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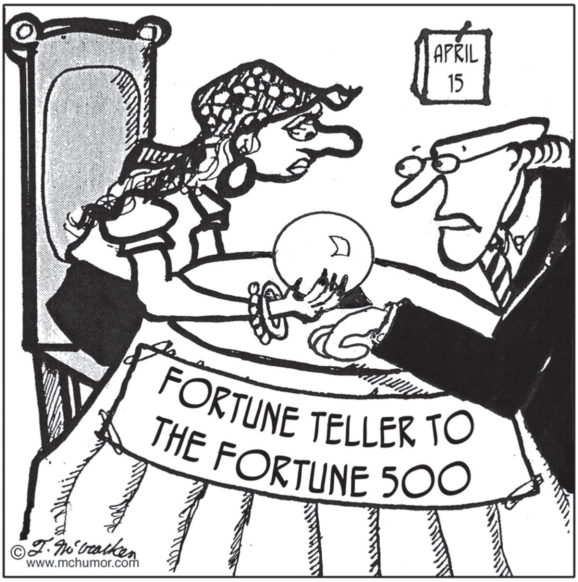
The Role of Mechanoevolution in Predicting the Future of Micro- and Nanoscale Technologies

Bradley Layton



"Tell me about the 4th generation of nanotechnology"

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Contents

Introduction

In this chapter, we take a "Kurzweilian" approach [1–3] to interpreting some of the technologies discussed thus far and cast these into a framework of *mechanoevolution*, a term recently introduced to describe how machines are selected by and form symbioses with humans (e.g., [4,5]). Although the prediction of specific technologies that may appear in the future is typically unreliable, if we place bounds upon the limits of sophistication that a technology is capable of reaching with a combination of Gould's Left-Wall Hypothesis [6], Shannon's Information Theory [7], and Carnot's mathematical presentation of the Second Law of Thermodynamics [8], some headway might be gained. To do so, we enlist the metric, α, which relates the physical entropy generation rate of a specific technology to its mathematical information generation rate. In general, the manufacturing of both small technologies and very large technologies consumes more energy per unit mass to produce than human-scale technologies and thus generates more environmental entropy per unit mass of product during a production cycle. Unexpectedly, however, during their operating life cycle, both smaller technologies and larger technologies have superior information to entropy ratios than mesoscale technologies. The result is that the information throughput density of the microdevices and likely nanodevices typically "pay off" on an energy-invested to quality-of-life basis as compared to their predecessors. This is because smaller technologies with high information processing rates typically result in a savings or beneficial reallocation of human metabolic energy or technological energy. This chapter begins with a historical perspective on the beginnings of technology, discusses key stepping stones, and concludes with a series of vignettes on where our technologies may lead us.

Confluence

We have arrived at confluence of our own species' evolution and the "evolution" of our technologies. The confluence of these two streams, one biological and the other technological, is becoming increasingly intermixed and, in many cases, inextricably so. This confluence has manifested as an irrepressibly large number of human as well as ecological symbioses with our machines. Just as the downstream waters of two previously unjoined streams become indistinguishable through the embedded micro- and nanotechnologies discussed in Chapter 16, the boundaries between our technologies and ourselves are disappearing.

This syncytium with nature that we have woven with our numerous technologies began with our accidental and fortuitous discovery of fire. The subsequent mastery of a variety of thermal energy sources for supplementing body heat, cooking food, and warding off predators essentially pushed us over a precipice whereby our ability to funnel energy, and to a limited extent, entropy gave us a distinct advantage over all other species on the planet. What particularly distinguishes man's use of fire to create order and predictability in his immediate environment is that it represents our species' ability to acquire energy without eating it. In fact, the mastery of fire was perhaps the key event that laid the first few stones upon the path that has enabled us not only to live more comfortably but also to transform matter through various phases, and, indeed, to aggressively and somewhat indiscriminately transform matter into pure thermal energy, via nuclear weaponry.

Fire was the beginning of mankind's use of external energy sources to produce order; a sequence that began with campfires and gas stoves is now converted to other forms of energy via secondary technologies, for example, the power grid that drives additional technologies such as laptop computers and personal digital assistants (PDAs). Indeed, combustion is responsible for approximately 85% of all technological energy consumed [9]. Nearly all technologies, unlike all biologies, are "born of fire." With very few exceptions, every human on the planet relies upon the technological harnessing of energy for maintaining a high quality of life. The campfire and the gas stove serve the purpose of supplying thermal energy to our "corporeal selves" and thus enhance the probability of propagating our "genetic selves." The laptop and the PDA, on the other hand, consume energy to maintain our "extracorporeal selves" and thus serve the purpose of maintaining and distributing our "memetic selves" [10].

Partition Entropy

The central thesis of this chapter is that the fundamental purpose of our technologies, be they micro, nano, or macro, is to partition entropy. Specifically, the sole purpose of all our technologies is to deentropicize our corporeal selves and, in some instances, our immediate environment in order to increase our probability of survival. In some cases, our technologies are used to map the external world, essentially converting that which was previously unknown into a useful, abstract, portable set of bits. This recording and internalization serve the same purpose of direct deentropization. In either case, energy must be converted resulting in a net production of physical entropy. It is my contention that the most successful and sustainable technologies will be those that create the greatest amount of information while keeping entropy production to a minimum.

TABLE 18.1
Nomenclature

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Symbol	Meaning	Units
b	Bits	1
I	Information	b
$\dot{I}$	Information processing rate	b s^{-1}
E	Energy	J
k_B	Boltzmann's constant	1.38 E-23 J K^{-1}
mEPP	Minimum entropy production principle	—
MEPP	Maximum entropy production principle	—
N	Gravitational-to-electrostatic-force ratio	1
p	Probability	0 – 1
P	Power	W, J s^{-1}
S	Entropy	J K^{-1}
$\dot{S}$	Entropy generation rate	J K^{-1} s^{-1}
$\ddot{S}$	Entropy acceleration rate	J K^{-1} s^{-2}
S_U	Entropy of the universe	J K^{-1}
T_H	High temperature	K
T_L	Low temperature	K
t_L	Lifetime	s
α	Entropy-information coefficient or "sustainability ratio"	J b^{-1} K^{-1}
α_m	Mass-specific entropy-information coefficient	J b^{-1} kg^{-1} K^{-1}
ϕ	Specific power throughput	W kg^{-1}
η	Efficiency	1
σ	Entropy generation rate	J K^{-1} s^{-1}
Ω	Energy probability weight	0 – 1

Note: The symbol, H, with dimensions of bits, which has conventionally been used to denote Shannon entropy has been avoided in order to make the clear distinction between physical entropy, S, with dimensions of joules per kelvin and the abstract amount of information, I, with dimensions of bits required to fully describe the entropy of a system.

Imagine that we were to be suddenly stripped of all technologies. In a sense, we would cease to be fully human. Imagine Bill Gates without the microprocessor, Jeff Gordon without the internal combustion engine, or John Glenn without the rocket. Each would still be a *Homo sapiens*, but the human potential of each of these men, specifically his ability to rise to prominence within the ecosystem, the technosystem, the media, and the economic infrastructure, would be diminished to the point that each of them would likely be less remarkable. In the absence of their respective technologies, Bill Gates might be leading an effort to move from dirt scrawlings toward the abacus, Jeff Gordon might be domesticating horses, and John Glenn might be leading expeditions into uncharted terrestrial destinations. However, without their advanced technologies, the amplification of their innate human abilities would be greatly dampened. The identity, power, and influence of each of these three men, and to a lesser extent the average person, are inextricably tied to their abilities to harness the power of their machines.

As described by Kurzweil [3], Chaisson [11,12], and Coren [13,14], the trend of increasing complexity of technology across all scales from nano to macro will continue to advance in a "Moore's Law fashion" [15], and the next few generations of humans will likely include members with abilities beyond those alive today. For example, medical technology has already enabled people to have better visual acuity than their genetics prescribed [16,17]. Recently, it was also proposed that a not-so-distant singular genetic mutation event led to our enlarged brains, and thus mental capacity compared to chimpanzees [18]. Presumably, in a simplistic and fundamental way, this led to the accelerating sophistication of our technologies.

What specific symbioses will be formed between the emerging technologies discussed in the preceding chapters of this book and the next generation of humans? Whatever form they ultimately take, these symbioses will define our fate as a species on this planet and potentially beyond.

This same seemingly irreversible trend toward increased human–machine symbiosis permeates our species even with very simple technologies. I have chosen to call them irreversible, because to abandon our technologies would be an abandonment from our path of competition with other species with the natural environment and, indeed, with mortality. For the technologist to do so, would be to make himself "less fit," so we press on with increasingly sophisticated technologies, essentially creating new worlds of high-tech "guns, germs and steel," which by design, or by default, suppress societies without them. As we will see shortly, there are four fundamental paths or modes in which a society may choose to proceed. In the author's opinion, the one with the lowest overall S:I ratio, or "sustainability ratio," α, a variable to be defined shortly, is the most likely to persist.

