Advanced Track, Epoch 7

Cultural Evolution

This Advanced Track provides a technical supplement to the introductory web site on cosmic evolution, produced by Eric Chaisson and based on courses taught mainly at Harvard University for the past few decades:
http://www.cfa.harvard.edu/~ejchaisson/cosmic_evolution/docs/splash.html

Currently, this Advanced Track is abbreviated while addressing mainly the concept of energy rate density—a numerical quantity proposed as a useful complexity metric for an underlying, unifying process that guides the origin, evolution, and destiny of all organized systems across the arrow of time, from big bang to humankind. In the summer of 2014, this supplement will grow dramatically, providing much more pertinent technical material at an advanced, quantitative level (suitable for colleague scientists and graduate students) well beyond that presented in the above-linked introductory web site (which is meant for non-scientists and beginning students).

A summary of this Advanced Track is here:
http://www.cfa.harvard.edu/~ejchaisson/advanced_track_sitesum.pdf

Further material related to the subject of cosmic evolution is available at:
http://www.cfa.harvard.edu/~ejchaisson
including a collection of recent research papers easily accessed and downloadable at:
http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf

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Cosmic Evolution

Cultural evolution is an integral part of the grand scenario of cosmic evolution:

Cosmic evolution = physical evolution + biological evolution + **cultural evolution**.

During this seventh, cultural epoch, human society and its technological gadgets display relatively high values of energy rate density, $\Phi_m \geq 10^5$ erg/s/g.

Cultural Evolution

If cosmic evolution qualifies as a comprehensive scientific worldview from big bang to humankind, then human society and its many cultural achievements must be included, anthropocentric criticisms notwithstanding. Nature, alone and without sentient, technological beings, could not have built the social systems and technical devices characterizing our civilization today. Humankind itself is surely a part of Nature and not apart from it, indeed an integral module of cosmic evolution writ large; schemes that regard us outside of Nature, or worse atop Nature, are misguided. To examine how well cultural systems resemble physical and biological systems, this Advanced Track for the CULTURAL EPOCH explores the evolution of cultural complexity, as gauged consistently and uniformly by the same quantity of energy rate density that has characterized all other complex systems encountered throughout these Advanced Tracks.

By cultural evolution, we denote the changes in the ways, means, actions, and ideas of societies, including the transmission of same (which some call "memes"; Dawkins [*Selfish Gene*, Oxford U Pr, 1976]) from one human generation to another. Human culture, in particular, is a collection of human minds, often acting cooperatively over the ages. Foremost among the more utilitarian changes that helped make us cultured, technological beings were the construction and refinement of useful tools, the development and teaching of meaningful communications, the invention and practice of profitable agriculture, and not least the discovery and harnessing of controlled energy. All of these are essentially manufacturing advances that expend energy and do work—decreasing entropy at the locality of the cultural change and increasing (by an even larger amount) entropy elsewhere in the wider world beyond. Thermodynamic terms may be unfamiliar to field anthropologists or cultural historians, but the fundamental processes governing the changes in intelligent life and its sentient society are much the same, albeit a good deal more complex, as for galaxies, stars, planets, and non-intelligent life.

Furthermore, humankind's cultural traits were advanced and refined over scores of generations. The bulk of human knowledge was, and is being, transmitted to succeeding offspring not by direct genetic inheritance but by the use and disuse of information available indirectly in the surrounding environment. Without enumeration, imagine the increase in complexity and sophistication gained gradually or episodically during no more than the most recent million years: implements, language, foodstuffs, and power, among many other cultural factors acquired on the road to humanity. Of all these, language was probably paramount, ensuring that knowledge and experience stored in the brain as memory could be accumulated by one generation and transferred to the next—which is why, for some neurobiologists, language and intelligence are virtually synonymous.

A mostly Lamarckian process (see next subsection) whereby evolution of a transformational nature proceeds via the passage of acquired characters and 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 methods of survival to their descendants by non-genetic, meme-like routes; communication passes behaviorally, from brain to brain and generation to generation, the result being that cultural evolution acts much faster than biological evolution. Genetic selection itself operates little, if at all, in these 2 evolutionary realms—physical and cultural—that sandwich the more familiar neo-Darwinism, for which selective pressures clearly dominate. Even so, a kind of selection works culturally, as noted more below; the ability to start a fire, for example, would have conferred a major selective asset for those hominids who possessed it, as would sharpening a tool or controlling energy. It is this multitude of cultural advancements in relatively recent times that accelerate and complexify change—advancements which, in turn with the scientific method, enable us to explore, test, and better understand the scenario of cosmic evolution.

As different as they are, biological and cultural evolution are not unrelated, as might be expected for adjacent phases of cosmic evolution (*cf*, penultimate section below of this Advanced Track for CULTURAL EPOCH). Somewhat surprisingly, though, these 2 phases enjoy a subtle reciprocal interplay. Discoveries and inventions may well have been made by talented individuals having the "right" combination of genes, and once made, an invention such as lighting a fire or sharpening a tool likely, in turn, granted a selective (*ie*, reproductive) advantage to those better endowed genetically to handle the skill. The 2 kinds of evolution thus partially complement one another, although in the recent history of humankind, Lamarckian (cultural) evolution has clearly dominated Darwinian (biological) evolution. Cultural acquisitions spread much faster than genetic modifications; our gene pool differs little from that of a Cro-Magnon human of 15 kya, yet our cultural heritage is now much more robust in the knowledge, arts, traditions, beliefs, and technologies invented and transmitted during the past ~600 generations.

Lamarckism: Jean-Baptiste de Lamarck, in his masterwork, *Philosophie zoologique* (Paris, 1809), developed the idea of "inheritance of acquired characters" and is often considered the founder of modern evolutionism. Favoring the uniformitarian (or slow-change) as opposed to catastrophic (or violent-change) school of geology, Lamarck repeatedly stressed the gradual, even sluggish tenor of the events that cause change, both physically and biologically. Lamarck's central thesis has come to be known as the law of use and disuse, whereby the environment does not affect changes in life forms; rather, individual life forms gradually change in proportion to the extent that they use, or not, their existing traits. We now realize that Lamarckism, as an alternative mechanism to Darwin's natural selection, is probably wrong, but it does seem to correctly describe much of cultural evolution.

