Bryan Wiltgen & Ashok K. Goel. Case-Based Reasoning All Over the Place: The Multiple Roles of CBR in Biologically Inspired Design. In workshop of Human-Centered and Cognitive Approaches to Case-Based Reasoning at 19th International Conference on Case Based Reasoning. Greenwich, London, UK. September 12, 2011.

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Case-Based Reasoning All Over the Place: The Multiple Roles of CBR in Biologically Inspired Design

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Abstract. Biologically inspired design is a rapidly growing movement in environmentally sustainable design. According to the biologically inspired design paradigm, nature is the best design case base. This recognition has led to a race to develop case-based techniques and tools to aid biologically inspired design. It is noteworthy that all current case-based tools perform only the task of generation of design concepts. However, some cognitive studies have suggested that case-based reasoning plays an important role in design solution evaluation and design solution explanation in addition to design concept generation. In this paper, we describe an ethnographic study of biologically inspired design that confirms the above finding. In addition, our study indicates that case-based reasoning may support a fourth task in biologically inspired design especially in the context of collaborative design: explanation of biological source cases. These findings suggest a significantly expanded role for case-based reasoning in biologically inspired design.

Keywords: Analogical Reasoning, Biomimicry, Biologically Inspired Design, Case-Based Reasoning, Memory-Based Reasoning.

1 Introduction

Biologically inspired design [1-4] is a widespread and important movement in modern design, pulled by the growing need for environmentally sustainable development and pushed by the desire for creativity and innovation in design. The paradigm espouses use of analogies to biology in generating conceptual designs for new technologies. Although nature has inspired many a designer in the history of design, including famous ones like Leonardo da Vinci, the Wright brothers, etc., it is only over the last generation that the paradigm has become a movement. One prominent example is the design of windmill turbine blades inspired by humpback whale flippers [5]. The designers adapted the shape of the whale flippers—specifically, the bumps on their leading edges—to turbine blades, creating blades that improve lift and reduce drag, increasing the efficiency of the turbine [6].

Note the match between biologically inspired design and case-based reasoning (CBR): biologically inspired design by definition uses nature as a large case base of designs! Thus, we want to draw the attention of the CBR research community to the challenge and opportunity that biologically inspired design presents not only to exploit existing CBR techniques, but to also use biologically inspired design as a context for developing new CBR theories and techniques.

Indeed, the rapid growth of biologically inspired design as a movement over the last generation has led to a race to develop case-based computational techniques and tools for aiding its practice as well as its education, for example, [3,7-16]. It is noteworthy that all these computational tools, including our own work on the DANE system [8,14,16], use CBR for one single task, namely, generation of conceptual design solutions. This is largely consistent with research on case-based design in general. (Goel & Craw [17] provide a review of case-based design research.)

However, some recent cognitive studies of biologically inspired design suggest that CBR may play an important role in multiple tasks, and not just the task of solution generation. In particular, Vattam, Helms, & Goel [18] suggest that analogies play an important role in multiple tasks of biologically inspired design, including design solution generation, design solution evaluation, and design solution explanation. Analogy for solution generation occurs when a case is utilized to develop a design solution. Analogy for solution evaluation occurs when a case is utilized to infer if the design solution works or not. Analogy for solution explanation occurs when a case is utilized to explain some part of a design solution.

To better understand the multiple roles of CBR in biologically inspired design we conducted an ethnographic study. Preliminary results from the study provide support for the role CBR plays in solution generation, solution evaluation, and solution explanation. Interestingly, they also indicate a fourth role for CBR in biologically inspired design especially in the context of collaborative design: source case explanation. In this task, cases that are assumed to be shared amongst the team members are used by a team member to explain another, novel case. For example, one team member might explain the flow of water moving up a tree's xylem by analogy to water flowing through a straw, a case others are assumed to know. Alternatively, source case explanation occurs when one or more team members attempt to build knowledge about a source case by comparison to an already known case.

2 An Ethnographic Study of Biologically Inspired Design

Georgia Institute of Technology's ME/ISyE/MSE/PTFe/BIOL 4740 course on biologically inspired design provides the context for our ethnographic study. This is a yearly, interdisciplinary, project-based undergraduate class taught jointly by biology and engineering faculty in which mostly senior-level design students work in small teams of 4-5 on design projects. The class is composed of students from biology, biomedical engineering, industrial design, industrial engineering, mechanical engineering, and a variety of other disciplines. The projects involve identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem [19].

For our study, we performed a participatory observation of a design team within a session of the course. This entailed the first author (Wiltgen) joining the course as a regular student and engaging in all activities expected of a student, including attending lectures, doing homework, and participating as a full-fledged design team member in the observed design team. The author gained permission to conduct the study from both the primary course instructor and the observed design team.

The design team we observed consisted of five students, including the first author. The primary course instructor formed the group with limited input given by the first author. One of the team members was not assigned to the group by the instructor and instead permanently joined the team during the first class session. Except for the participating author, who is a Ph.D. student in computer science, all the team members were senior-level undergraduate students. The team was highly interdisciplinary, consisting of five separate majors: computer science (the participating author), mechanical engineering, architecture, biology, and industrial engineering.

