AC 2009-2244: INTEGRATING AFFORDANCES INTO FUNCTION-BASED REVERSE ENGINEERING WITH APPLICATION TO COMPLEX NATURAL SYSTEMS

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Integrating the Concept of Affordance into Function-based Reverse-engineering with Application to Complex Natural Systems

Abstract

The practice of reverse engineering is not only receiving increased attention in fields involving artificial systems such as computer software development, but also in fields involving natural systems such as molecular and cellular biology. As an example, a recent pronouncement of the National Academy of Engineering lists "reverse engineering the human brain" as one of the grand challenges for the next century. The applicability of engineering design principles to natural systems has been well recognized, but ambitious attempts to further reverse engineer such complex systems will require the latest advances in design thinking. The recent concept of design affordance readily lends itself to the analysis and understanding of complex natural systems that exhibit multiple interactions between subsystems.

Traditionally, reverse engineering has been based on the analysis of decomposing engineered systems into functional components. Recently, the concept of affordance, or what one system provides to a user, or to another system, has broadened the way engineers look at design. This paper attempts to provide an alternate method of reverse engineering that incorporates the idea of affordances. It is anticipated that this method will be particularly useful for illuminating our understanding of natural systems. By looking at the affordances of a system and the interrelationships illustrated by the affordance structure matrix, significant information can be obtained that might otherwise be missed if only considering functionality. Reverse engineering with respect to affordances should lead to a better understanding of not only the system, but also the purpose and plan behind it.

In addition, the introduction of reverse engineering of complex natural systems in the engineering curriculum provides a rich vehicle for making connections with several other fields of study, which engineering students would do well to consider. An example is developed which considers the system of life on Earth as a complex network of multiple interacting and interrelated subsystems. The integration of the concept of affordance into a function based reverse engineering approach is sketched. This approach provides additional insight into the system, which may lead to significant implications for the humanities and social sciences.

Reverse Engineering in the Undergraduate Curriculum

Much of modern engineering education typically involves the infusion of ideas from the humanities and social sciences in an effort to help engineering students communicate better, become more ethical, and see the task of engineering in a larger cultural context. This is as it should be, but is it possible that the field of design engineering might lend insight and wisdom back to the humanities? If engineering design principles are so helpful in unraveling the mysteries of biology, might they also be useful in the social sciences? These are just some of the questions being posed in an engineering elective course at Oral Roberts University (ORU), where undergraduate students wrestle with advanced concepts in reverse engineering. A recent article in *ASEE Prism*[1] touts the benefits of having engineering students engage in the dissection of mechanical devices to reverse engineer the design thinking that went into their development.

It is widely recognized that this constitutes a valuable design training exercise. But now, with the realization of the powerful utility of reverse engineering for understanding complex natural systems, engineering students at ORU are challenged to consider how this finding impacts the bigger picture of life on Earth. The study of the reverse engineering of natural systems not only enables students to relate engineering to other technical fields such as biology, chemistry and physics, but also fields such as psychology, sociology, anthropology, cosmology, philosophy, religion, and other humanities. Thus, a valuable mechanism for enriching the engineering education with topics from the liberal arts, as suggested in an article entitled "Polymers to Poetry" in *ASEE Prism*[2], is proposed. These connections are found to be meaningful to undergraduate engineering students at ORU. This tends to motivate them to further studies and interaction with some of the areas mentioned above.

Human Affinity for Science

When scientists undertake to comprehend the cosmos and describe how it behaves, they immediately make use of multiple advantageous circumstances that are often taken for granted. Firstly, although natural systems are often incredibly complex, these systems exhibit extensive order and generally follow orderly laws. In addition, the ordering of matter and energy, and the laws of nature are readily and accurately described by abstract entities and operations known as mathematics, which are somehow apprehended by the minds of scientists. Furthermore, human beings appear to be particularly well-suited and often highly motivated to decipher the mysteries of the universe. They are especially successful in this pursuit when they make good use of all the tools at their disposal, and their efforts are remarkably profitable for humanity. Indeed, nature seems to be laid out in such a way as to facilitate scientific discovery. [3,4] Albert Einstein recognized the significance of this match between human mental capacity and cosmic complexity when he famously remarked that the most incomprehensible thing about the world is that it is comprehensible. The result has been a steadily advancing understanding of nature that, when integrated with human resourcefulness and creativity, has shown great potential for the improvement of the human condition.

The Surprise Appearance of Engineering in Nature

Using this same body of mathematics to model, control and create complex systems, engineers often borrow innovations from nature when implementing their designs. This has resulted in the rapidly expanding new field known as biomimetics. Engineers and inventors have even developed ingenious devices that were later found to already exist in nature in almost exactly the same form (design isomorphs[5]). Consider the ubiquitous electric motor of the 20th century compared to the bacterial flagellum and other molecular motors recently discovered in living organisms. In fact, the more that scientists and engineers learn about natural systems, the more similarities they uncover between human engineering and the way nature works. This is especially true for living systems. Biologist E. O. Wilson has recently written that "the surest way to grasp complexity in the brain, as in any other biological system, is to think of it as an engineering problem."[6] In other words, he seems to be suggesting that researchers will make the most headway if they adopt the mindset that these natural systems were intentionally planned and implemented in order to accomplish one or more functions, goals, or purposes. A survey of the technical literature illustrates that he is not alone in advocating this approach to biological systems.

The National Academy of Engineering recently announced that one of their grand challenges for the 21st century is to "reverse-engineer the human brain." Their choice of wording for this particular challenge belies a growing trend in biology toward teleology.[7] Reverse engineering has traditionally referred to the dissection and analysis of humanly engineered devices for the purpose of recovering their original design information. This is typically conducted in an effort to reproduce the device, or assist in further engineering enhancements; a process known as re-engineering or value engineering. But recently the term "reverse engineering" is being used more frequently in reference to complex natural systems. A leading microbiology researcher with the Scripps Institute, Dr. Gaudenz Danuser, was trained as an engineer, but as a graduate student, he became fascinated with the way engineering principles were so useful in understanding the inner workings of the cell. Now he successfully conducts what he calls "reverse systems engineering of dynamic cellular processes."[8] The word "systems" is inserted as an indication that these cellular processes consist of the interactions of multiple complex subsystems that work together as a single unit.

The January 2008 joint issue of the *IEEE Transactions on Automatic Control* and *IEEE Transactions on Circuits and Systems* was a special issue devoted entirely to "systems biology". The editors define systems biology as "the quantitative analysis of networks of dynamically interacting biological components, with the goal of reverse engineering these networks to understand how they robustly achieve biological function."[9] Similar approaches to understanding biology can be found in recent journals representing the biological and medical sciences.[10] If reverse engineering really is a fruitful way of studying natural systems, then this method of conducting science, which effectively marries the fields of engineering and science, should be thoroughly explored to ensure that maximum benefit is achieved.

