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Biologically Inspired Design: A New Paradigm for AI Research on Computational Sustainability?

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Abstract

Much AI research on computational sustainability has focused on monitoring, modeling, analysis, and optimization of existing systems and processes. In this article, we present another exciting and promising paradigm for AI research on computational sustainability that emphasizes design of new systems and processes, and, in particular, on biologically inspired design. We first characterize biologically inspired design, then examine its relationship with environmental sustainability, next present a computational model of the process of biologically inspired design, and finally describe a few computational systems for supporting biologically inspired design practice.

Biologically Inspired Design

Biologically inspired design (also known as biomimicry, biomimetics and bionics) is a growing movement in modern design that espouses the use of nature as an analogue for designing technological systems and as a standard for evaluating technological designs (French 1994; Gleich et. al. 2010; Turner 2007; Vincent & Mann 2002; Vogel 2000). This paradigm has inspired many designers in the history of design, such as Leonardo da Vinci, the Wright brothers, etc. However, it is only over the last generation that the paradigm has become a movement, pulled in part by the growing need for environmentally sustainable development and pushed partly by the desire for creativity and innovation in design. The Biomimicry 3.8 Institute (2011) provides numerous examples of biologically inspired design. The design of windmill turbine blades mimicking the design of tubercles on the pectoral flippers of humpback whales is one example of biologically inspired design. As Figure 1 illustrates, tubercles are large bumps on the leading edges of humpback whale flippers that create even, fast-moving channels of water flowing over them. The whales thus can move through the water at sharper angles and turn tighter corners than if their flippers were smooth (Fish et al 2011). When applied to wind turbine blades, they improve lift and reduce drag, improving the energy efficiency of the turbine. The field of biologically inspired design is characterized by a rapidly growing literature, including both patents (Bonser & Vincent 2007) and publications (Lepora et al. 2013).

Figure 1: Design of windmill turbine blades to increase efficiency inspired by the tubercles on humpback whale flippers. (Biomimicry 3.8 Institute 2011)

Note that although our examples in this article – flippers of humpback whales and blades of windmill turbines – are 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 may cover many spatial scales ranging from nanometers (e.g., biomolecules) to hundreds of kilometers (e.g., ecosystems), as well as many temporal scales ranging from nanoseconds to centuries (Benyus 1997). Further, 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 socio-technical systems, processes, and policies.

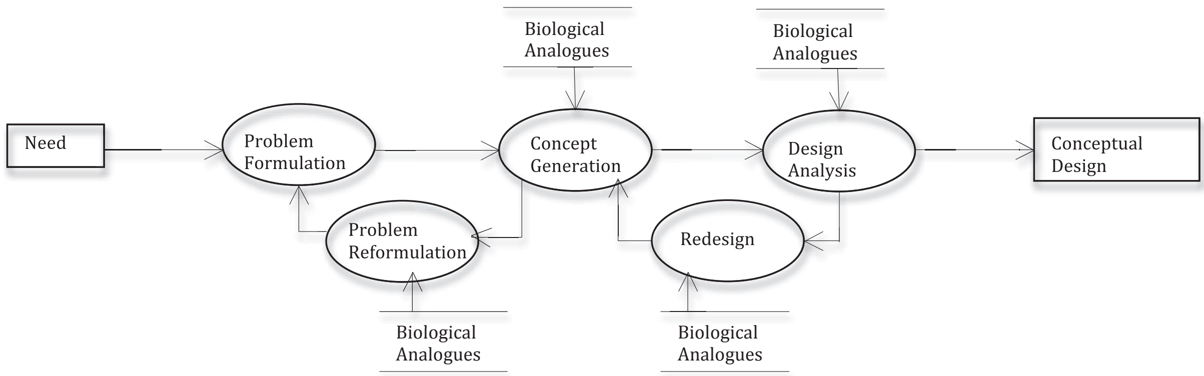

Figure 2: A data flow diagram for a simplified version of the general process of preliminary design: ovals depict functions, rectangles depict inputs and outputs, and parallel horizontal lines denote data sources. The process starts with a need and results in one or more conceptual designs. It consists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

Biologically Inspired Design and Environmental Sustainability

Environmentally sustainable design refers to the design of products, materials, processes and services in accordance with the principles of biological diversity, ecological integrity, and environmental responsibility (Ehrenfeld 2008). According to many leading proponents of the biologically inspired design paradigm, for example Benyus (1997), environmental sustainability is, or should be, the driving force of the movement. Thus, environmentally sustainable design is one of the fundamental organizing principles of Biomimicry 3.8's educational programs and courses on biologically inspired design. Georgia Tech's Center for Biologically Inspired Design's too has used sustainable design as a primary goal in some offerings of its ME/ISyE/MSE/PTFe/BIOL 4740 course on biologically inspired design. Course (Yen et al. 2011). Even in years when sustainability was not an explicit goal of the ME/ISyE/MSE/PTFe/BIOL 4740 course, as a whole sustainability nevertheless was a major factor in about a third of the design projects, and an explicit design goal in about a fourth (Goel et al. 2014). Thus, there is a *prima facie* relation between biologically inspired design and environmental sustainability.

