Article

Technology, Complexity, and Engineering Design: A Rationale for a Connectionist Approach

Gayle E. Ermer


Gayle E. Ermer

The recent Fukushima Daiichi power plant failure has pushed nuclear system safety to the foreground of public awareness. Nuclear power plants are examples of the complexity of the engineered products that undergird contemporary civilization. The avoidance of technological failure depends heavily on accurately predicting, as part of the engineering design process, how complex technological systems and the individuals and societies with which they interact will behave. This article will recommend a connectionist rather than a reductionist approach to engineering design, in order to better compensate for the complexities and uncertainties inherent in technological activity. This approach is based on a Christian perspective of technology as a cultural, and therefore value-laden, activity.

Contemporary society depends on many large-scale technological systems to enable our everyday lives, including electric power transmission grids, roadway and building infrastructures, chemical processing factories, and air traffic control procedures. These systems often remain beyond our awareness, taken for granted as long as they function reliably. The six nuclear reactors at the Fukushima Daiichi facility on the eastern side of the island of Honshu, Japan, comprised just such a system. At 2:46 p.m. on March 11, 2011, normal operation was proceeding at the site, with reactors 1–3 active and reactors 4–6 on shutdown for routine maintenance.[1]

At that time, an earthquake of unprecedented magnitude (at least according to modern records) reverberated through the sea-bed to the east of the plant. Upon detection of the earthquake, the working reactors were immediately shut down in accordance with design plans. However, the earthquake also generated a tsunami that surged through the area approximately an hour later. The wave's destructive power devastated the region surrounding the plant, resulting in great loss of life, severe structural damage to buildings and infrastructure, and the loss of electrical power. The height of the wave exceeded the design capacity of the plant's flood protections, resulting in inundation of the backup diesel generators used to power the cooling water pumping systems. Even in shut-down mode, nuclear reactors generate considerable amounts of latent heat that needs to be dissipated. Without circulating fluid, reactors 1, 2, and 3 began overheating. As water

Gayle E. Ermer *is a professor of engineering at Calvin College, where she has taught mechanical engineering courses for seventeen years. Her technical specialties include machine/system dynamics and manufacturing system quality. She has also written papers on engineering ethics, women in engineering, and Christian perspectives on technology, many of which have been contributions to the Christian Engineering Education Conference (CEEC). She resides in Hudsonville, MI, with her husband Eric and their three school-age children, which necessitates an ongoing quest for the elusive state of work/life balance.*

evaporated from the reactor cores, exposed fuel rods partially melted down and generated hydrogen gas explosions within the containment buildings. Despite strenuous efforts to contain the situation, significant amounts of radioactive material were released into the environment.

After years of relative complacency about the safety of nuclear power, this incident has generated a serious reconsideration of the benefits and consequences of future reliance on this technology. Responses so far have been mixed. The following May, the environmental minister of Germany announced that his country would discontinue all nuclear power generation by 2022, challenging industry to replace it with renewable alternatives.[2] The United States and Japan both vowed to take a close look at safety improvement, without committing to future decreases or increases in nuclear electricity production rates.[3] Nigeria and India, on the other hand, announced their intention of increasing nuclear generating capacity, despite the risks highlighted at Fukushima.[4]

What principles should guide engineers and scientists as they seek to design new reactors and promote safe nuclear policies? Developers of technology need to understand why technological disasters such as Fukushima Daiichi happen, not only to prevent future disasters, but also to improve the effectiveness of all technology in promoting the flourishing of God's human and nonhuman creation. For a Christian, a vocation as an engineer or scientist includes creatively participating in the furthering of Christ's kingdom and serving creation through technological development. Our motivation in creating and implementing technological solutions is not simply to generate profit or to play with powerful toys. Rather, we are committed to glorifying God by using our skills and knowledge to provide for the needs of our fellow humans, reducing their suffering and enriching their lives. We also are committed to protecting the nonhuman aspects of creation, both because we recognize the extent to which human flourishing is dependent on the ecosystems surrounding us, and because we accept our role as stewards of the beauty and diversity of everything God has created.

The avoidance of technological failure depends heavily on accurately predicting how technology, and the individuals and societies with which it interacts, will behave in the future. This article will recommend a connectionist rather than a reductionist approach to engineering design that is based on Christian principles that guide us toward specific ways of understanding the role of technology in contemporary society. This approach explicitly takes into account the different levels of complexity present in engineered systems. The following section develops some definitions and concepts related to the nature of technology as viewed from a Christian perspective. The next section describes and illustrates several of the complexities inherent in technological systems. The last section suggests improvements to engineering design, and recommends a connectionist approach.