Reverse Engineering and Design Recovery

Many engineering programs are now training their students in reverse engineering techniques by facilitating student engagement in product dissection activities, as described in the October 2008 issue of *ASEE Prism* magazine.[11] However, there are very few textbooks on the subject in general. Because of the popularity of reverse engineering in the computer industry, much has been written on applying reverse engineering to computer software[12], but not much has been written regarding its application to hardware systems. A valuable resource that discusses function-based methods for hardware is *Product Design: Techniques in Reverse Engineering*.[13] However, a more foundational description of the reverse engineering process for complex hardware systems is found in an article entitled "On Reverse Engineering" by M.G. Rekoff, Jr.[14] He defines reverse engineering as "the act of creating a set of specifications for a piece of hardware by someone other than the original designers, primarily based upon analyzing and dimensioning a specimen or collection of specimens." Rekoff describes a method for systematically conducting the reverse engineering activity, noting that it "is not really greatly different from that of detective work in a criminal investigation or of conducting military intelligence operations."

In a nutshell, Rekoff recommends the decomposition of existing structural hierarchy in developing functional specifications until the mechanism-of-operation is completely understood. This is unpacked in the following steps of his grand plan for conducting a reverse engineering effort…

- "System-engineer" [analyze the interconnectivity with an engineering mindset] first to establish hypotheses based on the information presently at hand and to identify the measurement/test needs.
- Disassemble to the extent required to verify or modify the hypotheses and to perform supporting tests. One will not only uncover information relating to the hypotheses but will possibly also uncover information that was not previously known to exist.
- Further "system-engineer" on the basis of all the information in hand, form new hypotheses, and prepare for additional measurement and testing.
- Further disassemble, measure, and test to validate hypotheses and uncover new information.

This process continues until the degree of understanding is adequate for the purposes of the reverse engineering effort. For any particular item within the overall system being analyzed, "the generic process consists of the following five sequenced steps; assimilate existing data; identify elements; disassemble; analyze, test, and dimension; and complete documentation." Each of these steps is explained in very helpful detail in Rekoff's previously-referenced article.

Another helpful article, although dealing mainly with the reverse engineering of computer software, introduces the concept of "design recovery". "Reverse Engineering and Design Recovery: A Taxonomy" by Elliot Chikofsky and James Cross defines design recovery as "a subset of reverse engineering in which domain knowledge, external information, and deduction or fuzzy reasoning are added to the observations of the subject system to identify meaningful higher level abstractions beyond those obtained directly by examining the system itself."[15] In other words, the goal of design recovery is to work out, at a higher level of understanding, what a system or component was engineered to do, and (to some degree of confidence) why, rather than just examining its subcomponents and their interrelationships. This generally involves extracting design artifacts, by detecting design patterns for example, and synthesizing abstractions that are less dependent on implementation. It is these higher level abstractions that are believed to be the key to fully reverse engineering complex natural systems. In another article, Ted Biggerstaff further expounds on the idea, "Design recovery recreates design abstractions from a combination of code [system], existing design documentation (if available), personal experience, and general knowledge about problem and application domains…Design recovery must reproduce all of the information required for a person to fully understand what a program [system] does, how it does it, why it does it, and so forth."[16] A design recovery framework for mechanical components[17] developed by engineering researchers at the University of Windsor in Canada appears to be a promising and comprehensive approach to this problem.

A classic and intriguing example of reverse engineering and design recovery is the case of the Antikythera Mechanism, as described completely in a recent book entitled *Decoding the Heavens*[18]. This corroded and coral-encrusted device was discovered in 1901 at a depth of about 70 meters off the coast of Greece in a shipwreck dated around the 1st century BC. Initially overlooked among the many other valuable pieces that were recovered, it was set aside to dry out. After a few months, it unexpectedly broke open, revealing parts of a complex gear train including planetary gears. The advanced engineering evident from the recovered pieces was totally unexpected for this time period, hence began a century-long quest to reverse engineer the device. Eventually, with the help of high-tech instruments, it was determined to be an intricate mechanism for predicting the positions of various celestial bodies, including eclipses; a kind of mechanical calendar, which was also the first complex analog computer. Working replicas have been constructed of this amazing device, which has provided additional insight into the engineering expertise that existed in antiquity.

A significant amount of design recovery was accomplished in terms of the purpose of the device and the identity and thinking of the original engineer(s). Consider the following quote from page 55, "He [reverse engineer] also noted that the letters were so precise they must have been engraved not by a labourer but by a highly trained craftsman." Key to the design recovery process was the incorporation of historical and cultural information from that time period. Consider this quote from page 61, "archeologists also studied the rest of the salvaged cargo. Their discoveries help to paint a vivid picture of when the ship sailed, where her load was being taken and the sort of world from which she came. From there, we can guess at the origins of the Antikythera mechanism itself, and how it ended up on its final journey." Thus when related historical information was combined with direct observations of the specimen, the process of design recovery was greatly facilitated. In the next section, the concept of affordance, which has recently been introduced in the field of design engineering, will be investigated for its applicability in reverse engineering and design recovery efforts.

Introducing the Concept of Affordance for Reverse Engineering

In a recent article in *Mechanical Engineering*, Jonathan Maier calls for a rethinking of design theory by emphasizing that design problems begin at the system level. He claims that, "individual components can be designed only after the whole problem has been understood and defined at the system level and then decomposed into subsystems and so forth, down to individual components that can be designed using the hard engineering sciences and traditional analysis methods."[19] Major engineering projects have become so complex and far-reaching that George Hazelrigg has argued that design is no longer just multidisciplinary; it is *omni-disciplinary* in that any and all disciplines may be involved in the solution to a particular design problem.[20] Maier is convinced that the complexities of systems thinking and user interactions require design engineers to move beyond the level of simply designing for component or product function. The concept that he proposes is *affordance*, which is what a system provides to a user or to another system. An (positive) affordance is what something is "good for" or "good at", and may serve as an underlying and unifying principle in the science of design.[21] It is important to note that the affordances of a system depend on the physical form of the system, whereas the functions of a system do not. This is a useful feature "because it allows engineers to analyze and compare the affordances of product concepts (especially at the system level) as well as of existing products for reverse engineering."[22]

Although the term "affordance" has its roots in Gestalt psychology[23], perceptual psychologist James Gibson defined it in the modern era as "what it [the environment] *offers* the animal [user], what it *provides* or *furnishes*, either for good or ill…I mean by it something that refers to both the environment and the animal [user] in a way that no existing term does. It implies the complimentarity of the animal [user] and the environment."[24] Donald Norman, in his book *The Design of Everyday Things*[25], steers the concept toward engineering design, but stops short of Maier's contention that it is fundamental to the design or reverse engineering of any artifact. However, Norman does admit that "affordances provide strong clues to the operations of things." Maier emphasizes that the affordance-based approach to design captures important interactions within the designer-artifact-user triad that the function-based approach misses. In reverse engineering applications, a fourth role must be added to the triad; that of the investigator, or reverse engineer. Interesting interactions may be elucidated among these four roles by incorporating the concept of affordances. Maier compares the strengths and weaknesses of function-based and affordance-based design and comes to an interesting conclusion; there are several "appealing synergies" or "ways in which strengths of function complement weaknesses of affordance, and ways in which the strengths of affordance complement the weaknesses of function."[26] These synergies include a better view of "the big picture", a uniting of design methods, and a theoretical underpinning of design that illuminates the proper role of function.

