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COSMIC EVOLUTION: SYNTHESIZING EVOLUTION, ENERGY, AND ETHICS

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Nothing seems to be more important philosophically than the revelation that the evolutionary drive, which has in recent years swept over the whole field of biology, also includes in its sweep the evolution of galaxies, and stars, and comets, and atoms, and indeed all things material.

Harlow Shapley

Introduction

We are currently entering an age of synthesis such as occurs only once every few generations. The years ahead will surely be exciting and productive times in the world of science, largely because the scenario of cosmic evolution grants us an opportunity to systematically and *synergistically* inquire into the nature of our existence – to mount an interdisciplinary effort to build a modern universe history (*Weltallgeschichte)* that people of all cultures can adopt—an «origins» narrative that traces generative and developmental change ranging from quark to quasar, from microbe to mind. As we enter the new millennium, such a coherent story of our origins can act as an effective intellectual vehicle to invite all our citizens to become participants, not just spectators, in the building of a whole new legacy. We are perhaps already on the road toward becoming wise, ethical human beings – to experience ethical evolution.

Evolution

From galaxies to snowflakes, from stars and planets to life itself, modern science is weaving an intricate pattern describing all of natural history – a sweepingly inclusive view of the order and structure of every known class of object in our richly endowed Universe. Cosmic evolution – the heart of this broad scenario – is the study of the sum total of the many varied developmental and generative changes in the assembly and composition of radiation, matter, and life throughout 14 billion years of cosmic time. These are the physical, biological, and cultural changes that have produced, in turn and among other systems, our Galaxy, our Sun, our Earth, and ourselves. The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties – physics, astronomy, geology, chemistry, biology, and anthropology, among others – a genuine narrative of epic proportions extending from the beginning of time to the present.

Figure 1 summarizes the major subject disciplines that combine to form the grand synthesis of cosmic evolution along the «arrow of time»—from big bang to humankind.

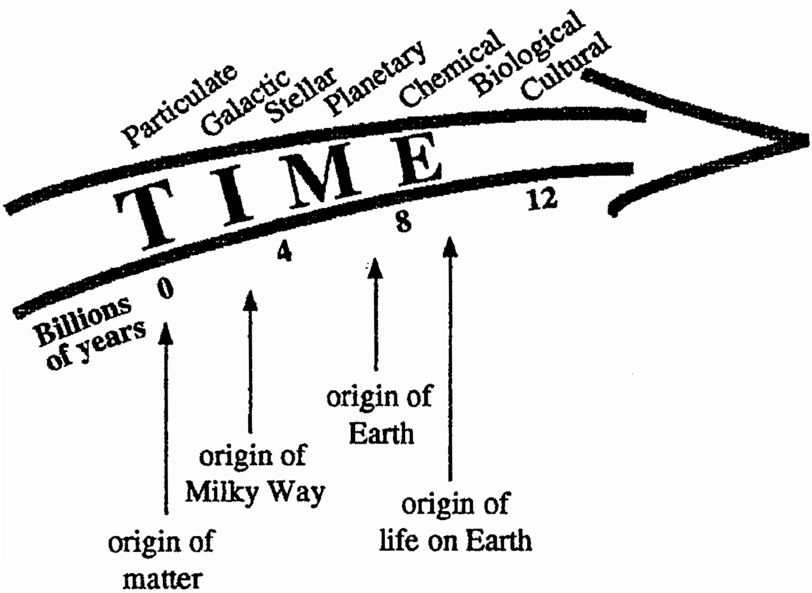

Figure 1. (a) This symbolic «arrow of time» highlights the major features of cosmic history, from its fiery origins some 14 billion years ago (at left) to the here and now of the present (at right). Labeled diagonally across the top are the major evolutionary phases that have produced, in turn, increasing amounts of order and complexity among all material systems: particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. Cosmic evolution encompasses all of these phases.

