Chapter 20
A Singular Universe of Many Singularities: Cultural Evolution in a Cosmic Context

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published in:
Singularity Hypotheses: A Scientific and Philosophical Assessment
Eden, Moor, Soraker and Steinhart, eds.,
Frontiers Collection, Springer Berlin, 2012

Abstract Nature's myriad complex systems—whether physical, biological or cultural—are mere islands of organization within increasingly disordered seas of surrounding chaos. Energy is a principal driver of the rising complexity of all such systems within the expanding, ever-changing Universe; indeed energy is as central to life, society, and machines as it is to stars and galaxies. Energy flow concentration—in contrast to information content and negentropy production—is a useful quantitative metric to gauge relative degree of complexity among widely diverse systems in the one and only Universe known. In particular, energy rate densities for human brains, society collectively, and our technical devices have now become numerically comparable as the most complex systems on Earth. Accelerating change is supported by a wealth of data, yet the approaching technological singularity of 21st century cultural evolution is neither more nor less significant than many other earlier singularities as physical and biological evolution proceeded along an undirectional and unpredictable path of more inclusive cosmic evolution, from big bang to humankind. Evolution, broadly construed, has become a powerful unifying concept in all of science, providing a comprehensive worldview for the new millennium—yet there is no reason to claim that the next evolutionary leap forward beyond sentient beings and their amazing gadgets will be any more important than the past emergence of increasingly intricate complex systems. Nor is new science (beyond non-equilibrium thermodynamics) necessarily needed to describe cosmic evolution's interdisciplinary milestones at a deep and empirical level. Humans, our tools, and their impending messy interaction possibly mask a Platonic simplicity that undergirds the emergence and growth of complexity among the many varied systems in the material Universe, including galaxies, stars, planets, life, society, and machines.

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A. H. Eden et al. (eds.), *Singularity Hypotheses*, The Frontiers Collection,
DOI: 10.1007/978-3-642-32560-1_20, © Springer-Verlag Berlin Heidelberg 2012

Introduction: My Philosophy of Approach

About a decade ago, a book of mine was co-reviewed along with another in the *Boston Globe* (Raymo 2002), both of them in the context of humanity's future prospects. *Cosmic Evolution* (Chaisson 2001) sought to explicate, from a strictly scientific viewpoint, the natural rise of complex systems throughout the nearly 14 billion year history of the Universe, including sentient humans and our useful yet disturbing technical devices. The other book, of which I was unaware at the time, *The Age of Spiritual Machines* (Kurzweil 2000) argued that the speed and volume of information processing are increasing so rapidly that computers will soon surpass humans as an event of singular importance—a cultural tipping point termed by some the Singularity—is fast approaching. Although our scholarship partly overlapped, Kurzweil's book seemed speculative and even passionate, so I never did critically assess the idea of a technological singularity until I was invited to contribute the present article to this Frontiers Collection.

For many years, my scientific agenda has aimed to go beyond mere words and speculation about humankind and its technological aids. I have striven to place human society into a cosmological framework and to quantitatively analyze just how complex we, our brains, and our machines really are. Frankly, as a confirmed empiricist, I am skeptical of forecasting our future because all such exercises entail much qualitative guesswork; nor do I regard future evolutionary events to be accurately predictable given that an element of chance always accompanies the necessity of natural selection. That said, it does seem inevitable, indeed quite ordinary, that new forms of complexity are destined to supplant humanity as the most complex system known, just as surely as people took precedence over plants and reptiles, and in turn even earlier life on Earth complexified beyond that of the galaxies, stars, and planets that made life possible. There is nothing abnormal about the oncoming clash of men and machines—other than perhaps damaging our egos. The Universe has spawned many such grand evolutionary, even transcendent, events in deep time, the scale used to measure biological, geological, and cosmological changes throughout history writ large. That carbon-based humans are about to merge with, or concede to, silicon-based machines during a so-called "technological singularity" (Kurzweil 2005) is entirely reasonable—although a more benign outcome is that we might simply learn to live with them, to coexist. Data presented in this paper suggest that singularities are part of the natural scheme of things—normal, broadly expected outcomes when concentrated energy flows gave rise to increasingly complex systems throughout the expanding Universe. (Note that the expression "singularity" in this paper matches that commonly used to mean a major evolutionary milestone, of which there were many in cosmic history and thus the word singularity, oddly, implies plurality, not the technical term that puzzles mathematicians when sizes and scales near zero and densities approach infinity, as in black holes.)

My philosophy of approach, as an experimental physicist, seeks to interpret natural history over many billions of years, and to do so by embracing the leitmotif of energy flow through increasingly complex systems. By contrast, Kurzweil, among many other strong artificial-intelligence advocates, prefer information content to explain and predict humanity's recent and impending changes over much shorter periods of time. This is not a criticism of those who characterize complexity and evolution by means of information theory, or even entropy production, although I personally find these concepts overly abstract (with dubious meanings), hard to define (to everyone's satisfaction), and even harder to measure (on any scale). Regarding the latter, neither maximum nor minimum entropy principles are evident in the data presented below. Regarding the former, I sense, but cannot prove, that information is another kind of energy; both information storage and retrieval need energy, and greater information processing and calculation require greater energy density. While information content and entropy production are powerful terms that offer much theoretical insight, neither provides clear, unambiguous empirical metrics. My practical stance is that information may be useful to describe some systems, but energy is needed to make and operate them.

Where we do all agree (apparently) is that cultured humans and their invented machines are now in the process of transcending biology, a topic bound to be emotional if only because it rubs our human nerves and potentially dethrones our perceived cosmic primacy (Dick and Lupisella 2009; Kelly 2010). The roots of this evolutionary milestone—perhaps it is a technological singularity—probably extend as far back as the onset of agriculture when our forebears began manipulating their local environs, yet has recently advanced rapidly as we now alter both our globe environmentally as well as our being genetically. Even so, these changes—and their outcomes—are probably nothing more than the natural way that cultural evolution developed beyond biological evolution, which in turn built upon physical evolution before that, each of these evolutionary phases being an integral part of a more inclusive cosmic evolution that also operates naturally, as it always has and likely always will, with the irreversible march of time.

Cosmic Evolution: A Scientific Worldview for the New Millennium

The past few decades have seen the emergence of a unified scenario of natural history, including ourselves as sentient beings, based on the time-honored concept of change. Heraclitus may well have been right some 25 centuries ago when he offered perhaps the best observation of Nature ever: *παντα ρει*—"all flows… nothing stays the same." From stars and galaxies to life and humanity, a loose community of liberal researchers is now weaving an intricate pattern of understanding using the fabric of all the sciences—an interdisciplinary rendering of the origin and evolution of every known class of object in our richly endowed Universe. Often called cosmic evolution, this uncommonly broad cosmology that includes life as an integral part can be defined as *the study of the many varied developmental and generational changes in the assembly and composition of radiation, matter, and life throughout the history of the Universe*. These are the changes that have produced our Galaxy, our Sun, our Earth, and ourselves, and as such include both evolution and development (Salthe 1993). A localized "big-history" version of this scenario that places into larger perspective specifically humankind on Earth (Christian 2004; Brown 2007; Spier 2010; Grinin et al. 2011) is part of a more universal cosmic-evolutionary narrative that addresses the Universe at large (Chaisson 2001, 2006, 2009a, b; Dick 2009; Vakoch 2009). The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties—physics, astronomy, geology, chemistry, biology, anthropology, among others and including the humanities—a genuine epic of vast proportions extending from the very beginning of time to the present—and presumably beyond in both space and time.

