FROM NATURES PROTOTYPES TO NATURAL PROTOTYPING

Fraser[1] BRUCE and Seaton BAXTER[2]
[1]DJCAD, University of Dundee, UK
[2]Schumacher College, Devon, UK

ABSTRACT
Most educational courses in Product Design and Engineering feature the practice of prototyping. We define prototypes by two conditions. They are both the first model and one which gives rise subsequently to multiple copies (offspring). All around us there are many examples of the offspring of successful prototypes both created by mankind's ingenuity and by the evolutionary processes of nature. This paper is concerned primarily with these evolutionary processes and their possible simulation by designers and engineers. We begin by briefly reviewing the main aspects and practices of conventional prototyping before comparing this with the way in which living systems continually prototype through evolutionary means. This we call biological prototyping. Here we briefly discuss the concept of evolution in nature and also where it is used to express progress in technological systems. The link between conventional and biological prototyping is conceived through developments in biomimicry and the philosophically aligned concept of biophilia. This combination we refer to as *Natural Prototyping* and we then enumerate ten (10) characteristics of natural prototyping. We conclude with some suggestions on how natural prototyping could be incorporated into the curriculum for engineering and product design education.

Keywords: Prototyping, nature, evolution, biomimicry, living machines, biophilia, Goethe.

1 INTRODUCTION

It is now widely acknowledged that research, development and innovation influences economic growth and prosperity [1]. Innovation is the 'critical success factor' for delivering value like market share, long-term growth and profitability. Hence, organisations must endeavour to create the conditions where innovation is considered central to all aspects of their systems, operations and culture, including their future strategies. Design is the fundamental link between creativity and innovation. From an educational perspective, design has been traditionally focused on the "making of stuff" [2]. For instance, product designers make physical and technical artefacts and graphic designers make flyers, brochures and websites. However, in a rapidly changing world, the multi-faceted design landscape has evolved in recent years to better address the social and environmental challenges that now span the disciplines. To some extent, design education has created positive impacts to these challenges through the emergence of new disciplines like interaction, service, transformation and experience design [2]. Moreover, because design is now being viewed as a highly complex activity involving a myriad of actors, many educational design courses are now transforming the way they teach and support their students. For example, in 2009, the Royal Society of the Arts (RSA) released a report identifying six key factors that are all highly relevant to the future development of product design and engineering courses and practices, and none more so than the role and value of prototypes and methods of prototyping [3]. This theoretical paper considers the possible development and interrelationships of conventional and biological prototyping and their manifestation in current biomimicry and living systems design. This results in our postulation of a new branch of prototyping that we refer to as Natural Prototyping. We then suggest how this might be explored by the incorporation as an option, for example, in the curriculum of product design and engineering courses. In parallel, we are currently exploring the idea through a new MA in Ecological Design Thinking at Schumacher College, Devon, UK.

2 CONVENTIONAL PROTOTYPING

Most educational courses in Product Design and Engineering feature the practice of prototyping. Indeed, Warfel (2009) has usefully pointed out that *'prototyping is practice for people who design and make things. It's not simply another tool for your design toolkit - it's a design philosophy. When you prototype, you allow your design, product or service to practice being itself. And as its maker, you learn more about your designs in this way than you ever could in any other way'* [4]. Product prototyping is essentially a generative synthesizing exercise, building up something new from an assembly of parts and ideas. Through incremental step changes in the development process, prototyping activities provide the means for individuals, and/or a group of prototypers, to *'organically and evolutionarily learn'* about their products under development [5], giving them opportunities to [2]:

- *"Experiment/explore ideas"*
- *"Identify problems"*
- *"Understand and communicate a form or structure"*
- *"Overcome the limitations of two dimensional work"*
- *"Support the testing and refinement of ideas, concepts and principles"*
- *"Communicate with others"*
- *"Sell the idea to the client"*

