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Biologically Inspired Design: A New Program for Computational Sustainability

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Computational sustainability—the use of computing to address problems of environmental sustainability—is emerging as a major theme in AI research. For example, since 2011 the Association for the Advancement of Artificial Intelligence (AAAI) has organized a special track on computational sustainability as part of its annual National Conference on AI. Thus far, most research on computational sustainability has focused on monitoring, modeling, analysis, and optimization of existing systems. I propose another exciting and promising AI research program on computational sustainability that emphasizes the design of new systems and processes, and, in particular, biologically inspired design.

Natural Designs

Biologically inspired design (also known as biomimicry, biomimetics, or bioinspiration) is a growing movement in modern design that espouses the use of nature as a source of analogies for designing technological products, processes, and systems.[1–3] This paradigm has inspired many designers in the history of design, such as Leonardo da Vinci, the Wright brothers, and so on. However, over the last generation or so, the paradigm has become a movement,[4–8] pulled in part by the growing need for environmentally sustainable development, and pushed partly by the rapid advances in biology and the desire for creativity and innovation in design.

The design of windmill turbine blades imitating the design of tubercles on the pectoral flippers of humpback whales is one example of biologically inspired design.[9] As Figure 1a illustrates, tubercles are large bumps on the leading edges of humpback whale flippers that create even, fast-moving channels of water flowing over them. These tubercles enable whales to move through the water at sharper angles and turn tighter corners than if their flippers were smooth. When applied to wind turbine blades, they improve lift and reduce drag, improving the turbine's energy efficiency. Another example is the design of the nose of the Shinkansen bullet train, which mimics the kingfisher's beak (see Figure 1b); this design lets the train travel at higher speeds with lower levels of noise.[10]

New Design Problems, Novel Biological Perspectives

Although biologically inspired design is rapidly growing as a design movement, its practice remains largely ad hoc, with little systematization of the design processes or of biological knowledge from a design perspective. To make these abstract points tangible, let's briefly consider a couple of design scenarios. Imagine that you're an architect designing a high-rise building. You need to find a mechanism for lifting water from the bottom of the building to its top. You might use current designs of electromechanical systems that can pump water thousands of feet of high. However, these systems consume large amounts of energy. One possibility is to monitor, model, analyze, and optimize these water-pumping systems so that they work and are used more efficiently. This kind of design optimization sometimes can result in significant savings in critical resources such as energy and water. Another possibility is to think about this problem in terms of the efficient—and thus, in the long run, more sustainable—mechanism of *transpiration* that redwood trees use to lift water thousands of feet

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high. Of course, this would require inventing new materials that can support transpiration at the scale of a high-rise building. But this is part of the point: biologically inspired design encourages designers to view traditional problems from novel perspectives. As this example illustrates, biological analogues could also help designers spawn new problem spaces, which might lead to the invention of new technologies.

Our in situ observations of biologically inspired design in practice have indicated the use of twin design processes, problem-driven and solution-based design,[11] both entailing multiple or compound analogies.[12] Figure 2 illustrates a simplified version of the general process of problem-driven preliminary design. As the figure shows, biological analogies are useful for several tasks of preliminary design including concept generation, design analysis, redesign, and problem reformulation.[13]

Now consider a second and bigger design problem. Water is a scarce resource in many parts of the world. Desalination of ocean water offers an obvious solution to the problem of water scarcity. However, current technologies for water desalination are inefficient and costly. Yet, if we search for "water desalination" on the Web, then although we get a few million hits, all the millions of hits appear to refer to current technologies. This is a missed opportunity, because there are a large number of biological organisms that perform water desalination quite efficiently—for example, some kinds of desert plants, snails, and mice. Nature provides the world's largest library of sustainable designs. So why not build a new generation of search engines that enable access to nature's design library? Why not reuse patterns of designs that nature already has discovered over billions of years?