While entering this new age of synthesis, we are beginning to decipher how all known systems—atoms and galaxies, cells and brains, people and society, among myriad others—are interrelated and constantly changing. Our appreciation for evolution now extends well beyond the subject of biology; the concept of evolution, generally considered (as in most dictionaries) as *any process of ascent with change in the formation, growth, and development of systems*, has become a potent unifying factor in all of science. Yet questions remain: How realistic is our quest for unification, and will the integrated result resemble science or philosophy? How have the magnificent examples of order on and beyond Earth arisen from chaos? Can the observed constructiveness of cosmic evolution be reconciled with the inherent destructiveness of thermodynamics? Most notably, we want to understand the emergence of diverse structures spanning the Universe, and especially the complexity of such systems as defined by *intricacy, complication, variety, or involvement among the interconnected parts of a system.* Particularly intriguing is the rise of complexity over the course of time, and dramatically so in the Phanerozoic during the past ~540 million years—a rise that has reached a crescendo on Earth with conscious beings, adroit machines, and their likely future intermingling. Could a technological singularity be the next great advance in the scenario of cosmic evolution?

Recent empirically based research, guided by huge new databases describing a multitude of complex systems, suggests robust answers to some of the above queries. Islands of ordered complexity that include galaxies, stars, planets, life, and society are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All quantitatively agrees with the valued precepts of thermodynamics, especially non-equilibrium thermodynamics. None of Nature's organized structures, not even life itself, is a violation (nor even a circumvention) of the celebrated 2nd law of thermodynamics. Both order and entropy can increase together—the former locally and the latter globally. Thus, we arrive at a central question lurking in the minds of some of today's eclectic thinkers (e.g. Mandelbrot 1982; Wolfram 2002): Might there be a kind of Platonism at work in the Universe—an underlying principle, a unifying law, or perhaps a

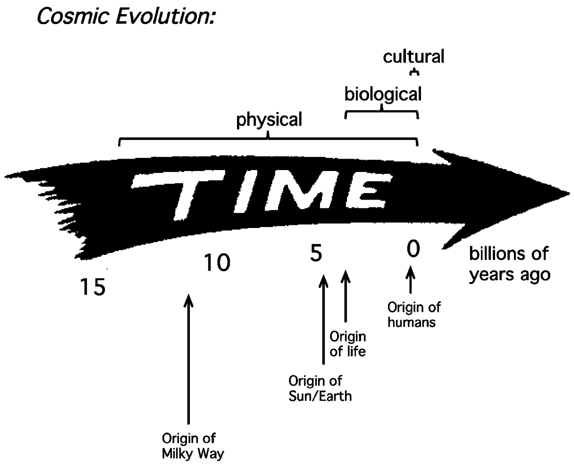

Fig. 20.1 An arrow of time, extending over nearly 14 billion years from the big bang at *left* to the present at *right*, symbolically represents the sweeping inclusiveness of cosmic evolution, an overarching subject that includes the three phases of physical, biological, and cultural evolution (*top* of figure). The arrow is not pointing at us; cosmic-evolutionary cosmology is not anthropcentric, yet it powerfully encapsulates the origin and evolution of our galaxy, star, and planet, as well as of life, humanity, and civilization (*bottom*)

surprisingly simple process that quite naturally creates, organizes, and maintains the form and function of complex systems everywhere?

Figure 20.1 depicts 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; it points toward nothing in particular, just the future generally. Anthropic principles notwithstanding, no logic supports the idea that the Universe was conceived to produce specifically us. We humans are unlikely the pinnacle or culmination of the cosmic-evolutionary scenario, nor are we likely the only technically competent beings to have emerged in the organically rich Universe. Time's arrow merely provides a convenient symbol, artistically depicting a ubiquitous flow that (somehow) produced increasingly complex structures from spiral galaxies to rocky planets to thinking beings. Nor is the arrow meant 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 simple 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. Changes in surrounding environments often precede change within ordered systems, and the resulting system changes have *generally* been toward greater amounts of diverse complexity, as numerically justified in the next section.

Energy Flows and Complexity Rises

Cosmic evolution as understood today is governed largely by the 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 best describes the concept of change—yet change dictated by a combination of randomness and determinism, of chance and necessity. Literally, thermodynamics, which tells us what can happen and not what does happen, 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." Energy flows engendered largely by the expanding cosmos do seem to be as central in the origin of structured systems as anything yet found in Nature. Furthermore, the optimization of such energy flows might well act as a motor of evolution broadly conceived, thereby affecting all of physical, biological, and cultural evolution, the sum total of which constitutes cosmic evolution.

Energy does play a role in creating, ordering, and maintaining complex systems. Recognized decades ago at least qualitatively in words (Lotka 1922; von Bertalanffy 1932; Schroedinger 1944), the need for energy should now be embraced as an essential feature not only of biological systems such as plants and animals but also of physical systems such as stars and galaxies; energy's engagement is also widely recognized in cultural systems such as a city's inward flow of food and resources amidst its outward flow of products and wastes, indeed for all of civilization itself. All complex systems—whether alive or not—are open, organized, dissipative, non-equilibrated structures that acquire, store, and express energy.

In contrast to my enthusiasm for energy as an organizing principle, I acknowledge that entropy production (Kleidon and Lorenz 2005; Martyushev and Seleznev 2006) and information content (Hofkirchner 1999; Gleick 2011) are more often espoused in discussions of origin, evolution, and complexity. Yet, these alternative aspects of systems science are less encompassing and decidedly less empirical than many practitioners admit, their theoretical usefulness narrow, qualitative, and equivocal as general complexity metrics (Meyers 2009). Although yielding insightful properties of systems and their emergent and adaptive qualities unlikely to be understood otherwise, such efforts have reaped an unusual amount of controversy and only limited success to date (Mitchell 2009). Nor are information or negentropy useful in quantifying or measuring complexity, a slippery term for many researchers. In biology alone, much as their inability to reach consensus on a definition of life, biologists cannot agree on a complexity metric. Some (Maynard Smith 1995) use non-junk genome size, others (Bonner 1988) employ creature morphology and behavioral flexibility, still others chart the number of cell types in organisms (Kaufmann 1993) or appeal to cellular specialization (McMahon and Bonner 1983). All these attributes of life have qualitative worth, yet all are hard to quantify in practical terms. Cosmic evolutionists seek to push the analytical envelope beyond mere words, indeed beyond biology.

We thus return to the quantity having greatest appeal to physical intuition—energy—a term that is satisfactorily definable, understandable, and above all measurable. Not that energy has been overlooked in more recent discussions of systems' origin and assembly. Many researchers (e.g. Morrison 1964; Morowitz 1968; Dyson 1979; Odum 1988; Smil 1999; Lane and Martin 2010) have championed in different ways and limited contexts the cause of energy's organizational abilities. Even so, the quantity of choice cannot be energy alone, for a star is clearly more energetic than an amoeba, a galaxy much more than a single cell. Yet any biological system is surely more complicated than any inanimate entity. Absolute energies are not as indicative of complexity as relative values, which depend on a system's size, composition, and efficiency. To characterize complexity objectively—that is, to normalize all such structured systems in precisely the same way—a kind of energy density is judged most useful. Moreover, it is the *rate* at which free energy transits complex systems of given mass that seems especially constructive (as has long been realized for ecosystems: Lotka 1922; Ulanowicz 1972), thereby delineating energy *flow*. Hence, "energy rate density," symbolized by Φ_m, becomes an operational term whose meaning and measure are easily understood, indeed whose definition is clear: *the amount of energy passing through a system per unit time and per unit mass*. In this way, neither new science nor appeals to non-science are needed to explain the impressive hierarchy of the cosmic-evolutionary story, from quarks to quasars, from microbes to minds.

