Is Biologically Inspired Invention Different?

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Abstract: The paradigm of biologically inspired design views nature as a vast library of robust, efficient and multifunctional designs, and espouses the use nature as a source of analogues for inspiring novel designs in domains of interest such as architecture, computing, engineering, etc. Over the last generation, biologically inspired design has emerged as a major movement in engineering, architectural, and systems design, pulled in part by the need for environmentally sustainable design and pushed partly by the desire for creativity and innovation in design. An important question is whether biologically inspired design is fundamentally different from other kinds of analogy-based creative processes. This question is critical because the computational theories, techniques and tools we need to develop to support biologically inspired design depend on the nature of the task itself. In this paper, we first summarize some of our empirical findings about biologically inspired design, then derive a task model for it, and finally posit that biologically inspired design indeed is a novel methodology for multiple reasons.

Biologically Inspired Design

The paradigm of biologically inspired design (also known as biomimicry, biomimetics and bionics) views nature as a vast library of robust, efficient and multifunctional designs, and espouses the use of nature as an analogue for designing technological systems as well as a standard for evaluating technological designs (Benyus 1997; French 1994; Gleich et. al. 2010; Turner 2007; Vincent & Mann 2002; Vogel 2000). This paradigm has inspired many famous designers in the history of design including Leonardo da Vinci, and in a wide variety of design domains ranging from architecture to computing to engineering to systems. However, over the last generation the paradigm has become a movement in modern design, pulled in part by the growing need for environmentally sustainable development and pushed partly by the desire for creativity and innovation in design. Thus, the study of biologically inspired design is attracting a rapidly growing literature, including patents (Bonser & Vincent 2007), publications (Lepora et al. 2013), and computational tools (Goel, McAdams & Stone 2014).

The Biomimicry 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.

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

From the perspective of computational creativity, two characteristics of biologically inspired design are especially noteworthy. Firstly, biologically inspired design often is creative: its products, such as the windmill turbine blades illustrated in Figure 1, are novel, valuable, feasible, and non-obvious (even surprising at first). Secondly, the conceptual phase of biologically inspired design engages analogical transfer of knowledge from biological analogues to design problems in the domain of interest. The latter point raises an important question: is biologically inspired design fundamentally different from other kinds of analogy-based creative processes other than the obvious fact the source domain here is biology? This question is important because the computational theories, techniques and tools we need to develop to support biologically inspired design depend on the nature of the task. For example, Nagle (2014) describes an engineering-to-biology thesaurus that maps function terms used in engineering into equivalent function terms used in biology. The (implicit) assumption in the work on the engineering-to-biology thesaurus is that biologically inspired design is not very different from other analogy-based creative processes (e.g., Veale 2003), that if we could only bridge the vocabulary gap between design and biology, we could borrow the rest from extant theories of design, analogy and creativity.

In this paper, we first summarize some of our empirical findings about biologically inspired design and then derive a Task Model for it. Finally, we will posit that biologically inspired design is a novel methodology for multiple reasons, and thus requires the development of new computational theories, techniques and tools.

Research Methodology

Theories of biologically inspired design process can be *normative and prescriptive* or *descriptive and explanatory*. Vincent's et al.'s (2006) BioTRIZ theory, for example, is a normative and prescriptive account of biologically inspired design. In contrast, we have developed a descriptive and explanatory account. Thus, our research methodology consists of three major elements: *In situ* observations of biologically inspired design practices, task analysis of biologically inspired design, and comparison with current theories of design, analogy and creativity.

Observations of Biologically Inspired Design Practices: Given that the professional biologically inspired design community at present is nascent, sparse and diffused, we studied biologically inspired design practices in the Georgia Tech ME/ISyE/MSE/BME/BIOL 4740 course from 2006 through 2013 taken by ~350 students. This a yearly, interdisciplinary, project-based course on biologically inspired design taught jointly by biology and engineering faculty. The class is composed of mostly senior-level undergraduate students from biology, biomedical engineering, industrial design, industrial engineering, mechanical engineering, and a variety of other disciplines. Although it evolves a little every year, the course is consistently structured around lectures, found object exercises, journal entries, and one or more design projects. Some lectures discuss biological systems; some lectures focus on case studies of biologically inspired design; and some lectures formulate, analyze and critique problems for students to solve in small groups. Yen et al. (2011, 2014) provide a detailed account of the teaching and learning in the course.

