FORUM

The Industrial Ecology of Emerging Technologies

Complexity and the Reconstruction of the World

Braden Allenby

Keywords:
complexity
industrial ecology
railroads
resilience
sustainable technologies
transhumanism

Supplementary material is available on the *JIE* Web site

Summary

The modern world increasingly reflects human activities, to the point that many scientists are referring to this era as the "Anthropocene," the Age of Humans. A major domain of human activity involves sociotechnical systems, which can be characterized as occurring in constellations of coevolving technological, cultural, institutional, economic, and psychological systems lasting over many decades. The current constellation, still in its early stages of development, brings together five powerful technology systems—nanotechnology, biotechnology, robotics, information and communication technology, and cognitive science—that are even more complex than historical precedents because they enable not just far more powerful capabilities to design domains external to humans but also the potential to design individual humans themselves. Understanding the implications of this sociotechnical landscape for industrial ecology suggests profound theoretical challenges as well as important new areas of research.

Address correspondence to:
Prof. Brad Allenby
Department of Civil, Environmental, and Sustainable Engineering
Arizona State University
P. O. Box 875306
Tempe, AZ 85287 USA
brad.allenby@asu.edu
enpub.fulton.asu.edu/cesem/

DOI: 10.1111/j.1530-9290.2009.00114.x

Volume 13, Number 2

Introduction: The Anthropogenic Earth

The modern world is fundamentally different from anything previously known, in that it is dominated by one species and the activities and products characteristic of that species, from automobiles to cities to the creation of vast new cyberspaces. It is a world where the critical dynamics of major earth systems, be they atmospheric, biological, or radiative—or, for that matter, cultural, economic, or technological—increasingly bear the imprint of the human (McNeill 2000; Allenby 2005). As *Nature* put it in a 2003 editorial, "Welcome to the Anthropocene" (709)—roughly translated, to the Age of Humans (*Nature* 2003). A small set of examples from different domains, although not adequate to enable understanding of the whole, nonetheless provides some illustrative grounding.

Perhaps the most fundamental physical property of a planetary body is its characteristic radiation emissions spectrum, determined by the planet's heat content, composition, and atmospheric physics and chemistry. The earth's spectrum, however, is no longer just a matter of reflections from clouds, emitted infrared radiation, and the like. Rather, it includes television and radio broadcasts and leakage from all sorts of technologies. For many people, this change may be best captured in the well-known picture of the earth from space at night, with electric lights spread over North America, Europe, and Asia. In the Anthropocene, perhaps the most fundamental physical aspect of our planet, its radiation spectrum, carries a human signature.

Another familiar example is provided by global climate change. Fitful and ad hoc as it is, the process of the Kyoto Treaty and associated short-term politics represents the dawning of a realization that, regardless of what happens with international politics, our species will be engaged in a dialogue with our climate, our atmospheric chemistry and physics, and the carbon cycle as long as we exist at anywhere near our current numbers on the planet. We can reduce—more likely, redistribute—some of our impacts on these complicated and interrelated systems, but we will not eliminate the growing human influence. Moreover, these particular perturbations are all part of interconnected global systems, and a population of more than six billion humans, each seeking a better life, ensures that our overall role in global systems will only increase, absent some sort of population crash.

With respect to biological systems, it is generally accepted among most conservation biologists that we are experiencing a crisis in biodiversity as human activity causes extinction levels to accelerate. But some note that even if the decrease in evolved biodiversity is as steep as alleged—something that the underlying data are somewhat sketchy on—this may not be true, given the rise of "synthetic biology." Over the past decades, scientists and engineers have begun the project of understanding and designing new forms of life; their efforts have coalesced into a new field called synthetic biology (See box 1).

The example of synthetic biology is instructive because it illustrates that these new technological directions are not merely incremental changes to existing knowledge. Synthetic biology does not just reconfigure the biological sciences; the potential implications are far more profound. To begin with, biodiversity increasingly becomes a product of design choices and industrial and political imperatives (security issues, e.g.) rather than evolutionary pressures. This has potentially serious implications for system stability and resiliency. Given that evolved biodiversity tends to coevolve in concert with its surrounding biological and physical systems and thus tends toward resiliency, but the high throughput and focus on economic value characterizing industrial systems, and thus synthetic biological systems, do not suggest such stability. More broadly, the behavior and structure of biological systems increasingly become a function of human dynamics and systems, so that understanding biological systems more and more requires an understanding of the relevant human systems. Thus, for example, the contingency that characterizes human systems comes to characterize biological systems. An obvious marketing example comes from conservation biology. In an arbitrary and profoundly cultural process some species are preserved because they are charismatic megafauna: pandas, tigers, or whales. Many, many others go extinct because they are only insects, or plants, or ugly, or unknown; a few, like smallpox,

Box 1

Synthetic Biology

Synthetic biology merges engineering with biology by, among other things, creating standard biological components that can be mixed and matched in organisms to provide desired functions. This allows researchers to treat biological pathways as if they were components or circuits and to create organisms from scratch—not to mention extending beyond existing biological systems by, for example, creating life based on different genetic codes than those found in the wild. MIT, for example, has established a Registry of Standard Biological Parts ("BioBricks") that can be ordered and plugged into cells, just like electronic components. The 2005 Intercollegiate Genetically Engineered Machine (iGEM) competition held at MIT in November 2005 attracted 17 teams, with designs that included bacterial Etch-a-Sketches; photosensitive t-shirts; and bacterial photography systems, thermometers, and sensors (Check 2005). Somewhat controversial, a number of viruses have been assembled from scratch, including the viruses for polio and the 1918 flu epidemic. Other researchers have engineered the genes of *Escherichia coli* to incorporate a 21st amino acid, opening up opportunities for design of biological organisms that have been unavailable to evolved biological systems for billions of years (*Nature* 2004). Commercialization of these biotechnologies continues to accelerate, led by the introduction in agriculture of genetically modified organism (GMO) technology. But as the growth in biotechnology companies in pharmaceuticals and other sectors indicates, GMO technology extends far beyond agriculture. Reflecting the ongoing commoditization of life, figures for biotechnology patent filings in Organisation for Economic Co-operation and Development (OECD) countries continue to rise sharply. Moreover, the speed of underlying technological advance in synthetic biology—Carlson's curve, measuring the improvement in DNA sequencing and synthesis capability—is even more rapid than the famed Moore's law in chip transistor capacity ("Life 2.0" 2006)..

disappear because humans detest and fear them. In short, biology increasingly becomes a social science.