In the session of the biologically inspired design class, each design team worked independently through three design episodes and every team had different projects. In this paper, we will focus on the first design episode, where the team developed the Shark Attack project. The goal of this project was to prevent shark attacks off the coast of the United States without harming the sharks. The design team designed an underwater sound-based shark repellant device inspired by the snapping shrimp [20], a small shrimp with the ability to create loud, underwater sound waves using one of its claws, which it uses to hunt prey and communicate with other snapping shrimp.

The original design problem of the Shark Attack project was simply to prevent coastal shark attacks. Inspired by the snapping shrimp, the team designed a decoy-like device that would attract the sharks to a location away from human population using sound. However, the team discovered new problems upon evaluation of the idea, such as durability of the decoy if sharks were going to attack it instead of humans. The overall problem then evolved to account for these newly identified issues (e.g., that one must prevent shark attacks with a design that doesn't get eaten by sharks), resulting in a changed solution from a shark-attracting to a shark-repelling device.

The final device design worked by emitting sounds, generated by the same mechanism that the snapping shrimp uses to emit sound, but at a frequency that sharks dislike. By placing a line of these devices between human beach-goers and shark populations, the design team envisioned creating something akin to an "invisible fence," a field that would repel sharks without harming them.

This design episode was an example of what our prior work in this area would term solution-driven analogy [21]. The team was initially presented with several biological cases, told to perform research on those cases, and then asked to generate problems for which to apply and adapt each case (e.g., the designers first encountered the snapping shrimp and then generated the problem of shark attack prevention to apply the underwater sound generation mechanisms of the shrimp).

This design process is the inverse of what one typically thinks: traditionally, a designer begins with a problem statement and seeks prior cases to resolve that problem.

2.1 Method

Several kinds of data were collected for this ethnography: audio recordings, individual and team assignments (including team presentations), e-mail communications amongst the team, copies of sketches made during team meetings, and field notes of class sessions.

For this paper, we focus strictly on the audio recordings, as they are an explicit record of team members using case based reasoning during their design activities. The audio recordings were taken of the class lectures, in-class activities, and out-of-class team meetings. We then transcribed the recordings into written form.

Once transcribed, we analyzed the transcripts related to the first design episode, looking for instances where case based reasoning explicitly occurred. Key phrases such as "like <X>" where used to identify passages. Once the instances were identified, we then categorized the instance by its CBR type. Originally, we used the three CBR types as given in [18] as our categorization scheme, but we expanded this scheme when the novel Source Explanation type was discovered.

3 Preliminary Results

In this section we present examples of each CBR type derived from transcript analysis. In the following section we will discuss the implications of these various CBR types within the context of developing interactive CBR tools. Note that in the examples we identify each of the five team members by their major: CS for computer scientist, ME for mechanical engineer, ARCH for architect, BIO for biologist, and IE for industrial engineer.

CBR Type	Example from Observation
Solution Generation This type of CBR is the conventional characterization of CBR. A problem is defined and then a prior solution, a case, is adapted to meet the parameters of that problem.	In the 6th class session, students were given an in-class exercise, which was for each member of the team to present the results of his/her individual homework assignment due that date. The assignment required each student to find and read two academic research papers on some biological organism, determine a problem that organism's mechanisms might be able to solve, and then find two sources on prior solutions to that problem. This class session was an excellent opportunity to see CBR for solution generation because each student presented a case-problem pair. For example, ME's source case was the flying fish, which is a fish that uses its fins to literally soar above the water for a short period of time. He adapted that solution to the problem of drag in maglev trains:

	ME: *"So, what I was thinking about was using these fins off the flying fish on the side of a maglev train to also create a little bit of lift where you, you actually use the air resistance to help you get over the actual friction and move more efficiently"*
Solution Evaluation In this type of CBR, a case related to the design solution is used to infer the quality of the design.	After the prior class discussion, the team was tasked with creating a problem decomposition related to the preliminary problem-solution-source triple they chose during the class exercise described in the above example. Recall that the team decided to pursue the problem of shark attacks, the solution of an underwater sound-generating decoy, and the snapping shrimp as their primary source case, In this snippet of discussion from an out-of-class meeting, the team is struggling with a critique given in the prior class: would sharks get desensitized to the sound? "Pavlov's dog" became a shared case among the team that they continued to use as an evaluation mechanism. Although it's implicit in this example, the comparison was that sharks might get desensitized to the team's decoy if they didn't find food at the source of the sound like how Pavlov's dogs got desensitized to their food chime without food reinforcement. ***ARCH:*** *"…well how do you know they won't like get used to the sound and just ignore it?"* ***CS:*** *"Right"* ***ARCH:*** *"But then at the same time it could be a good thing because if it does mimic the frequency of humans what if it makes them you know, it's the opposite of Pavlov's dog where"* ***CS:*** *"Oh desensitizes them?"* ***ARCH:*** *"Yeah it desensitizes them."*
Solution Explanation In this type of CBR, a case shared among the team members is used to explain the entirety or some aspect of the design solution.	The first complete design document for this design episode was due on the 9th class session. A few days before, the team met outside of class twice to finish developing their design and start compiling the design document. This example comes from the first of those meetings. In this example, the architect is describing a component of the design solution: a proximity sensor that would turn on the sound generator only when a shark passes nearby. She utilizes the case of a fish detector to explain her solution component to the team. ***ARCH:*** *"Let's say it comes within a certain boundary of the coast like a large organism."* ***ME:*** *"Yeah"* ***ARCH:*** *"Cause I mean there's already things that like"* ***ME:*** *"Let them come off the-"* ***ARCH:*** *"Can detect large organisms. You know, like a*