Experimental data and detailed computations of energy rate densities are reported elsewhere (Chaisson 2011a, b), most of them culled or calculated from values found in widely scattered journals over many years. In the briefest of compact summaries:

- For physical systems, stars and galaxies generally have energy rate densities (10^{-3}–10^{2} erg/s/g) that are among the lowest of known organized structures. Galaxies show clear temporal trends in rising values of Φ_m while clustering hierarchically, such as for our Milky Way, which increased from $\sim 10^{-2}$ to 0.1 erg/s/g while changing from primitive dwarf status to mature spiral galaxy. Stars, too, adjust their states while evolving during one or more generations, their Φ_m values rising while complexifying with time as their interior thermal and chemical gradients steepen and differentiate; for the Sun, Φ_m increases from ~ 1 to 120 erg/s/g from young protostar to aged red giant.
- In turn, among biological systems, plants and animals regularly exhibit intermediate values of $\Phi_m = 10^{3}$–10^{5} erg/s/g. For plant life on Earth, energy rate densities are well higher than those for normal stars and typical galaxies, as perhaps best demonstrated by the evolution of photosynthesizing gymnosperms, angiosperms, and C_4 plants, which over the course of a few hundred million years increased their Φ_m values nearly an order of magnitude to $\sim 10^{4}$ erg/s/g. Likewise, as animals evolved from fish and amphibians to reptiles, mammals, and birds, their Φ_m values rose from $\sim 10^{3.5}$ to 10^{5} erg/s/g, here energy conceivably acting as a fuel for change, partly selecting systems able to utilize increased power densities, while forcing others to destruction and extinction—all likely in accord with neo-Darwinian principles.
- Furthermore, for cultural systems, advances in technology are comparable to those of society itself, each of them energy-rich and having $\Phi_m \geq 10^{5}$ erg/s/g—hence plausibly among the most complex systems known. Social evolution can be tracked, again in terms of normalized energy consumption, for a variety of human-related cultural advances among our ancestral forebears, from early agriculturists ($\sim 10^{5}$ erg/s/g) to modern technologists ($\sim 10^{6.5}$). Machines, too, and not just computers, but also ordinary engines that drove the 20th century economy, show the same trend from primitive devices of the industrial revolution ($\sim 10^{5}$ erg/s/g) to today's jet aircraft ($\sim 10^{7.5}$).

Of special note often neglected, although the absolute energy in astronomical systems is vastly larger than in our human selves, and although the mass densities of stars, planets, bodies, and brains are all comparable, the energy rate density for people and our society are upwards of a million times greater than for stars and galaxies. That's because the quantity Φ_m is an energy rate *density*. Although, for example, the Sun emits a vast luminosity, 4×10^{33} erg/s (equivalent to nearly a billion billion billion Watt light bulb), it also has an unworldly large mass, 2×10^{33} g; thus each second an amount of energy equaling only 2 ergs passes through each gram of this star. Many colleagues are likewise surprised to realize that, despite its huge size and scale, the Sun's mass density is small enough (well less than a rock) that this star would almost float if we could get it into a bathtub. By contrast, more energy flows through each gram of a plant's leaf during photosynthesis, and much more radiates through each gram of gray matter in our brains while thinking—which is why we have a hope of deciphering who we are and the Sun cannot!

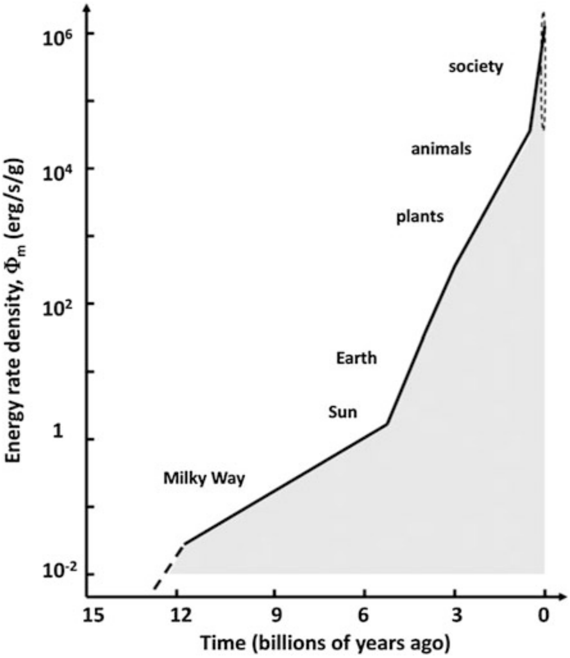

Fig. 20.2 Energy rate density, Φ_m, for a wide spectrum of systems observed throughout Nature displays a clear increase during ~14 billion years of cosmic history—in fact, an exponential rise whereby cultural evolution (steep slope at *upper right*) acts faster than biological evolution (moderate slope in middle part of curve), and even faster than physical evolution (smallest slope at *lower left*). The shaded area includes a huge ensemble of Φ_m values as individual types of localized systems continued changing and complexifying within the wider Universe that has become increasingly disordered. The Φ_m values and historical dates plotted here are estimates, each with outliers and uncertainties; yet it is not their absolute magnitudes that matter most as much as the perceived trend of Φ_m with the passage of time. The thin *dashed oval* at *upper right* outlines the magnitude of Φ_m and the duration of time plotted in Fig. 20.3

Figure 20.2, which is plotted on the same temporal scale as in Fig. 20.1, graphically compiles those data compactly presented in the three bullets above, depicting how physical, biological, and cultural evolution have transformed homogeneous, primordial matter of the early Universe into organized systems of increased intricacy and energy rate density—and it has done so with increasing speed, hence the exponentially rising curve. The graph shows the increase of Φ_m as measured or computed for representative systems having approximate evolutionary times at which they emerged in natural history. (For specific power units of W/kg, divide by 10^4.) Values given are typical for the general category to which each system belongs, yet variations and outliers are inevitable, much as expected for any simple, unifying précis of an imperfect Universe.

Energy is likely a common currency for all complex, ordered systems. Even for structures often claimed to be “self-assembled” or “self-organized,” energy is inexorably involved. Energy flow is among the most unifying processes in all of science, helping to provide cogent explanations for the origin, evolution, and complexification of a whole array of systems spanning >20 orders of magnitude in scale and nearly as many in time—notably, how systems emerge, mature, and terminate during individual lifetimes as well as across multiple generations. Robust systems, whether stars, life forms, or civilizations, have optimum ranges of energy flow; too little or too much and systems abort. Optimality is favored in the use of energy—not too little as to starve a system, yet not too much as to destroy it; no maximum energy principles, minimum entropy states, or maximum entropy production are evident in these data (Lotka 1922; Nicolis and Prigogine 1977; Prigogine 1978). Better metrics might describe each of the individual systems governed by physical, biological, and cultural evolution, but no other metric seems capable of uniformly describing them altogether. The significance of plotting "on the same page" (as in Fig. 20.2) a single empirical quantity for such an extraordinarily wide range of complex systems observed in Nature should not be underestimated.

Energy Rate Density of Embodied Brains

Humans deserve more than a passing note in any study of complex systems, not because we are special but because we are them. Each individual adult normally consumes ~2,700 kcal/day in the form of food to fuel our metabolism. This energy, gained directly from that stored in other (plant and animal) organisms and only indirectly from the Sun, is sufficient to maintain our body structure and temperature as well as drive our physiological functions and tetrapodal movements. (Note that the thermodynamical definition of a calorie, $1\ \text{cal} = 4.2 \times 10^7$ erg—the amount of heat needed to raise 1 g of H_2O by 1 °C—does not equal a dietician's large Calorie with a capital "C," which is 10^3 times more energetic than a physicist's calorie.) Therefore, with a body mass of 70 kg, a typical adult maintains $\Phi_m \approx 2 \times 10^4$ erg/s/g while in good health. Humans have mid-range mammalian metabolic values because our bodies house average complexity among endothermic mammals, all of which harbor comparable intricacy, including hearts, livers, kidneys, lungs, brains, muscles, and guts. Despite our manifest egos, our bodily beings do not have the highest energy rate density among animals (birds do, probably because they operate in 3 dimensions; Chaisson 2011b), nor are we more demonstrably complex than many other mammalian species.

