Design Patterns and Cross-Domain Analogies in Biologically Inspired Sustainable Design

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Abstract

Sustainable design is as an important movement in design. Biologically inspired design is a major paradigm for sustainable design. In this paper, we analyze a corpus of biologically inspired design projects in terms of sustainability. We then describe a case study of analogical design of a fog harvesting net, and abstract from it the patterns of Hydrophobia and Hydrophilia. We indicate how these two function-mechanism design patterns occur in several design projects in our corpus. This analysis indicates how biologically inspired sustainable design can be analyzed in terms of cross-domain analogical transfer of design patterns.

Introduction

Sustainable design, sometimes also known as environmental design or ecological design, is as an important, widespread and growing movement in design. Biologically inspired design, sometimes also called biomimicry or bionics, is a major paradigm for sustainable design. A big challenge in biologically inspired sustainable design is how to transform a promising paradigm into a principled methodology. We believe that investigating biologically inspired sustainable design from the perspective of AI will help us address this challenge.

Studying biologically inspired design from the viewpoint of knowledge-based AI provides opportunities to better understand design in terms of knowledge representations and information processes that can be modeled and implemented in computational systems. This also provides opportunities to understand cognition in interdisciplinary design, including memory, learning, communication and collaboration.

Our investigations thus far have led to an information-processing account of biologically inspired design that entails compound cross-domain analogies (Helms, Vattam & Goel 2009; Vattam, Helms & Goel 2010). Earlier work on cross-domain analogies suggests that design patterns are one of the fundamental units of analogical transfer between the target problem and the source analogue (Bhatta & Goel 1997; Goel & Bhatta 2004). Thus, we posit that design patterns may be a useful unit of analysis for understanding biologically inspired sustainable design.

Alexander (1964) analyzed architectural design in terms of design patterns, and later developed pattern languages to codify architectural design patterns (Alexander, Ishikawa, Silverstein 1977). The notion of design patterns and pattern languages has had substantial impact on software design (e.g., Gamma et al. 1995). We see two kinds of benefits to developing design patterns for biologically inspired sustainable design. Firstly, a set of standard patterns can enable systematization to the practice of sustainable design. It gives designers a shared language with which to both communicate and analyze each other's designs, as well as the ability to design conceptually without being burdened by implementation level details. A collection of well-documented patterns also allows designers to better reuse design ideas. The "patterns from nature" project on identifying design patterns based on the principles of ecosystems has a similar goal (Hoeller et al. 2007). Secondly, computational systems capable of generating designs using design patterns can potentially apply the patterns of biologically inspired design to augment current practice of sustainable design practices. AI methods can then partner human designers through mixed-initiative strategies.

A major portion of the rest of this paper is dedicated to the discussion about design patterns in the context of sustainable design, and to illustrating how such patterns can be derived from specific case studies of biologically inspired sustainable designs.

Background

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 (Anastas & Warner 2000; Birkeland 2002; Ehrenfeld 2008; McDonough & Braungart 1992; Papanek 1984; Van der Ryn & Cowan 1996; Wann 1990). Design for reuse and design for recycling have long been a part of product lifecycle management (Fiksel 1996; McDonough & Braungart 1992; Pahl & Beitz 1996), and their importance likely will increase with time. However, sustainable design goes much further than design for reuse or recycling: sustainable design engages a new set of economic, social, and cultural values such as use of local resources, water conservation, energy efficiency, and minimal carbon emissions. By bringing new design requirements and constraints into the design problem statement, sustainable design changes the nature of the design problem itself.

Biologically inspired design espouses the use of biological analogues to address technological problems (Bar-Cohen 2006, Benyus 1997; Collins & Brebbia 2004; French 1998; Bonser & Vincent 2007; Vincent & Mann 2002; Vogel 2000; Yen & Weissburg 2007). While biologically inspired design strongly aligns itself with sustainable design, it is also understood that not all biologically inspired design leads to sustainable design (Reap, Baumeister & Bras 2005; Vincent et al. 2006). Compared to technological designs, biological designs typically are robust, efficient, multifunctional, and adaptable. Further, while human technology tends to use energy to address many design problems, biological systems often rely on information for the same functions (Vincent et al. 2006). Biological designs also tend to use a limited set of locally available materials, avoiding scarce, toxic, or exotic materials. The Biomimicry Institute's web portal called AskNature (http://www.asknature.org/) and Georgia Tech's Center for Biologically Inspired Design (CBID) (http://www.cbid.gatech.edu/) provide many examples of biologically inspired sustainable design.

