

## Chapter 1



# Cosmic Evolution

## *State of the Science*

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Evolution, broadly considered, has become a powerful unifying concept in all of science, providing a comprehensive worldview for the new millennium. Among all of nature's diverse systems, energy—acquired, stored, and expressed—is a principal driver of the rising complexity of galaxies, stars, planets and life-forms in the expanding universe. Our cultural curiosity is both a result of, and a key to understanding, myriad cosmic-evolutionary events that have shaped our material origins.

### *Introduction*

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Emerging now from modern science is a unified scenario of the cosmos, including ourselves as sentient beings, based on the time-honored concept of change. Change does seem to be universal and ubiquitous in nature, much as the ancient Greek philosopher Heraclitus claimed long ago that “everything flows and nothing stays.” Nowadays we have evidence for change virtually everywhere, some of it obvious, other subtle. From galaxies to snowflakes, from stars and planets to life itself, scientists are weaving an intricate pattern penetrating the fabric of all the natural sciences—a sweepingly inclusive worldview of the order and structure of every known class of object in our richly endowed universe.

Cosmic evolution is the study 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 changes that have produced our galaxy, our Sun, our Earth, and ourselves. The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties—physics, astronomy, geology, chemistry, biology, and anthropology, among

others—a genuine narrative of epic proportions extending from the very beginning of time to the present, from the Big Bang to humankind.

While entering this new age of synthesis, today's researchers are truly embracing interdisciplinarity; we are thinking bigger, broader, and more holistically. We are deciphering how all known objects—from atoms to galaxies, from cells to brains, from people to society—are interrelated. For the more we examine nature, the more everything seems related to everything else. Our appreciation for evolution now extends well beyond the subject of biology; indeed, the concept of evolution, generally considered, has become a potent unifying factor in all of science. Yet questions remain: how valid are the apparent continuities among nature's historical epochs and how realistic is the quest for unification? Can we reconcile the observed constructiveness of cosmic evolution with the inherent destructiveness of thermodynamics? Specifically how have the magnificent examples of order all around us arisen from chaos?

We especially want to know about the origins of the diverse structures spanning our universe, notably those often characterized by the intuitive term “complexity”—a state of intricacy, complication, variety, or involvement, as in the interconnected parts of a system. Particularly intriguing is the rise of complexity over the course of time, indeed dramatically so within the past half-billion years since the start of the Cambrian Era on Earth. Resembling a kind of Neoplatonism, perhaps some underlying principle, a unifying law, or an ongoing process creates, organizes, and maintains all structures in the universe, enabling us to study everything on uniform, common ground—“on the same mental page,” so to speak.

Recent research, guided by notions of mathematical elegance and bolstered by vast new observational databases, suggests affirmative answers to some of those queries: islands of ordered complexity—namely, open systems that are galaxies, stars, planets, and life-forms—are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All is in quantitative agreement with valued precepts of thermodynamics, especially nonequilibrium thermodynamics. Indeed, the underlying, ubiquitous phenomenon mentioned above may simply be energy itself. Energy flows engendered largely by the expanding cosmos do seem to be as universal a currency in the origin of structured systems as anything yet found in nature. Furthermore, 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 sum total of which constitutes cosmic evolution—much as presented in Figure 1.

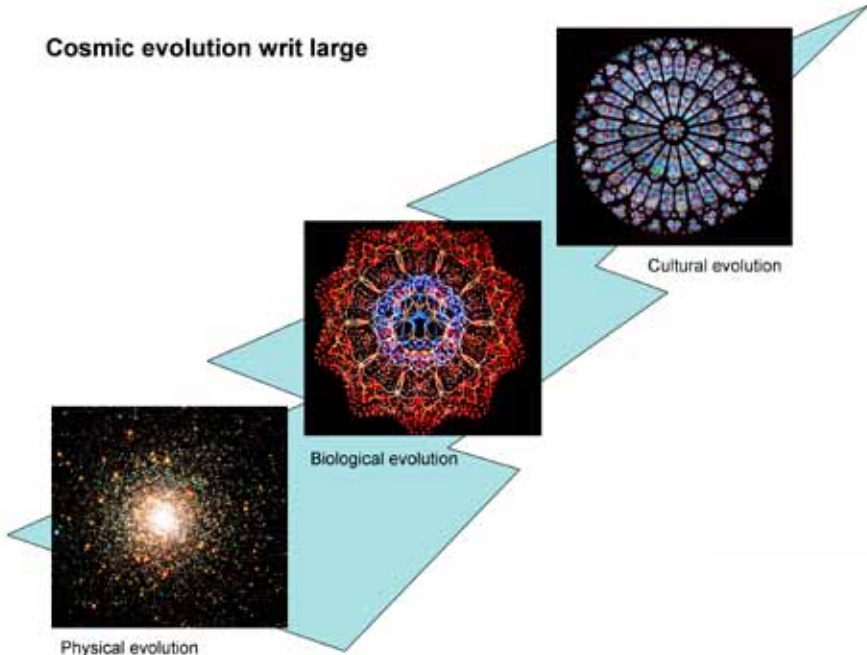


Figure 1. **Cosmic evolution writ large:** Changes in the physical, biological, and cultural domains are governed by underlying scientific principles that guide the emergence of increasingly complex structures in the universe. Resembling the beautiful stained-glass window in the south transept of the great Gothic cathedral in Paris (shown at top right), the pattern at center actually represents a pseudo-colored array of atoms viewed along the axis of a double-helical DNA molecule some two nanometers across. (Red denotes oxygen atoms; blue, nitrogen; green, carbon; yellow, phosphorus; hydrogen is not shown.) Likewise, images of colorful globular star clusters (as at bottom left, where thousands of aged red giants dominate youthful blue stars) exemplify change-filled events in the earlier universe; shown here is the M80 star cluster nearly 120 light-years across and about 28,000 light-years distant.

