Evolutionary Theories and Design Practices

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Introduction

How widely applicable are evolutionary theories? What can they tell us about design practices? The concept of evolution often is used in design research, yet Langrish[1] argues that many of our evolutionary ideas are confused or pre-Darwinian, and that they should be replaced by a non-progressive Darwinism. The theories we use inform our analysis, and hence a clearer theoretical understanding of evolution has the potential to improve our interpretation of empirical data on design practices.

In this paper, I argue that the Darwinian concepts of variation and selection provide a useful theoretical lens for understanding longer-term changes across design families, but that they can be misleading when applied to design practices within particular projects. To support these arguments, I consider the treatment of evolution in literature about technological change, as well as the contemporary debates and controversies in human and cultural evolution. Analysis and comparison suggests that there is a broad spectrum of neo-Darwinian evolutionary thinking. This includes, but is not limited to, the notion of "memes," currently discussed by design theorists. I highlight the questions and challenges that this rich heritage of evolutionary theorizing poses to researchers of design, who are engaged in analyzing activities and the outcomes of human labor.

Of course, it may seem paradoxical to include a discussion of evolutionary theories in *Design Issues;* given the deliberate and intentional nature of design practice. Darwin's theory of natural selection provides a mechanism for the evolution of the species, which disposes with the hand of God as the designer of individual living things. It drew him into conflict with the creationists, who believe that all living creatures are individually designed. While there is a long history of speculation that biological evolution is just one instance of a more generic phenomenon,[2] a number of dissimilarities between the realms of the natural and the artificial raise potential challenges to the legitimacy of evolutionary claims. Designers clearly are involved in the realm of the artificial. Hence, we are justified in approaching the application of evolutionary theories to design as skeptics.

1 John Z. Langrish, "Darwinian Design: The Memetic Evolution of Design Ideas," *Design Issues* 20:4 (2004): 4–19.

2 See, for example, John Ziman, "Evolutionary Models for Technological Change" in *Technological Innovation as an Evolutionary Process,* John Ziman, ed. (Cambridge: Cambridge University Press, 2000), 3–4.

Nevertheless, evolutionary concepts do have great appeal when we consider human culture, and the objects that are designed and made within it. Historical studies of technology describe long-term changes in the structure and form of hammers, steam engines, and automobiles; paperclips, forks, pins, and zippers; bicycles, Bakelite, and bulbs; automotives; bridges and airplanes.[3] There also are rich traditions of using biological analogies to understand design, for example, through work at the Cambridge School of Architecture in the 1960s and 1970s.[4] In striving to develop robust theories of design practice, we must be prepared to analyze critically and to seek to falsify all contenders. The potential utility of valid evolutionary theories makes evaluating the validity of their application to design particularly important.

The Nature of Evolutionary Theories

Variation and selection are central to Darwinian theories. In *On the Origin of Species*, Darwin outlines processes of variation, under domestication and under nature; and processes of natural selection. He goes to great lengths to set out the logical basis for his argument for evolution, and to address the counter-arguments that could disprove his claims. Crucially, he introduces qualifiers. Hence, in considering the conditions that may be favorable to natural selection, he states: "A large number of individuals ... is, I believe, an extremely important element of success."[5] Inheritable and diversified variability also are characterized as favorable, though Darwin believes that mere individual differences are sufficient.

Evolution is, in biological terms, quite different to development: it focuses on the evolution of a population over many generations rather than the growth of an individual over a lifespan. In the social sciences, the term evolution sometimes is used loosely to mean any form of development or change. But evolutionary theories need to be more precisely defined and characterized to be useful. Darwin was not the first to propose a mechanism. Prior to Darwin, Lamarck had proposed a mechanism for evolution based on the inheritance of characteristics acquired during their lifetime, such as the passing on of learned knowledge or well-exercised muscles.[6] However, Darwin's theory is the only one to have stood up to comparison with empirical data. Modern theories of evolution typically require variations across a population to result in competition between variants, and differential inheritance of their characteristics in the next generation of the population. This process has been described as one of blind variation and selective retention.[7] It increases the fit between characteristics of the population and the local selection environment, and hence increases diversity.

