Intelligent Design and Engineering Design Education

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Abstract

This paper briefly explores the intersection of current controversies about evolutionary theory and ideas from intelligent design (ID) with engineering education. Some of the statements about the nature of design that were brought to the fore in recent controversies in the United States and elsewhere over evolution and intelligent design can have significance for engineers and engineering educators [1]. From the time of the first discussion of the "blind watchmaker" in the early 1800's to current day arguments, reference to human-made works and engineering abound in literature, theology, and the works of both proponents and opponents of evolutionary theory. Whatever else one says about the controversy, careful review highlights some commonly held misunderstandings about the nature of intentional design and the engineering process. Understanding these misconceptions can provide a guide for changes in engineering curricula. By exploring some of the assumptions about the design process that are implicit in these arguments we may gain insight into the learning aims and needed goals for engineering design education.

Introduction

Evolution is a scientific theory which proposes specific mechanisms by which species change over time. Three key components of the mechanisms described by evolutionary theory are random mutation, natural selection, and time itself. Random mutation provides a basis and a physical mechanism for the variability within a population and its slow change or drift with time. Natural selection provides the pressure that operates on the level of an individual's reproductive success but has the effect of moving a population's distribution along some physical attribute, changing the mean or shape of the distribution. All of this needs time, what is sometimes called "deep time" or "geologic time" to operate. There are continuing controversies about the details of the mechanisms of evolution. For example the detailed nature and dynamics of mutations are unclear; whether it is mostly point mutations of a single gene that lead to a small shift in the mean or variance of a population or whether larger mutations, "megamutations" are needed that represent a more radical shift in the population characteristics. As expressed by Steven Jay Gould and others in the theory of punctuated equilibrium the key question is whether natural selection operates on populations gradually with the gradual accumulation of change over long geologic time spans or whether one can expect abrupt changes over a relatively short geologic time span (or both) [2-4].

However these controversies may appear to those outside of the discipline it is important to keep in mind that evolution is a well-tested theory of science with great explanatory power and success across a wide range of biological scales and systems. From botany and animal husbandry to bacteriology and the evolution of sub-cellular structures, the mechanisms and predictions of evolution have held true**.** Unlike the accepted usage and terminology in physics and engineering fields, in biology a theory never comes to be called a law or principle.

Intelligent Design

The intelligent design argument is not that different from the “blind watchmaker” proposition that was first espoused by William Paley in his Natural Theology of 1802, fifty years before Darwin [5]. This proposition was that if one were to find a watch in a field one would know that the watch was too complex and had to come from some “watchmaker” and could not be part of a “natural process”. The watch therefore has all the hallmarks of intelligent design, although the underlying assumptions about what made something designed and what are the hallmarks of knowing that something is designed by some intelligence are not presented in detail, but remain implicit. The leap is then made to the manifest complexity evidenced in nature being a hallmark of a divine designer. These arguments do seem intuitively obvious and have a great deal of understandable appeal.

One of the basic contentions of intelligent design is that the complexity evident in the natural world can not arise from natural processes driven by probabilistic elements and it is therefore evidence of an intelligent designer. However, when one looks more closely at both natural forms and human designed objects one finds much that is ill-considered, irrational, and sub-optimal in some way. One can find evidence that both natural and human objects build on the constraints of past designs as well as use materials and building blocks that are readily available. This is not hard to appreciate, as any optimization process, whether intentional or “blind”, tries a path of least resistance, least cost, whether in energy or materials. In some ways this is analogous to the principle of least action which gives rise to the forms of the trajectories of objects, such as the curve of fastest descent or the solution to the brachistochrone problem. In fact, the calculus of variations and the principle of least action were seen as teleological, meaning they seem to reflect design and purpose. What we have learned from recent research in complex systems, nonlinear dynamics, and cellular automata is that relatively simple, but nonlinear, governing equations and relationships among parts can lead to complex phenomena and also what has been called “emergent behavior” or “self-organization”.

To frame the question of intelligent design, the images below show both natural and human engineered objects. How are we to differentiate which are “designed” and in what ways?

Relation of Intelligent Design to Engineering Design

This is where the engineer and educator come in. It is now necessary for us to develop a better understanding of the nature of design for ourselves and our students and perhaps also to explore some of the misconceptions of the nature of design that are held by the general public and by those arguing for the intelligent design concept in the evolution debates. One reason that someone is inclined to immediately say that a watch is designed is the sense that it is manufactured and not natural. By this we mean something about the materials used to construct it. We already have some *a priori* understanding that to find that amount of formed metal in one place implies a much larger set of processes in the background (of mining, extraction, machining) that are hard to think of as random and purposeless. This represents an intuitive understanding of the nature of thermodynamics and entropy and the improbability of finding formed metal in the middle of a field. This is why Richard Dawkins, one of the most radical supporters of Darwinian evolution calls one of his books "Climbing Mount Improbable" and why the idea of deep geologic time is so important to evolutionary theory [6-8]. The understanding of evolution is that something highly improbable, given enough time, is not only possible but likely to occur.

