**Advances in Natural Science**
**Vol. 3, No. 2, 2010, pp. 27-40**
**www.cscanada.net**

**ISSN 1715-7862 [PRINT]**
**ISSN 1715-7870 [ONLINE]**
**www.cscanada.org**

*The 3rd International Conference of Bionic Engineering*

# Evaluating Biological Systems for Their Potential in Engineering Design

**Jeannette Yen**[1]

**Michael Helms**[2]

**Swaroop Vattam**[3]

**Ashok K. Goel**[4]

**Abstract:** A team of biologists, engineers, and cognitive scientists has been working together for the past five years, teaching an upper level undergraduate course in biologically inspired design where half the class of forty students are biologists and other physical scientists and the other half are engineers (mechanical, materials, industrial, others). From this experience, we provide insights on how to teach students to evaluate biological systems for their potential in engineering design. We have found that at first, students are not familiar with developing their own question since, in most engineering design classes, the problem is prescribed along with clients who would like to have them solved. In our class, we challenge the students with defining a significant problem. The students with common challenges then are placed together in an interdisciplinary team with at least one biologist and one engineer. A detailed problem decomposition follows, identifying the hierarchy of systems and clearly specifying functions. This is essential for the next step of analogical reasoning. Analogical reasoning as applied to BID is a process of matching biological functions to engineered functions and transferring functions and mechanisms from biology to engineering. For each desired function, students may ask: what mechanisms does nature use for achieving the function? This question guides the exploration of the wealth of knowledge in biology by asking them to clearly define the function of interest, then search for natural processes that perform this function. To expand on this search space, the students next make a list of the same function performed by other organisms for a comparative analysis to deepen their understanding and extract key biological principles. Students then invert the function and identify keywords to search. They also must refer to general biology books to identify key organisms that perform the function the best (and hence are included in textbooks). Using databases, such as the Web of Science functions, they can try to select the 'best' articles. If one is lucky, a single biological system may serve

[1]Center for Biologically-Inspired Design Georgia Institute of Technology Atlanta, GA. 30332, USA.
[2] Center for Biologically-Inspired Design Georgia Institute of Technology Atlanta, GA. 30332, USA.
[3] Center for Biologically-Inspired Design Georgia Institute of Technology Atlanta, GA. 30332, USA.
[4] Center for Biologically-Inspired Design Georgia Institute of Technology Atlanta, GA. 30332, USA.
*Received 2 May 2010; accepted 6 July 2010

as a near perfect match to lead to a successful BID. However, some of the most innovative designs are built from more than one biological system, something that evolution cannot always do. We call these compound analogies. At this point, the design iteration can take on a different approach, namely solution based rather than problem based. Here, the team takes a natural system and asks, how can this biological principle improve an engineered design or function. These twin processes: solution vs problem-based approaches both have led to innovative and creative design concepts in this interdisciplinary class.

**Key words:** Biological systems; engineering design; interdisciplinary class

# INTRODUCTION

When Sir Georg Maestral removed the burrs from his dog's fur which inspired the invention of Velcro, did he know how pervasive his invention would become? Kids now don't need to learn how to tie their shoes because of Velcro fasteners, and arthritic hands can easily attach clothing without managing with buttons, zippers and hooks. Yet it took 50 years (Maestral's patent was filed in 1951) before scientists took another leap in the field of biomaterials, specifically bioadhesives, to transfer the principle by which geckos adhere to surfaces to 'stickybo, gecko tape, and its offspring (Autumn et al. 2000, Full et al. 2004: US Patent No. 6,737,160.).

As we catch this intensifying wave of interest in biologically inspired design (Bonser & Vincent 2007), designers in all fields seek methods that have proven useful in selecting the biological system with the potential to change the world. Convergent evolution, where organisms from completely different lineages arrive at the same solution to similar conditions is one means to identify key biological mechanisms that may be useful for engineered design. Many different lineages of organisms all evolved the ability to stick to surfaces using van der Waals forces and this principle has prompted today's research on bioadhesives. It may be most useful to start with these solutions when translating them into engineered designs. The biological principle of self cleaning of the Lotus plant has led to over 200 patents. What are other successful BIDs? Why are they successful? We propose that it is the process that enhances the product. In this paper, we would like to share how the synergy between biologists, engineers and cognitive scientists has defined a process that may be useful for interdisciplinary research and education where BID serves as an excellent means toward this transformative effort.

# ANALOGY EXERCISES

As alluded to in our companion paper (Weissburg, Tovey & Yen 2010), in practice, BID is a technique for complex problem solving using analogical design. Novel designs in one domain (engineering, architecture, etc.) are created by drawing upon solutions and patterns in the different domain of [e.g. biology; Bar-Cohen, 2006; Benyus, 1997]. Recent research on design, especially creative design, has explored the use of analogies in proposing solutions to design problems in the conceptual phase of the design process [e.g., Qian & Gero, 1996; Goel, 1997; Goel & Bhatta, 2004; Casakin & Goldschmidt, 1999; Gross & Do, 1995; Mostow, 1989; Hey et al. 2008; Davies et al., 2009]. Recognition of BID as a process of analogical transfer also has led to a few cognitive studies (Mak & Shu 2008; Linsey et al. 2008) as well as computational tools for supporting biologically inspired design [Chiu & Shu 2005, 2007; Chakrabarti et al., 2005; Sarkar & Chakrabarti 2008; Vattam et al. 2010b; Bruck at al. 2007]. However, BID remains cognitively challenging despite the advancement of relevant theories and supporting tools. Here, we present the results of five iterations of teaching a semester-long course by a team of biologists, engineers and cognitive scientists. They have been working together, team-teaching an upper level undergraduate course in biologically inspired design where half the class of forty students are biologists and other physical scientists and the other half are engineers (mechanical, materials, industrial, others). Our first iterations of the BID course implicitly incorporated many ideas and techniques of analogical reasoning. However, over the last few years we have made several empirical findings about analogical reasoning in BID [e.g., Helms et al., 2008, 2009; Vattam et al., 2007, 2009, 2010a]. We then analyzed these findings from the perspectives of design theory and design cognition, and identified several patterns of content and process of analogies in BID, e.g., problem-driven and solution-based processes of BID [Helms et al. 2008, 2009; Vattam et al. 2010a], and compound analogy [Helms et al., 2009; Vattam et al., 2010a]. Over time, we explicitly included these content and process accounts into our teaching. From this experience, we provide insights on how to teach students to evaluate biological systems for their potential in engineering design.

