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Natural and Engineered Systems

As its title suggests, this book is concerned with how humans interact with engineered systems. This immediately raises questions as to what we mean by an engineered system, what other systems might exist, and how an engineered system differs from other systems. Can the natural environment be considered an engineered system with evolution (natural selection) as the design driver? If not, what characteristics distinguish evolution through natural selection from the sort of engineered systems that are the topics of this book? Where can we draw the boundary?

In our view, the difference between natural and engineered systems is a function of three factors:

1. Design for a purpose
2. Design for a certain class of users
3. Design against failure

PURPOSEFUL DESIGN

Engineered systems have a goal, a purpose lacking in natural design. The modern scientific view of evolution (i.e., natural design) holds that there is no goal either at the level of an individual organism, a species, or an ecosystem as a whole. Rather, evolution uses mutation to generate diversity and natural selection to eliminate variants that are less competitive. According to modern theory, the world we see around us is the result of billions of such experiments having been conducted over billions of years. The natural world exists as it does because it worked, not because someone wanted it to work that way.

Contrast this with any of the millions of tools we have engineered, each with a clear purpose. Razors are meant to cut hair, clothes to be worn, televisions to project pictures, and so on. Even a computer, a device with multiple purposes, is really a mega-tool used to run software for doing specific jobs. Compare the modern racing bicycle with a cheetah. Every feature of the racing bicycle has been carefully crafted for speed. Design teams developed specifications, prototypes were constructed, and through iterative testing and modification the final product emerged. Similarly, the features of a cheetah are also shaped by the need for speed. The difference is that whereas the bicycle was deliberately designed for the purpose of speed, ancestors of the modern cheetah who were slightly faster than other of their species were able to exploit a niche and eventually their own species. The cheetah wasn't designed with the goal of running fast; that ability evolved because it proved useful to run fast. Successive generations of selective pressure have given the cheetah the speed and body characteristics it now possesses; those cheetah ancestors that were poorer runners left fewer of their genes surviving into the next generation.

This sense of purpose doesn't end with tools or instruments. It also characterizes how we organize ourselves into working, military, and social units, as well as our financial systems and educational institutions. Our laws are intended to produce a social environment that meets the expectations of its people and government. For example, the strict hierarchies that characterize military command structures, the organization of businesses, and even some social structures are desirable when it is important to guarantee top-down control over individuals and smaller units. It is true that hierarchies are a natural way for humans to think about structures, and because of this, hierarchies could be seen as natural forms of social organization shaped by evolution. But that would be overstating the case. When the need arose for more rapid decision making in the business domain, hierarchies were abandoned and more flexible control structures adopted—most notably by high-technology start-up companies—to reduce delays in getting products to market and to take advantage of rapid advancements in technology. Similarly, in military domains where high reliability is essential (e.g., aircraft carrier operations), strict command structures are relaxed to improve the reliability of information transfer (Pfeiffer, 1989). Thus, the trend toward decentralization has been driven by a deliberate desire to reap the benefits of more egalitarian organizations. The fact that it is often difficult to achieve the desired social or institutional engineering results does not reflect a general lack of deliberate purpose. Rather, it emerges from trying to engineer a complex system, one in which there are many decision makers, each pursuing goals that may or may not be compatible with those of the lawmakers or each other.

In differentiating engineering from natural selection, we do not mean to say that every implication of an engineered system, whether a nuclear power plant, organization, or society, is completely determined at the outset. On the contrary, trial and error—largely through iteration in the design process—has been the dominant paradigm in engineering, whether in the development of the modern graphical user interface, organizational structure, or social policy. The point is that these iterations are driven specifically to achieve a clearly stated purpose (fly faster than the speed of sound, win the battle, give a competitive advantage). The process reflects this purpose-driven engineering. At each stage of design, teams of engineers evaluate all aspects of the prototype system with respect to its purpose. Only when the system meets a set of predetermined criteria, which have been derived from a statement of goals, will it be fielded.