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

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

In two brief paragraphs, here is the essence of today's big-bang scenario: Radiation completely ruled the early Universe some 14 billion years ago. Life was then non-existent and matter itself was only a submicroscopic precipitate suspended in a glowing, expanding fireball of intense light, x-rays, and gamma rays. Structure of any sort had yet to emerge; the energy density of radiation was too great. If single protons captured single electrons to make hydrogen atoms, radiation was then so fierce as to destroy those atoms immediately. Prevailing conditions during the first few tens of millennia after the origin of time were uniform, symmetrical, equilibrated, and boring. We call it the Radiation Era.

Eventually and inevitably, owing solely to cosmic expansion, the primacy of radiation gave way to matter. As the Universe naturally cooled and thinned, charged particles assembled into neutral atoms, among the simplest of all structures; the energy density of matter began to dominate. This represents a change of first magnitude – perhaps the greatest change of all time – for it was as though an earlier, blinding fog had lifted; cosmic uniformity was punctured, its symmetry broken, its equilibrium destroyed. The Universe thereafter became transparent, as photons no longer scattered aimlessly and destructively. The bright Radiation Era gradually transformed into the darker Matter Era; it occurred about a half-million years after the big bang.

Energy

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

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

Even so, the key quantity of unification cannot simply be energy, since the most primitive weed in the backyard is surely more complex than the most intricate nebula in the Milky Way. Yet stars have much more energy than any life form, and the larger galaxies still more. Our complexity metric cannot merely be energy, or even just energy flow. That energy flow must be normalized to open systems' bulk makeup, enabling all such systems to be analyzed «on that same page». The result is a clear and impressive trend – one of increasing energy per unit time per unit mass for a wide range of ordered systems throughout all of cosmic history.

Such an «energy rate density», Φ_m, is a useful way to characterize, indeed to quantify, the complexity of a system – any system, physical, biological, or cultural. This should not surprise us, since it was competing energy rate densities of radiation and matter that dictated events in the early Universe, as noted in the previous section.

Consider stars and their progressive changes – examples of physical evolution. Stars do grow in complexity as their thermal and elemental gradients increase with time; more data are needed to describe stars as they age. Normalized energy flows increase from small protostars at «birth» ($\Phi_m \sim 0.5$ erg/s/g), to main-sequence stars at «maturity» (~2), to huge red giants near «death» (~100). These values are essentially light-to-mass ratios, converting gravitational potential energy into luminosity rates and then normalizing by the mass of the system; the present-day Sun, for example, has 4×10^{33} erg/s and 2×10^{33} g, whereas a typical red-giant star (with increased internally ordered thermal and elemental gradients) has an order-of-magnitude higher luminosity for the same mass, hence a larger value of Φ_m. On and on, nuclear cycles churn; build up, break down, change— a kind of 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.

Consider plants and animals, all of them examples of biological, neo-Darwinian evolution. With few exceptions, rising complexity is evident throughout the biological world, again if modeled by energy-flow diagnostics. Life forms process more energy per unit mass ($\Phi_m \sim 10^{3-5}$ erg/s/g) than does any star, and increasingly so with biological evolution. These values are specific metabolic rates, again normalizing incoming energy to system mass: plants, for example, need 17KJ for each gram of photosynthesizing biomass and they get it from the Sun (only 0.1% of whose radiant energy reaches our planet's surface), thus for a biosphere of 10^{18} g, $\Phi_m \sim 10^3$ erg/s/g; more ordered 70-kg humans take in typically 2800 kcal/day and thus have a considerably higher value of $\Phi_m \sim 10^4$ erg/s/g; in turn, for human brains with ~20 W/day for proper functioning and a ~1300 g cranium, Φ_m is yet higher, ~10^5 erg/s/g (see Chaisson 2001 for many more such calculations). Onward across the bush of life – cells, tissues, organs, organisms – we find much the same story. Starting with life's precursor molecules and proceeding all the way up to plants, animals, and brains, the same *general* trend typifies life forms as for inanimate galaxies, stars and planets: The greater the complexity of a system, the greater the flow of energy density through that system – either to build it or to maintain it, and often both.

