Biologically-Inspired Innovation in Engineering Design: A Cognitive Study

Swaroop Vattam, Michael Helms, and Ashok K. Goel
Design Intelligence Laboratory
School of Interactive Computing
Georgia Institute of Technology
Email: {svattam, mhelms3, goel} @cc.gatech.edu

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Abstract: Biologically-inspired design uses analogous biological phenomena to develop solutions for engineering problems. Understanding, learning and practicing this approach to design is challenging because biologists and engineers speak different languages, have different perspectives on design, with different constraints on design problems and different resources for realizing an abstract design. In Fall 2006, we attended ME/ISyE/MSE/PTFe/BIOL 4803: Biologically-Inspired Design, an interdisciplinary introductory course for juniors and seniors offered at Georgia Tech. We collected course materials, took class notes, observed teacher-student and student-student interactions in the classroom. We also observed some sessions of a few interdisciplinary teams of students engaged in their design projects outside the classroom. We then analyzed the observations in terms of existing cognitive theories of design, modeling, and analogy. The goals of this cognitive study were to (1) understand the cognitive basis of biologically-inspired innovation in engineering design, (2) identify opportunities for enabling more effective learning of biologically-inspired design, and (3) examine the implications for developing computational tools for facilitating effective biologically-inspired design. This report summarizes our main observations about learning biologically-inspired design, and presents our preliminary analysis of biologically-inspired design in a classroom setting.

Keywords: Biologically-Inspired Design, Biomimetic Design, Engineering Design, Biological Systems

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Outline:

Section 1: Introduction

1.1 Biologically-Inspired Innovation

Biologically-inspired design (or BID) has become an important and increasingly wide-spread movement in design for environmentally-conscious sustainable development (e.g., Benyus 1997). By definition, BID is based on cross-domain analogies; further, biologically-inspired approaches to design have a certain degree of openness to innovation. From the perspective of cognitive science, and especially that of design cognition, four factors make BID an especially interesting problem to study. (1) Since the objects, relations and processes in biology and engineering are very different, biologists and engineers typically speak a very different language, which makes communication between them difficult. (2) Since biologists in general seek to understand designs occurring in nature while engineers generally seek to generate designs for new problems, they typically use different methods and often have different perspectives on design, which adds to the difficulty of communication. (3) The constraints on biological designs typically are much more complex than on engineering designs, e.g., a bird needs to eat, feed, and reproduce among other tasks, while an airplane only needs to fly. (4) The resources, such as materials and processes, available in nature to realize an abstract design concept typically are very different from the resources available in the engineering domain, e.g., the material and processes in a bird's design vs. the materials and processes in an airplane design.

To a certain extent some of the same issues also occur in cross-domain analogy within engineering: mechanical, textile and industrial engineers, for example, speak different languages, have different perspectives on design, with different constraints on design problems and different resources for realizing an abstract design concept. Thus, the difference in the complexity of BID apparently is one of degree, not of type. Nevertheless, the difference in complexity is very large because of the large methodological, epistemological and linguistic differences between biology and engineering. Thus, BID provides an ideal domain for studying both design innovation, and the cognitive and social processes underlying innovation in interdisciplinary endeavors.

1.2 Studies of Biologically-Inspired Innovation

The literature in the design sciences contains many case studies of BID. Vincent & Man (2002), for example, describe their imitation of the design of pinecones to design clothing that can help regulate body temperature, and Ayre (2003) surveys several cases of biomimetic designs. However, at present there are few cognitive analyses, let alone any established theories of BID. As a result, while retrospectively we can see how an engineer or a scientist may have used analogy, we cannot yet prospectively identify the kinds of social, cognitive and technological environments that lead to productive BID. For example, Ayre makes little connection between the case studies of BID and any cognitive analysis or information-processing theory of design, modeling or analogy; Further, his analysis is entirely retrospective, not prospective.

Recently there also have been some attempts to build databases for supporting BID. The Biomimicry Institute (http://www.biomimicry.net/), for example, provides an online library of research articles on biomimetic design. Chakrabarti et. al.'s (2004) SAPPHIRE tool provides English language descriptions of the structures, behaviors and functions of biological and engineering designs previously used in biomimetic design. It also uses English verbs to describe engineering design problems, and retrieves biological and engineering designs based on matches between the verbs used in the problem descriptions. However, once again, the perspective in these databases is retrospective, not prospective. More importantly, beyond the general notions of analogy (e.g., observe, abstract, apply, evaluate), these databases seem removed from any cognitive analysis or information-processing theory of BID.

In 2005, Georgia Tech established an interdisciplinary Center for Biologically-Inspired Design (CBID) [http://www.cbid.gatech.edu/]. CBID conducts research on BID, e.g., the design of micro-robots inspired by insects, the design of genetically-engineered nanotechnology materials and processes, etc. It also teaches interdisciplinary undergraduate courses, which are jointly taught by faculty from biology, chemistry, engineering, and architecture. Thus, CBID provides both a community of researchers engaged in BID, and classroom laboratories in which to study BID *in situ*.

In Fall 2006, In Fall 2006, the first two authors of this report (Vattam and Helms) attended ME/ISyE/MSE/PTFe/BIOL 4803: Biologically-Inspired Design, an interdisciplinary introductory course for juniors and seniors. We collected course materials, took class notes, observed teacher-student and student-student interactions in the classroom, and also observed some sessions of a few interdisciplinary teams of students engaged in their design projects outside the classroom. Simultaneously, we analyzed the observations in terms of selected information-processing theories of design, analogy and creativity. The goals of this cognitive study were to (1) understand biologically-inspired innovation in engineering design, and (2) identify opportunities for enabling more effective learning of biologically-inspired design, and (3) examine the implications for developing computational tools for enabling effective biologically-inspired design. This report summarizes our main observations about learning biologically-inspired design, and presents our preliminary analysis of biologically-inspired design in practice.

The rest of the report is organized as follows: Section 2 presents our observations and analysis of the BID processes. Section 3 summarizes our observations of communication among small groups of students engaged in BID project. Section 4 describes the final BID projects submitted by the student groups. Section 5 presents our observations of the cognitive challenges faced by the students in their BID projects. Section 6 describes our preliminary analysis of BID in terms of existing theories of design, modeling and analogy. Section 7 summarizes and concludes this report. Appendix A describes our method for observation of the BID classes. Appendix B presents a compilation of all case studies of BID used in the BID course.

Section 2: BID Processes

Our observations indicate that the BID process typically begins from one of two different starting points, the solution or the problem, and follows two distinct patterns, solution-to-problem or problem-to-solution. While each approach involves iterations through solution-to-problem (or problem-to-solution) cycles, the two processes are quite different depending on where the student team began.

2.1. Problem-Driven BID Processes

In some classroom exercises, instructors asked students to first identify a problem, then "biologize" the problem, and find solutions in biology to that problem. Generally this approach works in the following steps:

- Step1: Problem Definition.
  Define a specific, tractable problem of human interest.
- Step 2: Problem Decomposition
  Understand precisely the terms of the problem, including functional and structural requirements, environmental constraints, etc.
- Step 3: "Biologize" the Problem
  Reframe the problem in biological terms. The order of steps 2a and 2b are somewhat interchangeable, and in some cases iterative.
- Step 4: Biological Search
  For some function required by the problem, find a biological organism or system that developed a solution for performing the required function.
- Step 5: Define the Problem
  Understand precisely the problem that the biological solution is solving. Defining the problem and extracting principles may occur interchangeably and iteratively.
- Step 6: Principle Extraction
  Through close scientific observation and experimentation understand the principles and techniques used by the organism to solve the problem, as well as the constraints on the solution.
- Step 7: Principle Application
  Apply the relevant principles to the initial problem.

Note that the above pseudo-algorithm only illustrates the high-level pattern of problem-to-solution approach to BID. In practice, the actual process is not necessarily ordered linearly; instead, the process may contain several iterations among the different steps. Examples of final design projects from the Biologically-Inspired Design class that appeared to follow the problem-driven process are listed in Table 2.1 below.

Table 2.1 Problem-Driven Final Projects

Starting Problem		**Explored Solutions**
Traffic congestion	→	Ant pheromones, Bee resource allocation, Geese migration patterns, fish schooling
Clothing with adaptive thermoregulation	→	Penguin feathers, Beehive phase transition material, Human circulatory system counter-current, Human vasoconstriction, sweating, shivering.
Surfboard camouflage	→	Pony fish bioluminescence, mimic octopus, parrot fish pointillism, brittle star light concentration through embedded lenses
Bomb detection	→	Dog nose, snake (Jacobson's organ), moth search techniques
Air filtration	→	Human lungs cilia and mucous, oyster mucous, coral "feathers"

2.2. Solution-Driven BID Processes

Some classroom exercises, and many of the case-studies provided to the class, began with a biologically inspired solution. A deep principle is extracted from the solution, and problems are found to which that principle can be applied. In general, the solution-driven BID process follows the steps listed below:

- Step 1: Biological Solution Identification
  For some interesting problem endemic to an organism's environment, an organism and its corresponding solution are observed, usually through casual study.
- Step 2a: Define the Problem
  Understand precisely the problem that the biological solution is solving. Defining the problem and extracting principles may occur interchangeably and iteratively.
- Step 2b: Principle Extraction
  Through close scientific observation and experimentation understand the principles and techniques used by the organism to solve the problem, as well as the constraints on the solution.
- Step3: "Humanize" the Problem-Solution pair
  The solution and applicable principles must be reframed in a context useful to human engineers. Since principles are typically already abstract, this may involve abstracting the solution's problem (but not always).
- Step 4: Problem Search
  For the "Humanized" solution, given the solution constraints, find an existing or define a new problem to which the solution applies.
- Step 5: Principle Application
  Apply the relevant solution principles to the new problem.

Note again that the above pseudo-algorithm only illustrates the high-level pattern of the solution-to-problem approach to BID. The actual process is not necessarily ordered linearly; instead, the process may contain several iterations among the different steps. Examples of final projects from the Biologically-Inspired Design class that appeared to follow the solution-driven process are listed in Table 2.2 below.

Table 2.2 Solution-Driven Final Projects

Starting Solution		Problems Explored (partial)
Abalone shell(1)	→	Bullet proof vests
Abalone shell(2)	→	"Break"-resistant phone
Copepods	→	Multi-modal movement: movement without wake, combined with movement at speed
Structural color	→	Computer screen display

2.3 Instruction on the BID process

While the instructors and the students, and especially case studies discussed in class, all used or alluded to solution-driven processes, the explicit instruction on methodology for BID focused primarily on the problem-driven BID process.[1]

2.3.1 Problem Definition

A major part of the problem-driven process is problem definition. Instructors focused on four main techniques to ensure proper problem definition: question assumptions, functional decomposition, functional optimization, and success criteria.

Question Assumptions: This technique assumes that students or designers begin with a problem definition. Designers, however, can use this technique whether another source provided the problem definition, or the designers themselves provided it. Noting that initial specifications often contain specifications based on assumptions and varied interpretations, this technique encourages students to look deeply into the assumptions and possible interpretations that defined their problem.

Instruction on this technique specifically asked students to take a specification document written in English and transform it into a list of the individual specifications implied by each sentence. The transformation then enabled students to question each item in the list, often resulting in questions that otherwise would not have been asked. The example provided for the class exercise described a specification for a self-powered rover for search and rescue at a disaster site. Given the specification, students uncovered many basic assumptions inherent in the specification that were unnecessary and which limited the range of considerable possibilities. For example, if the rover requirements specify operation over dry land it would be unusable for much of the Katrina victims.

Functional Decomposition: In the words of one instructor, "Biological systems are complex, inter-connected and multi-functional. It is difficult to extract a single concept to use from the tangled mess." Functional decomposition takes complex problems and decomposes them into their corresponding functions. The technique continues to decompose functions until the functions are defined at a level of sufficient granularity, which can be ambiguous. One possible definition of sufficient granularity is a level detail that yields to function optimization; an alternative is a level of detail to which standard engineering principles may be applied.

Designers require functional decomposition because problems and problem specifications often involve many functions, often with complex interactions. While functional decomposition simplifies the problem space, making it more tractable, it often results in a loss of information. This may account, at least in part, for the difficulties in creating multi-function solutions.