USER-CENTERED DESIGN

The second factor, design for a certain class of users, points to another deep difference between engineered and natural systems. We build tools, engineer social systems, write music, and create art, all with the intent that our product will be used or appreciated by other people—not just as an audience but also as active users. The identification of the intended user is a critical step in engineering design. We even build special devices for animals. Some of the earliest tools include harnesses that make it possible for animals to pull carts and chariots. More recently, adaptive devices for disabled pets have become more common.

Perhaps it is counterintuitive, but nothing is more illustrative of user-centered design than the arts: music, painting, literature, theater, and the cinema. On the surface, watching a movie or viewing a painting may seem to be a passive activity, but that is only because we cannot directly see the mental state of the viewer. In truth, a movie or painting is successful only to the extent that the human user actively engages with it; that is, to the extent that it evokes some emotional or mental response in a viewer. It is perhaps easier to see how designing for human use plays a role in video games and virtual environments, where it is important to have displays and controllers that not only work well, but also allow the person to become immersed in the artificial world (see, e.g., Bystrom, Barfield, & Hendrix, 1999; Cunningham, Billock, & Tsou, 2001; Ellis, Kaiser, & Grunwald, 1993). In a broader sense, this is true for all engineered systems. Indeed, the fact that success depends on a fit with human physical and mental characteristics is central to this book. If one devises a spear that is too heavy to be thrown or a social system that is unresponsive to human needs, those systems will fail.

Although it is easy to understand the examples of how a spear that is too heavy, or a computer mouse that is too sensitive, represent a poor fit to human capabilities, it may be a bit counterintuitive, or even controversial, to maintain that successful social systems are "designed" around human characteristics. After all, societies seem somehow organic, more an accumulation of customs and laws than a planned enterprise. They seem more like the twisted, crowded alleyways of old, medieval towns than the stately promenades and grid layouts of planned cities. Yet, some insight into the role of human nature can be gleaned from examining the "utopian" societies that have been established from time to time.

According to some sources, some 3,000 experimental utopian societies have been documented in human history, the vast majority of which have been in the United States, predominately in two periods: the early 19th and middle 20th centuries (Oved, 1993; Sosis, 2000; Sosis & Bressler, 2003). Many of these attempts at ideal societies were based on religious principles. Indeed, the Puritan settlement of New England and the Quaker settlement of Pennsylvania were in the main attempts to establish communities that embodied their religious beliefs about what constituted a perfect society. In the early 19th century, several communal societies were established based on religious principles, including the Shaker community in New York; the Amana Colonies, the Zoar Colonies, and the Bishop Hill Colonies; and Harmony, to name just a few (Oved, 1993). Shortly thereafter, secular communal colonies began to spring up, many of them based on the theories of social philosophers such as Charles Fourier (brought to the United States by Albert Brisbane) and Robert Owen. A basic tenet of these utopian societies, whether religious or secular, was the abandonment, or sublimation, of the twin concepts of ownership and competition in favor of communal property and cooperation. Virtually all of these utopian attempts were abandoned within twenty or thirty years of their initial establishment (Oved, 1993; Sosis, 2000; Sosis & Bressler, 2003). The principal reasons had to do with internal discord arising from conflicts in the distribution of goods and disparities in the degree of perceived cooperative effort (see, e.g., Sosis & Bressler, 2003). As a species, we appear to be possessed of a complex mix of traits, some of which encourage us to adopt group identities and cooperation, while others foster individual gain and competition. These perfect societies failed, in part at least, because they explicitly and knowingly rejected the individual orientation basic to our nature.

Nevertheless, a few of these societies flourished for far longer than others, and some are still with us today. The Hutterites, originally a 16th-century German religious group that later settled in the United States, still live in small communal settlements (Peter, 1987; Wikipedia, 2009), as do the Amish and Mennonites (Smith, 1981). An analysis of 250 such ideal communities of the early 19th century attributes success to strong religious and cultural pressures both to participate in cooperative endeavors and to support others in the community through the distribution of goods and labor (Sosis & Bressler, 2003). It is interesting to contemplate these successful societies as experiments that provide insight into the characteristics of the human social constitution.