Recently there have been several attempts at systemizing biologically inspired design as a general methodology for innovative design. Vincent et al. 2006, for example, describe BioTRIZ, an effort to apply TRIZ's (Altshuller 1984) inventive principles to biologically inspired design. Another set of efforts describes cognitive studies of biologically inspired design (e.g., Helms, Vattam & Goel 2009; Linsey, Wood & Markman 2008; Mak & Shu 2008; Vattam, Helms & Goel 2010). A third set of attempts at systemizing biologically inspired design describe knowledge-based interactive systems for capturing, organizing, accessing, and presenting knowledge of biological systems (e.g., Chakrabarti et al. 2005, Chiu & Shu 2007, Nagel et al. 2008, Nagel et al. 2010, Sarkar & Chakrabarti 2008, Sartori, Pal & Chakrabarti 2010, Shu 2010, Vattam et al. 2010).

In this paper, we adopt a different stance towards biologically inspired design. Firstly, while most of earlier work mentioned above has been motivated by the goals of understanding and supporting innovative design, this work is driven by the need to understand sustainable design. Secondly, while earlier work has focused on representing and accessing designs of specific biological systems, we posit design patterns as a fundamental unit of analogical transfer from biological systems to technological problems.

A design pattern is an abstraction of design solutions for a class of design problems (Alexander, Ishikawa & Silverstein 1977). A design pattern typically consists of three parts: a pattern name or label, a design problem, and an abstract design solution that specifies some arrangement of relationships among some objects or features to address the problem. For example, a design pattern in architecture may capture the spatial arrangement of columns to achieve a specific structural goal in a particular context. An actual design may instantiate one or more design patterns, and thus is a design instance. In this paper, we focus on design patterns in which the design goal pertains to the accomplishment of a function and the arrangement of relationships refers to a causal mechanism for achieving the function.

The origin of our hypothesis about design patterns being one of the fundamental unit of analogical transfer lies in our earlier AI work on we have developed computational accounts of cross-domain design analogies in conceptual engineering design (Bhatta & Goel 1997; Goel & Bhatta 2004). In cognitive science, Holyoak & Thagard (1989) describe a similar information-processing model of analogies called "Process Induction." In our work, we postulated two kinds of design abstractions: Generic Physical Principles (or GPPs) and Generic Teleological Mechanisms (or GTMs). GPPs are general domain principles that capture behaviors such as flow of heat from a hot body to a cold body. GTMs are function-mechanism pairs in which a particular abstract causal mechanism results in the achievement of a particular abstract function, for example, closed loop feedback (a particular abstract causal mechanism) results in the achievement of regulating the output variable of a system (a particular abstract function). The IDeAL system implemented the GTMs and

GPPs in a computer program. It is in the sense of the GTM, where an abstract function (or class of problems) is related to an abstract causal mechanism, that we use the term "pattern" in this paper.

An open issue is if such generic function-mechanism patterns occur in biologically inspired sustainable design. If similar design patterns do occur in biologically inspired sustainable designs, then we wonder whether existing computational theories of cross-domain design analogies based on design patterns provide a useful starting point for developing computational accounts of analogical transfer in biologically inspired sustainable design

Data Sources

Each fall term since 2005 Georgia Tech's Center for Biologically Inspired Design has offered a senior-level, project-based interdisciplinary course in biologically inspired design (ME/ISyE/MSE/PTFe/BIOL 4740). Faculty members from Georgia Tech's Schools of Biology, Mechanical Engineering, and Industrial & Systems Engineering teach the course jointly. Many guest lectures by other biologically inspired design researchers are also included. The course typically attracts forty to forty five (mostly) undergraduate students every year. The class composition too is interdisciplinary: in Fall 2009 the class was comprised of fifteen biology students, eleven mechanical engineering students, and fourteen other students from a variety of academic disciplines, including biomedical engineering, chemical engineering, industrial engineering, material science, and mathematics.