Theories of evolution do not provide a basis for extrapolation of design prescriptions. The progressive view of the mechanism behind evolution is simply not supported by empirical data, and should be little more than a footnote in contemporary discussion.

3 The evolution of hammers, steam engines, and automobiles is described in George Basalla, *The Evolution of Technology, Cambridge Studies in the History of Science* (Cambridge: Cambridge University Press, 1989); paperclips, forks, pins, and zippers in Henry Petroski, *The Evolution of Useful Things: How Everyday Artifacts—from Forks and Pins to Paper Clips and Zippers—Came to Be as They Are* (New York: Vintage Books, 1992); bicycles, Bakelite, and bulbs in Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs* (Cambridge, MA: MIT Press, 1995); automotives in Paul Gardiner, "Robust and Lean Designs" in *Design, Innovation, and Long Cycles,* Christopher Freeman, ed. (1984); and bridges and airplanes in Walter G. Vincenti, *What Engineers Know and How They Know It* (Baltimore, MD: The John Hopkins University Press, 1990).

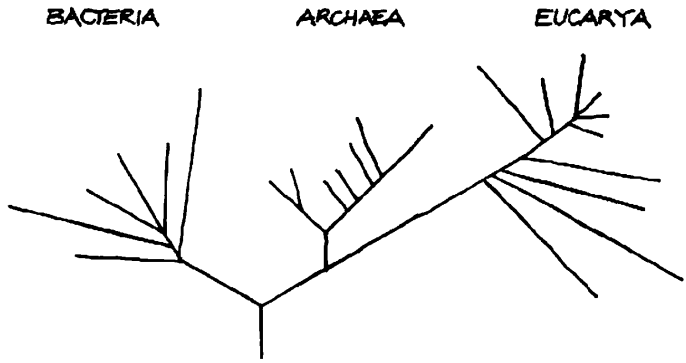
4 Philip Steadman, *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts* (Cambridge, UK: Cambridge University Press, 1979); and Christopher Alexander, *Notes on the Synthesis of Forms* (Cambridge, MA: Harvard University Press, 1964).

5 Charles Darwin, *On the Origin of Species* (London: John Murray, Albemarle Street, 1859).

6 Jean-Baptiste Lamarck, *Zoological Philosophy: An Exposition with Regard to the Natural History of Animals* (Paris: 1809).

7 Donald Campbell, "Variation and Selection Retention in Socio-Cultural Evolution," *General Systems* 16 (1969).

Figure 1
Sketch of one of a number of contemporary phyiogenetic trees.



Developed in the nineteenth and twentieth centuries through the work of (non-Darwinian) evolutionary theorists such as Lamarck and Spencer,[8] it sees all biological species moving up a "chain of being" which culminates in human beings. In their critique of progressive evolution, Laland and Brown go so far as to argue that:

> [H]istorically, certain ideas have tended to go together: a Lamarckian view of evolution with species arranged on a ladder and a linear, progressive concept of change, perhaps inevitably engenders prejudice as some evolved forms must be regarded as more advanced, or "higher" than others.[9]

As Langrish shows, it is this progressive view that often is criticized by design scholars. For example, Tonkinwise criticizes evolution as "a way of explaining what results from interrelated random processes, not the mechanism that brings about those results." [10] In fact, evolutionary theory does exactly the opposite, explaining the mechanism for change but not the results. Despite the development and refinement of scientific theories of evolution, erroneous beliefs in progressive evolution have been widely influential,[11] and are still deeply entrenched in debates on technological evolution.

One way of understanding the difference between the non-Darwinian prescriptive views of the historical sequence, and the modern, neo-Darwinian descriptive view of the historical sequence, is to consider the different versions of the "tree of life" that these theories propose. The progressive tree proposed by Ernst Haeckel shows a linear progression up a tree, with man at the top while contemporary phylogenetic trees, which are based on an analysis of molecules rather than species, show a broader divergence of life in which man holds no privileged position.[12] It is important to note that evolutionary research seeks to explain a number of phenomena: it is not only used to describe and analyze such historical sequences over the long-term, but also used to study the mechanisms for changes at any point in time.