In further work by Jonathan Maier and Georges Fadel on affordance-based methods for design and reverse engineering, they describe two kinds of affordances. Artifact-user-affordances (AUA) are defined as "the set of interactions between artifact and user in which properties of the artifact are or may be perceived by the user as potential uses. The artifact is then said to *afford* those uses to the user. Now we can define artifact-artifact-affordances (AAA) as the set of interactions between two artifacts in which some properties of one artifact interact in some useful way with properties of the other artifact."[27] In addition, they explain how both types of individual affordances can be considered as positive or negative depending on whether the interaction is good for the system or not. Furthermore, each affordance can have a quality of interaction associated with it depending on how well the interaction serves its role. For example, a chair may afford sitting much better than a large rock, and the weight of a large rock may be seen as a negative affordance if portability is an issue. Maier and Fadel claim that a systematic evaluation of the affordances of each part of a system can be combined into a comprehensive affordance structure matrix (ASM), including both AUA and AAA. [28, 29] The system is then effectively reverse engineered in the sense that its operation is well understood. The development of a detailed ASM will be illustrated with an example later in this paper.

Researchers are beginning to see the usefulness of affordances for design, especially when used in conjunction with function-based approaches. While confirming this, a recent study also points out a major difficulty associated with affordances. They may be difficult to identify, as described in the following observation, "Our conclusion is that while affordances as 'possible actions' are an important consideration while designing, it isn't always easy to reason out what they are, as the search space is large. Using function helps to focus the search, as it is backward reasoning. However, once a design or conceptual design is developed, affordances clearly have a role to play in investigating undesirable possible actions, perhaps leading to designs that are safer and easier to use."[30] Maier and Fadel have responded to this concern with a paper on how to identify affordances.[31] They discuss four methods: pre-determination, direct experimentation, indirect experimentation, and automated identification. Direct experimentation would be most applicable for reverse engineering, but indirect experimentation such as "thought experiments" may be useful if the natural systems in question do not readily lend themselves to direct experimentation. Automated identification is an intriguing concept in which a computer database of known affordances is used as a reference to match patterns discovered in system geometries. However, in order to be effective, this must be conducted with a specific user group in mind. Although such a database of affordances does not yet exist, the computer software industry has been steadily working on methods of reverse engineering using automated detection and identification of design patterns in code.[32] This is a very-much related activity that could contribute to the development of a similar database approach for automatically identifying affordances. A flow chart to guide the process of affordance-based reverse engineering is shown in Figure 1.

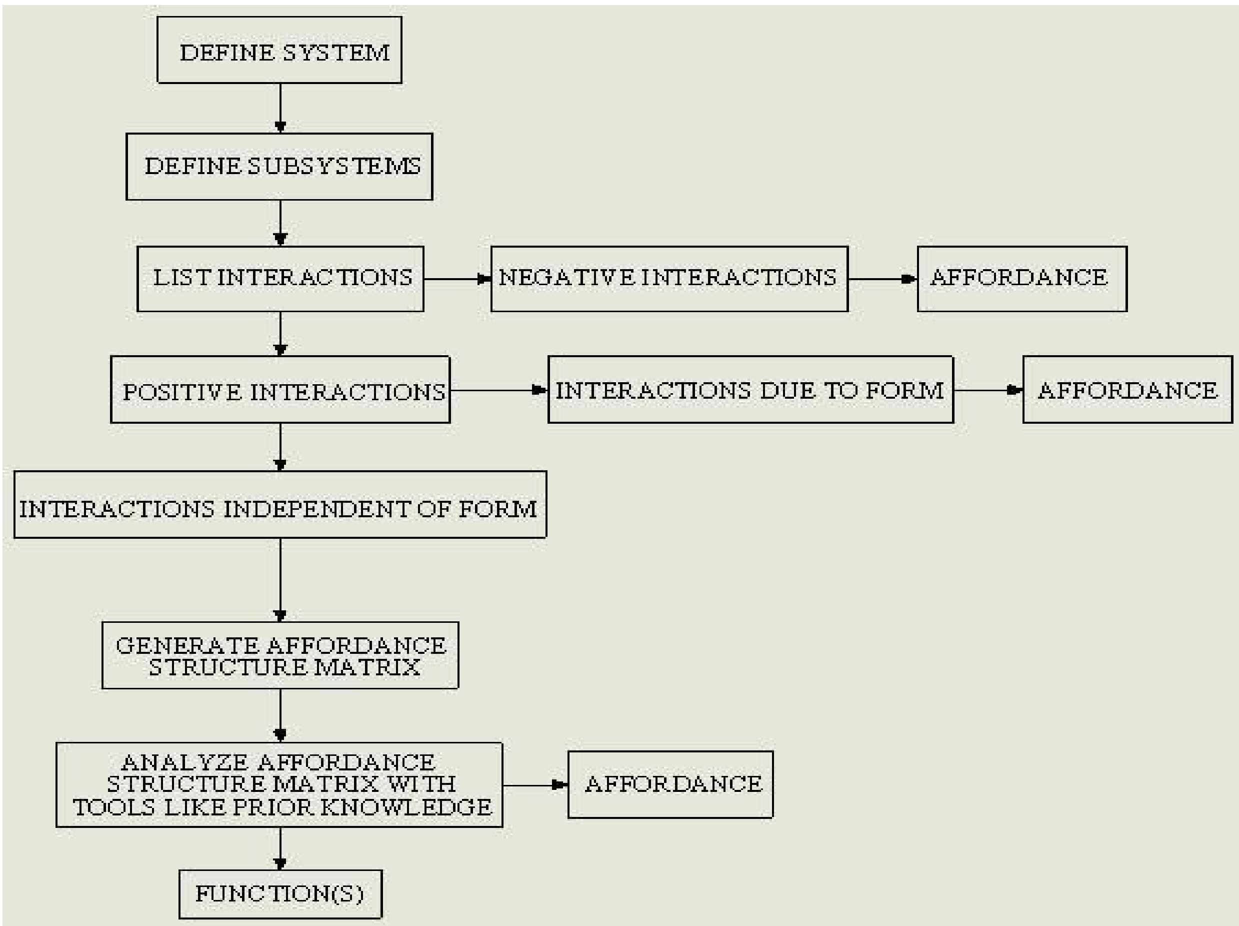


Figure 1. Flowchart for Affordance-based Reverse Engineering

How Affordances Assist in Reverse Engineering Natural Systems

In March of 2002, the cover story for *Science* was entitled "Reverse Engineering of Biological Complexity" [33], which encouraged the application of engineering concepts like those borrowed from control theory to better understand the complex workings of biological systems. It also emphasized the modularity and protocols that were being discovered within such systems at the time. Protocols were described as "rules that prescribe allowed interfaces between modules, permitting system functions that could not be achieved by isolated modules". Thus, understanding interacting modules and the protocols that specify those interactions is critical to identifying the affordances between modules (AAA). An interesting analogy was drawn between biological structures and the modules and protocols of the Lego toy system, demonstrating in multiple ways how biological systems exhibit features that are readily associated with engineered devices. The article concludes by encouraging biologists and engineers to "compare notes". Since this paper was published, it seems that many have been doing just that.