In the classical example cited in most of today's biology textbooks, Lamarckism maintains that giraffes have long necks because the necks of some of their predecessors were used extensively, even stretched in order to reach the leaves high in the trees of the African plains, after which the long necks were inherited. Similarly, wooly mammoths produced more hair in cold climates because in glacial times parents grew thicker hair and transmitted hereditary potential for hair growth to their offspring. Little or no genetic selection is involved in Lamarckism as the dynamic regards the individual. However, carefully controlled experiments have since strongly implied that such contributions are factually incorrect; necks stretched, hair thickened, and muscles made large by heavy use are not passed on to the next generation of offspring.

Given neo-Darwinism's 20th-century success accounting for life's many varied changes by means of natural selection within a population of individuals (*cf*, Advanced Track for BIOLOGICAL EVOLUTION), Lamarck's explanation for the mechanism of biological evolution is no longer tenable within the scientific community; rather, we accept, with Darwin, that those giraffes that are genetically endowed with longer necks are the ones that survive better and reproduce more progeny because of their advantage in reaching higher leaves.

By contrast, much of cultural evolution, which follows biological evolution and does incorporate the direct passage of traits and factors that made us human, obeys (at least in part) Lamarckism; the "good" traits invented, used, and accumulated by one generation are granted directly to the next generation by means that favor schooling, memory, tradition, among other social means that communicate knowledge.

As such, Lamarckism emphasizes change for isolated, individual organisms; this mechanism, in principle, could work even if no more than a single individual were alive at any one time. By contrast, Darwinism, which affects change among populations of many organisms, cannot operate with only 1 organism; it's a group concept. In fact, perhaps the most distinguishing characteristic of Darwinism is that it works on populations, not individuals. This explains in part why Darwinism dominates biological evolution, Lamarckism cultural evolution.

Cultural Complexity: That social systems represent some of the most complex phenomena in the known Universe is undeniable. Human actions, largely dependent on energy use and now influenced by irregularly changing environments, are what makes social studies so difficult. Unlike for much of the physical and biological sciences, controlled experiments in cultural evolution—humans interacting (social psychology), cities functioning (urban economics), or nations jousting (risky geopolitics)—are nearly impossible to conduct objectively. Modeling social behavior, let alone experimenting with it, is much harder to accomplish than manipulating molecules in chemistry laboratories or sending spacecraft to distant planets; the number, diversity, and interconnectedness of factors influencing human relations greatly exceed those affecting the fate of stars or the evolution of plants. Although a physicist or chemist might never have a concern for an individual atom or molecule, sociologists often treat the human behavior of single individuals as paramount—and that, ironically, is what makes their task all the more difficult, subjective, and complex, for not even statistical reasoning can help much.

A few examples of Lamarckian-style cultural change toward greater complexity will suffice. Consider first the above-noted preeminent exemplar of culture: language. Language is transmitted largely through the media of teaching and schooling, passing on knowledge from adult to offspring, not perfectly but adequately (and including imitatively) over the years. Not only do we transfer information to our children in this way, but the body of available knowledge itself also grows with the acquisition of new stories, facts, and techniques. And because that knowledge accumulates faster than it is forgotten (especially with the onset of recorded history), the sum total of culture passed along builds, indeed grows richer and more complex. That's why it now takes a third of human lifetime to train for a doctorate in science or medicine, despite deep specialization. Human knowledge today far exceeds that of any one individual. Hardly any of our cherished educational facts, models, and methods are transmitted via the biochemistry of genes; those genes do grant hard-wired abilities to learn from other human beings, but learning itself is a surprisingly long, hard struggle, often overcome by application of, yes, energy. Cosmic evolution is itself a cultural story, indeed one hereby disseminated on this web site as a scientific narration—albeit a gross simplification of an exceedingly complex approximation of reality.

Society Advancing

Consider modern civilization *en masse*, which can be considered the totality of all humanity comprising a (thermodynamically) open, complex society going about its daily business. Today's ~7 billion inhabitants utilize ~18 TW to keep our global culture fueled and operating, admittedly unevenly distributed in developed and undeveloped regions across the world (UN Dept Econ Soc Affairs, Population Div, *World Population Prospects,* 2008). The cultural ensemble equaling the whole of humankind then averages $\Phi_m \approx 5\times10^5$ erg/s/g.

Unsurprisingly, a group of intelligent organisms working collectively is more complex than all of its individual human components, who each display Φ_m values an order of magnitude less, lest their human bodies literally fry. This accords well with the complexity metric of energy rate density hypothesized in these Advanced Tracks—a good example of "the whole being greater than the sum of its parts," a common characteristic of emergence fostered here by the flow of energy through organized, and in this case social, systems.

Note that in calculating Φ_m for contemporary society, only the mass of humankind per se is used. The mass of modern civilization's infrastructure—buildings, roadways, vehicles, and so on, are not included—any more than is the mass of the clothes we wear when calculating Φ_m for the human body, or the mass of the human body itself when evaluating the human brain, (*cf*, Advanced Track for BIOLOGICAL EPOCH), or the mass of the host Galaxy when considering the Sun (*cf*, Advanced Track for STELLAR EPOCH). That is, human society is taken to mean literally the mass of humanity, for what matters is the flow of energy through the human social aggregate. While attempting to assess the degree of systems' complexity, it is reasonable and proper to consider systems separately from their environments, much as has been consistently done in earlier thermodynamic analyses throughout these Advanced Tracks. As with all systems studied in this work, the sum total of complexity for a system *and* its environment will always be unimpressively low (in fact technically negative), as demanded by the 2nd law of thermodynamics.

Rising energy expenditure per capita has been a hallmark in the origin, development, and evolution of humankind, an idea dating back decades (*e.g.*, White, *Evolution of Culture*, McGraw-Hill, 1959). However, none of these early energy-centered cultural claims addressed causality or were in any way quantitative, as noted the anthropologist Richard Adams (*Energy and Structure*, U Texas Pr, 1975; *World Futures: J Gen Evol*, v66, p470, 2010): "To ask whether this increase in energy in the system is 'caused' by something or another is not helpful if one seeks a 'prime mover'; the fact that it conforms to the widely observed principle of natural selection and the Second Law of Thermodynamics will have to stand as an 'explanation' for the present. The concentration of energy within life systems follows the Second Law, and such a concentration will continue insofar as conditions of life may be met and the continuing supply of energy from the sun is available." By contrast, these Advanced Tracks seek to specify, if broadly, that causative agent, or prime mover, in the guise of cosmic expansion, which, in turn, advances the arrow of time and with it flows of energy within increasingly evolved, complex systems.