Technology as Cultural Activity

The complexities of technological design can be better understood from an appropriately broad definition of technology. Technology is often assumed to refer to a collection of hardware or tools, objects that are entirely subject to our will in using them to achieve our ends. In this conception, engineering is a rather "thin" activity, involving only scientific laws and deterministic behavior. In contrast, a Christian perspective can inform a more robust framework for understanding and guiding technological work. This framework arises from a holistic and contextual understanding of technology and supports the need for a connectionist approach to engineering design.

Creativity and Cultural Mandate

Central to Christianity, Judaism, and Islam is the recognition of an all-powerful Creator God who initiated and sustains everything that is in existence. This includes ourselves and the materials that we manipulate as engineers and scientists. Scripture reveals that God has created human beings in his image as responsible developers and caretakers of his creation. We are capable of doing technology because God has gifted us with that ability. Thus, our creativity in engineering design reflects the creativity of our Maker, although our efforts are limited by our finiteness and tainted by our sinfulness. We have been gifted with the ability to abstract concepts and analyze conditions, using logic and creativity. Throughout history, engineers and scientists have made great strides in developing an understanding of various aspects of the creation in order to better predict the effects of our engineered systems. Technology is also one of the ways we as Christians respond to the cultural mandate of Gen. 1:28, "Be fruitful and increase in number; fill the earth and subdue it." As Steven Bouma-Prediger interprets Gen. 2:15, we are "to serve and protect the garden that is creation—literally to be a slave to the earth for its own good, as well as for our benefit."[5] God intends that we should cultivate the earth, develop it responsibly, and creatively participate in the unfolding of his creation. Doing technology is central to what God calls us to be and to do as humans.

Nonneutrality

Within this context, it becomes clear that technology is not value free. The authors of *Responsible Technology* recognized this distinction in the following definition:

> We can define technology as a distinct human cultural activity in which human beings exercise freedom and responsibility in response to God by forming and transforming the natural creation, with the aid of tools and procedures, for practical ends or purposes.[6]

Jack Swearengen, in his more recent book, *Beyond Paradise*, concludes,

> Engineering design projects cannot be value-neutral because they are developed with integral values, principles, and goals in mind. In other words, the worldview of the designer influences the design.[7]

Carl Mitcham also emphasizes the broad scope of technological activity and its relationship to society in his book *Thinking through Technology.* He points out that engineers themselves often define technology too narrowly. In defining engineering, he writes,

> Engineering as a profession is identified with the systematic knowledge of how to design useful artifacts or processes, a discipline that (as the standard engineering educational curriculum illustrates) includes some pure science and mathematics, the "applied" or "engineering sciences" (e.g., strength of materials, thermodynamics, electronics), and is directed toward some societal need or desire. But while engineering involves a relationship to these other elements, artifact design is what constitutes the essence of engineering, because it is design that establishes and orders the unique engineering framework that integrates other elements. The term "technology" with its cognates is largely reserved by engineers for more direct involvement with material construction and the manipulation of artifacts.[8]

Mitcham goes on to set up a framework for analyzing technological pursuits that distinguishes four aspects: (1) technology as object, (2) technology as knowledge, (3) technology as activity, and (4) technology as volition.[9] A holistic view of technology as a cultural activity should take into account the whole process of conceiving, designing, building, producing, implementing, maintaining, disposing of, refining, and regulating technological objects and processes, in which many values interact as decisions are made.

Through this cultural activity, values become embedded in the technological artifacts themselves, causing them to be "biased" toward certain uses and behaviors.[10] Charles Adams emphasizes that

> … the designers, manufacturers, and marketers of technological artifacts are responsible not only for the physical or biotic properties of such artifacts, but also for the values that, inherent in the design process, are transmitted by those products. Thus, computer programmers designing recreational software for the mass market must consider the psychological, pedagogical, and sociological implications of their products.[11]

An interpretation of technology as a value-laden cultural activity highlights the challenges that engineers face in designing systems that are effective and safe, and suggests the complexities generated, not just by artifacts, but also by interactions between people and materials at each step in design implementation.