Physiologist Robert Eisenberg comments that it is most helpful to "look at biological systems through an engineer's eyes"[34]. Emphasizing how this leads to successful experimentation, he writes, "But it seems clear, at least to a physiologist, that productive research is catalyzed by assuming that most biological systems are devices. Thinking today of your biological preparation as a device tells you what experiments to do tomorrow." Many of these types of experiments serve to identify affordances. At Stanford University, an aerospace engineer, Claire Tomlin and a molecular biologist, Jeffrey Axelrod, teamed up to sing the praises of recent efforts aimed at "understanding biology by reverse engineering the control"[35]. They summarize an extensive reverse engineering study of the mechanism used by bacterium E. coli to combat heat shock[36], claiming that it "is just what a well-trained control engineer would design, given the signals and the functions available." Viewing the heat shock response as a control engineer would, the researchers developed a reduced order mathematical model to analyze the dynamics of each of the interacting modules. This analysis then motivated a series of simulation experiments on a larger mathematical model. The experiments involved disconnecting one or more information pathways (both feedback and feedforward protocols) which allowed comparison of various closed-loop and open-loop responses. As a result, they obtained a clearer picture of how certain information pathways and protocols afforded robustness, efficiency, and noise attenuation. This is an example of the "subtract and operate" technique for reverse engineering described in Otto and Wood's book on *Product Design*.[13] Tomlin and Axelrod claim that this analysis "is important not just because it captures the behavior of the system, but because it decomposes the mechanism into intuitively comprehensible parts. If the heat shock mechanism can be described and understood in terms of engineering control principles, it will surely be informative to apply these principles to a broad array of cellular regulatory mechanisms and thereby reveal the control architecture under which they operate…Certainly these kinds of analyses promise to raise the bar for understanding biological processes."

Marco Piccolino highlights the important role that information networks play in such protocols in his article entitled "Biological Machines: From Mills to Molecules"[37]. He writes of a "flux of biological information…carried by specific messengers, which act on systems that recognize them and develop specific responses. Through this complex flux of information, different mechanisms can be organized in more complex systems, resulting in highly integrated and efficient processes." Others attempt to quantify biological information as a measure of system complexity, as in a recent paper entitled "Functional Information and the Emergence of Biocomplexity"[38]. The authors rigorously define functional information to represent "the probability that an arbitrary configuration of a system will achieve a specific function to a specified degree". In addition to assisting in "understanding the behavior of systems composed of many interacting agents", they suggest that this "functional information formalism may also point to key factors in the origin and emergence of biocomplexity. In particular, functional information quantifies the probability that, for a particular system, a configuration with a specified degree of function will emerge." James Shapiro's forty years as a bacterial geneticist has led him to the stunning conclusions that bacteria are "natural genetic engineers" and "that even the smallest cells are sentient beings." In an article entitled "Bacteria Are Small but Not Stupid: Cognition, Natural Genetic Engineering and Socio-bacteriology"[39], he writes "The take-home lesson of more than a half century of molecular microbiology is to recognize that bacterial information processing is far more powerful than human technology…these small cells are incredibly sophisticated at coordinating processes involving millions of individual events and at making them precise and reliable. In addition, bacteria display astonishing versatility in managing the biosphere's geochemical and thermodynamic transformations: processes more complex than the largest human-engineered systems." These networks of affordances are also observed to function at the level of individuals, with great utility. In an article entitled, "Plant-Animal Mutualistic Networks: The Architecture of Biodiversity,"[40] Jordi Bascompte and Pedro Jordano assert that "Network structure has important implications for the coexistence and stability of species as well as for the coevolutionary process. Mutualistic networks [AAA] can thus be regarded as the architecture of biodiversity." Hence information-related affordances between modules at the individual and microscopic levels appear to lead to affordances between modules and systems on a global scale.

The Earth Ecosystem

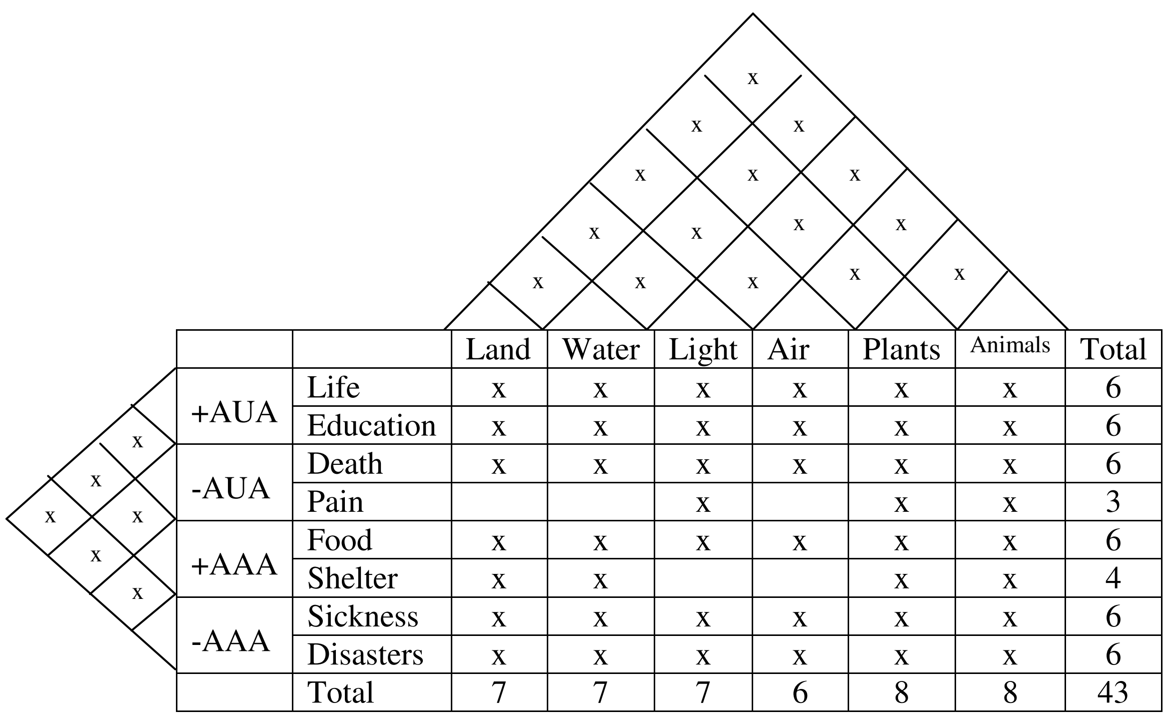
Consider the complex system of life on Earth. In referring to affordances, unless specifically stated, they will be assumed to be positive affordances. Starting at the microscopic level, one could consider the function of a cell. The basic function of any cell is to grow and multiply. However, depending on the type of cell, various affordances are exhibited. Take for example E. Coli. Some strains of these bacteria are afforded movement through a structure known as a bacterial flagellum. The bacterial flagellum does not assist the function of the cell, other than it affords the bacterium with the ability to move rapidly and efficiently to new environments that are better suited for growth. This can be seen clearly by use of the "subtract and operate" procedure mentioned above. By removing the bacterial flagellum from the E. Coli, the bacterium loses its primary method for transportation. The result is that the E. Coli loses efficiency, but not its function. The bacteria can still reproduce and grow; it just cannot spread as rapidly. Now the "subtract and operate" procedure would classify the bacterial flagellum as a sub function of the E. Coli. It is true that this is a sub function but it is also an affordance. In fact, any sub function that enhances the primary function but is not vital to it can be considered an affordance. Any of these affordances can be positive or negative depending on the point of reference. Take for example the interactions between E. Coli and the human body. E. Coli can thrive in the human intestine. In this way the body affords the survival of E. Coli. However, the body also affords death to E. Coli by attacking them with white blood cells. From the bacteria's point of view the environment in the intestine is a positive affordance, while the fact that the white blood cells will attack the E. Coli is a negative affordance. From the point of view of the human body the E. Coli offers only the negative affordance of sickness. This is a basic example of how affordances relate between multiple systems.