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For example, Industrial Revolution technologies such as eyeglasses, shovels, spinning wheels, and needles all contribute to their own selection by consistently performing their respective tasks. Each of these technologies, of course, also contributes to the "selectability" of their respective users. If we briefly examine each of these technologies in a manner similar to that taken by Henry Petroski [19], we easily see that eyeglasses enhance the survival potential of their users by allowing information to stream into the user's brain at a greater rate, $\dot{I}$, and to a greater degree of accuracy than would be possible with the user's imperfect ocular lens. The shovel, while it cannot amplify mechanical power, can amplify mechanical stress from foot to soil by a factor of 10^3 to 10^6, enabling the shoveler to gain access to water or mineral resources more quickly than would be possible with more primitive technologies such as sharp rocks or sticks. Even though water and mineral resources are difficult to equate in units of either mechanical power, P, or information, b, we will see shortly that enhanced access to both enables the user to effectively "bend down" his or her own entropy curve (i.e., $\ddot{S} < 0$), per Ziegler's minimum entropy production principle (mEPP) [20]. (Note that a single dot above a symbol denotes the first derivative with respect to time, and two dots denote the second derivative with respect to time.) Shovels and shovel-like technologies also give us the ability to sculpt and contour the land in a manner that lessens the energy required to navigate the terrain, thus allowing for faster access to additional material or information resources. More sophisticated in many ways than both eyeglasses and shovels, if only by the presence of moving parts, the spinning wheel enables the organization of natural fibers into long, continuous one-dimensional structures to be subsequently arranged into membranous structures for maintaining warmth, avoiding the sun's rays, or in the case of ornamental dress, elevating the perception of one's social status or sexual attractiveness and thus the probability of reproduction. The humble needle, a favorite of Petroski, enables the production of more sophisticated arrangements of woven fiber-based clothes; two-dimensional membranes can now be shaped into intersecting tubes to conform to bodies, domesticated animals, or technologies. Each of these technologies represents a specific arrangement of matter that was "selected for" based upon its specific ability to interact with light and matter; eyeglasses bend light, shovels move soil, spinning wheels funnel fibers, and needles guide thread. In all four cases, the specific funneling of light and matter benefits the human user in ways that enhance the practitioner's Darwinian chances for survival. It is the case with each of these technologies and with all technologies that their ability to control the movement or bending of light and matter make the immediate human world less entropic and thus more predicable for the human user. A more predictable, less entropic world is, of course, one with either less randomness or less perceived entropy at the human scale. However, since the second law of thermodynamics is never violated, the reduction in entropy caused by each of these technologies is channeled to the molecular scale where it is absorbed by the environment at a commensurate rate. Thus, it is one of the primary theses of this chapter that $\dot{S}_{\text{humanity}} > \dot{S}_{\text{universe}}$ and that there is some entropy acceleration that humans are creating on earth (i.e., $\ddot{S} > 0$) which is greater than the background universal entropy acceleration rate if, indeed, such a metric exists. Terrestrially at least, the persistent entropization of the environment occurs either via the production of heat or by the creation of smaller molecules with less chemical potential to perform mechanical work [21,22].

Without the successive discovery or design of each of our technologies, beginning with the first sharp stones, we would not have climbed our own technological version of what Richard Dawkins refers to as "Mount Improbable," which, in fact, is the world as manifest today and which happened one genetic mutation at a time over the course of the lives of the ~10^{22} organisms that have lived in the 3.7 billion year history of this planet (~10^{8} species multiplied by an average of 10^{14} organisms per species) [23]. The difference, of course, between biological evolution and technological evolution is that, while biology has to "wait" on mutations and material transfer of actual genetic material, technology can get away with being much more impatient by spreading memetically via whatever new technological media emerges. In the case of genetic algorithms used for design optimization, this happens at rates as great the speed of light as design algorithms are run on computers. Some of the fastest biological generations can occur on the order of minutes [24], but technological evolution can occur even faster. In fact, if you classify some of the algorithms written by hedge fund investors to destabilize and ultimately crash the markets in 2008 [25] as technologies, these have generation cycles on the order of milliseconds.

Just as Spencer Wells is working to trace every human alive [26] both temporally and spatially, every technology is traceable along a set of discrete steps all the way back to the first sharpened stones and the first flames fanned by humanity. Even though no such formal study has been conducted, presumably every technology could be placed into a specific location on a phylogenetic tree in a manner similar to that used in evolutionary biology studies [27,28]. A rough outline of what such a tree might look like is depicted in Figure 18.1.

Every technology exists in two forms: the purely abstract and the purely material. In the case of the airplane, the abstract form is the set of drawings, material specifications, and testing protocols required to build the airplane. An abstract form of the airplane existed in the notebooks of Leonardo da Vinci long before the first successful material form took flight at Kitty Hawk. And while the material form of any technology ultimately falls prey to entropic effects imposed by its environment, the ideal form of the airplane can effectively achieve immortality insofar as it lives at least as long as its creator. This idea is not completely new. It was first proposed by Pythia of Delphi nearly 3000 years ago when deliberating whether a boat that had been slowly patched and rebuilt until none

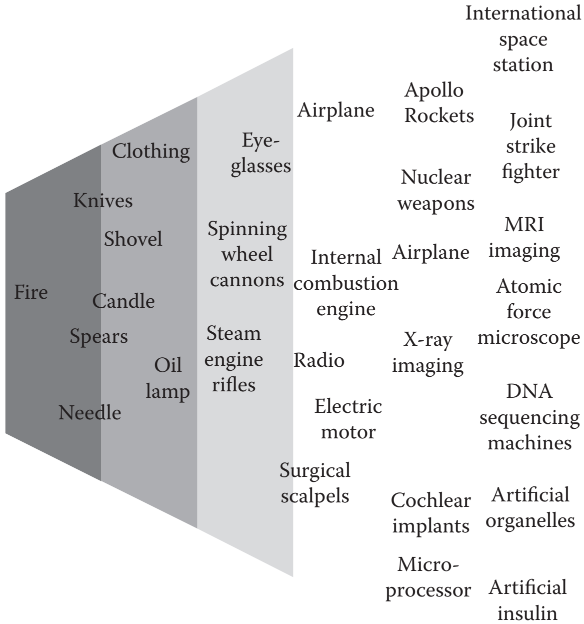

Figure 18.1 A phylogenetic tree of technology, with the past to the left and the present on the right. Larger technologies are at the top, and smaller ones are on the bottom. Conceivably, every technology has a predecessor, or in some cases, multiple "parents." An obvious example is the Swiss Army Knife, which is a combination of multiple tools or technologies. Technologies, however, unlike biologies, do not require direct transfer of matter from parent to child, and mutations are not bound by naturally dictated generation cycles. Actual lineages of inheritance have been left out of this figure. A more complete version would have lines connecting each technology, just as a biological phylogenetic tree would. Similar to a biological phylogenetic tree, specific genes may emerge at multiple times. Unlike a biological phylogenetic tree, individual technologies may have more than two "parents."

of the original material remained was indeed the same boat. The instructions for building an airplane can be maintained unmutated as long as proper backups are made on reliable media, be they paper, magnetic media, or stone. Each of these media will also ultimately fall prey to entropy, as long as the copying is robust, the airplane, or any technology, will remain immortal. Even as the material forms of all of our technologies undergo perpetual negative mutations, ultimately becoming a dispersed set of atoms, molecules, or fragments of metal, glass, and plastic with no apparent relation to its former structure, with the proper maintenance of our oral and written traditions, our technologies can attain immortality. However, as we have already transformed the planet's biosphere to a point that it unfortunately will require additional vigilance, if not maintenance, we will likely find little use for many of the technologies that were responsible for its transformation.

Information and Entropy

While composing this chapter, finding an author who had previously fully captured the central theme was difficult. There have been a few attempts to unify the works of Shannon and Carnot, but most have been unsatisfactory. However, the invocation of the works of both of these engineers, along with contributions from Gibbs and Darwin, ~~seem paramount~~ if we are to develop a comprehensive framework for predicting future technologies. Perhaps the closest echoing of this chapter's central point was made recently by Matt Ridley in *Genome*. Ridley was quoted by Dawkins in the *Oxford Book of Modern Science Writing*, stating that

> *Shannon's idea is that information and entropy are opposite faces of the same coin and that both have an intimate link with energy. The less entropy a system has, the more information it contains. A steam engine parcels out entropy to generate energy because of the information injected into it by the designer.*

are necessary

These three sentences mention three key metrics for comparing technologies: energy, entropy, and information. Although concise and thought provoking, these three sentences contain at least one flaw as well as an oversight. The *flaw* is that an engine does not generate energy, it transforms energy from chemical to mechanical, which ultimately becomes thermal, a concept not clearly understood or appreciated by a surprising number of engineers and scientists. A steam engine has a combustion chamber as well as a closed system of interconnected chambers for converting liquid water to steam and back. This cycle of hot and cold exploits water's expansion and contraction as it moves through the engine. This expansion and contraction then converts a change in gas volume to a linear displacement, which is then converted to a rotational motion used to drive wheels, gears, and so forth. The end result, of course, is the transportation of humans from one location to another, the plowing of a field, or the production of an electric field to supply computing power, motive power, chemical potential, and so forth [9]. Ridley's *oversight* is in "the less entropy a system has, the more information it contains." Of course, the reverse is true; a more entropic system requires more information to fully describe. Greater entropy may be the result of either a greater quantity of matter to describe or a greater number of configurations available to a system in proportion to its temperature via the Boltzmann distribution. What Ridley seems to be hinting at is the fact that Shannon entropy and Gibbs entropy may be expressed similarly. The difference, of course, is in the fact that Shannon entropy that has dimensions of bits and Gibbs entropy has dimensions of joules per Kelvin.

