Systems and scenarios for a philosophy of engineering

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Nano-, bio-, and information based engineered systems as well as large-scale socio-technological systems, such as the electric grid and the regional surface transportation network, are complex systems for which the temporal evolution and outcomes states may not be predictable because emergent phenomena are ubiquitous. Given that engineers may not be capable of predicting the outcome of an engineered system, the issue arises as to how engineers ensure system performance and engineer ethically. A pragmatic philosophy of engineering with both instrumental and reflective aspects is essential. This philosophy will incorporate both systems analysis and scenario planning as tools to learn about how a system may perform over time, and engineers may thereby gain insight to how they ought design and manage complex systems even though they may not fully understand them. The creation of feedback mechanisms by using such tools as the semantic World Wide Web may be one way that a reflective dialogue about engineering systems emerges and influences the evolution of these complex systems.

William Wulf, a former President of the US National Academy of Engineering (NAE), stated in the keynote address to a NAE workshop titled *Emerging Technologies and Ethical Issues in Engineering*: 'When systems reach a sufficiently high level of complexity, it becomes impossible to predict their behavior. It's not just hard to predict their behavior, it's *impossible* to predict their behavior. The question can't be answered by taking more things into account or thinking harder about the problem or using a new set of tools. At a certain threshold of complexity, it becomes impossible to predict all system behaviors.' (Wulf 2003: 4) Wulf went on to ask, 'How can we make ethical decisions when we cannot predict what the outcomes will be? Yet doing nothing is, in fact, also doing something. We do not have the option of not doing anything and avoiding the ethical choice.'(Wulf 2003: 6).

Charles Vest, President Emeritus of Massachusetts Institute of Technology and the current NAE President, in his essay, 'Educating engineers for 2020 and beyond' continued this line of questioning: 'As Wm. A. Wulf (2004) has warned us, we work every day with systems so complex that we cannot know all of their possible end states. Under those circumstances, how can we ensure that they are safe, reliable, and resilient? In other words, how can we practice engineering?' (Vest 2007). Vest identified two frontiers of engineering systems. The first is the nano-bio-information technology frontier. It is the engineering frontier of the small and fast. The second frontier is that of large-scale socio-technical systems – for example transportation or energy systems – which are linked in complex ways.

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After carefully considering the statements of Wulf and Vest, at least three interesting themes may be identified towards developing a philosophy of engineering. The themes are philosophically interesting because they raise many issues regarding the nature of knowledge about the world and, given some beliefs about how the world is or may be, how one ought to act. First, Wulf asks about the relationship between the prediction of outcomes and ethical decision-making. To what extent is the prediction of an outcome a necessary condition for making an ethical decision regarding an engineered system? Second, Vest suggests that knowledge of a system's end state is necessary, if one is to make truthful claims about a system's performance. An expected end state provides a benchmark to evaluate whether a particular engineered product or process achieves its intended goal. Third, systems may be predictable up to a point after which they become unpredictable. How do engineers know prior to reaching a point of unpredictability and then passing it, that they are approaching that point? What knowledge is needed to identify the bounds of predictability such that this knowledge would inform engineering practice? Natasha McCarthy, in her essay, 'What use is the philosophy of engineering', raises somewhat similar questions (McCarthy 2007).

One may look to the great engineering achievements of the twentieth century as examples of the type of engineering that Wulf and Vest appear to reference, where the outcomes were thought generally predictable (Constable and Somerville 2003). Indeed, the NAE grand challenges for engineering in the twenty-first century address solving the pressing problems in society – problems that are in part the consequences of the twentieth-century achievements.[1] Although widespread electrification and the use of automobiles have clearly improved our quality of life, both rely largely on the combustion of fossil fuels, which emits carbon dioxide into the atmosphere and is a major cause of climate change. Nuclear technology, also a great achievement of the twentieth century, presents environmental and security challenges that need to be solved in the twenty-first century.

Wulf and Vest address an important philosophical issue: What is the relationship between our knowledge of technological systems and our design and use of these systems? In creating nano-bio-information technologies or large-scale socio-technical systems to address human concerns, the intention is to improve the human condition. If we cannot predict the outcome of these complex systems, how do we know that the systems will do that?

