AC 2007-834: ENGINEERING FOR NON-ENGINEERS: LEARNING FROM "NATURE'S DESIGNS"

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Engineering for Non-Engineers: Learning From "Nature's Designs"

Abstract

This paper presents a course on biologically inspired design and engineering offered at Art Center College of Design. While most engineering classes are designed for engineering majors, and offered at schools with an engineering program, this course, "Nature's Designs," serves as a stand-alone introduction to basic engineering principals to artists and designers. Using the natural world as a reference point, particular emphasis is placed on principles of strength, structure, and form.

Introduction

"Nature's Designs" is intended to serve as a stand-alone course for in basic engineering principles as demonstrated by nature and natural systems. All students in the class are enrolled in the college as majors in an art or design discipline. The course has no prerequisites and thus a large percentage of the students have only minimal high school math and science training. Many of the students enter the class admitting to a fear of science and engineering, and claim to be "no good" at these topics. These factors combine to create a nontraditional engineering classroom. Therefore, this class strives to teach both engineering concepts as well as the relevance of engineering for non-engineers.

Over the course of this semester-long course, students are challenged to observe the world around them and investigate the "whys" behind naturally occurring phenomena. Students are asked to compare and contrast man-made design and construction techniques with structures and systems in nature. Special effort is made to choose topics which are especially relevant for students in design disciplines: Why does nature seem to favor flexible materials? What is color and what role does it play in biology? How do the five senses actually work? Why are there no wheels on Nature's transportation systems? The course closes with the students doing a final project on a topic of their choosing that bring together their major discipline (e.g. transportation design, product design, advertising or fine arts) with an in-depth study of a natural system, which can be anything from echolocation in bats to airflow in termite mounds.

Course Objectives

The premise of "Nature's Designs" is that, while many non-engineering students are intimidated by an engineering class, they are almost certainly comfortable observing the world around them. Using observations from nature as a starting point, this class compares and contrasts the natural world with the manmade world and uses basic engineering and biology to explain the similarities and differences. As published in the school's course catalog, the summary and objectives of this course are as follows.

Course Summary: *Students will learn how to use natural systems and designs to inspire their work. In particular, we will look at how natural constructions differ from manmade designs. Special emphasis will be placed on sustainability. Students will be encourages to apply knowledge gained in this class to their own work in their major field.*

Learning Objectives:

- *Identify different methods and materials used by natural systems, and be comfortable doing research to understand these systems.*
- *Use the principles learned in this class to design systems*
- *Compare natural and manmade solutions to related problems*
- *Assess the appropriateness of a biomimetic approach to specific problems*

Given that this may be one of the first and last science/technology classes that the student may take, there are some other, less content specific, course goals. The first of these is addressing the concept of reliable versus unreliable sources of scientific information. In the weekly writing assignments and the final project, attention is given to the process of assessing the reliability of a source. With the prevalence of digital information repositories, such as Wikipedia, students are repeatedly faced with the challenge of determining whether a source is an appropriate reference for research.

Another objective is demystifying engineers and the field of engineering in general. Many of the students admit to knowing very little about scientists and engineers and what they do on a day to day basis. Through guest lectures and field trips the students are exposed to engineers and engineering laboratories and encouraged to correspond with scientists and researchers while working on their final projects. Something as seemingly insignificant as a post field-trip luncheon with a group of engineers has been reported as a highlight of this course.

Course Development and History

The "Nature's Designs" course was taught at Art Center College of Design by Dr. Thomas for 4 semesters (Fall 2004, Spring 2005, Summer 2005, and Fall 2005). It is an elective course which fulfills part of the science requirement that all degree-seeking students must complete. The course is based on one developed at MIT by Dr. Thomas, while she was an undergraduate, and Professors Triantafyllou and Yue. The MIT class was designed as an introduction to the concept of *biomimicry* for first semester undergraduates. Given the assumption that freshman at MIT had already had basic Physics and Mathematics, the course dealt more mathematically with issues in biologically inspired design. While the Art Center College of Design class presented in this paper differs dramatically from the MIT course in terms of intended audience, it is important to note that the origin of this class lies in an engineering program.