Task Analysis of Biologically Inspired Design: Given our observations in the ME/ISyE/MSE/BME/BIOL 4740 classes from 2006 through 2013, we conducted a task analysis of the macrostructure of biologically inspired design practices. Crandall, Klein & Hoffman (2006) describe the methodology of task analysis in detail. Task analysis helps identify the task decomposition of a complex task, the methods used to accomplish the various subtasks in the task decomposition, and the contents of knowledge used by the different methods. For example, Chandrasekaran (1990) presents a high-level task analysis of the general design task while Goel & Chandrasekaran (1992) present a task analysis of the specific method of case-based design. In general, task analysis may describe the behaviors of an individual designer, the interactions among a team of designers, or the behaviors of a design team viewed as a unit. Although we are interested in all three levels of aggregation, in this work we focus on interdisciplinary design teams of biologists and engineers viewed as the unit of analysis. Our task analysis of biologically inspired design by interdisciplinary design teams generates a task model of biologically inspired design: the task model describes the processes and the knowledge used in biologically inspired design.

Comparative Analysis with Theories of Design, Analogy and Creativity: Given our task model of biologically inspired design, we compared it with theories of biologically inspired design such as BioTRIZ (Vincent et al. 2006) and Design Spiral (Baumeister et al. 2012). However, because of space limitations, here we will compare our task model only with BioTRIZ. We also compared our task model with established theories of analogical reasoning such as Gentner (1983), Hofstadter (1996), Holyoak & Thagard (1996), and Kolodner (1993). Again because of space limitations, here we will compare our task model only with Gentner's structure-mapping theory of analogy.

Data

The ME/ISyE/MSE/BME/BIOL 4740 classes from 2006 through 2013 resulted in 83 extended, open-ended design projects. The 83 case studies of the design projects in the classes were the focal points of our data collection. The projects involved identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem. Each design project grouped together an interdisciplinary team of typically 4-5 students. Each team had at least one student with a biology background and a few from different engineering disciplines. Each design team also had at least one faculty member. Each team identified a problem that could be addressed by a biologically inspired solution, explored a number of solution alternatives, and developed a final solution design based on one or more biologically inspired designs. Each design team presented its final design to an interdisciplinary design jury. Goel et al. (2015) describe a digital library, called the Design Study Library (DSL), of all 83 case studies.

Empirical Findings

Cross-Domain Analogies: By definition, biologically inspired design engages cross-domain analogies from biology to engineering Although we have observed that extended episodes of biologically inspired design involve both within domain and cross-domain analogies (Vattam, Helms & Goel 2010), it is the essentialness of cross-domain analogies that defines the paradigm of biologically inspired design.

Problem-Driven and Solution-Based Analogies: We observed the existence of two high-level analogical processes for biologically inspired design based on two different starting points – *problem-driven analogy* and *solution-based analogy* (Helms, Vattam & Goel 2009). In the problem-driven analogical process, designers identify a problem that forms the starting point for subsequent problem solving. They usually formulate their problem in functional terms (e.g., stopping a bullet). In order to find biological sources for inspiration, designers "biologize" the given problem, i.e., they abstract and reframe the function in more broadly applicable biological terms (e.g., what characteristics do organisms have that enable them to prevent, withstand and heal damage due to impact?). Designers use a number of strategies for finding biological sources relevant to the design problem at hand based on the "biologized" question, and then they research the biological sources in greater detail. Important principles and mechanisms that are applicable to the target problem are then extracted to a solution-neutral abstraction and applied to arrive at a trial design solution.