In what ways is the problem that Wulf and Vest raise a new one? Both recognise that engineering of complex systems requires a rethinking of how engineers understand phenomena and how they engineer systems that may exhibit unpredictable behaviour. Systems analysis and scenario planning are techniques that ought to play a greater role in developing the philosophies of engineering that will guide the practice of engineering in the 21st century.

TWO ASPECTS OF A PHILOSOPHY OF ENGINEERING

In his book *The Sciences of the Artificial*, Herbert Simon discussed the view of engineering reflected in the comments of Wulf and Vest. 'The engineer, and more generally the designer, is concerned with how things *ought* to be – how they ought to be in order to *attain* goals, and to *function*.' (Simon 1996: 4) On this view – an instrumental one – one may think of a philosophy of engineering as a general approach or strategy for practice. A philosophy of engineering then would address what in the world needs to be engineered to solve a problem, such as a road that needs to be built to provide for the transport of people and freight to a location. In this example, a philosophy of engineering would also address issues related to how the road should be built, as well as when, where, and who will build the road. Economic, social, political, and environmental factors will have to be taken into account in deciding these questions.

Traditionally, an instrumental philosophy of engineering presumes that phenomena have a certain stable physical reality or existence and those phenomena may be transformed in predictable ways. The basis for this instrumental philosophy is empirical observation. Empirical observation also justifies the use of perceived laws of nature, such as Newton's laws of motion. Because one knows Newton's second law of motion, one can calculate forces, given masses and accelerations. Adjustments are made to theoretical calculations to account for situation-specific details. As a major contributor to the modern theory of chaos, Edward Lorenz stated, 'In practice, it may be impossible to purge a real system of its actual randomness and observe the consequences, but often we can guess what these would be by turning to theory. Most theoretical studies of real phenomena are studies of approximations.' (Lorenz 1993: 5) The Nobel Prize winning physicist, Robert B. Laughlin reiterated this view as follows (Laughlin 2005: 23):

> Regularity in the natural world had been well understood since ancient times, and Renaissance figures like Galileo, Kepler, and Tycho Brahe had recently refined and quantified this knowledge through careful experimental observation. But Newton went beyond observation of regularity to identify mathematical relationships that were simple, applied always, and accounted for apparently unrelated behaviors simultaneously. Newton's laws of motion turned out to be so trustworthy that incompatibility with them soon became a reliable indicator of false observations. *They found important applications in engineering, chemistry, and commerce and eventually became the logical basis for our entire technological world* (emphasis added).

The foundation of this view that there are fundamental, indissociable laws which wholly enable engineering is, however, nowadays being reconsidered.

A complementary philosophy of engineering is reflective: it not only answers the 'what', 'how', 'when', 'where', and 'who' questions, but addresses the 'why' question too. A reflective philosophy of engineering is concerned with the meaning of engineering our world. Asking why about the meaning of an engineered system or artefact may be as straightforward as asking, 'what does the road "mean" '? A straightforward answer may be that it means one can travel from point A to point B in four hours instead of in 14. A more complex answer would, in addition, address how the road changed the conditions of life, for better and for worse, for those who use the road as well as those who live near it. The more complex answer considers the road as part of a larger socio-technical system. For example, the Interstate highways in the USA have clearly transformed commerce along with the lives of individuals, the communities they live in, and the condition of the natural environment.

A reflective philosophy of engineering is evident in the NAE reports on the engineering achievements of the 20th century and the grand engineering challenges of the 21st. A satisfactory philosophy of engineering must have both instrumental and reflective aspects that may be thought of as the two sides of the same coin.

TOWARDS 'ENGINEERING' EMERGENT SYSTEMS: UNDERSTANDING AND COPING

Let us return to the challenge posed by Wulf and Vest: How do engineers deal with systems that are emergent and impossible to predict? First let us re-examine Newton's laws of motion as a paradigmatic body of knowledge that engineers use to interpret and transform phenomena (Lindeburg 1992). A belief is that Newton's laws are primitive or foundational and that the behaviour of objects follows from these laws. Laughlin, however, recognised this belief as a myth. 'The myth of collective behavior following from the law is, as a practical matter, exactly backward. Law instead follows from collective behavior, as do things that flow from it, such as logic and mathematics. The reason our minds can anticipate and master what the physical world does is not because we are geniuses but because nature facilitates understanding by organizing itself and generating law.' (Laughlin 2005: 209). 'Thus Newton's legendary laws have turned out to be emergent. They are not fundamental at all but a consequence of the aggregation of quantum matter into macroscopic fluids and solids – a collective organisational phenomenon. They were the first laws to be discovered, they brought the technological age into existence, and they are as exact and true as anything we know in physics – yet they vanish into nothingness when examined too closely.' (Laughlin 2005: 31).