Like Langrish, I argue that the Darwinian concepts of variation and selection provide a firmer foundation for theorizing about design than the non-Darwinian understandings that his work

8 Lamarck, *Zoological Philosophy: An Exposition with Regard to the Natural History of Animals* and Herbert Spencer, *The Factors of Organic Evolution* (London: Williams & Norgate, 1887).

9 Kevin N. Laland and Gillian R. Brown, *Sense and Nonsense: Evolutionary Perspectives on Human Behaviour* (Oxford: Oxford University Press, 2002).

10 Cameron Tonkinwise, "Design + Evolution = Eugenics: Mimetological Analogies, or Why Is Design So Enamoured with Evolution?" (paper presented at the European Academy of Design 06, Bremen, 2005).

11 Belief in a linear and progressive mechanism infiltrated twentieth-century thinking about society in a number of ways; from the erroneous idea that individual humans climb up the "evolutionary ladder" during development, which influenced Freud's view of infants as sexual creatures; to Marx's notions of human society progressing through various levels, punctuated occasionally by revolutions that take a society to a higher level. See Laland and Brown, *Sense and Nonsense: Evolutionary Perspectives on Human Behaviour,* 41–49.

12 Evolutionary trees do not provide evidence for evolution, but codify and present the data and analysis. Modern phylogentetic trees show scientists' understanding of genealogical descent. The tree in Figure 1 is based on the tree in Gary J. Olsen and Carl R. Woese, "Ribosornal Rna: A Key to Phylogeny," *FASEB Journal* 7 (1993).

replaced. As the following sections show, there has been significant refinement and elaboration of Darwinian evolutionary theory over the last century, both in terms of its application to technology[13] and in terms of the biological sciences themselves.

Evolutionary Thinking and Technological Change

The concepts of variation and selection are well established in the evolutionary economics tradition. In a challenge to equilibrium models of the economy, Schumpeter introduces a dynamic component into economic analysis by arguing that capitalism is a form or method of economic change that is never stationary.[14] Nelson and Winter draw on this Schumpeterian model of competition to develop an evolutionary theory of economics, which has become widely influential.[15]

Though this model uses the ideas of variation and selection, it is not strictly Darwinian in nature. Nelson and Winter describe themselves as unabashedly Lamarckian since their theory describes learning playing a role through the "inheritance" of acquired characteristics and appearance of variation under the stimulus of adversity.[16] According to them, the three basic concepts for an evolutionary theory of economic change are: first, the idea of an organizational routine; second, the idea of "search" to denote all those organizational activities associated with the evaluation of current routines, and which may lead to their modification or replacement; and, third, the idea of the "selection environment," which includes other firms in the market, the patent system, and other institutional configurations.[17]

Likewise, Freeman[18] describes the historical rise of science-related technology through developments in process innovations, synthetic materials, and then electronics. Influenced by Marxist views of technological progress, the dominant nature of different technologies at different junctures in history is explained using the metaphors of waves, paradigms, and trajectories; such as Kondratiev long-waves,[19] which are considered as long economic cycles that occur approximately every fifty years, techno-economic paradigms, and technological trajectories.[20] While, again, this work is not strictly evolutionary, the idea of technological trajectories and the related concepts of path dependence and lock-in[21] have a resonance with evolutionary theorizing.

Much modern work emphasizes the branching nature of technological change. From this perspective, the theory indicates that there will be branches, but cannot identify the ones that will be taken.[22] Variation is not random, but prestructured by regimes or paradigms. In addition to selection processes working on products, there are shifts in selection environments leading to the coevolution of technology, industry structure, and supporting institutions. In sociological and historical approaches, for example, attention is focused on the political processes underlying trajectories of change

13 Campbell, "Variation and Selection Retention in Socio-Cultural Evolution" in John Ziman, *Technological Innovation as an Evolutionary Process* (Cambridge: Cambridge University Press, 2000).