Culture itself is often defined by social researchers as a quest to control greater energy stores (Smil, *Energy in World History*, Westview, 1994). Cultural evolution occur, 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. Values of Φ_m can be estimated by analyzing society's use of energy by our relatively recent hominid ancestors.

Rate Density for Society: The following few paragraphs gauge energy usage among different types of human groups throughout time, illustrating how, in turn, advancing peoples of the genus *Homo* utilized increasing amounts of energy beyond the 2-3000 kcal/day that each person actually eats as food (Cook, *Man, Energy, and Society*, WHFreeman, 1976; Bennett, *Ecological Transition*, Pergamon, 1976; Simmons, *Changing the Face of Earth*, Blackwell, 1996; Spier, *Soc Evol & History*, v4, p87, 2005; Chaisson, *Complexity*, v16, p27, 2011, DOI 10.1002/cplx.20323).

Australopithecines, among the most primitive societies of hominids, had available for work only the physical energy of their individual work ethic. For a 50-kg post-australopithecine forager ~3 Mya, that energy would have been ~2000 kcal of food eaten per day, granting it $\Phi_m \approx$ 19,000 erg/s/g.

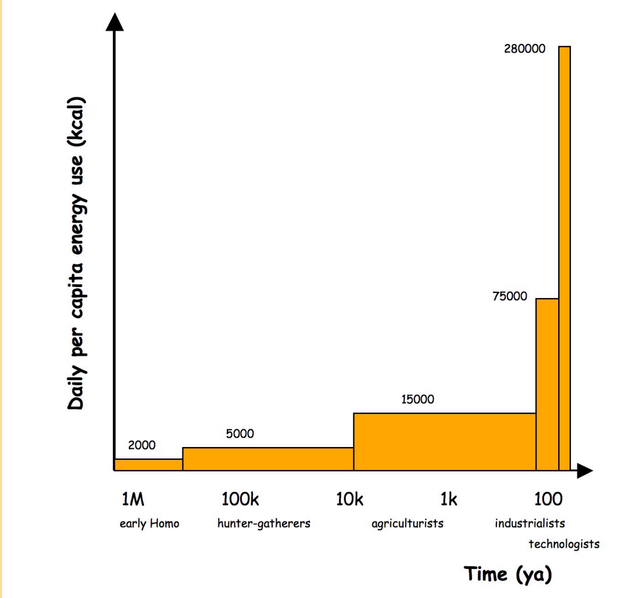
Hunter-gatherers as long ago as ~300 ky likely augmented by small amounts the basic energy of food needed to survive. Anthropologists have studied these relatively simple material cultures and the energy flowing through their ecosystems, not only by unearthing ancient habitats of extinct forebears but also by observing mores of modern hunting groups extant in today's tropical forests. Besides food requirements that granted their (40-kg) australopithecine foraging ancestors ~2000 kcal daily, thus $\Phi_m \approx$ 22,000 erg/s/g, small amounts of additional energy were likely used both to gather the food and also to prepare it for consumption. For example, early domestication and subsequent use of dogs would have aided the hunt for food, but of course the dogs too need nourishment. Fire useful in the hunt and also in the preparation of some foods would have also employed more energy; in particular and possibly as much as 165 kya, not only for cooking but also heat-treating stone to make better tools (Webb and Domanski, *Science*, v325, p820, 2009), the exploitation of energy would have roughly doubled to 40,000 erg/s/g for slightly heavier, archaic *H. sapiens*. Ample evidence exists that even earlier hominids, notably *H. erectus*, used pits for roasting animals, and perhaps even in the drying of foodstuffs prior to their preservation and storage to guard against lean periods. Fire also allowed the preparation of certain vegetables known to have been then widely consumed, such as yams that require washing, slicing, and leaching with hot water to remove alkaloid poisons. To what extent hunter-gatherers merely used fire when and where available, in contrast to actually possessing it or controlling it, is unknown—but it does represent, at least in some small way, an addition of primitive culture to the basic metabolic energy used by early humans.

Agriculturists ~10 kya not only used fire but clearly controlled it, constructed irrigation ditches and terraced fields, probably employed rudimentary windmills and watermills, and used draft animals to plow fields more deeply and extensively (such animals typically delivering ~600 W of power, compared to human exertion averaging 75 W)—all with the intent of increasing crop productivity. Such advances have been documented by anthropologists throughout more recent, if still prehistoric, times, especially where remains of fully domesticated varieties of plants and animals are evident in archaeological contexts. Such occurred in many locales globally including, for example, southwest Asia (~9 kya, or ~7000 y BCE), the Middle East and Mediterranean (~8 kya), and Meso-America (~7 kya), although agriculture may well have begun in western Asia where collections of wild grains are found ~11 kya among nomadic tribes who were still at the time hunter-gatherers. Later domestication allowed human societies to actively alter the genetic composition of organisms by breeding (*i.e.*, replacing biological natural selection with human-directed cultural selection, mostly by trial and error and without any knowledge of genes; *cf*, Advanced Track for BIOLOGICAL EPOCH), thereby cultivating plants such as maize (now 7X the size of its original, undomesticated cobs) and sugarcane (now much more efficient than its natural strain). The poverty of energy apparently limited cultural development, yet with the onset of agriculture and the use of trained animals ~10 kya, the equivalent energy available to individual *H. sapiens* (assumed here to be a 50-kg body) increased to ~12,000 kcal/day, or $\Phi_m \approx 10^5$ erg/s/g; in turn, these would have easily doubled with the invention of advanced farming techniques and the invention of metal and pottery manufacturing a few millennia ago. (Today, the most intensive agricultural methods yield as much as 40,000 kcal/day/person.) Ecosystems had clearly shifted from food collection gathered in the wild to food production by deliberately managed plans, and the results included the growth of cities, the dawn of industry, and soon thereafter the advent of professional warriors, regional alliances, and ultimately nation states. Agriculture's greatest achievement was to feed the growing human population, which rose from ~170 M people ~2 kya (1 C.E.) to ~450 M some 500 ya and to ~900 M about 200 ya. Underlying all this cultural advancement was greater energy usage per unit mass at each and every step of the way.