According to Bruce and Baxter (2013) *"the activity of prototyping is usually an intentional, problem-solving activity that culminates in some form of an artefact"* [6]. This artefact is typically known as a 'prototype'. However, for an artefact, process or event to be defined as a prototype, it should fulfil two conditions: 1) It should be the first version of its type; and 2) It should give rise to many copies of itself (we later refer to these as offspring). So, the prototype can be viewed *"as both an activity and an artefact where the artefact or potential artefact is always embedded within the activity"* [6]. As prototyping is now being recognized as an increasingly collaborative activity, it is not surprising that the term has produced many interpretations leading to ambiguity and inconsistencies within the academic literature. From a product design and development perspective, Ulrich and Eppinger (2008) have developed a 2x2 matrix to compare *types* of prototypes along two independent, continuous dimensions [7]. The first dimension represents the extent to which an individual or group of prototypes perceive the prototype to be either 'physical' or 'analytical' (or non-tangible). The second dimension represents the level of fidelity and hence the resolution of the prototype, referred to by the authors as 'comprehensive' or 'focused' prototypes. More specifically, a 'comprehensive' prototype captures most of the attributes (i.e. size, colour, shape, weight, functionality etc.) of a product, thereby making it distinct from all other types of prototypes. Prototypes with these characteristics are most closely associated with *"fully integrated, full-scale version"* of the final product [7]. On the other hand, 'focused' prototypes implement only a few attributes of the product, and are commonly referred to by designers as "looks-like" or "works-like" prototypes [7]. Classifying prototypes along these two dimensions, allows individuals and/or groups of prototypers to view any output from any stage of the prototyping process as a prototype. Alternatively, in human-computer interaction, Houde & Hill (1997) have proposed a classification system to help describe the *purpose* of the prototype rather than its physical characteristics [8]:

- Role relates to questions that address the function of a product from a user perspective.
- Look-and-Feel relates to questions that explore how a user interacts with a product through the stimulation of human senses e.g. how the product looks, feels, sounds, smells etc.
- Implementation corresponds to questions on the technical and engineering methods and components and sub-assemblies needed to perform the product's function.

This simple classification allows designers to locate the focus of their prototyping investigation, enabling them to make trade-offs and better-informed design decisions about the kind of prototypes to build and the tools and techniques to be used. Additionally, Ullman (2003) provides four classes of prototypes based on their *purpose* during different stages within the product development cycle [9]:

- A proof-of-concept prototype is used in the initial stages of the development process to understand customer needs and to establish product design specifications.
- A proof-of-product prototype refines the physical geometries, functional and technical requirements of the product.
- A proof-of-process prototype validates the geometry and the manufacturing process (i.e. pre-production methods and materials).

- Finally, a proof-of-production prototype verifies the entire production process.

Most of what has been discussed above has focused on the aspects and practices of conventional prototyping. However, we believe that prototyping at all systems levels will be a key feature of future "design" activities and will increasingly adopt a living systems approach. So, what now follows is a short discussion on biological prototyping.

3 BIOLOGICAL PROTOTYPING

The biological world is diverse and complex and has been changing for millions of years through the process we know as evolution. Even now, it is speculated that there are many living organisms on our planet, which remain undiscovered, unexplained and unidentified by science. According to Arthur (2009) evolution has two central meanings: 1) the gradual development of something; and 2) the process by which an object is related by ties of common descent [10]. Based on the Darwinian theoretical principles that include natural selection (or the struggle for existence) and the origins of new mutations [11], biological evolution is a subset of biology that helps us to understand the complex interactions between living organisms (i.e. animals, fungi, plants and bacteria) and their environments over successive generations. Darwin understood evolution to be a slow and complex process, writing: "*…Natural selection acts only by taking advantage of slight successive variations; she can never take a great and sudden leap, but must advance by short and sure, though slow steps*" [12]. John Maynard Smith (as cited in Ziman, 2000) argued that for Darwinian evolution to occur, multiple organisms of a single species (commonly known as a population) require the following three properties [13]:

1. *"The entities must be able to multiply and give rise to variation"*
2. *"There must be variation within the population"*
3. *"Some of the variations must be hereditary"*