The Complexities of Contemporary Technology

One of the challenges in predicting and controlling technological system behavior is the increasing complexity of contemporary systems. Clearly, many physical systems being designed are becoming more complicated, containing ever larger numbers of components and subsystems. The sheer number of products produced is increasing as well. Perhaps more importantly, interactions are multiplying within systems, as well as between technological artifacts and the humans and societies who create and use them, and between the technological artifacts and the living world in which they are embedded. All of these factors increase the risk of engineering disaster, whether large or small; Charles Perrow has documented that disaster most often happens when multiple failures interact in ways that are not anticipated.[12]

The term complexity encompasses a variety of concepts and interpretations. Popular usage of the term rarely goes beyond the idea of complicatedness, the sense that technological systems have many interacting parts whose function is difficult for users to comprehend. While complicatedness is an aspect of technology that needs to be addressed in design, clarifying the other senses in which technology demonstrates complexity can help encourage a more complete approach to design and a better anticipation of possible risks. These complexities can be characterized in three ways: (1) Complexities of human finitude relate to the inability of humans to adequately predict how technological objects will behave in real life situations, and how to cope with that limitation; (2) Complexities of societal fallenness focus on the systemic effects of sin on the cultural and social landscape within which engineered designs are implemented; and (3) Complexities of personal sinfulness encompass the unethical choices and sinful dispositions of people as they interact with technology.[13] An appreciation of each of these types of contributions to technological system failure will result in more perceptive preparation for risk avoidance. This article will also consider the relationship between complexity and system boundaries, and the identification of truly complex systems.

Complexities of Human Finitude

The recognition of human finitude is often overlooked by Christians as a primary contributor to the risk of failure in today's technological systems. (These Christians often identify sinfulness or natural evil as possible explanations.) The creation accounts in Scripture clearly indicate that humans were created as finite beings. Simple reflection on the history of engineering reveals that our power over the resources God has entrusted to us for our creative activity has never been complete. Scripture and our own observations reveal the inexhaustible complexity of God's creation, within which we are challenged by the finiteness of our models as we attempt to describe creation and discover its usefulness.

Complicatedness. As was mentioned previously, one aspect of complexity that contemporary technological systems demonstrate is complicatedness. Engineered products contain many individual components and connections that need to be analyzed correctly in order to predict system behavior. Engineers rely primarily on reductionism and deterministic models to divide highly complicated systems into smaller pieces that can be more easily understood, simulated, and controlled. The assumptions required to reduce complicated behaviors to simple ones imply that our mathematical models do not completely capture the way things actually behave.

To allow engineers to better predict the behavior of systems that are too complex to be handled with explicit equation solutions, numerical modeling techniques have been developed. Numerical solutions allow engineers to simulate the behavior of systems that are too complicated to be modeled with straightforward explicitly derived equations. A complicated geometry can be subdivided into many elements of simpler geometry whose behavior and interactions are better understood and predicted. A digital computer can then be used to solve simultaneously the many equations used to represent the system connections and externally applied constraints. The danger of these models is that they tend to promote a black box approach to behavior prediction. It is difficult to determine whether predicted results obtained in this way are reasonable, unless a parallel modeling method is available or a significant level of experience with the systems being modeled has been obtained. The more complicated the system, the more difficult it becomes to identify a possible error in the model or to recognize when the system is operating outside the model's assumed range of behavior.

Uncertainty. The recognition that some system variables exhibit unpredictable or random variation in values suggests the need for incorporation of statistical modeling into the engineering design process. Stochastic models can aid in predicting system behavior in situations in which a specific state may not be known, but the anticipated range of states can be estimated. Of course, decision making based on different sets of responses, which might occur with different levels of probability, adds another level of complexity to the design process.

The mischaracterization, based on historical data, of the probability and magnitude of possible earthquake events was one of the contributing factors to the Fukushima disaster.

Trade-offs. All engineering design is based on compromises between multiple and often incommensurable requirements. Safety considerations must be balanced with other goals. Prioritization of these requirements is a complex and challenging task. Ranking various design alternatives relative to the different requirements amounts to comparing apples and oranges. For example, in considering safety levels in a nuclear plant versus the cost of redundant backup systems, all of the stakeholders need to come to a consensus about what is just. Unfortunately, the processes currently used to adjudicate these issues are often hidden from the general public and therefore lack accountability. Engineers may be tempted to focus on purely technical specifications in order to avoid the controversies and politics that surround the "nontechnical" constraints.