Gibbs entropy, which is physical in nature, and has dimensions of energy per temperature is typically written as

$$S = k_B \ln(\Omega_i(E_i))$$

where k_B is Boltzmann's constant, E_i is the set of all possible energy states with weights Ω_i. *Shannon entropy*, or what we define here more unambiguously as *Shannon information*, is expressed as

$$I = -\Sigma\, p_i \log_2 p_i,$$

where p_i is the probability of a given symbol occurring within a message. Both entropy and information are scalar values and both are extensive (extrinsic) values, in contrast to metrics such as temperature which is intensive (intrinsic). However, just as a scalar such as temperature or pressure may be used to describe a multidimensional physical system and just as a digitized three-dimensional

(3D) computer-aided drawing may be sent as a dimensionless sequence of bits, both entropy and information can be used to characterize and thus evaluate disparate systems, thus making them ideal metrics for evaluating technologies via a single scalar, α, which will be defined later in the chapter. Again, the critical distinction to make and one that is frequently overlooked in the literature is that physical entropy, or more succinctly *entropy*, is always evaluated in units such as joules per Kelvin. Information, which is dimensionless, has units of bits. Having made this distinction, there have been previous attempts to establish a relationship between entropy and information (John Avery, *Information Theory and Evolution, 2003)*. For example, a physical system with less entropy takes less information to describe. A radio signal that is 100% "noise" takes more information to record, store, and reproduce than one transmitting a "pure" tone. A physical system with a greater mass, temperature, and number of chemical constituents is likely to be more entropic than a small amount of pure substance at low temperature. Commensurately, a greater amount of information is required to completely describe the larger, hotter less pure system and less required to describe the small cool pure one. Paradoxically though, it may require more energy to maintain the small, cool, pure system than the large hot multicomponent system depending upon how far from equilibrium the two systems are. Certainly there exists a unique minimal amount of information, I_m, required to reproduce a given technology. Furthermore, this amount of information is media independent. For example, the information required to reproduce a given physical manifestation of a steam engine could just as readily be transferred via memory stick as it could via blueprints. However, normalizing the bit density on an energy, mass, or volume basis, the memory stick will likely be superior to that of the blueprint. Shannon also explored message fidelity on an energy basis when considering the "cost" of sending an error-free message with

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a given amount of signal power. So while the number of bits required to reproduce a given technology must have some minimum value, the efficiency of its reproduction will be media dependent. It is also worth extending the discussion to the environmentally dependent entropy production rates of any heat engine. For example, the engine will have a greater Carnot efficiency when operating in a colder environment. If we assume that the engine operates at a given internal temperature of T_H and an environmental temperature of T_L, the Carnot efficiency is expressed as $\eta = (T_H - T_L)/T_H$. Thus, if we fix T_H at the safe upper limit for the engine, it will operate more efficiently in a cooler temperature. In principle, this would be absolute zero. However, practical constraints such as maintaining water in liquid form must also be considered. For example, a steam engine, or any heat engine, operating at a greater temperature will need to do more irreversible work and thus generate more entropy in order to overcome the same (i.e., gravitational) energy barrier than it would at a lesser temperature. In order to create a superior engine, specifically one that is capable of not melting at a greater temperature, requires additional time, insight, and without question, access to more information than was required to create the more archaic engines with lower maximum operating temperatures.

Thus, Ridley would be more correct in stating that "the greater a system's ability to partition entropy, the more information required to design it." This statement has held true from the very early Savery → Newcomen → Watt steam engine development that occurred 200 years ago to the improvements in microscale and nanoscale technologies that are occurring today. As Ridley points out, the system only remains successful if it continues to maintain a low entropy state (i.e., not exploding or corroding). But ironically, the most successful machine may be one that requires relatively little information to describe. The "information injected into it by the engineer" is, of course, detained in all of the tried and failed attempts

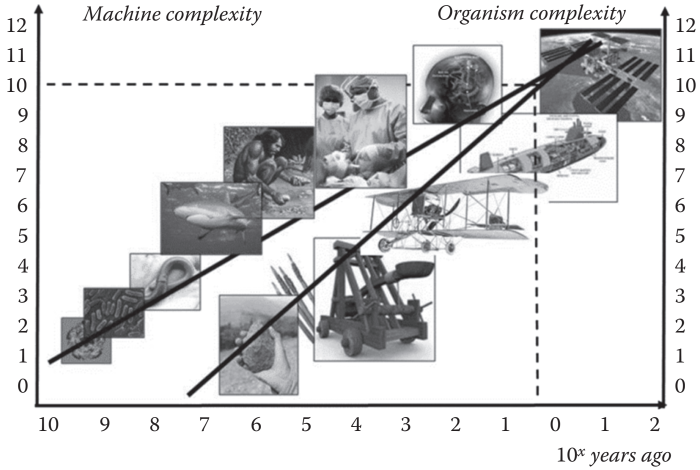

***Figure* 18.2** Qualitative representation of the relative rates of complexity acceleration in the biological and technological spheres. The abscissa is logarithmic time in years. The left ordinate represents a relative complexity metric for machine complexity, roughly quantified as the number of parts in a machine. The right ordinate represents a relative complexity metric for biological complexity, roughly quantified as the number of molecular interactions or potential to produce a wide spectrum of behavioral characteristics. The point of convergence is Kurzweil's singularity. (See Kurzweil, R., *The Singularity Is Near: When Humans Transcend Biology*. 2005, New York: Viking.)

that were performed prior to arriving at the final embodied form. What remains to be seen, however, is if our technologies are capable of *both* reducing human corporeal entropy while simultaneously minimally affecting environmental entropy. To the author's knowledge, this has yet to be formally quantified [5]. Taking a long-sighted look at the confluence mentioned in the opening paragraphs, biological and technological evolution may be plotted qualitatively and approximately with general complexity as a function of time. This exponentially increasing complexity in both the technological and biological realms is depicted in Figure 18.2. Similar plots have been made by cosmic evolutionist Eric Chaisson [11] who has chosen specific energy throughput, ϕ ,with dimensions of energy per time per mass as an ever-increasing variable with no apparent bound to describe how much energy passes through a system of a given mass per unit time. Nature constantly produces systems capable of greater amounts of specific energy throughput [12]. Chaisson attributes this propensity to the very expansion of the universe and to the thermal gradient that typically exists between radiant bodies and massive bodies (i.e., the sun is hotter than its planets; thus, thermal energy flows from the sun to the planets "down" the thermal gradient). Specifically, he states that as hot as the sun is, its power per unit mass is relatively paltry in comparison to a living organism or an energy-hungry technology. The earth essentially "feeds" upon the "waste" radiation from the sun. And just as the steam engine must maintain a specific configuration to continue to convert energy, so must photosystems I and II as they convert radiant energy to chemical energy [29]. In fact, as discussed in Chapter 15 on micro- and nanosolar technologies, we have a long way to go until we have achieved anywhere close to the efficacy of PSI and PSII, both of which have molecular weights of X, dimensions of Y, are found at a density of X per X and, thus, have a global quantity of X and convert radiant energy from photons to electrons at a rate of X per second and at room temperature. Meanwhile, our typical industrial-scale solar cells have efficiencies of X and typically generate substantial heat as a result of electron transfer. Micro- and nanosolar technologies that are capable of enhanced biomimicry may become an economic and sustainability imperative as we approach the "photosynthetic ceiling" [30,31]. For the reader not familiar with the photosynthetic ceiling, this is a concept introduced by Diamond in 2005 to quantify the ratio between human technological energy consumption which stands near 16 TW and solar incident radiation which is approximately 1 EW. Although it is true that this "ceiling" neglects to include other nonsolar energies such as tidal, geothermal, and nuclear (either fission or fusion based), it does account for 85% to 90% of our current energy supply, namely fossil fuels, which are solar derived. The main point here is that in order power our future technologies, be they nano or macro, we will need to pay an increasing amount of attention to their energy consumption rates. Even if fossil fuel–based power generation diminishes (as it certainly must within two centuries based upon current reserve-to-consumption ratios), every technology emits heat; thus, we will have to deal with the thermal load of

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500 EJ of thermal energy whether or not it is hot CO_2 or hot nongreenhouse gases.