On the other hand, in the solution-based analogical process, designers begin with a biological source of interest. The designers understand (or research) their biological source to a sufficient depth to support the extraction of deep principles from it. Then they find human problems to which the principle can be applied. Finally, they apply the principle to develop a design solution to the identified problem.

The two analogical processes have different characteristics. Compared to problem-driven analogical processes, solution-based analogical processes tend to exhibit not only design fixation but also a fixation on the structure of the biological design (Helms, Vattam & Goel 2009). Again compared to problem-driven processes, solution-based design processes also tend to more often result in the generation of multifunctional designs, i.e. where a single design principle meets multiple functional goals (Helms, Vattam & Goel 2009). In general, a single case study may contain both problem-driven and solution-based analogical processes.

Problem Decomposition and Level of Abstraction of Biological Analogy: Biologically inspired design engages decomposition of the target design problem as well as functional decomposition of the biological system that acts as a source analogy to the design problem (Vattam, Helms & Goel 2007). Problem decomposition and functional decomposition of course are familiar ideas in design (e.g., Brown & Chandrasekaran 1989; Chandrasekaran 1990; Dym & Brown 2012; French 1996; Simon 1996). However, these decompositions appear to play a special role in biologically inspired design. The decomposition of the target design problem and the functional decomposition of the source biological system help identify the appropriate level for the analogical transfer from the biological system to the design problem.

Problem Decomposition and Compound Analogies: Problem decomposition appears to play a second special role in biologically inspired design. We found that biologically inspired design often entails compound analogies in which a new design concept is generated by composing the results of multiple cross-domain analogies (Vattam, Helms & Goel 2008). This process of compound analogical design relies on an opportunistic interaction between the processes of memory and problem solving. In this interaction, the target design problem is decomposed functionally, solutions to different subfunctions in the functional decomposition are found through analogies to different biological systems retrieved from memory, and the overall solution is obtained by composing the solutions for achieving the different subfunctions. Thus, the subfunctions in the functional decomposition of the design problem act as probes into a memory of biological systems.

Interactive Analogical Retrieval: Most designers are novices at biology (just as many biologists are naïve about design). Thus, designers typically do not have a large number of biological analogues stored in their long-term memory. Instead, we found that designers searched online for biological cases analogous to the target problems. Based on our observations, this was one of the predominant approaches for finding biological cases that typically were in the form of biology articles. Designers reported using a range of online information environments to seek information resources about biological systems. These included: (1) online information environments that provided access to scholarly biology articles like Web of Science, Google Scholar, ScienceDirect, etc., (2) online encyclopedic websites like Wikipedia, (3) popular life sciences blog sites like Biology Blog, (4) biomimicry portals like AskNature, and (5) general web search engines like Google. We call this phenomenon interactive analogical retrieval (Vattam & Goel 2013).

Serendipity in Biologically Inspired Design: The coupling of design problems and biological analogues often is serendipitous. For example, a design team may formulate a design problem, then find itself unable to make progress on it, and thus suspend additional work on the problem. At a later time, while working on a different problem, the team may serendipitously come across a biological analogue that provides a solution to the earlier problem, and therefore switch to the earlier problem.

Abstraction and Transfer of Design Patterns: We found biologically inspired design engages abstraction and transfer of several kinds of design patterns. Design patterns are abstractions of design cases, including generic domain principles (Bhatta & Goel 1994) and generic teleological mechanisms – causal mechanisms that achieve specific types of functions (Bhatta & Goel 1996). In particular, we have so far studied three kinds of design patterns in biologically inspired design: domain principles, causal mechanisms for accomplishing specific functions types,