The implicit understanding of the watchmaker argument is that "purpose" and "intention" equate with "intelligence" and are antithetical to random processes. A detailed exploration of purposes or "ends" and the role of randomness, though key to the debates about evolution, is beyond the scope of this paper. What is of interest is that within this framework intelligence is especially linked with rational, analytic, deductive cognition and engineering design is often taught as that kind of process with a faint nod towards a period of "brainstorming" and "right-brained thinking". This is something of a distortion in that innovative and creative aspects of design often come not from a *tabula rasa* or from an expert, but from a user, experience or pressures for adaptations to physical, market, economic, social, or political constraints. This bears some repeating and emphasis, design innovation can come from many sources; the user is an important but underutilized source of design evolution. Many nontechnical pressures as well as changes in the external environment and other technical advances can change the environment in which a product functions and thereby force changes in the product, *some never intended or foreseen by their original inventor*. "High" and "low" technology continue to live side-by-side, inventions intended to help one small segment of a population often enter general use. None of this may bear significant relationship to the original intention of the original design engineers [9].

The expert engineer knows the importance of nontechnical constraints and necessity, "the mother of invention" and will even take advantage of this and the general environment in which their design operates. That survival or necessity as a selection mechanism, whether intentional or strangely purposeless, is what drives evolution, whether by the human designer or a random mutation. Successful practicing engineers and the great engineers of the past, such as the bridge builders John and Washington Roebling and Othmar Amman, had a fine grasp of political and social constraints and necessities, as well as those of scientific theory [10-17]. If our students are to become truly global and holistic, they need to learn these adaptive skills as well.

One of the most enjoyable scenes for engineers in the movie Apollo 13 is where the engineer as hero is called upon to adapt a round CO_2 filter into a square hole. This illustrates some important aspects of the unique nature of engineering design, its creative and adaptive nature. This image of the engineer exists side-by-side with the image of the engineer as a careful, intentional analyst. In fact Dym [18, 19] and others argue that social aspects of engineering and what makes it different from the analysis of engineering science is underserved in our current curriculum.

On the other hand, people may be surprised to realize that human-made objects display evidence of their past and the constraints under which they were designed and perhaps even more surprising one must reach the conclusion *that on the basis of design features alone, one can not easily differentiate random evolutionary processes from those of deliberate design*. Each designed product carries its history with it, just as animals and plants do. There are dead-end designs, vestigial elements, spandrels, "kludges" in the parlance of computer engineering, and problems with backward compatibility in both natural and human domains. This is a blow to some elements of the arguments of evolutionary theorists such as Stephen Jay Gould, who in the "Panda's Thumb" and other essays and books [20-24], highlighted such dead-end evolutionary designs or their vestigial remains as evidence or proof of the random nature of evolution as opposed to intentional design. Gould often made fascinating connections to engineering such as his reference to architectural elements in his idea and use of the word "spandrels". He wrote a paper with Richard Lewontin that introduced the evolutionary concept of a spandrel, to mean a feature of an organism that exists as a necessary consequence of other features and not built directly, piece by piece, by natural selection [25]. Henry Petroski has also shown, from an engineer's perspective, that there is an important two-way relation between engineering ideas, design, and purposes and the mechanisms of evolution. Engineering is also replete with examples of "evolution" and dead-end designs from paperclips to bridges. He even made an evolutionary taxonomy of paperclips to illustrate the point [26-33].

Again what seems to emerge from this is not either a proof or refutation of an intelligent designer, but rather an insight into the fact that engineering design as practiced by human engineers from moderate to great intelligence seems to follow certain kinds of evolutionary principles. For example prototyping often relies on preexisting parts used in novel or unintended ways, designs rely on the materials at hand or augment earlier designs, generally keeping most elements in a slow process of change with occasional rapid shifts that are not backwardly compatible; a kind of "punctuated equilibrium" from the terminology of evolutionary theory. Famously, Henry Petroski has done much to both bring engineers and the design process to the public attention and to conceive of the design process as truly evolutionary in nature making the relationship between engineering and biological analogues function in both directions [26-33]. Thus evolution can be accomplished by random process or intentional intelligence and telling the difference between the two is not easy.