	fish monitor if you're going fishing it can-" ***CS:*** *"Yeah"* ***ARCH:*** *"And then so if there's like a large organism that passes through maybe then it triggers something."*
Source Explanation Similar to Solution Explanation, this type of CBR is when a case shared among the team members is used to explain a case that is novel to one or more team member. This type of CBR is also when a case is used as an explanatory tool to help build understanding about another case.	Since Source Explanation is a new extension to our model of analogy use within biologically inspired design, we present here two examples of its use. The first example comes from an in-class activity during the 4th class session. Each student was tasked with finding an object in nature, researching two articles on that object, and then presenting his/her object to his/her design team during this class session. In this example, ME had previously presented a magnolia leaf as his found object. A magnolia leaf has two distinct sides, a top, waxy side and a fuzzy brown bottom side. In his explanation of the leaf, he could not explain the bottom side, so the team set forth to generate an explanation. BIO tried to explain the bottom of the leaf by appealing to the case of an umbrella, where water collects on the umbrella's underside. He proposes that the fuzzy-like bottom side of the magnolia leaf helps it overcome this problem: ***ME:*** *"Yeah, there's not really a lot about the brown on the bottom."* ***BIO:*** *"What I'm thinking is, uh, you- you just mentioned that kinda good for the umbrella"* ***ME:*** *"Yeah"* ***BIO:*** *"Yeah, cause uh, yeah I agree with you. Cause uh, all the umbrellas I think I've kinda experienced that if the water pours out then the water kinda, kinda getting into like underneath of the umbrella."* ***CS:*** *"Huh"* ***BIO:*** *"But if it's [[inaudible]] stuff then that kinda prevents the water going underneath, so I think that's [good]"* The second example comes from the team activity in 6th class session that was described in the Solution Generation example. Each member of the team was tasked with describing a source organism, a target problem, and a design solution that was adapted from the source case. In this passage, CS has chosen to explain his source, the snapping shrimp, in terms of other cases. The novel case of the snapping shrimp is being shared to the team through cases that CS assumes others have in common, such as a pistol, a ratchet, and a plunger-socket mechanism. Note that despite the snapping shrimp being a biological case, very little biological facts are explicitly being expressed in

	his explanation. ***CS:*** *"It has like uh- it looks like a pistol. It can ratchet back one thing that looks like a plunger. And it'll shoot this plunger into a socket on its under- on its other claw, and shoot out a jet of water."*

4 Conclusions

According to the paradigm of biologically inspired design, nature is the best design case base, especially for environmentally sustainable design. In this paper, we briefly described an ethnographic study of biologically inspired design. Our analysis of the study indicates that CBR plays multiple roles in the design process. In particular, CBR appears to play an important role in at least four tasks: solution generation, solution evaluation, solution explanation, and source explanation.

The current generation of computational methods and tool for aiding biologically inspired design however focuses only on the task of solution generation. However, developing computational methods and tools for supporting and scaffolding all four of the above tasks requires answering at least three sets of questions. First, from the perspective of cognitive modeling, how are cases stored, organized and accessed in human memory so that they can support multiple tasks? Second, from the viewpoint of knowledge system engineering, how might we develop digital libraries of cases such that the cases have multiple indices and thus can be retrieved to address multiple tasks? Thirdly, in terms of human-centered computing, how might an interactive system support a design team in all of above four tasks in order to aid biologically inspired design as a whole? We posit that in the context of biologically inspired design, these questions present CBR with a both a great opportunity and a grand challenge.

Acknowledgments

We thank the anonymous student designers that allowed us to observe and record their design activities during the semester of MS/ISyE/MSE/PTFe/BIOL 4740 at Georgia Tech. This research has also benefited from many discussions with Michael Helms, Swaroop Vattam, and other members of the Design & Intelligence Laboratory (http://www.dilab.gatech.edu). Cristina Weiler helped with transcription and analysis of the ethnographic data. We are also grateful to Professor Jeannette Yen, Director of Georgia Tech's Center for Biologically Inspired Design (http://www.cbid.gatech.edu) and coordinator of the MS/ISyE/MSE/PTFe/BIOL 4740 class for her strong support and encouragement for this work. We also thank the US National Science Foundation that has generously supported this research through an NSF CreativeIT grant (#0855916) entitled "Computational Tools for Enhancing Creativity in Biologically Inspired Engineering Design."

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