Consider society and its cultural evolution. Once again, we can trace social progress in terms of normalized energy consumption for a variety of human-related advances among our hominid ancestors. Quantitatively, that same energy rate density increases from hunter-gatherers of a million years ago ($\Phi_m \sim 10^4$ erg/s/g), to agriculturists of several thousand years ago (~10^5), to industrialists of contemporary times (~10^6). Again, a whole host of energy per unit mass values can be used to track ancestral

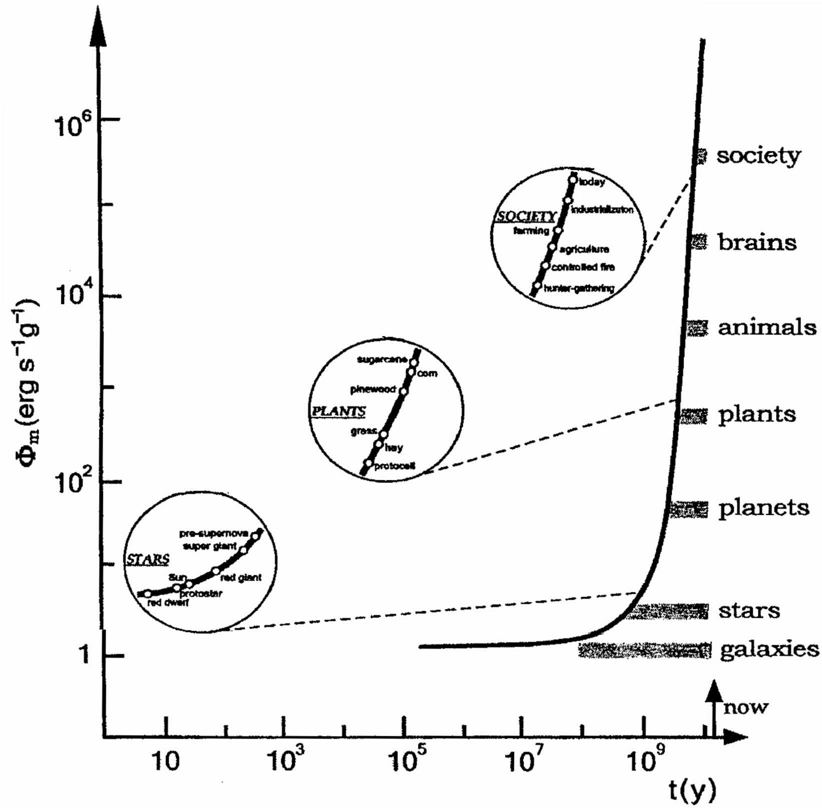

Figure 2. The rise of free energy rate density, Φ_m, plotted as histograms starting at those times when various open structures emerged in Nature. Circled insets show greater detail of further measurements or calculations (Chaisson 2001) of Φ_m for three representative systems—stars, plants, and society—typifying physical, biological, and cultural evolution, respectively.

evolution, a highly averaged value of which today derives from ~6 billion inhabitants needing ~18 TW of energy to keep our technological culture fueled and operating, thus Φ_m nearing 10^6 erg/s/g, and sometimes exceeding that for specialized energy needs (again, see [Chaisson 2001], for a whole host of examples). And here, along the path to civilization, as well as among the bricks, machines, and chips we've built, energy is a principal driver. Energy rate density continues rising with the increasing complexity of today's gadget-rich society.

Figure 2 plots the above values of Φ_m, among many others that are modeled in my Harvard University Press book [Chaisson 2001].

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

Not least, the concept of normalized energy flow aids in unifying the sciences – namely, to diagnose aspects of physical, biological and cultural systems in a uniform manner, rather than fragmenting them further. More than any other single factor in science, energy flow would seem to be a principal means whereby all of Nature's ordered, diverse systems have naturally spawned rising complexity in an expanding Universe.