The energy budget derived here for humans assumes today's average, sedentary citizen, who consumes ~65 % more than the basal metabolic rate of 1,680 kcal/day (or $\Phi_m \approx 1.2 \times 10^4$ erg/s/g) for an adult fasting while lying motionless. However, our metabolic rates increase substantially when performing occupational tasks or recreational activities—that's function, not structure. Even so, Φ_m once again scales with the degree of complexity of the function. For example, leisurely fishing, violin playing, tree cutting, and bicycle riding require about 3×10^4,

5×10^4, 8×10^4, and 2×10^5 erg/s/g, respectively (Ainsworth 2011). Clearly, jamming a musical instrument or balancing a moving bicycle are complex functions, and therefore more energetically demanding events, than waiting patiently for fish to bite. Thus, in the biological realm, the value-added quality of functionality does indeed count, in fact quantitatively so. Complex tasks actively performed by humans on a daily basis are typified by values of Φ_m that are often larger than those of even the metabolically imposing birds.

Nearly all zoological Φ_m values for bodies are tightly confined to within hardly more than an order of magnitude of one another—the great majority of specific metabolic rates for animals vary between 3×10^3 and 10^5 erg/s/g, despite their masses ranging over ~11 orders of magnitude from fairy flies to blue whales (Makarieva et al. 2008)—all of them midway between smaller botanical values for photosynthesizing plants and higher neurological ones for central nervous systems. This, then, is how humankind, like all of the animal world, contributes to the rise of entropy in the Universe: We consume high-quality energy in the form of ordered foodstuffs and then radiate away as body heat (largely by circulating blood near the surface of the skin, by exhaling warm, humidified air, and by evaporating sweat) an equivalent amount of energy as low-quality, disorganized infrared photons. Like the stars and galaxies, we too among all other life forms are wasteful, dissipative structures (in our case glowing warmly in the infrared as a 130 W bulb), thereby connecting with earlier thermodynamic arguments that some researchers might (wrongly) think pertinent only to inanimate systems.

Regarding brains, which nuclear magnetic resonance (fMRI) imaging shows are always electrically active regardless of the behavioral posture (even while resting) of their parent animal bodies, they too derive nearly all their energy from the aerobic oxidation of glucose in blood; thus, for brains, basal and active rates are comparable. Similar trends in rising complexity noted above for bodies are also evident for brains, though with higher Φ_m brain values for each and every animal type—much as expected since cerebral structure and function are widely considered among the most complex attributes of life (Jerison 1973; Allman 1999). Here, some quantitative details are compiled from many sources, again treating brains as open, non-equilibrium, thermodynamic systems, and once more casting the analysis of energy flow through them in terms of energy rate density. (While several other potentially useful neural metrics exist—cortical neuron numbers, encephalization quotients, and brain/body ratios (Roth and Dicke 2005)—I have evaluated brains here in terms of their Φ_m values in order to be scrupulously consistent with the complexity metric used above for all inanimate and animate systems.) Caution is advised since brain metabolic values taken from the literature often suffer from a lack of standard laboratory methods and operational units; many reported brain masses need correction for wet (live) values (by multiplying measured in vitro dry masses by a factor of 5 since in vivo life forms, including brains, are ~80 % H_2O). Note also that the ratio of brain mass to body mass (used by some neuroscientists as a sign of intelligence) differs from the ratio of brain power to brain mass (which equals Φ_m); nor is "brain power" the same as that used in colloquial conversation, rather here it literally equals the rate of energy flowing through the cranium.

No attempt is made here to survey brain Φ_m values comprehensively, a task seemingly impossible in any case given the primitive state of neurological data to date; rather, representative mean values suffice for a spectrum of extant animals. Comparing mammals and reptiles, $\Phi_m \approx 10^5$ erg/s/g for mice brains (in contrast to $\sim 4 \times 10^4$ for their whole bodies) exceeds $\sim 5 \times 10^4$ erg/s/g for lizard brains ($\sim 3 \times 10^3$ for their bodies) (Hulbert and Else 1981); this is generally the case for all such animal taxa as Φ_m values are somewhat greater for mammalian brains than those for reptilian brains by factors of 2–4, and those for mammal bodies by roughly an order of magnitude (Hofman 1983). The great majority of vertebrate fish and amphibians show much the same 5–10 times increase in brain over body Φ_m values (Freeman 1950; Itazawa and Oikawa 2005), with, as often the case in biology, some outliers (Nilsson 1996). Even many invertebrate insects show several factors increase in Φ_m values for their brains ($\sim 5 \times 10^4$) compared to their bodies ($\sim 10^4$), most notably the flying insects (Kern 1985). Among mammals alone, primates have not only high brain/body mass ratios but also relatively high Φ_m brain values ($\sim 2 \times 10^5$ erg/s/g). Although primates allocate for their brains a larger portion (8–12 %) of their total bodily (resting) energy budget than do non-primate vertebrates (2–8 %) (Armstrong Armstrong 1983; Hofman 1983; Leonard and Robertson 1992), average primate brains' Φ_m values tend to be comparable to those of brains of non-primates; Φ_m brain values remain approximately constant across 3 orders of magnitude in mammalian brain size (Karbowski 2007). As with bodies above, brains do not necessarily confer much human uniqueness; brains are special, but all animals have them, and our neural qualities seem hardly more than linearly scaled-up versions of those of other primates (Azevedo et al. 2009). Even so, brain function and energy allocation are revealing: Among living primates, adult humans ($\sim 1.5 \times 10^5$ erg/s/g for brains and $\sim 2 \times 10^4$ for bodies) seem to have the highest brain power per unit mass—that is, not merely ~ 10 times higher Φ_m than for our bodies, but also slightly higher than for the brains of our closest, comparably massive, ape relatives, including chimpanzees. This substantial energy–density demand to support the unceasing electrical activity of myriad neurons within our human brains, which represent only ~ 2 % of our total body mass yet account for 20–25 % of the total bodily energy intake (Clarke and Sokoloff 1999), testifies to the disproportionate amount of worth Nature has invested in evolved brains—and is striking evidence of the superiority of brain over brawn.

The tendency for complex brains to have high Φ_m values, much as for complex whole animal bodies, can be tentatively correlated with the evolution of those brains among major taxonomic groups (Allman 1999). Further, more evolved brains tend to be larger relative to their parent bodies, which is why brain-to-body-mass ratios also increase with evolution generally—mammals more than reptiles, primates notable among mammals, and humans foremost among the great apes (Hofman 1983; Roth and Dickey 2005). Part of the reason is that relatively big brains are energetically expensive. Neurons use energy as much as 10 times faster than average body tissue to maintain their (structural) neuroanatomy and to support their (functional) consciousness; the amount of brain devoted to network connections increases disproportionately with brain size and so does the clustering and layering of cells within the higher-processing neocortex of recently evolved vertebrates (Stevens 2001; Jarvis 2005). Much of this accords with the "expensive tissue hypothesis" (Aiello and Wheeler 1995; Isler and van Schaik 2006; Navarrete et al. 2011), which posits that high brain/body ratios are indeed more energetically costly, at least for mammals and many birds, that energy flow through brains is central to the maintenance of relatively large brains, especially for primates, and that relatively large brains evolve when either brain energy input increases or energy allocation shifts to the brain from other bodily organs or fat reserves. Although the human brain's metabolic rate is not much greater than for selected organs, such as the stressed heart or active kidneys, regional energy flux densities within the brain greatly exceed (often by an order of magnitude) most other organs at rest. The pressures of social groups and social networking might also drive growth in brain size, cognitive function, and neurophysiological complexity along insect, bird, and primate lineages (Dunbar 2003; Smith et al. 2010); evolving societies require even more energy to operate, at least for humankind advancing (cf. next section). Throughout Earth's biosphere, the high-energy cost of brains might reasonably limit brain size and constrain natural selection's effect on an animal's survival or reproductive success; indeed, the brain is the first organ to be damaged by any reduction in O_2. This, then, is the observed, *general* trend for active brains in vivo: not only are brains voracious energy users and demonstrably complex entities, but evolutionary adaptation also seems to have favored for the brain increasingly larger allocations of the body's total energy resources.