Which characteristics of the user community are important considerations depend, of course, on the purpose for which the device or system is constructed. The social tendencies of humans may matter in the founding of a society, or the development of interactive websites, but will be less critical to the design of a new mouse or pointing device, the success of which will depend more critically on characteristics of the human motor system. Regardless, all human-engineered systems, in the sense we mean here, share the property that they are intended for use by an external agent. Very few systems in the natural world have use by an external agent or organism as the principal design feature. Indeed, antelope are not designed to be food for lions. Quite the contrary: Evolution has equipped them with mechanisms to thwart predators. A few anatomical structures, such as sexual organs (genitalia) and the mammalian nipple, do seem to have evolved to be used by other members of the same species. Still, even in these cases, it could be argued that these are adaptations designed to increase the chance of passing on an individual's genes. Nonetheless, the fact that engineered systems are designed for specific users has an important implication: It means that the designer must understand the physical, mental, and emotional makeup of the user community. For example, it will not do to create a social structure that many will feel is unfair, just as people will not adopt computer software that is too difficult to use. Designing for others requires an understanding of how people perceive fairness. Likewise, it will not do to devise a tool that people find too effortful to use or too complicated to learn.

DESIGN AGAINST FAILURE

Natural selection succeeds by failure. That is, better fit individuals outperform less fit individuals. We do not mean to restrict this to the overly simplistic notion of 19th-century social Darwinism. There are many strategies to succeed in nature, and often-popular conceptions of conflict and competition omit the more important qualities of cooperation, friendship, intelligence, talent, and sociability. Nonetheless, the process of natural selection means that some organisms will fail. Mutation, the key to variability, is itself most often deleterious, leading to failure more often than to success. The difficult quest for food and mates also takes its toll.

In contrast, success by failure is not a particularly desirable approach to design for human-engineered devices, social systems, and entertainment. We do learn from failure, more perhaps than we learn from success. But, unlike natural selection, engineering design is often geared toward preventing failures, as they can incur substantial cost. Indeed, we have engineered laws that more often than not allow us compensation in the case of failure. Among other things, this makes failure very expensive for the designers. Then too, as our systems become more complex, with the lives of many people depending on their success, failure can become a tragedy. Thus, we cannot have aircraft design eventually succeed by having the poorer designs crash (though this occurred frequently in the very early history of powered flight). The same is true of cars, trains, medicine, and many other endeavors. As a result, aircraft designers spend years developing and testing all the systems that go into a new aircraft before that craft is actually produced. This is true of many industries. Failure is, we hope, confined to the design process.

Nonetheless, it is expensive to produce a complex device that is as free of defects as needed. The capital investment in research and development is a major expense for many companies. Not only is it expensive, but adequate testing also can add years to the development cycle. For example, in 2011 Boeing announced further delays in the development of its 787 Dreamliner, which has direct financial implications for the many airlines that have placed orders for these aircraft.

The process of designing and testing to eliminate failure is a rigorous engineering discipline. Not only does it include the physical and software systems, but it has also increasingly come to include the human response to the new system. The reason for this concern with the human operator is that as engineered systems have become increasingly complex, human behavior has remained much the same—and it will continue to be the same, at least for the near future. The role of the human in engineered systems has evolved with the access to vast amounts of data, linked communication systems, joint activity by several team members, and the requirement to make rapid analyses and decisions in increasingly complex environments, often with the lives of many at stake. Yet, evidence suggests that our brains are not that different from those of our ancestors in antiquity. The burden is on designers of modern information systems to understand the abilities and limitations of the human operator and to ensure that information presentation and control authority are predicated on these abilities and limitations.

The complicated logic of modern computerized devices can baffle even the most experienced users. When advanced automation was introduced into modern aircraft, there were numerous incidents in which the pilots made poor, sometimes disastrous, decisions based on a flawed or incomplete understanding of how the system worked. Add to this the fact that we now carry around with us cell phones, portable video players, and mp3 players that distract us rather than helping us fully attend to the world around us. The potential for cell-phone use to distract drivers has become a real issue, as evidenced by major rail accidents attributed to the train driver being distracted by texting or talking on a cell phone (Associated Press, 2008, 2009; National Transportation Safety Board, 2003, 2009, 2010, 2011).