Affordances can readily be identified in even more complex systems. Take for example any symbiotic relationship, such as that between the clown fish and the sea anemone. The sea anemone, with its stinging tentacles, affords the clown fish protection from predators. The clown fish is protected from the tentacles by a layer of mucus. This process also affords the sea anemone with more food, as the predators sometimes follow the clown fish into the stinging tentacles. Although this significant behavior is characteristic of these two species, it does not define the function of either creature. It is simply behavior that takes advantage of affordances. These symbiotic relationships exist between animals and plants as well. There is the oxygen cycle; where animals produce the carbon dioxide as a byproduct that plants need in order to live. The plants in turn produce oxygen as a byproduct, which animals need to live. There is also the example of bees spreading pollen from flower to flower, allowing for germination. Of course, there are also examples of negative affordances found in the same symbiotic relationships. Parasites cause harm to their hosts, yet benefit from doing so. In this case, there are negative affordances from the point of view of the host, yet positive affordances from the perspective of the parasite.

So what about life on Earth as a whole? What does life itself afford? These questions are difficult, especially as answering them requires us to take a step back and look at life as though we were not part of the system. The best, and perhaps most unexpected, answer we have come up with is that life affords life. In order to better understand this answer, let's look at a brief overview of the life cycle of an animal. When an animal is born into the world, it first has to mature to the reproductive stage. During the maturation process, and until the point of death, the animal eats plant or animal matter, keeping the population in check. Once the animal gains the ability to reproduce, they can now fulfill their primary function. So while the animal is working to fulfill this function, that of reproduction, we see that it provides certain affordances to other species by keeping the population from growing too large for an ecological system. However, the usefulness of an animal does not end with death. When an animal or plant dies, the nutrients from its body are put back into the soil. The restored soil is a prime plot for growing plants, which in turn grow fruit that herbivores and omnivores eat, eventually reaching all the way to carnivores before returning to the soil. Of course, there are some negative affordances between the two systems. The fact that animals consume animal and plant matter is a prime example of this with the negative affordance being on the side of the plant or animal being eaten, of course.

In order to begin to reverse engineer the system of life on Earth, it is helpful to identify the user (mankind, from an anthropocentric point of view), the artifact (the planet and its resources), and the associated subsystems of the artifact. The “subtract and operate” procedure is again an excellent method for finding these subsystems, and their functions. Once all the subsystems and their functions have been classified, an Affordance Structure Matrix (ASM) can be developed. Consider for example, the ecological state of the Earth as the system, with its primary function being to sustain life. The subsystems are then divided into animal life and plant life with further subsystems under animal life being herbivores, omnivores, and carnivores. The primary function of each of these subsystems seems to be survival. The survival of each of the respective subsystems thus affords the survival of the system as a whole. Each of these subsystems also provides affordances to the other subsystems.

The next step is to look at the interactions between subsystems (AAA), the subsystems and the artifact as a whole, and the artifact and the user (AUA). The function of a subsystem is typically something positive for the overall artifact, thus any interactions that appear to be negative, such as predation, is possibly an affordance that must be tolerated for a greater good. However, not all of the negative affordances are necessarily obvious, and those that may seem negative to a user may turn out to be positive given more information about the total system. It is interesting that in order to promote a healthy growing environment, one of the most important aspects is population control. After separating the positive and negative affordances, the positive affordances are analyzed to see which ones occur due to form. An example of this is in our subsystems of herbivores, carnivores, and omnivores. Although they have their specific functions when viewed as independent systems, as subsystems of the system of life this fact becomes one of form, and consequently an affordance. The next step is to analyze the system using prior knowledge about common affordances the system exhibits. Unfortunately for our example, there is only one planet discovered that contains life. Once the subsystems and interactions have been identified, the ASM is developed. Of course, because our system is so large and complex, we will not be able to list all the various subsystems and affordances, but we can get a relatively good start and demonstrate the process of assembling a simple ASM, as shown in Figure 2. System components are listed across the top of the matrix, while positive and negative affordances are listed on the left. Boxes are filled to indicate which components are involved in providing affordances, and which components and affordance have significant interaction. The fact that the ASM is so densely populated in all three areas speaks of the interconnectedness of Earth's elements and the system of life it affords.



		Land	Water	Light	Air	Plants	Animals	Total
+AUA	Life	x	x	x	x	x	x	6
	Education	x	x	x	x	x	x	6
-AUA	Death	x	x	x	x	x	x	6
	Pain			x		x	x	3
+AAA	Food	x	x	x	x	x	x	6
	Shelter	x	x			x	x	4
-AAA	Sickness	x	x	x	x	x	x	6
	Disasters	x	x	x	x	x	x	6
	Total	7	7	7	6	8	8	43

Figure 2. Simple Affordance Structure Matrix for Life on Earth

Human Life

In order to illustrate the application of this approach to even more complex natural systems, consider the further example of human life. Is it possible, or even reasonable, to apply reverse engineering and design recovery techniques in an effort to gain insight into this situation? (A very interesting and extensive attempt is documented in a book entitled *Origin of Life: The Fifth Option*[41] by an engineer named Bryant Shiller, which finishes with some very surprising conclusions.) Of course, this approach assumes the possibility of a designer whose products lend themselves to such techniques. Multiple popular worldviews adhere to the existence of a master engineer/architect of some kind, and the point was made earlier that complex natural systems are currently being successfully reverse engineered. Thus, this seems like an interesting and fruitful pursuit, particularly at a Christian institution such as ORU. This approach is especially fitting under the further assumption that humans are "made in the image" of such a master engineer, which is characteristic of a Christian worldview. This would presumably help to explain why there is such a profitable match between the complexity of the cosmos and the mental capabilities of humans. Remember that such a match forms the basis for any successful reverse engineering studies of natural systems. However, the Christian worldview also entails the existence of an adversary who opposes the work of the master engineer, which may make the reverse engineering task more difficult.