Among more recent prehistoric societies of special relevance to humanity, the genus *Homo*'s growing encephalization during the past ~2 million years may be further evidence of natural selection acting on those individuals capable of exploiting energy- and protein-rich resources as their habitats expanded (Foley and Lee 1991). By deriving more calories from existing foods and reducing the energetic cost of digestion, cooking was likely central among cultural innovations that allowed humans to support big brains (Wrangham 2009). Energy-based selection would have naturally favored those hominids who could cook, freeing up more time and energy to devote to other things—such as fueling even bigger brains, forming social relationships, and creating divisions of labor, all of which arguably advanced culture. As with many gauges of human intelligence, it's not absolute brain size that apparently counts most; rather, brain size normalized by body mass is more significant, just as the proposed Φ_m complexity metric is normalized by mass, here for brains as well for all complex systems at each and every stage along the arrow of time, from big bang to humankind.

The net finding for brains, broadly stated though no less true for the vast majority of animals, is that their Φ_m values are systematically higher than those for the bodies that house them. Nearly all such brain values fall within a rather narrow range of Φ_m between lower biological systems (such as plants) and higher cultural ones (such as societies). Although absolute brain masses span ~6 orders of magnitude, from insects to whales, their Φ_m brain values cluster within a few factors, more or less depending upon their absolute size and evolutionary provenance, of $\sim 10^5$ erg/s/g.

Energy Rate Density of Humankind Advancing

For cosmic evolution to qualify as a comprehensive scientific worldview, human society and its many cultural achievements should be included, anthropocentric criticisms notwithstanding. Nature, alone and without sentient, technological beings, could not have built the social systems and technological devices characterizing our civilization today. Humankind itself is surely a part of Nature and not apart from it; schemes that regard us as outside of Nature, or worse atop Nature, are misguided. To examine how well, and consistently so, cultural systems resemble physical and biological systems—and thus to explore cultural evolution in a cosmic context—this section explores the evolution of cultural complexity as quantified by the same heretofore concept of energy rate density. (Some colleagues prefer to relabel long-term cultural evolution as "post-biological evolution," especially as regards clever machines that may someday outwit flesh-and-blood humans (Dick 2003); they assert that technological civilization is guided by intelligence and knowledge, yet both these factors resemble the earlier-abandoned information theory. By contrast, I aim to skirt the vagueness of social studies while embracing once again empirical-based energy flow as a driver of cultural evolution—especially, in the interest of unification, if that driver manifests the same common process that governs physical and biological evolution as well.)

Consider modern civilization *en masse*, which can be deemed the totality of all humanity comprising a (thermodynamically) open, complex society going about its usual business. Today's $\sim$7 billion inhabitants utilize $\sim$18 TW to keep our global culture fueled and operating, admittedly unevenly distributed in developed and undeveloped regions across the world (U.N. 2008). The cultural ensemble equaling the whole of humankind then averages $\Phi_m \approx 5 \times 10^5$ erg/s/g. Here human society is taken to mean literally the mass of humanity, not its built infrastructure (of buildings, roadways, etc.), for what matters is the flow of energy through the aggregated human social network. Unsurprisingly, a group of brainy organisms working collectively is more complex than all of its individual human components (who each consume an order of magnitude less energy, lest our bodies fry), at least as regards the complexity criterion of energy rate density—a good example of the "whole being greater than the sum of its parts," a common characteristic of emergence fostered by the flow of energy through organized, and in this case social, systems.

Rising energy expenditure per capita has been a hallmark in the origin, development, and evolution of humankind, an idea dating back decades (White 1959; Adams 1975). Culture itself is often defined as a quest to control greater energy stores (Smil 1994). Cultural evolution occurs, at least in part, when far-from-equilibrium societies dynamically stabilize their organizational posture by responding to changes in flows of energy through them. A quantitative treatment of culture, peculiar though it may be from a thermodynamic viewpoint, need be addressed no differently than for any other part of cosmic evolution (Nazaretyan 2010). Values of Φ_m can be estimated by analyzing society's use of energy by our relatively recent hominid ancestors, and the answers illustrate how advancing peoples increasingly supplemented their energy budgets beyond the 2–3,000 kcal/day that each person actually eats as food (Cook 1976; Bennett 1976; Simmons 1996; Spier 2005; Chaisson 2008; 2011a): Hunter-gatherers $\sim$300,000 years ago used $\sim 3 \times 10^4$ erg/s/g, agriculturists $\sim$10,000 years ago increased energy expenditure to $\sim 10^5$, industrialists beginning nearly two centuries ago utilized $\sim 5 \times 10^5$, and today's technologists in the most developed countries use $\sim 2 \times 10^6$. Underlying, and quite possibly driving, all this cultural advancement was not only greater energy usage but also greater energy usage per capita (i.e., per unit mass) at each and every step of the way.

Much of this social advancement is aided and abetted by culturally acquired knowledge accumulated from one generation to the next, including client selection, rejection, and adaptation, a decidedly Lamarckian process. Cultural inventiveness enabled our immediate ancestors to evade some environmental limitations: Hunting and cooking allowed them to adopt a diet quite different from that of the australopithecines, while clothing and housing permitted them to colonize both drier and colder regions of planet Earth. Foremost among the cultural advances that helped make us technological beings were the invention and utilization of tools, which require energy to make and use, all the while decreasing entropy within those social systems employing them and increasing it elsewhere in wider environments beyond. The 2nd law demands that as any system complexifies—even "smart" human-centered systems—its surroundings necessarily degrade. Thermodynamic terminology may be unfamiliar to anthropologists or historians, but the fundamental energy-based processes governing the cultural evolution of technological society are much the same, albeit measurably more complex, as for the evolution of stars, galaxies, and life itself (Adams 2010). As for biological organisms before them, specialization permits social organizations to process more energy per unit mass and this is reflected in increased Φ_m values over the course of time.

Notable among social practices widespread on Earth today, not only in developed countries but also intensifying rapidly in undeveloped countries, is technology. Advancement of machines is a premier feature of cultural evolution—and also one that increases order in manufactured products mainly by means of energy expenditures that inevitably ravage the larger environment of raw materials used to make those goods. Of today's many cultural icons, surely one of the most prominent is the automobile, which for better or worse has become an archetypical symbol of technological innovation worldwide. Values of Φ_m can be calculated for today's average-sized automobiles, whose typical properties are $\sim$1.6 tons of mass and $\sim 10^6$ kcal of gasoline consumption per day; the result, $\sim 10^6$ erg/s/g (assuming 6 h of daily operation), is likely to range higher or lower by several factors, given variations among vehicle types, fuel grades, and driving times, yet this average value accords well with that expected for a cultural invention of considerable magnitude. Put another way to further illustrate evolutionary trends and using numbers provided by the U.S. government (U.S. Highway Traffic Safety Administration 2005) for the past quarter-century, the horsepower-to-weight ratio (in English units of hp/100 lb) of American passenger cars has increased steadily from 3.7 in 1978 to 4.1 in 1988 to 5.1 in 1998 to 5.5 when last compiled in 2004; converted to the units of Φ_m used here, these values equal 6.1, 6.7, 8.4, and 9.1, all times 10^5 erg/s/g respectively. Not only in and of themselves but also when compared to less powerful and often heavier autos of >50 years ago (whose Φ_m values are less than half those above), the trend of these numbers confirms once again the general correlation of Φ_m with complexity, for who would deny that modern automobiles, with their electronic fuel injectors, computer-controlled turbochargers, and a multitude of dashboard gadgets are more culturally complex than Ford's model-T predecessor of a century ago? The bottom line is that more energy is required per unit mass to operate the newer vehicles—a rise in Φ_m that will almost certainly continue as machines soon fundamentally switch their inner workings by substituting lightweight electrons for burning fuel and fast computers for mechanical linkages.