14 Joseph A. Schumpeter, *Capitalism, Socialism, and Democracy* (New York: Harper & Brothers, 1942).

15 Richard R. Nelson and Sidney Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Harvard University Press, 1982).

16 Ibid., 11.

17 Ibid., 400–1.

18 Christopher Freeman, *The Economics of Industrial Innovation*, 2nd ed. (London: Frances Pinter, Ltd., 1982).

19 Carlota Perez, "Structural Change and Assimilation of New Technologies in the Economic and Social Systems," *Futures* 15:4 (1983).

20 Giovanni Dosi, "Technological Paradigms and Technological Trajectories—A Suggested Interpretation of the Determinants and Directions of Technical Change," *Research Policy* 11:3 (1982).

21 Nathan Rosenberg, *Inside the Black Box* (Cambridge: Cambridge University Press, 1982).

22 Arie Rip, "Technological Innovation—in Context" (paper presented as the keynote at the International Network on Innovation Research Workshop, January 14, 2003).

23 Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs* (Cambridge, MA: MIT Press, 1995).

24 Ibid., 51–52.

25 Darwin, *On the Origin of Species*; Lamarck, *Zoological Philosophy: An Exposition with Regard to the Natural History of Animals*; and Richard Dawkins, *The Selfish Gene* (Oxford: Oxford University Press, 1976).

in modern objects. In developing an empirically based socio-technical theory of technological development, Bijker argues that trial-and-error models, often cast in evolutionary terms, have specific advantages over models that stress the goal-oriented character of technological development.[23] However, Bijker[24] highlights two problems associated with an evolutionary explanation of the empirical data: first, its complexity: such an evolutionary representation would need three layers, with variation and selection in terms of problems, solutions, and resulting artifacts; and, second, if this representation is not completely adequate, the almost inevitable assumption is that the artifact is a constant fixed entity—to be generated through the variation process and then ushered in through the selection process.

Contemporary Work on Biological, Human, and Cultural Evolution

When borrowing from evolutionary ideas, there is a tendency for authors in the design community to see biological evolution as a "closed" field of established theory. Design scholars habitually reference Darwin, Lamarck, and sometimes refer to the modern scholar Dawkins.[25] For practitioners in the field, however, there are a number of inherent debates and controversies, and there is an evolving knowledge-base. The discovery of genes and genetic bases for natural selection in the 1930s and 1940s served as an important spur to modern theorizing in biology. Thus, modern biological evolution tends to be concerned with genes, phenotypes, and populations;

Table 1:
Contemporary research traditions in human and cultural evolution

Human socio-biology	Builds on new evolutionary methods and ideas, including evolutionary game theory, kin selection, and reciprocal altruism. Kin selection is proposed to explain why individuals sometimes behave in ways that decrease their chances of surviving and reproducing and increase others' reproductive success. Reciprocal altruism suggests that altruistic behavior, which is initially costly to the actor but beneficial to the recipient, is selected if there is a high probability that the altruistic act would be reciprocated on a future occasion.
Human behavioral ecology	Uses mathematical models to compute the optimal human behavior in a given context on the assumption that this is what might have evolved. It then tests the model's predictions, primarily by studying traditional societies.
Evolutionary psychology	Interested in the evolved mechanisms that underlie human behavior and see modern human beings as creatures adapted to the environments of our stone-age ancestors. It looks at topics such as the evolution of memory, emotions, and reasoning. Critics argue, however, that what is known about our ancestors' way of life to make these analyses valid is insufficient.
Memetics	Builds on the idea of the meme. This describes aspects of our behavior and knowledge, such as particular skills, songs, ideas, and rituals that are transmitted between individuals through imitation and social learning.
Gene-culture co-evolution	Involves the development of models to explore the co-evolution of genes and culture. For example, it explains why Western people can drink milk without getting sick, while the majority of the world's adults cannot, by pointing to the co-evolution of dairy farming with genes for processing milk.

whereas Darwin is concerned mainly with organisms, speciation, and individuals.[26] Laland and Brown[27] analyze contemporary evolutionary theories in human and cultural evolution: their taxonomy and analysis is summarized in Table 1.