Functional Optimization: Functional optimization takes a specific function, and defines it in terms of an optimization problem (represented as an equation). Defined in this way, designers can analyze potential new solutions by measuring their performance against the optimization criteria. Likewise, biologists can

[1] Our description of the instruction on the BID process has been adapted from class notes of the BID course.

frame biological solutions in terms of an optimization equation. Abstracted to this level, designers can more easily transfer engineering requirements to biological solutions, and vice versa.

For example, in the analysis of moss in a found object exercise, the functional goals of the structure and placement of moss are to: (a) Reduce water loss, (b) Increase surface area for photosynthesis, (c) Position relative to the sun, and (d) Protect reproductive structures from environmental stress. However, the functions of reducing water loss and protecting reproductive structures oppose increased surface area and sunlight exposure functions. The structure and placement of moss must therefore optimize the balance between these two opposing groups of functions.

Functional optimization requires both a deep knowledge of the problem space and an ability to abstract that knowledge to a set of mathematical equations. *Perhaps because of this, despite the emphasis placed on functional optimization during class, we found that students rarely specified optimization equations for framing problems during exercises and presentations.*

Success Criteria: In addition to the three techniques above, designers must specify their criteria for success. If designers used the functional optimization technique, the optimization equations specify success criteria, although they may not explicitly cover all success criteria, such as environmental operating conditions. During final presentations, most students, when stating success criteria, framed the criteria at a very high level, such as: "make the phone scratch resistant and less breakable," "withstand a knife and a bullet," "reduce hip replacement failure, and "reduce traffic congestion." However, stated at such a high level of generality, *success criteria are a restatement of the original problem.*

2.3.2 Solution Search Heuristics

Instructors provided four general strategies/techniques for finding biological solutions relevant to a problem. (We believe that some of these techniques may be applicable for the reverse search process as well, i.e. for finding problems relevant to solutions as well.)

Table 2.3 Solution Search Heuristics

Search Technique	Technique Description
Change Constraints	If the problem is narrowly defined, such as "keeping cool", change the constraints to increase the search space, for instance to "thermoregulation".
Champion Adapters	Find an organism or a system that survives in the most extreme case of the problem being explored. For instance, for "keeping cool", look for animals that survive in dessert or equatorial climates.
Variation within a Solution Family	Where multiple organisms have faced and solved the same problem in slightly different ways, e.g. bat ears and echo-location, look at the small differences in the solutions and identify correlating differences in the problem space.
Multi-Functionality	Find organisms or systems with single solutions that solve multiple problems simultaneously.

During the search process, some students noted that "there were far too many solutions applicable to their problem, and so choosing among the possibilities was very difficult". Other students noted exactly the opposite problem, saying they could find few, one or no applicable biological organisms for their problem space. In almost all cases, students quickly honed in on target solutions or problems already discussed at length during instructor presentations. Once a student or group "locked onto" a solution, they stuck with their original solution even when looking for additional inspiration from other sources.

2.3.3 Solution Generation

Once designers identify target biological organisms or systems, they must convert these targets into solutions applicable to their problem. Ideally, starting from a deep understanding of the organism or system in question, designers extract the underlying principles used to solve the target problem. However, *in general students focused on understanding structures and materials, rather than functions and* *behaviors.* For example, during found object exercises, students most often commented on the qualities of the object rather than the solutions the composite structures represented (Table 2.4 shows the contrast))

Table 2.4 Structural Qualities and Functions (not related)

Structural Qualities	**Functions**
Texture	Seed protection
Strength	Insect attraction
Relative positioning	Seed dispersal
Orientation	Light concentration
Durability	Force dispersal
Weight	Predator protection
Flexibility	Water retention

Additionally during the process of extracting a principle and applying it to a problem, designers must translate the principle into the new domain. This translation involves an interpretation from one domain space (e.g. biology) into another (e.g. mechanical engineering). This interpretation sometimes led to incorrect analogies. For example, interpreting the self-healing properties of an abalone shell as material regeneration led student designers initially to assume it could be used to regenerate bullet impacts to bullet proof vests. Designers ruled out this possibility later when they developed more explicit interpretations of (biology's) self-healing and (engineering's) material regeneration.

This interpretation across domains occurred iteratively as knowledge increased for both the problem and solution, in many cases resulting in the discarding of an idea as no longer applicable. Often groups reasoned in circles about the applicability of a particular solution to a problem, arriving at the same starting interpretation over and over. This occurred most often when the groups tried reasoning about solutions where their knowledge was limited.

Section 3: BID Group Communication

Our observations of communication pertain mostly to the interaction of students during problem-solving exercises in the classroom and work sessions in preparation for final design projects outside the classroom. By design, the student project teams were made up of students from a variety of different backgrounds. As a result, in addition to a common vocabulary acquired in the BID class, each student started with different communication preferences, styles, and vocabulary developed within his/her own field of study. In general, engineering students talked in terms of physical properties and forces, mechanical design principles, material alloys, and mathematics, while biology students talked in terms of cells, systems, interactions, chemical compounds, and organic chemistry. In particular, in the context of the BID, (1) engineering students focus on the structural issues of a problem, while biology students consider systems and interactivity among systems, (2) engineering students look at the macro-scale, whereas biology students think in terms of cellular and sub-cellular microscopic environments, and (3) engineering students focus on problems, and biology students on the solution. In the words of one biology student, "It is difficult to relate a biological behavior or system to an engineering problem."

In addition to the above linguistic, epistemological and methodological differences between biology and engineering students, we found four additional patterns of communication:

1. Similarity and Reminding: When first discussing their initial problems (or solutions), students explored a space of possibilities through interactive dialogues. These dialogues wandered from topic to topic, until students agreed upon some common themes for follow up. Far from a random exploration of ideas, the students followed a distinct conversational flow. Beginning with a single question such as "What problem do we want to explore," one student would posit a starting point, such as "The problem I submitted was on dog noses." Starting from that point, students volunteered information related to, but different from the opinions already expressed. As each opinion varied, the students collectively explored an increasingly large space. From the previous opening statements, students proceed with statements like: "I know dogs are much better at detecting scents than humans;" "Dogs can be trained to detect drugs, and bombs, and dead people;" "I heard dogs can detect cancer in people just from their scent;" "Dogs can detect dead people even under water;" "Sharks have a remarkable sense of smell too. They can detect one drop of blood from a mile away;" and "Snakes use their tongue to detect smell." In this example, each student uses cues from the previous conversation to remind themselves of similar things they know, which they contribute to the conversation. The pattern of (reminding → new input → reminding → new input → etc) creates a dialogue or conversation vector that explores the student's collective knowledge within some related space.

2. Multiple Levels of Abstraction: While students communicated about an idea, they typically stayed within a single conversational trajectory. Occasionally the conversation would backtrack to an earlier point in the trajectory, and redirect itself. It appears that this occurred most often when the conversation either became too detail oriented, where usually only a single member of the group could speak on the subject matter, or the conversation became too high level where many people in the group tended to contribute ideas too far removed from the topic to be useful.

3. Multi-model Communication: Both instructors and students used both verbal and diagrammatic means to effectively communicate their ideas. While conversations usually began with verbal descriptions, whenever a student required clarification, or an idea was complex, or an idea was primarily concerning structure, both instructors and students usually adopted a diagrammatic approach to communication. This occurred pervasively throughout class and group discussions. One important difference between the instructors' use of diagrams and the students' use of diagrams is that students most often represented a thing as itself in a diagram. Instructors, on the other hand, occasionally represented things in terms of abstract graphs or charts.

4. Imprecision and Ambiguity: As noted earlier, each student begins with his/her own communication preferences and styles. These communication biases and the imprecise nature of language (English) lead to ambiguities in communication. Additional time and overhead for explanation is one of the most obvious side effects of this imprecision and ambiguity. When a student's explanation or comment is either unclear or misinterpreted, and the lack of clarity or misinterpretation becomes obvious, the group must spend time and energy clarifying the comment. However, in addition to this excess overhead, imprecise communication may also lead to interesting new ideas that might otherwise not be explored.

Section 4: BID Design Projects

This section summarizes our observations of the final design projects submitted by the various student teams. We used the following framework to highlight the important aspects of the design projects:

1. *Goal* is a concise description of the function the team was attempting to address. In most cases the design goal pertained to the conceptualization of a new technology.
2. *Biologized Question* refers to the translation of the target problem from human domain to problem in nature. The Biologized question is often the starting point for searching and identifying biological sources that can inspire design solutions. It often follows the form "How does nature achieve this function?"
3. *Biological Models Considered* lists the various biological sources that each team considered and cites the reasons for considering each and reasons for rejecting most. In many cases only one model is accepted and the solution is derived from it. In a few cases, more than one source is used and the final solution is a composition of design concepts derived from them.
4. *Design Trajectory* highlights the ultimate design, as well as shows how a project's conceptual design evolved through multiple stages if these intermediate stages were included in the student's project report.

Project 1, Abalone Armor

Goal: Conceptualization of a biologically inspired bullet-proof vest (material that combines the qualities of strength, toughness and self-healing properties).

Biologized Question: What characteristics do organisms have that enable them to prevent and withstand damage?

Table 4.1 Biological Models Considered for Abalone Armor

Biological Model	**Reasons for Considering**	**Reasons for Rejecting**
Spider Silk	Strength to weight ratio.	Manufacturing on industrial scale is not currently possible and not resistant to knife wounds.
Lobster Exoskeleton	Ability to blunt cracks (dampen fractures as occur) using overlapping plates.	This process requires water in order to be effective and would not scale-up to level required by body armor.
Sea Star	Ability to regenerate entire structure from a small fraction of its original mass.	The regeneration process (through cell division) is only available to living organisms and cannot be replicated in inorganic materials.
Rhino Horn	Strength and its ability to re-grow (the same way that finger nails re-grow).	Unknown
Human Bone	Strength and its ability to re-grow and it's modestly flexible.	Healing properties of bone are not viable under "normal" circumstances, requiring suspension in a solution of calcium.
Abalone Shell	Toughness, strength and ability to "repair" itself.	ACCEPTED

Understanding the Biological Model:
Structure: Understanding what the material is made up of and how the various elements are organized at various scales.
Behavior: Understanding how the material behaves upon application of force.

Patent Search:
Solution-driven search: All patented designs that use Abalone shell structure as inspiration for design (functions: tear resistant gels, composites and artifacts; modular, energy-dissipating materials and methods for using them; self-assembly of nano composite materials)
Problem-driven search: Latest patents issues for devices or materials that are used to protect from bullet and knife wounds (high-strength polyethylene fiber; stab-resistant material; flexible fabric; body armor employing combination of desiccant and ballistic material)

Design Trajectory:
Abalone shell was the starting point.
Initially thought of literally mimicking structure and materials.
Analyzing the fracture mechanics of such a material's response to bullet impact based on criteria such as facture stress, surface energy, strength intensity, and minimum initial crack size.
This analysis showed that body armor made from mimicking Abalone shell would be 2 orders of magnitude away from withstanding the necessary stress to stop a bullet.

Table 4.2 Comparison of Kevlar and Abalone Vest

Criteria	**Kevlar**	**Abalone**
Thickness	0.6 cm	0.9 cm
Weight	2.3 kg	20.5 kg
Stress	$2.6*10^7$ GPa	$2.5*10^5$ GPa

Although thickness is comparable, the Abalone vest is an order of magnitude heavier and 2 orders of magnitude weaker.

Healing mechanism of Abalone shell was excluded from the scope of the problem. The reason cited was that the mechanism was not well understood.

Project 2, Enhanced Visibility of Electronic Screen Displays Utilizing Natural Principles of Structural Coloration

Goal: To conceptualize a display screen that is resistant to drowned illumination in bright sunlight and one that is power efficient.