Plots similar to those used by Chaisson have also been used by Coren to explain the saltatory nature of emergent life forms and technologies [13,14]. In this case, *saltatory*, similar to the term as used biologically where a process happens in jumps or leaps rather than continuous equal increments, implies that the "birth" of a new technology typically leads to a spawning of numerous other technologies. These then mature and eventually fizzle, and then a new burst occurs. Before Coren, Gould described evolution as saltatory [6]. In fact, Kurzweil has produced a metaplot of several studies similar to that of Coren's [3]. Of particular interest is the point in the near future where machine complexity reaches a level comparable to, or surpasses, that of the arguably most complex biological system, our own brain. This is roughly represented by the intersection of the biological and technological trajectories of

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According to Kurzweil, this will happen before the close of this century, and the implications could be as simple as a permanently implanted neural prosthetics for accelerated cognition in a large fraction of the human population to a reality as complex as one where all humans achieve a sort of immortality through continuous upgrades to their consciousnesses. These "people" will have completely abandoned their own carbon-based cognition systems but will be fully "alive" and "aware" as "apps" on next-generation computers [2].

We have already seen early manifestations of embedded human–machine symbioses such as cochlear implants (Chapter 16) and direct brain interface devices (Chapter 16). Presently, these prosthetics are designed as an attempt to either restore or mimic normal human capabilities. However, there are other recent technologies such as exoskeleton projects [32], Lasik surgery [17], or of course anabolic steroids [17] that have had the effect of allowing a small subset of humans to exceed what even the most gifted would be able to achieve naturally. The other manifestation of what the future holds exists in the (typically physics violating) art of science fiction. The increased prevalence of movies such as Terminator, Ironman, Spiderman, and the X-Men are evidence of this trend.

Mechanoevolution

As a first attempt to cast a formal framework for mechanoevolution, let's classify all machines into four types, numbered I through IV (Table 18.2). Each of the four types may be classified along four bases. The four bases selected are not independent. The first basis is "entropy source." A designation of "no" indicates that once the machine or artifact has been manufactured, it is susceptible to thermal degradation just as all machines and biological systems are. However, in the absence of a human operator, it is incapable of generating entropy, but simply becomes a victim of environmentally induced entropic effects. This is why a Type I machine receives a designation of yes/no, rather than a clear "yes" as logic would seem to imply from the other fields in the table. A clear example of a Type I machine is a garden hoe left outside to weather. While working the soil, the hoe is dentropicizing the soil, raising lower layers to the top to create orderly rows, but once set aside, the hoe merely falls prey to entropy. If left alone long enough, the hoe becomes soil. We have lived with Type I machines for roughly two million years [33,34]. The surface rocks we used to form early tools are entropy sinks. Once sharpened, a surface rock becomes more susceptible to wear.

The triage criterion for a Type I machine versus a Type II machine is whether or not the machine is capable of accelerating the universal rate of entropy generation without the direct guidance of a human operator. The first Type I machines appeared during the Modern Stone Age (MSA), 300 kYa to 50 kYa, prior to the Early Stone Age (ESA) 2.5 MYa to 300 kYa, which produced stone artifacts but nothing resembling the honed tools of the MSA. The transition from ESA to MSA could roughly approximate the likely unabrupt transition from the predominate usage of tools with only a single part (i.e., the hand-axe of Galeria and Gran Dolina to the prevalent usage of spear points), which would have needed at least three parts; tip, shaft, and binding. This transition is located at roughly the "5" on the abscissa of

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TABLE 18.2
Categorization and Examples of the Four Basic Machine Types

Machine Type	Entropy Source	Motorized	Self-Operating	Self-Regenerating	Examples
I	Yes/no	No	No	No	Shovel, wheelbarrow
II	Yes	Yes	No	No	Power lawnmower, power screwdriver
III	Yes	Yes	Yes	No	Auto-piloted airplane, computer server cluster
IV	Yes	Yes	Yes	Yes	Self-replicating robot, artificial organelle

Clearly the bases "entropy relation" and "motorized" of Table 18.2 are nearly perfectly correlated and, thus, technically do not compose a mathematical bases. However, if we imagine a scenario where all tools are being used all of the time, Table 18.1 becomes one with "yes" along and below the diagonal and "no" above. Were we to be able to hit a "pause" button on all human activity and observe the resulting behavior of our technologies, the yes/no of the upper left corner would become a "no." If this imaginary pause button were to be held long enough, "no" would ultimately fill in the entire table. Thus, the basis with four axes is not a true mathematical basis because all four are not strictly independent. In other words, the presence or absence of a human operator is ultimately responsible for the immediate classification of the machine; a Type I machine becomes an entropy source rather than a sink when in the hands of its operator.

For better or worse, frequently, the advancement of weapons technology drives the advancement of our understanding of light and matter more than any other applied science. This is symbolized by the catapult of and continues through the development of TNT, napalm, and into the present with technologies, such as, the F-35 Joint Strike Fighter (JSF), which has been touted as the most technologically sophisticated single machine conceived by humankind, (www.jsf.mil/). Other obvious examples of exceptionally complex machines include the International Space Station (ISS) and the Hubble Space Telescope (HST). Each of these three "big" technologies, the JSF, the ISS, and the HST, can be classified as bridges between Type II and Type III machines. Each has the ability to extract chemical or radiant energy from the environment, maintain a trajectory somewhat autonomously, and sense its environment in a semiautonomous manner. The general purpose of each of these advanced technologies, as with any technology, is twofold. The first is to give their operators access to information about the environment which those who do not possess the technology cannot access. The second, more subtle but implicit purpose, is to "shed entropy" via the maximum entropy production principle (MEPP) [20] onto those without access to the technology. The contrapositive to "entropy shedding" is "information shielding." Whereas entropy shedding onto one's enemy gives the shedder the upper hand, "information shielding" has the same end effect—greater probability of survival of the shedder and reduced probability of survival of the shedee. All three of these technologies, either by design or by their very nature, shield their information from people without the ability, access, or interest to comprehend it.

To a crude approximation, the JSF, the ISS, and the HST are leaf blowers. The owner of the leaf blower uses the blower, a Type II machine, to deentropicize his or her swath of the earth's surface. The typical purpose of this is to enhance the appearance of the landscape by removing leaves that would either be tracked into the house, clog the street gutter, or leave an impression of slovenliness to passersby. The resulting physical entropy spread from the blower's use may be quantified via the second law as

$$\Delta S = \Delta Q \cdot T^{-1} \tag{18.1}$$

where ΔS is the change in entropy of the environment, ΔQ is the chemical energy consumed by the engine, and T is the operating temperature of the machine. Gasoline has an energy density of roughly 50 $MJ{\cdot}kg^{-1}$. Thus, if the blower is consuming chemical energy at a rate of 1 kW, then it is generating entropy at a rate of approximately 3.3 $J{\cdot}s^{-1}{\cdot}K^{-1}$ or a mass-specific entropy generation rate of about 0.67 $J{\cdot}s^{-1}{\cdot}K^{-1}\,kg^{-1}$. More challenging is to quantify both the information embodied in the leaf blower as well as the information gained as a result of the leaves being blown. However, the amount is equivalent to the number of bits required to store the mechanical drawings used to manufacture each part (~200 Mb), the assembly instructions (~50 Mb), the operating instructions (~0.5 Mb), and the formulation for the fuel (~0.1 Mb). In the case of the leaf blower, there is no obvious resulting information gain to the user. And, in terms of its information processing, because it does not have an on-board computers, it essentially has an information processing rate of one bit per unit time that it is on since it is in only two states. The lawn may now be visible, but the information required to encode this image is likely less than that required to encode the image of the leaves. Turning back to our three more advanced technologies, the JSF, the ISS, and the HST, each of these have mass-specific entropy generation rates of 113, 0.45, and 0.07 W/K/kg, respectively.

The JSF, the ISS, and the HST consume energy at a rate of 34 MW, 500 kW, and 2250 W, respectively. The purpose of the JSF is to entropicize the enemy, the purpose of the HST is to collect information on the state of the universe, and the purpose of the ISS is to explore the potential for living beyond the confines of our planet. Notably, if a Kurzweilian future becomes manifest and we avoid asteroid impact, efforts of the ISS become moot. So how are three of the most advanced technologies like a leaf blower? Like the JSF, the leaf blower sprays entropy elsewhere, leaving the operator to enjoy an environment devoid of intrusive organic debris. Like the ISS, the leaf blower creates a habitat for its user that is devoid of organic particulate matter. Like the HST, the leaf blower allows the user to know where all foreign objects lie. In this regard, the leaf blower may be superior to the HST in that it can put the foreign objects, however inefficiently, into a pile. The same measurements may be made of any technology, regardless scale. Micro- and nanoscale technologies of course have lower masses, and because most are typically designed for information processing (i.e., integrated circuits), they have greater specific information throughput rates as well as comparable specific power throughput rates and, thus, greater specific entropy generation rates with respect to the ambient environment than the larger technologies. In fact, the estimates for the information throughput rates for the large technologies discussed thus far were based primarily upon the number of processors that each has.