The first step is to define the roles of artifact, user, investigator, and designer that make up the big picture of design and reverse engineering. For this case the artifact can be considered as the entire cosmos, with particular emphasis on human life. The user will be the human mind, or consciousness, while the investigator is anyone who is curious enough to pursue this kind of study. It is important to recognize this so that the investigator can limit the amount that their bias affects their analysis. As for the designer, whether it is the tinkerer of evolution, or space aliens, or theistic in nature, it is hoped that more can be discovered about its motives and intentions (or lack thereof) by properly applying the reverse engineering process. The diagram below represents the separation or overlap that is found between these roles.

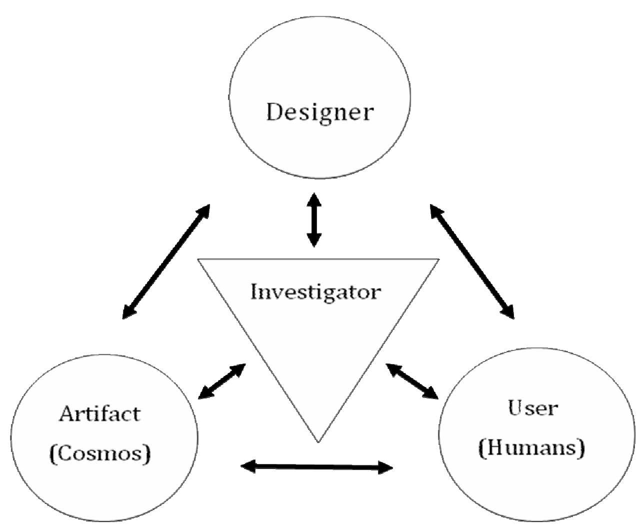


Figure 3. Example of Artifact-User-Investigator-Designer Roles in Reverse Engineering

Just listing all the affordances that the universe (artifact) exhibits towards the human consciousness (user) is a complex and time-consuming task, but by looking at those that are the most significant, insights can begin to be gleaned. To start off, the cosmos affords humans with the ability to learn. By studying the universe and its interactions, such as those between stellar bodies, molecules, or light, humans are able to gain knowledge about why previous natural events occurred the way they did, and predict how future events might roughly follow the same pattern. The human mind is able to experience these because of the sensory organs, which the human body, part of the artifact, affords to the human mind.

This brings up an interesting question; what else does the human body afford the consciousness? According to Oxford Philosopher Richard Swinburne[42], in order to be able to interact and learn about the environment in which it is placed, and yet still be a humanly free intelligence, the mind needs the human body to contain:

1. Sense organs with enormous capacity to receive information regarding distant world states
2. An information processor to turn sense organ states into brain states (resulting in beliefs)
3. A memory bank to file states correlated with past experiences (needed to reason)
4. Brain states that give rise to desires, both good and evil
5. Brain states caused by many different purposes that we have
6. A processor to turn these states into limb and other movements (needed to act on purposes)
7. Brain states that are not fully determined by other physical states (needed for free choice)

Another affordance that the universe provides the human consciousness is an environment to thrive in. One key aspect of the universe is the fact that it is so finely tuned. As Swinburne states, "Not all initial conditions (ICs) or laws of nature would lead to, or even permit, the existence of human bodies at some place or other, and at some time or other, in the universe. So we may say that the universe is 'tuned' for the evolution of human bodies if the laws and initial conditions allow this to occur. If only a very narrow range of laws and ICs allow such evolution, then we may say that the universe is 'fine-tuned' for this evolution. Recent scientific work has shown that the universe is fine-tuned."

Now, the existence of the human body, due to these fine tuned conditions is an important aspect of human consciousness because of the affordances mentioned above. What is even more amazing is that the fine tuning of the universe not only allows for life, but allows for persons who are able to question why the universe is the way it is[43]. The fine-tuning of the universe then also affords the human consciousness with the ability to discover attributes of the designer by questioning and observing how something so encompassing as our cosmos can be so elegant and well-engineered. With this in mind, the investigator can then appreciate the overlap with the area of the user as the human consciousness.

Considering that the user and investigator are roles filled by the same person brings a new dynamic and even more complex affordances between the different areas of the system. As the investigator, the human consciousness begins to question why things are the way they are within the system, and if there is any way to improve the system. Humans have been attempting this from the beginning of conscious thought with innovations and inventions meant to increase the quality of life. Recently, what scientists have discovered is that many of these new inventions have already existed in nature. A prime example of this is the boat propeller and the bacterial flagellum mentioned earlier.

The ability of humans to not only perceive affordances but also imagine how they might be creatively achieved is discussed in an article entitled "Affordances are Signs" [44] by psychologist John Pickering. He asserts, "The characteristic reflexivity of the human condition means that we are not only able to perceive the world as it is, that is, to perceive the affordances that actually surround us, but also to perceive affordances that do not yet exist, that is, to perceive the world as if it were otherwise. When we take a rock and modify it with blows until it functions as a blade, we do just that. We not only perceive what is, but also what may be and hence we may take meaningful, intentional action to bring it about if we so choose." The interesting thing that Swinburne points out is that the choices humans make not only tend to affect the world and others around them, but also affect their own characters (recursion), giving them some measure of influence over the kinds of people they eventually become. This is a very interesting affordance, which when coupled with the human ability to envision a preferable future, leads people to form various purposes related to self-organization (autopoiesis) and self-improvement. However, a common experience among humans is the inability to realize accepted standards and expectations. In an article entitled "The Kingdom of God and the Epistemology of Systems Theory: The Spirituality of Cybernetics,"[45] William Buker, a Professor of Counseling, suggests that features of the human condition such as recursion and autopoiesis, combined with the nature of the universe, serve to invite humans into a more complementary coupling with the larger mind of the master engineer. He also points out how this idea of fitting with the environment rather than fighting against it is consistent with Jesus' message of the kingdom of God.