Taken together, stars, genes, and art represent manifest expressions of complexity rising over the course of cosmic time. Increasing energy densities typify the construction of physical and biological structures, such as fusing stars and functioning molecules; even more energy density is needed to fashion cultural entities, such as organized societies and today's global civilization. The flow of energy, as dictated by nonequilibrium thermodynamics in an expanding universe, does seem to provide a powerful means to explain the growth of order, form, and complexity on all scales, from quarks to quasars, from microbes to minds. (Images courtesy of Cathedrale Notre-Dame de Paris; University of California, San Francisco; STScI/NASA)

Heraclitus, with his unifying mantra of "all flows ( $\pi\alpha\nu\tau\alpha \rho\epsilon\iota$ )," would likely be proud of modern cosmic-evolutionary ideas, but he would also be surprised by our huge array of empirical findings supporting those ideas. Others have been down this path before, most originally perhaps the 19th century encyclopedist Robert Chambers (1844), who anonymously penned a pre-Darwinian tract of wide insight, and the mid-20th century astronomer

Harlow Shapley (1930), whose “cosmography” went well beyond biology by classifying all known structures according to dimensional size and scale. Among others, philosopher Herbert Spencer (1896) championed the notion of increasing complexity in biological and cultural evolution, the mathematician Alfred North Whitehead (1925) sought to undergird broad scientific thinking with his “organic philosophy,” and the biologist E. O. Wilson (1998) appealed to “consilience” for unification in the sciences.

### *Arrow of Time*

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Figure 2 (a) shows the archetypal illustration of cosmic evolution—the arrow of time. Regardless of its shape or orientation, such an arrow represents a symbolic guide to the sequence of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos to order. That sequence, as determined by a large body of post-Renaissance data, accords well with the idea that a thread of change links the evolution of primal energy into elementary particles, the evolution of those particles into atoms, in turn of those atoms into galaxies and stars, and of stars into heavy elements, the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, and of intelligent life into the cultured and technological society that we now share. Despite the compartmentalization of today’s academic science, evolution knows no disciplinary boundaries.

As such, the most familiar kind of evolution—biological evolution, or neo-Darwinism—is just one, albeit important, subset of a 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 of understanding by helping to free us from the notion 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 beyond.

Anthropocentrism is neither intended nor implied by the arrow of time—which is why some researchers prefer to draw it opening up in variety and diversity as in Figure 2 (a), instead of pointing anywhere in particular, other than toward the future generally. Anthropic principles notwithstanding, there is no logic to support the idea that the universe was conceived to produce specifically us. We humans are surely not the 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 depicting a mixture of chance and

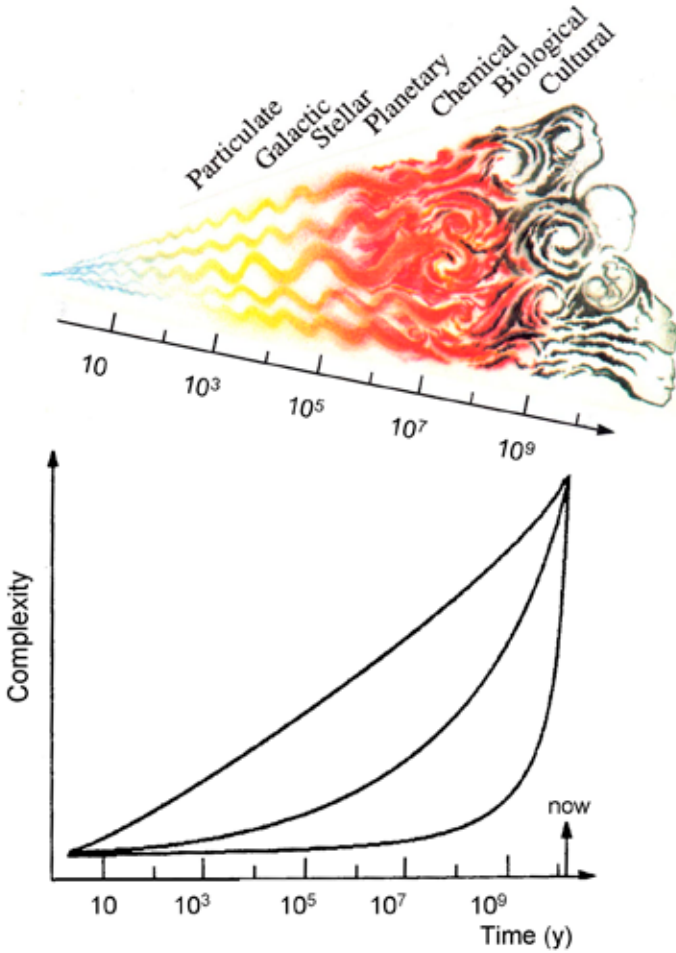


Figure 2. (a) **Arrow of Time:** This stylized arrow of time highlights salient features of cosmic history, from its fiery origins some 14 billion years ago (at left) to the here and now of the present (at right). Sketched diagonally across the top are the major evolutionary phases that have produced, in turn, increasing amounts of order and complexity among all material things: particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. 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, unfolding at a steady pace, much as other central tenets are presumed, such as the fixed character of physical law or the notion that  $2 + 2 = 4$  everywhere. (Drawing by Lola Judith Chaisson)

(b) **Rising complexity, intuitively judged:** Graphed here qualitatively is the rise of order, form, and complexity of localized material structures throughout the history of the universe. This family of curves represents more an innate feeling than a quantitative proof, in accord with the subjective impression that complex ordered structures have generally increased (with some exceptions) over the course of time. Whether this rise of complexity has been linear, exponential, or hyperbolic (as sketched here), current research aims to specify this curve and to characterize it empirically. (For an objective view, see Figure 5)

necessity that operate together while building increasingly complex structures from spiral galaxies to rocky planets to thinking beings.