Ethics

Of all the known clumps of matter in the Universe, life forms are surely the most fascinating, especially those enjoying membership in advanced technological civilizations. And that's not an anthropocentric statement; the arrow of time is not pointing at us. Technically competent life differs notably from lower forms of life and from other types of matter strewn throughout the Universe, not only because we can manipulate matter and radiation but also because we can tinker with evolution itself.

Given enough time, even evolution evolves.

Be assured, stellar evolution continues unabated in the cores of stars everywhere. Chemical evolution occurs in such remote sites as galactic clouds and exotic moons. Biological evolution persists for most species on Earth and possibly on distant planets as well. And cultural evolution endures in many corners of our world and conceivably on alien worlds beyond. But for technologically intelligent life, evolution per se is undergoing profound change.

Whereas previously the gene (strands of DNA) and the environment (whether physical, biological, or cultural) guided evolution, we humans on planet Earth are suddenly gaining control of both these agents of change. We are now tampering with matter, diminishing our planet's resources while constructing the trappings of utility and comfort. And we are now beginning to manipulate life itself, potentially altering the genetic makeup of human beings. The physicist unleashes the forces of Nature, the biologist experiments with maps of genomes; the psychologist influences behavior with drugs. We are, in fact, forcing a change in the way things change.

The emergence of sentient, technological beings, on Earth and perhaps elsewhere, heralds a whole new era – the Life Era. Why? Because technology enables life to begin to control matter, rivaling that previous transformation when matter began uncoupling from, and then dominating, radiation more than ten billion years ago. In turn, matter is now losing its dominance, if only at those isolated places where technologically intelligent life resides. To be sure, given the industrial devices and plentiful goods of our modern lives, human beings have literally taken matter into our own hands, granting ourselves the option of a grand and glorious future, or perhaps one marked by self-destruction, devolution, and death.

For clarity, the onset of the Life Era coincides not with the origin of life itself, nor even with the emergence of humanity or consciousness. Rather, it occurs when technological life forms begin manipulating matter more than matter influences life, much as matter eventually came to dominate radiation earlier in the Universe. For humans, this novel event is here and now.

The transition from the Matter Era to the Life Era will not be instantaneous. This change is a demonstrably evolutionary, not revolutionary, process. Just as much time was needed for matter to conquer radiation in the early Universe, long durations will likely be needed for life to best matter. Life might not, in fact, ever fully dominate matter, either because civilizations fail to gain control of material resources on truly galactic scales or because the longevity of technological civilizations everywhere is inherently short.

Though a mature Life Era may never come to pass, one thing seems certain: Our generation on planet Earth, along with any other neophyte technological life populating the Universe, stand on the verge of slowly becoming a meaningful factor in the future evolution of the Universe. This is a transition of astronomical significance – a fundamental change from matter-dominance to life-dominance – indeed the dawn of the second great transformation in all of history. A quintessential event in the evolution of the Universe, it's the threshold beyond which life forms can begin to fathom at least their position, and perhaps their role, in the cosmos. Accordingly, we have an obligation, a moral responsibility to survive, especially if we are alone in the Universe. The great experiment that intelligent life represents must not end in failure.

Humans are undeniably the highest form of intelligence on planet Earth. That is not to say that we shall inherit the Earth; the microorganisms, however meek and submissive, may well outlast us, indeed overwhelm us. Yet, currently, we are the only species able both to communicate culturally and to construct technologically. We are the only ones capable of knowing our past and worrying about our future. Even so, intelligence is one trait, wisdom quite another. Just how wise are we, and how shall we use that intelligence to ensure the survival of life in general and humanity in particular?

As often the case in evolution, the issue is timing. Can our civilization get its act together quickly enough to ensure its own survival? In the language of the evolutionist, Shall we be selected by Nature to endure? Not inconceivably, a grander selection process may well be at work in the cosmos – a principle of cosmic selection, akin to Darwin's natural selection, that operates on larger scales, beyond biology and on into the cultural, indeed astronomical, realms, to wit: Those technological civilizations anywhere in the Universe that develop in time a planetary society, or global ethics, will survive, and those that do not, will not.

