Industrial Ecology

The View From Complex Systems

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Our social and technological systems are becoming increasingly global and interconnected.

These changes provide opportunities for individuals and organizations to capitalize on access to more extensive markets and more people—potential customers, employers, friends, and sources of ideas. But, clearly, this increasing connectivity also poses new challenges for the design of the underlying infrastructure and technology that makes it all possible. The technology must be resilient to potential hazards caused by new and changing use patterns and couplings to other systems, while still meeting the needs of society now and in the future.

Stated this way, the problem of building and managing sociotechnical systems appears daunting: Its uncertainties paralyze us; the lack of a clear-cut design objective saps our ability to summon the social and political will necessary to create change. For example, what is the best way to design a power grid for a sustainable society? What is the budget? More generally, how much do we need to know about the present and future of life and human societies to design our present technologies and build infrastructure that will meet the needs of both current and future users?

These conceptual and practical questions are central to industrial ecology. In this short piece, we hope to shed some light on their underlying issues from our own perspective of research in complex adaptive systems (Mitchell 2011).

The hallmark of the analysis of complex systems is the development of an integrated multidisciplinary perspective (Bettencourt 2013). This means that we look primarily for a way to articulate many aspects of the problem at a rough and conceptual level, before we try to create detailed models or policies. We hope to show that such a strategy is not only fruitful, but also necessary to solve sociotechnical problems as social systems become more closely mediated by technological systems and dependent on large, complex infrastructure systems.

The problem of incorporating current and future human behavior into the design of technological systems is that social and technological systems appeal to very different models of the world and strategies for problem solving (Bettencourt 2014). We have attempted to present a scheme of these differences in figure 1.

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Let us first consider a typical engineering problem. Whenever objectives are clear and measurable and we have some means to intervene fast enough, we have the ingredients for transformative engineering solutions, no matter how complicated the context. Such problems can be defined through optimal design and often lead to hierarchical solutions, either as human organization or technological systems. We will focus on the type of problem where an adaptive solution is necessary because they are more interesting and more challenging: Cruise control and thermostats are simple examples, but similar principles make self-driving cars, autonomous power grids, supersonic flight, and error-free computers possible. The operation of all these systems depends on—often very sophisticated—feedback-control loops that hold a system to a prescribed optimal performance range and operate on it, as necessary, to achieve such an objective. These approaches have deep roots in the history of complex systems, from cybernetics to systems theory, and from nonlinear dynamics and chaos to the network structure of organizations.

What is remarkable about the engineering approach is that it does not require ultimate knowledge of the phenomena involved. This is perhaps surprising and has lead to overly simplistic statements about the death of fundamental science in an age of big data (Bettencourt 2014). Although it is certainly true

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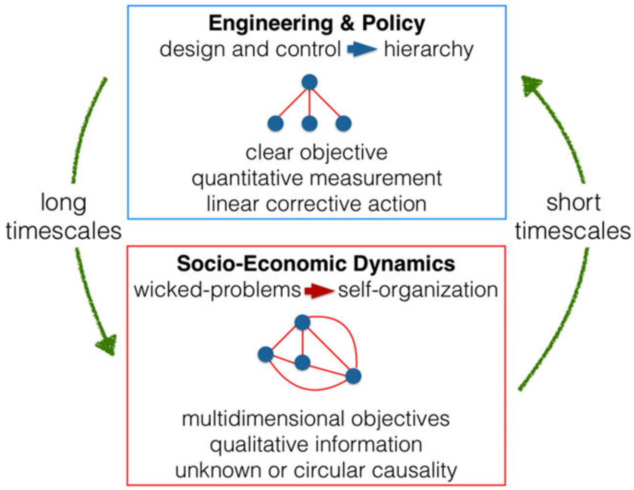

Figure 1 Scheme of the main features of engineering, policy, and socioeconomic problems, emphasizing their different character and their articulation over time.

that heat engines were invented and operated before formal knowledge of thermodynamics and control theory, the advent of these scientific innovations made such engineered systems more efficient and useful in more contexts. Thus, it is important to embrace all the circumstances where "simple" engineering solutions are possible while, at the same time, being aware of conditions when they are not the best solution. Engineering solutions can fix problems where we can predict the scope of service required, something much easier under shorter time periods. As our objectives become more exacting, demanding, or different entirely, and as our knowledge evolves, which inexorably happens over longer and larger scales, the engineered solution must adapt and people come back in.