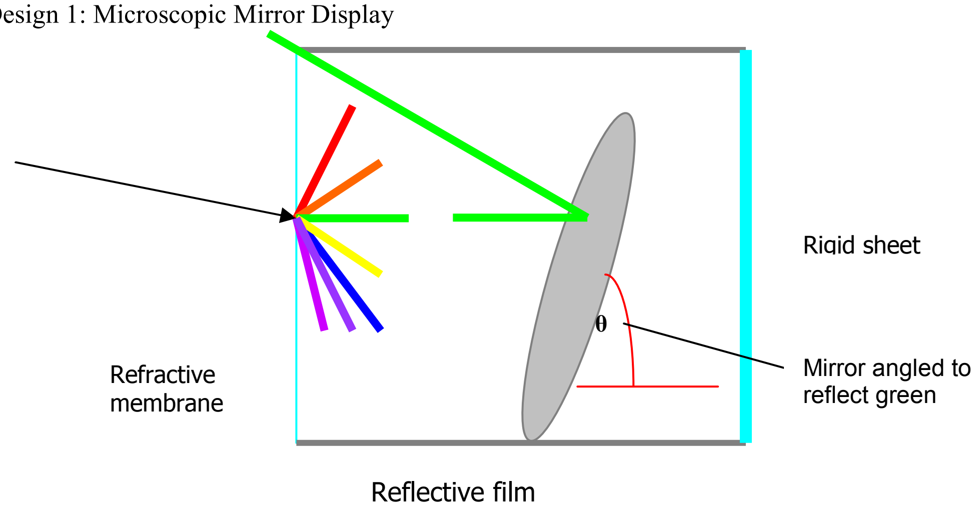
Biologized Question: How do objects in nature generate bright, crisp colors in the sunlight?

Table 4.3 Biological Models Considered for Electronic Screen Displays

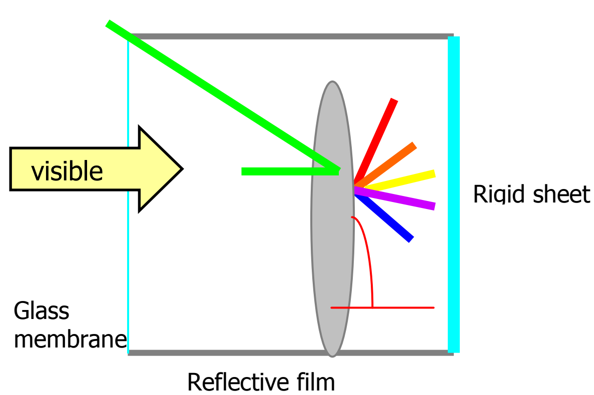
Biological Models	Reasons for Considering	Reasons for Rejecting
Morpho Butterfly Wings	Exhibits iridescence (single dimensional structure).	ACCEPTED.
Hummingbirds and Duck Feathers	Exhibits iridescence (single dimension structure).	ACCEPTED.
Peacock Feathers	Exhibits iridescence (multi-dimensional structure).	Requires dynamically changing the geometry (changing the lattice parameters such as spacing between repeated crystal elements).

Design Trajectory (graphics from student project report)

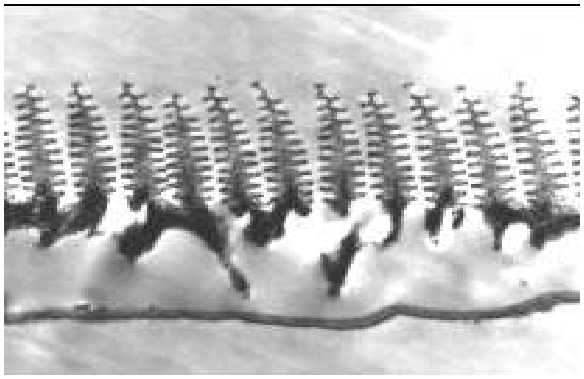
Design 1: Microscopic Mirror Display



Design 2: Diachronic Mirror Display



Design 3: Thin-film Display – Phasic Control (Bio-inspired)



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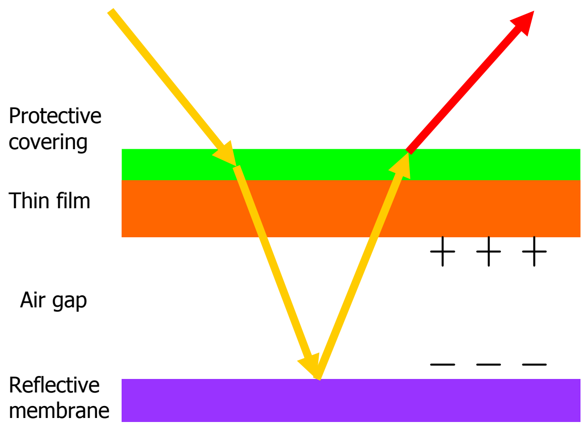
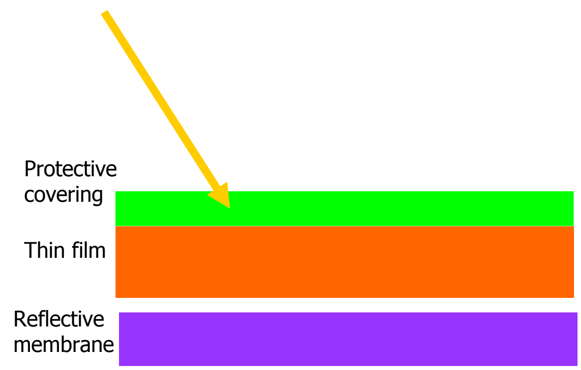




The thin film produced iridescence. The air gap controls which color is produced.

Project 3,The Shell Phone

Goal: Conceptualizing a cell phone covering that is resistant to everyday wear and tear and that is tough and fracture-resistant

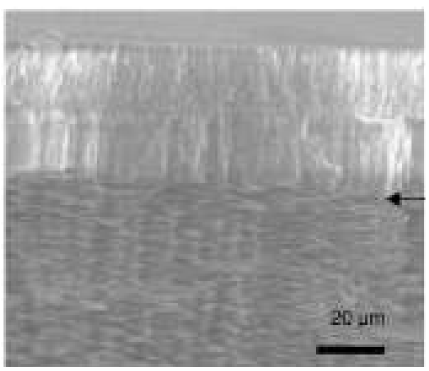
Biologized Question: How do organisms in nature protect themselves from getting crushed or injured?

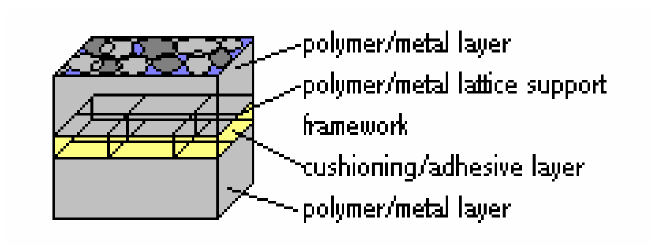
Table 4.4 Biological Models Considered for the Shell Phone

Biological Models	**Reasons for Considering**	**Reasons for Rejecting**
Elephant Tusk	Toughness.	Prone to fracture.
Mollusk Seashell	Toughness, strength and hardness.	ACCEPTED.
Arthropod Shells	Strength and stiffness.	As they are extremely thin and may not offer ideal protection.
Spider Silk	Tensile strength.	As the material ages, interactions between proteins weaken and along with them, the mechanical properties weaken. Also, it responds actively to environmental conditions such as humidity and would constantly modify its shape and tensile properties.
Hagfish Slime	Tensile strength and toughness.	slime has to be constantly hydrated
Tortoise Shell	Toughness and flexural strength.	Material characteristics vary greatly within different parts of the shell. Tortoises are an endangered species, which could limit scientists' ability to research.

Design Trajectory:

Design *(graphics from student project report):*





Their design mostly dealt with the process of bio-mineralization of such a structure.

Project 4, i-Fabric

Goal: To propose a thermally responsive and adaptive fabric that can be made into clothing in order to provide thermoregulation for the user in extreme weather environments.

Biologized Question: How are organisms in nature capable of maintaining consistent body temperatures using the least amount of energy possible for the process of thermoregulation?

Table 4.5 Biological Models Considered for i-Fabric

Biological Models	Reasons for Considering	Reasons for Rejecting
Antarctic Penguins (feather system)	Externally manipulated insulation layer.	ACCEPTED.
Wood Stork	Countercurrent heat exchange.	ACCEPTED.
Artic Wolves	Countercurrent bypass system.	ACCEPTED.
Bee Hive Structures	Phase change materials.	ACCEPTED.
Kenyan Chameleon	Thermoregulation through color change.	Unknown.
Humans	Behavioral responses (sweating and shivering) that generate heat by increasing amount of physical activity or decrease heat by decreasing amount of physical activity.	Unknown.

Design Trajectory:

Design 1: Create a fabric made from a paraffin wax called octadecane. Detailed analysis of heat properties of the wax was made. Calculations for the surface area required were also made.

Design 2: Concurrent bypass system: Redirecting heat through channels of conducting fibers to important parts of the body.

Project 5, Robohawk: An Aerial Bomb Detection Device

Goal: To conceptualize a technology for chemical sensing of nitromethane and ammonium nitrate. It should also maneuver effectively so as to be able to trace the detection.

Biologized Question: The biologized question was broken into two sub-functions*:*

1. Sensing: What are the common principles through which organisms detect chemical scents?
2. Tracing/Tracking: What are the mechanisms by which organisms track scents over extreme distances and move toward or away from it?

Analogical Mapping:
Signals given off by bombs = animal pheromones
Bomb-sensing devices = special sensory organs of animals
Signal-tracing methods = tracking methods in insects, birds, dogs etc.

Table 4.6 Biological Models Considered for the Robohawk

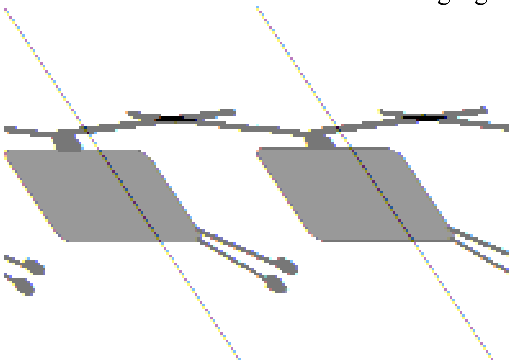
Biological Models for Movement/tTacing/Tracking	Reasons for Considering	Reasons for Rejecting
Antarctic Procellariiform Seabirds	exceptionally good at tracking scents over an extreme distance	
Albatross	None	None
Biological Models for Sensing/Detection		
Membrane/Enzyme Systems*	Has proved efficient in detecting and differentiating signals in nature	

*No particular organism is mentioned, but a broad reference is made to a number of animals like moths, dogs, roaches that utilize these kinds of sensors.

Design Trajectory:

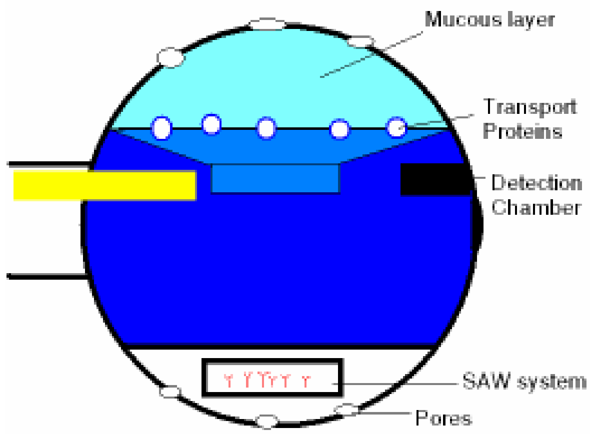
Design *(graphics from student project report):*
Overall function is divided into two sub-functions, motion and sensing.

Sub-function 1: Motion alludes to the zigzag algorithm inspired from seagull movement patterns.



Sub-function 2: Two systems of sensors are used to detect two types of chemicals.

- The Surface Acoustic Wave (SAW) for ammonium nitrate (not biologically-inspired), and
- Membrane/Enzyme system for detecting nitromethane (biologically-inspired).



Next step – limitations: One possible problem that might be encountered is that the liquid might leak out through the pores, especially if the antennae are highly mobile as envisioned. A solution was suggested to this problem that included incorporating the use of the lotus-effect demonstrated in nanostructure literatures.

An analysis was also made of nitromethane distribution in air, which was used to calculate the rate of detection of the membrane system.

Project 6. The InvisiBoard

Goal: To conceptualize a technology that prevents the formation of the surfboard and surfer silhouette (which typically resembles the silhouette of a shark prey) to prevent "hit and run" shark attacks due to mistaken identity.