## SEARCH STRATEGIES

Our class is comprised of undergraduates in engineering and biology who have not taken classes together before and therefore may have difficulties communicating to each other (Fig. 1).


**Figure 1**

To begin the process of breaking down barriers of communication between disciplines, we chose to form interdisciplinary design teams of engineers and biologists where the complementary skills of both engineers and biologists can be taken advantage of. When the divide between these disciplines narrows and a common knowledge base is formed where principles are recognized, an effective efficient search strategy needs to be practiced to deepen an understanding and facilitate the ability to articulate these principles. Currently, we ask the students to search the biological literature, using keywords. Three approaches are used to obtain keywords: functional indexing, inverted function, and model systems.

We have found that in general the larger number of function matches, the better is the final design. This requires a shared, interdisciplinary language, and we provide the structure-behavior-function (SBF) language to serve as the communication link between unlikely disciplines. Once the students learn how to use the SBF language (Goel & Stroulia 1996; Prabhakar & Goel 1998; Goel, Rugaber & Vattam 2009), both biological and mechanical functions become clearer and the analogies can be more easily made.

*Case Study:*
To explain how we use these approaches, we present an example from our 2009 class where one of our challenges was to understand how nature conserves water, the essence of life. By selecting an issue of topical interest globally, students immediately were engaged in a design that matters. Motivation was spurred with statements backed by data such as these:

1. Of the 6 billion people on earth, 1.1 billion do not have access to safe, clean drinking water. (www.charitywater.org)
2. The U.S. Environmental Protection Agency currently does not regulate 51 known water contaminants. (www.foodandwaterwatch.org)
3. While the average American uses 150 gallons of water per day, those in developing countries cannot find five. (www.charitywater.org)
4. The water and sanitation crisis claims more lives through disease than any war claims through guns. (www.water.org)
5. According to the National Resources Defense Council, in a scientific study in which more than 1,000 bottles of 103 brands of water were tested, about one-third of the bottles contained synthetic organic chemicals, bacteria, and arsenic. (www.nrdc.org)
6. Water is a $400 billion dollar global industry; the third largest behind electricity and oil. *CBS News, **FLOW**.*
7. There are estimates that from five hundred thousand to seven million people get sick per year from drinking tap water. *Erik Olson, Deputy Staff Director of Barbara Boxer's Environmental and Public Works Committee (EPW), **FLOW**.*
8. California's water supply is running out – it has about 20 years of water left in the state. *Maude Barlow, author of Blue Covenant and co-author of Blue Gold, National Chairperson of the Council of Canadians, **FLOW**.*
9. There are over 116,000 human-made chemicals that are finding their way into public water supply systems. William Marks, author of Water Voices from Around the World, ***FLOW***.
10. In Bolivia nearly one out of every ten children will die before the age of five. Most of those deaths are related to illnesses that come from a lack of clean drinking water. *Jim Schultz, founder of the Democracy Center in Bolivia, **FLOW**.*
11. The cost per person per year for having 10 liters of safe drinking water every day is just $2 USD. *Ashok Gadgil, Senior Staff Scientist in the Lawrence Berkeley National Laboratory, **FLOW** .*

The class voted on student-suggested topics to identify key issues of common interest to the majority of the class (Fig 2).

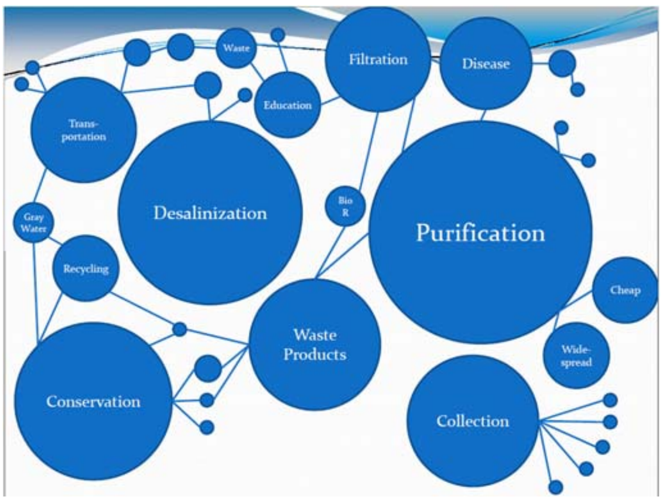



**Figure 2: The size of the bubble corresponds to the #votes given by the class for a particular concept presented by one of their classmates that addressed the challenge of water conservation**

To search the databases, we constructed the following table to identify keywords. Keywords were identified by function, by inverting the function, or by going to a general biology text or 'google' search for model organisms that have adapted well to certain environments subject to extremes in water availability.