The connection between complexity and the advance of cultural evolution can be more closely probed by tracing the changes in internal combustion engines that power automobiles among many other machines such as gas turbines that propel aircraft (Smil 1999). To be sure, the brief history of machines can be cast in evolutionary terms, replete with branching, phylogeny, and extinctions that are strikingly similar to billions of years of biological evolution—though here, cultural change is again less Darwinian than Lamarckian, hence quicker too. Energy remains a driver for these cultural evolutionary trends, reordering much like physical and biological systems from the simple to the complex, as engineering improvement and customer selection over generations of products made machines more elaborate and efficient. Modern automobiles are better equipped and mechanically safer than their simpler, decades-old precursors, not because of any self-tendency to improve, but because manufacturers constantly experimented with new features, keeping those that worked while discarding the rest, thereby acquiring and accumulating successful traits from one generation of cars to the next. For example, the pioneering 4-stroke, coal-fired Otto engine of 1878 had a Φ_m value ($\sim 4 \times 10^4$ erg/s/g) that surpassed earlier steam engines ($\sim 10^4$ erg/s/g), but it too was quickly bettered by the single-cylinder, gasoline-fired Daimler engine of 1899 ($\sim 2.2 \times 10^5$ erg/s/g), more than a billion of which have been installed to date in cars, trucks, aircraft, boats, lawnmowers, etc., thereby acting as a signature force in the world's economy for more than a century. Today's mass-produced automobiles, as noted in the previous paragraph, average several times the Φ_m value of the early Daimler engine, and some intricate racing cars can reach an order of magnitude higher still. Among aircraft, the Wright brothers' 1903 homemade engine ($\sim 10^6$ erg/s/g) was superseded by the Liberty engines of World War I ($\sim 7.5 \times 10^6$ erg/s/g) and then by the Whittle-von Ohain gas turbines of World War II ($\sim 10^7$ erg/s/g). Boeing's 707 airliner inaugurated intercontinental jet travel in 1959 when Φ_m reached $\sim 2.3 \times 10^7$ erg/s/g, and civilian aviation evolved into perhaps the premier means of global mass transport with today's 747-400 wide-body, long-range jet whose engines create up to 110 MW to power this 180 ton craft to just below supersonic velocity (Mach 0.9) with $\Phi_m \approx 2.7 \times 10^7$ erg/s/g.

The cultural rise of Φ_m can be traced particularly well over several generations of jet-powered fighter aircraft of the U.S. Air Force (though here engine thrust must be converted to power, and for unloaded military jets operating nominally without afterburners typically 1 N $\approx$ 500 W, for which Φ_m values then relate to thrust-to-weight ratios). First-generation subsonic aircraft of the late 1940, such as the F-86 Sabre, gave way to 2nd-generation jets including the F-105 Thunderchief and then to the 3rd-generation F-4 Phantom of the 1960s and 1970s, reaching the current state-of-the-art supersonic F-15 Eagle now widely deployed by many western nations; 5th-generation F-35 Lightning aircraft will soon become operational. (Fighter F-number designations do not follow sequentially since many aircraft that are designed never get built and many of those built get heavily redesigned.) These aircraft not only have higher values of Φ_m than earlier-era machines, but those energy rate densities also steadily rose for each of the 5 generations of military aircraft R&D during the past half century—2.6, 4.7, 5.7, 6.1, and 8.2, all times 10^7 erg/s/g respectively, and all approximations for their static engine ratings (U.S. Air Force 2010).

Stunning advances in computer technology can also be expressed in the same quantitative language—namely, the rate of energy flowing through computers made of densely compacted chips. In all cases, Φ_m values reveal, as for engines above, not only cultural complexity but also evolutionary trends. (To make the analysis manageable, I have examined only computers that I personally used in my career, except for the earliest such device.) The ENIAC of the 1940s, a room-sized, 8.5 ton, 50 kW behemoth, transformed a decade later into the even larger and more powerful (125 kW) UNIVAC with $\sim$5,200 vacuum tubes within its 14.5 ton mainframe. By the 1970s, the fully transistorized Cray-1 supercomputer managed within each of its several (<1 ton, $\sim$22 kW) cabinets less energy flow yet higher energy rate density as computers began shrinking. By 1990 desktop computers used less power but also amassed less bulk ($\sim$250 W and $\sim$13 kg), making Φ_m still high. And now, MacBook laptops need only $\sim$60 W to power a 2.2 kg chassis to virtually equal the computational capability and speed of early supercomputers. During this half-century span, Φ_m values of these cultural systems changed respectively: 6.4, 9.5, 32, 20, and 28, all times 10^4 ergs/s/g. Although the power consumed per transistor decreased with the evolution of each newer, faster, and more efficient computer generation, the energy rate *density* increased because of progressive miniaturization—not only for the transistors themselves, but also for the microchips on which they reside and the computers that house them all. This growth of Φ_m parallels Moore's law (Moore 1965)—whereby transistor numbers etched on silicon chips double roughly every 18 months—and may be the underlying reason for it.

Although these and other cultural Φ_m values often exceed biological ones, machines are not claimed here to be “smarter” than we humans. Values of Φ_m for today’s computers approximate those for human brains largely because they number-crunch much faster than do our neurological networks; even laptops now have central-processing units with immense computational features and not surprisingly, in cultural terms, high Φ_m values. That doesn’t make microelectronic devices more intelligent than humans, but it does arguably make them more complex, given the rapid rate at which they functionally process data—and not least consume energy per unit mass. Accordingly, our most advanced aircraft have even higher Φ_m values than our most sophisticated computers. Modern flying machines rely on computers but also possess many additional, technologically advanced widgets that together require even more energy density, making them extraordinarily complex. That computers per se are amazingly complex machines, but not amazing enough for them to fly on their own, does suggest that perhaps there is something significant—and inherently more complex—about both living species and technical devices that can operate in 3-D environments on Earth; whether insects, birds, or cutting-edge aircraft, airborne systems exhibit higher values of Φ_m within each of their respective categories, more so to execute their awesome functions than to support their geometrical structures.

Much of this cultural advancement has been refined over many human generations, transmitted to succeeding offspring not by genetic inheritance but by use and disuse of acquired knowledge and skills. Again a mostly Lamarckian process whereby evolution of a transformational type proceeds via the passage of adopted traits, cultural evolution, like physical evolution, involves neither DNA chemistry nor genetic selection that characterize biological evolution. Culture enables animals to transmit modes of living and survival to their descendants by non-genetic, meme-like routes; communication passes behaviorally, from brain to brain and generation to generation, and that is what causes cultural evolution to act so much faster than biological evolution (Dennett 1996; Blackmore 1999; Denning Denning 2009). Even so, a kind of selection acts culturally, arguably guided by energy use (Chaisson 2011a); the ability to start a fire or sow a plant, for example, would have been major selective advantages for those hominids who possessed them, as would sharpening tools or manipulating materials. The result is that selection yielded newer technologies and systematically cast older ones into extinction, often benefiting humanity over the ages. It is this multitude of cultural advancements in recent times that has escalated and complexified change—advancements which, in turn with the scientific method that derives from them, enable us to explore, test, and better probe the scenario of cosmic evolution.

Figure 20.3 collates all of the above-cited human- and machine-related values of Φ_m, noting that these data pertain only to the uppermost part of the graph in Fig. 20.2. That’s because modern society and our technological inventions are, in the cosmic scheme of things, only very recent advances in the rising complexity of generally evolving systems in the Universe.