The strength of encoding solutions into engineering practices is illustrated through a real-life example from Las Vegas, Nevada, where a suite of successful water conservation policies were implemented in the 1990s and 2000s. Water consumption in the average home built in 2007 is approximately half the average consumption of a home built in 1996! Because Las Vegas also experienced enormous population growth during that period, the city-wide average household water consumption fell by 30%. Using detailed records of household water consumption, housing characteristics, and vegetation coverage, we have shown (Brelsford 2014) that the biggest factors influencing household water consumption were declining average vegetation area in new construction and decreased water consumption for newer homes, even after controlling for changes in many physical characteristics such as home size or number of bathrooms.

These changes were brought about by both economic factors and building code changes intended to cause reductions in household water consumption. These kinds of infrastructure design improvements reduced the water necessary to maintain a typical single-family home and so reduced city-wide water consumption without requiring individuals to deliberately change their behavior or politically risky price increases. Thus, attention toward efficiency in long-term water use during the design process can have large and lasting effects on resource utilization in cities without requiring detailed knowledge of individual behavior.

The other risk of engineering solutions is that they lock in certain technologies. New (scientific) knowledge, even if not always essential, can help improve engineering design. For example, without the laws of motion and gravity, it would have been impossible to achieve the "moon shot" in 1969. Scientific knowledge often leads to approaches that appear counterintuitive, such as launching a rocket in the opposite direction to the moon in order to use the gravitational pull of the earth to catapult it toward it, thus using much less fuel and simpler thrusters. Thus, the messy and slow social practice of assembling new knowledge is often a necessary precursor to successful engineering and design by constraining the space of possible solutions and suggesting less-obvious possibilities.

To appreciate this point, consider most problems central to human societies and their sustainable development. Issues of economic growth, human development, and ecological sustainability are often described as "wicked problems" (Rittel and Webber 1973). These are problems with circular causality, multidimensional objectives that cannot be easily addressed individually, and an evolving horizon. For example, what does it mean for a human society to develop sustainably in terms of quantitative objectives? What level of biodiversity loss in the Amazon gives Brazil the most consistent economic growth rate over the next two centuries? What is that growth rate? What are the best ways to achieve such targets?

Quantitative answers to these questions are hard to come by. This is mostly because we do not yet have sufficient knowledge about mechanisms of evolution and growth in complex systems. In fact, these are likely to be altogether the wrong questions. How can we achieve a more productive change of perspective?

The "problem-solving" strategies for wicked problems are, needless to say, very different than those used in typical engineering design. They appeal not to optimization, but to "self-organization." Such processes rely on distributed nonhierarchical networks of heterogeneous agents, who are able to pool their information together to create new solutions. These dynamics involve other aspects of complex systems research, such as formal models of evolution and innovation, the interplay between information and energy, and the dynamics of complex networks.

Although much work is necessary in these areas, emerging perspectives allow us to unify open questions in economics and the social sciences with methods and some concepts from statistical physics and computer science. For example, the appeal to economic markets as the means to solve certain socioeconomic issues follows from the fact that the information necessary to solve society-wide issues is typically distributed across many different entities and that the means to organize it and put it to practice requires, initially at least, large-scale fluid coordination of many agents. The issue is therefore informational: The computational complexity of solving such problems of massive scale coordination is combinatorial, which makes a centralized ("optimal") solution intractable and requires bottom-up self-organization.

In such cases, we also know that the absolute optimality of solutions must be foregone in favor of local adaptive approaches. As a result, a kind of evolutionary dynamics is to be expected, where path dependence is the norm and improvement should be continuously sought after and expected.

In such systems, the role of engineering and technology is primarily to enable social and economic network dynamics by lowering communication, coordination, and transaction costs. Occasionally, though, particular problems, over the short term, become available for simpler optimization solutions, such as water management in Las Vegas. Such information can then be encoded into organizations or technological practices, leaving people and social networks free to attempt to solve remaining wicked problems.

It now comes into focus why we should not attempt to engineer the economy or self-organize the circuits in our computers. But what happens where these two pictures come together? How can we develop engineering solutions for the long run that respond to the growing knowledge and needs of human societies and of life on earth? And how do we encode social and economic knowledge efficiently into engineered solutions?

This convergence challenges us to think of engineering systems in increasingly adaptable ways and over the longer term, while they also suggest that socioeconomic systems will require greater integration with technologies that reduce information management overhead.

In our opinion, this is the frontier of industrial ecology and the place where emerging complex systems theory and methods may be most helpful in creating transformative, new, integrated approaches for a more sustainable planet.

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