Technology as Systems Function: The Railroad Example

To fully appreciate the challenges that the complexity of modern, rapidly evolving technology systems present to the industrial ecologist, one must understand technologies as integral parts of the human/natural/built systems that characterize our present age, not just a collection of artifacts. It is not just that our technologies physically construct a human earth. Rather, much of the complexity of technological systems arises not from their physical attributes, complicated as they may be, but from their necessary coupling to human and social systems, which have a far different and higher degree of complexity (Bijker et al. 1997; Heidegger 1997).

This is perhaps best illustrated through historical example. Railroads are by now a familiar element of the human environment—perhaps even a little mundane compared to other forms of transportation. But in the middle 1800s, as it began its rapid expansion phase, the railroad was not just the most impressive piece of machinery most people had ever seen: It was a sociocultural juggernaut. The world before the railroad and the world after the railroad were different in profound ways. Among the changes the railroads brought in their wake were the following:

1. As a regional-scale integrated technology network, railroads required a uniform, precise system of time and thus created "industrial time" and its associated culture (Rosenberg and Birdzell 1986). Before railroads, local times were isolated and charmingly idiosyncratic: London time was 4 minutes ahead of Reading, more than 7 minutes ahead of Cirencester, and 14 minutes ahead of Bridgewater (Schivelbusch 1977). Moreover, the adaptation to uniform systems of time was not smooth;

for a considerable period in the United States, each train company had its own time, so that stations serving several train companies had different clocks (Buffalo had three different clocks at one point, Pittsburgh six). Regional standard time did not gain legal recognition in the United States until 1918 (Schivelbusch 1997).

2. Railroads created the need for and coevolved with national-scale communications systems. In particular, telegraph technology was both coextensive with rail networks (frequently laid along the same rights of way) and a necessary coordination mechanism for the creation and operation of regional integrated rail systems (Grubler 1998).
3. Railroad firms shaped modern managerial capitalism. Whereas previous industrial technologies had called forth a division of labor among factory workers, the scale of railroad enterprises required a division of labor at the management level, with modern and professional accounting, planning, human resources, and administrative systems (Freeman and Louca 2001).
4. Railroad firms shaped modern capital and financial markets (railroad construction was the single most important stimulus to industrial growth in Western Europe by the 1840s). The early factory system was supported initially by aristocrats and landowners and subsequently by factory owners using their own capital, an essentially individualistic financial structure that was nowhere near adequate to support the huge capital requirements of railroad firms (Freeman and Louca 2001).
5. Particularly in the United States, railroads became a potent symbol of national power and, more subtly, instantiated and validated the American integration of religion, morality, and technology. This was reflected in the language used by those who viewed railroads as evidence of human ascension to godlike power (Daniel Webster, e.g.) and the not insignificant in number who viewed them as Satanic: "If God had designed that His intelligent creatures should travel at the frightful speed of 15 miles an hour by steam, He would have foretold it through His holy prophets. It is a device of Satan to lead immortal souls down to Hell" (Ohio School Board, 1828, quoted in Nye 1994, 57). The railroads thus initiated a coupling between religion and the technological sublime that forms an important basis of American exceptionalism[1] and continues in the United States into modern times. Consider Robert Oppenheimer's famous musing at Trinity Test Site at White Sands, New Mexico, in 1945 at the first successful nuclear test, echoing Vishnu from the *Bhagavad Gita*: "Now I am become Death, destroyer of worlds."[2] Notice also the critical shift that technology enables: The aspect of destroyer of worlds in the *Gita* is divine; at White Sands, the divine has become human.
6. Railroads transformed landscapes at all scales, both physically and psychologically. Chicago existed, and structured the Midwest economically, physically, and environmentally, because of railroads (Cronon 1991). Psychologically, railroad technology did not just extend but obliterated the sense of place and rhythm that previous transportation technologies, the horse and carriage and the canal, had encouraged, and early reports of railroad travel frequently emphasized the psychological dislocation induced by the increase in speed and reduction in perceived distances that the technology introduced (Schivelbusch 1977).
7. Like most major technological systems, railroads fundamentally changed economic and power structures. In the United States, for example, railroads validated the continental scale of the American state and the doctrine of manifest destiny[3] and restructured the economy from local and regional business concentrations to trusts (because of scale economies of national markets). With the railroad, economic power passed to industrial firms from agriculture; more subtly, so did cultural authority (Marx 1964; Nye 1994).
8. The railroads fundamentally and radically shifted the dominant American

worldview from Jeffersonian agrarianism, an Edenic vision, to a technology-driven New Jerusalem (Marx 1964; Nye 1994; the Edenic vision is one of humans living in nature without technology, as if in Eden, whereas the New Jerusalem vision is one of a high-technology, intensely designed environment. Both draw from Euro-Christian roots, but they have very different cultural and political implications). This cultural schism replays itself even today, with the sustainability and environmental discourses leaning toward the Edenic and the industrial, commercial, and science and technology communities supporting the New Jerusalem worldview (Allenby et al. 2007).

Technology Clusters

The constellation of social, economic, cultural, values, theological, institutional, and policy patterns associated with a core technology is by no means unique to railroads. Indeed, the railroad example is only one of what economic historians call "long waves" of innovation (sometimes called "Kondratiev waves"), with accompanying cultural, institutional, and economic changes, developing around core fundamental technologies. Each core technology supports "technology clusters": Railroads and steam technology powered a wave from about 1840 to 1890; steel, heavy engineering, and electricity, from about 1890 to 1930; the automobile, petroleum, and aircraft from about 1930 to 1990; the information cluster, with its computerization of the economy, from about 1990 to the present. Although the dates are somewhat imprecise, the general idea of clusters of technology—which, it cannot be emphasized enough, always carry with them institutional, organizational, economic, cultural, and political changes—is a useful one (Freeman and Louca 2001). Thus, specialized professional managerial systems and associated industrial efficiency techniques ("Taylorism") characterized the heavy industry cluster, whereas a far more networked, flexible structure began to evolve during the information cluster (Castells 2000).