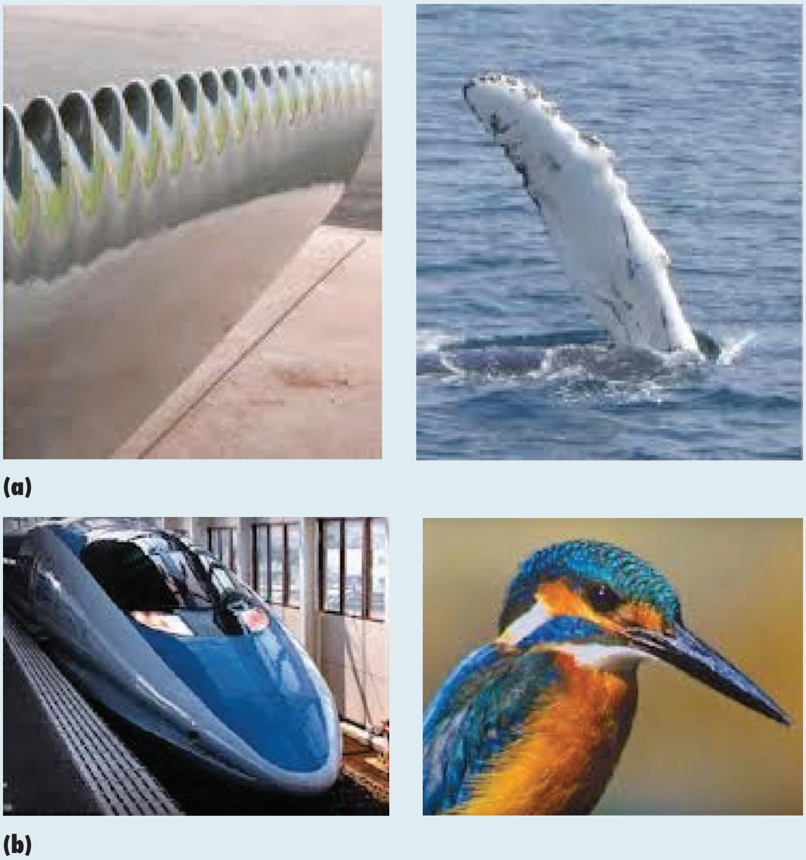

Figure 1. Examples of biologically inspired design. (a) Design of the windmill turbine blades to increase efficiency, inspired by the tubercles on humpback whale flippers. (b) Design of the Shinkansen 500 bullet train's nose to decrease noise, inspired by the kingfisher's beak.

What Can AI Offer to Biologically Inspired Design?

These example scenarios raise a myriad of questions that are fundamentally AI issues. For example, what knowledge representation language do we need to capture knowledge of billions of biological systems in a manner that's meaningful to designers? How might we use the collective intelligence of tens or hundreds of thousands of biologists across the world to construct a knowledge base of biological designs? How might we support designers in deeply understanding the working of biological designs? What learning techniques might help in abstracting useful design patterns and principles from the billions of biological designs? How might we automatically access the right set of design cases and design patterns at the right time in the design process? How might we support human designers in viewing old problems from new perspectives? How might we support them in transferring biological knowledge to their design problems? How might we support them in evaluating new designs for sustainability? How might we help human designers in using biological knowledge to identify novel design opportunities that they might not think of otherwise?

In recent years, computational research on biologically inspired design has started to explore some of these questions. As I mentioned, Figure 2