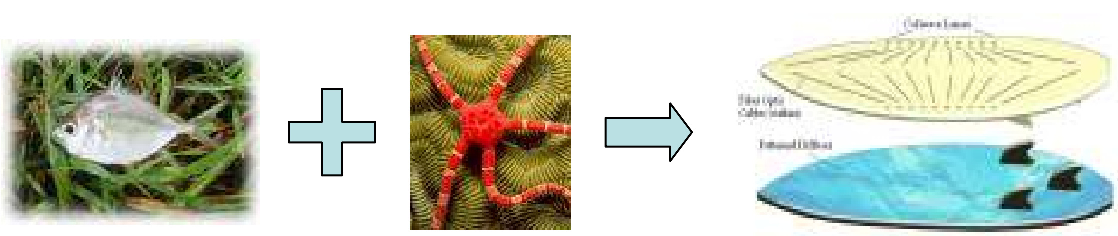
Biologized Question: How do organisms in water camouflage themselves to prevent detection by their predators?

Table 4.7 Biological Models Considered for the InvisiBoard

Biological Models	Reasons for considering	Reasons for rejecting
Pony Fish	Produces and gives off light that is directly proportional to the amount of ambient downwelling light for the purpose of counter-illumination. The concept of a ventral light glow is transferred.	ACCEPTED.
Indonesian Mimic Octopus	Expert camouflage artist. Can mimic various animals based on which predator is close by.	A surfboard is rigid does not have the same flexibility as the octopus.
Bullethead Parrotfish	Pointillism: When viewed at close range, the fish appear bright and colorful but when viewed from a further distance, the combination of the complementary colors creates the illusion that the fish is grey-blue. This trick blends the parrotfish into the backlight of the reef, and in essence it disappears.	A reef predator cannot detect the fish whereas sharks will have no trouble spotting them since they can see better at a distance rather than close-up. This is because sharks have a mirror-like layer in the back of the eye which allows for better reception of incoming light.
Brittle Star	Properties of photo-reception: The dorsal side of the brittle star is covered with thousands of tiny eyes, or microscopic lenses, making the entire back of the creature into a compound eye. This mechanism can be used to collect surrounding light rather than have to produce luminescence as in Pony fish.	ACCEPTED.

Design Trajectory:

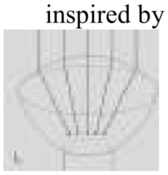
Design *(graphics from student project report)*:



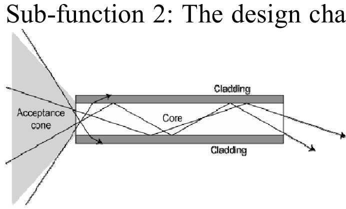
Pony Fish Brittle Star InvisiBoard

Overall function is for the surfboard to produce counter-illumination (inspired from Pony fish). This function is divided into 3 sub-functions: collect sunlight, channel the light, and distribute the light.

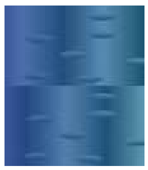
- Sub-function 1: Collection of sunlight is achieved using the mechanism of photo-reception inspired by the Brittle star.



- Sub-function 2: The design channels light with fiber optic cables embedded within the surfboard.



- Sub-function 3: The design distributes the light on the bottom of the surfboard with patterned light diffusers.



Project 7, Ant-Inspired Pheromone Sensors for Traffic Control

Goal: To conceptualize a system that reduces traffic congestion on roads.

Biologized Question: How do animals that display communal behavior avoid traffic jams through efficient movement as in flocking, swarming, foraging and schooling?

Table 4.8 Biological Models Considered for Traffic Control

Biological Model	Local Environment	Method of Sensing	Method of Signaling	Traffic Management
Bees	Air	Scent	Waggle Dance	Random
Geese	Air	Sound	Sound, Body Posture, Action	V- Shape
Schooling Fish	Water	Visual, Scent, line of sight	Visual, Scent,	Collective Movement
Ants	Land	Scent	Pheromone	Optimal Path Selection: Pheromones

Analogical Mapping:
(a) Vehicles (cars, trucks, and semis) = ants.
(b) Substances released by the car, particularly carbon dioxide (CO_2) = pheromone.
(c) Roadway = ant's trail.
Transfer: While ants use increased pheromones as a positive-feedback mechanism, their design proposes to use increased levels of CO_2 (pheromone) as a negative-feedback mechanism.

Design trajectory:

Design 1: Initial Design Proposal
This design uses an illuminating device that dims in the response to high levels of CO_2 and brightens in response to lower levels of CO_2. The device would be similar to the passive reflectors embedded in the roadway that separate individual car lanes. Groups of reflectors would illuminate paths with less CO_2 (those less likely to be congested). Drivers would take this more-illuminated path, reducing overall congestion. Limitations include: lighting may be hard to visualize during daylight and the system does not route drivers in advance.

Design 2: Prototype A

This design uses the currency of travel time and correlates measured CO_2 levels with historical travel times from a database. It sends this travel time to a GPS unit which then calculates the optimal path based on the shortest travel time. Limitations include: historical data only points to an estimate of the congestion, but not the actual congestion. There's room for error. Also, the travel time is not solely dependent on [CO_2] but also on time of day, weather, accidents, and construction (each of which may or may not generate additional CO_2).

Design 3: Prototype B
Instead of travel time as above, the number of vehicles was taken as a currency. But it was noted that this will not work because the CO_2 output of a vehicle was found to vary based on factors like velocity, make, model, etc.

Design 4: Prototype C
This design uses a simple strategy to calculate the optimal path: If the [CO_2] on a roadway exceeded the roadway's baseline [CO_2] by a factor X, congestion was present and traffic should attempt to route around the roadway. Here the roadway system is represented as a connected graph. One matrix holds the connectivity and the other matrix holds the distances between the nodes. If the [CO_2] levels on a particular road exceed the threshold, its connectivity is severed from other nodes in the connectivity matrix. The next time a path is calculated, this road is not an option.

Project 8, BioFilter
Goal: To create a bio-inspired portable, stand-alone, home air filtration unit to trap allergens and other harmful particles.

Biologized Question: What are some of the cleaning and filtration mechanisms found in organisms in nature?

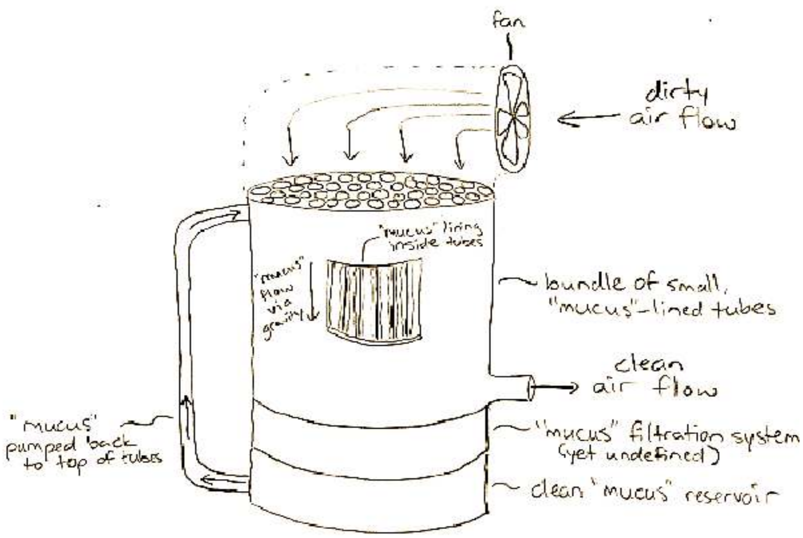
Table 4.9 Biological Models Considered for the BioFilter

Biological Model	**Reasons for considering**	**Reasons for rejecting**
Human Respiratory System	The cleaning and filtration capabilities of the mucus and cilia present in the respiratory track.	ACCEPTED
Zebra Mussel	Particulate interception attributed not only to mechanical filtration, using the "net", but also to complex current formation and overall gill hydrodynamics, thereby capturing particles without actually physically trapping them.	the ciliary and complex hydrodynamic motions are very difficult to replicate with the available contemporary technologies.
Oysters and Clams	Uses two different mechanisms (mucociliary and hydrodynamics) in capturing and transporting food particles to the labial palps. Fairly efficient model, with the ability to capture particles smaller than 1 µm at 90% efficiency.	Same as above, plus production and filtering of the contaminated mucus would make process more complicated.
Baleen Whales	Employs an efficient filtration mechanism for filterfeeding.	It would only filter some, not all, of the targeted particle sizes.
Diatoms	They have regularly spaced, uniformly sized pores in their cell walls, just the right size for filtering out the smallest particles from the air. They replicate very quickly and come in a variety of shapes; so the size, shape, and pore size of the diatoms that would work best can be chosen, and grown as the filter media.	ACCEPTED
Cyclosalpas and Larvaceans	Utilize mucus nets to filter out food from their environment. Adept filter feeders.	Difficult to maintain since the filtering efficiency of the mucus depends on its

		moisture and constant flow of water.
Human Kidneys	The human kidney can filter small particles and normal kidneys function with a high efficiency	human kidney is a multi-cellular organ, it would be difficult to replicate such an intricate system.
Human Lungs	Able to filter out small particles like bacteria and hazardous chemicals via the mucociliary system	Same as above.
Spider Silk	extremely lightweight and strong structure with adhesive properties that can weaved into a net to trap particles.	The adhesive material is non-polar.
Hemoglobin	Capable of filtering oxygen from air. It has the capability of binding oxygen very strongly out of a variety of gasses present in the air.	Unknown.

Design Trajectory

Design 1: Initial design, early in the course *(graphics from student project report):*



Conceptual Sketch of the Original Design

This design was based on human respiratory system. This design examined the cleaning and filtration capabilities of the mucus and cilia present in the respiratory track. The function of the mucus is to trap small particles before the air reaches the alveoli in the lungs. the contaminated mucus is then transported to the esophagus (the point of disposal) by the rhythmic beating of cilia. This was replicated in the above conceptual design.

Table 4.10 Evaluation of BioFilter Design 1 (from student project report)

Model	>1 µm	<1 µm	Efficiency	Maintenance	Feasibility	Cost
Zebra Mussels	-	+	+	+	-	-
Bivalves	-	+	+	-	-	-
Whales	+	-	-	+	+	-
Diatoms	-	+	+	+	+	+
Spider Web	+	-	+	+	+	+
Salps	+	-	+	-	-	-
Human Kidney	-	+	+	-	-	-
Hemoglobin	+	-	+	-	-	-
Human Airway	+	+	+	-	-	-

Design 2: Final Design
This design used a multi-stage filtration process. The first stage filter is inspired by spider silk. It will be similar to the current fiber-based filter designs. The second and third stage filters will be sheets of diatom frustules, with pore diameters of 0.2 and 0.02 microns respectively.

Project 9, The Eye In the Sea

Goal: To design an underwater micro-bot with locomotion modality that would ensure stealth by either minimizing or matching wake.

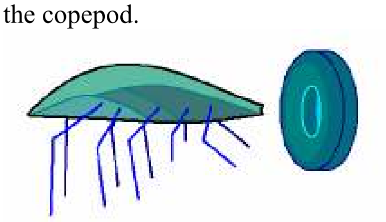
Biologized Question: How do marine animals stalk their prey or avoid predators without being detected?

Table 4.11 Biological Models Considered for Underwater Micro-Bot

Biological Models	Reasons for Considering	Reasons for Rejecting
Squid	Uses one opening for both intake and expulsion of water, providing jet propulsion.	ACCEPTED.
Copepod	Uses two kinds of motion, escape (with a high Re number), and foraging, (with a small Re number).	ACCEPTED.

Design Trajectory:

Design *(graphics from student project paper)*:
The design is a combination of squid and copepod locomotion. For faster locomotion, the design uses a single-orifice interrupted jet propulsion for forward movement (because it mimics squids, which are commonly found in reefs and the disturbance it creates matches with the environment). For slower locomotion, it uses the design of a copepod with its appendages and movement of appendages mimicking the copepod.