Entropy Generation Rate and Background Entropy

How does the entropy generation rate of a given technology compare to the overall background entropy generation rate of the universe? In other words, how far above the background rate of entropy increase is a given technology and is there a limit to this? Lloyd recently discussed the limit [35] but again did not make the distinction between entropy and information. According to Chaisson, the universe reached maximum entropy after only a small fraction of its current age [11]. Questions that remain unanswered from Chaisson's work, however, are the effects of the expansion of space. For example, is the universe becoming more entropic simply because there is more physical space and, thus, a longer ledger required to track all 10^{80} particles, or is the universe becoming more entropic because the various energy manifestations (i.e., material, electromagnetic, etc.) have yet to come to equilibrium? Also, there is continuing debate about the entropy at the event horizon of a black hole and the information thus required to describe its behavior (Stephen Hawking). Nevertheless, what is certainly clear of any terrestrial system, either biological or technological, is that both use their embodied information to partition entropy by exploiting the second law. As long as thermal gradients exist, such as the one between the earth and the sun, there will be "free" energy available to drive biological and technological engines. For six of the most prevalent technological engines such as the Atkinson, Brayton, Otto, Dual, Miller, and Diesel, Chen, Zhang et al. (2007), defined maximization of the ecological function

$$E = P - T_0\dot{S} \tag{18.2}$$

to be the limit of technological "effectiveness." In Equation 18.2, E has dimensions of power per effectiveness, P is the power output of one cycle, T_0 is the temperature of the environment, and $\dot{S} = \sigma$ is the entropy generation rate with dimensions of energy per Kelvin. This approach has been used by other authors such as Angulo-Brown et al. [37] to maximize the effectiveness of the power generated by power plants. However, effectiveness has been left poorly or completely undefined. Efficacy is the more common term for converting between various units or dimensions. For example, a reading light is more efficacious if the reader can absorb more bits per joule.

We must now establish a working definition of the relationship between energy and information, and a new relationship between entropy and information emerges. The first definition that much be established is that *information has dimension of bits and is a purely abstract* (nonphysical) entity, and *entropy has dimensions of energy per temperature* and is physical. Frequently this distinction is not made. However, the two state variables may be related via

$$\dot{S} = \hat{\alpha}\dot{I} \tag{18.3}$$

where α is a system-dependent coefficient defined as the rate at which information is generated proportional to the rate at which entropy is generated. But as mentioned above, the purpose of any technology, be it macroscale or nanoscale, is to partition entropy, by reducing it locally at the expense of increasing it environmentally. We thus rewrite Equation 18.3 as

$$\Delta\dot{S} = \alpha\dot{I} \tag{18.4}$$

where the Δ represents the difference between the mEPP and the MEPP (i.e., $\Delta S = S_{\mathrm{MEPP}} - S_{\mathrm{mEPP}}$).

This relation is similar to Shannon's original work in the field of data transmission, specifically, how many bits of information can be reliably transmitted per energy consumed per unit time [7].

A distinction was made between the maximum entropy production rate (MEPP) and the minimum entropy production principle (mEPP) by [20]. These two curves represent the upper and lower curves of Figure 18.1.

The expression in Equation 18.3 must be applicable to all technological and biological systems. For example, as a large organism uses its sensory organs, it does so to gain access to information about its environment. Of particular interest is the location of potential predators or other threats to the organism's corporeal self. For humans, the power devoted to vision is on the order of 2 to 3 watts, and the rate of information throughput can range anywhere from a few dozen bits per second for a slow reader reading a newspaper to several gigabits per second for someone moving through a richer four-dimensional space such as an National Basketball Association (NBA) basketball player, a surgeon, or someone panning for gold. However, on this topic a more detailed analysis is warranted. In *The User Illusion*, Tor Norretranders discusses the "user illusion" in computing the desktop graphical user interface (GUI): the friendly, comprehensible illusion presented to the user to conceal all the bouncing bits and bytes that do the actual work.

Contemporary gene sequencing machines, such as those of 454 Life Sciences, Lynx, Solexa, and Illumina, the GS20 and the GS FLX Titanium series and, more recently, a Helicos Biosciences machine developed by Stephen Quake ,consume energy at a rate of 1-10 kW and produce genetic information about organisms at a rate of 10 to 10,000 bits per second. At a mass of 100 to 1000 kg, this gives them an α of 0.003 J $\times$ s^{-1} $\times$ K^{-1} and a mass-specific $\alpha_m = 5 \times 10^{-6}$. By comparison, the JSF, ISS, and HST have $\alpha_m = 1.2 \times 10^{-10}$, 9×10^{-13}, and 6.8×10^{-13}, respectively. As gene sequencing machines evolve, the information gain rate per energy expenditure rate and, thus, entropy generation rate will increase, driving up α itself, implying a nonlinear and potentially exponential between α and itself—that is,

$$\dot{\alpha} \propto \alpha \tag{18.5}$$

In other words, the better a technology is at partitioning entropy with minimal information (both embodied and throughput), the greater the probability that the particular technology will evolve an even greater ability to partition entropy. What we have not considered, however, and what will be left for future work, is to describe the relationships and symbioses among various technologies. As an example, consider a technology such as the manufacturing and usage of carbon nanotubes, which have already found their way into several commercial applications such as memory devices and structural materials as mentioned in Chapter 7. Currently, these are manufactured in vacuum furnaces at high temperature and low pressure. A constant input of energy is required to maintain these gradients. Current prices of carbon nanotubes are primarily driven by research and development costs as well as by the specific chemistry and morphology being produced, but as the research and development costs become absorbed by emerging markets, what remains to be seen is whether energetic costs will come into play in dictating the market value as appears to be the case with the manufacturing of silicon-based photovoltaic cells. Silicon, phosphorous, and boron are all cheap. The manufacturing time and manufacturing energy required to essentially drive the entropy out of them by arranging them in a single-crystal form is not. The same is true of carbon nanotubes, carbon nanowires, and so forth. Each must be manufactured bottom-up, one atom at a time, and thus intimately linking a monetary cost function with the "negentropy" that essentially flows into an assembly of atoms in a highly unlikely, yet highly repetitive configuration. Just as a full description of a silicon crystal requires only the specification of the relative three-dimensional positions of

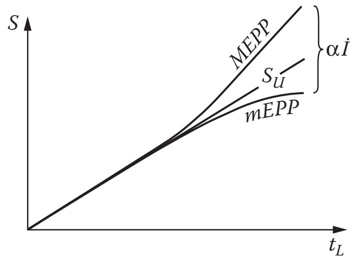

Figure 18.3 The relationship between the maximum entropy production principle (MEPP), the minimum entropy production principle (mEPP), and the rate of information throughput, $\dot{I}$. The coefficient, α, defines a given technology's ability to partition entropy. The greater a technology's α, the better that technology is at reducing its user's local entropy level against the universal rate of entropy increase $\dot{S}_U$, and maximizing entropy shed to the environment.

fewer than 10 unit-cell atoms and the gross dimensions of the crystal requires relatively little information, a full description of a multiwalled carbon nanotube requires relatively little information: chirality, number of walls, and length. The point here is that, typically, a relatively greater amount of time, temperature, and money is required to create a material with relatively little information content as quantified by the number of bits to specify the locations of all the atoms.

However, consider the case where there are a few impurities in the single-walled carbon nanotube. Not only does this configuration require a commensurately greater number of bits to describe exactly where these imperfections are, but now the technology that employs the nanotubes should, if our prediction of Figure 18.3 is correct, for the same, α, almost certainly result in a greater fraction of ΔS ending up above S_U. Specifically, let's say that a new membranous material composed of one continuous carbon nanotube has been developed and woven into an enormous sheet to replace the failed levies of New Orleans. If the sheet is indeed pure, one need only know the chemistry, the weave pattern, and the extent of the fabric. However, if impurities exist in the continuous tube, it will be weaker in proportion to the number of impurities [38–40]; thus, while it may be capable of maintaining a relatively low mEPP for some time, protecting those within the membrane from destructive pressure gradients, given a large enough load and enough time, the membrane will rupture, resulting not only in a shift in the environmental entropy above S_U, but will also eliminate the portion of ΔS represented by $S_U - S_{mEPP}$.

Carbon sequestration, which will increasingly become a byproduct of microfabrication and nanofabrication, in large, pressurized concentrated regions is likely a bad idea because of its relevance to contemporary environmental concerns. Pumping a gas that is a toxin to much of life on earth, especially in pressurized tanks, virtually ensures that at some point these vaults will rupture, killing all nearby life in a blanket of suffocation. What was an ordered, low information content concentration of gas becomes a disorderly array of dying organisms.