Industrialists of a couple centuries ago learned to use energy to drive machines to power their homes and shops, thereby causing huge demand for fossil fuels and hydropower, which in turn revolutionized the production of goods, agriculture, transportation and communications. The burning of coal at the start of the Industrial Revolution afforded each member of a young, mechanistic society (especially in Britain, Germany, and the United States) a great deal more energy for use in daily, societal activities. Although human population rose greatly by ~5 billion people since 1800 C.E., reaching ~6 billion by the year 2000, per capita energy usage also increased—in fact, well exceeded the energy contained in the food that people physically consumed or even produced. Thus, the total energy utilized during this period climbed dramatically and globally, much more so than when our earlier ancestors mastered the use of fire or invented solar-driven agriculture. Comparing the prior agricultural age with the current fossil-fuel-driven industrial age, the per capita energy usage easily rose 5-fold. Typically, throughout the world today, each citizen averages 5×10^5 erg/s/g, which is roughly an order of magnitude more than our hunter-gatherer forebears. Again, as with estimates of Φ_m for galaxies, stars, plants, and animals in earlier epochs of these Advanced Tracks), this is an average value within a range of variations, since residents of advanced, OECD (Organization for Economic Co-operation and Development) countries, such as those in Europe and N. America, use several times more, whereas developing (non-OECD) countries, such as China, India, and all of Africa, use several times less. For example, per capita expenditure of energy now averages 2.7 kW globally, yet varies regionally from ~0.5 kW for Africa to ~4.5 kW for Europe and to ~12 kW for N. America (*UNEP, Environmental Report, 1993-94*, Blackwell). The result, ecologically, is that the stored photosynthetic energy of fossil hydrocarbons has been added to the daily energy arriving from the Sun (and more recently that of terrestrial nuclear energy as well), all of which are employed by human societies in various ways to access more resources and yield yet more productivity as well as to change the fabric and constitution of our earthly environment. Such unprecedented use of energy to produce goods, services, and knowledge (which, in turn, furthers the acquisition of still more energy) has also taken a toll on that environment. Regardless of all else, the 2nd law of thermodynamics demands that as any system complexifies—even a human social system—its surroundings necessarily degrade (*cf*, Advanced Track for FUTURE EPOCH).

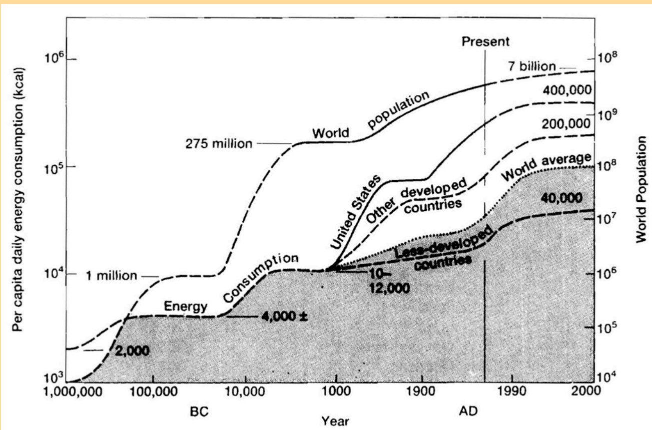
Technologists represent the most developed and energy-intensive, yet wasteful, part of society today, displaying during the past half-century large electricity and transportation allocations in their energy budgets. Distinguished from industrialists, technologists employ an energy rate density (>10^6 erg/s/g) that is several times greater than that of traditional commercial society, (perhaps epitomized by astronaut-elites who individually enjoy energy shares of ~10^7 erg/s/g while orbiting aboard the International Space Station, or an equivalent per capita energy use of ~1.5 million kcal/day, which is fully ~500X more than each of us actually consumes as food daily). Symbolized by the most heavily energy-using countries such as the United States, Canada, Bahrain, and Qatar, technological societies have distinctly higher Φ_m values than the average global citizen on Earth today or even than those living in the developed countries of Europe. To give but a single example of such energetic excess: With coordinated power generation and widespread distribution systems boosting the effective daily usage of energy, the per-citizen expenditure in *all* countries averaged 80,000 kcal by 1970, or ~5×10^5 erg/s/g; now, early in the 21st century, with ~25% of the world's total power consumed by only 5% of the world's population mostly living in the U.S., this one country averages 2×10^6 erg/s/g (which amounts, by the way, to ~12.5 kW for each U.S. citizen, compared to ~3 kW per person globally). Thus, modern high-tech conveniences, from automobiles, aircraft, and centralized heating/cooling to a wide variety of energy supplements enhancing our information-based society (including wired homes, networked businesses, and consumer electronics of all sorts), have empowered today's individuals well beyond their daily food intake (*World Energy Outlook*, Int Energy Agency, Paris, 2009; *Int Energy Outlook*, US Dept of Energy, Washington, 2006). And all these energy budgets are still rising—in both absolute energy terms as well as per capita energy accounts.

The following figure graphically summarizes all these societal Φ_m values, showing a set of histograms displaying estimates of energy used by different types of human groups throughout time.



Per capita daily energy usage by human groups at various historical stages displays a dramatic rise in recent times. All groups need a minimum of ~2000 kcal for daily food. Hunter-gatherers needed more to feed their animals, and agriculturists even more so when using energy for rudimentary trade and commerce. Industrialists ~2 centuries ago used considerably more energy for commerce, industry, and transportation of goods. Today's technologists utilize much more energy, about equally distributed among those three sectors, of which much of the first two are powered by electricity. (Adapted, updated, and revised from Bennett, Ecological Transition*, Pergamon, 1976).*

The growth of energy use throughout the world as a whole can be put into perspective by considering another useful diagram. The figure below depicts the rise of both energy consumption and world population, showing how, not only has global population grown, but so has per capita energy usage—making clear humankind's formidable, ongoing, and rising energy demands, along with potentially serious consequences for environmental degradation and our future well being. The bottom line is that our complexity metric of energy rate density has continued rising right up to the present, as today's world has indeed become a humming, beeping, well-lit place—and there seems no reason to think that it will not continue rising, indeed increased per capita energy use might well be an cultural imperative if the human species is to survive.