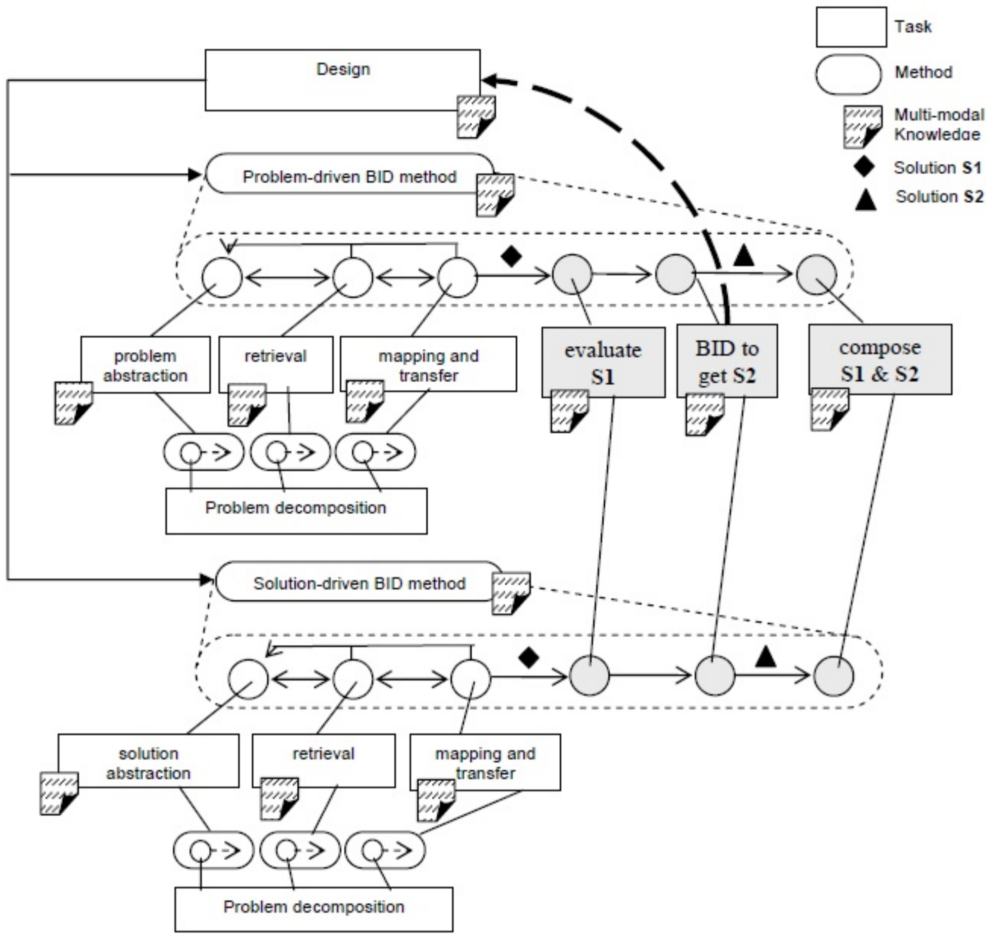

Figure 2. A generic task model of biologically inspired design.

and arrangements of structural components for accomplishing function types. We expect that there are many other types of design patterns yet to be discovered in biologically inspired design.

Bridging Spatial and Temporal Scales: Note that although the example in Figure 1 of this article is about product design at a spatial and temporal scale 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. Often, a design pattern abstracted from a biological analogue may bridge across several spatial and temporal scales. For example, Weiler & Goel (2015) describe the crinkles on the surface of mitochondria cells as a source of analogy for designing human-scale devices for harvesting water from fog.

Problem-Solution Co-Evolution*:* Conceptual design in biologically inspired design entails problem-solution co-evolution (Helms & Goel 2012). That is, the design process iterates between defining and refining the problem and the solution, with both the problem and the solution influencing each other (Maher & Tang 2003; Dorst & Cross 2001). As a solution (S) is developed and evaluated for a given problem (P), it reveals additional issues, spawning a new conceptualization of the problem (P+1). The process continues with the development of a new solution (S+1) and will iterate until a final solution is decided upon.

Task Model

Figure 2 illustrates our generic task model of biologically inspired design based on the above findings. The overall *task* is design. This is accomplished by using two *methods:* problem-driven analogy and solution-driven analogy. Each method sets up *subtasks* like abstraction, retrieval, and mapping and transfer. Each subtask (e.g., retrieval) might, in turn, be accomplished by one of several methods (e.g., feature-based similarity matching for retrieval). *Knowledge* here refers to the knowledge used by a task or a method, for example, knowledge of design patterns. Note that knowledge may be multimodal, for example, descriptive and depictive.