For the industrial ecologist, this is a somewhat daunting landscape, for it implies couplings and linkages among social, cultural, belief, technological, and physical systems that lie beyond most industrial ecology studies to date. In the case of individual analyses and studies, of course, consideration of these broad dimensions of technology systems may not be required. But a robust industrial ecology that addresses questions of technological evolution through time cannot afford to ignore them. Whether these domains are the core or even a part of industrial ecology as a field is less important than understanding that these couplings exist and must be evaluated for relevance and importance depending on the particular analysis at hand.

More subtly, industrial ecology is not just a technocratic field of study and practice; as with any intellectual framework, it is also a reflection of its culture, its times, and relevant ideologies. These factors, of course, also arise from (a primarily Enlightenment,[4] technocratic, and rationalistic) culture, and industrial ecology cannot be independent of them. Thus, the role of technology systems in structuring cultural attributes creates a reflexivity underlying industrial ecology that cannot be ignored, but most industrial ecologists remain unaware of the power of technology systems in creating these cultural frameworks (*reflexivity* refers to the way that, as humans develop information about themselves and their systems, it feeds back into their systems, thus changing the analysis and system behavior in unpredictable ways).

Again, the railroad offers a case in point. The shift from technology as a challenge to agrarian Eden to technology as a means to achieve the New Jerusalem is a critical step in the relationship between technology and theology generally but particularly in the embrace of technology in the New World. It remains a potent cultural archetype underlying much of America's self-image and hence is critical to global cultural and power patterns. For an industrial ecologist trying to study genetically modified organisms (GMOs) or any culturally charged technology—especially where major cultural units such as the United States and the European Union disagree fundamentally—it is essential to understand this dimension (Nye 2003).

These technology clusters illustrate several critical points regarding technology. Most important, technological change cannot be understood as an isolated technocratic event. Rather, it represents movements toward new, locally stable, earth systems states. These states integrate natural, environmental, cultural, theological, institutional, financial, managerial, technological, built, and human dimensions and even construct our sense of time and space. Technologies do not define these integrated earth system states, except by convenience, but technological evolution can destabilize existing clusters and create conditions leading to the evolution of new ones.

It is important to recognize that technology is a major means by which the human will to power is reified, expressed, and channeled. This is not just an academic observation. Cultures that develop technology and create frameworks within which it can react on itself and so accelerate its own evolution thereby gain power over competitors. Because technologies create such powerful comparative advantages between cultures, those cultures that attempt to block technology will, all things being equal, eventually be dominated by those that embrace it. Thus, technological evolution will likely be difficult, if not impossible, to stop, despite the efforts of many in the environmental and sustainability communities. Indeed, whether and how technology systems can be moderated in the age of global elites become important research questions extending far beyond mere questions of regulation. As the rate of change of these systems continues to accelerate, they stretch the bimodal distribution between those who constitute the global elite and who, primarily through education and culture, are able to prosper under such conditions and those who are left behind. The latter have a strong tendency to seek stability in outmoded ideologies and fundamentalist movements and become an important, and unpredictable, modulator of technologies in particular cultures (e.g., the Bush Administration and its opposition to stem cell research).

Technological Evolution: The Five Horsemen

The railroad example helps clarify several general principles of technological evolution. First, a technology of any significance will destabilize existing institutions and power relationships and thus, to some degree, cultural assumptions. Accordingly, it will be opposed by many. To the extent that such opposition is successful, it will not halt the evolution of technology, but, in a globalized culture, technological leadership is likely to simply pass to other cultures where opposition is less effective. Second, projecting the effects of technology systems before they are actually adopted is not just hard but, given the complexity (especially reflexivity) of the systems, probably impossible. Thus, for example, the time structure that we moderns take for granted was not the time structure of prerailroad American agrarian society or European cultures; it is a product of our technology. Globally ordered time frames were not just unpredictable a priori, they were difficult to conceive in social and cultural systems that had neither any need for nor any concept of unified and ordered temporal frameworks at a planetary scale. This raises a more subtle but equally important point: We are able to perceive our world and create our cultural constructs only through the lens that our technology provides. Virtual reality, courtesy of information and communications technology (ICT), is only the latest manifestation of a long history of technologically mediated human conceptualizations of reality.

Unfortunately, however, the problem is not just that the history of technological change indicates that technology systems are far more complex than usually contemplated in industrial ecology literature and studies. If the history of technological evolution is a warning, it is an entirely inadequate one for the wave bearing down on us. Technological change, as suggested by the example of the railroads, is always potent, but now we do not just have one or two enabling technologies undergoing rapid evolution, we have the Five Horsemen: nanotechnology, biotechnology, robotics, ICT, and applied cognitive science (these technologies are sometimes referred to collectively as NBRIC[5]; Garreau 2004).

These technologies in some ways are the logical end of the chapter of human history that began with the Greeks 2,500 years ago. Nanotechnology extends human will and design to the atomic level. Biotechnology extends it across the biosphere, making us, over time, in the words of environmental historian J. R. McNeill (2000), "lords of the biosphere" (193–194). ICT gives us the ability to create virtual worlds at will and facilitates a migration of functionality to information rather than physical structures. Robotics and biotechnology merge the biological and technological realms, enabling integration at the level of information systems. Cognitive sciences rationalize cognition and thus enable ever-expanding cognitive networks that increasingly merge human and technology systems, especially ICT. Think, for example, of the way that Google has so dramatically extended human memory, creating a cognitive system that includes not just the human elements but vast swaths of Net technology, or the way that many militaries are building "augmented cognition" technologies—technologies intended to scan the battlefield for threats that are integrated into each soldier's cognitive systems (Hutchins 1995).