World population is logarithmically plotted here as the right ordinate and per capita energy use as the left ordinate, both against time dating back ~10^5 y. (Cook, Man, Energy, Society*, WHFeeman, 1976)*

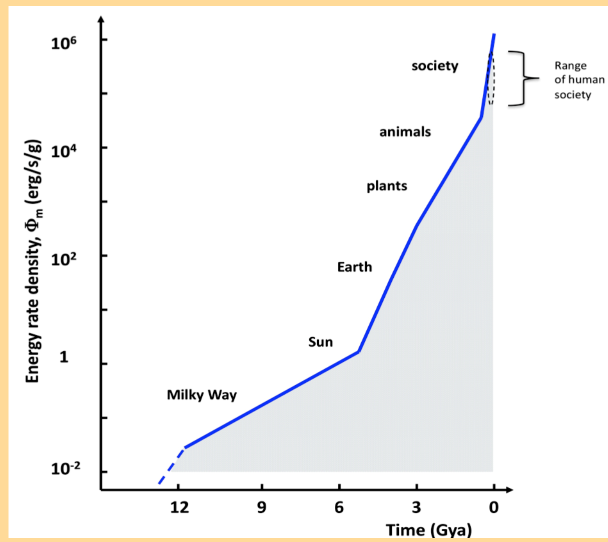
Much confusion surrounds the use of different unit systems to describe the rate of energy flow through various human groups and societies. To help make a connection between the cgs metric units used in these Advanced Tracks and other units often used by natural scientists (SI) and social scholars (per capita), the table below summarizes Φ_m values in different, but equivalent, units, compiled from several of the sources listed above. Researchers from different specialties tend to use seemingly incompatible (and sometimes non-metric) units to express the same quantity, and so this table cross-correlates 4 sets of commonly used units. (Numerical values are rounded off, as they are all approximations, based on estimates available in 2012.)

Cultural Φ_m Values in Different Units

human category	erg/s/g	W/kg	kW/person	kcal/day/person
technologists*	2×10^6	200	12.5	280,000
modern citizens**	5×10^5	50	3	90,000
industrialists	4×10^5	50	2.7	80,000
agriculturists	10^5	12	0.6	15,000
hunter-gatherers	4×10^4	5	0.2	5,000
australopithecines	2×10^4	2	0.1	2,000

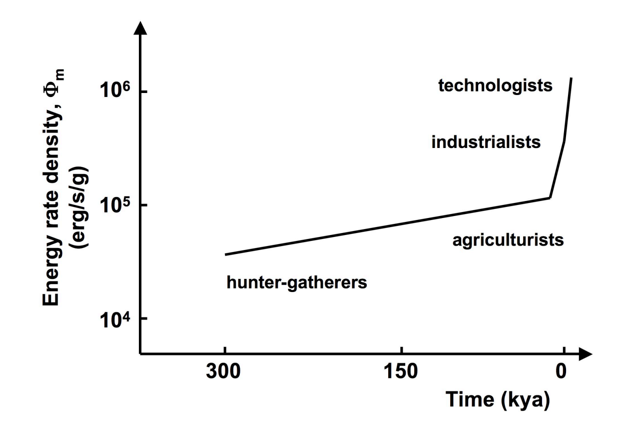
*Mainly citizens of USA and a few other energy-rich countries
**All citizens of the world today, globally averaged

The figure below shows the range of cultural advance among our relatively recent ancestors, graphed in a manner similar to our previous energy-flow analyses in these Advanced Tracks for galaxies and stars, or plants and animals, indeed for any complex system in Nature—of which today's increasingly sophisticated, energy-hungry society is just one more example.



This graph repeats the essence of an earlier one (cf, end of Advanced Track for PARTICLE EPOCH), suggesting Φ_m as a measure of rising complexity over all historical time. The dashed oval includes the range of increasingly ordered structures for a variety of human-related advances—in this case, usage of energy by ancestral groups in the cultural-evolutionary phase of cosmic evolution.

The next figure shows a more detailed, expanded view of Φ_m during more recent times—mainly to illustrate cultural advancement and their times of origin contained within the small dashed oval of the previous figure. Note how industrialists of hundreds of years ago had higher energy rate densities than agriculturists or hunter-gatherers of thousands of years ago, and, in turn, more energy affluent western society today still higher values. Here, social progress, unapologetically expressed in terms of energy consumption and quantified by Φ_m, is graphically traced for a variety of human-related strides among our recent hominid ancestors.



The complexity of humankind, expressed in terms of Φ_m, is shown here only for the range of the previous figure outlined by the dashed oval. Note how the rise has been truly dramatic in very recent times as our civilization became so heavily wedded to energy for its health, wealth, and security.

Technology Evolving

Foremost among the advances that helped make us cultured, technological beings were the invention and utilization of tools, which require energy to make and use, all the while decreasing physical entropy within those social systems employing them and increasing it elsewhere in wider environments beyond. Thermodynamic terminology may be unfamiliar to cultural anthropologists or world historians, but the primary 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.

Thus, caution is urged when claiming teleologically (Spier, *Big History and the Future of Humanity*, Wiley-Blackwell, 2010) that the cultural complexity of powered devices differ fundamentally from other forms of complexity because they perform functions for the humans who built them. Rather, it would seem that humans, their machines, among all the other complex systems encountered throughout these Advanced Tracks and across the history of time to date, are merely members of a continuum of rising complexity, from big bang to humankind. History repeatedly shows that we like to regard ourselves and our accomplishments as special, yet even in the unlikely event that we are alone in the Universe, it is still likely that we are no different, at any kind of basic level, than all the other complex systems in the richly endowed Universe.

Engines and Aircraft: Among many current cultural icons, one of the most prominent is the automobile, and not just in developed countries whose citizens can afford this transportation tool. Motor vehicles are ubiquitous across planet Earth, for better or worse archetypical symbols of technological innovation in our modern society. In keeping with the energy-based analyses applied throughout these Advanced Tracks—and as a reality check on our thermodynamic interpretation of cultural evolution—a value of Φ_m can be calculated for today's average-sized automobile, whose typical properties are ~1.6 tons of mass and ~10^6 kcal of gasoline consumption per day; the answer, $\Phi_m \approx 10^6$ erg/s/g (assuming 6 hours 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—indeed, for what some still claim is the epitome of American industry. Put another way to further illustrate evolutionary trends and using numbers provided by the U.S. Highway Traffic Safety Administration (*Automotive Fuel Economy Program*, Annual Update 2004, DOT HS 809 512, U.S. Dept. of Transportation, 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 uniformly and consistently through the Advanced Tracks, these values equal 6.1, 6.7, 8.4, and 9.1, all times 10^5 erg/s/g respectively. (By comparison, a literal draft horse's power density equals ~745 W/800 kg, or ~10^4 erg/s/g, a value appropriately within the midst of the mammalian range, as noted in the Advanced Track for the BIOLOGICAL EPOCH). Not only in and of themselves but also when compared to less powerful and often heavier autos of >50 ya (whose Φ_m values average well less than half those above), the trend of these numbers confirms once again the general correlation of Φ_m with complexity. No one can deny that modern automobiles, with their electronic fuel injectors, computer-controlled turbochargers, and a multitude of dashboard gadgets are more complicated than Ford's "Model-T" of nearly a century ago—and that more energy is expended per unit mass to drive them.