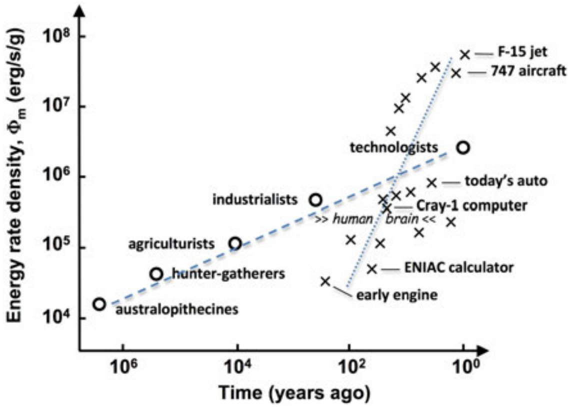

Fig. 20.3 Machines of the fast-paced 21st century not only evolve culturally, but are also doing so more quickly than humans evolve, either culturally or biologically—hence the reality, numerically delineated here, of a technological singularity. This graph shows some representative cultural systems that populate the uppermost part of the Φ_m curve plotted in Fig. 20.2. The time scale here covers only the past few million years, which is merely 0.02 % of the entire temporal scale of cosmic history illustrated in Figs. 20.1 and 20.2. This is a log–log plot, allowing meaningful display of data for society (plotted as Os linked by a *dashed line*) and for machines (Xs linked by a *dotted line*) over millions and hundreds of years, respectively, in the same figure. The value of Φ_m for the human brain is also indicated—but note well that Φ_m is a proposed measure of complexity, not necessarily of intelligence

Discussion: The Technological Singularity in Perspective

Today's civilization runs on energy for the simple reason that all complex, functioning systems need energy to survive and prosper. Whether aging stars, twirling galaxies, buzzing bees or redwood trees, it is energy that keeps open, non-equilibrium systems ordered and operating—to help them, at least locally and temporarily, avoid a disordered state (of high entropy) demanded by the 2nd law of thermodynamics. Whether living or non-living, dynamical systems need flows of energy to endure. If stars do not fuse matter into heat and light, they collapse; if plants fail to photosynthesize sunlight, they shrivel and decay; if humans stop eating, they die. Likewise, human society's fuel is energy: Resources come in and wastes go out while civilization conducts its daily business.

Throughout the long and storied, yet meandering, path of cosmic evolution, many complex systems have come and gone. Most have been selected out of Nature by Nature—destroyed and gone extinct—probably and partly because they were unable to utilize optimum amounts of energy per unit time and per unit mass; in all aspects of evolution, there are few winners and mostly losers. Is humankind among the preponderance of systems destined for extinction—owing perhaps to environmental degradation, societal collapse, or loss of control to machines? Will machines dominate us in the future, or might we merge with them to our mutual benefit? Would a technological singularity be good, bad, or irrelevant for us? Just what is the technological singularity and can we quantitatively assess its implications in ways that go beyond mere words?

To my mind, there is no purpose to any of the observed growth in universal complexity—no overt design or grand plan evident in cosmic evolution. Nor is there any obvious progress either; we who study Nature make progress while deciphering this grand scenario, but no compelling evidence exists that the cosmic-evolutionary process itself is progressive (as in "movement toward a goal or destination"). Admittedly I cannot prove these statements, which are themselves hardly more than squishy opinions. As a confirmed empirical materialist, my forte is to closely observe Nature and to numerically test conjectures about it—a mainstream application of the traditional scientific method. Not that subjectivity is absent in science while it's practiced; rather, objectivity eventually emerges only after much quantitative probing of qualitative ideas. Those ideas that pass the test of time survive—and those that don't are discarded; theoretical ideas are subject to selection and adaptation much like the complex material systems featured in this article. Hence my skepticism of parts of this volume that entail merely, mostly, and often exclusively beliefs, pronouncements, and speculations.

In the interest of full disclosure, I am also skeptical of much of what constitutes frontier physics these days. Progress toward a unified understanding of Nature need not postulate metaphysical schemes in abstract cosmology or untestable ideas in theoretical physics; nor does it necessarily require multiple universes, extra dimensions, or string theories for which there is no direct evidence (Greene 2011; Kragh 2011). A coherent, phenomenological explication of what is actually observed in our singular, four-dimensional universe populated mainly with galaxies, stars, planets, and life comprises a useful advance in comprehending, and to some extent unifying, the extended, diverse world around us. That is the intellectual stance from which I prefer to examine the idea of a technological singularity.

Figure 20.1 places cultural evolution on Earth during the past ~50 thousand years into the larger perspective of the more inclusive scenario of cosmic evolution that spans ~14 billion years. The arrow of time is an artistic graphic, not a numerical graph per se; it need not be examined closely. Figure 20.2 is that numerical graph and one that merits focused scrutiny, indeed one for which the key factor of this article—energy rate density—is plotted against precisely the same linear temporal scale as in Fig. 20.1. It compactly displays the rise of Φ_m for a wide array of systems throughout universal history to date. It rank-orders complex systems from the early Universe to civilization on Earth. And it shows, during each of the physical, biological, and cultural phases, how Φ_m rose increasingly rapidly—the growth of Φ_m accelerated. That, then, is what accelerates—Φ_m, the rate at which increasingly complex systems utilize energy—and it puts meat on the bones of all those soft and airy claims over the years that "something" is accelerating in our sophisticated world today. To be clear, on a linear plot as in Fig. 20.2, the whole graph taken together shows an exponentially rising trend; the slope of the curve is steeper for cultural evolution than for biological evolution, which in turn is steeper than for physical evolution. At least in terms of the Φ_m diagnostic discussed here, it seems unequivocal that the central mechanism of cosmic evolution, and the complexity products derived therefrom, have indeed accelerated with the march of time over billions of years.

Furthermore, though not shown here as much as elsewhere in detail (Aunger 2007; Chaisson 2011a, b), Φ_m rises exponentially for each type of complex system only for limited periods of time, after which their sharp rise often tapers off. Caution is warranted in order not to over-interpret these data, yet some but not all complex systems seem to slow their rate of growth while following a classic S-shape curve—much as microbes do in a petri dish while replicating unsustainably or as human population is expected to plateau later this century. That is, Φ_m values for a whole array of physical, biological, and cultural systems grow quickly during their individual evolutionary histories and then level off throughout the shaded area of Fig. 20.2 (whose drawn curve is then the compound sum of multiple S-curves); Φ_m for viable, complex systems show no noticeable decrease, rather often depict decreased rates of growth and S-shaped inflection perhaps once those systems have matured (Chaisson 2012). Some colleagues assume that means Φ_m decreases—it does not, at least not for surviving systems able to command optimal energy; others interpret that as complexity declining—but it also does not. The rate of change of Φ_m—which is itself a rate—might eventually decrease, but that means only that complexity's growth rate is lessening, not the magnitude of complexity per se.

Figure 20.3 allows a closer, numerical examination of the notion of a technological singularity—an occasion of some significance now probably underway during Earth's cultural evolution, which surely does transcend biological evolution. Note that the graph in Fig. 20.3 pertains only to the uppermost part of the curve in Fig. 20.2 and furthermore that this plot is not temporally linear; it is fully logarithmic. As such, the (dashed and dotted) straight lines exhibit exponential growth—as indicated individually for society advancing (plotted as Os, topped by modern technologists in developed countries today) and for machines rising (plotted as Xs, topped by 3-D, computer-controlled, military aircraft). *Prima facie*, the plotted graph does literally seem to display transcendence, as commonly defined "going beyond, surpassing, or cutting across," of machines over humankind. This is often claimed to be an event beyond which human affairs cannot continue—akin to mathematical singularities beset by values that transcend finite limitations—one for which humankind and the human mind as we currently know them are superseded and perhaps supplanted by strong, runaway, even transhuman artificial intelligence (Von Neumann and Ulam 1958; Kurzweil 2005). Alas, data in this paper are not accurate enough to test this unsettling fate.

The sum of the two curves for today's dominant cultural systems *en toto* results in faster-than-exponential growth—that is, the combined curve, dashed plus dotted in Fig. 20.3, sweeps upward on a log–log plot. Cultural change is indeed rapidly accelerating and the Φ_m data prove it. However, the data of Fig. 20.3 imply no evidence for a singularity of singular import or uniqueness. The technological singularity, which seems real and oncoming, may be central (and even threatening) to beings on Earth, yet is only one of many exceptional events throughout natural history, and unlikely more fundamental than many other profound evolutionary developments among complex systems over time immemorial. The cosmic-evolutionary narrative comprises innumerable transcendent phenomena that can be regarded as singularities all across the arrow of time in Fig. 20.1 and all the way up the rising curve of Φ_m in Fig. 20.2, including but by no means solely the birth of language (transcending symbolic signaling), the Cambrian explosion (land life transcending sea life), the onset of multicells (clusters transcending unicells), the emergence of life itself (life transcending matter), and even before that the origin and merger of stars and galaxies, among scores of prior and significant evolutionary events that led to humankind and its current existential crisis. Singulartarians need to think bigger and broader, thereby embracing the transformative concept of singularity in wider, cosmic settings extending all the way back along the arrow of deep time in reverse.