**Table 1: Sample search criteria to retrieve information from databases that address the challenge: how does nature conserves water. The specific challenge was simply described as: "water scarcity"**

| Technique | Result |
|---|---|
| Functional Indexing<br>WATER SCARCITY | Water purification<br>Water filtration<br>Water collection<br>Water storage<br>Water transport |
| Model Systems | Lotus flower<br>Kelp<br>Ecosystem<br>Namibian beetle<br>Transpiration in trees<br>Egg shell<br>Camel<br>Sweat and pant<br>Leaf structure<br>Tardigrade |
| Inverted Function<br>WATER OVERUSE | Evaporation<br>Leakage<br>Flooding<br>Reduce need of water |

Working with the class, we noted that a good problem definition is difficult. Because problem statements were generally vague, we recommended that the class perform an ethnographic analysis and consider who was involved and what their constraints were. To sharpen the definition of the problem, students needed to state what function their design would provide under what conditions and environmental constraints as well as determine when the device could be deployed. Because many problem statements assumed a solution, we asked them to carefully consider the mechanism and materials needed for a feasible design. We concluded the lesson with a description of different angles on looking to nature for design inspiration.

Bio-utilization takes the actual natural system and places them in a situation to target a specific problem and thus maximizes the benefit of their natural function. Copying can be done on a macroscopic level, but it is unlikely to use the principles of nature at the microscopic level. Instead, learning from nature and applying principles releases us from structural constraints to focus on achieving functional fidelity that can be useful in many more designs.

## PROBLEM DECOMPOSITION

Once students attain a deeper understanding of the biological principles from reading the primary literature, they are ready for the process of translation from biology to engineering. This requires both problem decomposition and analogical reasoning. For problem decomposition, the designer iteratively decomposes the presented problem into sub-problems to create a problem hierarchy. Assuming that the problem is decomposed along functional lines (other decompositions are possible), each node in this hierarchy is a function to be achieved. When developing these problem decompositions, each function can be used as a cue to retrieve known solutions that achieve that function, thus expanding the number of alternative solutions. Solutions are transferred to the current problem, and aggregated to generate the overall solution.

A representative decomposition (**Figure 3**) illustrates one potential functional analysis of the process of filtering unwanted particles out of air. This particular decomposition was derived collectively by the class as an instructor-led in-class exercise.


**Figure 3: Functional decomposition for air filtration**

Three key functions of air filtration are injecting unfiltered air into the filtration system, removing the particles from the air, and releasing the air back into the household, forming the first level of the hierarchy of the decomposition. To achieve the function of removing the particles, the system can either adhere to particles as they pass by, or can prevent particles passing through. The adhere to particles sub-function appeals to some notion of how the lung operates, where mucous in the lining of the lungs captures particles as they come in contact with it. This technique requires further sub-functions, including maximizing the surface contact area, and disposing of captured particles. The function of matching the underlying capturing medium to the particle-type suggests students are considering the problem at finer and finer scales, and bringing to bear concepts of bonding at chemical/molecular levels. It is not uncommon for scales to change across or even within levels of the decomposition. Note however, for these problem decompositions there are no right or wrong decompositions, only more or less useful ones.

To be more useful, it is important to identify functions, clearly articulating why the system performs these functions. Deep thinking about the behavior requires understanding how the function works, and the mechanisms and processes involved. Awareness of common principles helps to abstract to higher-level more general functions that may be applied more universally, thus expanding the usefulness. While it is necessary to play with the arrangement to make the best links from structures to mechanisms to functions, one also must make commitments and move on.

We show how an analysis of plant growth provided inspiration for improving solar energy conversion (**Figure 4**). Here both the natural solution and the problem have been decomposed into functions until finally a level is reached where functions overlap and a crossover can occur. In this example, the interaction of surface structural properties and ambient water was the inspiration for a self-cleaning mechanism. This functional decomposition shows how deep our understanding was needed to understand the source of inspiration.