Nor does time's arrow mean to imply that "lower," primitive life-forms biologically change directly into "higher," advanced organisms, any more than galaxies physically change into stars, or stars into planets. Rather, with time—much time—the environmental conditions suitable for spawning primitive life eventually changed into those favoring the emergence of more complex species; likewise, in the earlier universe, environments were ripe for galactic formation, but now those conditions are more conducive to stellar and planetary formation. Change in the surrounding environment often precedes change in ordered systems, and the resulting system changes have *generally* been toward greater amounts of diverse complexity.

Figure 2 (b) graphs the widespread impression that material assemblages have become more organized and complex, especially in relatively recent times. This family of curves refers to "islands" of complexity that are systems per se—whether swollen stars or buzzing bees—not to the vastly, indeed increasingly disorganized sea of chaos surrounding them. Modern science aims to explain this rise of complexity and to do so with known scientific principles that avoid mysticism, vitalism, creationism, and the like.

### *Nonequilibrium Thermodynamics*

Cosmic evolution, as understood today, is governed largely by the known laws of physics, particularly those of thermodynamics. Note the adverb "largely," for this is not an exercise in traditional reductionism. Of all the known principles of nature, thermodynamics perhaps most pertains to the concept of change—yet change as driven, again for emphasis, by a combination of randomness and determinism, of chance and necessity. Literally, thermodynamics means "movement of heat"; a more insightful translation (in keeping with the wider connotation in Greek antiquity of motion as change) would be "change of energy."

To be sure, the cosmic-evolutionary narrative is much too complicated to be explained merely by equilibrium thermodynamics—the kind most often used to describe closed systems isolated from their environments and having maximum entropy states. All structures, whether galaxies, stars, planets, or life-forms, are demonstrably open, nonequilibrium systems with flows of energy in and out being a central feature. And it is this energy, often called available, or "free," energy—literally the ability to do work—that helps to build structures.

At face value, the second law of thermodynamics—arguably the most cherished principle in all of physics—practically prohibits systems from changing

spontaneously toward more ordered states. Structures left alone naturally tend to break down and increase entropy. When unattended, for example, domestic households grow more disorderly: lawns become unkempt, stoves greasy, roofs leaky. Even human beings who fail to eat gradually become less ordered and die; and when we die we decay to ultimate disorder, thereby returning our elemental resources to Earth and the universe that gave us life. All things will eventually degenerate into chaotic, randomized, less ordered states.

By utilizing energy, however, 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. To extend our example, some human sweat and hard work—an energy flow—can put a disarrayed house back in order, yet this reordering comes at the expense of those cleaning the house; we get tired and increasingly disordered ourselves. In turn, humans can become reinvigorated (i.e., personally reenergized or reordered) by eating again—which is also an energy flow—but this renewed order arises, further in turn, at the expense of the agricultural environment that was ravaged to produce the food consumed.

In short, energy flow does play an important role in creating, ordering, and maintaining complex systems—all quantitatively in accord with the second law of thermodynamics. None of nature's ordered structures, not even life itself, is a violation (nor even a circumvention) of the second law. Considering both any system of order as well as its surrounding environment, we find good agreement with modern, nonequilibrium thermodynamics. In this way, both order and entropy can increase together—the former locally and the latter globally. (For quantitative details, see Chaisson 2001.)

Championed decades ago by the German-Canadian systematist Ludwig von Bertalanffy (1932) and later espoused by the German quantum mechanic Erwin Schroedinger (1944), the need for energy is now recognized as an essential feature, not only of biological systems such as plants and animals, but also of physical systems such as stars and galaxies; indeed acknowledged for social systems, too, such as a city's inward flow of food and resources amidst its outward flow of products and wastes. The analysis is much the same for any open system, provided we think in broad, interdisciplinary terms.

Figure 3 is a schematic diagram, adapted from the work of Belgian physical chemist Ilya Prigogine (1972) and American immunologist Jonas Salk (1982), illustrating the emergence of structure in the presence of energy flow. By crossing certain energy thresholds that depend on a system's status, bifurcations can occur, fostering the emergence of whole new hierarchies of novel structures that display surprising amounts of coherent behavior. Such