Another hallmark of the intelligent design school is the idea of "irreducible complexity". This is the idea that some subsystems, such as ears, eyes, or a current favorite, bacterial flagella [34,35], are so complex that it is hard to imagine the utility of partial forms of those subsystems or of them evolving from simpler components (reductionism). This is mistaken in both natural forms and engineered objects where one does see evidence for partial forms and their utility and for the smallest of subparts having multiple uses and reuses within one design and across generations of design. For example, a partial light sensing or hearing epithelium does have survival advantages, proteins can get used to make many different kinds of cellular machines and engineers are always looking for ways to "package complexity", have systems expand their functionality or be reused for entirely new functions. Another aspect of this ID argument about irreducible complexity is that one cannot, for example, make a functional mousetrap, or functional flagellum, out of fewer parts. Such is proposed to be the case for various cell biochemical pathways that may have evolved from other, very different biochemical solutions to other environmental challenges to the organisms. Indeed, such is the case in engineering as well. With a little thought one can indeed make a functional mousetrap out of fewer parts, or even more interestingly, once can use the parts of a mousetrap to do many other useful things and the parts or components at hand may then be "cannibalized" to be used in a wide variety of radically different functions. The original designer may never have conceived of such modifications or uses for their parts, and more typically, they could never have imagined some of the other changes that occurred in technology and society around them that changed the environment for their product or solution. So the idea that objects or parts have single or a few well defined functions is probably false. Engineers might consider such designs, "jury-rigged" or "suboptimal", but they are still functional design solutions to the problem at hand.

An interesting case study is the evolution of personal computers. One can see clearly delineated vestigial elements in many aspects of the hardware architecture from earlier generations of computer design. One of the most famous examples is that of the so-called 640K memory barrier and the various memory addressing schemes that were developed subsequent to developments in hardware. The Y2K problem was also evidence of all of the elements of "good enough" engineering. With limited memory resources, the solution of a 2 digit year made perfect sense. It wasn't that people weren't far sighted enough but rather they could not imagine that their systems would still be in active use as the 21st century approached. At some point however the computer manufacturer or chip designer may indeed decide to no longer make systems backwardly compatible or to rely on fundamental notions from an earlier era but to make a more radical shift in design, which results in a kind of punctuated equilibrium. The presence or absence of vestigial elements neither proves nor disproves the existence of an intelligent designer, since the intelligence of an engineer is liable to do both things.

Computer science has shown us the pitfalls of a one size fits all type approach to large complex problems such as generalized language processing and artificial intelligence. The problems become much more tractable the more specific their domains are. They become adapted to their local environment, so to speak. There is also a relationship between hardware and software that is ignored in the education we provided engineering students, where some are seen as "software types" and some as "hardware types". What we lose is an appreciation for the way one can influence the other, that real advances in parallel or vector processing or other truly different machine architectures from the first envisioned by John Von Neumann, Alan Turing and others requires evolutions in Si or GaAs devices or perhaps a leap to optical or quantum computing (a true "punctuated equilibrium", radical event, somewhat similar to a paradigm shift).

Finally one can study and use arguments from ecology as well as evolutionary theory to support the need for open-source software or multiple operating systems and platforms lest the entire crop of genetically identical PCs fall prey to the same virus. The MACs, being a minority platform, are not an interesting host for a virus. Designers should pay heed to the moral from "War of the Worlds" where it was the viral/bacterial kingdom that laid low the alien invaders from Mars. The essence of robustness and survivability in a population is (genetic) diversity.

The Design Process

A typical understanding of the engineering design process may include some steps to the methods such as the following:

- Problem statement
- User needs definition
- Requirements, objectives, goals
- Specifications, preliminary design
- Prototyping, build and test and iterate
- Marketing, evaluation, iterate

Other words or details may be used, but most descriptions of the method look largely similar to this outline [36, 37]. Some may emphasize the importance of testing and evaluation criteria or the fact that this is to be an iterative process, but probably too infrequently is the idea of a specific design as a response to an overall environment of need and constraint presented.

Most engineers will spend their careers in the process of slow modifications within a given toolset of known solutions, which make reference books such as “The Art of Electronics” by Horowitz invaluable [38]. Students can be taught to go to the reference and to not reinvent the wheel, but rather to use a toolbox of ready-made solutions and components. This does package complexity and reduce the time of product development, but it can also lead to poor design solutions. Many engineering students are not taught to explicitly understand the design process even as they may go through a senior design capstone course. In their technical careers many will work in teams on projects that were well defined before them and will continue after them and wherein they play a small role in perhaps test, measurement, or optimizing parameters, once a basic solution as been specified. Other design courses focus on design as process, project management and the like. Still others do most everything on paper and never get to the full build and test phase. There is some attempt now to bring in other “abilities” into the demands of senior design, manufacturability, sustainability, recyclability or end-of-life-cycle issues, social relevance, green solutions that minimize environmental impact, marketability and profitability and the like. Some, but too few, engineering courses explore the nature of the design process in terms of searching solution space wherein there are many possible designs and then choosing an optimal design, not in any absolute sense, but simply in the sense of meeting the explicit and implicit design criteria. As in any large complex optimization problem, there is probably no one unique achievable solution, but something that is good enough or at least it is difficult, time-consuming and of little utility to an engineer to prove the uniqueness of their solution or even that it is optimal. Rapidly acquired, adequate sup-optimal solutions in the competitive environment are good enough.