Like many art and design schools, the liberal arts and sciences department at Art Center College of Design is a non–degree program that offers courses intended to enrich and

deepen the educational experience of the studio-based art and design majors. Offering an array of classes in the humanities, social sciences, as well as the natural and applied sciences, the curriculum contributes much of the content and conceptual rigor that will be translated into visual forms by student designers. Art Center College of Design transformed its liberal arts and sciences offerings five years ago with particular attention to the research and business components in the social sciences and also to the role of science in art and design education. The logic behind these areas of emphasis can be explained by the Venn diagram shown in Figure 1, in which the intersection or overlap of the three fields demonstrates the conditions and opportunities of innovation. Our business and science/technology courses are not intended to produce the kind of depth or expertise that schools focusing in those areas would provide, but rather to allow designers to have meaningful and productive conversations with experts in business and science/technology and to encourage future collaboration. At the same time, especially in the science/technology-based courses, we wanted our students to be aware of developments in new scientific fields that might inspire creative applications of design. This desire, and the realization that biologically inspired technologies have the potential for great impact, is what led to the creation of the "Nature's Designs" course.

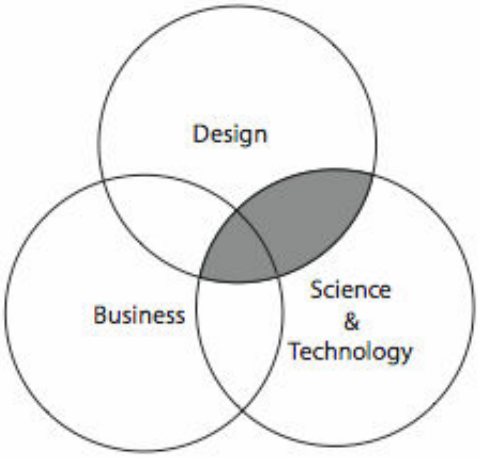

Figure 1: Schematic of Art Center College of Design's approach to Liberal Arts and Science curricula. "Nature's Designs" is intended to fall in the gray region of this diagram.

Perhaps the most critical challenge to developing a curriculum that brings scientific expertise into design studios is to find scientists who are able to translate the depth and complexity of their fields into a language that visually-oriented designers would find meaningful—to bridge a version of the "two cultures" famously described by C.P. Snow[1] without resorting to over-simplification or caricature. At Art Center College of Design located in Pasadena, California, we have the distinct advantage of our proximity to California Institute of Technology and to the Jet Propulsion Laboratory, both of which have given us faculty who are eager and especially adept at making their areas of expertise accessible and inspiring to our students. Reciprocally, many of our science faculty have found their interaction with our design students—with their different

expertise in visualizing ideas, understanding the human experience and making unexpected conceptual leaps—useful in their own research and thinking.

The newly designed science curriculum includes courses in the applied sciences that provide a basic understanding of scientific principles that designers must consider in their creative practices. Classes in ergonomics and aerodynamics, for example, are indispensable for our transportation designers. "Properties of Artistic Materials" is a standard for all our students. Product and environment design students take courses in theory of structure and materials, the latter supported by the color and materials laboratory. Such courses are likely to be found at most art and design colleges. But the more advanced courses we created went beyond showing our students the potential constraints to visualizing their ideas to finding in science inspiration for their creativity. These courses include "The Anatomy and Psychology of Perception," in which understanding the neurological basis of seeing can lead to new visual experiences as in the work of M.S. Escher and the movement known as Op Art (packaging designers have also mined this field). New courses such as "Robotics," "Nanotechnology," "The Future of Science and Technology" (including an ethics component), and a variety of courses in sustainable technology and ecology have all opened up new ways of thinking about design and its applications. But the course that best exemplifies all of our educational aims in the new science curriculum is "Nature's Design," the focus of this paper.