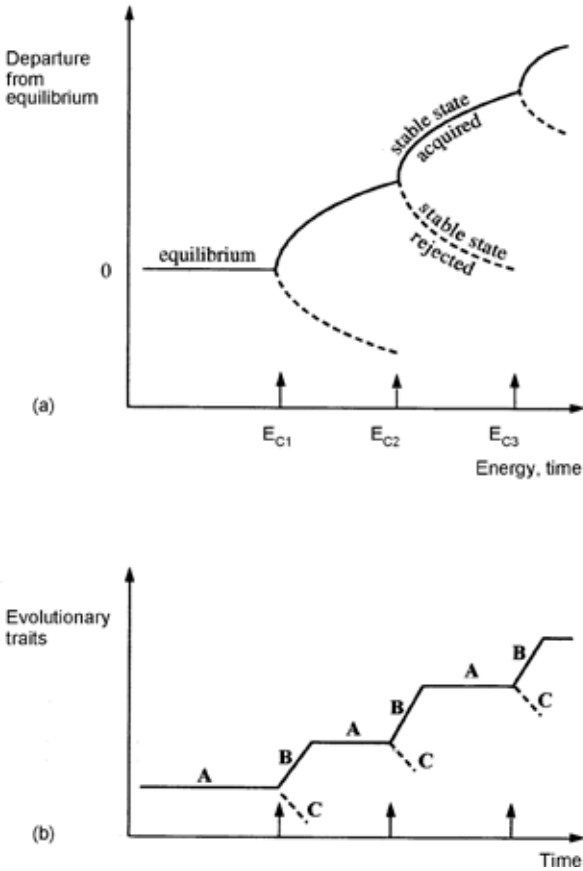


Figure 3. (a) **A physicist's visualization of rising complexity:** Sketched here is an arbitrary equilibrium coordinate for an open system as a function of both time and energy, either of which quantity serves to illustrate the extent of departure of that system from equilibrium. The time axis makes clear that this is a historical, evolutionary process, whereas the parallel energy axis denotes the 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, nonequilibrium, 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. Not all new systems survive (solid curve); some are rejected (dashed curve). The process, as always, is an interplay of randomness and determinism, therefore the end result is inherently unpredictable, as with all of evolution.

(b) **A biologist's visualization of rising complexity:** Events in evolutionary biology mimic those of the diagram in (a), although the results are richer in structural detail, system function, and energy flow. In phases marked A, the main task of a species is to survive and thus persist until such time that the environment changes (vertical arrows), after which further evolution occurs—along phase B toward renewed survival and perhaps speciation or along phase C toward extinction. Neither upward rising graph implies progress or inevitability, but they do suggest a *general trend* toward increased complexity with time—a trend undeniable among organized systems observed throughout nature.



dissipative structures can export some of their entropy (or dissipate some of their energy) into their external environments. Accordingly, order is often created and sustained by routine consumption of substances rich in energy, accompanied by a discharge of substances low in energy.

How does such structuring actually occur? How can ordering emerge from a condition where originally there was no such thing? We know well that fluctuations—random deviations from some average, equilibrium value of, for example, density, temperature, or pressure—are common phenomena in nature. Fluctuations inevitably yet stochastically appear in any system having many degrees of freedom. Normally, as in equilibrium thermodynamics, such instabilities regress in time and disappear; they just come and go by chance, the statistical fluctuations diffusing as quickly as they initially arose. 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 themselves out. Microscopic temperature fluctuations, for instance, are said to be thermally relaxed. 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 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 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 energy more rapidly than the ensuing, and damaging, heat can smooth out 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. The resulting phenomenon—termed “order through fluctuations”—is a distinctly evolutionary one, complete with feedback loops that help drive the system further from equilibrium. And as the energy consumption and resulting complexity accelerate, so does the evolutionary process. This is the realm of true *thermodynamics*, 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 ones as well. Naturally occurring phenomena such as convection cells in a pot of warm water, river eddies behind rocks in flowing streams, and atmospheric storms that grow

into hurricanes all display enhanced order when energies flow above some threshold. Yet biological systems also obey the rules of nonequilibrium thermodynamics, for we and our living relatives are demonstrable examples of dynamic steady states that have emerged via energetically enhanced neo-Darwinism. Even artificially made devices such as kitchen refrigerators and coherent lasers, among a whole host of similar examples of culturally produced systems, promote or maintain order when amply fed with sufficient energy.

### *Three Eras in Natural History*

The origin of nature's many varied structures depends on the flow of free energy. And this, like the arrow of time itself, is a direct consequence of the expansion of the universe. Independently pioneered by astrophysicists Thomas Gold (1962) and David Layzer (1976), among others, time marches on and free energies surge because the cosmos dynamically evolves. Indeed, it is cosmic expansion, and nothing more, that has caused the entire universe to depart from its initial state of thermodynamic equilibrium. The stark contrast between myriad hot stars and the vast, cold interstellar space surrounding them now guarantees a state of nonequilibrium.

The run of density and temperature in the standard, Big Bang model of the universe, shown in Figure 4 (a), encapsulates the essence of change on the largest observable scale (Chaisson 1998). Knowing only the density and temperature of something, we can derive a great deal about its physical properties. Here our interest centers on the big picture—the whole universe—so the curves of this figure pertain to nothing in particular, just everything in general. They show the main trends, minus the devilish details, of big-bang cosmology: the cooling and thinning of radiation and matter based largely on measures of the microwave background radiation and of the distant receding galaxies (Figure 4 [b]).

Radiation completely ruled the early universe. Life was nonexistent and matter only a submicroscopic precipitate suspended in a glowing fireball of blinding 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 managed to capture single electrons to make hydrogen atoms, the radiation was so fierce as to destroy them immediately. The first few hundreds of millennia after the beginning of time were uniform, symmetrical, informationless, and boring. We call it the Radiation Era.

