer inspection, they are recognized not to be exceptions at all. That the smallest animals have the highest such rates is often taken [70] as an explanation of their frequent eating habits (hummingbirds ingest up to half of their body mass daily), extreme levels of activity (bumblebees flap their wings up to 160 times per second), and relatively short lifespans (few years typically, given the heavy toll on their metabolic functions); those are operational tasks, namely, function, not structure. Given that birds and bees normally function in a three-dimensional aerial environment while solving advanced tasks in spatial geometry, materials science, aeronautical engineering, molecular biochemistry, and social stratification, then perhaps they ought to have large values of Φ_m. That birds, while airborne, have higher values than for resting humans should not surprise us since we ourselves have not solved the art of flying, an admittedly complex task. By contrast, when bicycling vigorously or sewing intricately, our specific metabolic rates do exceed even those of birds in flight as noted above. Moreover, when humans do fly, aided by built aircraft, machine values of Φ_m are indeed higher ($\sim 10^7$ erg/s/g) than for even the most impressively ingesting hummingbirds, as discussed in the next section on cultural evolution.

Cultural Evolution

Society is a good example of cultural evolution. Here, the cosmic-evolutionary chronicle continues, yet with greater normalized energy flows to power our obviously complex civilization. As plotted in the upper circled inset of Fig. 6, social progress can be tracked, again in terms of 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 ($\Phi_m \approx 10^4$ erg/s/g)
- To agriculturists of several thousand years ago ($\sim 10^5$)
- To industrialists of two hundred years ago ($\sim 5 \times 10^5$)
- To western society today, on average ($\sim 10^6$).

That a cluster of brainy organisms working collectively in a social group is more energy intensive per capita (and thus more complex) than each of its individual human members – at least as regards the present criterion for order of free energy rate usage per capita – is a good example of a "whole greater than the sum of its parts", in this case for the open, non-equilibrated society that constitutes modern civilization [15].

The road to today's technological society was unquestionably built with increased energy use, as has been earlier recognized by many cultural historians (e. g., White [71]; Cook [18]; Brown [6]; Jervis [35]; McNeill and McNeill [50]), who noted the importance of rising energy expenditure per capita, a factor also more recently emphasized by practitioners of "big history" (Christian [17]; Spier [65]; Aunger [1]), a newly emerging subject that treats conventional history more deeply, indeed parallels the scenario of cosmic evolution.

Machines, too, and not just computer chips, but also ordinary motors and engines that typified the fast-paced economy of the 20th century, can be cast in evolutionary terms – though here the mechanism is less Darwinian than Lamarckian [39], with the latter's emphasis on accumulation of acquired traits. Either way, energy remains a driver, and with rapidly accelerating pace. Aircraft engines, for example, display clear evolutionary trends as engineering improvement and customer selection over generations of products have made engines more intricate, complex, and efficient, all the while utilizing enriched flows of energy density [63]:

- Gas-guzzling SUVs have greater Φ_m ($\sim 10^6$erg/s/g) than model-T automobiles ($\sim 10^5$)
- Boeing-747 jumbo jets of the last few decades have more ($\sim 10^7$)
- Military F-117 stealth aircraft of the present have even more ($\sim 10^8$).

Finer-scale evolutionary analysis of many technological advancements display evident progress toward greater complexity, such as for the typical American passenger car over the past two decades that can be cast in terms of growing horsepower-to-weight ratios provided by the US Highway Traffic Safety Administration: $\Phi_m = 5.9 \times 10^5$ erg/s/g in 1978, 6.8×10^5 in 1988, and 8.3×10^5 in 1998. Not surprisingly, silicon chips – a cultural icon of today's vibrant, digitized 21st-century economy – have immense flows of energy density, currently reaching values of $\sim 10^{10}$ erg/s/g mostly caused by chip miniaturization despite reduced power consumption.

Rare exceptions in cultural evolution's apparent drive toward greater complexity sometimes cause regression toward simpler systems, much as for minor aspects of the physical and biological subsets of cosmic evolution. Collapse of civilizations, either internally (because of societal conflict) or externally (owing to environmental change), that then resort to social chaos is are examples of infrequent retreat from society's overall drive toward greater complexity [20,67].

Occasional exceptions aside, increasingly sophisticated 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 a whole array of silicon-based devices now inundating our global economy. In keeping with the upper part of the curve in Fig. 6, many of these cultural devices do have complexity measures comparable to, and often greater than, biological systems, including brains. Technology clearly allows individual humans to accomplish things that cannot be done by us alone, and usually faster too, which partly explains why most of society continues to embrace technology, despite its pitfalls, to aid our senses and improve our increasingly complex lives.

Conclusions and Future Directions

This article has taken the liberty of extrapolating the word "evolution" in an intentionally broad way to analyze change on all spatial and temporal scales. Within the grand context of cosmic evolution, common threads have been identified linking a wide spectrum of ordered structures during an extremely long period of natural history, from big bang to humankind. More than any other single factor, energy flow seems to be a principal means whereby Nature's diverse systems naturally became increasingly complex in an expanding Universe, including not only galaxies, stars and planets, but also lives, brains and civilization.