Although it is useful to characterize these traditions for purposes of analysis, the reality is more complex, and these traditions are not autonomous.[28] Human sociobiology, in some ways, is a forerunner of the other schools. It has, at its heart, the idea of reciprocal altruism, described by a number of eminent evolutionists as one of the most important, or the most important, idea in evolutionary theory.[29] Following the development of human socio-biology, human behavioral ecology and evolutionary psychology focus primarily on the dynamics of human behavior. Culture plays a larger role in work in memetics and gene-culture coevolution. The term "niche construction" is used to describe the activities, choices, and metabolic processes of organisms through which they define, choose, modify, and partially create their own niches in another important extension to the variation-selection model of evolution.[30]

Comparing Theories of Cultural and Technological Evolution

There are similarities between the development and contemporary theories of human and cultural evolution, and technological evolution. Similarities in thinking relate to the transmission mechanism between generations, and the relationship, or coevolution, with the environment.

There is, for example, a similarity between the concept of "memes," which Dawkins sees as operating by infecting individual minds, and "routines," which are used by organizations to encode and reuse their knowledge. Researchers of technological change use both concepts; while, in the growing literature on evolutionary theories in design, the former has a privileged place.[31] Memes are seen to be infectious, while routines are seen as one of the core capabilities of a firm, and a means of internal replication of knowledge rather than its external transmission.

In studying modern technologies, it has been argued that it is difficult to justify the assumption that a selection environment is truly independent of a particular technological trajectory.[32] Some scholars, therefore, see the evolutionary analogy as being rather limited. However, there is a growing emphasis on coevolution in both biological sciences, through the work on gene culture coevolution; and in studies of technology and organizations. For example, French Impressionists were successful in radically altering the type of art seen as high quality. Changes to the selection environment, from one based on assessment by established academic artists to one based on assessment by independent critics, have been used to explain this.[33] Niche construction is used to explore ways of intervening to create the alternative technological trajectories required for achieving environmental sustainability.[34]

26 Douglas J. Futuyma, *Evolutionary Biology* (Sunderland, MA: Sinauer Associates, 1986).

27 Kevin N. Laland and Gillian R. Brown, *Sense and Nonsense: Evolutionary Perspectives on Human Behaviour* (Oxford: Oxford University Press, 2002). The table and the following paragraph are largely based on this work.

28 Ibid., 88.

29 Ibid., 77.

30 Kevin N. Laland, John Odling-Smee, and Marcus W. Feldman, "Niche Construction, Biological Evolution, and Cultural Change," *Behavioral and Brain Sciences* 23:1 (2000).

31 For memes in the technology literature, see Joel Mokyr, "Evolutionary Phenomena in Technological Change" in *Technological Innovation as an Evolutionary Process,* John Ziman, ed. (Cambridge: Cambridge University Press, 2000). In the design literature, see Artemis Yagou, "Rewiring Design History from an Evolutionary Perspective: Background and Implications" (paper presented at the European Academy of Design, Bremen, 2005); and John Z. Langrish, "Evolutionary Design Ten Years On: Memes and Natural Selection" (paper presented at the European Academy of Design 06, Bremen, 2005).

32 Henk van den Belt and Arie Rip, "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry" in *The Social Construction of Technological Systems,* Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, eds. (Cambridge, MA: The MIT Press, 1987), 140–41.

33 Nachoem M. Wijnberg and Gerda Gemser, "Adding Value to Innovation: Impressionism and the Transformation of the Selection System in Visual Arts," *Organization Science* 11:3 (2000).

34 Arie Rip, "Technological Innovation—in Context" (paper presented as the keynote at the International Network on Innovation Research Workshop, January 14, 2003).