Eventually, and inevitably so, the primacy of radiation gave way to matter. As the universe naturally cooled and thinned owing solely to its expansion,

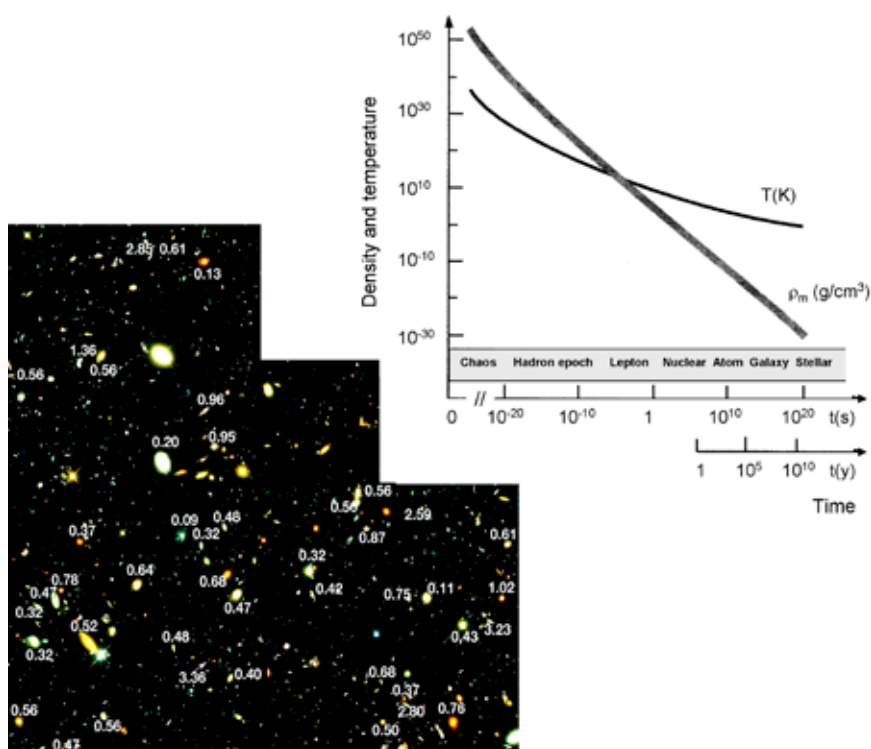


Figure 4. (a) **An evolving universe:** The change of the density ( $\rho$ ) of matter and the temperature ( $T$ ) of radiation, from near the origin of the universe to the present. The thick width of the density curve displays the range of uncertainty in total mass density, whose true value depends on the amount of “dark matter.” By contrast, the cold cosmic background temperature is very accurately measured today (2.7 K), and its thin curve equally accurately extrapolated back into the hot, early universe. The recent finding that universal expansion is accelerating should not much affect these curves.

(b) **Hubble deep field:** This fabulously rich collection of thousands of galaxies, with their measured red shifts (proportional to galaxy recessional velocity) superposed, bolsters the standard Big Bang model of the universe, as characterized by the curves of density and temperature above. However complex astronomical structures may seem, including huge galaxy clusters and peculiar filaments and voids on even larger scales than that shown here, all physical systems are simpler than any biological systems—grand spiral galaxies much less complex than the most primitive microbes. (Image courtesy STScI/NASA; redshift data courtesy Keck Observatory/CARA)

the charged particles became bound into neutral atoms, which are among the simplest of all structures. This represents a change of first magnitude, for it was as though an earlier, blinding fog had lifted—its uniformity punctured, its symmetry broken. The universe slowly became transparent, meaning that photons no longer scattered about aimlessly and destructively. The Radiation Era gradually transformed into the Matter Era, an event claimed by some

researchers to be the greatest change of all time; it occurred about a half-million years after the Big Bang.

With the onset of the Matter Era, matter literally began dominating radiation. Natural history became more interesting. The results, over billions of years and minus the details, were galaxies, stars, planets, and life, one by-product of which is intelligence—at least on one planet called Earth. And this, in turn, has anthropogenically changed nearly everything on our planet.

Some 14 billion years after the beginning of space and time, the Life Era has now begun, at least locally. Here, the emergence of technologically intelligent life, on Earth and perhaps elsewhere, heralds a whole new era—one where life, in its turn, has gradually come to dominate matter. This second of two great transformations was not triggered by the origin of life; rather, it is technologically advanced life (perhaps as early as the onset of agriculture yet at least by later industrialization) that differs dramatically from primitive life and from other types of inanimate matter scattered throughout the universe.

These are not anthropocentric statements. Technology, despite all its pitfalls, enables life to manipulate matter, even to control it, much as matter evolved to overwhelm radiation billions of years ago. Accordingly, matter is now beginning to lose its dominance, at least at those isolated locales of hi-tech civilization, such as on planet Earth. To use a popular cliché, life is now taking matter into its own hands, for nonsentient nature could not have built books, machines, museums, and the like. Humankind constructs such artificial things; they are products of cultural evolution. Our narrative has transitioned across all known time from plain and simple protogalaxies to stratified societies of extraordinary order. We have reached the here and now.

Key questions flood the mind: what caused the plethora of changes throughout the ages and how has complexity actually increased with time? Have humans truly become the agents of change on Earth, able to tinker with both matter and energy, including genes and environments, more than these ingredients now affect us? How did the neural network within human brains acquire the sophistication needed to fashion nations, weapons, cathedrals, philosophies, and scenarios of cosmic evolution? In short, what caused us to become conscious enough to contemplate our complex selves?

### *Empirically 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 became established owing naturally 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 structure—indeed, of complexity.