Even though Newton's laws are emergent rather than foundational, they enable prediction and control. Recognising this change of perspective raises the question whether there are other laws that emerge from collective phenomena that are as yet undiscovered? Laughlin suggested that there is much more scientific study of emergent phenomena to be conducted and that study is the frontier of science. 'I think a good case can be made that science has now moved from an Age of Reductionism to an Age of Emergence, a time when the search for ultimate causes of things shifts from the behavior of the parts to the behavior of the collective.' (Laughlin 2005: 208). Uncovering these laws gives us hope of learning to engineer phenomena that currently just appear without underlying order. This is, in part, the study of chaos, which refers to processes 'whose variations are *not random but look random* . . . [Processes] that appear to proceed according to chance even though their behavior is in fact determined by precise laws.' (Lorenz 1993: 4).

Simulation of emergent phenomena may provide insight into what these laws are. One would then seek to practice engineering using these newly found laws. A strategy would be to classify the characteristics of phenomena into those that appear random and those that truly are. Following this strategy then, one would seek to understand these emergent laws, which would in turn provide some sense of the degree of true randomness. The question is whether and for how long can an engineering system tolerate residual random variations. Understanding emergent laws that operate at all scales of phenomena – for example, from the micro- to macro-scale as well as below and beyond – may enable some understanding of possible outcomes. One must be cautious since, 'to say that we "understand" does not imply that we can predict.' (Simon 1996: 178). Some emergent laws may be scale-invariant while others may not be.

Emergence is an essential quality not only of physical laws, as Laughlin suggested, but may be an inherent property of all aspects of our world. Laughlin insightfully wrote 'that organisation is important in and of itself – in some cases even the *most* important thing.

The laws of quantum mechanics, the laws of chemistry, the laws of metabolism, and the laws of bunnies running away from foxes in the courtyards of my university all descend from each other, but the last set are the laws that count, in the end, for the bunny.' (Laughlin 2005: 219). This line of thought furnishes an example of a complex, adaptive system. According to the Santa Fe Institute's statement on complex research, complex, adaptive systems are to be understood as follows:

> Complex systems research attempts to uncover and understand the deep commonalities that link artificial, human, and natural systems. By their very nature, these problems transcend any particular field, for example, if we understand the fundamental principles of organization, we will gain insight into the functioning of cells in biology, firms in economics, and magnets in physics. This research relies on theories and tools from across the sciences. Part of the rise of the complex systems research agenda can be tied to the use of theoretical computation as a new way to explore such systems.[2]

Although prediction may not be possible, learning more about possible outcomes through computer simulation is a strategy that better enables engineers to cope with emergent phenomena in their system designs.

Even though phenomena may be unpredictable, they are not necessarily unmanageable. 'Designers frequently construct systems (e.g. airplane and ships) that produce, and cope successfully with, turbulence and perhaps other kinds of chaos . . . Turbulence is frequently present in hydraulic and aerodynamic situations and artifacts. In such situations, although the future is not predictable in any detail, it is manageable as an aggregate phenomenon. And the paths of tornadoes and hurricanes are notoriously unstable but stable enough in the short run that we can usually be warned and reach shelter before they hit us.' (Simon 1996: 179).

Although engineers do rely on scientific principles (such as Newton's laws of motion) to engineer, there is also an art to the design, construction and operation of systems. The view of engineering knowledge transcending scientific knowledge is expressed in Walter Vincenti's book, *What Engineers Know and How They Know It*. 'The creative, constructive knowledge of the engineer is the knowledge needed to implement that art. Technological knowledge in this view appears enormously richer and more interesting than it does as applied science.' (Vincenti 1990: 4). For example, in designing a system, 'it typically involves tentative layout (or layouts) of the arrangement and dimensions of the artifice, checking of the candidate device by mathematical analysis or experiment test to see if it does the required job, and modification when (as commonly happens at first) it does not. Such procedure usually requires several iterations before finally dimensioned plans can be released for production. Events in the doing are also more complicated than such a brief outline suggests. Numerous difficult trade-offs may be required, calling for decisions on the basis of incomplete or uncertain knowledge.' (Vincenti 1990: 7).