Whether or not the universe became "fully entropicized" very early as Chaisson suggests, deserves further attention. However, what is clear is that without entropy gradients, energy would not flow and life would be incapable of tapping into "free energy" reserves. So as Gibbs, to some degree [21], and later Schrödinger pointed out [41], we thrive on entropy gradients and amplify them. Eventually, as with the carbon nanotube levy example, the boundaries fail and the gradients vanish into a more entropic state than at earlier times. The collapse of the Twin Towers represents the rapid diminishment of the entropy partitioning they were performing for over 30 years. The resulting pile of technological rubble and biological death that resulted greatly entropicized lower Manhattan and produced a drop in the Stock Market volume, which represents reduced information partitioning. The closing of this entropy partition is depicted as the collapsing bubble in the upper right of Figure 18.1. /4/

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However, in Ian Morris' recent work, *Why the West Rules for Now*, he included a cofactor that he terms *energy capture* as a metric for discrepancies in the relative success of Western versus Eastern societies. His basic argument is that Western societies have either had greater access to agricultural energy either via biological, climatological, or geographical disparities. This brings up the fundamental question of what the best metric might be for measuring the success of a society. Is it merely a society's ability to exploit natural resources, be they material or energetic? Is a society's success measured by its

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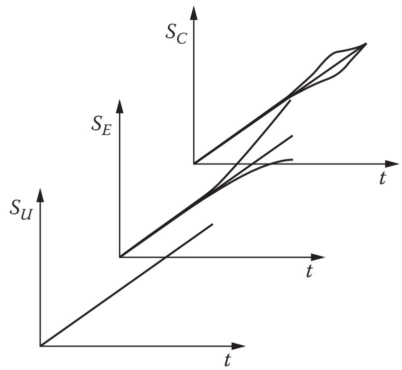

Figure 18.4 Three possible scenarios for entropy production in the universe. In the foreground, in black is the overall entropy increase of the universe, S_U. Just above this in dark gray is depicted a region of the universe such as the earth where life has used its information base to partition entropy, S_E. At the top of the figure in light gray is depicted a region of the universe where entropy partitioning began but collapsed as perhaps by war or overexploitation of the environment, S_C.

financial resources? Certainly these two contribute, but the more fundamental metric for measuring a society's success is certainly the quality of the physical and mental health of its citizens. Frequently, greater access to material energetic and financial resources results in superior physical and mental health. However, when material extraction (i.e., mining or energy consumption [i.e., carbon-based combustion], result in "excessive entropization" of the environment [i.e., watershed pollution and anthropogenic climate change], then, surely, the measure of success is diminished when the society ends up "drowning in its own entropy").

If you are reading this chapter on a computer or other microelectronic device, energy is flowing through the machine at Chaisson's energy throughput rate, ϕ, and information, I, is also flowing from it into your visual cortex and then through the language processing regions of your brain to then be transformed and stored in your neural circuits. In this specific example, the energy throughput rate is approximately 25 W·kg^{-1}. A laptop runs at approximately 100 W and weighs approximately 4 kg. Reading rates vary, but range from 100 to

1000 words per minute. This is the equivalent of 200 bits per second. Thus, α for reading on a laptop is approximately

$$\alpha = \frac{\dot{S}}{\dot{I}} = 0.0016 \text{ J b}^{-1} \text{ K}^{-1} \qquad (18.6)$$

New microtechnologies such as microengineered lithium-ion battery technologies and microcapacitive screen technologies have enabled information to flow from these devices nearly as rapidly as from a newspaper and with less environmental entropy produced per bit.

An increasing fraction of our technological primary energy consumption is being funneled into power micro-devices and in researching nanodevices. Already, we are within four orders of magnitude of Diamond's photosynthetic limit [30]. In other words, we use the equivalent of 1% of 1% of the sun's incident energy for heating, cooling, transportation, manufacturing, and now computing. This occurs on a continuous basis. We do not, in fact, harvest 1% of 1% of solar energy directly for purposes such as water heating, electricity generation, or transportation. But we do consume as a species approximately 200 MJ of technological energy per day, which is the equivalent to the solar energy received by 10 to 20 square meters at typical location in a day. With conversion efficiencies of 10%, this requirement raises to 100 to 200 square meters. It also does not account for metabolic energy which is 10 MJ per day and has an efficiency of a fraction of 1%. All of our technological and metabolic energy consumption is consumed for the purpose of maintaining our corporeal selves, a large fraction of which is devoted to brain maintenance. So, arguably, whatever fraction of metabolic energy is not spent on genetic reproduction is spent on memetic production, reproduction, and consumption. Computers are the preferred media for spreading memes.

Sustainability

Already computing and the Internet allow us to share information at a rate that well exceeds our collective abilities to process it. What remains to be seen, however, is whether a greater number of bits per joule will result in a decrease or an increase in joules per capita per unit time. Obviously, in order to become sustainable, new microtechnologies and nanotechnologies must be capable of delivering to their users information cost-effectively in order to avoid energy-hungry and entropy-intensive consequences (in other words, devices with a large $\dot{I}$ and a small ϕ and $\dot{S}$, or equivalently a small α). A few simple examples are the new remote home power monitoring systems, small remote seismographs for regions with poor infrastructure, or portable health-care devices. Respectively, these represent a saved trip home to turn off the furnace, an expensive search and rescue mission, or emergency trips to the hospital. The overall goal of sustainability as we move to adopt a greater number of microdevices and nanodevices is thus threefold:

1. Reduce the entropy of our corporeal selves for the purpose of sustaining our own lives or enhancing the probability of our own genes, stored in the DNA of our children, or enhancing the probability of survivability of our memes through what is typically referred to as the "grandmother hypothesis" [42].
2. Increase the entropy level in the environment of competitors or enemies. This is carried out constantly through direct warfare such as the 9/11 bombings, the use of radar jamming equipment, or the use of chemicals to kill plants and animals.
3. Increase the access level to pure information which serves the purpose of driving points 1 and 2. This is done on an individual organism level, a societal level, and likely at a genetic level with individual genes within a single organism competing as well as cooperating for expression levels.

It may even be fair to conclude that when the majority of human technological artifacts are engineered at the atomic scale, they will be fully capable of converging with the extant biologies. In many ways, they could become fully and inextricably symbiotic with us at a molecular level, just as mitochondria became inextricably symbiotic with a separate discrete cell early in the history of life. We live in what Martin Rees calls the mesoscale. In fact, it is the specific ratio, N, between the magnitude of the force of gravity at our planet's surface and the magnitude of electrostatic forces between the molecules within living organisms on our planet that allow for the rich diversity of life that we see. Each human is composed of between 10^{28} and 10^{29} atoms. If the smallest object that humans typically manipulate is a pin and the largest object is a sofa, then we manipulate agglomerations of matter that are between 100 mg and 100 kg, or between 10^{21} and 10^{29} atoms, with our bare hands. With the advent of optical microscopy, the lower end of this range drops by one or two orders of magnitude. With the advent of the internal combustion engine and conventional rocketry, we can move masses on the order of 500 million kilograms or between 10^{34} and 10^{35} atoms (many more times this much mass was moved during some of the largest atomic weapons detonations, but not in an orderly manner). A distinction is necessary between mass moved and mass transported, because modern nuclear weapons tests can be sensed from across the planet, but the energy released by some of the largest nuclear weapons, approximately 200 GJ is enough energy to give every human on the planet a trip into space of 70 km, or to give one fifth of the planet's population a trip to the International Space Station.

Paradoxically, it is our continued ability to manipulate matter at the microscale and nanoscale that has enabled the movement of such large quantities of mass and energy. Also somewhat paradoxically, some of the largest energy-consuming scientific instruments are required to probe some of the smallest and transient particles in the universe. And it is likely that advances in computing will further enable this. Moore's law has held true for over four decades and has been written about extensively. In fact, in a recent paper by Seth Lloyd [43], he predicts that the ultimate limit of a computer with a mass of 1 kg and a volume of 1 L is capable of performing 5.4258×10^{50} calculations per second, which falls well beyond Kurzweil's singularity, which itself occurs when computers operate at 10^{14} to 10^{15} calculations per second. Unfortunately, in the Lloyd ultimate computer, all of the mass turns to energy, so it is not clear whether the "information" generated will be useful, or purely entropic.

Another idea that is germane to our discussion of the evolutionary trajectory that technologies might take is Gould's "left wall hypothesis" [44], namely, that most living organisms exist at some average level of complexity with fewer complex organisms being capable of living far out to the right on the complexity scale, and those that live too far to the left are incapable of survival and are thus consumed. This is certainly true of technologies as well. For example, some of the most primitive and simple technologies, such as knives, utensils, and other hand tools demonstrate utility over entire lifetimes and frequently over many generations, whereas complex technologies, such as personal computers, automobiles, and cellular phones, are considered old well before their first decade.