Using biology as a method to teach design, engineering and/or architecture is an increasing trend. In 2005, a paper[2] written by Dennis Dollens, architect and educator at the Universitat Internacional de Catalunya, looked at examples of incorporating biomimetic concepts and theory into the teaching of architecture and industrial design. It should be noted that the Art Center College of Design "Nature's Designs" course is one of the five courses he discusses in his paper. Our class differs from most of the other discussed courses in that it is designed as an introductory course open to students from a wide array of majors (as opposed to being designed specifically for architects or engineers.)

Course Structure

As this class is taught at an art and design college, courses tend to meet only once a week for a long block of time so as to accommodate studio classes. Therefore, "Nature's Designs" meets once a week for three hours over the course of twelve weeks. Three-hour long classes differ in significant ways from a typical one to two hour lecture-based engineering class. To maximize student participation and alertness, class periods were structured such that at least half of the three hour period was dedicated to an in-class activity, film or discussion meant to complement the day's lecture and readings.

Choosing a set of texts for an engineering class intended for non-engineers is a challenge. This is particularly true when the majority of the students have little or no science and mathematics training beyond the high school minimum. Over the four iterations of the course a primary textbook was used and supplemented by additional books, articles, and recommended readings. The primary text, Steven Vogel's *Cats' Paws and Catapults*[3],

was chosen for its thorough, yet primarily nonmathematical, treatment of the intended course topics. It should be noted that this is the same textbook that was chosen for the above-mentioned MIT course. *Cats' Paws and Catapults* was deemed to do a good job as an introductory text for students on the topics of size/scaling, stiffness, rigidity and strength. Additional readings were drawn from other books, magazines and scientific articles. These will be listed under the respective subject in the Course Topics section of this paper.

Given the three hour length of the class meetings, as well as the art and design focus of our school, it became clear that incorporating occasional videos into the class would be beneficial. One unexpected source of high quality, short films was the Technology Entertainment and Design (TED) conference. The theme of the multi-disciplinary TED conference for 2004 was "Inspired by Nature." Many of the talks from this conference are complementary to the "Nature's Designs" syllabus. Of particular note were talks given by Janine Benyus, Robert Full, Frans Lanting, and Ross Lovegrove. The TED conference provides a DVD of the proceedings to all attendees and has begun to release the talks for free to the public.[4]

Course Topics

Course topics were chosen based on their ability to meet two criteria. First, it must be easy to convey to students the importance of the topic. Second, the topic should have some relation, directly or indirectly, to the fields of Art and/or Design. The authors must state that it is their belief that any engineering topic could be made to meet the second criteria, however, the use of this criteria keeps relevance on the mind of the instructor when writing lectures and course materials. Below is a listing of some of the main course topics, as well as information on how they were presented.

1. Biologically Inspired Products:
Students are introduced to products, buildings, and materials which are consciously based on biological systems. This unit is also used to stress the difference between being inspired by nature and in superficially copying the appearance of a natural organism. Janine M Benyus' *Biomimicry*[5] is recommended as supplemental reading as it gives examples of commercially viable biologically inspired design. The list of possible products to discuss in this lesson is large, but the following two have been among our students' favorites.

- ***Gecko Inspired Adhesive*:** One intriguing natural phenomenon is the ability of geckos to climb up vertical glass surfaces. We discuss the difficulty of designing a machine to accomplish this feat and then explore the mechanism through which geckos achieve it. An explanation of the biological mechanism, essentially "split hairs," can be found in the article by Autumn et al.[6] For one semester of "Nature's Designs," we were fortunate enough to have one of the authors, Robert Full, give a guest lecture. As this is a topic that is best explained through visuals, when a guest lecture by Dr. Full was not possible, a video of his presentation at the 2004 TED conference was substituted.[3]

- ***Swarm Robotics***: The concept of "swarm robotics"[7] is discussed in parallel with lessons on the communication methods of swarm insects such as ants. Almost without exception, students are familiar with ants traveling in lines, one after the other. When asked, however, many are unaware of the method which allows them to do this. Pheremones are discussed, and students are asked to brainstorm applications of this form of passive communication. When possible, a guest lecturer from the nearby California Institute of Technology comes and gives a lecture on current trends in swarm robotics.