Engineers have recognised this broader view of engineering knowledge but, until recent historical scholarship, have been ignored.[3] Computer simulations of complex phenomena add to the stock of knowledge of engineers so that they may bridge the gap between science and engineering to craft adaptive solutions. In other words, the computer enables one to experiment with different designs, construction layouts, and operations of systems so that one may get a sense of what a system would look like and perhaps how it would perform. Cave automatic virtual environments (CAVE) are an example.[4] One project at the Penn State University CAVE is the design of nextgeneration nuclear power plants. The CAVE enables one virtually to walk through the power plant so that designers may visualise how all the systems are laid out. For example, the placement of piping may appear satisfactory in the design drawings, but when a future plant manager walks through a CAVE simulation, he or she may note that in practice such a piping configuration may be difficult for maintenance workers to access. The simulation enables engineers to access experiential knowledge that is clearly distinct from the scientific knowledge guiding plant design.

FROM SYSTEMS TO SCENARIOS AND THE CREATION OF MEANING

As Wulf and Vest rightly point out, complex, emergent phenomena challenge traditional conceptions of engineering. Recognising that the material world is an assemblage of emergent phenomena and that the discovery of principles (laws) of organisation may enable a scientific understanding of those phenomena, gives hope that what currently appears without order may be understood so that ways to engineer may be created. Concurrently, even though complex, emergent phenomena may not be completely understood, engineers can know enough about the behaviour relevant to a specific purpose that they may engineer artifacts and systems that are good enough or 'satisfice'.[5]

One way of learning to understand a complex engineered system is to model and analyse it. In a traditional and useful way, one may define a system as 'a set of elements so interconnected as to aid in driving towards a defined goal' (Gibson *et al.* 2007: 2). For example, one may model the traffic system of a metropolitan area better to understand and manage the patterns of traffic flow, which is the defined goal. The elements include the number of vehicles, vehicle speed, as well as other factors influencing traffic, such as the weather. The behaviour of the model is a way to justify belief in how an actual traffic system may perform. The model is not the reality, but a representation or an abstraction of it such that the elements of a system relevant to a purpose and the relationships among the elements are specified.[6] Confirmation of a model depends on the degree to which the model corresponds to the empirical features of the world.[7]

How then does one make intelligent, ethical engineering decisions when the outcome of an engineering activity is not known? If a bridge of advanced materials is constructed, how do engineers know the bridge will perform as expected? How can they know that there will not be a catastrophic failure? One answer is that models of the phenomena give them enough confidence that the technology or technological system will perform as expected. Another answer is provided through testing of the components. Of course, accidents happen and that is why safety systems exist. The designers can also over-engineer. If a bridge needs to withstand forces of magnitude X, the engineer can build to $2X$. Increases in the scientific understanding of forces on bridges enable the engineer to estimate what X is and therefore what $2X$ is. Monitoring systems can be created that enable engineers to recognise possible problems in performance and gives them sufficient warning to take corrective action before a catastrophic failure occurs. In the case of the failure of one part, a redundant system can be built to take over the function of a failed component. Systems can be created so that, in the event of an accident, the effects are mitigated; for example, positioning shock absorbers around a bridge's pillars to mitigate the impact of an automobile crashing into the pillar or placing airbags in cars to mitigate the impact of a crash to the automobile occupant.

How do engineers make inferences about future engineering performance from the available evidence? How do they address the fallacy of inductive inference – of thinking that knowledge of the past performance of an engineered system is necessarily indicative of its future performance – and still make intelligent, ethical decisions? The short answer is to create safety systems. Then, although one may not be able to predict in advance the exact trajectory of an automobile's collision with a bridge's pillars, which depends on many situation-specific aspects, one can nevertheless engineer a safe bridge. One need not know the exact trajectory of every crash, or even a single crash, to accomplish that. Developing a deeper knowledge of chaotic conditions – that is distinguishing what appears random from what truly is random – may uncover traffic patterns that may be changed to create less favorable conditions for accidents. One is not attempting to predict and control explicitly, but one is attempting to change the conditions of what is possible, thereby essentially engineering the probability distribution of the outcome space.