Interactions. According to Perrow, the defining features of technology in the developed world today are its complexity and tight coupling.[14] These features make the anticipation of interactions difficult and often limit our options for responding to failures once certain conditions have occurred. For Perrow, these factors make it almost inevitable that disasters, which he identifies as "normal accidents," will occur in some technological systems, including nuclear power electricity generation. This can be interpreted as another manifestation of human finitude. Some technologies may have outstripped our own abilities as designers to understand and control them.

Complexities of Societal Fallenness

Implementing engineering designs is also risky because humans live in societies whose institutions have been impacted by the Fall. Cultural development has been corrupted in many ways because of our spiritual estrangement from our Creator. This has resulted in what Plantinga describes as "… spoiling of shalom, any deviation from the way God wants things to be."[15] The corruption of culture and social institutions contributes to engineering failures; these systemic problems contribute another level of complexity to the problem of predicting how well technology systems will work. For example, in a capitalistic economic system, the tendency to increase profits by cutting corners to reduce costs is a constant presence. In a socialistic economy, the lack of direct rewards for additional work can contribute to negligence. Whether in a democratic or a totalitarian political system, there is a strong incentive for those in control to place the risks of technology disproportionately on those who have little representation.

It is difficult to predict how cultural factors will influence design decisions, and conversely, how new technologies will influence societal practices. L. J. Van Poolen rightly describes engineering as "prophetic activity," recognizing the complexity of the technology/society interaction and the difficulty in predicting the future.[16] The potential for not recognizing the importance of societal influences is increased by the fact that we live within a current cultural context that has been described as given over to "technicism"[17] or"technopoly."[18] These terms express the realization that contemporary North American culture overly relies on technical solutions to problems, and has too much faith in science and engineering. The tendency to idolize technology increases the risks of technology. Without a respect for the limits of technology, technological development can take place at a pace that leaves no time for careful risk assessment.

Complexities of Personal Sinfulness

The risks in technology are also magnified because of personal choices. Occasionally, people design, manufacture, or use technology to deliberately hurt other people. Often, they negligently make choices in their own interests rather than those of others. Users of technology sometimes apply technological artifacts in ways the designers never intended. The ability of human beings to make their own choices complicates our predictions about how they will interact with technological artifacts, and opens up possibilities for unanticipated modes of failure. This should not surprise Christians who recognize the relative "free will" of humans. Humans are not machines that can be programmed to behave only in desired ways. Instead, we need to recognize and compensate for the reality that all persons have been endowed by our Creator with the ability to make choices for which they need to be held accountable.

Complexity and System Boundaries

The nature of the models necessary to analyze a given design is dependent on the specification of system boundaries. Consider a nuclear power plant, which consists of many interacting subsystems. An engineer working on the design of the diesel backup generator might draw a system boundary that isolates the generator from the rest of the plant. This engineer would use mathematical models of the combustion reaction and associated generator behavior as the focus for optimizing the design. If the goal of the engineer is to design or choose an efficient, low-cost generator, then a reductionist mathematical model that describes the relationship between fuel input and voltage output is very helpful. The model will predict the behavior of the generator, thus optimizing the functioning of this system subcomponent toward better satisfying design constraints. However, if the ultimate goal of the designer is consistent reliable operation of the overall nuclear plant under all conditions, then the system boundaries would need to be expanded to account for the complexities of other possible interactions.

As the Fukushima incident made clear, the interaction between the generator and cooling water pumping (or the lack thereof) is critical to the safe functioning of the reactor. Would widening the system boundaries to include the water pumping system and reactor flow requirements, and perhaps to include the possible interactions between the generator and water influx from flooding, have influenced the engineer to design a different generator configuration which would have avoided the overheating that affected the Fukushima reactors? Without making a serious attempt to anticipate these interactions and to integrate additional requirements into the subcomponent design process, predictions or tradeoffs in the design of that subcomponent may compromise the integrity of the system as a whole.

Complex Systems and Emergent Behavior

Many complicated technical systems can be successfully modeled with reductive strategies. The macroscale behavior is essentially equal to the sum of the behavior of the parts, even if the scope and scale of the system present challenges in finding solutions and interpreting results. On the other hand, the interdisciplinary field of complexity theory has recently been bringing to light systems that are impossible to model reductively. These types of systems, particularly biological systems, are described as "complex" in a narrower sense of the term. More than in individual component behavior, the dynamic configuration of connections determines the response of the system to changing environmental conditions. This phenomenon has been described as "irreducible complexity."[19] Even seemingly simple systems, such as metal alloys and convection cells in boiling liquids, can be described as exhibiting this sort of behavior.