But how shall we characterize complexity, a slippery term for many researchers? In biology alone, much as their inability to reach consensus on a definition of life, biologists cannot agree on a complexity metric. Evolutionist John Maynard Smith (1995) uses nonjunk genome size, biologist John Tyler Bonner (1988) employs being morphology and behavioral flexibility, theorist Stuart Kauffman (1993) charts the number of cell types in organisms, and bioengineer Thomas McMahon (1983) appeals to cellular specialization. All these attributes of life have qualitative worth, yet all are hard to quantify in practical terms. We must push the envelope beyond mere words, beyond biology.

Putting aside as unhelpful the traditional quantitative ideas of information content (of the Shannon-Weiner type, which is admittedly useful in some contexts, but controversial in others) and of negative entropy (or “negentropy,” which Schroedinger first adopted but then quickly abandoned), we return to the quantity with greatest appeal to physical intuition—energy. More than any other term, energy seemingly has a central role to play in any attempt to unify physical, biological, and cultural evolution. Energy is an underlying, universal driver like no other in all of modern science.

Not that energy has been overlooked in many previous discussions of systems’ origin and assembly. Biometrician Alfred Lotka (1922), physicists Philip Morrison (1964) and Freeman Dyson (1979), biologist Harold Morowitz (1968), ecologist Harold Odum (1988), and geographer Vaclav Smil (1999), just to name a few, 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 biological system is surely more complex than any inanimate entity. Thus, absolute energies are not as telling as relative values, which depend on a system’s size, composition, and efficiency. Nor are maximum energy principles or minimum entropy states likely to be operative, as nature is neither black nor white, but more like shades of grey throughout. Rather, organization is seemingly 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 structured systems on that same level page—a kind of energy density is

useful, much as it was competing energy densities of radiation and matter that dictated events in the earlier universe. Moreover, it is the *rate* at which free energy transits complex systems of given mass that seems most constructive. Hence, “energy rate density” becomes an operational term whose meaning and measurement are clear and easily 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.

The modeled flow of energy through a wide variety of open systems, be they animate or inanimate, does closely resemble the intuitive rise in complexity implied by Figure 2 (b). Complexity has indeed increased over the course of history, and at a rate that is at least exponential in recent times. Figure 5 plots a sampling of findings, where energy rate densities, in units of erg/second/gram, are graphed as horizontal histograms proportional to various systems’ historical longevities. As expected, yet here only briefly stated: red giant stars are more complex than main-sequence stars, eukaryotes more complex than prokaryotes, animals more complex than plants, industrial society more complex than hunter-gatherers, and so on up the system hierarchy. To be sure, energy flow diagnostics have also been used recently by some unfettered historians, including David Christian (2004) and Fred Spier (2005), to bolster their pioneering studies of “big history,” which parallels the subject of cosmic evolution.

This is not to say, by any means, that galaxies per se evolved into stars, or stars into planets, or planets into life. Rather, this analysis suggests that galaxies gave rise to environments suited to 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 Figure 5 serve to reinforce 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 Figure 2’s arrow of time, yet both such systems continue presently developing and evolving, as do plants and animals that emerged much later. In fact, as depicted by those histograms, and unlike customary geological periods that do have set time intervals, currently all evolutionary phases noted in Figures 2 and 5 are engaged simultaneously and indefinitely.