The course is structured into lectures, found object exercises, and a semester-long design project. Most lectures are focused on exposing student designers to specific case studies in BID, while found object exercises require designers to bring in biological samples and to analyze the solutions employed by these samples. The semester-long design projects group an interdisciplinary team of 4-6 students together based on similar interests. Instructors ensure that each team has at least one designer with a biology background and a few from different engineering disciplines. Each team identifies a problem that can be addressed by a biologically inspired solution, and develops a design based on one or more biological design cases. Each team has one or more faculty as mentors who give expert advice as and when needed. All teams present their problem and initial design concepts during the middle of the term, then submit final designs during the last two weeks of class along with a final design report. Yen, Helms, Vattam & Goel (2010); Yen, Weissburg, Helms & Goel (2011); Yen, Weissburg & Tovey (2010) describe the pedagogy in ME/ISyE/MSE/PTFe/BIOL 4740.

The ME/ISyE/MSE/PTFe/BIOL 4740 class is both a teaching and a research laboratory for us. From 2006 onwards, we have collected data on all student design projects, and in some cases, recorded details of the design trajectories. These design projects are the data for our analysis of biologically inspired sustainable design.

Initial Data Analysis

In Table 1 we present synopses of each of the final biologically inspired design projects in ME/ISyE/MSE/PTFe/BIOL 4740 since 2006. We categorize each project as either (a) intentionally addressing issues of sustainability, (b) incidentally addressing issues of sustainability, or (c) not sustainability focused. Our analysis aimed at identifying whether increasingly sustainability was the primary goal of the design project. This is in contrast to whether or not a project included a secondary objective of increasing characteristics of sustainability. For example, if the goal of the design is to increase the energy efficiency of solar thermal heaters, we consider that an "intentionally sustainable" design. Another intentionally sustainable design, the WASP Paper project in 2009, designed a paper production system that conserved water and energy relative to existing methods. In contrast, a luminescent surfboard designed to reduce the incidence of shark attacks that was solar powered, we consider "incidentally sustainable." This is because while some design decisions were made to include features that increased characteristics of sustainability ("solar powered"), the primary goal ("preventing shark attacks") did not pertain to sustainability per se. As second example of incidentally sustainable designs, the Antifouling Armor project in 2007 designed a biofilm-resistant catheter to reduce the number of infections caused by conventional catheters. Despite not being the primary goal of the project, the improved catheter had stronger sustainability characteristics because it was longer-lasting and required less energy to clean than a conventional design.

In either case, we make no claims as to the net impact of these designs in terms of sustainability; it is the intent of increasing sustainability in the design concept that we considered in our analysis. We recognize that this definition of sustainability does not address the entire product lifecycle (i.e., manufacturing and end-of-life). Since our corpus of designs was at the conceptual level, we felt that making judgments about manufacturing and end-of-life sustainability would be premature and error-prone.