The scenario of cosmic evolution accords well with observations demonstrating an entire hierarchy of structures to have emerged, in turn, throughout the history of the Universe: particles, galaxies, stars, planets, life, intelligence, and culture. As a general trend, an overall increase in complexity is apparent with the relentless march of time, without any progress, purpose or design implied. With cosmic evolution as our guide, we can begin to understand the environmental conditions needed for matter to have become increasingly ordered, organized, and complex. This rise in order, form, and structure violates no laws of physics, and certainly not those of modern thermodynamics. Nor is the idea of ubiquitous change novel to modern worldviews. What is new and exciting is the way that frontier, non-equilibrium science now helps us unify a holistic cosmology wherein complex life plays an integral role – namely, to address the origin and evolution of all things by means of logic, rationality, and the methods of natural science.

When studying complexity in Nature, some researchers prefer the concept of information rather than energy, often becoming displeased when the former is put aside as done in this article. But information content has had a muddled history full of assorted interpretations – meaningful information, the value of information, Shannon information, algorithmic information, raw information. Furthermore, no one has yet shown quantitatively and unambiguously, that information content rises throughout the ages for physical, biological, and cultural systems. A useful future research direction would clarify the role of the information sciences in complexity studies and cosmic evolution, including the possibility that information is merely other forms of energy – energy acquired, energy stored, and energy expressed.

By contrast, it is encouraging that a single quantity such as free energy rate density, defined here clearly and with units well understood, affects all ordered systems, given that some systems are regulated by gravity and others practically not. Thermodynamics does pertain to all such systems universally, whether massive enough like stars subject to gravity or less so as for life-forms governed mostly by electromagnetism. Energy flow is a common feature of every open, non-equilibrium system, and it is insightful not only that one such quantity is uniformly applicable but also that it seems to map reasonably well the rise of complexity among many known systems. 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 smaller than the Universe per se – such as the islands of order that are stars, life, and civilization itself. Indeed, our use of energy wisely and optimally will likely guide our fate along the future arrow of time, for we humans are also part of the cosmic-evolutionary scenario.

Humankind is now moving toward a time, possibly as soon as within a few generations, when we shall no longer be able to expect Nature to easily provide for our own survival. Rather, civilization on Earth will either have to adapt to the natural environment with ever-accelerating speed, or to generate artificially controlled environments (either on or beyond Earth) needed for our ecological existence. From two of Nature's most advanced yet locally ordered systems – society and machines – will likely emerge a symbiotic technoculture, the epitome (thus far as best we know) of complexity in the Universe – a new technology-based system that will likely require even greater values of energy rate density, as the curve in Fig. 6 continues racing upward. Can humanity endure despite its own increasing complexity? Or will our species transform into some other intricate entity as complexity continues to rise?

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Article Outline

Glossary

Chiral, achiral and racemic A molecule is chiral if its three-dimensional structure is different from its mirror image. Such molecules tend to be optically active and turn the polarization plane of linearly polarized light in the right- or left-handed sense. Correspondingly, they are referred to as D- and L-forms, which stand for dextrorotatory and levorotatory molecules. An achiral molecule is mirror-symmetric and does not have this property. A substance is racemic if it consists of equally many left- and right-handed molecules. A polymer is said to be isotactic if all its elements have the same chirality.

Enantiomers and enantiomeric excess Enantiomers are a pair of chiral molecules that have opposite handedness, but are otherwise identical. Enantiomeric excess, usually abbreviated as e.e., is a normalized measure of the degree by which one handedness dominates over the other one. It is defined as the ratio of the difference to the sum of the two concentrations, so e.e. always falls between -1 and $+1$.

Epimerization and racemization Epimerization is a spontaneous change of handedness of one sub-unit in a polymer. Racemization indicates the loss of a preferred handedness in a substance.

Catalysis and auto-catalysis Catalysts are agents that lower the reaction barrier. A molecule reacts with the catalyst, but at the end of the reaction, the catalyst emerges unchanged. This is called catalysis. In autocatalysis the catalyst is a target molecule itself, so this process leads to exponential amplification of the concentration of this molecule by using some substrate. Biological catalysts are referred to as enzymes.

Nucleotides and nucleic acids Nucleotides are monomers of nucleic acids, e. g., of RNA (ribonucleic acid) or DNA (deoxyribonucleic acid). They contain one of four nucleobases (often just called bases) that can pair in a specific way. Nucleotides can form polymers, and their sequence carries genetic information. One speaks about a polycondensation reaction instead of polymerization because one water molecule is removed in this step. Other nucleotides of interest include peptide nucleic acid or PNA. Here the backbone is made of peptides instead of sugar phosphate.