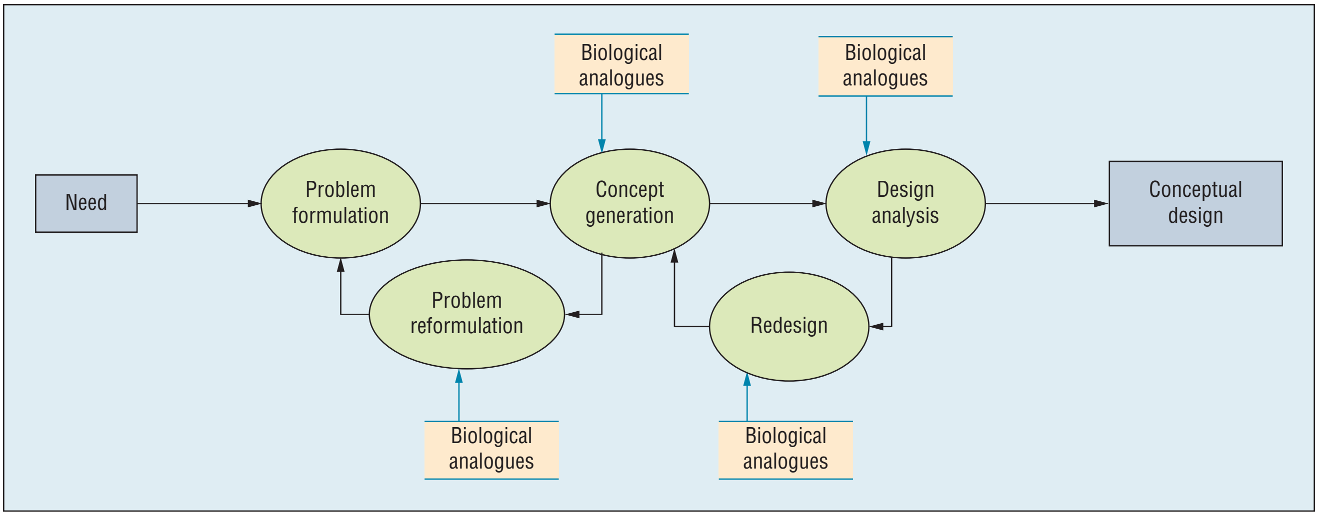

Figure 2. A data-flow diagram for a simplified version of the general process of preliminary design: ovals depict functions, rectangles depict inputs and outputs, and parallel horizontal lines denote data sources. The process starts with a need and results in one or more conceptual designs. It consists of the functions of problem formulation, concept generation, and design analysis. Generation of a design concept might lead to problem reformulation and design analysis might lead to redesign. As indicated by the data sources in blue, biological analogues are useful for several functions in biologically inspired design, including concept generation, design analysis, redesign, and problem reformulation.

