Evolution as a Metaphor for Design in Bioengineering Programs

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Abstract

As much of the traditional incremental engineering efforts of the 21st century can be undertaken outside of the U.S. (off-shored), engineers in the U.S. will need to increasingly focus on seeking out new opportunities and creating innovative products or processes capable of exploiting those opportunities. We suggest that bioengineers have some distinct advantages in this process, being able to draw extensively on their understanding of living systems to create effective biomimetic designs. Unlike traditional engineering design, the theory of evolution teaches us that biology does not attempt to optimize designs, but relies on permutations of extant technology to create new products (species), which then exploit environmental niches. Biomimetic design, or evolutionary design, draws on these concepts of evolution which have been conceived over the last two centuries by Lamarck, Darwin, Wallace, Gould, Eldsbergh, et al. The concepts of biological mutation, recombination, transformation, transduction, and fusion are excellent metaphors for teaching the innovative engineering design process. Here, we show how evolutionary concepts are used as a foundation for teaching evolutionary design and how these concepts can be implemented in a bioengineering design course to help students learn to become innovators.

Introduction

In engineering, particularly at the beginning of the 21st century, there is growing need to ensure that our graduates are both comfortable with, and capable of creating novelty, or what is more commonly called innovation. It is particularly important that this message be delivered to engineering students in the US, as more traditional engineering tasks, specifically, design improvements, will most efficiently be done in the developing countries. The idea that opportunity arises in response to change is the foundation of innovation and the concept that is key to a successful engineering career. With this in mind, educators need to consistently deliver this message to students. For engineering students, it is essential that they also understand that purposeful innovation can be learned as these are the individuals that will be responsible for many, if not most, of the innovative products and processes in the coming years. We cannot know what changes are in store for our students, and so cannot teach them the specific knowledge they will need to successfully handle the new opportunities they will experience. However, we can teach them the strategies that have passed the test of time, and so will always be available to them. To assist in the teaching of creative design and innovation, we suggest utilizing a conceptual metaphor based on evolutionary biology.

The evolutionary design process draws on the theories of biological evolution conceived over the last two centuries by Lamarck, Darwin, Wallace, Gould, Eldsbergh, et al. Biological evolution does not attempt to optimize designs, but relies on permutations of extant technology to create new species, which then exploit environmental niches. The theory of evolution theorizes that local, or global, environmental changes create new environmental niches into which new organisms can move and thrive. While the origin of these novel organisms is not well understood, many of the processes which have the potential to create novelty have been identified. Biology makes use of several distinct processes to "move" genetic material between organisms and therefore give rise to new novel organisms. These processes, of course, are undirected in the world of biology, but they have such close analogies to processes available to engineers that an awareness of these processes can serve as a remarkably useful tool to assist us in the development of products, whether it a modification of an existing product or an innovative breakthrough product.

Processes Underlying the Origin of Biological Novelty

The dominant biological processes involved in creating variation are mutation, recombination, transformation, transduction, and fusion. These processes provide a spectrum of organismic variations where mutation produces the smallest change and fusion results in a fundamentally different organism. Correspondingly, in terms of engineering design, a mutation represents a small change to an existing product while a fusion brings about a whole new technology. In the following discussions, the term "technology" is taken as the analogy for a biological family or kingdom, a "product" is analogous to a biological genus or species, and a "product feature" is analogous to the biological phenotype or trait. Figure 1 graphically shows the relationship between engineering design and the biological metaphor.