Table 1: Corpus of biologically inspired design projects from 2006-2010

Year	Design Name	Design Synopsis
2006	Abalone Armor	Better bulletproof vest inspired by abalone shell.
	Ant Inspired Pheromone Sensors for Traffic Control	**Sensor to intelligently route cars away from traffic congestion inspired by ant pheromone trails.**
	BIO_Filter	**Portable, efficient, indoor air filter inspired by spider silk and diatoms.**
	The Eye in the Sea	**Underwater micro-bot for oceanic exploration inspired by squid and copepod.**
	iFabric: Smart, Adaptive Fabric for Thermoregulation Applications	Dynamic thermo regulating clothing inspired by reptile and penguin thermoregulation abilities.
	Improving Hip Implants through Protein Surface Treatment	A Failure-resistant hip replacement inspired by oysters, human bone growth cells, and coral.
	The InvisiBoard: A Biologically Inspired Design	**Passively camouflaging surfboard to protect against sharks inspired by the ponyfish and brittlestar.**
	RoboHawk: An Aerial Bomb Detection Device	Bomb detection robot inspired by Seabirds and animals' chemical pheromone detection.
	The Shell Phone: A Biologically Inspired Design	More durable cell-phone inspired by the abalone shell.
2007	Applications for Color-Changing Techniques Found in Nature	Color-changing vehicle panels, visual indicator systems, HVAC, drywall, and glass lenses inspired by biochromes and chromatophores.
	***AF (Antifouling) Armor**	**Biofilm-resistant catheter inspired by sharks and lotus leaves.**
	Biologically Inspired Designs Using the Focal Adhesion Complexes	Improved several products by inspiration of cells' focal adhesion complexes. Example: better rock climbing shoes with improved grip.
	Cartilage	Improved several products by inspiration of cartilage. Example: lower-friction bearings.
	Collision Avoidance System	Collision-detection system for cars inspired by bats, fish, owls, and snakes.
	Proposal for Creating Bio-Inspired Behavioral Protocols for Automatic Oil Spill Cleaning Robots	**Oil-spill cleaning robots inspired by ants and bird flocking.**
	Safer Motorcycle Helmet	Impact resistant motorcycle helmet inspired by the woodpecker and honeycombs.
	SQUID: Stealthy Quick Underwater Investigation Device	Stealthy underwater robot that can operate in debris-filled environments inspired by the squid.
	***The Xylem: A Bioinspired Problem Based Approach**	**Improved mine structures for supporting mine shafts and controlling toxic water movement inspired by silkworms, paper wasps, and trees.**
2008 *Sustainability-focused Semester*	**#*Balloon Fog-water Collectors**	**Passive water collection using textured balloons inspired by the namibian beetle and California redwood trees.**
	***The Divine Flush (Phi Flush)**	**Redesigned toilet-bowl that requires less water for cleaning inspired by the lotus leaf, ciliate flow, whale feeding, and hydrologic flow.**
	Everflo	**Self-healing underground water pipe inspired by Blood Platelets, Bones, Circular shells, and Tissue inflammation.**
	#*FoCoS: Fog Collection System	**Device that can collect water from fog inspired by the thorny devil, sponge, lungs, the spiral shape, and the namibian beetle.**
	FOOP: Filtration of Organic Particles	**Three-stage, portable, inexpensive filter for drinking water inspired by the baleen whale, human liver, and human glomerulus.**
	Foro	**Water desalination system inspired by the human small intestine.**
	PharmaFree: The Ecological Antibiotical Annihilation Station	**Water filter for removing antibiotics from tap water inspired by DNA, Sponges, Bacterial Enzymes, and Diatoms.**
	The Urban Pearl	**Oil filter for water inspired by the Oyster, Sea Anemone, Baleen Whale, and Flamingo.**
	WASP Paper: Water-Saving Adhesively-Bonded Sustainable Pulp-Molded	**Water-efficient, paper production system inspired by the wasp.**
2009 *Sustainability-focused Semester*	**BioWat: Passively actuated solar water heater/insulator**	**Pipe improvement that provides a passive water-heating system inspired by fish fins and pinecones.**
	The FireBox	Fire-detecting sensor inspired by the jewel beetle.
	#*Flowfex	**Architecture that allows for passive air ventilation inspired by lotus leaves, termite mounds, transpiration, and bull kelp, and salamanders.**
	From GRAY to GREEN	**Wall that harvests and filters gray water from homes for reuse inspired by the human epiglottis and kidneys.**
	Seal Skin Passive Heat Flow Transfer System	**Mechanical, efficient, air-flow regulation system inspired by Seals.**
	Septivent	**Novel turbine for harvesting wind energy inspired by fish.**
	Solshield	**UV shield that prevents damage to solar-panel due to overheating inspired by golden tortoise beetle and**
	Tembo 2.0	**Sensor that reduces home energy consumption by detecting occupants' locations inspired by owls, elephants, and scorpions.**
2010	**Desert Chiller: Passive Refrigeration System for Regions with Limited Access to Electrical Power**	**Passive cooling system for perishables inspired by termite mounds, prairie dog burrows, and bird legs.**
	***Hydrospot**	**More appealing public water fountain inspired by lotus leaves, the mitral valve, and herding behavior.**
	Iron-Bull Bumper System	Impact Resistant Front-bumper for Cars inspired by the iron-snail shell and elk antlers.
	Leverage Building: Modular, Scalable, Energy Efficient Building that Leverages Environmental Dynamics	**Modular housing with passive systems improvements, inspired by hornet nests, prairie dogs burrows, leaves, and coral colonies.**
	NOLA for NOLA: Novel Optimized Levee Architecture for New Orleans, Louisiana	Impact resistant levee inspired by iron-snail.
	*Shed-It	Automatically cleaning windows inspired by ivy, toad skin, and mammalian eyes.
	SymPhonic	Auditory sense augmentation device inspired by bats, dolphins, and predator/prey interaction.