The postulated evolution-complexity correlation 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, *Energies*, MIT Pr, 1999)—all notable examples of technological innovation during the power-greedy 20th century. 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 less Darwinian than Lamarckian, hence quicker too. Energy remains the 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. For example, the pioneering 4-stroke, coal-fired Otto engine of 1878 had a Φ_m value (~4×10^4 erg/s/g) that surpassed earlier steam engines, but it too was quickly bettered by the single-cylinder, gasoline-fired Daimler engine of 1899 (~2.2×10^5 erg/s/g), more than a billion of which have been installed to date in cars, trucks, planes, 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 racing cars (akin to temporarily active galaxies or metabolically charged race horses) can reach an order of magnitude higher still. Among aircraft, the Wright brothers' 1903 homemade engine (~10^6 erg/s/g) was superseded by the Liberty engines of World War I (~7.5×10^6 erg/s/g) and then by the Whittle-von Ohain gas turbines of World War II (~10^7 erg/s/g). Boeing's 707 airliner inaugurated intercontinental jet travel in 1959 when Φ_m reached ~2.3×10^7 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 generate up to 110 MW to power this 180-ton craft to just below supersonic velocity (Mach 0.9) with $\Phi_m \approx 2.7\times10^7$ erg/s/g.

The rise in Φ_m can be traced particularly well over several generations of jet-powered fighter aircraft of the U.S. Air Force, further testifying to the ever-increasing complexity of these supersonic and sophisticated machines (though here engine thrust must be converted to power, and for unloaded military jets operating nominally without afterburners typically 1 N ≈ 500 W, for which Φ_m values then relate to thrust-to-weight ratios). First-generation subsonic aircraft of the late 1940s, 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 70s, 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 progressively rose for each of the 5 generations of 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 (*cf*, USAF Factsheets for various aircraft: http://www.af.mil/information/factsheets/factsheet.asp?id=101).

Computing Machines: Another striking example of contemporary cultural evolution—this one a communication tool—is of course the computer, including stunning achievements in memory capacity and data processing speed. At the heart of every computer (as well as smart phones, digital cameras, ATMs, and many other consumer electronics) is the silicon chip whose complexity has grown geometrically in the past few decades. The number of transistors—miniature semiconductors acting as electrical amplifiers and logic gates—that fit within a single microprocessor has doubled every ~1.5 y, popularly known as "Moore's law" marking each computer generation; Pentium-II chips of the 1990s that still power many of our home computers hold >10^3 times as many transistors (7.5 million) as the Intel-8080 chip (6000 transistors) that pioneered personal computers a (human) generation ago, and today's state-of-the-art chip, the Itanium-2, holds nearly 100 times still more. Chip development has been so rapid and its multiplication so pervasive that our post-industrial society is often claimed to have already built more transistors than any other product in human history, including clay bricks.

Such stunning advances in computer technology can be expressed in the same quantitative language expressed elsewhere in these Advanced Tracks—namely, the rate of energy flowing through computers made of such 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 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 ~5200 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, ~22 kW) cabinets less energy flow yet higher energy rate density as computers began shrinking. By 1990 desktop computers specified much less power and mass (~250 W and ~13 kg), yet Φ_m remained high. And now, MacBook laptops need only ~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 new 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.

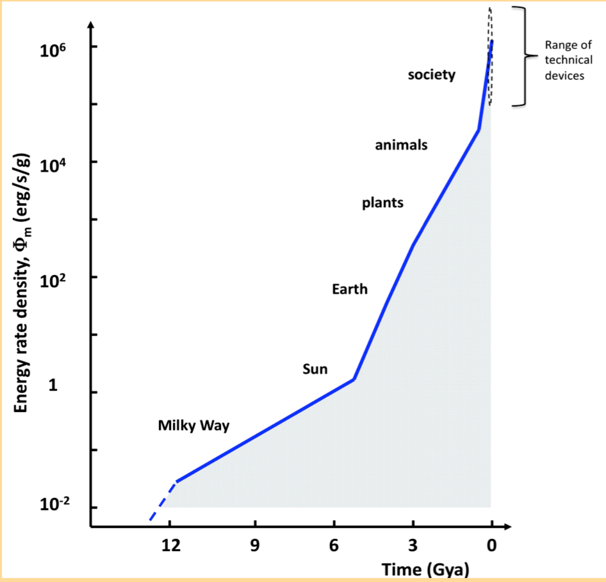
Although these and other cultural Φ_m values often exceed biological ones, machines are not claimed here to be "smarter." Values of Φ_m for today's computers approximate those for human brains (*cf*, Advanced Track for BIOLOGICAL EPOCH) largely because they number-crunch much faster than do our neurological systems; even slim 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 sentient than humans, but it does arguably make them more complex, given the extraordinary rate at which they can functionally acquire and process data—and not least digest energy per unit mass. Accordingly, our most advanced aircraft have even higher Φ_m values than our most sophisticated computers. Modern aircraft rely on computers but also possess many additional, technologically advanced features that together require even more energy density and make them yet more complex. That computers per se are amazingly complex machines, but not amazing enough for them to fly, does suggest that perhaps there is something significant—and perhaps inherently more complex—about both living species and technical devices that operate in 3-dimensional environments on Earth; whether insects, birds, or cutting-edge aircraft, these airborne systems exhibit higher values of Φ_m within their respective categories, more so to execute their extraordinary functions than to support their geometrical structures.