Or, is it in the natural scheme of things that sentient, organic beings are merely way stations on the path to systems of greater complexity? A symbiotic merger of silicon-based systems – machines – with carbon-based systems – humans – has often been cited as the next dramatic expression of increased complexity in the Universe. Perhaps such cyborgs will be among our descendants, or perhaps something else entirely inhuman is our destiny. Does humankind as we know it, in whole or in part, have a future?

Or – it must be considered – do complex, technical systems like ourselves naturally self-destruct? At roughly the same time as any technological society emerges, its citizens and its nation-states gain the ability both to discover Nature as well as to destroy themselves, ironically with many of the same tools. Simultaneous with the invention of science and technology used to explore our origins, today's civilization is confronted with the means of mass destruction, indeed mass extinction. Many of the problems now threatening our species' longevity – from the foremost issues of overpopulation and nuclear warfare to genetic degeneration and environmental pollution, among a host of other ills – are unlike any encountered by our ancestors. For ours are now *global* problems, the likes of which will confront us forevermore. Although we can envision the Life Era as a period when intelligence could conceivably dominate, it's unclear if we humans have the wisdom to achieve and sustain that lofty plateau in the cosmic hierarchy, given the quickening onslaught of *le monde problematique*. Regrettably, perhaps no one, anywhere in the Universe, makes it into the Life Era.

Ethics, it would seem, now takes center stage in the cosmic-evolutionary story, at least for humankind on planet Earth. Ethics itself – broadly defined as conduct collectively recognized regarding all classes of human actions comprising our global culture – may well be the beacon that charts our way into the Life Era. To be sure, ethical evolution will likely become the next great epoch along the arrow of time, potentially enabling our descendants to take another evolutionary leap forward toward a higher-ordered state of complexity. At the least, an awareness of cosmic evolution aims us, indeed like an arrow, toward a period of moral consciousness as a firm prerequisite for our future well-being.

The idea of ethics, and especially its relevance as an instrument of behavior, has been around since the beginning of recorded history. Philosophers of old probably invented the idea and theologians have warmly embraced it (or maybe it's the other way around), but who among them today speaks for planet Earth? Nor is it likely that the needed ethics will arise from science alone, what with our heavy reliance on technology and our dogmatic determination to probe deeper and farther, beyond the world without end. The notion of a worldly ethic, broadly conceived, is easy to grasp in principle, including a mandate for society to embrace global morality and planetary citizenship as a means to survival. But, in practice, it would seem that only an amalgam of these three powerful institutions will together engender, or if necessary demand, the required ethics – a kind of evolutionary advance possible only when we harmonize the agendas of science, philosophy, and religion, indeed one that broadens still more our cosmic-evolutionary scenario.

Now is the time for scientists to become more eclectic and less specialized – to explore holistic worldviews systemically and synergistically, and not merely to undertake the reductionistic science that has been so heavily supported by funding agencies for decades and just as myopically honored by our universities. The scientific community needs to welcome synthesis as well as specialization, teaching as well as research, dissemination as well as discovery. This is by no means a call to abandon the focused research and development that have been the hallmark of a productive economy for decades, but a recognition that it is now appropriate to widen the span of intellectual effort in science and beyond, indeed to engage the larger philosophical and religious communities in an ambitious attempt to understand truly who we are, whence we came, and where we are headed as wise, ethical human beings.

Summary

Evolution, energy, ethics. Those are the core elements that will guide us along the challenging path toward the Life Era. The first – *evolution* – because a good understanding of our universal roots and of our place in the cosmic scheme of things will help us create a feasible future course. The second – *energy* – because our fate will depend strongly on the ways that humankind learns to use energy efficiently and safely. And the third – *ethics* – because global citizenship and a planetary society are crucial factors in the survival of our species.

To employ cosmic evolution as an intellectual as well as practical roadmap to the Life Era is to think in dynamic rather than static terms, to forge a link between natural science and human history, to realize the evolutionary roots of human values, to renew a sense of hope.

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