In reading Table 1, note that darkly shaded designs are those where sustainability was a primary goal of the project. Lightly shaded designs are those where the design appears sustainable but only incidentally so. Designs whose names begin with an asterisk (*) implemented the Hydrophobic/hydrophilic design pattern, and designs whose names begin with a hash (#) were inspired by the Namibian Beetle.

Looking at the whole corpus of 42 designs, we saw that 26 of the designs appeared sustainable, with 20 intentionally designed to address sustainability and 6 incidentally addressing sustainability. However, this is perhaps an unreliable statistic, as the 2008 and 2009 semesters were specifically aimed at producing sustainable designs. Looking only at the projects from 2006, 2007, and 2010, we see that out of 25 projects, 10 of the designs addressed sustainability, with 5 intentionally addressing sustainability and 5 incidentally addressing sustainability. Thus, even when sustainability was not a class focus, a sizable portion of the class still produced designs that showed features of sustainability.

Detailed Case Study

In this section we provide a case study highlighting a biologically inspired design produced by a team of students ME/ISyE/MSE/PTFe/BIOL 4740 in Fall 2008 that showed strong sustainability characteristics. The goal of the design is to harvest water in areas that do not have access to ground water, but which receive fog and dew on a regular basis. People in these regions typically do not have the means to afford water piped in from elsewhere and are also economically limited because of the shortage of water. The design problem was further complicated by the need for simplicity of use, ease of maintenance, and low cost.

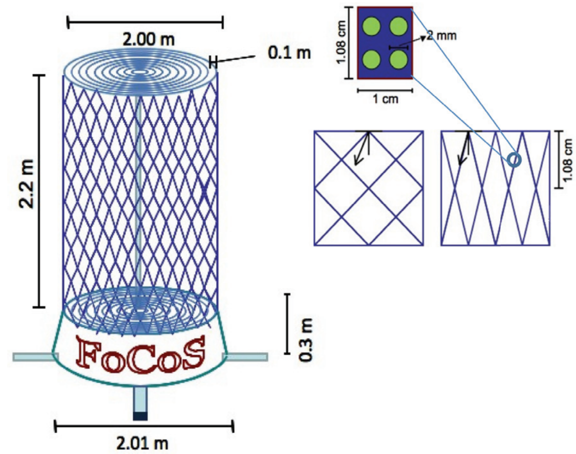

Figure 1. Final design of fog net cylinder.