For an assignment in this section, students were asked to do some research a biologically inspired product. Additionally, they were asked to assess whether this was an example where something was truly learned by observing nature, or if the company had more superficially mimicked nature. This is an important distinction, as evidenced by historical failures. In *Cats' Paw and Catapults*[2] Steve Vogel gives examples of questionable attempts at learning from nature. One of his examples, the Eddystone Light, was hailed as being innovative for using a tapered tower for the lighthouse's body. The claim was that this was done in emulation of an oak tree. While building a lighthouse based on a strong oak tree at first seems like a logical choice it can be seen as naïve, for as Vogel points out, an oak tree is actually an end-loaded beam due to the drag on its leaves. The Eddystone Light therefore represents an almost artistic rendering of part of an oak tree's trunk without gaining any of the oak tree's strength. Such examples are used to illustrate to the student's the need for in-depth study of organisms which are intended to be the basis for a biologically inspired design.

2. Evolution versus Design:

One stark contrast between manmade and biological systems is the method in which they are designed. It has often been joked that nature spends millions of years on research and development, through evolution. While man and nature may both be successful in creating structures and devices, nature's method of random genetic mutation and "survival of the fittest" differs significantly from commercialized product design. In this section students are taught basic Mendelian genetics and introduced to the computer science concept of "genetic algorithms."

3. Transportation:

A large number of our students major in Transportation design, and thus quite a few of the students in "Nature's Designs" are interested in this topic. A comparison of manmade transportation methods with biological transportation methods yields many more differences then similarities. Students are asked to come up with as many forms of manmade transportation systems as possible. Inevitably, the majority of their list consists of wheeled vehicles or vehicles otherwise driven by a rotary shaft (such as propeller driven boats.) They are then asked to create a list of transportation schemes used by animals. This list tends to be filled with a diverse array of propulsion methods ranging from the slithering of snakes to the hopping of kangaroos. From

here a discussion can be launched on the pros and cons of wheeled transportation and hypotheses on why it is not seen in nature.

4. Strength in Nature:

An assignment precedes this lecture. Students are asked *to "Pick something natural that you consider 'strong.' What is it that makes you consider this thing strong? Write at least one paragraph on why you consider it strong. Do some research on what gives your chosen topic its strength. Write another paragraph on what you've learned from this research."* Popular answers to this assignment are trees, seashells, bone, spider webs, muscle and rocks. In class a second list is created by asking students what manmade objects they consider strong. This list typically contains iron, other metals, and stiff solid objects. By comparing and contrasting these lists, the students are challenged to define what "strong" really means. Often their natural examples of "strength" include objects which are flexible, such as trees, where the list of manmade strong objects is predominately made up of rigid objects. The follow up reading and lecture for this exercise focus on the differences between strength, extensibility, toughness, resilience and extensibility. A second component of this section is the propagation and stopping of cracks. Students are introduced to the field of materials science, and the concepts of composite materials.

5. Why Size Matters:

The scale on which nature works is typically much smaller than the scale of manmade designs. Often when we think of a manmade object we think of a something such as a desk or table. When pressed further on what such an object is made of, we may answer "a tabletop and four legs." On the other hand, when someone is asked what they are made up of they will often answer "cells." In this lecture we look at organisms from both a micro and macro perspective. Students are challenged to investigate how cells interact with one another to make up an organism. We also look at how volume and surface area scale as a creature grows, and the effect that this has on functions such as temperature maintenance, metabolism and weight.

Clearly, scale has a large impact on locomotion, so concepts from the lecture on transportation are looked at again. Creatures which walk on water, such as water striders, are discussed and students are asked why it is that they themselves can not walk on water. This leads to discussions of surface tension and weight distribution.

It should be added that one of the more creative "Nature's Designs" final projects stemmed from this lecture. A student chose to look at fictitious creatures from movies, such as oversized insects, and assess whether they could feasibly exist. This entailed a study of how the volume of various objects changes as their characteristic length increases. Unsurprisingly, he showed the class that if a "gigantic" insect were to have the same body to limb ratios as a normal insect, it would be unlikely that the creature would be able to support itself.