The problem-driven analogical process incorporates the design subtasks of problem formulation, problem reframing, biological solution search, defining biological solution, principle extraction and principle application. Similarly, the solution-based analogical process incorporates the design subtasks of defining biological solution, principle extraction, solution reframing, problem search, problem definition, and principle application. To avoid cluttering, Figure 2 illustrates only some of these subtasks of problem-driven and solution-based design.

Our task model of biologically inspired design also accounts for problem decomposition and compound analogies. In Figure 2, S1 represents the initial solution obtained. We add a new subtask "evaluate" to both problem-driven and solution-based methods. This subtask evaluates the initial solution S1 generated by a method. If the evaluation of S1 indicates that S1 addresses only a part of the design problem, then a new design sub-problem is spawned to address the remaining part(s) of the problem. Addressing the new sub-problem may lead to another partial solution S2. The subtask "compose" composes S1 and S2 to obtain a more complete solution to the original problem. For expediency, it is assumed here that subtask execution for compound analogy is sequential, represented by one-way arrows between the circles denoting the evaluation, designing and composition. The actual process may in fact involve much more complex interactions.

Comparative Analysis

In this section, we compare the task model for biologically inspired design with both computational theories of analogical reasoning in creativity and creativity in biologically inspired design. Due to space limitations, here we will compare the task model only with Gentner's structure-mapping theory of analogy and Vincent et al.'s BioTRIZ theory of biologically inspired design.

Structure Mapping: Gentner's structure-mapping theory is one of the classical theories of analogy. Falkenhainer, Forbus & Gentner (1989) describe the structure-mapping engine, a computational implementation of the structure-mapping theory. Gentner & Markman (1997) discuss structure mapping as a more general theory of similarity and analogy. The process of analogical reasoning using structure mapping process starts with a target problem, and the method spawns the subtasks of retrieving a source analogue, finding mappings between the target problem and the source analogue, transfer of knowledge from the source to the target to generate a candidate solution, evaluation of the candidate solution, and storage of the new case in memory for potential reuse. The mapping task aligns the representations of the target problem and the source case – structure here refers to the structures of the two representations, and the principle of systematicity gives preference to higher-order relations.

A comparison of our task model of biological inspired design and the theory of analogical reasoning shows several similarities and differences:

- The structure-mapping theory of analogical reasoning is problem-driven. In contrast, biologically inspired design engages two distinct processes: problem-driven analogy and solution-based analogy.
- There are broad correspondences between some subtasks in the process of analogical reasoning and subtasks in the problem-driven analogical processes of biologically inspired design. For example, the "biological solution search" task in the problem-driven analogical process corresponds to the "retrieval" subtask in the structure-mapping theory. The aggregate of "defining biological solution," "principle extraction" and "principle application" subtasks in the problem-driven process corresponds to the "mapping" and "transfer" subtasks in the structure-mapping theory.
- On the other hand, there are subtasks in the problem-driven and solution-based analogical processes of biologically inspired design that are not directly matched by subtasks in the theory of analogical reasoning. In particular, the "problem abstraction" and "solution abstraction" subtasks in our task model of biologically inspired design that are preparatory to the subtasks of retrieval, mapping and transfer that follow.
- The structure-mapping theory of analogical reasoning does not itself address problem decomposition, but it can be extended to include problem decomposition, and, with it, the use of compound analogies that may potentially be at multiple levels of abstraction.
- While the structure-mapping focuses on the structure of the representations of the target problems and the solution analogues, our task model of biologically inspired design emphasizes the role of contents of knowledge, for example, the abstraction, acquisition, and use of knowledge of the design patterns.
- Most designers typically are novices in biology, and thus most biologically inspired designers rely on interactive analogical retrieval from online information sources. This is in contrast to the structure-mapping that assumes that the source analogues are available in the long-term memory of the agent.