How have we now reached a point where the devices that are supposed to make our lives better and easier actually make it more difficult? If we have been designing for ourselves for so long, you might think we had solved the problem. In part, this is because designers are only now beginning to come to a formal understanding of how people work. It has often been assumed that with practice people could adapt to whatever was required of them to use a device. We have reached a point where this is no longer true. To see how that has happened, it is useful to consider the historical roots of the practice of engineering for human use.

SUMMARY

This chapter described the differences between natural and engineered systems as a function of three factors. First of all, engineered systems have a goal or a purpose that is lacking in natural design. Second, designs are focused on users. We build tools, engineer social systems, write music, and create art all with the intent that our product will be used or appreciated by other people—not just as an audience but also as active users. Finally, unlike natural selection, engineering design is often geared toward preventing failures, not towards allowing systems to fail through natural selection.

REFERENCES

Associated Press. (2008). Commuter train engineer didn't hit brakes. Retrieved from www.msnbc.msn.com/id/26732536/ns/us_news-life/t/commuter-train-engineer-didnt-hit-brakes/#.Tp0F4k-Kzow

Associated Press. (2009). Train crash probe focuses on cell phones. Retrieved from www.msnbc.msn.com/id/29494331/ns/us_news-life/t/train-crash-probe-focuses-cell-phone-use/#.Tp0FR0-Kzow

Bystrom, K.-E., Barfield, W., & Hendrix, C. (1999). A conceptual model of the sense of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, *8*(2), 241–244. doi:10.1162/105474699566107

Cunningham, D. W., Billock, V. A., & Tsou, B. H. (2001). Sensorimotor adaptation to violations of temporal contiguity. *Psychological Science*, *12*(6), 532–535. doi:10.1111/1467-9280.d01-17

Ellis, S. R., Kaiser, M. K., & Grunwald, A. C. (1993). *Pictorial communication in virtual and real environments*. London, UK: Taylor and Francis.

National Transportation Safety Board. (2003). *Railroad Accident Report RAR-03-01: Collision of two Burlingon Northern Santa Fe freight trains near Clarendon, Texas, May 28, 2002* (No. RAR-03/01). Retrieved from www.ntsb.gov/investigations/summary/RAR0301.html.

National Transportation Safety Board. (2009). *Railroad Accident Report RAR-09-02: Collision between two Massachusetts Bay Transportation Authority Green Line trains, Newton, Massachusetts, May 28, 2008* (No. RAR-09-02). Retrieved from www.ntsb.gov/investigations/summary/RAR0902.html.

National Transportation Safety Board. (2010). *Railroad Accident Report RAR-10-01: Collision of Metrolink train 111 with Union Pacific train LOF65-12, Chatsworth, California, September 12, 2008* (No. RAR-10-01). Retrieved from www.ntsb.gov/investigations/summary/RAR1001.html.

National Transportation Safety Board. (2011). *Railroad Accident Brief RAB-11-06: Collision of two Massachusetts Bay Transit Authority light rail passenger trains, Boston, Massachusetts, May 28, 2009* (No. RAB 11-06). Retrieved from www.ntsb.gov/investigations/fulltext/RAB1106.html.

Oved, Y. (1993). *Two hundred years of American communes*. New Brunswick, NJ: Transaction Publishers.

Peter, K. A. (1987). *The dynamics of Hutterite society: An analytical approach*. Edmonton, Canada: University of Alberta Press.

Pfeiffer, J. (1989). The secret of life at the limits: Cogs become big wheels. *Smithsonian*, *20*, 38–48.

Smith, C. H. (1981). *Smith's story of the Mennonites*. Newton, KS: Faith and Life Press.

Sosis, R. (2000). Religion and intragroup cooperation: Preliminary results of a comparative analysis of utopian communities. *Cross-Cultural Research*, *34*(1), 70–87. doi:10.1177/106939710003400105

Sosis, R., & Bressler, E. R. (2003). Cooperation and commune longevity: A test of the costly signaling theory of religion. *Cross-Cultural Research*, *37*(2), 211–239. doi:10.1177/1069397103037002003

Wikipedia. (2009). Hutterite. Retrieved April 17, 2012, from http://en.wikipedia.org/wiki/Hutterite.