All things considered, this much seems evident from Fig. 20.3:

- Φ_m is increasing for humans and for machines, with the latter system rising faster
- Φ_m for humans and machines individually might each be slowing their rates of growth
- Φ_m for both humans and machines collectively accelerates hyper-exponentially
- a technological singularity, viewed as an evolutionary milestone, is indeed near.

Must we fear machines? Will they dominate or displace us, or merely aid us? The Φ_m data to date are not reliable enough to extrapolate an answer to these fateful questions, and in any case evolution is not a predictive science. Random chance always works in tandem with deterministic necessity, the two comprising natural selection that acts as a ruthless editor or pruning device to delete those systems unable to command energy in optimal ways; that is why "non-random elimination" is perhaps a better term for natural selection broadly applied to all complex systems (Mayr 1997). Thus, and sadly for those who agonize about future outcomes, Φ_m analyses cannot presently determine if humans will merge with machines or be overwhelmed by them in the coming years—although the data of Fig. 20.3 do imply that some machines are already more complex (higher Φ_m) than the humans and their brains who created them. Given that so many aspects of Nature are neither black nor white, rather shades of grey throughout, it is not inconceivable that humankind could survive while becoming more machine-like, all the while machines become more human-like—these two extremely complex systems neither merging nor dominating, as much as coexisting. After all, earlier evolutionary milestones that could easily have been considered transcendent singularities at the time—such as galaxies spawning complex stars, primitive life emerging on hostile Earth, or plants and animals adapting for the benefit of each—did not result in dominance, but rather coexistence.

Men and machines need not compete, battle, or become mutually exclusive; they might well join into a symbiotically beneficial relationship as have other past complex systems, beyond which even-higher Φ_m systems they—and we—may already be ascending with change, that is, evolving a whole new complex state that again becomes greater than the sum of its parts. The technological singularity—one of many other singularities among a plethora of evolutionary milestones in natural history and not likely the pinnacle or culmination of future cosmic evolution—fosters controversy because it potentially affects our human selves, and even elicits calls for ethical constraints and regulatory restrictions on technological innovation and advancement. Should we strive to preserve our essential humanity and halt the growth of machines? To my mind, given the natural rise in an expanding Universe of the curves in Figs. 20.2 and 20.3, we should not and could not.

The culturally increasing Φ_m values reported here—whether slow and ancestral such as for controlling fire and tilling lands by our provincial forebears, or fast and modern as with operating engines or programming computers in today's global economy—relate to evolutionary events in which energy flow and cultural selection played significant roles. All of this complexification, which has decidedly bettered the quality of human life as measured by health, education, and welfare, inevitably came—and continues to come—at the expense of greatly increased demand for more and enriched energy, which now drives us toward a fate on Earth that remains unknown.

Summary

Cosmic evolution is more than a subjective, qualitative narration of one unrelated event after another from big bang to humankind. This extensive scientific scenario provides an objective, quantitative framework that supports much of what comprises material Nature. It addresses the coupled topics of system change and rising complexity—the temporal advance of the former having apparently led to the spatial growth of the latter, yet the latter feeding back to make the former increasingly productive. It implies that basic differences both within and among the many varied complex systems in the Universe are of degree, not of kind. And it contends that evolution, broadly construed, is a universal concept, indeed a unifying principle throughout modern science.

More than perhaps any other single factor, energy plays a central role throughout the physical, biological, and cultural sciences. Energy seems to be an underlying, universal driver like no other in the evolution of all things, serving as a common currency in the potential unification of much of what is actually observed in Nature. Energy rate density, in particular, is an unambiguous, weighted measure of energy flow, enabling assessment of all complex systems in like manner—one that gauges how over the course of natural history writ large some systems optimally commanded energy and survived, while others apparently could not and did not.

Human society and its invented machines are among the most energy-rich systems known, hence plausibly the most complex yet encountered in the

Universe. Cultural innovations, bolstered by increased energy allocation as numerically tracked by rising Φ_m values, enable 21st century *H. sapiens* not only to circumvent the degrading environment on Earth but also to challenge it, indeed manipulate it. Technological civilization and its essential energy usage arguably act as catalysts, speeding the course of cultural change, which like all of cosmic evolution itself is unceasing, uncaring, and unpredictable.

Whatever our future portends—whether a whole new phase of cosmic evolution or merely the next, gradual step in cultural evolution, be it complex survival or simple termination—it will be a normal, natural outcome of cosmic evolution itself. For humanity, too, is part of Nature—and however humbling, we are likely just another chapter in a meta-story yet unfinished. Grand evolutionary events such as the oncoming technological singularity of human–machine interplay have occurred in the past many billions of years, and they will likely continue occurring indefinitely, forevermore yielding creativity and diversity in a Universe that expands, accelerates, and evolves. Think big, accept change, use energy wisely, adapt and prosper.

Acknowledgments I thank colleagues at the Smithsonian Astrophysical Observatory and students at Harvard University for discussions of this topic, and la Fondation Wright de Geneve for research support.

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Chapter 20A

Theodore Modis on Chaisson's "A Singular Universe of Many Singularities: Cultural Evolution in a Cosmic Context"

The concept of Φ_m is the best attempt at rigorously quantifying complexity that I have seen, albeit with shortcomings, e.g. no one will accept that bicycle riding is ten times more complex than violin playing or that a jet engine is 1000 times more complex than a mammalian organism! My attempt to quantify complexity (discussed in the second part of my essay) is only in relative terms and is based on data that may be subject to subjective judgment. Of course there must have also been some subjective estimates in Chaisson's data, for example, in the calculation of Energy Rate Densities of hunter-gatherers, agriculturists, industrialists, etc., which may mask a leveling-off of the straight-line trend of the O data points in Fig. 20.3, similar to the visible leveling-off of the X data points. These leveling-offs are evidence that we are dealing with S-curves and combined with the acknowledged leveling-off of the two early curves in Fig. 20.2, reinforces the general conclusion that exponential trends of Phi are in fact early parts of S-curves.

Chaisson is being conservative. He modestly says that "I sense, but cannot prove, that information is another kind of energy" while he could have easily argued that information content is proportional to entropy which is equal to Q/T (heat over temperature), which IS energy. He also says that the drawn curve of the shaded area of Fig. 20.2 is the compound sum of multiple S-curves, but stops short of using S-curves to extrapolate it into the future. In fact he refrains from committing himself to any future eventuality one way or another. (One would have welcomed at least an educated guess from such an expert!)

Having spent most of my career with S-curves I can see in Chaisson's Fig. 20.3 that the two "S-curves" depicted by the dashed and dotted lines determine the shape of the late part of the third "S-curve" labeled society on Fig. 20.2. Furthermore, these two curves in Fig. 20.3 have life cycles that become shorter with time (acceleration effect). Life cycles getting shorter is evidence for saturation. As I mention in my essay there is a fractal aspect to S-curves. A large-scale S-curve can be decomposed to smaller constituent S-curves the life cycles of which become shorter as we approach the ceiling of the envelope curve (see also publication http://www.growth-dynamics.com/articles/Fractal.pdf). I can then conjecture that the line labeled society in Fig. 20.2 is an S-curve that presently finds itself beyond its midpoint, i.e. experiences a progressive slowdown of its rate of growth. An imminent slowdown in the rate of growth of Phi (and complexity) corroborates a similar conclusion in my essay.