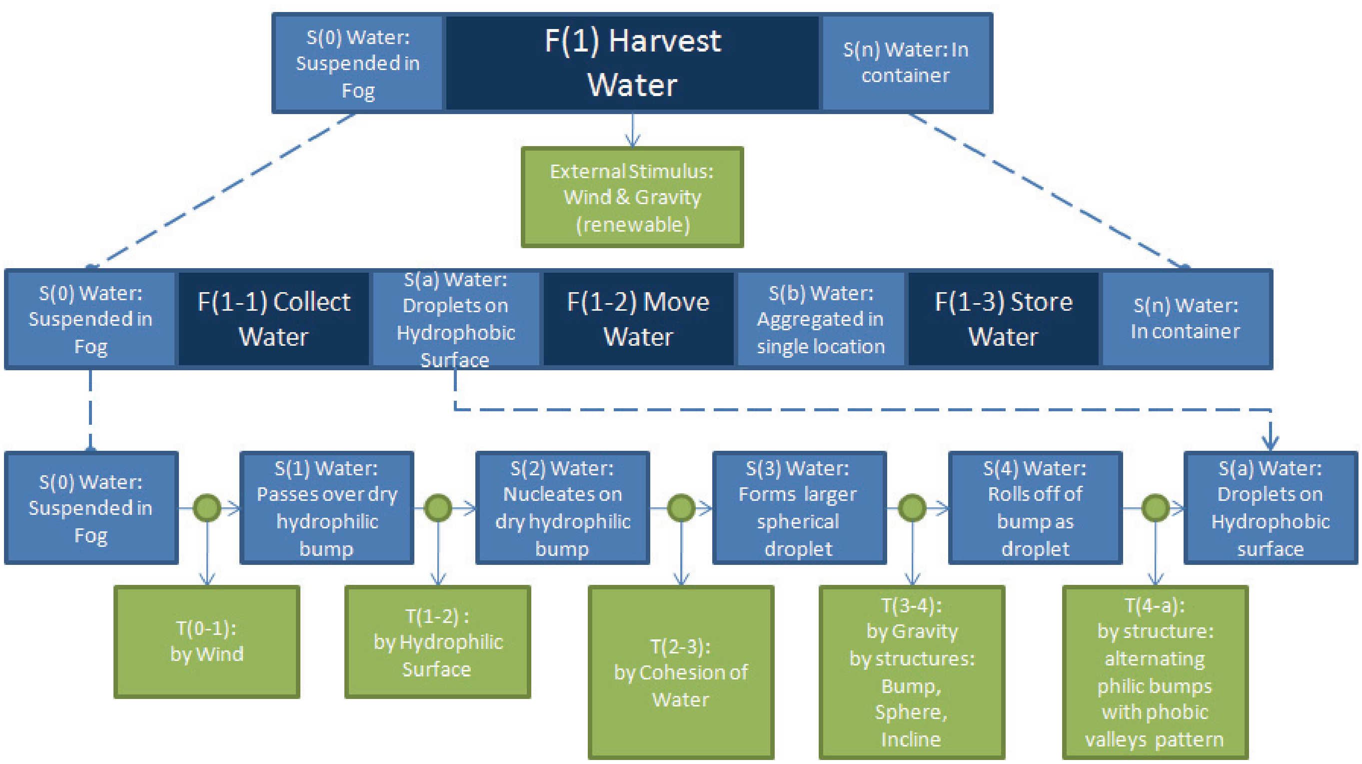

Figure 2. Graphical representation of function/mechanism/sub-function relationships in the fog net design.

The Design

Figure 1 illustrates the final design proposed by the interdisciplinary design team of biologists and engineers. As Figure 1 indicates, the design consists of a fog net cylinder on which fog would condense as is passed through the net fabric. Net designs in rectangular patterns, hung between two vertical poles, are already in use (Vince, 2010). The design team proposed that their design improves on the existing design in three ways. First, the cylindrical shape means that the water collection is independent of wind direction, and could be deployed in areas where wind direction was not always predictable. Second the netting material itself, instead of being made of a uniform material, was to be made of a textured material, consisting of (1) hydrophilic (water-attracting) bumps, approximately 2mm in diameter, surrounded by (2) hydrophobic (water-repelling) materials. The hydrophilic bump provides an initial site for airborne water to gather, and because of its shape, water can be expected to bead at the crest of the bump.

When the water bead reaches sufficient mass, gravity will offset the attractive force between the water and the surface, and the bead will roll into a hydrophobic valley. Because of the water repellency of the valley, the bead of water will continue to roll down the net, where it will collect in the container below the net. The third improvement in the proposed design relative to the current design is in the angle of the mesh of the netting itself. The mesh in the netting will have more acutely vertical alignment, orienting the rolling drops downward, more than outward, increasing the rate at which water droplets descend the net.

Figure 2 shows a graphical representation of the function/sub-function relationships in the design, with harvest water as the primary function, and three sub-functions: collect water, move water, and store water. Each function is preceded by an input state, and followed by its output state. Furthermore, in this figure, the causal process of the collect water function is elaborated, providing a detailed state-transition diagram annotated with the causal processes that result in each transition. From this detailed description, we see that water is brought to the net "by Wind" and nucleates on the hydrophilic bump as a result of the principle of "by Hydrophilic Surface". Such a detailed causal account of the process used in the final design provides leverage for indentifying, extracting and transferring the key patterns in the design.

Biological Analogies and Design Patterns

Based on our interpretation of the artifacts produced in this design project, the design of the material for the net apparently was inspired by analogy to one primary biological system, the Namibian beetle. This beetle lives in an arid dessert, several miles inland from a coast. During certain daily weather patterns, a fog rolls across the dessert, during which time the beetle positions itself on the crest of a dune, raises its body into the air, with its head lower than its rear. The shell of the beetle has the same arrangement of hydrophilic bumps and hydrophobic valleys as we described in the net, which performs the same function of harvesting water from the fog. The water rolls down the channels of the shell toward the head of the beetle, where it can be consumed.