In 1943, Salvador Luria demonstrated that when exposed to environmental challenges or opportunities, bacteria both retool their metabolic and defensive molecular machinery to enhance their probability of survival, t_L, by simultaneously maintaining their energy throughput, ϕ. Telomerase and its embodied information plays a similar role in maintaining the material integrity of the distal-most ends of ends of our precious chromosomes. Remarkably, but not surprisingly, the ability of these molecular machines, designed through natural selection to simultaneously deentropicize a cell by cobbling together stray nucleic acids and chemically welding them back onto the fraying split ends of the double helix, manifests at the organism scale. In fact, it appears that, literally, more information as embodied in the length of chromosomes increases longevity [45]. This is true on an organismal basis, not as a cross-species comparison. An organism with a longer genome is not necessarily likely to live longer than one with a short genome. However, if during cell division, genetic information is lost during division, the chance of mortality of healthy daughter cells, and thus the organism, in general,

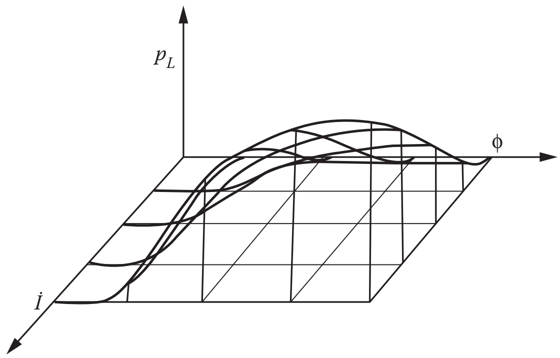

Figure 18.5 All technologies or molecular machines may be placed at a point on these three axes. P is the extensive power flowing through the machine and is directly proportional to the entropy emanating from it, $\dot{I}$ is the rate of information flowing through the machine, and t_L is the lifetime of the machine. This plot is intended to suggest that entities that are "smart" and powerful have a greater probability of survival.

diminishes. For specific cancers, there may be exceptions whereby the loss or mutation of inherited DNA may render a cell immortal yet diminish the life span of the organism that carries the resulting tumor. By doing so, telomerase reduces the degrees of freedom that the cell has by reducing the total number of molecules in the cell and thus reducing the entropy. It also adds to the amount of information contained by the cell. The result of this is that the cell and its progeny are more likely to persist longer into the future. Thus, we see that, with the emergence of molecular machines such as telomerase, they seal their fate as invaluable arrangements of matter that propel their host cells farther along the $\dot{I}$, ϕ, p_L axes (Figure 18.5). One way to define the sophistication of a machine is to do so on a triaxial basis consisting of the ability to funnel energy at a given rate, ϕ, the ability to process information quickly, $\dot{I}$, and its propensity toward longevity, t_L.

Another broader perspective worth exploring on the relationship between technological evolution and society is the complex relationship among scientific thought: the ability to program a computer, the ability of other talented people to hire computer programmers, and the resulting flow of abstract money through machines. Only a tiny fraction of financial transactions involve hard currency. Now, most financial transactions are attached to some thread, either through the financial records kept of a check written, the issuance of a stock or bond, or the numerical signature left on a broker's disk. Money has memory [46]. Perhaps the most poignant statement in Lanier's article is

> *There's an old cliché that goes "If you want to make money in gambling, own a casino." The new version is "If you want to make money on a financial network, own the server." If you own the fastest computers with the most access to everyone's information, you can just search for money and it will appear. A clear example of this principle is the rise of "high-frequency trading," in which the clan that owns the server gets to pull money out of a market before nonmembers can even try to make trades.* pp 127,

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How does Lanier's observation apply to the assertion of this chapter that the human–machine symbioses that will control the future will be ones with the greatest values along the $\dot{I}$, ϕ, p_L axes? We have already seen that each of these three metrics, namely the ability to funnel energy, ϕ, and the ability to funnel information, $\dot{I}$, can determine the ability to do this for a long time, p_L. There are other situations where the three are independent. For example, a machine can be very powerful but have a very short lifetime and almost no information processing ability. An example is an improvised explosive device (IED). A machine may have a very low power requirement but have the ability to process a relatively large amount of information such as a PDA. Or, a machine may persist for a very long time, have no power requirement, and have modest information processing capacity, such as an abacus.

Human–Machine Symbiosis

The fallacy of the common misconception that humans are "more evolved" than our close genetic relatives the chimpanzees implies that all contemporary living organisms may be "equally evolved" [18,47]. It is also a misnomer to state that a particular machine or a particular human–machine symbiosis is more evolved than another. Consider the sophistication of a system consisting of a camera being developed for special needs children that will allow them to take photographs and share them with friends. These students would be nearly non-ambulatory without their wheelchairs, crutches, and walkers. This symbiosis that is developing between the students and their ambulatory prosthetics is facilitated by a highly trained staff that serves to prevent the students from getting injured and to enrich their environments so that their brains stay stimulated and engaged. Thus, the system consists of camera, student, and trainer. This is much more sophisticated of a system than any single “normal” human. In earlier societies, children with these disabilities would not likely have lived beyond 1 or 2 years. Thus, even though these people as individuals may be “evolutionarily challenged,” in a purely Darwinian sense, through their technological symbioses, they are “more human” as were Gates, Glenn, and Gordon. It is, of course, the charge of academic leaders at our institutions of advanced education to enrich the experiences of their students. It is the responsibility of our best aging athletes to provide role models for the next generation. It is also the role of our best intellectuals to challenge the wise-cracking 18-year-old in the lecture hall and the job of the most far-thinking technologists to challenge the minds and hands of burgeoning and aspiring young students to bring into reality the next generation of machines that will propel our species to the stars, unravel the molecular mechanisms that make life possible, and to conceive of the next generation of micro- and nanotechnologies that will make the Kurzweilian dream of human immortality a reality.

Some of the most profound changes to humanity will come from what Kurzweil refers to as the NGR revolution: “N” for nanotechnology, “G” for genetics, and “R” for robotics. The idea is that once each of these fields of study matures, they will reach a crescendo where nanoscopic robots are able to both read and write genetic code in its native language. Some test-tube scale experiments have yielded preliminary results [48–50]. However, none of these use nanobots per se. Some attempts have been made at scales approaching the nanoscale (i.e., [51,52]), but there is always an issue with actuation. We are, thus, typically constrained to dealing with small batches using conventional bottom-up techniques or frequently painstaking top-down techniques (e.g., [53]). For example, in order to manipulate even a few femtoliters (1 μm^3) of matter to extract a single parameter such as Young's modulus, which can be represented with 64 bits of data, from a nanopipette can take nearly 1 kW of power and several hours [54]. So, in this case, $\alpha = 750$, or a relatively poor return on information per joule. Most of Shakespeare's works contain approximately 30,000 words. Someone reading at 500 words per minute and 25 bits per word, has in information processing rate of 208 bits per second, resulting in $\alpha = 0.0016$. From the local maximum that emerges in Figure 18.6 wherein α is plotted as a function of volume at the mesoscale of about 1 cubic meter, at least for the technologies discussed, there is a relatively poor return on bits per joule. Or, restated, unless there is substantial information processing occurring at a relatively low energy consumption rate, the α for a given technology is poor. The

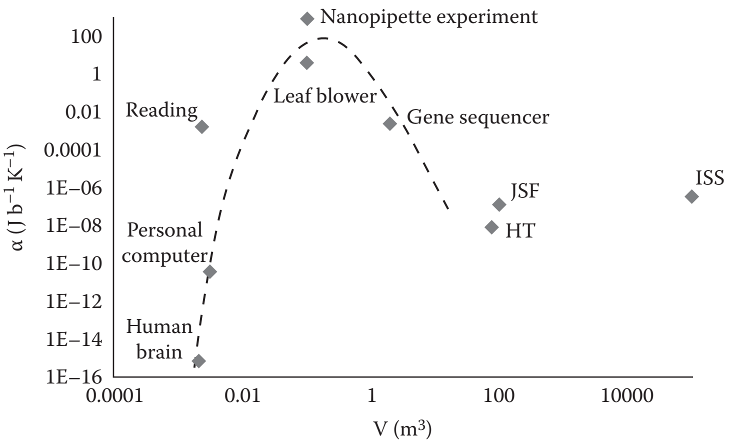


Figure 18.6 The technologies discussed in this chapter appear to follow a trend, whereby mesoscale technologies have poorer bit return per joule invested. The goal of any microtechnology or nanotechnology should logically demonstrate an economy that has a large bit return per joule invested or bit return per entropy unit (J/K). Here, the volume of a personal computer includes the volume of the tower, screen, keyboard, and so forth. The single data point indicates a rough estimate. The number of personal computers that are smaller than human brains is large and growing. The point indicating "reading" represents the actual act of serial reading one word at a time. Consequently, the bit rate is lower and a is greater than that required of the visual cortex when engaging in an activity such as basketball.

ISS, JSF, and HST do well because of their on-board computing power. In general, most other advanced imaging systems are going to have relatively large α values because extracting information from very small volumes of space requires more energy than does extraction at the human scale. Two extreme α values to find would be that of the Search for Extra-Terrestrial Intelligence (SETI) experiment, which is essentially being conducted with a large number of computers over a large fraction of the universe as well as advanced high field gradient magnetic resonance imaging techniques or atomic force microscopy experiments. The difficulty is in defining the boundaries of the experiment. The overall goal, however, in any advanced experiment or technology is to have a high return on information for a low investment in energy and subsequently entropy. We will also develop machines that read DNA on a desktop [55,56] that will surpass the gene sequencer tag, essentially tunneling from the right side of the curve to the left as size diminishes and information production rates rise. Also worth noting are still-evolving nanodevices. Many of the devices described in Freitas's Nanomedicine [57] are yet to materialize, but these, too, will likely, in principle, have very high bit to joule production ratios.