BioTRIZ: Vincent et al.'s (2006) BioTRIZ is an information-processing theory of biologically inspired design derived from the earlier theory of engineering invention called TRIZ (Altshuller 1984). The TRIZ theory begins with a repository of design cases with known solutions, where each case is indexed by contradictions that arose in the original design situation. For example, consider a case in the repository that represents the design of an airplane wing. In this case the designer faces the contradiction of obtaining a material that is both strong and light-weight, and solves it using a solution, say S_1. This case is then indexed by the contradiction “strong yet light-weight material.” Additionally, if the particular solution S_1 belongs to a more general way of resolving contradictions of a particular kind, it may be categorized as a generic abstraction, such as “use porous materials” (to resolve the contradiction of strong yet light-weight material). TRIZ posits the existence of 40 generic ways of resolving conflicts, called *inventive principles.* The inventive principles were extracted by dropping the specifics of a particular case and domain and retaining the essence of how a particular class of contradictions is solved, so we can imagine each principle pointing to numerous cases (potentially belonging to different domains) in which that principle was used to resolve a conflict. The contradictions and the principles are organized in a contradiction matrix.

When the designer is presented with a design problem, she reformulates the problem to identify certain key contradictions in the requirements of the design. For each contradiction, she is reminded of a general inventive principle that is applicable for resolving that conflict. In addition to suggesting the essence of a solution for resolving that conflict, the inventive principle also points to a number of cases in which that general principle was instantiated. These cases can originate from domains different from the one in which the designer is currently working. TRIZ, however, does not address the issue of how transfer occurs.

Vincent et al. (2006) recently developed a modified version of TRIZ, called BioTRIZ, specifically for biologically inspired design. The primary difference between the two theories is a change in the features that compose the contradiction matrix. Whereas TRIZ defines 39 features with which to determine contradictions and index into inventive principles, the current version of BioTRIZ has six “operational fields”: substance, structure, space, time, energy, and information.

A comparison of our task model and BioTRIZ reveals the following similarities and differences:

- Both BioTRIZ and our model address cross-domain analogies between biological and technological systems.
- BioTRIZ is a prescriptive theory of biologically inspired design, derived from best practices in mechanical engineering design. In contrast, our task model is a descriptive theory based on *in situ* observations of biologically inspired design.
- The processing in BioTRIZ is problem-driven. The processing in BioTRIZ always begins with a specification of a design problem. It does not directly address solution-based analogical process. Our task model accounts for both problem-driven and solution-based analogies.
- BioTRIZ does not directly address compound analogy. However, since a design problem may contain multiple contradictions, and the various contradictions may require the invocation of different principles, compound analogy appears to be feasible in BioTRIZ.

So Is Biologically Inspired Design Different?

The above comparative analysis brings us to the question often asked by design theorists: is biologically inspired design different from other design paradigms? After all, analogical reasoning is used extensively in other design paradigms, and cross-domain analogies often are the basis of creativity in the other design paradigms. So is analogical reasoning in biologically inspired design different from analogical reasoning in other design paradigms, other than the obvious fact the source analogues are from biology? Or, put a little differently, what precisely makes biologically inspired design a new design paradigm from the perspective of analogy and creativity?

Note that the question here is not whether biological and technological systems are different. As Vincent et al. (2006) note, “biology and technology solve problems in design in rather different ways:” biological systems often use information for functions for which technological systems tend to use energy. French (1994) and Vogel (2000) make detailed analyses of the similarities and differences between biological and technological systems: biological systems in general tend to be more multifunctional than technological systems. Instead, the question here is: are the *processes* of analogical reasoning in biologically inspired design fundamentally different from that of other design paradigms?