Compare this to natural design as exemplified by termite mounds or the workings of growth, morphology or embryology and we see a very different situation. In the case of the social insects, such as termites, one would tend to start with the assumption that there is no intelligence to their design process and yet their final products show exceedingly intelligent design or at least utilizing the physical world and materials around them in ways that approach optimal and that are adaptive to the local and current situation. Even stereotyped behavior can become part of a repertoire of choices that the individual animal “chooses” based on adaptation to local condition and circumstance. This can create a complex interaction and learning environment for the adaptive system. One can develop exceeding complex structures, such as the termite mound, without the obvious intervention of intelligence, so complexity per se is not a hallmark of intelligence per se. In fact, the human engineer has yet to approach the flexibility of adaptation evidenced in the natural world. We can now understand this better with developments in the fields comprising complexity theory, such as nonlinear dynamics. The concepts of self-organized behavior and emergent phenomena are central to understanding this new way of thinking about the basic structure and function of physical law. Thus processes described by relatively “simple” equations with an appropriate nonlinearity can represent complex phenomena and give rise to complex behaviors. There is still a strong tendency towards linearization and reductionism or at the least to reduce problems to ones that we already know how to solve or that are “in the textbook”.

Relation to Engineering Education

Education for the future will require a shift to teach young students these new ways of thinking, so that being faced with complexity is not novel and appreciating the complex natural environment and interactions is part and parcel of the way engineers work. For example the “law of unintended consequences” and the problem of, “Why Things Bite Back” [39]**,** appreciating the complex nonlinear interactive quality in systems from cities to climate to oceans to stars. In fact it is common nowadays to use the idea of biomimicry as a guide for engineering design and to look to biological systems to be our teachers in solving the fundamental physical limits of design solutions [40]. Adaptive design, self-learning, moderating and even “self-healing” materials solutions from the natural world are often looked to as exemplars. With the advent of nanotechnology and the convergence of mechanical and electrical systems, such as in micro electro-mechanical systems (MEMS), there are yet other strong changes in practice that push towards an integration of engineering knowledge and education and a restatement of fundamental design principles.

The implications for teaching design are profound, because we usually try to show design as a process proceeding from user needs, to requirements, design specifications, preliminary prototype, test and redesign. Although iterative elements in the process are acknowledged, it is generally thought of as being more amenable to analysis than might, in fact, be the case. As much of the recent emphasis on green engineering and sustainable engineering shows as well, these are complex problems where the cost function that is being optimized is not made explicit and it is impossible to have any kind of predictive function about what the future holds. The mechanisms of evolution also operate under extreme conditions of uncertainty and can provide a way to understand the nature and need for adaptation and resiliency in a population of designs.

What does the future hold for engineering education? Since much has also been said about innovation being the value-added that is needed to compete in this “flat world” [41] and global marketplace it will be essential to revisit carefully the education of students in design methodology and creative problem-solving. As we look towards ABET criteria and other calls for a more holistic engineering education, truly intelligent design of engineering education is called for [42].

Perhaps a new design curriculum would be based more explicitly around integrated knowledge and skills in four disciplinary areas and a number of conceptual domains such as the following:

- Disciplines
    - Structures (Civil)
    - Machines (Mechanical)
    - Networks (Electrical)

    - Processes (Chemical)
- Concepts
    - Adaptive/Flexible
    - Interconnected
    - Packaged complexity
    - Dynamic vs. static
    - Distributed vs. discrete
    - Stability
    - Unintended consequences, unpredictable
    - Green social and sustainable engineering ideas can provide an important and authentic context and background for engineering design projects to reflect all of the constraints and uncertainties that students will experience in real world practice.

We can begin to see the impact of these concepts extended to the metaphor and example of biomimicry [40, 43] and the whole lifecycle approach to the engineering of products from extracting materials to end-of-life disassembly, disposal and recycling. Additional principles from biomimicry sift the lens of engineering education more generally to life-friendly manufacturing processes, and the advantages of a hierarchy of structures and self-assembly to achieving many of the conceptual goals listed above. In fact this field of engineering is growing rapidly as a quick check of current titles shows [44]. So that thinking of engineering design can illuminate biological science and our understanding of evolutionary theory while, reciprocally, biological systems can provide insight for a new era of engineering design education.

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Biography

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