Nation-states and Economies: The makeup and operation—structure and function again—of whole cities, states, and nations can also be diagnostically analyzed in non-equilibrium, thermodynamic terms, for these too are dissipative structures (Dyke, in *Entropy, Information, and Evolution*, BHWeber [ed.], MIT Pr, 1999; Jervis, *System Effects: Complexity in Political and Social Life*, Princeton U Pr, 1997). Cities are dynamic steady-states, like any open system; they are the engines of growing economies, but they are also sources of air pollution and climate change. Cities acquire and consume resources, as well as produce and discard wastes, while processing energy for all manner of services: transportation, communications, construction, health, comfort, and entertainment, among a whole host of maintenance tasks. Modern cities are as much a product of an evolutionary process as any physical star or biological organism, and many are still developing, seeking to establish dynamically stable communities within our planet's larger, vibrant ecological system. Their populations are dense, their structures and functions highly complex; cities are voracious users of energy, their values of Φ_m higher than any in the previous paragraph (all normalized to the mass of the system for valid comparison). In a way, it is too early to tell if cities will survive; they are among the youngest advances of cultural evolution, prone to physical and social constraints that might well fundamentally change, or even eliminate (via selection), those very same cities. Urban planners could do worse than an integrated, evolutionary analysis of the social and environmental challenges now confronting human settlements.

Economies, too, are products of evolution; they are modes of organizing ecological space for increased flux, enhanced dissipation, and greater productivity. Although orthodox economic theory—even that which embraces thermodynamic thinking (Georgescu-Roegen, *Entropy Law and Economic Process*, Harvard Univ Pr, 1971)—treats the action of goods exchange as if it were reversible and equilibrated, much could be gained if economies were modeled as open systems enjoying a far-from-equilibrium status (Day, *Economic Evolution* *and Structural Adjustment*, v293, p46, 1987; Ayers, *Information, Entropy, and Progress*, AIP Pr, 1994).

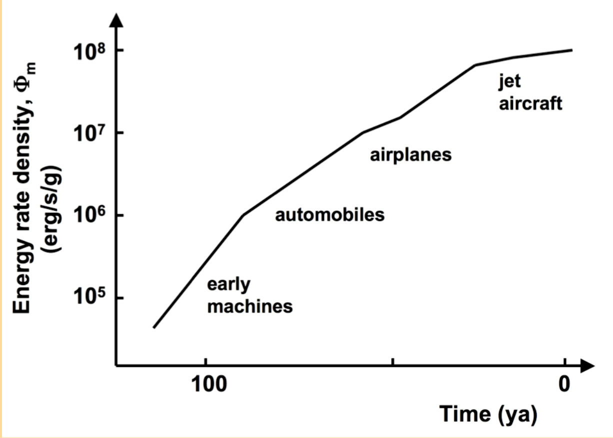
The emerging interdisciplinary subject of ecological, or evolutionary, economics highlights the celebrated concept of energy flow (including material resources), just as other bastions of specialization have rallied around energy flow as central to the interdisciplines of astrophysics and biochemistry. Understandably, social scholars concerned about natural science treading on their turf will at first reel at the notion of non-equilibrium conditions, market gradients, and institutional flux, all implying economic life (and politics) on the ragged edge of chaos. Yet if we have learned anything from the foregoing analysis, it is that organized, complex entities exist uneasily "on the edge," from unstable giant stars to struggling life forms to endangered ecosystems. It is, again, their dynamic steady-states that act as sources of innovativeness, creativity, and the very way that systems take advantage of chances to advance steadfastly along the scale of complexity. That mixture, once more, of randomness and determinism is also why realistic economies will never be predictable in detail, but will remain process-dependent, dynamic, and always evolving. By contrast, with regard to nation-states and the financiers who seek to control them, economic equilibrium would signify a meltdown, indeed a "heat death" of modern society—the unequivocal collapse of global markets.

The figure below places the range of cultural Φ_m values just discussed into our cosmic-evolutionary perspective. As with previous surveys of many complex systems within these Advanced Tracks, today's technologically sophisticated society is merely another example (albeit among the latest on Earth) of rising complexity with the advance of evolution writ large.



This graph repeats the essence of an earlier one (cf, end of Advanced Track for PARTICLE EPOCH), suggesting Φ_m as a measure of rising complexity over all historical time. The thin, dashed oval near the top includes the range of increasingly ordered stages for a variety of technological advances—in this case, usage of energy by human-built gadgets in the cultural-evolutionary phase of cosmic evolution.

The next figure summarizes in greater detail several of the above-derived, culturally oriented values of Φ_m as pertains to machines. Engines are only one of a multitude of technical devices invented, improved, and now used by humankind on Earth; many other cultural advances could be similarly analyzed, and most would display comparably high values of Φ_m. This graph illustrates for today's technologically sophisticated society, much as for so many other complex systems considered in these Advanced Tracks, how energy rate density parallels the rise of complexity in time.



The complexity of technological devices, expressed in terms of Φ_m, rises to illustrate increased utilization of power density by invented machinery. That rise has been dramatic within the past few generations as contemporary civilization has become so heavily dependent upon energy. Note that the timescale for this graph is much, much shorter than for the previous figure—here, roughly the past century of natural history—so it represents only a very small part of the curve within the narrow oval near the upper right of the previous figure.

Cultural Selection

Increases in Φ_m values have been the result of evolutionary, competitive processes in which once again selection—in this case, cultural selection—was at work, indeed in much the same way, albeit over shorter durations, as noted earlier for galaxies, stars, plants, and animals, to be sure for any other complex system. The technological advancement of humankind is a premier feature of cultural evolution occurring on Earth today. Technology is a cultural practice that decreases entropy locally by artificially manufacturing complex products, yet only with the sweat and toil of spent energy that inevitably increases entropy in the larger environment of raw materials used to make those goods. The result has been newer technologies systematically casting older ones into extinction, while usually benefiting humankind over the ages (Brown, *Ann Rev Energy*, v1, p1, 1976). Throughout the past few centuries, people chose shorter travel times, lower transportation costs, and heavier shipping loads; steam-powered iron ships replaced the wind-powered clipper ships, while wide-bodied jets have superseded them all. Likewise, "horsepower" provided literally by horse and mule was first marginalized and then intentionally eliminated by steam and eventually gas engines as work animals on most farms the world over; people elected to concentrate energy for greater efficiency. Typewriters, ice boxes, and slide rules, among many other innovative inventions in their own time, were selected out of existence by the pressure of customer demand and commercial profit, often replaced initially by luxuries that eventually became necessities, such as word processors, refrigerators, and computers.