Most authors working in this field admit that it is difficult to form an explicit definition of such a complex system. Instead, general characteristics of complex systems are identified in order to distinguish them from merely complicated systems. Melanie Mitchell notes that these characteristics imply system behaviors that are collective, i.e., they arise from the combined actions of many relatively simple interacting elements without central control. Her definition of a complex system is

> a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.[20]

These behaviors are often described as self-organizing. The term "emergent behavior" is also used. Examples of this kind of behavior include ant colonies, the human brain, and the national economy. While traditional engineering approaches might capture some of these characteristics (e.g., feedback loops), many characteristics (e.g., operating under nonequilibrium conditions) are contradictory to the assumptions typically made in engineering approaches.

Complexity theory has been, until now, a somewhat esoteric scientific enterprise that has remained peripheral to engineering work. These concepts are just beginning to filter into other domains where the prediction of system behavior is important. For example, Swilling and Annecke have recently appropriated a complexity approach for determining ways to respond to the need for global sustainability.[21] The approach has also been used for analyzing homeland security systems.[22] The power of complexity theory lies in its nonreductive approach to evaluating and solving problems. The focus is often situation specific, based on narrative and analogy, rather than exclusively on global, abstract principles. In this sense, complexity theory applies a postmodern sensibility, rather than the modernist viewpoint that underlies reductive modeling of traditional engineering analysis. As an example, Paul Cilliers cites the postmodern philosopher Jean-François Lyotard by describing knowledge "as the outcome of a multiplicity of local narratives."[23] As opposed to thinking about knowledge as a repository of isolated, objectively determined principles, he suggests that knowledge is determined by trying "to find meaningful relationships among the different discourses."[24] In other words, knowledge must include the connections between things and people. The next section will suggest that an emphasis on connections, rather than on system boundaries, is an appropriate response to the various types of complexity that have been described in this section.

Connectionism in Engineering Design

The introduction to this article posed a question related to the design of large-scale technological systems: What principles should guide engineers and scientists as they seek to design new reactors and promote safe nuclear policies? This section will focus on several approaches that I will refer to as "connectionist" approaches,[25] which, based on the understanding of technology and complexity that has been developed so far, should help to improve the safety and functionality of engineering designs. Before addressing these topics, two inappropriate approaches to risk analysis will be pointed out.

Some Christians (and others) who identify themselves as strongly "pro-life," that is, committed to the sanctity of human life as a precious gift of God, might reject nuclear technology altogether because of its potential for harm. While this might seem like a consistent position, those who think this way need to be reminded that no technology is risk free. We all currently (and without much concern except when it impacts us personally) participate in an automobile transportation system which predictably results in almost 40,000 deaths per year in the United States. We do not insist on perfectly safe cars because reducing the risk involves other costs, which introduce issues of distributive justice (e.g., poor people could not afford to buy such a vehicle) and stewardship (i.e., a safe car is typically heavier, and therefore less fuel-efficient). This illustrates that our perception of risk is easily skewed.[26] For example, people seem to be much more willing to participate in risky systems if they believe that events are under their own control. This may explain why people tolerate the possible harms of driving, while overestimating the possible dangers of nuclear power.

Christian engineers working in nuclear technology need to recognize that it is not feasible to implement safety systems that mitigate all conceivable risks, since there are costs associated with those systems. For example, building a 100-foot-tall wall around a nuclear reactor might mitigate possible damage from a tsunami, but doing so would significantly increase costs and introduce new safety issues, e.g., the possibility of structural collapse. A concern for the sanctity of human life should not result merely in a call for the rejection of certain technologies that are perceived as too dangerous, but, rather, a call to invest more resources in careful analysis so that risk can be reduced in all areas of our lives.

The opposite extreme would consist of accepting an entirely economic view of human life (and often of the environment, as well). Although levels of victim compensation might sometimes drive the evaluation of risk within particular industries, safety and risk of death cannot be evaluated by purely economic factors. The loss of a precious human life or the contamination of an ecosystem cannot be reduced to a dollar cost. When all of creation is viewed from a technical, utilitarian perspective, the value of human life is diminished, and inappropriate risks are encouraged.