Note that the design illustrated in Figure 1 is one of two independent cases of the Namibian beetle inspiring a fog-harvesting device in ME/ISyE/MSE/PTFe/BIOL 4740. Furthermore, in another design project in ME/ISyE/MSE/PTFe/BIOL 4740, this same Namibian beetle analogy was also used to inspire water collection and water flow down a "self-cooling" wall in a building, which was designed to passively cool a building. Thus the same function-mechanism pattern used for water harvesting served a higher-level function, that of cooling.

In another, similar biological system, the lotus leaf uses a hydrophobic surface to cause water to bead up and roll down the leaf, taking with it debris particles and pathogens, maintaining a cleaner, more productive and healthier leaf. In this case, the mechanism of hydrophobia directs the behavior of the water towards the function of passive self-cleaning. We have also seen this function-mechanism pattern used in class in the development of a catheter that is manufactured with a surface similar to the lotus leaf. The catheter will, in theory, remain cleaner and prevent infection more than would a traditional catheter.

We note that the same general patterns appear to occur in two very biological systems, the Namibian beetle and the lotus leaf. For this reason, we will call them the "Hydrophobia" and "Hydrophilia" design patterns, rather than a "Namibian beetle" pattern or a "lotus leaf" pattern. The Hydrophobia and Hydrophilia patterns are abstractions over the designs of the Namibian beetle and the lotus leaf.

Note also there seem to be two design patterns here, not one. The lotus leaf uses only the Hydrophobia pattern to achieve one function. The Namibian beetle uses a combination of the Hydrophobia and Hydrophilia patterns to accomplish a different function. One can imagine other combinations of the two patterns, perhaps with other design patterns, to produce a range of system designs.

In addition, we note that both patterns are a function-mechanism pair (as in GTMs in our earlier work). The Hydrophobia design pattern for example has the function to repel water, with an associated mechanism borne out of structural regularities of a particular type for accomplishing the function. The Hydrophilia design pattern has the function of attracting water, with a different mechanism arising out of a different type of structural regularities to achieve the function.

Conjectures

It is much too early in our analysis of biologically inspired sustainable design in terms of design patterns to draw any firm conclusions. At this stage, we can only adopt a stance, posit hypotheses and make conjectures.

Sustainable design is an emerging interdiscipline. As with any new interdiscipline, there is a need to systemize the knowledge and processes of sustainable design. We believe that AI, especially knowledge-based AI, can be helpful in this systemization of knowledge, reasoning, and learning in sustainable design. AI develops content accounts of knowledge and builds schemes for representation and organization of knowledge. AI also builds process accounts of complex tasks and constructs computational techniques for the use, access, acquisition, and communication of knowledge in the process accounts.

In this paper, we have tried to use AI as a lens to analyze a corpus of design projects in biologically inspired sustainable design. We have posited that design patterns may be a useful unit of analysis for developing content and process accounts of biologically inspired sustainable design. We have also illustrated what such a content account might look like.

These process and content accounts might potentially play several roles. From one perspective, such accounts could be used to support human designers. A process account could aid in the education of biologically inspired sustainable designers by providing a template upon which to develop curricula, and robust knowledge representations could help designers describe what they know and integrate new information about biological systems or patterns from prior successful designs into their own designs. As we mentioned in our introduction, a good knowledge representation allows users of that representation to ignore unnecessary or distracting details and to focus on those features that are pertinent to the task at hand. We believe articulating design patterns in the manner that we have done in this paper is one small step to achieving this vision.

From another perspective, process and content accounts could lead to the development of AI agents that enact biologically inspired sustainable design. Systems already exist for partially automated analogical design in the domain of simple engineering systems (Bhatta & Goel 1997; Goel & Bhatta 2004), and we are currently pursuing the goal of re-implementing such systems for biologically inspired design. A next logical step would be to include design patterns that may lead to sustainable design such as the one identified in this paper, allowing for mixed-initiative generation of biologically inspired sustainable designs.

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