Current accelerating rates of technological evolution are unprecedented. They have the effect of dramatically extending the spaces within which humans can, intentionally and unintentionally, impact existing systems and design new ones. In doing so, they not only raise the level of complexity of systems that we must strive to understand. Because they also give us rapidly increasing tools to design the human itself, they also render contingent much of what we have taken to be fixed.

The Human as Design Space

Consider for a brief moment some of the implications for industrial ecology of the NBRIC wave in just one area, human biology. As good industrial ecologists, let us begin by defining relevant life cycles. But this is not a matter of simple assumptions or curve extensions anymore. At one extreme, some predict the achievement of "functional human immortality" within 50 years, either as a result of continuing advances in biotechnology or as ICT and computational power enable downloading of human consciousness into information networks (Moravic 1988; Kurzweil 2005). Although such predictions are viewed by most experts as highly unlikely, there is a growing consensus that substantial extensions of average life spans, with a high quality of life, are achievable in the next few decades. For example, the *IEEE Spectrum*, a mainstream technical journal, ran a series of articles in 2004 on engineering and aging that concluded that using "engineered negligible senescence" to control aging will allow average ages of well over 100 within a few decades, and a number of experts claim that the first people who will live to 150 with a high quality of life have already been born (IEEE 2004; De Grey and Rae 2007).

From an industrial ecology viewpoint, what is interesting about this age extension scenario (and any discussion of future technology should be regarded as a scenario rather than a prediction) is that, even though the scientists and technologists are perceiving such possibilities as age extension as increasingly probable, those in other areas of science, engineering, technology and policy, environmental and sustainability analysis, and, indeed, industrial ecology itself remain unaware of these possibilities, despite their obviously challenging implications. In an analysis with a relatively short time frame (current use of chlorine in industrial systems, e.g.), this is not necessarily problematic, but as industrial ecology begins to extend its analyses through time (e.g., long-term patterns of material and energy flow or contributions to the dialogue on global climate change, with its century-long time frames), ignorance of plausible technology scenarios becomes highly problematic.

Equally challenging, it is becoming apparent that not just the earth but the human itself is in the process of becoming a human design project and that substantial changes in what it means to be human are probably inevitable. N. Katherine Hayles (1999), for example, in her aptly named book *How We Became Posthuman*, traces the evolution of the posthuman through the concepts of homeostasis, reflexivity, and, finally, virtuality. Although Hayles is cautious about the implications of this ongoing and accelerating process, some foresee enormous potential: Roco and Bainbridge (2003), in a U.S. National Science Foundation report titled *Converging Technologies for Improving Human Performance*, for example, conclude, "With proper attention to ethical issues and societal needs, converging technologies could achieve a tremendous improvement in human abilities, societal outcomes, the nation's productivity, and the quality of life" (ix). They continue,

> Examples of payoffs may include improving work efficiency and learning, enhancing individual sensory and cognitive capabilities, revolutionary changes in healthcare, improving both individual and group creativity, highly effective communication techniques including brain-to-brain interaction, perfecting human–machine interfaces including neuromorphic engineering, sustainable and "intelligent" environments including neuro-ergonomics, enhancing human capabilities for defense purposes, reaching sustainable development using NBIC tools, and ameliorating the physical and cognitive decline that is common to the aging mind.

To some, the idea of the human becoming a design space presages a millenarian conflict of human versus technology (as per the movie *The Matrix*); it is, however, equally likely to result in the continuing merging of human and technology to the end of greater economic efficiency (along the lines of the anime movie *The Ghost in the Shell*). The Enlightenment Romantics had their Frankenstein model, and it remains powerful today (as in Greenpeace's Frankenfood public relations campaign). If history is any guide, this is at best a temporary opposition; previous technological advances, although admittedly of less potency than the Five Horsemen, have generally seen a merging of individuals, institutions, and society with the new technologies (think of the printing press, which was perhaps the first mass externalization of memory, similar to Google but at a different scale). That integration seems to be the historical pattern should not be taken to imply that changes will be merely incremental, especially in older concepts of what constitutes the human. Nor does it mean that we will not see varietals of humans—as, indeed, the "digital natives" that are comfortably embedded in their ICT networks may already be (Tapscott 2009). At the level of nature, it means that we should expect integrated human/natural/built earth systems, rather than those we currently idealize. Indeed, some current "mashups," in which representations of the real world are mixed online with virtual representations of data sets or imaginary spaces, are already going in that direction, and acceleration of such trends promises yet more integration of virtual and real-world environments (generally called augmented reality; "Reality" 2007). Where the human begins and ends in such systems is ambiguous (Hutchins 1995).

Effects of technological convergence on the human form only one small area of research and speculation; similar suites of possible scenarios are being developed in many other areas. It is obviously premature to regard most of these predictions as anything more than possible outcomes. Indeed, much of the thinking on technological futures is marked by a strong tendency to focus on a particular aspect of a technology or its implementation and to implicitly hold other social, technological, or environmental systems fixed. This almost automatically ensures that the scenarios are implausible, because technological change, especially at this fundamental level and across virtually the entire technology salient, is integrated with most other human systems, and under such conditions they, too, will be evolving and contingent. Additionally, except for the easy cases in which particular applications of these core technologies are already in the process of being commercialized, it is very difficult to determine how probable even the most outré scenarios might be. The line between science fiction and tomorrow's headlines has seldom been quite so blurred, in part because technologies frequently tend to follow cultural precedents that are often established in science fiction. Thus, for example, the structure of virtual realities shows a strong resemblance to the work of writers such as Gibson and Stephenson—and, accordingly, not only is it hard to tell the difference between fiction and soon-to-be fact, the latter is constructed, in fact, by the former.