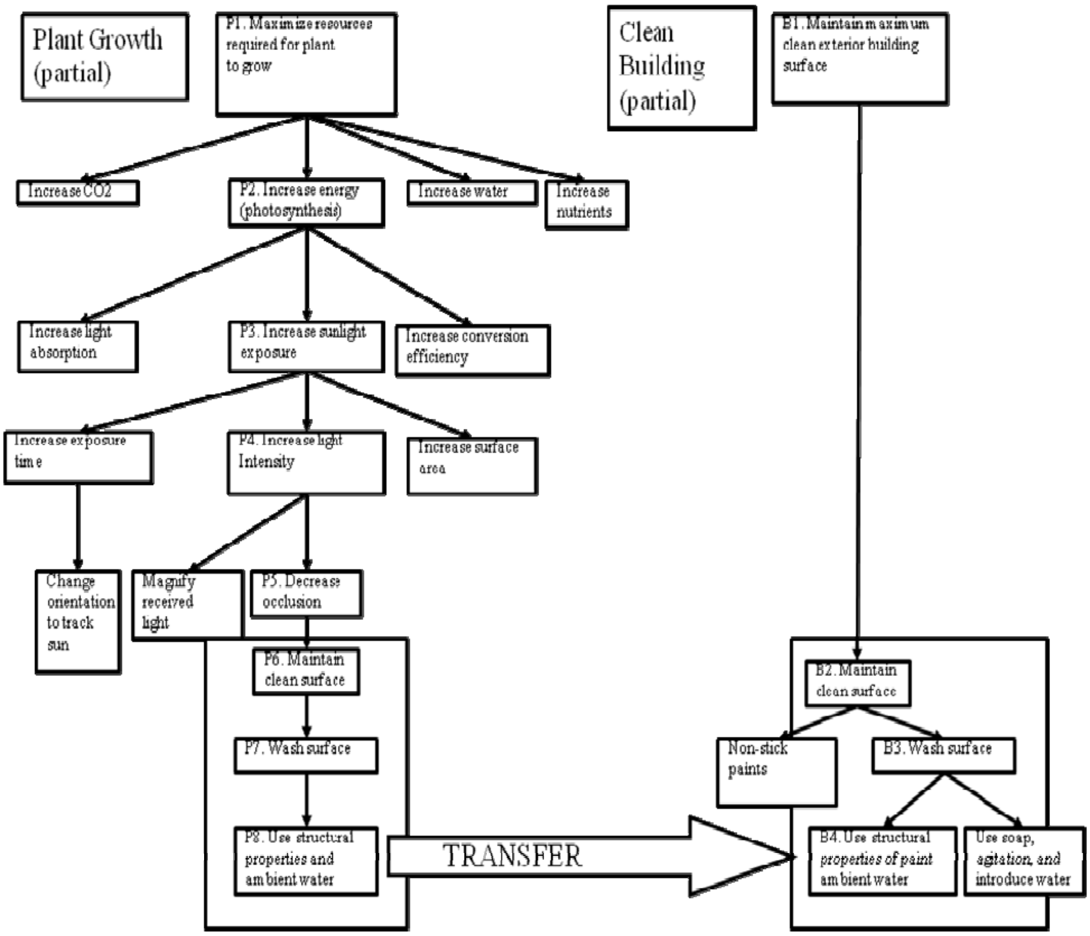



**Figure 4: The functional decomposition of the process of plant growth was constructed in parallel to similar analyses of the problem of solar energy conversion. By specifying the structures and processes involved in the mechanism of photosynthesis by the plant and the mechanism of photon conversion in solar collectors, a common solution -- use of structural properties and ambient water to keep surfaces free of debris that could occlude light capture -- led to a bio inspired solution of self cleaning photovoltaic surfaces. [Adapted from Vattam et al., 2007]**

## COMPOUND ANALOGIES IN BID

Our analyses of the design products and processes in BID revealed a complex interplay between solution knowledge, analogical references and problem understanding, leading to the incremental, iterative development of compound analogical solutions. In short, the process of compound analogy involves the use of two or more analogies in the design of a target system [Helms et al., 2008, 2009; Vattam et al., 2010a]. Beginning with an initial problem description P1, one is reminded of an initial source S1 (**Figure 5, 6**). During the process of transferring information from the source to the target problem, a greater understanding of the target problem evolves. The new understanding P2 may include new sub-problems, constraints, or functions to be accomplished, which may in turn remind one of an additional source S2. This additional source then may be applied to the new problem to yield a yet more elaborate problem description P3. This problem description and its resulting solution is said to be a compound analogy as it is a result of the application of more than a single analogical transfer. Figure 5 illustrates how a problem, decomposed into its functions, can be mapped onto or matched to a series of analogues.

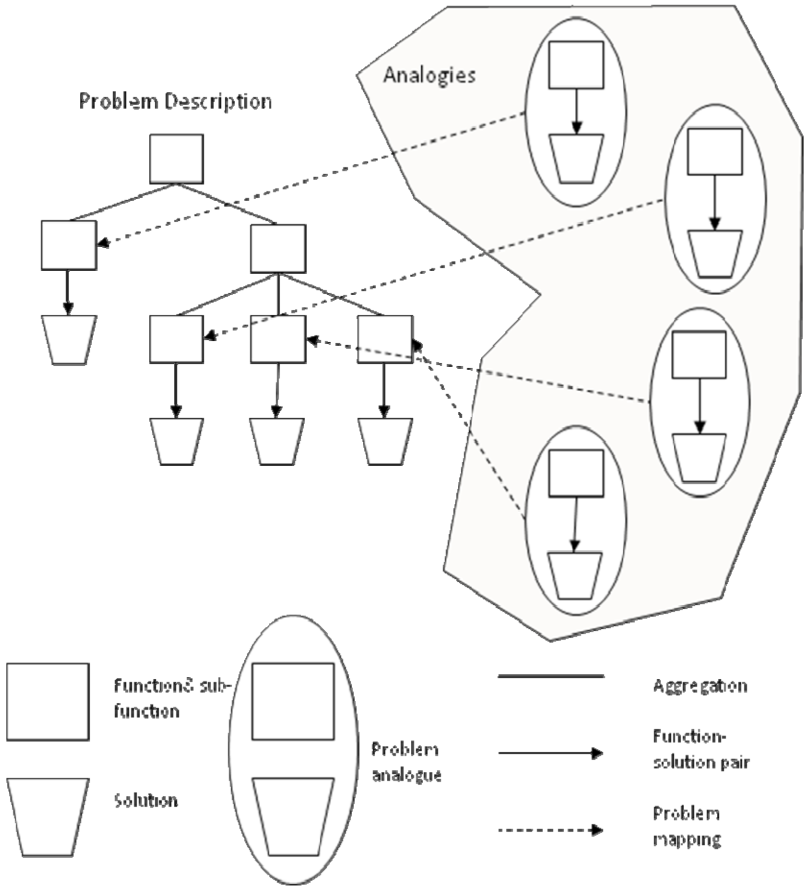



**Figure 5: Analogical generation of a problem description, where analogical reasoning matches functions of the problem to those found in the natural systems (Helms et al. 2008)**

We draw two main conclusions from our analysis. First, successful BID requires that designers carry representations of previous problems that are organized at different levels of abstraction and aggregation. This organization facilitates the decomposition of solutions and allows solution analogues to be retrieved with cues taken from each level. Second, the mapping between the problem space and a target solution allows for identification of potential new solutions, but also permits inferences about problem decomposition. The design problem therefore evolves as a result of the interplay between problem decomposition and the analogy-making process. The use of compound analogies illustrates that value of incorporating principles that are deeply understood, instead of mimicking a given system. It results in creative solutions that incorporate diverse principles that may not be found in a single natural example (e.g. 'geckel' combines adhesion of geckos and mussels: [Lee et al., 2007]). It also facilitates reevaluation and reinterpretation of the design problem, and refinement of potential solutions.