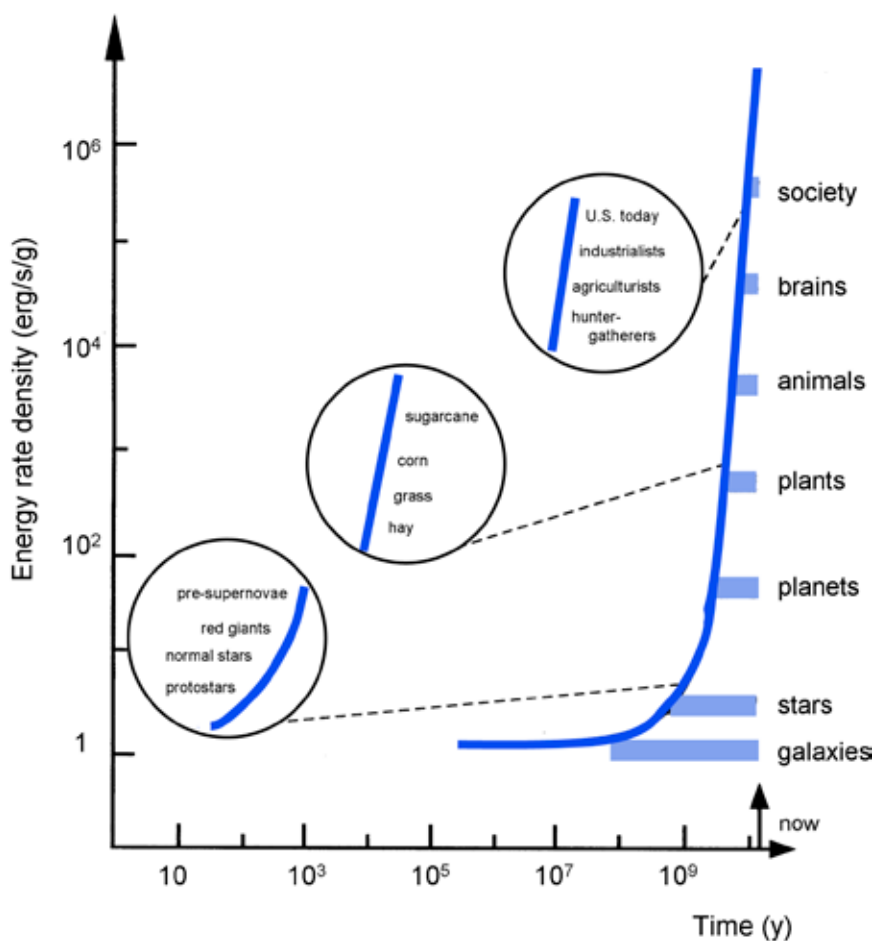


Figure 5. **Rising complexity, empirically based:** The increase in energy rate density, plotted as histograms starting at those times when various open structures dominantly emerged in nature, has been especially rapid in the last billion years, much as expected from human intuition and Figure 2 (b). The solid blue curve approximates the increase in normalized energy flow that best characterizes order, form, and structure throughout the history of the universe. The three insets (circled) show greater detail of further calculations of energy rate densities passing through stars, plants, and societies, which are classic examples of physical, biological, and cultural evolution, respectively, all of which are now operative in our increasingly complexified universe. (Adapted from Chaisson 1998, 2001, 2003)

### Evolution, Broadly Considered

The word *evolution* need not be the sole province of biology, its utility of value only to life scientists. Charles Darwin never used it as a noun, in fact only once as a verb in the very last sentence of his 1859 classic, *On the Origin of Species*. Nor need the principle of natural selection be the only mechanism of evolutionary change, past and present. Darwin surely embraced it as we do

today to describe much of biological change, but there 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 there is no known agent in nature that 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 “nonrandom elimination,” a phrase long championed by one of the 20th century’s leading evolutionists, Ernst Mayr (1997). What we really seek to characterize is the aggregate of adverse circumstances responsible for the deletion of some members of a group. Accordingly, selection can be generally taken to mean preferential interaction of any object with its environment—a more liberal interpretation that also helps widen our view 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 command energy; and this energy is the “force,” if there is any at all, in evolution. Briefly and broadly, 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 selection that together, working in tandem, underlie the self-assembly noted in Figure 3—the former driving an initial system beyond equilibrium, the latter aiding the emergence of higher order in that system. Even more strongly stated, it may well be that energy flow rate itself is the trait most often selected by successful systems of the same kind. A handful of cases will suffice, among many others so documented (Chaisson 2001, 2003, 2004), to illustrate the action of this energy-selection duo among a spectrum of increasingly ordered 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 aging—a developmental process—allowing stars to be tracked as their interiors undergo cycles of nuclear fusion causing them to change in size, color, brightness, and elemental composition, all the while passing from “birth” to maturity and thence to “death”; red giant stars, for instance, are clearly more complex than normal, main-sequence stars such as our current Sun, which is in turn more complex than protostars perched on the verge of stardom, as noted in Figure 5. At least as regards energy flow, material resources, and structural integrity while experiencing change, stars have much in common with life. None of which claims that stars are alive, a common misinterpretation of such an eclectic stance. Stars



do not evolve in the strict and limited biological sense; yet close parallels are apparent, including populations, variation, modification, selection, adaptation, and perhaps even a kind of reproduction among the stars—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 groups of stars to emerge in turn, with each generation's offspring showing slight variations, especially among the heavy elements contained within. Waves of "sequential star formation" propagate through many such clouds like slow-motion chain reactions over eons of time—shock waves from the death of old stars triggering the birth of new ones—neither one kind of star displaying a dramatic increase in number nor the process of regeneration ever being perfect. Those massive stars modified by gravity and selected by nature to endure the fires 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. On and on, the cycle churns; build up, break down, change—a stellar "evolution" minus any genes, inheritance, or overt function, for these are the value-added qualities of biological evolution that go well beyond the evolution of physical systems.

Next, consider plants as an example of biological evolution. Here, we trace the rise in complexity with evolution among plant life, much as we could for myriad and wondrous life-forms both more and less advanced. And here natural selection—that is genuine neo-Darwinism—is clearly at work, making use of energy rate densities well in excess of those of galaxies, stars, and planets. As shown in Figure 5, energy-flow diagnostics display a clear increase in complexity among various plants that best locally and temporarily the normal entropy process: photosynthesis operates more efficiently in flowering angiosperms than in gymnosperms or algae and, in turn, more efficiently still for more organized, cultivated (C4) crops such as corn and sugarcane. Similar trends are apparent for animals, yet with even higher and rising energy rate densities along a broad evolutionary sequence spanning protocells, prokaryotes, ectotherms, and endotherms. To be sure, system functionality and genetic inheritance are two factors, above and beyond mere system structure, tending to enhance order among animate systems that are clearly living compared to inanimate systems that are

clearly not. Unsurprisingly, then, life-forms require the acquisition of more energy per unit mass for their well-being.

Onward across the bush of life (or the arrow of time)—cells, tissues, organs, organisms—we find much the same story unfolding. Starting with life’s precursor molecules (the realm of chemical evolution) and all the way up to human brains exemplifying the most complex clump of animate matter known, we encounter the same *general* trend found earlier for stars: the greater the perceived complexity of the system, the greater the flow of energy density through that system—either to build it, or to maintain it, or both.

Finally, consider society as an example of cultural evolution. Here, the cosmic-evolutionary narrative continues, yet with greater normalized energy flows to account for the rise of our obviously complex civilization. As plotted in Figure 5, once more we can trace social progress, again in energy consumption, for a variety of human-related advances among our hominid ancestors. Quantitatively, hunter-gatherers of a million years ago utilized considerably less energy rate density than did agriculturists of several thousand years ago; and these, in turn, much less than pioneering industrialists and now contemporary western society. The path to today’s civilization is undoubtedly paved with increased energy use.