Machines of the fast-paced 20th century can surely be cast in evolutionary terms—though here, as with all cultural articles, the process is less Darwinian than Lamarckian. Either way, energy remains the driver, and with accelerated pace—a clear display of evolutionary trends as engineering improvement and customer selection over generations of products made machines more intricate and efficient, yet more complex. Modern gadget-filled automobiles, for instance, 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 well while discarding the rest, thereby acquiring and accumulating successful traits from one generation of cars to the next. Today's cultural selection works by means of company competition and citizen preference in the social marketplace; Lamarckian use and disuse aids change and improves technology in automotive style, operation, and safety, all of which feed back to increase the pace of our lives and the thrust toward even greater complexity—for the bottom line is that more energy is expended per unit mass to drive those newer vehicles.

Emerging Bioculture

With the arrival of human-induced problems of a global, technological nature—atmospheric pollution, ozone depletion, overpopulation, species extinction, scarce food, water and natural resources, to name several—Earth's biosphere not merely remains the environment *for* society but has also now become a key ingredient *of* society (Csanyi, *Evolutionary Systems and Society*, Duke U Pr, 1989). By any evolutionary standard, such technically driven changes are extraordinarily rapid, so much so that the biosphere no longer seems able to respond quickly enough and well enough to the assaults of humankind. Even if the Gaia concept has merit (*cf*, Advanced Track for BIOLOGICAL EPOCH) and our atmosphere ably resists perturbations, the time scale for such repair is far slower than human-induced change. The result might well portend an impending environmental crisis on our planet. The rate of cultural change is changing so fast.

The hard realities of cultural complexity in an industrialized society are now upon us. Civilization's increased influence on our immediate environment has been so sudden and so great in recent years that the ecological conditions needed for the normal operations of society seem no longer provided by our naturally changing biosphere. Humankind is moving toward a time, possibly as soon as within a generation or two, when Nature will likely be unable to continue providing the essential environmental conditions needed for our survival; rather, our quest for survival will have to generate artificially the necessary conditions for our own ecological existence. From the two, society and the biosphere, will likely emerge a socially controlled bioculture. Here the essential components will become ideas, artifacts, technology, and humans, along with all the other living organisms on Earth—the epitome of complexity writ large in Nature.

Throughout the past million years or so, Darwinian biological and Lamarckian cultural evolution have been inextricably interwoven. Their interrelationship is natural, their overlap consistent with other adjacent phases of cosmic evolution that also interact, for the development of culture bears heavily on one of those key factors affecting all of evolution—the environment. 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, clothing and housing permitted them to colonize both drier and colder regions of planet Earth, and tools allowed them to manipulate their localities, however primitively. Much as for biological organisms before them, specialization permits social organizations to utilize more energy per capita, and this is reflected in increased Φ_m values over the course of time.

Likewise, though even more dramatically, present cultural innovations enable 21^{st}-century *H. sapiens* not merely to circumvent the environment but also to challenge it directly. Technology now allows us to fly high in the atmosphere, explore deep within the oceans, and even journey far from our home planet. Change indeed now quickens and with it the pace of life. Culture and its most common currency—energy; acquired, stored, and expressed—arguably act as catalysts, speeding the course of change on Earth toward an uncertain future. Humankind is now largely in charge of life on our planet; controlling most events, making key decisions, doing the selecting. We have become the agents of change, the human drivers of cultural evolution.

If there is any one factor that has most characterized the evolution of culture, it is almost surely an increasing capacity to extract energy from Nature—but not merely to capture energy, rather to store it, to transfer it, in short to utilize energy in an effective manner. Over the course of the past ~10 ky, humans have steadily mastered wheels, agriculture, metallurgy, machines, electricity, and nuclear power. Soon, solar power will emerge in its turn; all intelligent civilizations, anywhere in the Universe, likely learn to exploit the energy of their parent star. Each of these innovations has channeled greater amounts of energy into culture, in fact increased the rate of energy density flowing through many an open Earth system that serves us daily. To be sure, the ability to harness abundant energy sources is the hallmark of modern society. But it is also clearly the source of an inexorable rise in entropy within our larger environment—widespread pollution, waste heat, and social tumult, among other societal ills (cf, Advanced Track for FUTURE EPOCH). Ironically, the use and abuse of energy and natural resources that are so vital to our technological civilization are root causes of the many sociopolitical problems now facing humankind at the dawn of the new millennium.

In Sum

Physical, biological, and cultural evolution span the spectrum of complexity, each comprising an essential part of the greater whole of cosmic evolution. Galaxies, stars, and planets, as well as life, society, and machines, all contribute magnificently to a coherent story of ourselves, our world, and our Universe. All these systems, among many other manifestations of order and organization, here and elsewhere, seem governed by common drives and attributes, as though a Platonic ideal may well be at work in the cosmos writ large. At all times in the Universe, and at all places, the laws of thermodynamics seem to be the ultimate arbiter of Nature's many varied transactions; specifically, ubiquitous energy flows directed by those laws embody the underlying process behind the origin and evolution of all material things.

Society and its invented machines, the topics of this Advanced Track for the CULTURAL EPOCH, are among the most energy-rich systems with $\Phi_m > 10^5$ egs/s/g, hence plausibly the most complex known. All of the culturally increasing Φ_m values computed here—whether slow and ancestral such as mastering fire and tilling land, or fast and contemporary as with machines and computers that help accelerate our 21^{st}-century economy—were and are related to evolutionary events in which energy flow and cultural selection played significant roles.

Yet all of this progress, 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—to what end humanity on Earth cannot be certain.

Earth is now in the balance. Our planet constitutes a precarious collection of animate and inanimate localized systems amid a complex web of global and cosmic energy flows. All these systems—whether entirely natural or engineered by humans—need to heed the 2nd law of thermodynamics as an unavoidable ground rule. Consciousness, too, including societal plans and technological advances likely to dominate our actions into the next centuries, must embrace an evolutionary, thermodynamic outlook, for only with an awareness and appreciation of the bigger picture can we survive long enough to experience the Life Era—as noted the Advanced Track for the FUTURE EPOCH—thereby playing a significant role in our own cosmic-evolutionary worldview.