This process explains complications that often arise during reintegration when the solutions from disconnected analogies do not integrate cleanly at their boundaries, or have overall constraint mismatches. Each new node from the source solution decomposition integrated into the problem space can act as an additional cue for retrieving another set of solution analogues. This process can continue iteratively leading to the incremental development of the problem space. At every stage of this iterative process, the designer can evaluate the partial solutions available and decide to take further actions. The iterative feedback between these two processes accounts for the incremental evolution of design problems.

If necessary, they use this feedback to refine and redefine their problem. We find that establishing the salience of biology to engineering is strengthened by showing similarity of constraints as well as problems. Clearly, the analysis of function as both an engineering and a biological pursuit helps define a common problem framework.

## MULTIFUNCTIONAL DESIGN AND PROBLEM-DRIVEN VS. SOLUTION-BASED BID

Multiple problems (**Figure 6**: P 1-5) often can be addressed by a particular natural solution due to the multifunctionality of natural systems. An example of a problem having more than one primary function is how the bullet proof vest provides both impact and puncture resistance. Hence, a single analogous natural system, such as an abalone shell, potentially may be applied to more than one problem and represents a multi-functional solution. Interestingly, we've noticed that multifunctional solutions are more likely to arise when students use a solution-driven vs. a problem-driven approach.

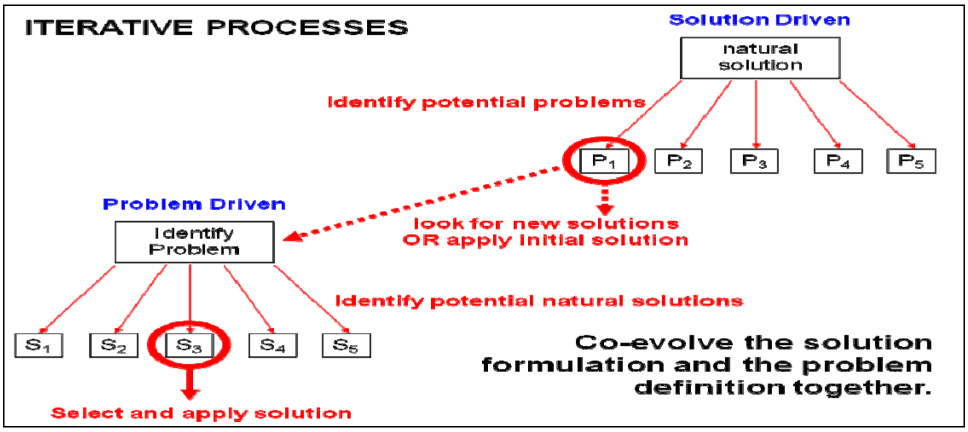
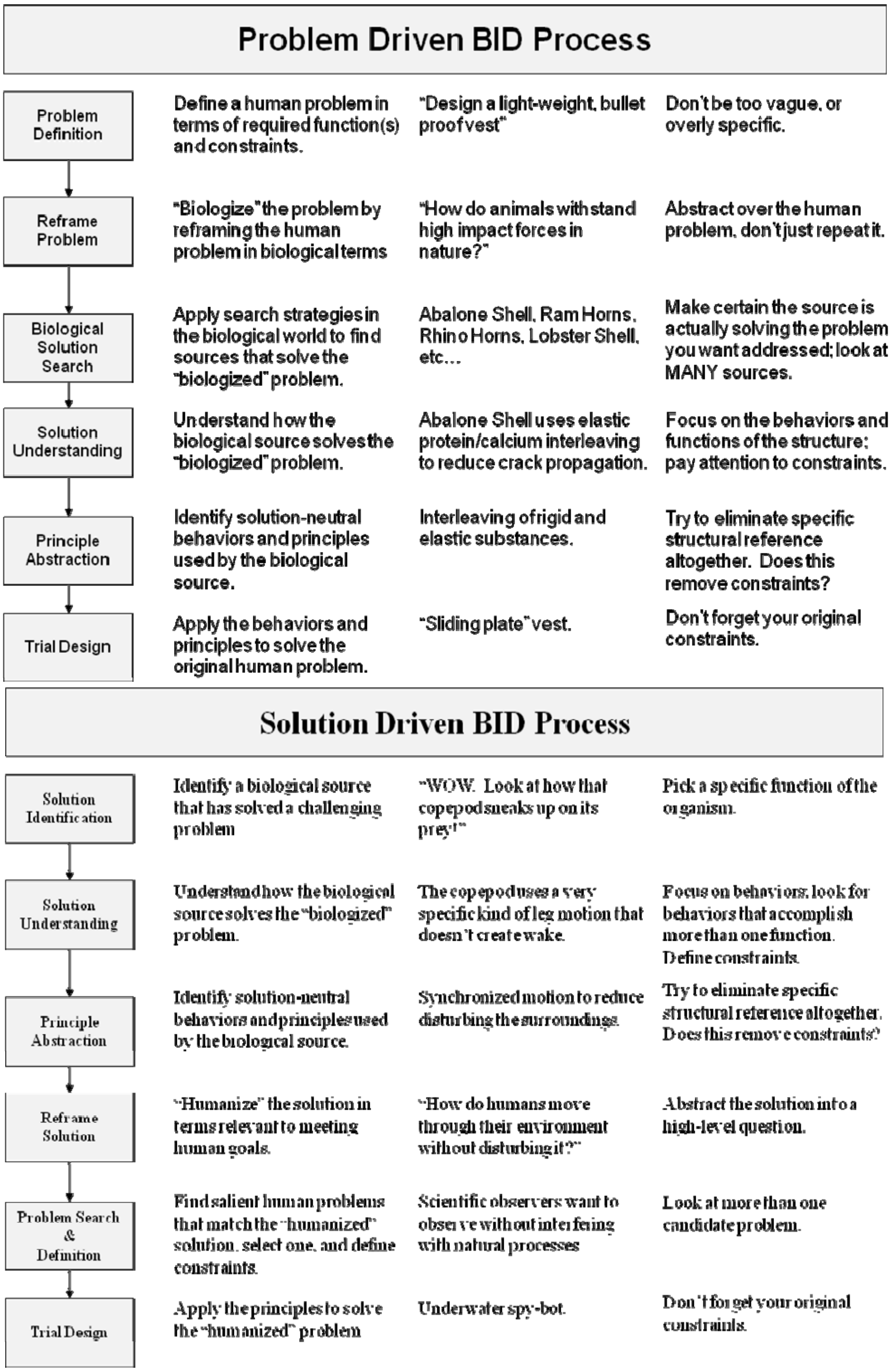