Section 5: BID Design Challenges

Students engaged in BID face many cognitive challenges, many of which were anticipated by the instructors. In the middle of the course, the students were required to propose a design problem and potential biological source that would help them come up with novel solution to the target problem. Essentially they defined a target problem and chose a source problem from which knowledge could be transferred to solve the target problem. Some of the examples discussed in class (Table 5.1) indicate, as per the experts' feedback, some of the challenges encountered by the students. These challenges generally span the (1) problem specification, (2) biological source(s) identification, and (3) target-source pairing/mapping, aspects of BID.

Table 5.1 Target-Source Mapping Examples

Proposed Target and Source	**Comments From Experts**
Target: ? Source: Animals protect themselves from predators through communication.	Does not start with a "function" or a "behavior" that can be mapped. This is not easily transferred to target problem. "Protection" and "communication" are both functions. What is the primary function in the target problem?
Target: Our dependence on oil as our only source of energy for transportation. Need to find alternate sources of energy Source: ?	Too general. Can be decomposed into any functional statements that can solve the general problem.
Target: How do we make more efficient engines? Source: Animals have efficient metabolism and thermoregulation. Look to them for burning fuel efficiently.	The problem is clearly functional. But the source and mapping is incorrect because both metabolism and thermoregulation are processes used to maintain a constant internal environment but not to propel the organism.
Target: Water purification Source: Introducing harmless microorganisms into the water that consume harmful water particles	The problem is again clearly functional. But using organisms is not a fruitful BID strategy. What have to be transferred are mechanisms and principles. Taking off the shelf solutions misses the whole point
Target: Reducing traffic congestion on highways Source: Load-balancing during foraging in ant colonies using pheromones	The problem is functional. The mapping breaks down because the problems are only similar at the surface. At the relationship level, they are not. For instance, the ants make round trips but humans need not.
Target: Minimizing food residue on cleaned dishes after cleaning cycle ends in dish washers Source: Lotus leaf and self-cleaning surface Solution: coating dishes with non-sticky surfaces	Incorrect mapping. Self-cleaning surfaces do not match the strategy of non-sticky surfaces

5.1 Cognitive Errors

Throughout the BID process, we observed cognitive errors that were common to a number of students. The following table summarizes the main types of errors:

Table 5.2 Common Student Errors

Category	Example
Problem definition and articulation is too vague or too specific.	Problem of animal defense and protection posed in terms of animal communication mechanisms.
	Shell-phone as a scratch-, shatter-, and shock-resistant material.
	We depend too much on oil.
	Moving a signal through a wire, versus signal processing.
	How do we coat any surface using protein bonding.
Problem-Solution pairing is ill-suited.	Engine efficiency problem and metabolism/thermoregulation solution.
	Dishwashing solution problem and altering the surface to be cleaned solution.
Problem framing missed significant features.	Missing the significance of an underlying principle because of poor word choice, such as using the term "simply writhing", when in fact writhing is a very deliberate, complex motion.
Using "Off-the-Shelf" solutions.	Using an organism to "do what it does" instead of leveraging the principles of the organism. For example, using fireflies themselves to produce light.
Selecting an incorrect optimization problem.	Moss as a surface area optimization, instead of as a complex interaction among sunlight, water preservation, surface area, and protection.
	Selecting an equilibrium problem instead of the underlying optimization problem, such as predator/prey equilibrium. In fact, the equilibrium is an optimization of system stability.
Design fixation.	Students fixate on the first solution offered
	Students fixate on applying solutions to problems already being addressed by similar solutions.
Misapplied analogy.	Problems that appear related at superficial levels, fall apart at deeper levels: Ant-traffic optimization vs. throughput optimization.
	A implies B analogies may be incorrect because of language: Regeneration implies self-healing over time vs. fast self-healing.
Improper analogical transfer.	The problem of what not to transfer: Dog nose is great at sorting through and identifying a multitude of different scents, but if you're looking for just one thing in particular, there are mechanisms in the dog nose (filters) that should not be transferred.
Solution is non-innovative.	Solutions often direct derivatives of solutions presented in class.

Section 6. Information-Processing Theories of Design, Modeling and Analogy

In this section, we briefly review selected information-processing theories of design, modeling and analogy. In general, we focus here on information-processing theories in the form of computational models because they make more precise commitments and because they more directly relate to our longer-term goals of developing computational tools for enabling effective biologically-inspired innovation.

6.1. Information-Processing Theories of Design

In *Sciences of the Artificial Intelligence*, Herbert Simon (1969, 1996) observed that: (1) Complex systems are nearly decomposable and hierarchically organized, (2) Designing a complex system is a kind of problem solving (and problem solving is a kind of search in a problem space), (3) Although problems of designing complex systems often are ill-structured, nevertheless they are solved as if they were well-structured (or by transformation into well-structured problems), (4) Functional explanations that explain what a design does (i.e., its functions) and how the design does it (i.e., how the internal processes in the design achieve its functions) are the right kind of explanations of complex system designs, and (5) Satisficing (and not satisfiability) of constraints is the right criterion for accepting a design (and thus terminating the design process). Simon's ideas have had a profound influence on design research. In artificial intelligence research on automated physical design, for example, Brown and Chandrasekaran (1989) have viewed design as a process of plan instantiation and refinement in a hierarchically-organized library of skeletal design plans. Similarly, in AI research on interactive software design, Rich and Waters (1990) developed the plan calculus, a high-level language for representing, organizing, accessing, instantiating, and displaying abstract algorithm templates called *cliches*. However, the last four decades of design research have also challenged some of Simon's. In particular, Simon's view of design as a problem solving has become quite controversial.

In *Notes on the Synthesis of Form*, Christopher Alexander (1964) noted that: (1) In a stable environment, new architectural designs typically are structure-preserving modifications of existing designs, (2) Design patterns capture the similarities among the known designs, and (3) New designs are generated by instantiating (or "unfolding") known design patterns in new contexts. Alexander's ideas too have had a profound influence on design research. In interactive software design, for example, Gamma et. al., (1995) provide a library of reusable design patterns for object-oriented programming. Similarly, in automated physical design, Goel and Bhatta (2004) describe a method for representing, abstracting, accessing, transferring and instantiating teleological design patterns.

TRIZ (Altshller 1984) is a theory of analogy-based invention. In TRIZ, a design principle abstracted from one domain is used to address a contradiction that arises in solving a design problem in a different domain. A contradiction is reached when two design goals are in conflict with each other. TRIZ provides taxonomy of forty basic design principles for resolving contradictions. Altshuller developed these principles by systematically inspecting a large corpus of inventions in patent databases. Altshuller ideas too have had a profound influence on design, especially innovative design. Some BID practitioners, such as Vincent and Mann (2000), have explicitly advocated the use of TRIZ as the methodology for BID.

Several design scientists have conducted empirical cognitive studies of design practitioners in various domains, including engineering, architecture and software design. Cross (2001) summarizes current understanding of effective design as follows: Effective designers (1) Treat the design as a system, made up of multiple components or technologies, each with its own function, (2) Treat design problems as ill-structured, questioning assumptions about function-to-form mappings and about constraints for each component and feature, even if the problem is well-defined, (3) Quickly consider different technologies or subsystems that respond to function, rather than analyze a solution deeply, (4) Generate multiple alternatives for each system and component, avoiding fixation to a single solution, (5) Use and take advantage of multiple representations and alternative ways of structuring a candidate design, (6) Utilize a fairly structured process that guides focus of attention and time spent on different activities, (7) Recognize and take advantage of unique configuration opportunities, and (8) Co-evolve the solution formulation and the problem definition together. Gero and McNeil (1998) add that: (1) Novice designers focus mostly on the structure of the design solution, spending only a little time on the design functions, and (2) expert designers spend about equal amounts on the functions, the structure and the behaviors (the processes, components and features that accomplish the design functions).

6.2. Information-Processing Theories of Modeling

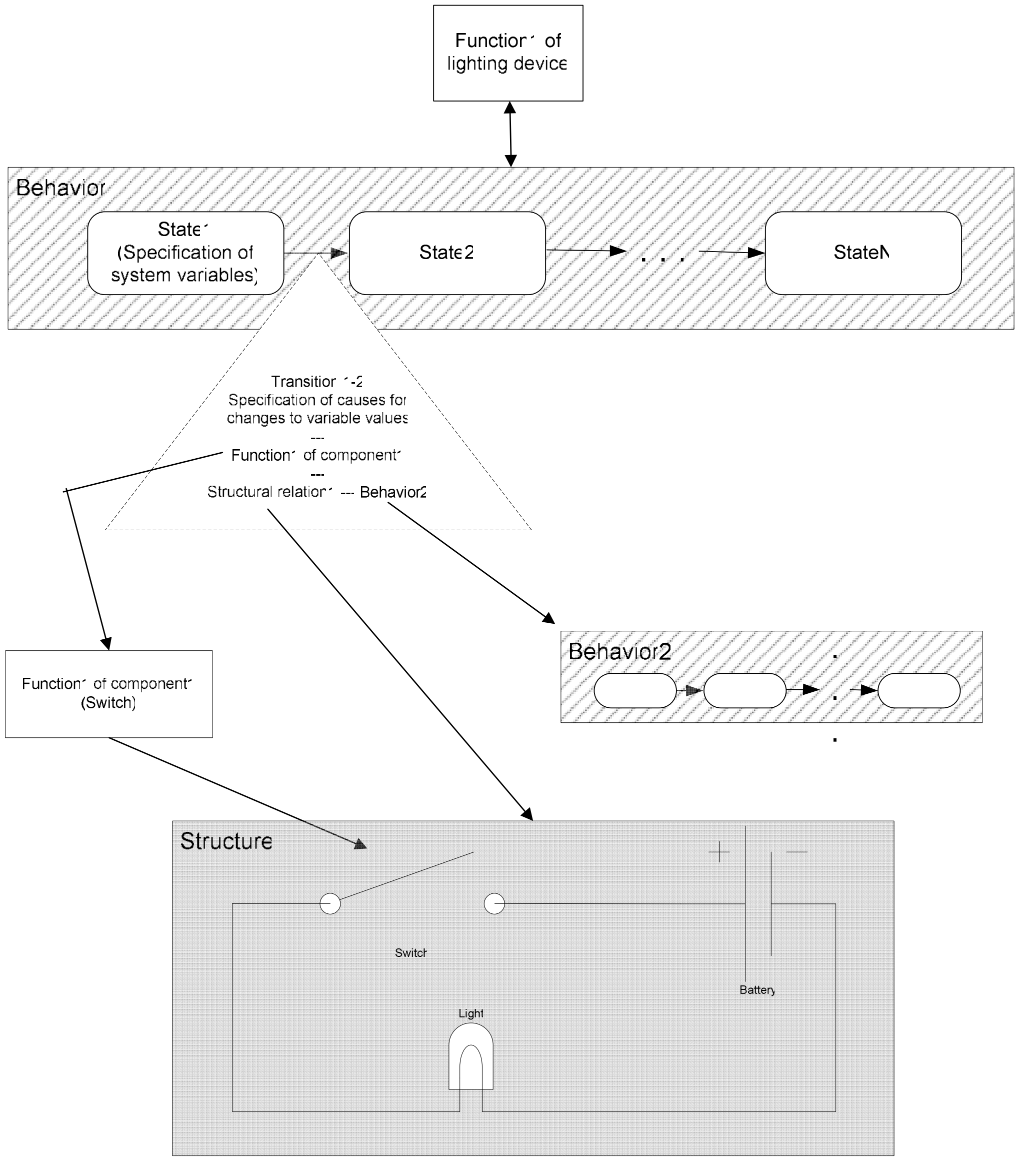
Developing accurate mental models of complex systems is an important part of learning in science and engineering. Mental models, with their explanatory and predictive power, are critical for explanation, analysis, prediction, monitoring, diagnosis, and design of complex systems, and subsequent acquisition of a more sophisticated understanding of complex systems. Complex systems can be characterized in a general, domain-independent manner as follows (Narayanan et. al., 2003): (1) Complex systems exhibit hierarchical structures composed of subsystems and components. (2) Subsystems and components exhibit natural behaviors or engineered functions. (3) These component/subsystem behaviors causally influence other components/subsystems. (4) The propagation of these causal influences creates chains of events in the operation of the overall system, and gives rise to its overall behavior and function. (5) These chains of events extend in temporal and spatial dimensions.