As an additional example of what we discussed in the introductory paragraphs, consider the portable scanners now being made available to remote regions of the world with almost no technological infrastructure. A portable scanner such as the GE LOGIQ Book XP with a few tens of watts of power is capable of collecting information about a pregnant mother's health status and that of her baby at a rate of several million bits per second. These form the images on the monitor, all of which then become condensed in the mind of the technician working locally and the trained expert working remotely. But what value of information throughput is the proper metric to use here? The number of bits flowing through the machine or the binary decision being made by the doctor or clinician: administer drug or not, admit to emergency room or not, and so forth. In other words, the definition of α may be relativistic in the sense that it is different for different observers. For the technician reading the output from the scanner, billions of bits move from the scanner's screen to the technician's retinas, there to be processed at a rate of terahertz in the technician's brain. However, from the patient's point of few, there is only a single bit of information to consider: C-section or vaginal birth?

How will we cool our computing devices? The author recently received a request to estimate the cooling power of Lake Michigan for a server farm. This practice is already common for nuclear technology and the steel industry, which severely alters local ecosystems. Global engineering issues such as this and the growing concern over the politics of energy (e.g., [58]) led a paper on the topic wherein energy densities and their associated monetary and societal costs were discussed [31]. The calculation for the server farm is simple. The heat thermal capacitance of water is 4.2 joules per gram per Kelvin, the volume of Lake Michigan is 5000 km^3, its mass is 5000 $km^3 \times 1000^3\ m^3\,km^{-3} \times 1000\ kg\ m^{-3} \times 1000\ g\ kg^{-1} = 5 \times 10^{18}$ g. For a cluster running at 100 kW for a year, the heat generated is $100{,}000 \times 356 \times 24 \times 60 \times 60 = 3 \times 10^{12}$ J. So one cluster of this size being cooled by Lake Michigan would raise its temperature by 3×10^{12} J ¸ 5×10^{18} g ¸ $4.2\ J\ g^{-1}K^{-1} = 0.15 \times 10^{-6}$ K, or about a sixth of a millionth of a degree in 1 year. Six thousand such clusters using a natural body of water to shed thermal energy would thus raise the temperature of Lake Michigan by one one-thousanth of a degree in a year. It would take an entire eon for these six thousand clusters (that's the equivalent of one every quarter mile) to raise the temperature of the lake 1°K, and that's assuming that the lake does not dissipate this thermal energy into the atmosphere or earth. A similar order of magnitude calculation yields that the 425×10^{18} J that we consume annually heats the atmosphere 0.1 K per year [31].

As stated in the opening paragraph, smaller technologies typically have greater "information payback" than larger ones. For example, a cell phone, which consumes energy at a rate of less than 1 watt, is capable of processing information at a rate of a few kbps, comparable to, or in many cases superior to a PC. How does this small technology already redirect human metabolic energy? For example, the cell phone can help the user find the nearest gas station, the nearest restaurant with the best menu, his favorite movie at a local theatre, or could be used to tell the user that his doctor's appointment has been canceled. It could also be used as a monitor for a home energy monitoring system or as an early storm evacuation warning. In each of these examples, information provided to the end user via the phone allows the user to minimize his or her own path to a rich source of information or energy. Place the smart cell phone with its embedded micro- and nanotechnologies in contrast with large technologies, such as earth-moving equipment, military equipment, commercial aircraft, or oil refineries. If we first consider large technologies such as these and strip them of all of their embedded small technologies, which are typically used for control, their embodied information or the information required to reproduce them (i.e., the information in the blueprints) is likely equal to that required to create the cell phone in the previous example. Obviously, in each of these cases, the gross energy throughput is much greater than that of the small technology. If the large commercial aircraft is not equipped with gadgets such as radar, radio, or other sophisticated telecommunication or control equipment, but merely its fuselage, seats, engines, and a simple power-assist manual control (basically only what is required for transportation of its passengers and crew), examining the same metrics that we did for the cell phone, the plane consumes energy at a rate of 50 MW, is capable of processing information at whatever rate the pilot is capable, say 10^{13} b s^{-1}, and thus has $\phi = 440$ W kg^{-1}, and thus, has $\alpha = 1.7 \times 10^{-8}$. If we were to add in all of the computer technology and equip all passengers with laptops, this number becomes 2×10^{-11}, comparable to a single computer. After having read this paragraph, the reader may wonder, what about the energy being consumed by the infrastructure to support the function of the cell phone? As with any thermodynamics problem, a boundary must be clearly defined. Certainly the cell phone is no more a singular discrete entity than the brain would be without motor, sensory, and communication organs. Thus, it becomes necessary to carefully define the boundaries. For example, in the definition of the machine types, the boundary of a Type II machine would enclose both the technology and the machine.

It may be worth considering an α_m and an α_M, the first of which gives the ability to stay under the background entropy generation rate, and α_M which defines the amount by which it is exceeded. For example, $S_{MEPP} - S_U = \alpha_M I_{M\_}dot$ and $S_U - S_{mEPP} = \alpha_m I_{m\_}dot$

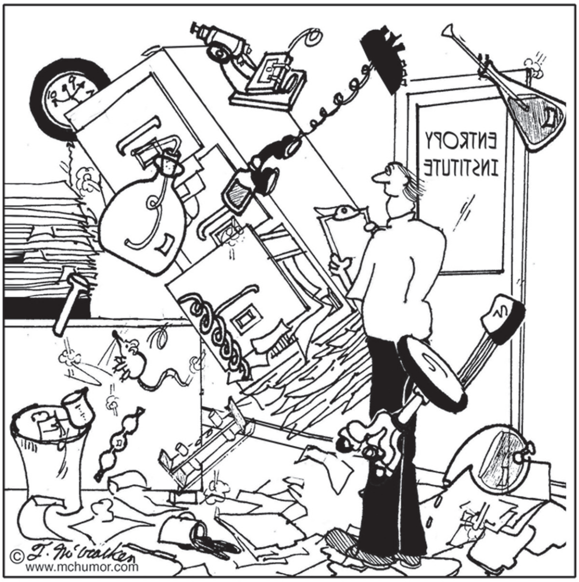
It has been suggested that natural physical entropy, S, is not a function of time, but that our observation of increasing entropy is responsible for the perception of time [59]. This is consistent with the fact that subatomic particles at temperatures we experience on earth have lifetimes essentially equal to that of the planet and thus do not "age." At high energy levels, neutron decay has a half-life of 17 minutes, but some heavy nuclei remain stable for billions of years, and carbon 14 takes 5700 years to decay into nitrogen, an electron, and an electron antineutrino. The proton itself is stable for at least 6.6×10^{33} years. Large molecules, of course, are more likely to fall victim to entropic events and thus have shorter lifetimes, yet some may have lifetimes that exceed that of the organism they serve. A poignant example is collagen, which was recently extracted from a *Tyrannosaurus rex* bone [60] revealing it to be closely related to birds. DNA that is tens of thousands of years old has also been found in *Homo* remains. If we then allow ourselves to consider that time is not an independent variable in the Newtonian sense or even a relativistic variable in the Einsteinian sense but a dependent variable that is a function of an entropy partitioning clock that is related to the information processing prowess of a biological or technological machine, then arguably, this allows less-sophisticated systems from the "past" and more-sophisticated systems of the "future" to coexist in the "present." In fact, the idea of coexistence is implicit in Einstein's general relativity. The question of whether our observed "arrow of time" is a result of the universe's expansion and the measureable increases in entropy we have discussed is still open for debate. Most physical theories either predict the absence of time or the reversibility of time at the quantum level, concluding that entropy measures are merely the result of statistical compilations of the numerous ways in which matter organizes itself, and the fact that the past may be known but not affected and the future affected but not known leads to a human perception of time.

Summary

In conclusion, the micro- and nanotechnologies that are most likely to persist and thrive will be ones that proffer the greatest selective advantage to their respective users. This selective advantage may be generally quantified as the human–technology symbioses that provide the owner/user with the greatest amount of usable information. To reiterate, the "usable information" is information that gives its user the ability to partition entropy: reduced entropy internally at the expense of above-background entropy acceleration environmentally. Usable information will emerge at multiple scales: individual RNA expression levels, basic blood chemistry, economic markets, weather and traffic patterns, and perhaps even geophysical and cosmological events.

Acknowledgments

This material is based upon work partially supported by the National Science Foundation under Grant No. 0900101. "Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation." This work was also conducted with funds from the Keck Foundation for the Drexel Center for ~~Nanofluidic~~ Attofluidics, the United States Department of Agriculture, USDA/CREES NRI grant 2008-35100-04413 and a grant from NetScientific. Opinions expressed by the author do not necessarily reflect those of these funding agencies.



Bad entropy day.

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