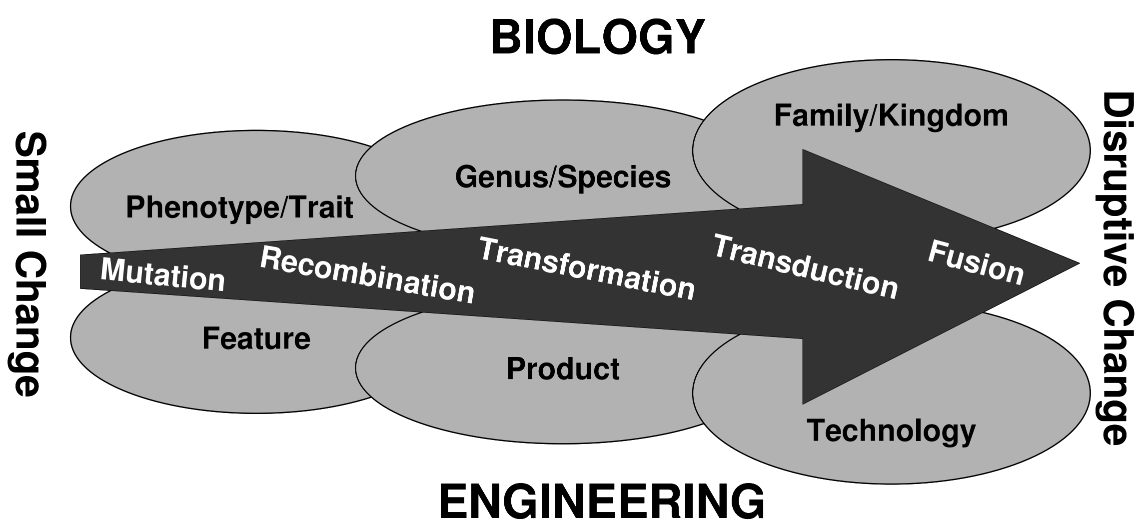

Figure 1: Spectrum of Change and the Conceptual Metaphor between Engineering Design and Biology.

In biology, a mutation is a random change in the genotype (genetic makeup) of an individual that may bring about a change in the phenotype (physical and physiological traits) of that individual regardless of the parental genotypes and can be compared to "serendipity" in science and engineering to explain accidental discoveries. As with the biological analogy, the mistake/change in the product may bring about no benefit (go unnoticed) or maybe result in the early death (failure) of the product when the product is in stability with the marketplace (environment). When the marketplace is in a state of flux, however, the mistake/change in the product may allow the product to not only survive, but to thrive.

Recombination, in contrast, is the formation of an individual's genotype by roughly equal gene contributions from the individual's parents (sexual reproduction). A population of individuals in a species can have many mating combinations that give rise to many possible recombinations of genotypes. This biological process can potentially produce much more variation than mutation, however, recombination is still severely limited. Applied to technological innovation, recombination is probably the most common process employed by engineers, and the process most commonly taught to engineering students. Recombination is exemplified by the translation of a feature from one closely related product to another. However, as in biological systems, relying on recombination approaches rarely results in the creation of innovative products, as the recombined features are typically selected from two closely, related successful (optimized) products.

Biological transformation, on the other hand, is a change in the genotype of an individual due to the passive incorporation of external DNA (literally DNA floating in the environment) by the individual. While the DNA incorporated in the genotype may not provide the organism with a useful phenotypical trait, the fact that this foreign genotypical feature was in the immediate environment indicates that this feature was useful to some other organism in the immediate vicinity, and therefore has a much higher probability of being useful than a genotypical change arising through random mutation, and may well provide a feature that could never be acquired through recombination. This can be compared to transformation in technology, when features are incorporated into the product from sources external to the product manufacturer. Here, the proverbial "hacking" of computer programs is a common modern example, though this was proceeded by electronic hackers, and before that, automobile hackers. In the realm of software, a program (the product) is released to users. If the source code can be found, users skilled in programming have the opportunity to modify the program to better fit their use. This is usually done to add a feature to the program that was not planned by the original programmer.

Transduction occurs through directed transfer, that is, when a vector (e.g. a virus) carries genes from one host cell to another. The corollary process in technology occurs when there is a deliberate transplantation of a feature between two unrelated products or especially between products in different technology families. Transduction is responsible for much of the novelty in the world yet is rarely emphasized.

In biology, fusion is a process by which one species fuses or integrates completely with another species. The critical feature of fusion is the property of emergence, two or more disparate species, each having a totally separate and distinct genome, fuse together to give rise to a wholly different organism, with new emergent behaviors. The resulting organism is not simply a new species, but an entirely new family/kingdom of organisms. Similarly in technology, fusion occurs when two or more disparate technologies are brought together, resulting in a new, transformative, or breakthrough, technology. In the fusion process, the fused technologies become integral to the emergent behavior, they are not simply added features. The emergent behavior associated with such technologies is so profound that they are often referred to as disruptive technologies as the technologies produce sufficient change to a society as to alter the way people live.

Innovative Design in Bioengineering Programs

The 20^{th} century has been called the century of physics, and the 21^{st} century has already been deemed the century of biology. Correspondingly, the bioengineering students are acutely aware of the principles of biology and have skills to study living systems. As a result, bioengineering programs are poised to utilize a biomimetic approach in the teaching of engineering design and innovation. We propose that a strong conceptual metaphor exits between the processes of evolutionary biology, which give rise to novelty in the living world, and the design processes available to the engineer focused on developing innovative products. Specifically, we propose that the processes of mutation, recombination, transformation, transduction, and fusion, have direct analogies with techniques utilized by engineers. We suggest that bioengineering programs initiate usage of this biological metaphor as we have had excellent experiences over the last several years teaching innovative engineering design using this approach.

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