Modeling is central to scientific inquiry and can lead to deep understanding (Darden 1991, Nersessian, 1990, 1995; Schwarz & White, 2005). Clement (2000) has argued that learning is fundamentally a process of model construction and revision. Constructing external representations of mental models can help students understand the complexity and multiple levels of organization in complex systems (Buckley, 2000). The external representation of models supports constructive discourse, which is associated with positive learning outcomes (Chi, Siler, Jeong, Yamaguchi, & Hausman, 2001; Greeno, 1998). Hmelo-Silver (Hmelo-Silver, Holton and Kolodner 2000; Hmelo-Silver & Pfeffer 2004) has shown that while experts model a complex system in terms of its interrelated structure, behaviors and functions, novices express primarily its isolated structure, demonstrate minimal understanding of its functions, and largely miss its behaviors (e.g.,

Teleological models have received significant attention in modeling and design of physical systems. In cognitive engineering, Rasmussen (1985) developed a Structure-Behavior-Function scheme for modeling complex physical systems and using the model of a system to aid human operators in trouble-shooting the system. In artificial intelligence research on problem solving, Chandrasekaran proposed a Functional Representation (FR) scheme for modeling physical devices and automatic generation of diagnostic knowledge for a device from its FR (Sembugamoorthy and Chandrasekaran 1986). Tomiyama (Umeda et. al. 1991, Umeda and Tomiyama 1997), Gero (Gero, Tham and Lee 1991), and Mizoguchi (Sasajima et. al. 1995) have developed similar representation schemes for describing the functioning of physical systems.

In our own work, we have developed a theory of modeling complex systems called Structure-Behavior-Function (or SBF) models (Goel and Chandrasekaran 1989, Goel, Bhatta and Stroulia 1997). An SBF model of a complex system explicitly represents its structure [S] (i.e., its configuration of components and connections), its functions [F] (i.e., its output behaviors), and its behaviors [B] (i.e. its internal causal processes that compose the functions of the components into the functions of the system). As Figure 1 illustrates, SBF models are organized in a $F \rightarrow B \rightarrow F \rightarrow B \ldots F \rightarrow S$ hierarchy, which captures function and teleology at multiple levels of aggregation and abstraction. The ontology of the SBF models also provides a vocabulary for classifying, representing, indexing and accessing specific design cases, primitive domain components, generic adaptation methods, and abstract design patterns.

A Partial Description of an SBF Model of a Simple System



Representation of Structure: Structure in SBF models is a configuration of components and the connections among them. It is represented in the form of component and connection schemas. The specification of a component includes its functional abstraction(s); the specification of a connection includes the behavior in which it plays a role.

Representation of Behavior: A behavior in an SBF model is an internal causal process that composes the functions of subsystems (or components) into the output behaviors of the system (or a subsystem). A behavior is represented as a sequence of causal states and transitions between them; one sequence specifies the evolution in the values of system variables characterizing a specific component (e.g., the switch) or a specific substance (e.g., light); temporal ordering is subsumed by causal ordering; continuous state variables are discretized. The state transitions in behavior are annotated by different types of causal labels; for example, while one type of label may act as a pointer to the functional abstraction of a structural component, another type of label may act as a pointer to another behavior (which, for example, may express the changes in the system variables characterizing a different component or substance), and yet another label type may act as pointer to a structural connection as an enablement condition. Additional types of causal labels include domain principles (such as Ohm's Law), mathematical equations (such as the equation for Ohm's Law), etc.

Representation of Function: Functions in an SBF model are a subset of its output (or observable) behaviors. For example, while the function of a flashlight circuit (shown at the bottom of Figure 1) may be to create light, its output behaviors may also include creation of heat. Devices can have functions of many types, e.g., achievement functions (which achieve a particular state), prevention functions (which prevent a particular state from being achieved), etc. An achievement function in SBF models (as in SBF models) is represented as a schema that specifies its input and output states. It also contains a pointer to the behavior that accomplishes the function.

6.3. Information-Processing Theories of Analogy

Nersessian (1999) has described analogical reasoning as a fundamental method for conceptual change in science. Analogical reasoning in general entails several steps: retrieval of a known source case similar to a new target problem; mapping between the source case and the target problem to identify corresponding elements and relations; transfer of some knowledge (e.g., relation, solution, or strategy) from the source case to the target problem; evaluation of the proposed solution to the target problem; and (possible) storage of the target problem as another case for potential reuse.

Gentner's (1983) Structure-Mapping Theory categorizes similarity between a source case and a target problem in three categories: similarity of both the elements and the relations among them (literal similarity); similarity of only the elements but not the relations among them (superficial similarity); and similarity of relations but not the elements (deep similarity). She characterizes analogy as transfer of relations based on deep similarity. The MAC/FAC system (Forbus, Gentner and Law 1995) – the acronym stands for "many are called, few are chosen" – first recalls sources cases based on superficial similarity and then selects specific cases for analogical transfer based on deep similarity. The Structure-Mapping Theory proposes a structural mechanism for finding mapping between a source case and a target problem based on the order of relations in the problem representations so that higher-order relations are preferred for transfer.

In contrast, Holyoak and Thagard (1996) propose that case retrieval is based on a matching of structural, semantic and pragmatic constraints in the target and source problem representations, where the pragmatic constraints pertain to problem-solving goals. They have further proposed that analogical transfer entails induction of higher-level schemas based on the similarity between the target and the source problem.

Hofstader (1995) views analogy as akin to high-level perception, in which representations for the target and source problems are dynamically constructed, evaluated and perhaps reconstructed, rather than simply mapped onto each other. Wills and Kolodner (1994) describe a working memory in which design goals suspended in solving one problem get connected with design cases generated in addressing another problem. Qian and Gero (1996) represent design prototypes as Function-Behavior-Structure models, in which behavior acts as an intermediate abstraction between function and structure, and use them to interactively support cross-domain analogies in conceptual design.

In our own work, we have developed a computational theory called Model-Based Analogy (or MBA) of cross-domain analogy in engineering design that uses the SBF models described above (Bhatta & Goel 1997; Goel & Bhatta 2004). The MBA theory is embodied in a computer program called IDEAL. According to MBA, known designs of complex systems are represented at multiple levels of abstraction such as design instances (or cases), prototypes, patterns and principles (e.g., removing from a hot object by bringing it into thermal contact with a cold object). New design problems too are represented at multiple abstraction levels. Design concepts for a new design problem are generated by abstracting the problem to multiple levels, and accessing matching design instances, prototypes, patterns and principles.

A design case in IDEAL contains the SBF model of a known design. Each design case in the case library is indexed by the functions delivered by the design contained in it. Design patterns (e.g., component-replication-in-series, open-loop-feedback, etc.) are abstractions over the (physical) structure of SBF models of multiple physical designs. A design pattern is represented as a Behavior-Function (BF) model, which specifies the abstract structure of a causal process (e.g., sensing of the fluctuations in an output variable of a device and transmission of the signal to an input variable) that achieves an abstract function (e.g., regulation of the output variable of a device). Each design pattern is indexed by its functional abstraction(s).

Given a specification of the desired function, IDEAL first retrieves the design case that delivers a function closest to the desired function. For example, given the desired function of generating light of 18 lumens, it may retrieve the design for a flashlight circuit that creates light of 6 lumens. IDEAL then uses the SBF model contained in the retrieved case, performs model-based teleological analysis to localize the modifications needed to achieve the desired function, and generates adaptation goals corresponding to the needed modifications. For the flashlight example, it could localize the needed modification to the battery in the flashlight circuit (among other candidates), and generate the adaptation goal of increasing the voltage of the battery from 1.5 volts to 3 volts. IDEAL is able to make this inference because of the modularity, compositionality and hierarchicalization of the SBF model, and the explicit representation of the functions, behaviors and structure in the model. Next IDEAL uses the current adaptation goal to retrieve generic adaptation plans. The first adaptation plan may look for a battery of 3 volts in the library of primitive components. Let us suppose that such a battery indeed is available, in which case IDEAL substitutes the 3 volt battery in the design of the flashlight circuit for the 1.5 volt battery and thus generates a candidate design; it also similarly revises the SBF model of the old design into an SBF model for the candidate design. IDEAL then iteratively completes the candidate by similarly attending to other needed modifications if any. It finally evaluates the candidate design by procedural simulation of its SBF model in which it propagates the perturbation generated by the above component substitution through the model. If the evaluation is successful, then IDEAL returns the design solution; if the evaluation fails, then IDEAL may chose a different adaptation goal for the current design case or a different design case altogether.

Now suppose that the library of primitive components does not contain a 3 volt battery and thus the above adaptation plan fails. In this case, IDEAL selects the next adaptation plan, which may seek an abstract design pattern that can help generate twice the function (3 volts) of a given component (a battery of 1.5 volts). Let us suppose that the library of design patterns does contain such a design pattern in the form of component-replication-in-series pattern. IDEAL instantiates this design pattern at the location of the identified component (the battery) and generates a candidate design with two 1.5 volts batteries connected in series. Again, IDEAL completes the candidate design solution, revises SBF model of the old design into an SBF model of the candidate design by propagating the changes in the system variables. Finally, it evaluates the candidate design by checking the revised SBF model for consistency. Thus, IDEAL's process of adaptive design is flexible and dynamic, and organized around teleology. Although for ease of exposition, we have briefly illustrated IDEAL's teleological models and adaptive design processes with a very simple example, in fact IDEAL can address a range of adaptive design problems in a variety of domains ranging from electrical circuits to heat exchangers to angular momentum controllers.

Section 7: An Information-Processing Analysis of BID

In this section, we present a preliminary information-processing analysis of some aspects of BID. In particular, we seek to explain three observations about BID noted earlier: (1) Effective analogical remindings in BID require problem specification at the right level of abstraction and the right degree of filtering, (2) Effective analogical transfer in BID is multi-modal and occurs across structure-behavior-function abstraction hierarchies, and (3) For analogical transfer to be effective in BID, it must occur at the right level of problem decomposition and accommodate constraints posed by the other levels of decomposition.

7.1 Analogical Remindings

As students attempt to explore a solution or problem space, a given student may find the number of solutions either too large to be tractable or so small that they feel limited by the available choices. Thus, some students felt overwhelmed by the number of potential solutions, while others thought that they had few choices to work with.

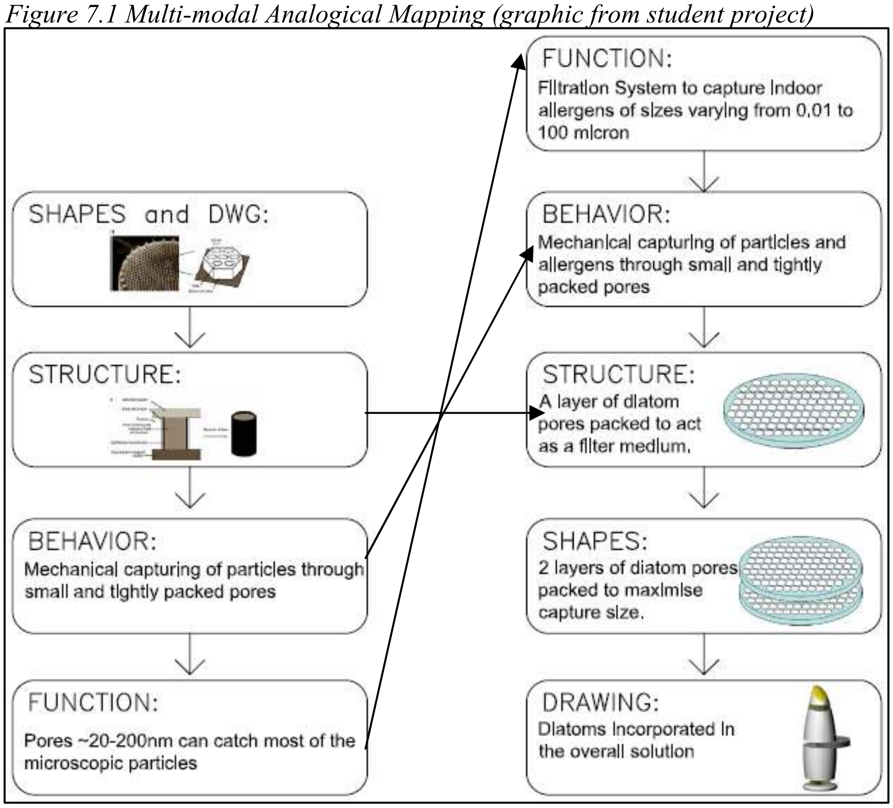
This may be explained by the process of reminding used in MAC/FAC. MAC/FAC first recalls many ideas based on superficial similarity. It then applies a filter to those ideas based deep relational similarity. The observation that students have either too many or too few ideas may be because they are applying too weak a filter (retrieving large numbers of solutions based mainly on superficial similarity) or too strong a filter (selecting only the solutions that have strong relational similarity).