8. Sustainability

Perhaps the most striking difference between nature's manufacturing processes and industrial processes is in their waste and byproducts. At Art Center College of Design we hope to instill in our students a sense of responsibility for the impact that their creations have on the planet as a whole. Throughout the evolution of "Nature's Designs" sustainability has always been a featured topic. Depending on the semester, students have been required to read either *Cradle to Cradle: Rethinking the Way We Make Things* by William McDonough and Michael Braungart,[8] or selections from *Nature's Operating Instructions* edited by Kenny Ausubel.[9] McDonough's book is the more technical of the two, and thus is now the preferred book for the course. The book edited by Ausbel is more episodic, consisting of essays on the environment. This topic comes towards the end of the semester so that it can be stressed that nature's processes are sustainable despite their complexity. Students are asked to look at the processes they use on a regular basis to create their school projects and assess the environmental impact of the chemicals and materials that they use. Then, using the knowledge that has been gained over the semester, we look for alternative ways to accomplish these projects. For example, we look at how nature achieves vivid color and compare that to the paints and pigments that are typically used in commercial art.

9. Other Topics

The above is a partial list of topics covered in the class. Other topics that are addressed include muscle, the five senses (an in-depth look at how the sense's work, and at engineering breakthroughs in augmenting and restoring the senses), the use of color in nature, and the filtration capabilities of plants. Each semester, one lecture is left open for topics suggested by students. During the second or third class meeting, students are asked to write down topics that they were hoping to learn about in this class. The instructor uses these suggestions to create a "student's choice" lecture touching on the topics that students are interested in.

Nature's Designs Notebook

To encourage observation of the natural world in an inquisitive way, students are required to keep a "Nature's Designs" notebook. A minimum of twice a week, students must record some naturally occurring creature or phenomenon that they find interesting. They must create a visual record of this, through a quick sketch or photograph, which must be notated with comments on why they are intrigued. For example, a student may observe a water strider walking on the surface of a pond. They would then snap a picture of the creature, or draw a sketch of it. Next they may add comments such as "Why doesn't it fall in the water," "notice the ripples forming around its feet," or even "cool colored bug." At the end of the semester students are encouraged to flip through their notebook when choosing a final project topic. Students have commented that keeping this record

forced them to look at nature in a different way and have been grateful for this assignment.

Final Project

The final assignment in the course is an independent research project. Students are given a choice of three project formats as described below.

> ***Choice A:*** *Pick a natural system that is particularly intriguing to you (for any reason). Write a 10 page (minimum) research paper on this system. You should explore your chosen system in depth. Highlight specific attributes of this system and discuss what function they serve. Analyze the design of your chosen system in terms of the characteristics which we have discussed in class.*
>
> ***Choice B:*** *Design a project that incorporates a study of a natural system.*
> ***Examples****:*
>
> - *Choose and research a natural system and use your findings to design a product. You would be expected to turn in some sketches and descriptions of your proposed product (ie. Velcro from burrs), as well as a 3-5 page research report.*
> - *Choose and research a natural system, and incorporate this into a finished piece. Design a poster about environmental awareness using your knowledge of nature's solution to "waste." In addition to your finished deliverable, you must include a 3-5 page research report on the system that inspired your work.*
> - *Research a natural system of your choice. Produce an informational poster on your topic, as well as a 3-5 page research report.*

Interestingly, out of the seventy four students who have taken this class the wide majority chose choice B. Less than 5 students have ever chosen the longer research paper (choice A). The prevalence of students choosing to do the research project involving the creation of a final deliverable is unsurprising given the studio-based format of most of the classes in the curriculum. Additionally, actually applying the research to a project, typically in the student's major field of study, serves the important role of showing the relevance of the course material to their future line of work. A common complaint among students entering Art Center College of Design is that they do not see how Liberal Arts and Sciences classes are relevant to their future careers as artists and designers. By integrating discipline specific elements into their final projects, the importance of technological literacy, particularly basic engineering principles, is hopefully conveyed. Our best metric for judging whether this goal was accomplished is by looking at the end of term evaluations, particularly those questions which ask students whether the course is relevant to their studio work, and whether they would recommend it to other students in their major. As can be seen in the Evaluations section of this paper, the response to those evaluation questions has been positive.