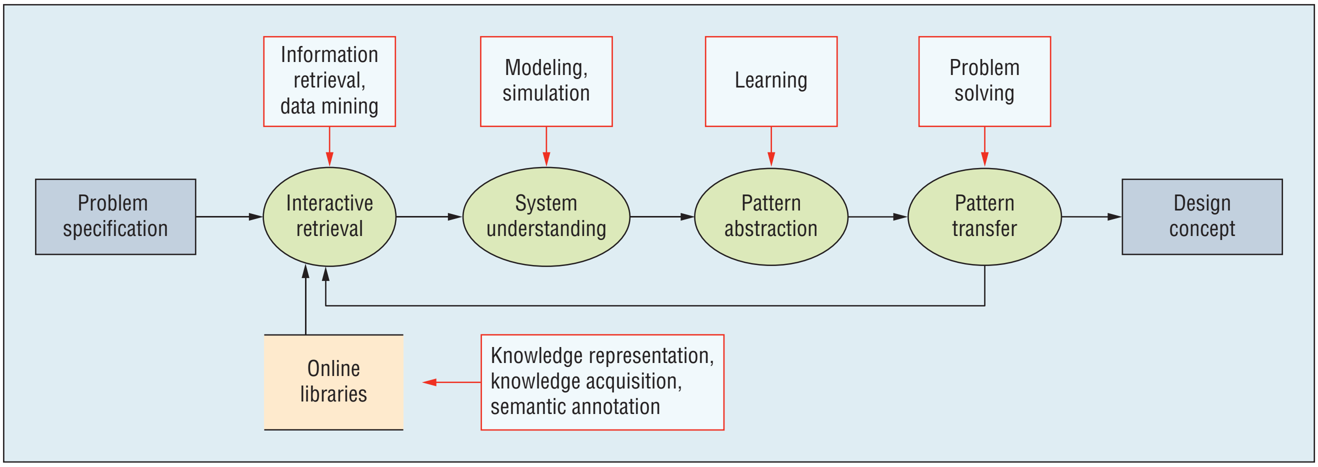

Figure 3. A data-flow diagram of the process of problem-driven analogical concept generation in biologically inspired design. The process consists of interactive retrieval of biological analogues online, understanding the biological systems, abstracting design patterns, and transferring the patterns to the given design problem. The design process is iterative. The red boxes indicate the fundamental roles that AI can play in systematizing the design process, as well as biological knowledge from a design perspective.

illustrates the general process of problem-driven preliminary biologically inspired design including concept generation. Figure 3 illustrates the general process of problem-driven concept generation in biologically inspired design.[14] Figure 3 also indicates some of the fundamental roles AI can play in systematizing the design process, as well as biological knowledge from a design perspective.

Computational research is also developing techniques and tools for supporting the practice of biologically inspired design.[15] AskNature provides interactive access to a functionally indexed digital library of articles describing biological systems.[16] Idea-Inspire[17] and the Design by Analogy to Nature Engine (DANE; http://dilab.cc.gatech.edu/dane)[18] provide interactive access to digital libraries of functional models of biological and technological systems. Jacquelyn Nagle and her colleagues[19] propose a functional approach to concept generation in biologically inspired design, and Bryan

Wiltgen and his colleagues[20] present a learning technique for automatic organization of digital libraries of biological designs into functional and structural discrimination networks. Ivey Chiu and L.H. Shu[21] describe a natural language technique for accessing biology articles online, and Swaroop Vattam and I[22] describe Biologue, a search engine for finding biology articles describing cross-domain analogies on the Web. In current research, we're also exploring formulation and specification of design problems,[23] and abstraction of design patterns in biological systems for transfer to engineering problems.[24]

Note that although the examples in this article—blades of windmill turbines and noses of bullet trains—have been about product designs at spatial and temporal scales visible to the naked human eye, the scope of biologically inspired design is much larger. Thus, biologically inspired products could cover many spatial scales ranging from nanometers (such as biomolecules) to hundreds of kilometers (such as ecosystems), as well as many temporal scales ranging from nanoseconds to centuries. Furthermore, the methodology of biologically inspired design potentially is useful not only for designing engineering products and materials, but for almost all design domains—ranging from built environments to sociotechnical systems, processes, and policies.

Of course, not all biologically inspired design is motivated by environmental sustainability (for example, the design of prosthetic devices). Within AI, the motivation for design of robots, artificial neural networks, and artificial genetic algorithms is to better understand animal intelligence and build intelligent machines. Systematization of the processes of biologically inspired design and of biological knowledge from a design perspective would facilitate design of many kinds of biologically inspired systems and processes, including biologically inspired robots.[25] Even when motivated by environmental sustainability, not all biologically inspired design will lead to sustainable technologies at scales useful for humans. Further, even with biologically inspired sustainable designs, there will be a need for monitoring, analysis, and optimization of the designs for sustainability. Nevertheless, if future biologically inspired systems are more sustainable than the systems in the market today, biologically inspired design would represent a win over current design paradigms.

Biologically inspired design provides a promising paradigm to help address the increasingly critical and urgent problem of environmental sustainability. This paradigm presents a challenge to apply existing AI methods and develop new techniques for a range of issues of longstanding interest to AI, such as design, analogy, creativity, knowledge representation, knowledge acquisition, information retrieval, memory, learning, and problem solving. AI thus has an opportunity not only to expand the scope of computational sustainability, but also, more importantly, to help make biologically inspired design a scientific discipline.

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