Alternatively, students may be starting from vaguely or abstractly defined problems, each of which can lead to an abundance of ideas, or from problem definitions that are very specific and thus lead to few remindings.

7.2 Analogical Transfer

The analogies used throughout the class consistently involved combinations of text descriptions, pictures, graphs, and mathematic representations. The use of multi-modal representations extended across disciplinary and experience level boundaries. Further, although many students focused on structure and sometimes ignored function, effective analogies occurred at multiple levels of abstraction including structure, behavior and function. The following figure (adapted from a student team's report) hypothesizes a multimodal analogical mapping for the BioFilter example described above:

Figure 7.1 Multi-modal Analogical Mapping (graphic from student project)



7.3 *Problem Decomposition*

As students navigate a problem space, they decompose the problem into sub-problems. If an analogy is performed at too high or too low a level of problem decomposition, it may lead to an ineffective design.

Effective analogies occur at the right level of problem decomposition; they also accommodate constraints posed by the other levels of decomposition. The following set of examples explains this concept in detail:

Figure 7.2 Plant Growth/Solar Energy Conversion Diagram

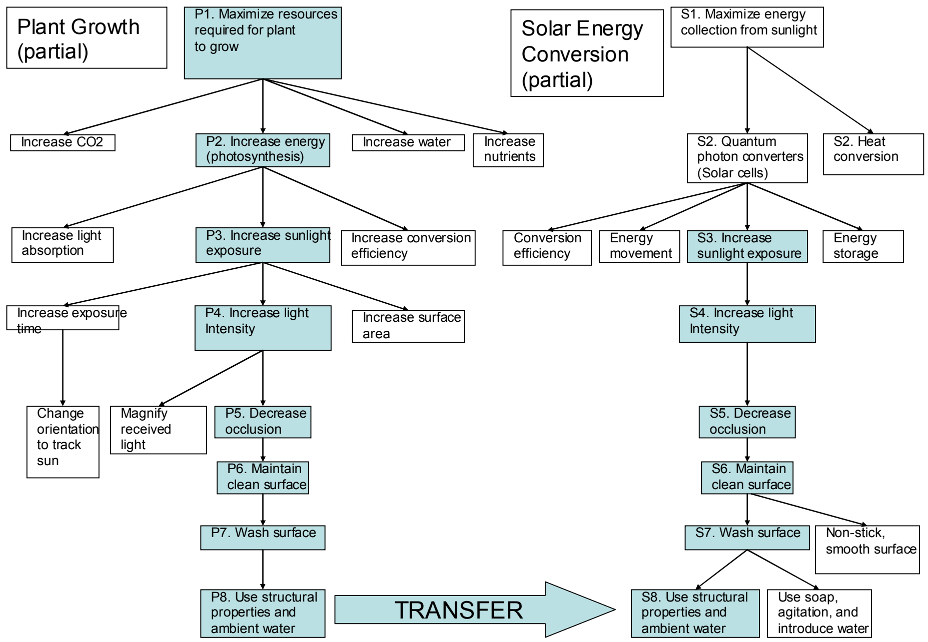
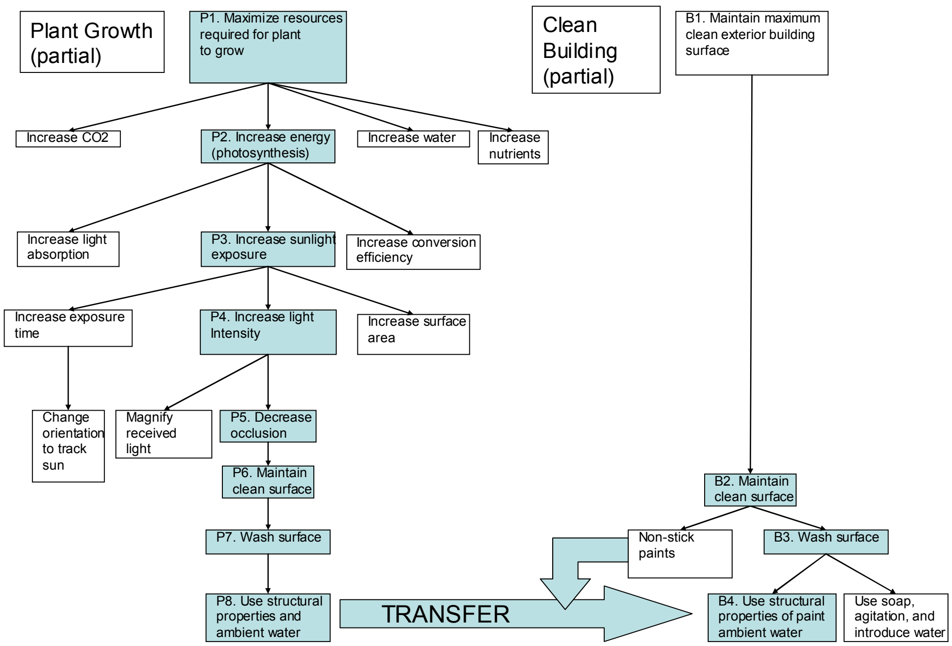


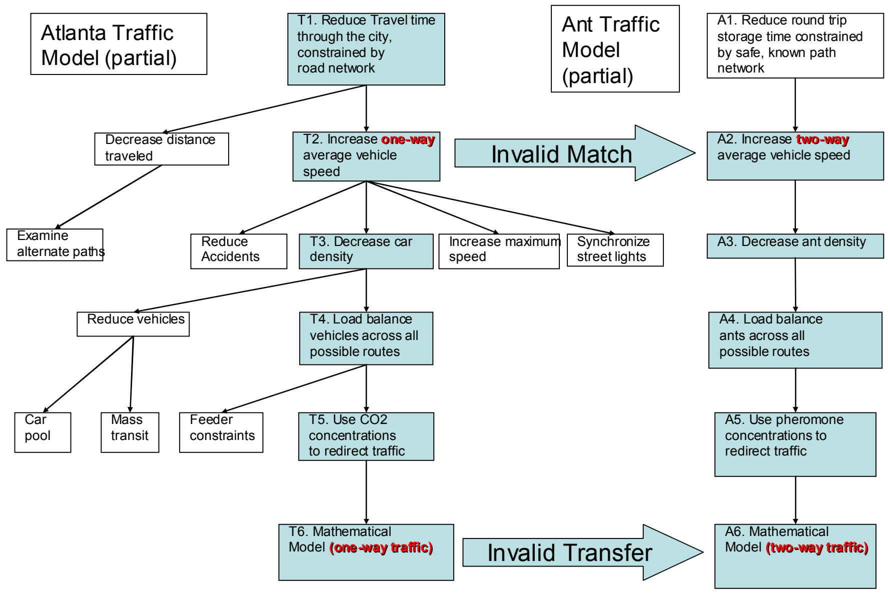
Figure 7.2 "Plant Growth/Solar Energy Conversion Diagram" demonstrates a proper analogical transfer based on analogical mappings across a hierarchy of problem decomposition. In this case P3 through P8 match S3 through S8 on a one-for-one basis. Abstractions above P3 and S3 do not match precisely, but in this case, they do not significantly affect the underlying model at the point of transfer.

Figure 7.3 Plant Growth/Clean Building Diagram



The next Figure, Figure 7.3 "Plant Growth/Clean Building", represents an analogical transfer that takes place from a very robust decomposition hierarchy to a very shallow hierarchy. This demonstrates that there need not be an exact match across many levels for effective transfer, only that matching is consistent where necessary in the hierarchy. This diagram also highlights an interesting possibility; that knowledge from within the same hierarchy can influence or add to the analogical transfer. In this case we use non-stick paints within the building hierarchy, in addition to structural properties with ambient water in the Plant Growth hierarchy to create a hybrid solution – a paint with structural properties that uses ambient water to maintain a clean surface.

Figure 7.4: Atlanta Traffic/Ant Traffic



In Figure 7.4 "Atlanta Traffic/Ant Traffic", the hierarchy has an incorrect transfer. In this case although T2 through T6 bear very close resemblance to A2 through A6, there is a slight difference in T2 and A2, specifically that one applies to one-way speed, and the other applies to overall round-trip time. The match is invalid, but as observed previously, other matches were invalid at higher levels. Why is this one different? In this case the transfer is incorrect because the information at levels A2 and T2 has a direct impact on the solution at A6 and T6. While T6 is optimized for one-way traffic, A6 is optimized for two-way traffic. When the transfer is made, the differences in optimization criteria cause an incorrect transfer and the solution doesn't work.

8. Summary and Conclusions

As mentioned in the introduction, this cognitive study has three main goals: (1) to understand biologically-inspired innovation in engineering design, (2) to identify opportunities for enabling more effective learning of biologically-inspired design, and (3) to examine the implications for developing computational tools for enabling effective biologically-inspired design. We summarize our observations and analyses accordingly.

1. *Observations on Effective Biologically-Inspired Innovation in Engineering Design:* Our analysis suggests that effective biologically-inspired innovation is characterized by (i) problem specification at the right level of abstraction with the right degree of filtering of remindings so that the designer retrieves useful biological cases for solving engineering problems, (ii) analogical transfer using multi-modal representations across structure-behavior-function abstraction hierarchies, and (3) analogical mapping at the right level of problem decomposition, with constraints posed by the other levels of decomposition taken into account.

2. *Opportunities for Enhancing Learning of Biologically-Inspired Design:* BID students face many cognitive challenges. While some of these challenges appear to also exist in other design domains, others are especially noteworthy in BID. We believe that identifying and addressing the following challenges have important educational implications: (i) although case-studies of biologically-inspired design discussed in the class used both problem-driven and solution-driven approaches to

design, the instruction generally prescribed the problem-driven method but the students typically used the solution-driven method; (ii) while some students get overwhelmed by the large number of analogical remindings, others become concerned by too few remindings; (iii) while the instructors repeatedly emphasized the importance of system functions in design, the students often focused on the system structure; and (iv) some students tend to make analogies at a level of problem decomposition without considering other levels or the constraints imposed by the other levels.

3. *Implications for Interactive Computational Tools for Supporting Biologically-Inspired Design:* In general, an interactive computational environment should (a) help users with tasks at which the humans are not good, and (b) not get in the way of tasks at which humans are very good. Thus, an interactive environment useful for BID would (i) support the analogical retrieval of biological cases relevant to engineering problems, (ii) provide access to structure-behavior-function abstraction hierarchies of biological designs for supporting effective analogical transfer, and (iii) monitor the analogical mappings between biological cases and engineering problems at different levels of decomposition and keep track of constraints imposed by the different levels.

Appendix A: Class Structure and Observation Technique

ME/ISyE/MSE/PTFe/BIOL 4803 is a project-based learning class, in which junior and senior students work in small teams of 4-5 students on assigned projects. Since the number of engineering students taking this course is more than the biology students, each team typically has one student from biology and a few from different engineering disciplines. The projects involve analysis of biological design principles, rationalization of engineering designs, and some forward design problem solving. Each team writes a 15-20 page report and makes an oral presentation towards the end of the class.

In Fall 2006, ME/ISyE/MSE/PTFe/BIOL 4803 was jointly taught by Profs. Jeannette Yen (School of Biology; Course Coordinator), Prof. Bert Bras (School of Mechanical Engineering), Prof. Nils Kroger (School of Chemistry), Prof. Mohan Srinivasarao (School of Polymer, Textile and Fiber Engineering), Prof. Craig Tovey (School of Industrial and Systems Engineering), and Prof. Marc Weissburg (School of Biology). The course also included guest lectures by several other faculty including Goel.