**Figure 6: A single natural solution (on the right) may solve one or more problems; one problem (on the left) can in turn be solved by one or more natural solutions**

Hence, the BID can be motivated by a technological problem or potentially useful biological properties (problem- vs- solution driven approaches; [Helms et al 2008; **Figure 7**]). Both approaches have resulted in the successful application of biological concepts to technological challenges [Yen and Weissburg, 2007]. The usual problem-driven design process (**Figure 7a**) begins with a technological challenge, such as designing a lightweight bullet proof vest, which we put before students as an exercise. We used functional indexing and reframed the problem in biological terms by asking: "How do animals withstand high impact forces in nature?" Subsequent biological literature searches revealed how different organisms withstood impact using structures with unusual construction that dissipate impact forces (ram's horn, abalone shells, and lobster carapace). The search also identified articles explaining these phenomena from a materials standpoint, with one potential mechanism consisting of the interleaving of rigid calcium carbonate tiles and elastic protein layers [Lin and Meyers, 2005]. The general principle of offset rigid structures with flexibility imparted by more elastic layers inspired a design for a 'sliding plate' vest. In contrast, the solution-driven process searches for a problem that can be solved by a selected natural system. In this example (**Figure 7b**), a series of articles described how an aquatic microcrustacean was able to approach a prey stealthily, using a specific kind of leg motion [van Duren and Videler, 2003] that creates a laminar wake with minimal water disturbance [Yen and Strickler, 1996]. Synchrony in the propulsion mechanism provided a general mechanism for stealth in water. Reframing the solution in terms relevant to meeting human challenges, the problem was defined by asking this question, 'How can humans move through their environment without disturbing it?' This led to the implementation of a novel mechanism for an underwater spy-bot which could be used to observe without interfering with natural processes.




a.

b.

**Figure 7: a) Problem-driven bio-inspired design process. Reframing the problem in terms of natural processes is a key step in bio inspired design. Principle abstraction allows the natural solutions to**

**find a broader range of application to technological challenges. b) Solution-driven bio-inspired design process. Often, the particular way that an organism solves a problem is so unique and fascinating that it drives the process to reverse engineer nature, searching for a human challenge that could be solved by the natural process. Again principle abstraction is an essential step in enabling a successful translation of natural functions to technological mechanisms**

Clearly, biological knowledge provided inspiration for novel designs through both the problem-driven as well as the solution-driven processes. Still, we see evidence that solution-driven and problem-driven approaches are different with respect to the final design outcome. An analysis of 9 BID design projects in Fall 2006 showed: 1) solution fixation limited the solution- driven design process; 2) multifunctionality dominated the solution-driven process; and 3) solution-driven approaches had a strong structural focus possibly the result of limited incubation time or limited understanding of the mechanisms responsible for the function.

These results make plain the different advantages of each approach, and possibly reveal something about the underlying design process. Whereas solution-centered approaches produce fixation probably because of the strong initial focus on a particular organism, the problem-driven approach tends to restrict the ability of the designer to reach outside of their initial framework and engage multi-functionality. Thus, we believe it is critically important to encourage students to iterate the process and switch between problem and solution focused approaches. Just as the iteration between technological problem and biological analogies may drive innovative compound solutions, it also may drive expansion and redefinition of the problem to incorporate multifunctionality, and in complimentary fashion, reduce the tendency towards design fixation.

## DISCUSSION AND CONCLUSIONS

Biologically inspired design captures the imagination of people from many fields. Learning how this process works and using this approach trains us to think “outside the box” and find links between different disciplines. Perhaps for this reason, as well as the success of BID in developing new products or processes [Bonser & Vincent 2007; Vincent et al. 2006], there has been increasing interest in teaching BID.