A wide array of final projects have been prepared for this course. Topics have included:

- *"The Helical Structure as Evidenced in Nature:"* a graphic design student's study of the various scales over which helices occur in nature.
- *"Sonar Echolocation:"* a poster and paper explaining how echolocation works using both dolphins and manmade sonar systems as examples
- *"The Secret Strength of Abalone:"* a study, by a student majoring in product design, of whether the methods through which abalone shells achieve their strength could be applied to bullet proof vests
- *"Nature's Packaging:"* various projects looking at different packaging methods nature uses for seed transport.

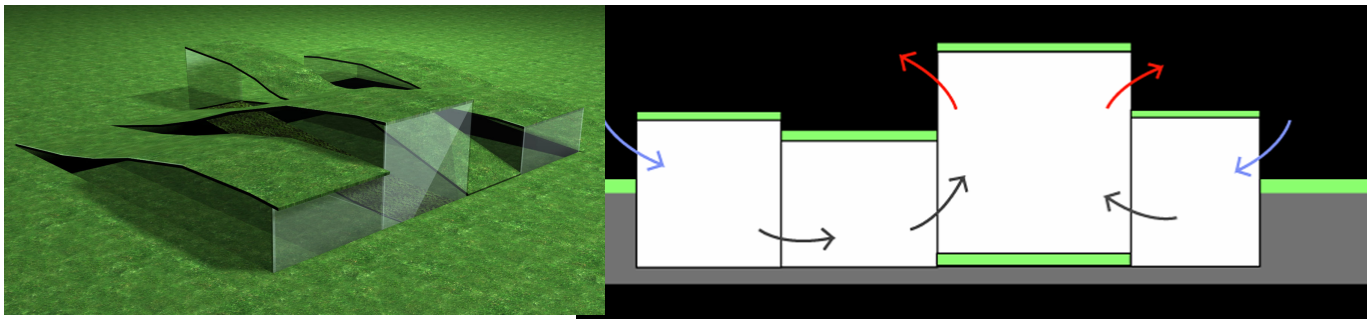

Figure 2: Images from the final project of student, Emi Fujita.

Figure 2 shows work done by Emi Fujita, an Environmental Design student. She researched the nests of leaf cutter ants and then used this knowledge to create a concept for housing ventilation. Another project, shown in Figure 3, completed by Robbyn Carter, also an Environmental Design student, focused on skin. She was interested by how skin could be both flexible and strong and was particularly intrigued by how skin cells connected to one another. Her project resulted in a research paper as well as some conceptual explorations of creating a synthetic skin.

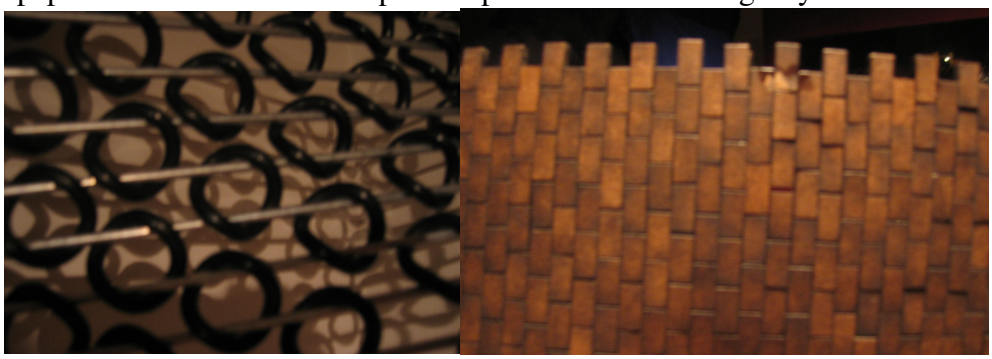

Figure 3: Images from the final project of Robbyn Carter.