The engineering design process needs to be approached from a different perspective in order to open up the imaginations of stakeholders to the required complexity of system models and to appropriate ways of balancing design requirements. The reductive engineering design approach is conceptualized in figure 1. This is the approach inculcated in engineers in their training and practiced in their professional work. In order to predict system behavior (and therefore to make choices about appropriate design for a given system), the system is subdivided into chunks that can be understood and mathematically modeled. The overall system boundaries are relatively fixed and impermeable, in the sense that few interactions from outside the system are allowed to impact the model of what goes on within the system. Each subsystem or component (A) has system boundaries which de-emphasize context. Thus "soft" effects are isolated so that they do not "corrupt" the objective technical perfection of the analysis and design. The required functions and attributes, that engineers commonly refer to as design criteria (1, 2, 3), are established based on conditions from within the system boundaries. These are the only constraints that are considered as potential trade-offs in optimizing the subsystem.

In the case of nuclear plant design, system A could be composed of the backup power generation system for the cooling pumps. The cooling pump system (C) would determine the power needed from the generation system (specification 1), the physical configuration of surrounding subsystems would determine the area footprint available for the system (specification 2), and other design criteria such as cost, reliability, and fuel efficiency requirements might be dictated by other subsystems. The danger in isolating subsystem A from the whole is that it is possible to model and optimize subsystem A while missing complex interactions that might compromise the performance of the system as a whole. If the engineers who designed the backup generator system had been more involved in discussions of flood potential or the local possibilities of power or personnel disruptions following a natural disaster, they might have made different decisions for locating or protecting the backup generator system.

The connectionist approach is illustrated in figure 2. Rather than starting with a top-down approach that establishes hard system boundaries, the process starts by looking outward from the specific subsystem to be designed; it expands system boundaries to absorb additional design constraints and modeling techniques both from other subsystems and also from the environment in which the system will operate. The new design criteria are derived by anticipating possible interactions caused by the complexity of the subsystem itself, as well as by interactions with the rest of the system.

The engineering design method of figure 2 is predicated on the cultural activity model of technology development. A nuclear plant is not just a collection of hardware (a reactor, a pumping system, a power generation system, etc.), but it has a history of events by which it has been actualized and is embedded in a context of geographical, economic, legal, and political constraints. We need to recognize this complexity, moving beyond the black-and-white, thumbs-up and thumbs-down choices that our society gravitates toward. We need action pursued via dialog within particular contexts, recognizing that humans, nonhumans, and their connections are constantly evolving.[27] Evolving, in this context, implies that new technologies are derived from combinations of previous technological components along with the appropriation of understandings of new phenomena.[28]

One particular modeling technique that is already available to the engineering community but not commonly taught, and can be used as a tool to stimulate