A central issue is that we currently lack strong cognitive science accounts of the thinking processes that underlie BID, and the necessary elements for successful teaching are not currently clear. Still, there is some consensus that BID requires the ability to describe function of human and biological systems, and the effective use of analogy. Vincent and colleagues (Vincent et al. 2006) have pioneered the use of TRIZ as a system to accomplish these goals. TRIZ is a method to describe principles that underlie function and define analogies between systems on the basis of shared properties. It can be very useful in identifying potential biological principles for a given problem, but it is not a cognitive science account of the underlying thinking process.

One limiting factor in BID is domain-specific terminology that diminishes the ability of biologists and engineers to indentify equivalent systems or principles across their respective fields [e.g. Chiu and Shu, 2005].. Computational tools are being developed that help non- biologists to retrieve information from the biological literature [Bruck et al. 2007; Chakrabarti et al., 2005; Sarkar & Chakrabarti, 2008; Chiu & Shu 2005, 2007; Vattam et al. 2010b]. These often take the form of libraries or repositories that allow students to find relevant examples, or systems for natural-language searching of the literature that help reduce the burden of field-specific terminology.

Another limitation is that true transference of biological principles requires the fabrication of a device or the development of a process based on the biological principle. Our 15-week course stops short of this goal as a result of our decision to focus student’s attention on using BID during the initial concept generation, and surveying different areas of BID. Students clearly do not have the benefit of translating their principles into a realized device where they may understand more fully the relevant principles, and gain valuable experience in understanding the steps required to engineer complex systems [Bruck et al. 2007]. Covering a more limited topical area (e.g. robotics, materials), and providing students knowledge required to fabricate their devices can result in students developing many of the same skills as we sought to encourage in our own course [Bruck et al. 2007]. Whether to pursue a more limited subject area and proceed all the way to fabrication (i.e. a vertical approach) vs. a more comparative course stressing the role of BID in ideation (i.e. our horizontal approach) may depend on the student population, and the extent to which grounding in particular technical approaches is desired. Technical expertise is more likely to result from a more focused, vertical organization around a given subject area.

In terms of design theory, there is a need for a theoretical approach for what *content* from the biological world is applicable for design. A formal design process and theory that leverage cognitive science, learning theory, engineering education, and design theory can improve how we teach and how well we can learn to use this process. Metrics for evaluating the output, in terms of creativity, communication, cross domain transfer and design skills are needed. BID can be used to bring science out of academia and increase the respect people have for nature as a mentor and source of knowledge for practical devices, materials and processes.

## ACKNOWLEDGEMENTS

Marc Weissburg and Craig Tovey have been our close partners in developing, teaching and assessing the course on biologically inspired design described in this paper. This work has also benefited from many discussions with Bert Bras, David Hu, Brent Nelson, Wendy Newstetter and David Rosen. This research has been generously supported by US National Science Foundation, through the Division of Undergraduate Education grant (#0737041) entitled "Biologically Inspired design: A Novel Interdisciplinary Biology-Engineering Curriculum and recently through a CreativeIT grant (#0855916) entitled "MAJOR: Computational Tools for Enhancing Creativity in Biologically Inspired Engineering Design." We thank the hard work and creative intellect of the bright undergraduate students at Georgia Tech who have taken our class over the past several years.

## REFERENCES

Autumn, K. (2006). Properties, Principles, and parameters of the gecko adhesive system In, *Biological Adhesives*, ed. A.M. Smith and J. A. Callow, Springer-Verlag, Heidelberg. pp. 225-256.

Autumn, K., Liang, Y. A., Hsieh, S. T., Zesch, W., Chan, W.-P., Kenny, W. T., Fearing, R. and Full, R. J. (2000). Adhesive force of a single gecko foot-hair. *Nature 405*, 681-685.

Bar-Cohen, Y. (2006). *Biomimetics. Biologically inspired technologies.* Taylor and Francis Group, LLC.

Benyus, J. (1997). *Biomimicry: innovation inspired by nature*. New York: HarperCollins.

Bonser, R.H.C. and J. F.V. Vincent. (2007). Technology trajectories, innovation,and the growth of biomimetics. *2007 Proc. IMechE. 221 C: J. Mechanical Engineering Science.*

Bruck, H. A., Gershon, A. L., Golden, I., Gupta, S. K., Gyger, L. S., Magrab, E. B. and B. W. Spranklin (2007). Training mechanical engineering stuents to utlize biological inspiration during product development. *Bionispiration and Biomemetics 2,* S198-S209.

Casakin, H.and G. Goldschmidt. (1999). Expertise and the use of visual analogy: Implications for design education. *Design Studies 20*: 153-175.

Chakrabarti, A., P. Sarkar, B. Leelavathamma, and B. S. Nataraju. (2005). A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas. *Artificial Intelligence for Engineering Design Analysis and Manufacturing. 19:* 113-132.

Chiu, I., and L. H. Shu. (2005). *Bridging cross-domain terminology for biomimetic design.* Paper presented at the 2005 IDETC Design Theory and Methodology, Long Beach, CA.

Chiu, I., and L. H. Shu. (2007). Biomimetic design through natural language analysis to facilitate cross-domain information retrieval. *Artificial Intelligence for Engineering Design Analysis and Manufacturing 21:* 45-59.

Davies, J., A. Goel and N. Nersessian. (2009). A computational model of visual analogies in design. *Journal of Cognitive Systems Research, Special Issue on Analogies - Integrating Cognitive Abilities 10:* 204-215.