Our task model offers some insights into what may make analogical reasoning in biologically inspired design different from analogical reasoning in other domains, thereby making biologically inspired design a new design paradigm:

1. Biologically inspired design by definition is based on cross-domain analogies. While many design processes in and out of biologically inspired design sometimes engage cross-domain analogies, and while biologically inspired design also frequently engages within domain analogies (Vattam, Helms & Goel 2010), insofar as we know there are not many other kinds of design that by definition are based on cross-domain analogies.
2. Biologically inspired design often entails compound analogies. In particular, the target design problem is decomposed functionally, solutions to different subfunctions in the functional decomposition are found through analogy to different biological systems retrieved from a functionally indexed memory, and the overall design solution is obtained by composing the solutions for achieving the different subfunctions. While problem decomposition could be introduced into the structure-mapping theory of analogical reasoning, compound analogy appears to be a stronger characteristic of biologically inspired design.
3. Biologically inspired design engages two different analogical design processes, namely, problem-driven analogy and solution-based analogy. We first observed these two analogical processes in our *in situ* studies of biologically inspired design in practice. Insofar as we know, all information-processing theories of analogy

(e.g., Dunbar 2001; Gentner 1983; Gick & Holyoak 1983; Goel 1997; Hofstadter 1996; Holyoak & Indurkhya 1992; Thagard 1996; Keane 1988; Kolodner 1993) focus on and emphasize problem-driven analogy. Further, insofar as we know, computational theories of all other kinds of design focus on and emphasize problem-driven design (e.g., Brown & Chandrasekaran 1989; Chandrasekaran 1990; Dym & Brown 2012; French 1996; Maher & Tang 2003; Simon 1996). Therefore, that biologically inspired design entails both problem-driven and solution-based analogies appears to be another definitional characteristic of biologically inspired design.

4. Most designers typically are novices in biology, and thus most designers rely on interactive analogical retrieval from online information sources while engaging in biologically inspired design. This is in contrast to all theories of analogical reasoning that assume that source analogues are available in the long-term memory of the agent.
5. In biologically inspired design, problems and solutions co-evolve. This is similar to creative processes in other design domains but in sharp contrast to current theories of analogical reasoning.

From the perspective of creativity in design, we should add that the question here is not binary. Most of the processes that occur in biologically inspired design also occur in other creative design. Instead, the difference lies in focus and emphasis. As an example, other types of creative design often engage cross-domain analogies irrespective of the design domains, but biologically inspired design is defined by cross-domain analogies.

Conclusions

In this paper, we found that biologically inspired design indeed is a novel methodology for creative design for at least five reasons: (1) Biologically inspired design by definition engages cross-domain analogies. (2) Problems and solutions in biologically inspired design co-evolve. (3) Problem decomposition plays a fundamental role in biologically inspired design. (4) Biologically inspired design often involves compound analogy, entailing a complex interplay between the processes of problem decomposition and the processes of analogical retrieval from memory. (5) Biologically inspired design entails two distinct but related processes: problem-driven analogy and solution-based analogy. For this reason, we now prefer the term biologically inspired *invention*, as in the title of this paper: while design always starts with a problem, invention need not, sometimes starting with a solution and only later finding a problem, perhaps by serendipity.

These distinctions make for important differences in developing computational theories, techniques and tools for supporting biologically inspired design. For example, as we mentioned in the introduction, Nagle (2014) describes an engineering-to-biology thesaurus, with the (implicit) assumption that biologically inspired design is not very different from other analogy-based creative processes, that if we could only bridge the vocabulary gap between design and biology, we could borrow the rest from extant theories of design, analogy and creativity. However, if biologically inspired design is different, then we also need a different set of computational tools based on a different set of hypotheses. For example, Vattam & Goel (2013) describe Biologue, a computational tool for interactive analogical retrieval from online information sources that is based on the observation that analogical retrieval in biologically inspired design is situated online.

Further, our work on biologically inspired design indicates that research on computational creativity may need to develop new theories of analogical reasoning that incorporate a more dynamic, a more flexible view of cognition, including problem-driven and solution-based analogies, problem decomposition and compound analogies, interactive analogical retrieval, and problem-solution coevolution. This makes for an exciting research agenda in computational creativity.

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