The Undermining of the Enlightenment—or at Least Industrial Ecology

The integrated cluster of technology that is rapidly beginning to redefine our world is also providing the scientific and technological basis for dramatically obsolescing many of the assumptions that underlie industrial ecology. The following points stand out in particular:

1. Industrial ecology must learn to understand and include radically increasing complexity of at least four different kinds—(1) static, (2) dynamic, (3) "wicked," and (4) scale—as we realize we must begin to design, engineer, and manage integrated human/natural/built earth systems at not just facility and industrial scales but at national, regional, and global scales (see Box 2). This complexity has already had profound institutional implications in our era: Marxism in the Soviet Union and China collapsed not from external conquest or even from Reagan's vaunted spending race but rather because the centralized economic model adopted by large Marxist societies simply became incapable of managing the complexity inherent in a modern industrial economy (Kauffman 1995). And note that our economies, financial networks, and technologies have become far more complex since then. In what amounts to a challenge not just to policy but to the paths of analysis currently popular in industrial ecology (e.g., mass flow accounting), not only can we not centrally control the global economy anymore, but it may be impossible to centrally conceptualize it for much longer, which suggests the reality of distributed collective intelligence rather than the Cartesian individual cognition that has long been the model of Enlightenment rationality. Industrial ecology must develop tools adequate to the complexity of the systems it purports to analyze.
2. An important element of this complexity is that it confirms an unavoidable relationship among observer, frame of reference, and derivation of partial and contingent truth from underlying complex systems. Consider a simple example. If I am interested in the rates of crime in the city of Phoenix, I am also implicitly defining the urban system by its political boundaries, because most measured crimes are local, and statistics are kept on a jurisdictional basis. If, conversely, I am interested in water and Phoenix, I am implicitly defining the system as including the Colorado River basin, not to mention American water law, patterns of tourism that make golf courses

Box 2

Complexity

Complexity is not a unitary concept. One way to parse complexity is by identifying four different components: static, dynamic, "wicked," and scale. Static complexity reflects the numbers of parts and their linkages: For a business manager, static complexity might reflect increasing numbers of competitors, regulations, jurisdictions, stakeholders, activists, and treaties. For a technology system such as the Internet, static complexity could reflect the increasing numbers of hubs and linkages that constitute the physical framework underlying Internet services. Dynamic complexity arises as these factors interact in new and unanticipated ways and create constantly changing emergent behaviors and network configurations; this category becomes even more challenging given the acceleration of technological evolution and information production and communication characterizing modern information dense societies. Wicked complexity arises from the psychological and social dimensions of the anthropogenic world and its characteristic integrated human/natural/built systems, which increasingly display the reflexivity and intentionality of human systems and institutions. Reflexivity is a key concept in wicked complexity: Information developed by humans about human systems is, by definition, a new part of the human system that it arises from, and thus it immediately affects and changes the underlying human system. Finally, there is the question of scale: That the Anthropocene arises because humans are impacting not just local environments and resource regimes but the global framework of physical, chemical, and biological systems is new and challenging, in that no discipline or intellectual framework enabling rational understanding at that scale yet exists (McNeill 2000; Allenby 2007).

popular in Scottsdale, and xeriscaping initiatives. Yet in both cases the relevant marker is Phoenix. What is happening, simply, is that my query to the system calls forth from an underlying complex world a particular network that is responsive to my query. The networks that are of interest in a particular situation will generally be determined by the dialectic of the underlying world with the particular questions being asked about it. There is a similarity to quantum mechanics here: What you perceive when you look at the system is determined by the purpose for which you are observing it. The system itself always remains more complex than you are able to capture at any one time.

3. The corollary is that a complex system can only be defined in terms of the reasons for which a definition is desired. The query identifies the particular networks of the system that are relevant, and they, in turn, define the boundaries of the system for the purpose of the inquiry. This reflexivity complicates any discussion of a complex system and reduces the value of standardized or ideological approaches. Our understanding and the complex nature of reality are not congruent but coupled weakly through our queries to the latter. The implications for industrial ecology are profound: Industrial ecology by its framework, which defines what appropriate industrial ecology queries and assessments are, also significantly bounds the validity of its findings. Failure to understand and explore the implications of this dynamic in part explains the continuing conflict between those who view industrial ecology as an "objective" science and those who value it only inasmuch as it directly supports environmental activism.
4. The accelerating evolution of technology systems, especially ICT, combined with the postmodern fragmenting of time, space, and culture, dramatically decreases the stability of all cultural constructs. In our particular case, it has two profound effects: It not only renders the social and cultural landscapes that we look out on more unstable but renders that which looks out—including the field of industrial ecology and, indeed, even our selves and our individuality—more contingent as well. The dramatic increase of fundamentalism across most belief systems and in most societies reflects, in part, an effort to create a stable ground even as technology ineluctably creates a future in which, as Marx presciently noted, all that is solid melts into air (Marx and Engels [1872] 1998). Note that this does not mean that the postmodern solutions of absolute solipsism[6] and relativism are valid (Lyotard 1984). It does mean, however, that if the mental models and cultural constructs underlying industrial ecology are going to continue to be adaptive and valid, we must learn to understand them as contingent and thus evaluate their continued validity, especially in the case of long-term or cross-cultural studies.
5. The traditional focus of industrial ecology on material and energy flows is useful but of increasingly limited relevance given the complexity of the systems emerging in the real world. Information and cultural structures, especially those associated with radical technological evolution, cannot continue to be regarded as beyond the pale of industrial ecology. The point is not that many industrial ecology studies should not focus on material and energy flows; rather, it is that the field as a whole must learn to treat cultural and informational realms with the same sophistication and seriousness as physical realms.
6. Ideology and rigid worldviews are particularly problematic at the dawn of the anthropogenic world, which, as we have seen, is characterized by exceedingly rapid, unpredictable, and profound change in fundamental relationships and systems involving natural, built, and human components of extraordinary static and dynamic complexity. To begin with, any ideology is necessarily a simplification of reality; in fact, that is usually an important part of its mass appeal. But because the elements and structure of this simplification necessarily

lie in the past, not the future, they embed assumptions and implications that are necessarily increasingly anachronistic in a period of rapid and discontinuous change.

Moreover, ideology creates an "ends justify the means" mentality; almost by definition, the power of the idea trumps the messy and contingent real world. In a world where technology coupled to state and industrial power increasingly exercises broad leverage, the damage that authoritarian ideologies can generate because of this mind-set becomes truly dangerous. Additionally, as part of the elevation of the idea over the real, ideology cuts off information transfer and dialogue and can thus limit dialogue and development of options at precisely the time when adaptation to new conditions would benefit from such discussion. It is not, then, just that ideologies are generally questionable, although many of them seem to be in application, as any familiarity with the 20th century would confirm; rather, it is that ideologies are *especially* dubious in a period of rapid, discontinuous, and fundamental change at a global, multicultural scale. For industrial ecology in particular, which is in many ways contested ideological terrain (scientism vs. environmentalism being the most obvious conflict at this point), the dangers of ideological bias are insufficiently appreciated.