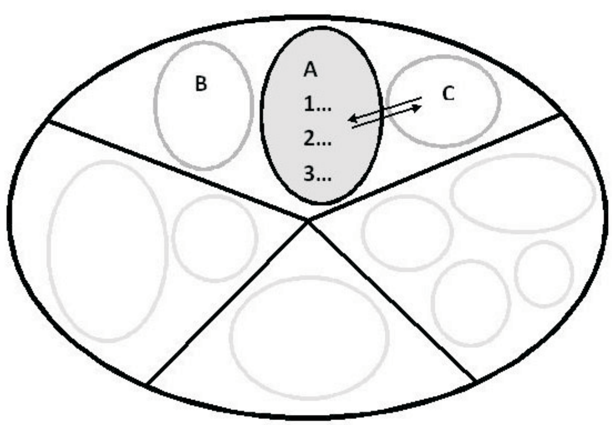

Figure 1. Reductionist Design Process

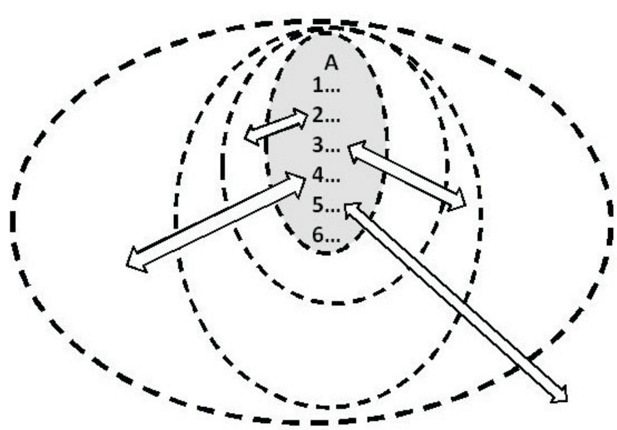

Figure 2. Connectionist Design Process

creativity in anticipating interactions, is Failure Mode and Effects Analysis (FMEA).[29] FMEA works by specifying a structured imaginative approach to predicting possible ways a design could fail, as well as calculating the probability and consequences of each failure. FMEA is currently required for safety-critical electronic systems (e.g., aircraft controls), but is not often taught or used systematically in other disciplines of engineering. Its primary advantage occurs in prioritizing responses to identified failure modes, in order to ensure quality of design. An FMEA analysis can be perceived as a series of check boxes and calculations that must be completed before a design can be approved, but, if applied rigorously, it should encourage out-of-the-box thinking related to how a particular design could be influenced by environmental effects or other interactions in a way that could degrade the performance of the system. Divergent thinking is necessary in order to anticipate modes of failure that have not been experienced in the past. We need to ask all the right questions during the design process. This creativity should be directed toward developing innately safe designs. Rather than focusing on the introduction of additional redundant safety systems, processes could be redesigned in ways that eliminate risk potential. For example, using a passive cooling system in a nuclear plant could eliminate the need for backup generators entirely.

Conclusions

In conclusion, recognition of different levels of complexity in technical systems pushes engineers beyond the use of reductive physical models in design analysis. Better safety may be gained, not by narrowing the focus onto every small system component, but by reaching out to connect a particular component to others, both within the system and with the environment surrounding the system. In the case of nuclear power, this means that engineers working on backup generator design and placement should consider not only the cost and efficiency of their particular subsystem, but they should also intentionally search for and investigate the interactions between the generators and the environment in which they are situated.

Modeling techniques from complexity theory, including chaos theory and neural networks, may provide useful tools for real progress in scientific analysis and engineering design. Perhaps the greatest gain from this approach will come, not from particular sets of equations, but from an ethos that serves as a corrective for modernist tendencies. Engineers and business leaders are bred within a modernist paradigm. Perhaps it is time to produce a new breed of postmodern engineers, by adopting a connectionist approach, driven by complexity theory. ✦

Notes

[1]Details of the event are taken from Ian Hutchinson, ed., *Christian Engineers and Scientists in Technology Newsletter* 18 (Spring 2011) and 19 (Summer 2011), and from the *New York Times* summary website, http://topics.nytimes.com/top/news/international/countriesandterritories/japan/index.html.

[2]"Germany Says No Nuclear Power by 2022," *UPI NewsTrack* May 30, 2011, http://www.upi.com/Top_News/World-News/2011/05/30/Germany-says-no-nuclear-power-by-2022/UPI-74941306772659/.

[3]Malcolm Foster, Associated Press, "Contender for Japan's Top Post Vows to Phase Out Nuclear Power," *Virginian-Pilot*, August 28, 2011: A9.

[4]"PM Backs N-Power, Mamata Sulks," *Hindustan Times* (Kolkata, India), August 21, 2011, http://www.hindustantimes.com/India-news/Kolkata/Mamata-sulks-as-PM-extends-support-for-Nuclear-power/Article1-735900.aspx; and "Fukushima Disaster: No Foreclosure On Nuclear Power—FG," *Africa News Service,* August 9, 2011, http://www.vanguardngr.com/2011/08/fukushima-disaster-no-foreclosure-on-nuclear-power-fg/.

[5]Steven Bouma-Prediger, *For the Beauty of the Earth: A Christian Vision for Creation Care* (Grand Rapids, MI: Baker Books, 2001), 74.

[6]Stephen V. Monsma, ed., *Responsible Technology* (Grand Rapids, MI: Eerdmans, 1986), 19.

[7]Jack Clayton Swearengen, *Beyond Paradise: Technology and the Kingdom of God* (Eugene, OR: Wipf & Stock Publishers, 2007), 89.

[8]Carl Mitcham, *Thinking through Technology: The Path between Engineering and Philosophy* (Chicago, IL: University of Chicago Press, 1994), 147.

[9]Ibid., 159.

[10]Steven H. VanderLeest, "Bias in Technology: From Creation or Fall?," *Proceedings of the Christian Engineering Education Conference* (2004): 61.

[11]Charles Adams, "Automobiles, Computers, and Assault Rifles: The Value-Ladenness of Technology and the Engineering Curriculum," *Pro Rege* (Dordt College), March 1991, 4.