Helms and Vattam attended approximately 90% of the classroom sessions in ME/ISyE/MSE/PTFe/BIOL 4803, collected all course materials, took detailed class notes, observed teacher-student interactions in the classroom, and also observed a few of the interdisciplinary teams of students engaged in their design projects. They paid special attention to (i) classroom instruction and dialogue, (ii) student small group discussion within the classroom, (iii) student and instructor examples and exercises, (iv) student group design discussions outside the classroom, and (v) student interim and final presentations. During the course of observation, Vattam and Helms had minimal interaction with the class, although occasionally they asked clarifying questions during small group activities.

In addition, we held weekly meetings in which the participants included Vattam, Helms, and Goel, as well as other student members of the Design Intelligence group engaged in research on design, analogy and creativity. In these meetings, we clarified and analyzed the observations made by Helms and Vattam, and attempted to develop hypotheses and frameworks to explain the observations. However, during the course of observation, Helms and Vattam attempted not to apply filters or categorizations, but merely to record the classroom proceedings.

The ME/ISyE/MSE/PTFe/BIOL 4803 class was structured into Traditional Lectures, Found Object Exercises, Journal Entries, and a Final Design Project:

<u>Traditional lectures</u> were carried out by a number of instructors from different disciplines, but were heavily weighted to educate students on existing biologically inspired case-studies, especially in later classes. Other lectures provided overviews on “biologizing” problems, functional decomposition, design processes, optimization algorithms, and the use of analogy in design. Some lectures posed problems for the students to solve in small group exercises.

<u>Found object exercises</u> required students to bring in biological samples and analyze the solutions employed by these samples. These exercises were intended to expand awareness of the biology and solutions all around the students, as well as encourage the student’s to dig progressively deeper into the underlying functions solved by biological systems. Students formed small groups during these classroom exercises, each speculating on and discussing the merits of their found object’s solution. Each class then presented a “best-of” object to the rest of the class, representing their most interesting found object.

<u>Journal entries</u> required students to contemplate more deeply and write about their classroom experiences, as well as to document their musings about if and how their own design processes were changing. Copies of journals are now available, but were not available at the time this report was completed.

<u>The Final Design Project</u> grouped a cross functional team of 5 students together, based on interest in similar problems or solutions. After each individual submitted to the Professors two Problem-Solution pairs, the Professors created groups based on (1) reasonable similarity and (2) team functional diversity. This grouping provided each team with a de facto starting point for the space of problems to explore, specifically the union of their Problem-Solution pairs. Each team was responsible for identifying a

problem that could be addressed by a biologically inspired solution, for exploring a number of solution alternatives, and then developing a final solution design based on one or more biologically inspired designs. The final solutions were presented as if the group was seeking additional funding from a venture capital group.

Appendix B: A Compilation of Case Studies of Biologically-Inspired Design

ID	Biological System	Principle/Mechanics	Problem/Solution	Status	Driver	Category	Ref#
1	Morpho butterfly	Nano-optics, structural color	Computer screens	Development	Solution	Optics	34, 36
2	Scarab beetle	Nano-optics, structural color	Car Paint	Applied	Solution	Optics	34
3	Morpho butterfly, Scarab beetle	Nano-optics	Waveguides and beamsplitters for photonic integrated ciruits	Theory	Problem	Optics	20
4	Hummingbird wing	Nano-optics, structural color	Unknown	Unknown	Solution	Optics	34, 36
5	Hawkmoth	Anti-reflective nipple arrays	Non-reflective camouflage	Unknown	Solution	Optics	36
6	Hawkmoth	Anti-reflective nipple arrays	Increased solar cell light capture	Applied	Solution	Optics	35
7	Brittlestar	Micro-lenses	Photoreceptors, photoconcentrators	Unknown	Solution	Optics	2, 36
8	Sponge	Silica optical fibers	Improved, silica-based optical fibers (optical properties)	Unknown	Solution	Optics	1, 33
9	Burdock plant	Hooked seeds	Velcro	Applied	Solution	Misc	11
10	Shark skin	Riblets (steamwise microgrooves)	Low-friction surfaces	Applied	Solution	Locomotion	11
11	Bird wings	Dynamic wing shape	Morphing aircraft wings	Applied	Solution	Locomotion	11
12	Pinecone	Thermoregulation via structural change	Temperature adaptive clothing	Unknown	Solution	Misc	24
13	Lotus flower	Super hydrophobic surfaces	Dirt and water resistant paint	Applied	Solution	Misc	11
14	Biological neural networks	Unknown	Neuromorphic computer chips	Unknown	Solution	Misc	22
15	Human legs	Models of running	Mobile, bipedal robots	Development	Problem	Locomotion	8
16	Muscles	Electroactive Polymers	Novel, motion producing devices	Applied	Solution	Locomotion	4
17	Aquatic plants	Planar growth in flow direction	Drag reduction	Unknown	Solution	Locomotion	37
18	Compliant and tensile grasses	Alignment of structural macromolecules	Drag reduction	Unknown	Solution	Locomotion	37
19	Corals	Growth orientation to flow direction	Drag reduction	Unknown	Solution	Locomotion	37
20	Aquatic plants	Preferential mineral deposits	Reinforcement to drag stress	Unknown	Solution	Locomotion	37
21	Diatom	Costae support structure	Nanotechnology Theory	Theory	Solution	Biomineralization	32
22	Diatom	Actin/Myosin motion	Nanotechnology Theory	Theory	Solution	Biomineralization	6
23	Diatom	Photonic crystals	High reflecting omni-directional mirrors, low-loss wave guiding	Theory	Solution	Biomineralization	7
24	Diatom	Enzyme immobilization	Enzyme activity preservation	Development	Problem	Biomineralization	26
25	Diatom	Porous surfaces	Filtration, biosensor filtration, imunoisolation	Development	Solution	Biomineralization	31
26	Magnetotactic bacteria	Magnetosome chains	Nanotechnology Theory	Theory	Solution	Biomineralization	33

27	Sponge silica	Hierarchical glass fiber synthesis	Structurally resilient glass optical fiber (structural strength)	Unknown	Solution	Biomineralization, Structural Hierarchy	33
28	Abalone	Biocomposite nacre	Impact resistant armor	Unknown	Solution	Biomineralization, Structural Hierarchy	33
29	Mouse enamel	Highly ordered hydroxyapatite crystallites	Hard, wear resistant material	Unknown	Solution	Biomineralization	33
30	Virus	Identification and binding of peptide motifs	Nanotechnology Theory	Theory	Solution	Biomineralization	15
31	Flies	van der Waals interactions, spatulate hairs	surface adhesion	Development	Solution	Locomotion	5
32	Spiders	van der Waals interactions, spatulate hairs	surface adhesion	Development	Solution	Locomotion	5
33	Spiders	tarsal silk (produced at feet)	surface adhesion	Unknown	Solution	Locomotion	20
34	Geckos	van der Waals interactions, spatulate hairs	surface adhesion	Development	Solution	Locomotion	5
35	Humans, Insects, et al	Computational Neuromechanics	Integrated neural-mechanical locomotion control systems	Unknown	Solution	Locomotion	18, 35
36	DNA	Darwinian Evolution, Genetic Encoding	Evolutionary Computing, Genetic Algorithms et al	Applied	Solution	Systems Optimization	12
37	None provided	Background pattern matching	Camouflage	Unknown	Solution	Optics	9
38	Moths	Disruptive coloration	Camouflage	Applied	Solution	Optics	9
39	Hawkmoth	Wing design, Leading Edge Vortex	Micro Air Vehicles	Applied	Problem	Locomotion	28
40	Hummingbird	Wing design	Micro Air Vehicles	Applied	Problem	Locomotion	28
41	Hagfish slime	Fibre-reinforced composites	Unknown	Unknown	Solution	Misc	17
42	Bat Toes (Fish catching)	Wave reducing leading edge	Hydroplane strut wave reduction	Applied	Problem	Locomotion	14
43	Black Skimmer Mandible	Wave reducing leading edge	Hydroplane strut wave reduction	Applied	Problem	Locomotion	14
44	Steamer ducks	Planing hull, hydroplaning	Unknown	Unknown	Solution	Locomotion	14
45	Humpback whale flippers	Leading edge tubercles	Increased lift, reduced drag	Theory	Solution	Locomotion	14
46	Tuna, dolphins, seals	Oscillatory motion propulsion, pitch changes	Human oscillatory propelled exoskeletons, flippers, and submarines	Applied	Solution	Locomotion	14
47	Tuna, dolphins, seals	Vorticity	Robotic oscillatory propulsion systems (Robo-Tuna)	Development	Solution	Locomotion	14
48	Boxfish	Volume, shape, wheel base	DaimlerChrystler Bionic Car chassis	Applied	Solution	Locomotion	35
49	Flies	Anatomically and functionally coupled eardrums	Sound localization for very small receivers	Theory	Solution	Misc	35
50	Dragon fly	Predatory approach vector	Camouflage	Unknown	Solution	Misc	35
51	Loliginid squids	Chromatomotor fields	Integrated systems for camouflage and visual signalling	Unknown	Solution	Optics	27

52	Goldfish	Snap turn	Agile turning for fin-actuated underwater robots	Theory	Solution	Locomotion	29
53	Mottled sculpin (fish)	Hair cells seonsors	Underwater sensing, target acquisition, obstacle avoidance	Development	Solution	Sensors	19
54	Honeybee Eye	Omnidirectional compound eye	Data storage and readout, medical diagnostics, surveillance, photography	Development	Solution	Sensors	23, 25
55	Moths, Lobsters	Plume tracing using instantaneous sensor input	Underwater plume tracing and source finding	Development	Solution	Sensors	13
56	C.Elegans	Chemotaxis search algorithms	Robotic source tracking using chemotaxis and c.elegans based neural network	Development	Solution	Sensors	39
57	Whale Eye	Hydraulic lens movement	Fluidic lens	Development	Solution	Sensors	25
58	Wood (misc)	Cellulose fibrils, material hierarchy	Fiber construction materials	Unknown	Solution	Structural Hierarchy	3, 15
59	Bone (misc)	Collagen fibrils, material hierarchy, organic/mineral composites	Fiber construction materials	Unknown	Solution	Structural Hierarchy	3, 10 15
60	Tendons	Collagen fibrils, material hierarchy	Fiber construction materials	Unknown	Solution	Structural Hierarchy	15
61	Seagoing birds	Plume tracing using instantaneous sensor input	Bomb detection	Theory	Project	Sensors	*
62	Ants	Pheremone detection, swarm control algorithms	Traffic routing	Theory	Project	Sensors, Systems Optimization	*
63	Abalone Shell	Biocomposite nacre	Body armor	Theory	Project	Biomineralization	*
64	Diatom	Porous surfaces	Air Filtration	Theory	Project	Biomineralization	*
65	Spider silk	Glycoprotein adhesive	Air Filtration	Theory	Project	Misc	*
66	Butterflies, hummingbirds	Thin-film refraction, variable air gaps	Low-power visual display, effective under variable lighting conditions	Theory	Project	Optics	*
67	Copepod	Metachronal stroke	Undewater stealth vehicle (stationary maneuverability)	Theory	Project	Locomotion	*
68	Squid	Interrupted underwater jet propulsion	Undewater stealth vehicle (fast motion)	Theory	Project	Locomotion	*
69	Abalone Shell	Biocomposite nacre	Scratch, impact, and shatter resistant cellphone case	Theory	Project	Biomineralization	*
70	Human Bone (structure)	Pourous structure	Hip Implant	Theory	Project	Structural Hierarchy	*
71	Human Bone (growth)	Morphogenic proteins	Hip Implant	Theory	Project	Biomineralization	*
72	Wood stork	Countercurrent heat exchange	Adaptive garment for thermoregulation	Theory	Project	Misc	*
73	Penguins	Externally manipulated insulation layer	Adaptive garment for thermoregulation	Theory	Project	Misc	*
74	Arctic wolves	Countercurrent bypass system	Adaptive garment for thermoregulation	Theory	Project	Misc	*
75	Bees wax	Thermoregulation via parafin wax state change	Adaptive garment for thermoregulation	Theory	Project	Misc	*

76	Pony Fish	Bioluminescent counter-illumination camouflage	Surfboard camouflage	Theory	Project	Optics	*
77	Brittlestar	Micro-lenses	Surfboard camouflage	Theory	Project	Optics	*

* Biologically inspired design examples taken directly from student reports.

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