Obviously, such possibilities require the recognition of valid epistemologies beyond those of science and history, such as found in human experiences of joy, faith, hope, and love. Some researchers are suggesting that it's time to more fully explore the wide breadth of knowledge found in the human condition if a clearer picture of mankind's purpose and place in the universe is to be achieved. Alexander Astin, Founding Director of the Higher Education Research Institute at UCLA, argues that spirituality deserves a central place in higher education.[46] He claims that "more than anything else…[this] will serve to strengthen our sense of connectedness with each other…This enrichment of our sense of community will not only go a long way toward overcoming the sense of fragmentation and alienation that so many of us now feel, but will also help our students to lead more meaningful lives as engaged citizens, loving partners and parents, and caring neighbors." At the beginning point of this reverse engineering project, perhaps it is too early to speculate about indications of the ultimate purpose for mankind, but it seems that Dr. Astin has put his finger on the pulse of what may be humanity's greatest desire, function and purpose; that of love. A scientific perspective of love is currently being pursued by the Institute for Research on Unlimited Love at Case-Western Reserve University. Thomas Jay Oord, theologian for the institute, has written extensively on this topic, including *Science of Love: The Wisdom of Well-Being*.[47] He says that "to love is to act intentionally, in sympathetic response to others (including God), to promote overall well-being." Given the high value that humanity has placed on love throughout history, and its power to change lives for the better, it is hard to imagine that, if humans do have purpose, it would not have something to do with love. One example of a scientifically rigorous and testable model of the cosmos, which postulates the love of a master engineer, and encourages humans to return that love as part of their primary purpose, is documented in the book *More than a Theory*[48], by Astronomer Hugh Ross.

Implications for Worldview

The advance of science in several areas is helping to identify the many affordances that the cosmos provides for higher life forms like human beings[49]. These affordances are facilitated by the integration of the many subsystems of our world, which also exhibits affordances between subsystems. The connectedness of the universe is aptly described in the following quote by the famous naturalist, John Muir, "When we try to pick out anything by itself, we find it hitched to everything else."[50] Some scientists have suggested that such affordances can lead us to a clearer understanding of worldview, and human meaning and purpose.[51] This is not surprising since that is ultimately what reverse engineering and design recovery procedures were designed to detect; what was the original engineer thinking? It is clear that the application of reverse engineering to natural systems cannot be separated from the worldview of the investigator because the concept of designer (or tinkerer in the case of Darwinism) is critical to the study. Recall the importance of the relationships between designer, artifact and user in this regard. The authors have suggested that there is another entity that should be included in this grouping; the investigator, or reverse engineer. In fact the worldview of the reverse engineer, while playing a role in the study, may also be further shaped in the midst of the study.

A classic example is the case of Charles Darwin, who, early in his career, greatly admired the works of natural theology, such as penned by William Paley. While later on, Darwin expressed doubts as described in one of his letters, "I cannot see as plainly as others do, and as I should wish to do, evidence of design and beneficence on all sides of us. There seems to me too much misery in the world. I cannot persuade myself that a beneficent and omnipotent God would have designedly created the Ichneumonidae with the express intention of feeding within the living bodies of caterpillars, or that a cat should play with mice…On the other hand, I cannot anyhow be contented to view this wonderful universe, and especially the nature of man, and to conclude that everything is the result of brute force. I am inclined to look at everything as resulting from designed laws, with the details, whether good or bad, left to the working out of what we may call chance. Not that this notion at all satisfies me. I feel most deeply that the whole subject is too profound for the human intellect. A dog might as well speculate on the mind of [Isaac] Newton. Let each man hope and believe what he can."[52]

In teaching the process of reverse engineering, and applying it to natural systems, it must be recognized that worldview plays an important role, and that worldview implications may result. The particular worldview of an investigator may, or may not, facilitate discovery and reverse engineering in natural systems. The extent to which a worldview is helpful in this regard is simply the extent to which a worldview is an accurate understanding of reality. Care should be taken to allow students and investigators to shape their worldviews in accordance with the evidence. Worldviews are determined based on various kinds of evidence and experiences, but scientific evidence typically plays a key role. The fact that the natural world is so readily and profitably reverse engineered suggests that the cosmos actually is an engineered system[53,54]. Investigators should not hesitate to consider this perspective, since it not only seems to facilitate discovery, but may also provide a sublimely satisfying understanding of personal meaning and purpose.

Conclusions

As the concept of reverse engineering is increasingly applied to natural systems, it will be helpful for students and investigators to understand the procedures for such studies. Such procedures appear to be largely absent from the current literature. A reverse engineering procedure is outlined which makes use of the concept of affordance; a recent innovation from the field of design engineering. It is suggested that affordance-based reverse engineering may be particularly useful when applied to complex natural systems. An example of life on earth is briefly discussed. It is recognized that investigator worldview is inseparable from such reverse engineering studies. Reverse engineering studies are not done in a vacuum. Furthermore, worldview may be significantly shaped by such studies, since reverse engineering and design recovery activities ultimately attempt to identify original meaning and purpose. Anecdotal evidence from undergraduate students engaged in such studies generally indicate an increased appreciation for the affordances of life and the ingenuity displayed in the cosmos. They also demonstrate an increased ability to articulate a satisfying and coherent understanding of the meaning and purpose of human life, as well as the reasons for the hope that they possess.

Bibliography

1. Wu, C., Some Disassembly Required, *Prism*, ASEE, Washington, D.C., pp. 56-59, October 2008.
2. Loftus, M., Polymers to Poetry, *Prism*, ASEE, Washington, D.C., pp. 42-45, December 2008.
3. Gonzalez, G. & Richards, J.W., *The Privileged Planet: How Our Place in the Cosmos is Designed for Discovery*, Regnery, Washington, DC, 2004.
4. Wiker, B. & Witt, J., *A Meaningful World: How the Arts and Sciences Reveal the Genius of Nature*, InterVarsity Press, Downers Grove, IL, p. 145, 2006.
5. Campana, J., The Design Isomorph and Isomorphic Complexity, unpublished manuscript, 2008.
6. Wilson, E.O., *Consilience: The Unity of Knowledge,* Knopf Publishing Group: Westminster, MD, p. 112, 1999.
7. Gene, M., *The Design Matrix: A Consilience of Clues*, Arbor Vitae Press, arborvitaepress.com, pp. 39-63, 2007.
8. Bardi, J.S., Mechanical Biology: Research on the "Leading Edge", Sept. 13, 2004, http://www.scripps.edu/newsandviews/e_20040913/movement.html
9. *IEEE Transactions on Automatic Contro*l and *IEEE Transactions on Circuits and Systems*, p. 4, January, 2008.
10. Himmelfarb, J., Dialysis at a Crossroads: Reverse Engineering Renal Replacement Therapy, *Clinical Journal of the American Society of Nephrology*, 1: pp. 896-902, 2006.
11. Wu, C., Some Disassembly Required, *Prism*, ASEE, Washington, D.C., pp. 56-59, October 2008.
12. Eilam, E., *Reversing: Secrets of Reverse Engineering*, Wiley, Hoboken, NJ, p. 3, 2005.
13. Otto, K. & Wood, K., *Product Design: Techniques in Reverse Engineering*, Prentice-Hall, Englewood Cliffs, NJ, 2000.
14. Rekoff, M. G. Jr., On Reverse Engineering, *IEEE Transactions on Systems, Man, and Cybernetics*, 15(2), pp. 244-252, March/April 1985.
15.Chikofsky, E.J. & Cross, J.H. II, Reverse Engineering and Design Recovery: A Taxonomy, *IEEE Software*, p. 15, January 1990.
16. Biggerstaff, T.J., Design Recovery for Maintenance and Reuse, *Computer*, pp. 36-49, July, 1989.
17. Urbanic, R.J. and El Maraghy, W.H., A Design Recovery Framework for Mechanical Components, *Journal of Engineering Design*, in press, ID 280275, 2009.
18. Marchant, J., *Decoding the Heavens*, Da Capo Press, Cambridge, MA, 2009.
19. Maier, J.R.A., Rethinking Design Theory, *Mechanical Engineering*, pp. 34-37, September, 2008.
20. Hazelrigg, G.A., *Systems Engineering: An Approach to Information-Based Design*, Upper Saddle River, NJ, Prentice Hall, 1996.
21. Maier, J.R.A. & Fadel, G.M., Affordance: The Fundamental Concept in Engineering Design, Proceedings of the ASME Design Theory and Methodology Conference, Pittsburgh, PA, Paper no. DETC2001/DTM-21700, 2001.
22. Maier, J.R.A., Rethinking Design Theory, *Mechanical Engineering*, p. 36, September, 2008.
23. Koffka, K., *Principles of Gestalt Psychology*, Harcourt Brace, New York, 1935.
24. Gibson, J.J., The Theory of Affordances, in *The Ecological Approach to Visual Perception*, Houghton Mifflin, Hopewell, NJ, p. 127, 1979.
25. Norman, D.A., *The Design of Everyday Things*, Basic Books, New York, 1988.
26. Maier, J.R.A. & Fadel, G.M., Comparing Function and Affordance as Bases for Design, Proceedings of the ASME Design Theory and Methodology Conference, Montreal, CA, Paper no. DETC2002/DTM-34029, 2002.
27. Maier, J.R.A. & Fadel, G.M., Affordance-Based Methods for Design, Proceedings of the ASME Design Theory