However, an interesting difference between these traditions is the way that they deal with industrialization and complex technological systems. Work on human and cultural evolution has tended to look at non-Westernized or prehistoric societies. In evolutionary economics and the sociology of science traditions, evolutionary thinking is used to describe post-industrial societies, and some attempts have been made to apply it to complex technological systems.

Application and Limitations of Evolutionary Theories

Do evolutionary theories fit with the empirical evidence of design practices? Are they useful in explaining design practices? What are the limits of their applicability? Empirical research on real-world design practices is greatly improving our understanding of design in a range of disciplines and settings, and is raising new challenges. Research is being conducted using protocol analysis, interviews with designers, and historical and ethnographic studies of commercial design practice.[35] This research is raising important questions regarding the nature of design practices at different levels of analysis, within a design project, and across a wider family of related design projects.

Evolutionary theories offer a range of new tools for understanding design; however, even their strongest advocates of evolution identify some limitations and objections. One objection relates to the unit of analysis:

> Virtually all the fundamental principles of biological evolution have proved troublesome when applied to technology. It is not at all clear what evolves .... It is not clear whether, or on what grounds, "selection" might be said to occur, or at what level.[36]

Concepts such as memes and routines have been criticized as evolutionary storytelling, because they are difficult concepts to "operationalize" in research, and related theories have not led to systematic empirical testing.

Another objection is to the assumption that technology is a fixed entity in the variation and selection process.[37] A further limitation, which was raised by Darwin, relates to the population size required for evolutionary phenomena to be a good explanation. Campbell describes this:

> There is bound to be a lot of the purely fortuitous or non-transferably specific in the life or death of a single biological individual or culture item. For a systematic selective criterion to make itself felt above this "noise level," there must be numerous instances involved, and a high mortality rate. Thus we would be more apt to expect effective selection criteria for neighborhood laundry organizations than for national organizational forms.[38]

35 For examples of research using protocol analysis, see Nigel Cross, Henri Christiaans, and Kees Dorst, eds., *Analysing Design Activity* (Chichester, UK: John Wiley & Sons, 1996). For interviews, see Michael Brawne, *Architectural Thought: The Design Process and the Expectant Eye* (Oxford, UK: Architectural Press, 2003); Bryan R. Lawson, *How Designers Think,* 3rd ed. (Oxford, UK: Architectural Press, 1997); and, for ethnographic studies, see Diane Bailey and Julie Gainsburg, "Knowledge at Work" (paper presented at the Academy of Management, New Orleans, 2004); Louis L. Bucciarelli, *Designing Engineers*; *Inside Technology,* Wiebe E. Bijker, W. Bernard Carlson, and Trevor Pinch, eds. (Cambridge, MA: MIT Press, 1994); Kathryn Henderson, *On Line and on Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering*; and *Inside Technology,* Wiebe E. Bijker, W. Bernard Carlson, and Trevor Pinch, eds. (Cambridge, MA: MIT Press, 1999).

36 Edward Constant, II, "Recursive Practice and the Evolution of Technological Knowledge" in *Technological Innovation as an Evolutionary Process,* John Ziman, ed. (Cambridge: Cambridge University Press, 2000), 219.

37 Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs* (Cambridge, MA: MIT Press, 1995).

38 Campbell, "Variation and Selection Retention in Socio-Cultural Evolution" in John Ziman, *Technological Innovation as an Evolutionary Process* (Cambridge: Cambridge University Press, 2000).

This suggests that there has to be a certain size of population for evolutionary explanations to provide adequate purchase on empirical situations.

Within a project, the observed activities of designers have been characterized as showing a reflective conversation with materials through the medium of a drawing.[39] There is evidence that experts use more effective design strategies than novices do.[40] Small numbers of individual options are considered, and designs are refined and changed over the lifetime of the process. Though there is considerable research on evolutionary design by computers,[41] this model of design is not found to resemble the messy practices of human designers.[42] At this level of analysis, I have found little to suggest that an evolutionary approach will shed light on empirical phenomena.