7. If industrial ecology as a field is to integrate its context into its analyses appropriately, it is important to recognize at least some of the difficult policy implications of increasingly rapid technological change and the entrained cultural, social, economic, and institutional implications (indeed, even the theological, as discussed in the appendix, available as Supplementary Material on the Web). For example, it may well be the case that the changes we are currently beginning to experience mark, in fact, the end of the great Enlightenment project of radical democratic power. Indeed, the rates of change we are now experiencing have already created an increasingly potent fundamentalist backlash, not just within virtually all major religions but within those belief systems—environmentalism, sustainability—that for many people, especially in secular societies, now begin to serve theological purposes. This is not random opposition to modernity but is generated by the fact that, as rates of technological change accelerate, increasing numbers of people in every society are disenfranchised. They are incapable of keeping pace with continuing change; unable to integrate into the information webs that increasingly define human cognition; and aghast at the changes in lifestyle, income distribution, relative power relationships, and changes in sexual and family roles and structures that have resulted. And these groups have not yet begun to understand the degree to which their fundamental values are rendered contingent by that self-same progress. Thus, accelerating technological change can only increase opposition to itself—yet it is an important component of cultural dominance. For those for whom Enlightenment-representative democracy is an important value, then, technological change creates a difficult conundrum: The more it succeeds, the more it creates an activist opposition that hobbles it in democratic cultures, giving the advantage to more autocratic cultures where the elite are able to exercise control. A prediction? No. A reasonably probable scenario that should be of concern to industrial ecologists? Yes.

Reinventing the Enlightenment, and Industrial Ecology: A Continuing Saga

Industrial ecology is solidly grounded in Enlightenment thought, and thus it is rendered contingent as the Enlightenment itself is—and it must adapt in the same way. Begin by observing that complexity and radical contingency have undermined the Enlightenment as it is now constructed and as it now underpins global culture. In some ways, this is desirable, as it opens new options for continued evolution of cultures, the species, and individuals. Moreover, this is only an extension of the dynamic that has always characterized the Enlightenment and, arguably, must characterize any cultural system that successfully evolves to dominate regional and global polities. Thus, the Enlightenment as global culture has succeeded, ironically, because it uniquely carries within it the seeds of its own negation as a uniquely "true" or "valid" culture. Indeed, the strongest critics of the Enlightenment have been internal, from Rousseau ([1754] 1964), whose criticism has become internalized to much of the environmental discourse, to Marx, to Freud, to Darwin, to postmodernists of all stripes. Thus, thinkers such as Rorty (1989) have emphasized two paradoxical observations:

1. Only a structure that, like the European Enlightenment, contained its own critique and negation within itself could possibly become the basis for a globalized cultural framework in a multicultural world.
2. The Enlightenment framework succeeds only to the extent that it continues to negate itself as a unique source of "truth." In these cases, the Enlightenment tradition not only has been the source of the negation but has itself been transformed, transcended, and made more universal and encompassing by the dialectic generated by the negation. This dialectical process, perhaps most closely associated with Marx and Hegel, is itself an important and self-conscious facet of the Enlightenment; in fact, much Romantic thought, with the important exception of Rousseau, saw the dialectic as the process by which human progress toward a reintegrated high civilization (in religious terms, recovery from the Fall, which was itself seen as introduced by intellectualization) occurred.

As the original Enlightenment evolved through modernity, the relatively integral worldview it entailed shattered against the increasing complexity of the cognitive networks that it enabled: So now must the science and technology enterprise, and industrial ecology as a part of it, transcend—not deny or oversimplify, but internalize and transcend—that complexity anew. The Enlightenment as explicit framing has been transcended yet again by the Enlightenment as process—and if industrial ecology is to live up to its promise, this also must become part of the way industrial ecology thinks of itself. Indeed, in some ways industrial ecology is the Enlightenment writ small: a nascent effort to apply the tools of rationality to increasingly complex, integrated sociotechnical systems. Thus, the research agenda suggested by this analysis should be interpreted in part as an effort to include self-critique and even self-negation as integral parts of industrial ecology itself—something to be desired, not fought against.

Possible Elements of a Research Agenda

Although the challenge of understanding these complex sociotechnical systems is daunting, it is not impossible, and even at this early stage one can suggest a few areas of research that might prove fruitful in expanding industrial ecology in appropriate ways. A few are listed below; they are best viewed as illustrative rather than definitive.

1. An obvious focus is complexity and complex adaptive systems and how their study may be incorporated into mainstream industrial ecology. This has already been suggested by some industrial ecologists (e.g., Ehrenfeld 2004; Allenby 2006) and would involve theoretical, applied, and methodological domains. For example, network theory is an area of intense interest right now (Barabasi 2002) and offers a new way of both framing complex industrial ecology problems and integrating social, legal and regulatory, economic, technological, and natural systems in industrial ecology analyses. An important topic within this category is applying our understanding of how system structure constrains current choices and future evolution of the system (Kauffman 1995); tightly coupled systems can be far less adaptive than more loosely coupled systems, but too loose a system is incapable of evolution.
2. The resilience of complex human/built/natural systems is an important framework

that should become part of the industrial ecology research agenda. Although it is similar in some ways to the cultural construct of sustainability, resilience has been more rigorously explored in both the complexity and the ecological literatures, and some efforts have been made to apply the concept to systems such as cities (Fiksel 2003; Allenby and Fink 2005). Resilience studies are not only topical and policy relevant, but at this early stage of development each such study potentially provides valuable theoretical input as well.