Computational Model of the Biologically Inspired Design Process

In addition to examining the design projects in Georgia Tech' ME/ISyE/MSE/PTFe/BIOL 4740 class from 2006-2012, we also observed the teaching, learning, and designing in the class. Several graduate students from our research laboratory took the course for credit in different years, attended the classes, participated in the design projects, and collected all the class materials. Our *in situ* observations of biologically inspired design in practice have indicated the use of multiple processes, including problem-driven design and solution-based design (Helms, Vattam & Goel 2009) entailing multiple or compound analogies (Vattam, Helms & Goel 2008). Figure 2 illustrates a simplified version of the general process of problem-driven preliminary design. As illustrated in Figure 2, biological analogies are useful in several tasks of preliminary design, including concept generation, design analysis, redesign, and problem reformulation (Vattam, Helms & Goel 2010).

Goel & Bhatta (2004) described a general process for cross-domain analogical design. Figure 3 illustrates a simplified version of the general process of problem-driven analogy-based concept generation in biologically inspired design. 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.

In particular, Figure 3 raises a myriad of questions for AI: What knowledge representation language do we need to capture knowledge of billions of biological systems in a manner that is meaningful to designers? How may 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 may 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 may we automatically access the right set of design cases and design patterns at the right time in the design process? How may we support human designers in viewing old problems from new perspectives?

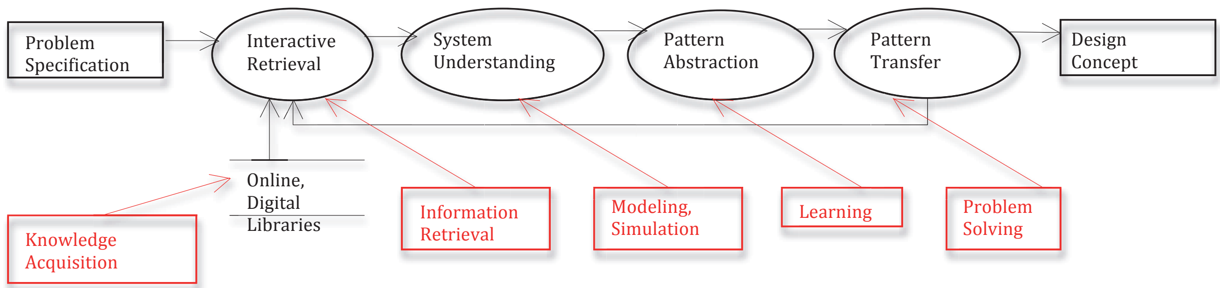

Figure 3: A data flow diagram of the process of problem-driven concept generation in biologically inspired design. The process consists of interactive retrieval of biological analogues online, understanding the biological systems, abstracting design patterns, and transferring the patterns to the given design problem. The design process is iterative. The red boxes denote some of the roles AI can play in systematizing the design process and the biological knowledge.

How may we support them in transferring biological knowledge to their design problems? How may we support them in evaluating new designs for sustainability? How may we help human designers in using biological knowledge to identify novel design opportunities that they might not think of otherwise?

Computational Techniques and Tools for Biologically Inspired Design

In recent years, research on biologically inspired has started to explore some of these questions (Goel, McAdams & Stone 2014). To illustrate some of the computational techniques and tools, let us consider a couple of design scenarios. Imagine that you are 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. Now 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, and thus we should pursue it. Another possibility, however, 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 high. Of course this would require invention of 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 new perspectives.

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" in, say, Google, 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, e.g., some kinds of desert plants, snails and mice. Nature provides the world's largest library of sustainable designs for many design problems. Thus, we want to build digital libraries of nature's design as well as design a new generation of search engines that enable access to nature's designs online.

To help designers address scenarios such as the two described above, AskNature provides interactive access to a functionally indexed digital library of high-level design strategies (Deldin & Schuknecht 2014; Biomimicry 3.8 Institute 2008; http://www.asknature.org/). Idea-Inspire (Chakrabarti et al. 2005) and DANE (Goel et al. 2012; http://dilab.cc.gatech.edu/dane/) provide interactive access to digital libraries of functional models of biological and technological systems. Shu (2010) describes a natural language technique for accessing biology articles relevant to a design problem from a database. Nagle (2014) presents an engineering-to-biology thesaurus for mapping functions in engineering to functions in biology. Vattam & Goel (2013) describe Biologue that is both an interactive tool for collaborative semantic annotation of biology articles and a search engine for semantically annotated biology articles relevant to a design problem from a knowledgebase as illustrated in Figure 4. DSL is a digital library of the 78 case studies we described earlier (Goel et a. 2014).