In a number of separate, but related, products, evolutionary phenomena have been noted across a range of sectors and product types.[43] To describe all the members of a particular technological trajectory, Gardiner introduces the idea of the design family,[44] using it to describe the range of automotive and airplane designs that have a common configuration; but which are variations tailored to specific markets. Evolutionary theories appear to describe phenomena across these families, and may be useful in addressing a number of questions. I suggest that the visualization of a design family provides a useful way of interrogating the historical development of existing technologies.

However, just as in modern biology different trees of life can be drawn by considering different genes, I suggest that different design families can be postulated based on different underlying ideas. The analysis of a portfolio of complex designs, such as those for architectural buildings, would propose different causal links in relation to the development of sustainable development, roof designs, etc.

Conclusions and Implications

Evolutionary theories may be used to challenge and extend our understanding of design practices in a number of ways. For example, by drawing attention to the way that the designer operates within a selection environment, an evolutionary perspective draws attention to the way the intentionality of the designer is, to some extent, contingent on this environment. Laland and Brown[45] describe one of the benefits of evolutionary theory as its ability to generate empirically testable hypotheses. However, we need to take great care to ensure that theoretical mechanisms for evolution are actually encountered in practice. There is a danger of conflating observed phenomena, which operate at different levels of analysis.

I argue that variation and selection are misleading when applied to design practice within particular projects. It is not clear what varies and what is selected, whether it is knowledge, designs,

39 Donald A. Schön and Glenn Wiggins, "Kinds of Seeing and Their Functions in Designing," *Design Studies* 13:2 (1982).

40 Manolya Kavakli and John Gero, "Difference between Expert and Novice Designers: An Experimental Study" in *Human Behaviour in Design: Individuals, Teams, Tools,* Udo Lindemann, ed. (Belin: Springer, 2003).

41 Jun H. Jo and John Gero, "Representation and Use of Design Knowledge in Evolutionary Design" (paper presented at the CAAD Futures), *The Global Design Studio: Proceedings of the Sixth International Conference on Computer-Aided Architectural Design Futures* (National University of Singapore, Singapore, September 24–26, 1995).

42 Henrik Gedenryd, *How Designers Work* (Lund, Sweden: Lund University Cognitive Studies, 1998).

43 Vincenti, *What Engineers Know and How They Know It,* and Petroski, *The Evolution of Useful Things: How Everyday Artifacts—from Forks and Pins to Paper Clips and Zippers—Came to Be as They Are.*

44 Paul Gardiner and Roy Rothwell, "Tough Customers: Good Designs," *Design Studies* 6:1 (1985), and Gardiner, "Robust and Lean Designs."

45 Laland and Brown, *Sense and Nonsense: Evolutionary Perspectives on Human Behaviour.*

sub-assemblies, or other contenders. The practices of expert designers are not easily explained through processes for creating surplus variation; creating competition between variants, and then selecting the most appropriate. Thus, I argue that variation and selection provide a useful theoretical lens for understanding longer-term changes across design families. Design families exhibit variation, competition between variants, inheritance of features, and the accumulation of successive cultural modifications over time. In many instances, there is a reasonable sample size to analyze. However, evolutionary phenomena are more easily traced in preindustrial societies and in industries such as machinery, than in the development of complex products such as buildings or infrastructure.

There is ongoing debate about whether technological evolution is Darwinian or Lamarckian in nature,[46] and learning has been proposed in a number of evolutionary understandings of technology. However, the literature reviewed in this paper points to a number of significant developments in evolutionary theories. Just as understanding the natural is changing through the discovery of genes and the development of concepts of kin selection and niche construction, understanding the artificial is changing through ideas such as path dependence, technological trajectory, and design families.

Evolutionary theories could be used in further research that seeks to understand the mechanisms through which innovative products are developed across a design family. More research is needed on the applicability and limitations of evolutionary theories for understanding design families in complex system industries.

46 Ziman, *Technological Innovation as an Evolutionary Process.*