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 with its emphasis on accumulation of acquired traits. Either way, energy remains the driver and with rapidly ramping 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—from the Wright engine of the early 1900s to the F-117 Nighthawk of the 1990s. Automobiles, from the pioneering Model Ts to today’s gadget-rich SUVs, can be likewise analyzed, as can the vaunted silicon chips that so clearly now accelerate our 21st century economy.

Humankind is now moving toward a time, possibly as soon as within a few generations, when we will no longer be able to expect nature to adjust rapidly enough to ensure our own survival. Rather, civilization on Earth will either have to adapt to the natural environment with ever-accelerating speed, or generate artificial environmental conditions needed for our ecological existence. From two magnificent yet local systems—society and machines—will likely emerge a symbiotically functioning technoculture, the epitome (as far as we know) of complexity writ large in nature—a new technology-based

system that will likely require yet greater values of energy rate density, as the curve in Figure 5 continues racing upward. This is truly the onset of the Life Era, wherein sentient, manipulative cyborgs potentially become the agents of change—or it will be a passing event in spacetime whereby human life on Earth and its great cultural experiment end.

## ***Conclusion***

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This article has taken the liberty of using the word “evolution” in an intentionally provocative way, to capture ontological, ecological, and phylogenetic change on all spatial and temporal scales by means surely including, but not restricted to, natural selection. Within the grand scenario of cosmic evolution, general trends have been identified among nature’s myriad changes affecting galaxies, stars, planets and life-forms throughout an extremely long duration of natural history, from the Big Bang to humankind. The result is a unifying worldview of considerable scope and insight, a scientific posture that not only embeds all cultures on Earth in a cosmic setting yet also itself creates a transcendent culture that people of all persuasions can know, welcome, and embrace. We have been especially alert to any universal process—developmental or generational, gradual or punctual—that might have allowed for, indeed driven, evolution from time immemorial. More than any other single factor, energy flow would seem to be the principal means whereby all of nature’s diverse systems have naturally spawned complexity in an expanding universe, in fact some of them evolving impressive degrees of order characteristic of life, mind, and civilization. Energy, specifically humanity’s use of it optimally and wisely, will also likely guide our fate along the future arrow of time. For we, too, partake in the cosmic-evolutionary narrative, an epic-class story of rich natural history for the new millennium.

## ***References***

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Bonner, J. T., 1988, *The Evolution of Complexity*. Princeton: Princeton University Press.

Chaisson, E. J., 1998, “The cosmic environment for growth of complexity,” *BioSystems* 46:13.

———, 2001, *Cosmic Evolution: The Rise of Complexity in Nature*. Cambridge: Harvard University Press. (For a popular rendition of this work, consult *Epic of Evolution*. New York: Columbia University Press, 2006.)

- , 2003, "A unifying concept for astrobiology," *Int. Journal Astrobiology* 2:91.
- , 2004, "Complexity: An energetics agenda," *Complexity: Journal of Santa Fe Institute* 9:14.
- Chambers, R., 1844, *Vestiges of the Natural History of Creation*. London: Churchill.
- Christian, D., 2004, *Maps of Time*. Berkeley: University of California Press.
- Darwin, C., 1859, *On the Origin of Species*. London: J. Murray.
- Dyson, F., 1979, "Time without end: physics and biology in an open universe," *Reviews of Modern Physics* 51:447.
- Gold, T., 1962, "The arrow of time," *American Journal of Physics* 30:403.
- Kauffman, S., 1993, *The Origins of Order*. Oxford: Oxford University Press.
- Layzer, D., 1976, "The arrow of time," *Astrophysical Journal* 206:559.
- Lotka, A., 1922, "Contribution to the energetics of evolution," *Proceedings of National Academy of Sciences* 8:147.
- Maynard Smith, J., 1995, "Non-junk DNA," *Nature* 374:227.
- Mayr, E., 1997, *This is Biology*. Cambridge: Harvard University Press.
- McMahon, T. and Bonner, J. T., 1983, *On Size and Life*. San Francisco: W. H. Freeman.
- Morowitz, H. J., 1968, *Energy Flow in Biology*. New York: Academic Press.
- Morrison, P., 1964, "A thermodynamic characterization of self-reproduction," *Reviews of Modern Physics* 36:517.
- Odum, H., 1988, "Self-organization, transformity, and information," *Science* 242:1132.

Prigogine, I., Nicolis, G., and Babloyantz, A., 1972, "Thermodynamics of evolution," *Physics Today* 11:23 and 12:38.

Salk, J., 1982, "An evolutionary approach to world problems," Paris: UNESCO.

Schroedinger, E., 1944, *What is Life?* Cambridge: Cambridge University Press.

Shapley, H., 1930, *Flights from Chaos*. New York: McGraw Hill.

Smil, V., 1999, *Energies*. Cambridge: MIT Press.

Spencer, H., 1896, *A System of Synthetic Philosophy*. London: Williams and Norgate.

Spier, F., 2005, "How big history works," *Social Evolution & History* 4:25.

von Bertalanffy, L., 1932, *Theoretische Biologie*. Berlin: Borntraeger.

Whitehead, A. N., 1925, *Science and the Modern World*. New York: Macmillan.

Wilson, E. O., 1998, *Consilience: The Unity of Knowledge*. New York: Knopf.

### Links

Links to Internet resources for "cosmic evolution" are available at: [http://www.tufts.edu/as/wright\\_center/cosmic\\_evolution](http://www.tufts.edu/as/wright_center/cosmic_evolution)