Conclusions

As our analysis of teaching and learning of biologically inspired design indicated, much of biologically inspired design is motivated by environmental sustainability. A new case study of biological inspired design that led to an

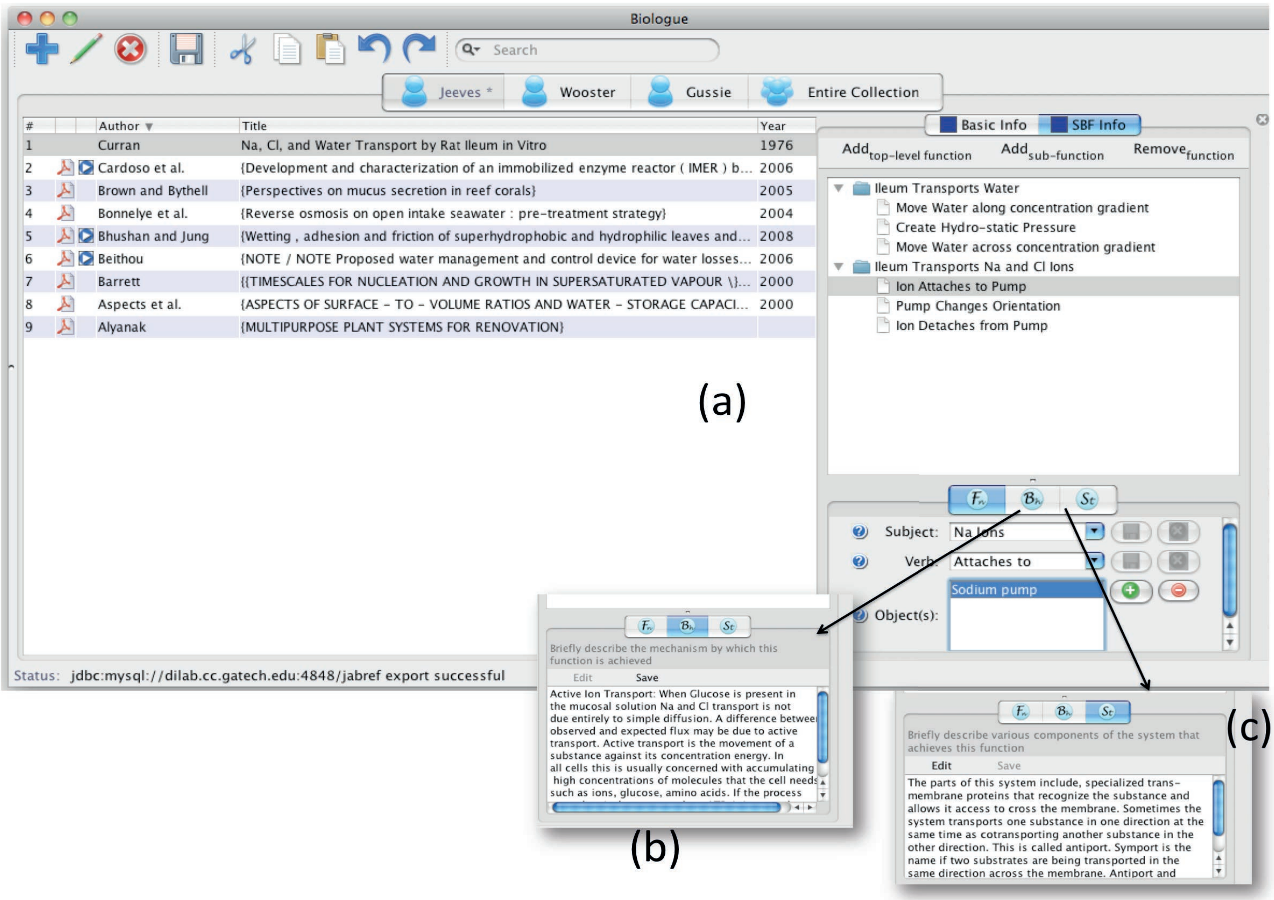

Figure 4: A screenshot from Biologue (Vattam & Goel 2013). The main window, (a), shows a listing of biology articles in a database. The two side windows, (b) and (c), illustrate the semantic annotations on a biology articles that express the function and the causal process of the biological system described in the article, respectively. Biologue uses the semantic annotations to access biology articles relevant to a design problem.

environmentally sustainable system for water harvesting (Weiler & Goel 2015) appears to confirm this analysis. Thus, there is a strong case for biologically inspired design as a paradigm to help address the increasingly critical and urgent problem of environmental sustainability.

As our analysis of biologically inspired design processes indicates, biologically inspired design presents a challenge to develop new techniques for a range of issues of longstanding interest to AI, such as knowledge representation, knowledge acquisition, memory, learning, problem solving, design, analogy, creativity. On one hand, systemization of the processes of biologically inspired design and of biological knowledge from a computational perspective would facilitate design of many kinds of biologically inspired products, systems and processes. On the other, biologically inspired design provides an opportunity to expand the scope of AI research on computational sustainability. It provides both a new avenue for exploring the use of AI techniques and a source for new AI problems.

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