According to Simon, many complex systems have a hierarchical structure, which he discussed as a property common to physical and social systems (Simon 1996: 183–216). A complex engineered system may be thought of as a socio-technical system in that there is an interaction of technological and social components. It is this hierarchical structure and its decomposition into subsystems that enable one to engineer, even though there may be chaotic behaviour within a subsystem. It is the effective property of the subsystem at the interface with other subsystems that is vital to the performance of the whole system. The focus of engineering a system then comprises the interfaces between the subsystems. Understanding and delineating the boundaries of subsystems and systems are therefore crucial steps.

In the example of the automobile collision with a bridge, one is engineering the boundary between the automobile and the physical structure of the bridge. The chaotic behaviour of a subsystem may be at one level the trajectory of the automobile impacting the bridge. At another level, it may be how an advanced material of which the automobile is constructed transfers the impact energy through the automobile's body. If the subsystems appear relatively straightforward to understand and delineate, their interactions may also be; we may think of these as linear interactions. However, even linear systems may have complex interactions. According to Charles Perrow, in his book, *Normal Accidents*, 'What distinguishes these interactions is that they were not designed into the system by anybody; no one intended them to be linked. They baffle us because we acted in terms of our own designs of the world that we expected to exist – but the world was different . . . [T]hese kinds of interactions [are] . . . complex interactions, suggesting that there are branching paths, feedback loops, jumps from one linear sequence to another because of proximity and certain other features . . . The connections are not only adjacent, serial ones, but can multiply as other parts or units or subsystems are reached.' (Perrow 1999: 75). A challenge then in understanding complex systems is recognising the ambiguity of subsystem boundaries, which stems in part from the act of defining the system and subsystems.

For example, when inquiring about the impact of an engineered system, the impact must be evaluated in some frame of reference. Over what scale of time are the impacts to be measured? What a specific technology 'means' is going to depend on the specific perspective from which it is to be interpreted. Discovering the possible meanings of an engineered system motivates the development of a scenario analysis of the system. These meanings may also not be intrinsically tied to a hierarchical conception of the system but rather to how the system is used, and the use may be open (Ogilvy 2002: 145).

From the point of view of creating a system that provides a specific output for a given set of inputs, the meaning of a system may devolve from whether it performs as expected. The George Washington Bridge spans the Hudson River and connects New York City and New Jersey. The bridge, completed in 1931, is a major automotive and truck crossing and performs a spanning function. The bridge, however, is also a part (subsystem) of a metropolitan transportation network so that when one asks about its function, one must consider the bridge's function in the context of that transportation network. How that network (system) may change and evolve will depend on many factors that include economic, social, political, and environmental as well as technological. Since the interaction of these factors may be difficult or even impossible to represent through a mathematical model, scenario planning may play a significant role in understanding and planning evolving socio-technological systems.

In such complex circumstances, it may thus be preferable to think in terms of analysing scenarios rather than systems. In a systems analysis, one assumes there is one correct interpretation of the world and that the difference in what actually occurs in the world from that which is predicted through a systems analysis varies probabilistically around that prediction. Scenario analysis is quite different. As Kees van der Heijden, former scenario-planning executive at Shell, explains, 'Initially scenario analysis was essentially an extension of the traditional "predict and control" approach to planning, except that a single line forecast was replaced by a probabilistic assessment of alternative futures, leading to a "most likely" projection.' (van der Heijden 2005: 3). He goes on to explain that 'scenario-based planning relies not on probability but on causality. As such it appeals more to the intuitive needs of the typical decision makers in their search for enhanced understanding of the changing structures in society.' Scenario analysis may also be thought of as a simulation. Scenario-planner Peter Schwartz argues that '[u]sing scenarios is rehearsing the future. You run through the simulated events as if you were already living them. You train yourself to recognize which [scenario] is unfolding. This helps you avoid unpleasant surprises, and know how to act.' (Schwartz 1997: 192).