3. Emerging technological systems should become a staple of industrial ecology research for a number of reasons, most importantly because such technologies have the potential to undermine many of the assumptions underlying current industrial ecology research programs. Among the particular issues that require further research is the vexed question of the degree to which emerging technologies can be "managed" or constrained; current efforts to stop genetically modified agricultural organisms or stem cell research, as well as sustainability studies along the lines of "go 50 years out and backcast," indicate that our knowledge of the dynamics and behavior of such systems is naive at best and willfully blind at worst. Equally important, it becomes apparent that even institutions that require knowledge of the evolving technological frontier have only a partial grasp of the overall technological project at this point (e.g., NRC 2005; CIA 2008), which suggests that research identifying reasonable scenarios for emerging technologies and exploring their implications remains an important priority. That we do not understand the world we have already created, much less the one we are studiously working to create, is a huge challenge to our ability to act rationally, ethically, and responsibly.
4. At the scale of these complex systems, ethical and theological issues cannot be evaded and must be understood as integral parts of the system. Accordingly, although such issues are far beyond most current industrial ecology work and cross not just disciplines but the "two cultures" divide identified by C. P. Snow ([1959]2001), they are unavoidably an element of systemic industrial ecology study and should be understood as such (Allenby 2008a, 2008b).
5. Whether earth systems engineering and management is an extension of industrial ecology or not, the research areas that have been identified in that domain, such as sustainable infrastructure and sustainable urban systems, have clear overlap with industrial ecology expertise and issues of complex adaptive systems (Allenby 2007). Thus, some effort to integrate across those areas, as well as more traditional ones, such as ecological economics, should continue. In this light, the desire to define industrial ecology in contradistinction to other related fields may be unhelpfully constraining the identification of important research areas; more important than ongoing debate, perhaps, is the development of an industrial ecology capability to work across such systems gracefully, regardless of what the resulting study is called.
6. Adjustment to rapid change requires development of knowledge of options, both technological and social. Creating and exploring robust option spaces is an area that is seldom explored and sometimes actively discouraged, as in the case of geoengineering options for climate change mitigation, but, as a general matter, the more options one has available, the more robust and rational the reaction to unanticipated consequences can be.

Conclusion

It is always difficult to perceive correctly during periods of rapid change, and there is a well-known tendency to overestimate the changes occurring in one's own time. Nonetheless, the broad and accelerating wave of technological evolution in which, by all indications, we are embedded arguably constitutes a period of unprecedented and fundamental physical, emotional, psychological, and cultural change. The increasing range of human technology and design, from the nano scale to global systems to the human itself as design space, puts virtually all of our disciplines, intellectual frameworks, and beliefs in play, in ways that they have not been before. As this happens, we also unintentionally but powerfully undermine most of the mental models, cultural constructs, and institutional systems we have created to structure our relationships with ourselves, our institutions, our politics, and our conceptualization of our role in the universe and relationship to our deities. We and our world are contingent in a way that, despite the massive changes we have experienced in past waves of technology, we have never been before. Clearly, we will need to reconstruct our world, and even ourselves, on the run, as it were.

This is potentially a profound challenge to industrial ecology, which stands at a crossroads. As a field, industrial ecology can simply become a relatively minor and increasingly unimportant set of tools focused on material and energy flows—indeed, this is the current path, and it is by far the more comfortable one. Increasingly irrelevant we may become, but at least we will have a defined boundary and set of tools.

But that is to overlook the obvious complexity and increasingly integrated structure of the regional and global human/built/natural systems, and their emergent behavior, that characterize the anthropogenic earth. This perspective calls for a reinvigorated industrial ecology, one that extends beyond the material and energetic patterns to the cultural, informational, and technological systems within which they are defined and determined. This new industrial ecology will arise from but cannot be defined by our past. It cannot consist of cultural constructs and mental models that are already anachronistic, even if we cannot bring ourselves to admit that just yet. It cannot be simple, for simplistic solutions and visions are dysfunctional in a world that is uncertain, unpredictable, and complex, a mélange of cognitive networks in dances and patterns that, for the most part, we do not even perceive yet. But it is important to understand where we have choices and where we do not. In particular, our choice is not the anthropogenic world, for that is already upon us. Rather, it is whether to grow into our responsibilities, to be rational, ethical, and authentic within a contingent and constantly evolving framework. It is, by understanding industrial ecology as embracing the complexity of the technological world that continues to evolve around us, to do our part in raising the contingent rationality of the Eurocentric Enlightenment that is passing into the wisdom of a new global, multicultural Enlightenment. It is perhaps our most profound challenge, not just as industrial ecologists but as sentient individuals:

> He, only, merits freedom and existence
>
> Who wins them every day anew.
>
> —Goethe, *Faust*

Acknowledgements

This work was supported by a grant from the Metanexus Institute to promote dialogue and research among the sciences, religion, theology, and philosophy. Portions of this article are based on the Templeton Research Lecture given at Arizona State University on October 22, 2007. I would also like to recognize the contributions by three anonymous reviewers of earlier versions of this article, although I remain solely responsible for content.

Notes

1. Although it has been interpreted differently in different eras, *American exceptionalism* generally refers to a belief that America differs qualitatively from the rest of the world in its history, institutional structure, and ideals and thus plays a unique role in world culture and history.
2. Movie of Robert Oppenheimer recounting his reaction to the Trinity Test. National Science Digital Library. www.atomicarchive.com/movies/movies.shtml.
3. *Manifest destiny*, a term first popularized in the 1840s, refers to the (American) doctrine that the United States was intended by God to extend from the Atlantic to the Pacific Oceans. Its more excessive proponents occasionally suggested that the doctrine required that the United States absorb Mexico, Canada, or other territories.
4. The Enlightenment was the period in European history around the 17th and 18th centuries when reason replaced religion as the source of authority and the primary mechanism for exploring human and natural systems, led by such thinkers as

Voltaire, Diderot, and Hume. Thus, the period is also sometimes known as the Age of Reason. Enlightenment values and modes of thought include an emphasis on scientific method and the technoscientific discourse as sources of authority, rationality as a hallmark of cognition and an important value in itself, individual autonomy and individualism, secularism and a humanistic ethical framework, and pluralism and democracy.