and Methodology Conference, Chicago, IL, Paper no. DETC2003/DTM-#####, 2003.
28. Maier, J.R.A., Ezhilan, T. & Fadel, G.M., The Affordance Structure Matrix – A Concept Exploration and Attention Directing Tool for Affordance Based Design, Proceedings of the ASME International Design Engineering Technical Conferences and Information in Engineering Conference, Las Vegas, NV, Paper no. DETC2007-34526, 2003.
29. Maier, J.R.A., Sandel, J. & Fadel, G.M., Extending the Affordance Structure Matrix – Mapping Design Structure and Requirements to Behavior, Proceedings of the 10th International Design Structure Matrix Conference, Stockholm, Sweden, Paper no. November, 2008.
30. Brown, D.C. & Blessing, L., The Relationship between Function and Affordance, Proceedings of the ASME Design Theory and Methodology Conference, Longview, CA, Paper no. DETC2005-85017, 2005.
31. Maier, J.R.A. & Fadel, G.M., Identifying Affordances, Proceedings of the International Conference on Engineering Design, Paris, France, August, 2007.
32. 1st International Workshop on Design Patterns Detection for Reverse Engineering, at the 13th Working Conference on Reverse Engineering, Benevento, Italy, October, 2006.
33.Csete, M. & Doyle, J., Reverse Engineering of Biological Complexity, *Science*, 295, pp. 1664-1669, March, 2002.
34. Eisenberg, R., Look at Biological Systems through an Engineer's Eyes, *Nature*, 447, p. 376, May 24, 2007.
35. Tomlin, C.J. & Axelrod, J.D., Understanding Biology by Reverse Engineering the Control, *Proc. Natl. Acad. Sci.*, 102, pp. 4219-4220, March 22, 2005.
36. El-Samad, H., Kurata, H., Doyle, J.C., Gross, C.A., & Khammash, M., Surviving Heat Shock: Control Strategies for Robustness and Performance, *Proc. Natl. Acad. Sci.*, 102, pp. 2736-2741, February 22, 2005.
37. Piccolino, M., Biological Machines: From Mills to Molecules, *Nature Reviews Molecular Cell Biology*, pp. 149-153, November 1, 2000.
38. Hazen, R. M., P. L. Griffin, J. M. Carothers, and J. W. Szostak, Functional Information and the Emergence of Biocomplexity, *Proc. Natl. Acad. Sci.*, 104, pp. 8574-8581, 2007.
39. Shapiro, J.A., Bacteria Are Small but Not Stupid: Cognition, Natural Genetic Engineering and Socio bacteriology, *Studies in History and Philosophy of Biological and Biomedical Sciences*, 38(4), pp. 807-819, December, 2007.
40. Bascompte, J. and Jordano, P., Plant-Animal Mutualistic Networks: The Architecture of Biodiversity, *Annu. Rev. Ecol. Syst.*, 38, pp. 567-593, 2007.
41. Shiller, B., *Origin of Life: The 5th Option*, Trafford Publishing, Victoria, BC, 2004.
42. Swinburne, R., *The Existence of God*, Oxford University Press, Oxford, 2004.
43. Ross, H., *Why the Universe Is the Way It Is*, Baker Books, Grand Rapids, MI, 2008.
44. Pickering, J., Affordances are Signs, *TripleC*, 5(2), pp. 64-74, 2007.
45. Buker, W., The Kingdom of God and the Epistemology of Systems Theory: the Spirituality of Cybernetics, accepted for publication by *Zygon: Journal of Religion and Science*, 2009.
46. Astin, A.W., Why Spirituality Deserves a Central Place in Higher Education, *Liberal Education*, 90(2), pp. 34-41, Spring 2004.
47. Oord, T.J., *Science of Love: the Wisdom of Well-Being*, Templeton Foundation Press, West Conshohocken, PA, 2004.
48. Ross, H., *More Than a Theory*, Baker Books, Grand Rapids, MI, 2009.
49. Barrow, J., Morris, S.C., Freeland, S., & Harper, C., (eds). *Fitness of the Cosmos for Life: Biochemistry and Fine-Tuning*, Cambridge University Press, Cambridge, 2008.
50. Muir, J., *My First Summer in the Sierra*, Sierra Club Books, 1988 ed., Houghton Mifflin, Boston, p. 110, 1911.
51. Denton, M., *Nature's Destiny: How the Laws of Biology Reveal Purpose in the Universe*, Free Press, New York, 1998.
52. Darwin, C.R., *The Life and Letters of Charles Darwin*: Including an Autobiographical Chapter. Edited by his son, Adamant Media Corporation, New York, 2001.
53. Halsmer, D., Halsmer, N., Johnson, R., and Wanjiku, J., "The Applicability of Engineering Design Principles in the Formulation of a Coherent Cosmology and Worldview," presented at the ASEE Annual Conference in Pittsburgh, PA, June 22-25, 2008.
54. Halsmer, D., Asper, J.M., Roman, N. and Todd, T, The Coherence of an Engineered World, accepted for publication by *International Journal of Design and Nature*, 2008.