A few applications of scenario-planning to engineered systems exist. In one transportation application, Zergras, Sussman, and Conklin present a case study of using scenarios better to understand the possible evolution of the Houston area regional transportation system (Zergras *et al.* 2004: 2–13). Aldrich, Newcomb, and Carlsen use scenarios to explore the future of synthetic biology, which conceptualises a biological organism as an engineered system (Aldrich *et al.* 2008). Samadja suggests scenario planning as a tool for choosing ethical nanotechnological futures.[8]

In the example of the George Washington Bridge, the metropolitan New York-New Jersey region has grown substantially since the 1930s, so that even though the GW Bridge is still a bridge as originally envisioned, it is an evolving structure embedded in an evolving regional transportation system. The installation of information systems, such as an electronic toll-collection system (EZ Pass) and traffic-monitoring devices that alert drivers to the extent of expected delays, have an effect on the traffic flow across the bridge and traffic flows in the surrounding region. One may imagine a scenario in which sensors embedded in cars convey information on location and speed to a network of intelligent traffic-controllers which, in turn, electronically adjust speed limits and access points in the region to achieve smoothly flowing traffic patterns. The vehicle, bridge, and controllers become part of an interactive system. How may engineers create this type of intelligent control of a transportation system?

INTELLIGENT CONTROL AND GOVERNANCE

The way to engineer intelligent control may not be through traditional hierarchical design. Computer scientist and engineer W. Daniel Hillis, suggested in his book, *The Pattern on the Stone*, that traditional 'reliance on a strict hierarchical structure is the Achilles heel of the engineering process, since it creates the kind of adamant inflexibility we associate with machines.' (Hillis 1999: 143). Furthermore, '[p]roducts of engineering are inherently fragile, because each part of an engineered system must meet the design specifications of how it should interact with other parts. These specifications serve as a kind of contract between components. If one of the components breaks its part of the contract, the design assumptions of the systems are invalid, and the system breaks down in an unpredictable way.'

In designing an intelligent transportation system that may include elements of nano-bio-information technology, it may be that those responsible for the overall concept never fully understand the make-ups or the functions of all of the components. What should be done according to Hillis is to 'arrange for intelligence to emerge from a complex series of interactions that *we do not understand in detail* (emphasis added) – that is a process less like engineering a machine and more like baking a cake or growing a garden. We will not engineer an artificial intelligence; rather we will set up the right conditions under which an intelligence can emerge.' (Hillis 1999: 138) Therefore, '[t]he greatest achievement of our technology may well be the creation of tools that allow us to go *beyond* engineering – that allow us to create more than we can understand.' (Hillis 1999: 138).

What are the implications for safety, reliance, and reliability? The answer is not clear. Hillis, comparing the human brain to the computer, noted that 'A single error in a computer's program can cause it to crash, but the brain is usually able to tolerate bad ideas and incorrect information and even malfunctioning components. Individual neurons in the brain are constantly dying, and are never replaced; unless the damage is severe, the brain manages to adapt and compensate for these failures. (Ironically, as I was writing this chapter, my computer crashed and required rebooting.) Humans rarely crash.' (Hillis 1999: 144).

A PRAGMATIC PHILOSOPHY OF ENGINEERING

The increasing complexity of our engineered systems may mean that our capacity to make meaningful statements about these systems may decrease, not increase, with time. 'One of the main goals. . .', Joel Moses noted, 'is to understand how to manage the processes that make it possible to deal successfully with the changes that occur during the lifetime of such [engineered] systems.' (Moses 2004: 12). But the human experience for several millennia is that not all future changes can be predicted, some because of our currently limited base of knowledge, others because certain emergent phenomena lie outside the known space of all outcomes. 'In time, many things now unknown will become known. We will learn more about what lies below the surface of the earth, and we may learn how neurons interact to let us perceive and think. The accumulating pile of data can be misleading, however. Beyond the currently unknown are the things that are inherently unknowable'. (Gomory 1995: 120).