[12]Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (Princeton, NJ: Princeton University Press, 1999), 70–1.

[13]These categories correspond to those described in a previous paper: Gayle Ermer, "Understanding Technological Failure: Finitude, Fallen-ness, and Sinfulness in Engineering

Disasters," *Proceedings of the Christian Engineering Education Conference* (2006): 132.

[14]Perrow, 97.

[15]C. Plantinga Jr., *Engaging God's World: A Christian Vision of Faith, Learning, and Living* (Grand Rapids, MI: Eerdmans, 2002), 51.

[16]L. J. Van Poolen, "A Philosophical Perspective on Technological Design," *The International Journal of Applied Engineering Education* 5, no. 3 (1989): 319–29.

[17]E. Schuurman, *Faith and Hope in Technology* (Toronto, ON: Clements, 2003), 66.

[18]See Neil Postman, *Technopoly: The Surrender of Culture to Technology* (New York: Vintage Books, 1992).

[19]Michael Behe defines and explores the concept of irreducible complexity in the context of evolutionary theory and intelligent design. See *Darwin's Black Box: The Biochemical Challenge to Evolution* (New York: Free Press, 1996). This paper is not as concerned with the origins of complexity in natural systems as it is with responding to the impact of irreducible complexity on designed systems and predictions of their behavior.

[20]Melanie Mitchell, *Complexity: A Guided Tour* (New York: Oxford University Press, 2009).

[21]Mark Swilling and E. Annecke, *Just Transitions: Exploring Sustainability in a Unfair World* (Cape Town, South Africa: University of Cape Town Press, 2010).

[22]Alfred A. Marcus and Zachary Sheaffer, "Analogical Reasoning and Complexity," *Journal of Homeland Security and Emergency Management* 6, no. 1 (2009): article 82.

[23]Paul Cilliers, *Complexity and Postmodernism: Understanding Complex Systems* (New York: Routledge, 1998), 114.

[24]Ibid., 118.

[25]Ibid., 3–5. The language of connectionism is used by Cilliers, although he promotes this as a technique within the context of modeling of complex systems. My use of the term is more broadly focused on identifying and including interactions in engineering design.

[26]"How Americans Are Living Dangerously," *TIME*, Nov. 26, 2006, http://www.time.com/time/magazine/article/0,9171,1562978,00.html. This article presents a journalistic take on risk perception and how Americans respond to different risks (some of them technologically generated).

[27]Bruno Latour, *Pandora's Hope: Essays on the Reality of Science Studies* (Cambridge, MA: Harvard University Press, 1999), chap. 6. Latour describes science and technology as the continuous integration of nonhumans and humans into the collective, which becomes more articulated and complex over time, as opposed to the traditional modernist separation of objects and subjects.

[28]W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (New York: Free Press, 2009), 187. The author refers to the process of technology development as "combinatorial evolution."

[29]As an introduction to this topic, see the American Society of Quality Engineering website, http://asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html.

ASA Members: Submit comments and questions on this article at www.asa3.org → FORUMS → PSCF DISCUSSION.

Reviewers in 2011

We wish to thank the following people for their helpful work in reviewing manuscripts.

Thomas P. Ackerman
Charles F. Austerberry
David Bartholomew
Robert C. Bishop
Thomas Boogaart
Rolf T. Bouma
James Bradley
Walter L. Bradley
Ethan Brue
Joel W. Cannon
Gerald B. Cleaver
C. John Collins
John W. Cooper
Edward B. Davis
John Dyer
Dennis Feucht
Kenneth H. Funk
Terry M. Gray
Loren D. Haarsma
John W. Haas Jr.
Steven G. Hall
Lee P. Hardy
Katherine Hayhoe
Peter Hess
Scott E. Hoezee
William M. Jordan
Christopher B. Kaiser
David S. Koetje
Denis O. Lamoureux
Clyde Layne
Arthur J. Mansure
Keith B. Miller
Paul E. Moes
George L. Murphy
Douglas F. Olena
Perry G. Phillips
Robert Prevost
Pattle T. Pun
Paulo Ribeiro
Paul H. Seely
William R. Stoeger
George Sverdrup
Mary L. Vanden Berg
Nolan Van Gaalen
James A. Van Slyke
Dennis Venema
Edwin M. Yamauchi
Ned Woodhouse
Amos Yong
David L. Wilcox
John W. Zwart
Paul J. Zwier
Uko Zylstra ✦