So, entities must adapt and respond to their current environments to survive, grow, develop and reproduce offspring. The entity must have a slight difference in variation but within certain limits and, any change in population is inherited over successive generations. In its simplest form, Dawkins (1976) captured the meaning of natural selection, describing it as *"the differential survival of entities'*, going on to say *"…entities live and others die but, in order for this selective death to have any impact on the world, an additional condition must be met. Each entity must exist in the form of lots of copies, and at least some of the entities must be potentially capable of surviving – in the form of copies – for a significant period of evolutionary time"* [14]. Classical Darwinism has progressed through the early work of Gregor Mendel and the latest work on epigenetics. At first sight, technological (or conventional) prototyping would appear to have many similarities to biological evolution. After, all, the natural world is always producing new things. To some extent, Ziman (2000) supports this view, pointing out that "*in many respects, both the underlying mechanisms and the broad patterns of technological change are quite reminiscent of those found in biological evolution"* [13]. In light of this, it is important to differentiate between evolution in the context of technological and biological prototyping. In this paper, we view evolution in its narrowest sense when referring to technological prototyping, emphasizing the incremental development of an artefact through small step changes in the process. In other words, prototypes will multiply, give rise to offspring and exist in the form of lots of copies. In biology and genetics, the term *genotype* refers to the heritable characteristics of what is inherited or transferred from one generation to another. Interestingly, Dunn (2005) tentatively suggests that technological artefacts always contain the 'gene of an idea' when moving through the development cycle and could therefore be considered as *genotypes* [15]. So, it is not difficult to appreciate that technological artefacts evolve in similar ways to biological organisms. Furthermore, we know that biological prototyping is a slow and complex process compared to the accelerated evolutionary process of technological prototyping. Indeed, in the natural world, it is difficult to know at times when one prototype ends and the other actually begins. However, one striking feature of biological prototyping is that "*after 3.8*' *billion years of evolution, nature has learned: What works. What is appropriate. What lasts"* [16]. All around us there are many examples of the offspring of successful prototypes both created by mankind's ingenuity and by the evolutionary processes of nature. Biological prototyping has already been utilized, to some extent, by designers/engineers in the design of Living Machines and the study of biomimicry and, it is to this link that we now progress our thinking.

4 LIVING MACHINES, BIOMIMICRY & GOETHE

Prototyping forms an intrinsic part of many design processes, so it should be no surprise that a "living system" version of prototyping should form an important part of ecological design. More than 40 years ago, John and Nancy Todd and Bill McLarney founded the New Alchemy Institute with the main aim of creating ecologically derived human support systems [17]. They pursued the design of systems which had a minimal reliance on fossil fuels and which would operate on a scale accessible to individual families and small groups. This was to be ecological design for sustainable communities. For this, they derived the following basic precepts for ecological design and, by implication, natural prototyping as an integral part of ecological design [18, 19]:

- The Living World is the Matrix for All Design
- Design should Follow, not Oppose, the Laws of Life
- Biological Equity must Determine Design
- Design must Reflect Bioregionality
- Projects should be based on Renewable Energy Sources
- Design should be Sustainable through the Integration of Living Systems
- Design should be Co-Evolutionary with the Natural World
- Building and Design should Help Heal the Planet
- Design should follow a Sacred Ecology

One of the most important developments to come out of their work was the "Living Machine," a biologically based system for the treatment of polluted water and waste-water systems. By using a complete ecosystem approach, the working of the "Living Machine" could effectively use the self-organizing and adaptive capabilities of the organisms to maintain, within limits, the efficiency of the whole system. In other words, each system is co-created and maintained by a collaboration of the human designer and the living organisms. Many "Living Machines" are now operating throughout the world. Janine Benyus [16] would refer to this as biomimicry at the ecosystem level. In this case, it is using an ecosystem to preform directly, and without manipulation, as a human support system. Other examples of biomimicry provide the initial inspiration for a technical idea but, following analyses, only result in an artificial, technical product divorced from its ecosystemic context. Nevertheless, the potential future benefits from biomimicry are immense and well formulated in Benyus's pioneering review [16]. Biophilia is another concept of great significance in this field [20]. When used in association with biomimicry, it produces a morally strong basis for ecological design thinking and for the associated practice of natural prototyping. Johann Wolfgang von Goethe (1749-1832) developed a way of science, which according to Henri Bortoft, embraces and explains a principle of authentic wholeness [21]. This is in sharp contrast to the essential reductionism of modern science. It also provides a method of observation which could prove useful in biomimicry without intervening in the living plant. The method involves four stages of Goethean observation shown below and briefly described and summarized by Wahl (2005) [22]:

- Exact Sense Perception
- Exact Sensorial Fantasy
- Seeing in Beholding
- Being One with the Object

The Goethean method has also been used in the study of ecosystems and landscapes [23] and architecture [24]. Following the brief reviews we have made of conventional and biological prototyping, together with their integration through biomimicry and the potential of using the Goethean method, we suggest a form of prototyping which brings together living and non-living systems in an integral technique we have called Natural Prototyping with the following characteristics.

5 TEN CHARACTERISTICS OF NATURAL PROTOTYPING

1. It takes its source of aesthetic and technical inspiration from the natural world of animals, plants, insects etc.
2. Its original source material always consists of living systems.
3. Its general knowledge comes from the domains of biology and ecology.
4. Its detailed technical knowledge of form and structure comes from the sub-domains of animal and plant physiology, biomechanics, sometimes collectively referred to as biomimicry or biomimetics.

5. Its state of inquiry is always inter/trans-disciplinary.
6. The starting point of inquiries is existing biological/ecological solutions with long evolutionary histories.
7. Its design processes use analytical techniques of scientific and technical reductionism of living systems, the results from which are then processed by technical and engineering synthesis to create artificial, non-living products with little or no evolutionary history.
8. It actively seeks holistic approaches to study the integration of living and non-living systems and the integration of analytical and synthesizing design methods.
9. Its source material and its manipulation are the subject of environmental and ecological ethics.
10. Its philosophical foundations are influenced by ecosophy (from deep ecology) and biophilia.

6 THOUGHTS FOR THE CURRICULUM

This paper is one of a series about our joint research concerned with introducing ecological thinking into the education and practices of product designers. In previous conferences, we have suggested a number of steps that would contribute to an ecology of product innovation and we have also reported on an exploratory experiment to design the content of a suitable Masters programme with the participation of a group of PhD research scholars. In a further attempt to align and integrate product design course and practices with evolutionary processes and living systems, we have used a variation in the well-known concept of prototyping, which occurs in nature and is usually exposed in biomimetic studies. In this paper, we have argued the link between conventional and biological prototyping is conceived through developments in biomimicry and the philosophically aligned concept of biophilia, referring to this combination as *Natural Prototyping*. We conclude with five recommendations that we believe are worth considering in the development of an option/elective in the product design and engineering curriculum:

1. These students interested in this development should be made aware of techno-biological evolution through the expanded application of prototyping. This could involve locating technological and biological prototypes at different systems levels, drawing upon the work of Miller's (1978) general theory of living systems [25].
2. These students should be taught systematic techniques in which they traverse backward and forwards along the art to science continuum. Techniques like "Pulsing and Lensing" reported by Baxter and Bruce (2008) should be encouraged [26].
3. These students should be given an opportunity to acknowledge an "unconscious response to nature" through biophilia. This could be achieved by engaging participants in prototyping activities in other natural environments such as the countryside, woodlands and local parks.
4. Adopting biophilic principles may in turn lead to a "conscious act though biomimicry" and so inspire the creative output of the designer. Therefore, students should be encouraged to study biomimicry, paying particular attention to the technological concepts and innovations that have emerged from design institutions and research organizations. Generating efficient wind power from the study of humpback whales, creating sustainable buildings from the study of termites and learning from the prairies on how to grow sustainable food are some good examples drawn from the literature.
5. Students should be introduced to the basic precepts for ecological design, drawing upon the work of John and Nancy Todd and Bill McLarney.

The research continues through the development of an MA in Ecological Design Thinking at Schumacher College, Devon, UK.

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