A pragmatic philosophy of engineering, then, recognises that (i) the engineered systems created today will evolve through time, and (ii) the design and creation of the initial conditions of the future are happening now. In other words, engineers design and fabricate evolving artefacts.[9] Simon suggested that homeostatic mechanisms and feedback rather than prediction is how evolution and humans successful create adaptive systems (Simon 1996: 149). As an example of homeostatic control, he cited electric generating plants, in which '[a] modest excess of capacity . . . avoids the need for precise estimation of peak loads. Homeostatic mechanisms are especially useful for handling short-range fluctuations in the environment, hence for making short-range prediction unnecessary. Feedback mechanisms, on the other hand, by continually responding to discrepancies between a system's actual and desired states, adapt it to long-range fluctuation in the environment without forecasting.' (Simon 1996: 149).

The increasing prevalence of real-time communications in transportation systems is one example of a feedback mechanism that will lead to adaption. The development of advanced and affordable communication and computer networking systems has created real-time energy-demand systems that are increasingly playing a role in energy management. On being provided real-time feedback of energy prices, some energy consumers will cut back their use, which means that less generation will be required during peak loads. Providing feedback in transportation and energy systems are examples of how both these large-scale systems are evolving through advances in small-scale systems. Modern transportation and electric systems are achievements of the 20th century that continue to evolve to address the problems that the success of these systems engendered.

Given that complete prediction of complex engineered systems is impossible, a focus of engineering should be the development of increasingly intelligent feedback mechanisms. These feedback mechanisms need not be designed as the hierarchical structures suggested by Hillis. It may be that a feedback mechanism for complex engineering systems is already taking shape in the development of the Semantic Web (also known as Web 2.0).[10] The use of the tools of Web 2.0 to create dialogues among scientists has recently been termed 'Science 2.0' (Waldrop 2008). It may be that such collaboration will also take place regarding the engineering of complex systems, which we may think of as 'Engineering 2.0'. The collective intelligence of engineers, scientists, and other stakeholders of engineered systems throughout the world may be used in the creation of scenarios, such that there is a collective recognition that the scenarios create a language for practical problem solving rather than a prediction of how the world will be. One may also think of Engineering 2.0 as part of the real-time technology assessment capacity that David Guston and Daniel Sarewitz advocate (Guston and Sarewitz 2002). An Engineering 2.0 would increase the world's capacity for reflection on engineering and may influence professional engineers' reflective practices (Schön 1983). Since mistakes will be made, insight into how the world may be presents the opportunity to recognise errors ahead of time and engineer error-correcting or error-avoidance mechanisms.

There is always going to be an incompleteness about the engineering of systems. The goal of perfectly engineered systems that will respond adequately to all problems that will arise in the future will remain elusive though always appear to be tantalisingly close. A pragmatic philosophy of engineering recognises that the meaningfulness of statements about engineered systems is limited, but recognises that in describing through scenarios how the world may be provides insight about how the world ought to be and that one engineers accordingly.

NOTES

1. National Academy of Engineering, Grand Challenges for Engineering in the 21st Century, available at www.engineeringchallenges.org.
2. Santa Fe Institute: What is Complex Systems Research, 2008. About SFI: FAQs http://www.santafe.edu/about/FAQ.php
3. 'Aeroplanes are not designed by science, but by art in spite of some pretence and humbug to the contrary. I do not mean to suggest for one moment that engineering can do without science, on the contrary, it stands on scientific foundations, but there is a big gap between scientific research and the engineering product which has to be bridged by the art of the engineer.' (Vincenti 1990: 4)
4. See CAVE, wiki entry, http://en.wikipedia.org/wiki/Cave_Automatic_Virtual_Environment
5. Herbert A. Simon coined the term 'satisfice' to distinguish it from optima as a criterion for success in the search for solutions in a systems model. (Simon: 4–5, 27)
6. See Griffin 2007.
7. See Oreskes *et al.* 1994.
8. E. J. Samadja: Scenario Planning as a Tool for Choosing more Ethical Futures: a Case Study in Nanoscale Science and Technology, available at www.sys.virginia.edu/sieds06/papers FAfternoon Session6.2.pdf.
9. Simon: pp. 139–167 particularly at 162–163.
10. See Feigenbaum *et al.* 2007. They define the semantic web as 'a set of formats and languages that find and analyse data on the World Wide Web, allowing consumers and businesses to understand all kinds of useful online information' (p. 91). Also see McCarthy (2007: 324).

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