5. More common is the slightly shorter acronym, NBIC. Another acronym in this domain is GRIN, for genetic, robotic, information and nano processes.
6. *Solipsism* is the philosophic position that only that which is in one's own mind is knowable and that external reality and other beings cannot be shown to exist.

References

Allenby, B. R. 2005. *Reconstructing earth*. Washington, DC: Island Press.

Allenby, B. R. 2006. The ontologies of industrial ecology? *Progress in Industrial Ecology* 3(1/2): 28–40.

Allenby, B. R. 2007. Earth systems engineering and management: A manifesto. *Environmental Science & Technology* 41(23): 7960–7966.

Allenby, B. R. 2008a. *The metaphysics of the anthropogenic Earth: Part I. Integrative cognitivism*. Arizona State University Center for Earth Systems Engineering and Management Working Paper No. 1, and Lincoln Center for Applied Ethics Working Paper No. 1. enpub.fulton.asu. edu/cesem/, and at www.asu.edu/clas/lincolncenter. Accessed 23 February 2009.

Allenby, B. R. 2008b. Real time macroethical assessment. *AAAS Professional Ethics Report* 21(2): 1–3.

Allenby, B. R. and J. Fink. 2005. Toward inherently secure and resilient societies. *Science* 309: 1034–1036.

Allenby, B. R., D. Allen, and C. Davidson. 2007. Sustainable engineering: From myth to mechanism. *Environmental Quality Management* 17(1): 17–26.

Barabasi, A. 2002. *Linked: The new science of networks*. Cambridge, MA: Perseus.

Bijker, W. E., T. P. Hughes, and T. Pinch, eds. 1997. *The social construction of technological systems*. Cambridge, MA: MIT Press.

Castells, M. 2000. *The rise of the network society*. Second edition. Oxford, UK: Blackwell.

Check, E. 2005. Designs on life. *Nature* 438: 417–418.

CIA (Central Intelligence Agency). 2008. *Global trends 2025: A transformed world*. Washington, DC: CIA.

Cronon, W. 1991. *Nature's metropolis: Chicago and the Great West*. New York: Norton.

De Grey, A. and M. Rae. 2007. *Ending aging: The rejuvenation breakthroughs that could reverse human aging in our lifetime*. New York: St. Martin's Press.

Ehrenfeld, J. 2004. Can industrial ecology be the science of sustainability? *Journal of Industrial Ecology* 8(1–2): 1–3.

Fiksel, J. 2003. Designing resilient, sustainable systems. *Environmental Science & Technology* 37(23): 5330–5339.

Freeman, C. and F. Louca. 2001. *As time goes by: From the Industrial Revolutions to the information revolution*. Oxford, UK: Oxford University Press.

Garreau, J. 2004. *Radical evolution*. New York: Doubleday.

Grubler, A. 1998. *Technology and global change*. Cambridge, UK: Cambridge University Press.

Hayles, N. K. 1999. *How we became posthuman*. Chicago: University of Chicago Press.

Heidegger, M. *The question concerning technology and other essays*. Edited and translated byW. Lovitt. New York: Harper Torchbooks.

Hutchins, E. 1995. *Cognition in the wild*. Cambridge, MA: MIT Press.

IEEE. 2004. Engineering and aging. *Spectrum* 41(9): 10, 31–35.

Kauffman, S. A. 1995. *At home in the universe: The search for the laws of self-organization and complexity*. Oxford, UK: Oxford University Press.

Kurzweil, R. 2005. *The singularity is near*. New York: Viking.

Life 2.0. 2006. *Economist*. www.economist.com/research/articlesBySubject/PrinterFriendly.cfm?Story_ID=7854. Accessed 23 February 2009.

Lyotard, J. 1984. *The postmodern condition: A report on knowledge*. Translated by G. Bennington and B. Massumi. Minneapolis: University of Minnesota Press.

Marx, L. 1964. *The machine in the garden: Technology and the pastoral ideal in America*. Oxford, UK: Oxford University Press.

Marx, K. and F. Engels. 1998. *The Communist manifesto*. 1872. New York: Signet Classic.

McNeill, J. R. 2000. *Something new under the sun*. New York: Norton.

Moravec, H. 1988. *Mind children: The future of robot and human intelligence*. Cambridge, MA: Harvard University Press.

Nature. 2003. Welcome to the Anthropocene (editorial). *Nature* 424: 709.

Nature. 2004. Starting from scratch. *Nature* 431: 624–626.

NRC (National Research Council). 2005. *Avoiding surprise in an era of global technology advances*. Washington, DC: National Academy Press.

Nye, D. E. 1994. *American technological sublime*. Cambridge, MA: MIT Press.

Nye, D. E. 2003. *America as second creation: Technology and narratives of new beginning*. Cambridge, MA: MIT Press.

Reality, only better. 2007. *Economist*. 8 — 14 December, 15–18.

Roco, M. C. and W. S. Bainbridge, eds. 2003. *Converging technologies for improving human performance*. Dordrecht, the Netherlands: Kluwer Academic.

Rorty, R. 1989. *Contingency, irony, and solidarity*. Cambridge, UK: Cambridge University Press.

Rosenberg, N. and L. E. Birdzell Jr. 1986. *How the West grew rich: The economic transformation of the industrial world.* New York: Basic Books.

Rousseau, J. 1964. *Second discourse*. 1754. In *The first and second discourses of Jean-Jacques Rousseau*, translated and edited by R. D. Masters. New York: St. Martins Press.

Schivelbusch, W. 1977. *The railway journey: The industrialization of time and space in the 19th century*. Berkeley: University of California Press.

Snow, C. P. [1959]2001. *The Two Cultures*. Reprint of The two cultures and the scientific revolution. Cambridge, UK: Cambridge University Press.

Tapscott, D. 2009. *Grown up digital.* New York: McGraw Hill.

About the Author

Braden Allenby is Templeton research fellow, founding director of the Center for Earth Systems Engineering and Management, Lincoln Professor of Ethics and Engineering, professor of civil and environmental engineering, and professor of law at Arizona State University in Tempe, Arizona, USA.

Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Appendix S1. Theological Implications of Technological Evolution.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supplementary materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.