Full, R.J., R. S. Fearing, T. W. Kenny, K. Autumn. (2004). *Adhesive microstructure and method of forming same (part 1).* US Patent No. 6,737,160.

Goel, A., S. Rugaber and S. Vattam. (2009). Structure, Behavior and Function of Complex Systems: The Structure, Behavior, Function Modeling Language. *International Journal of AI in Engineering Design, Analysis and Manufacturing, Special Issue on Developing and Using Engineering Ontologies 23:* 23-35, 2009.

Goel, A.,and S. Bhatta. (2004). Use of design patterns in analogy-based design. *Advanced Engineering Informatics 18*: 85-94.

Goel, A. and E. Stroulia. (1996). Functional device models and model-based diagnosis in adaptive design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Special issue on functional representation and reasoning 10*: 355-370.

Goel, A. (1997). Design, analogy, and creativity. *IEEE Expert-Intelligent Systems and their Applications 12*: 62-70.

Gross, M. and E, Do. (1995). Drawing analogies - supporting creative architectural design with visual references. in *3d International Conference on Computational Models of Creative Design,* M-L Maher and J. Gero (eds), Sydney: University of Sydney 37-58.

Helms, M., S. Vattam, A. K. Goel, J. Yen, and M. Weissburg. (2008). Problem-driven and solution-driven design: twin processes of biologically inspired design. In *Proc. ACADIA-2008.*

Helms, M., S. Vattam and A. Goel. (2009). Biologically inspired design: products and processes. *Design Studies 30:* 606-622.

Hey, J., J. Linsey, A. Agogino & K. Wood (2008). Analogies and Metaphors in Creative Design. *International Journal on Engineering Education, 24(2):* 283-294, 2008.

Lee, H., B.P. Lee and P. B. Messersmith. (2007). A reversible wet/dry adhesive inspired by mussels and geckos. *Nature 448:* 348-344.

LI, CHEN, P.B. Umbanhowar, H. Komsuoglu, D. E. Koditschek, and D. I. Goldman. (2009). Sensitive dependence of the motion of a legged robot on granular media. *Proceedings of the National Academy of Sciences, USA 106:* 3029–3034.

LIN, A., and M.A.Meyers. (2005). Growth and structure in abalone shell. *Materials Science and Engineering A 390:* 27–41.

Linsey, J., Wood, K., & Markman, A. (2008). Modality and Representation in Analogy. *Artificial Intelligence for Engineering Design and Manufacturing. Special issue on multi- modal design, Goel, Davis & Gero (editors). 22(2):* 85-100.

Mak, T., & Shu, L. (2008). Using descriptions of biological phenomena for idea generation. *Research in Engineering Design, 19:1*:21-28.

Nakrani, S., and C. Tovey. (2004). On honey bees and dynamic server allocation in Internet hosting centers. *Adaptive Behavior 12*: 223-240.

Prabhakar, S., and A. Goel. (1998). Functional modeling for enabling adaptive design of devices for new environments. *Artificial Intelligence in Engineering 12:* 417-444.

QIAN, L., and J. S. Gero. (1996). Function-Behavior- Structure paths and their role in analogy-based design. *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing 10*: 289-312.

Sarkar, P., and A. Chakrabarti, (2008). The effect of representation of triggers on design outcomes. *Artificial Intelligence for Engineering Design and Manufacturing. Special issue on multi- modal design,* Goel, Davis and Gero (editors). 22(2).

Schild, K., C. Herstatt, and C. Luthje. (2004). How to use analogies for breakthrough innovations. *Hamburg, Germany: Technical University of Hamburg.63:*495-508.

van Duren LA, and J.J. Videler. (2003). Escape from viscosity: the kinematics and hydrodynamics of copepod foraging and escape swimming. *Journal of Experimental Biology 206:* 269-279.

Vattam, S., M. Helms and A. Goel. (2007). *Biologically-inspired innovation in engineering design: a cognitive study*. Technical report, Graphics, Visualization and Usability Center, Georgia Institute of Technology, GIT-GVU-07-07.

Vattam, S., M. Helms and A. Goel. (2009). Nature of Creative Analogies in Biologically Inspired Innovative Design. In, *Proc. Seventh ACM Conference on Creativity and Cognition,* Berkeley, California, October.

Vattam, S., M. Helms, and A. Goel. (2010a). Biologically Inspired Design: A macrocognitive account. In *Proc. 2010 ASME Conference on Design Theory and Methods,* Montreal, Canada, August 2010.

Vattam, S., Wiltgen, B., M. Helms, A. Goel and Yen, J. (2010b). DANE: fostering creativity in and through biologically inspired design. *Proccedings First International Conference on Design Creativity*. Kobe, Japan.

Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A. and A.-K. Pahl. (2006). Biomimetics: its practice and theory. *Journal of the Royal Society Interface 3*, 471-482.

Vincent, J. F., and D. L. Mann. (2002). Systematic technology transfer from biology to engineering. *Philosophical Transactions: Mathematical, Physical, and Engineering Sciences 360:* 159-173.

Weissburg, M., C. Tovey & J. Yen (2010). Enhancing Innovation through Biologically Inspired Design. To appear in *Proc. Third International Conference on Bionic Engineering,* China.

Yen, J. and M.J. Weissburg. (2007). Perspectives on biologically inspired design: introduction to the collected contributions. *Bioinspiration and Biomimetics 2:* DOI 10.1088/1748-3190/2/4/E01

Yen, J. and J.R. Strickler. (1996). Advertisement and concealment in the plankton: What makes a copepod hydrodynamically conspicuous? *Invertebrate Biology115*: 191-205.