In one case, the class led to a student choosing Bio-Inspired Design methodologies as the topic of his Masters thesis (see Figure 4). Chul Kim, a Masters student in the Industrial

Design department wrote a dissertation entitled *Bio-logical innovation: Strategy of Design Innovation By Incorporating Natural Reference*."[10]

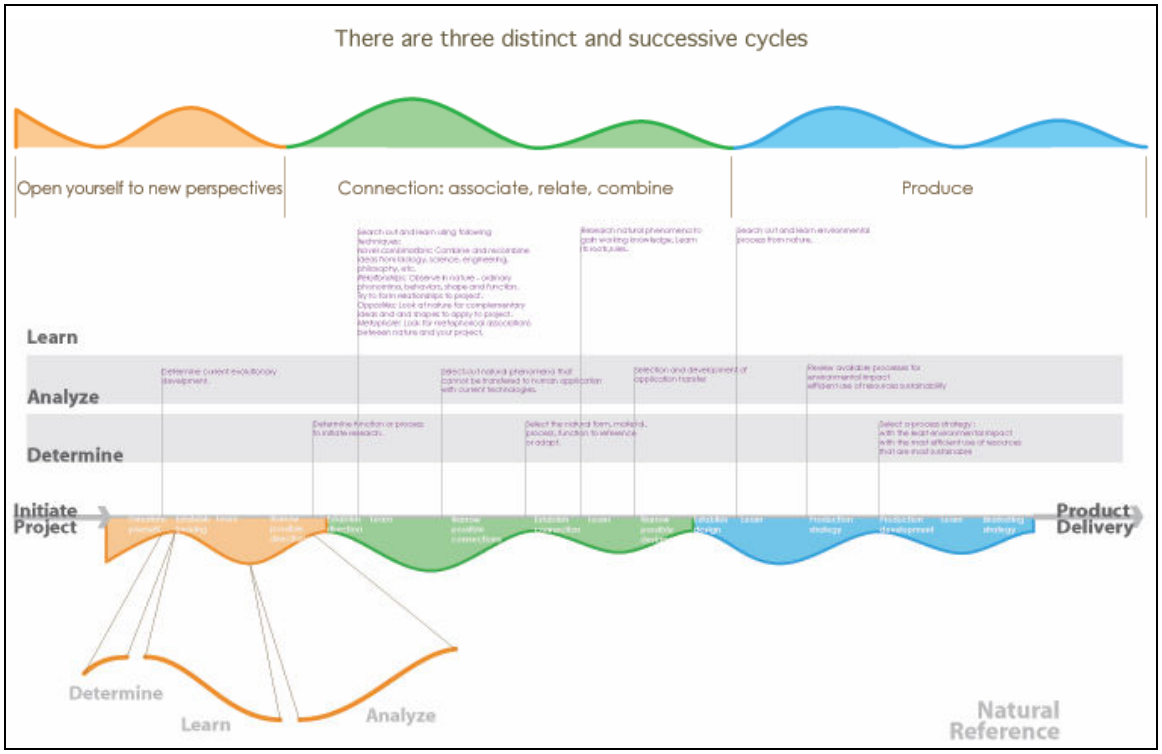

Figure 4: Images from the thesis of Chul Kim, which was based on work he did in the "Nature's Designs" class.

Evaluations

At the conclusion of each semester the standard Art Center College of Design course evaluation was performed. As can be seen in the grid below, the course was well received by the students. All rating values are out of a possible 5 points.

	Fall 2004	**Spring 2005**	**Summer 2005**	**Fall 2005**
Number of Students in the class	28	16	20	20
Number of Survey Responses	16	14	14	12
Overall, rate this class on a 1-5 scale, 5 being the best	4.13	4.00	4.29	4.08
The class has provided me with knowledge I consider relevant and helpful to my studio work	4.19	3.86	4.64	3.92
I would recommend this class to other students in my department	4.25	4.07	4.21	3.92
Teaching methods of this class were appropriate to the course content	4.19	4.21	4.64	4.08

This class has challenged me	4.125	4.21	4.36	4.09
Assignments helped my understanding of the subject matter	4.38	4.14	4.57	4.00

Figure 5: Results of end-of-term course evaluations.

Conclusion

As part of Art Center College of Design's new Liberal Arts and Sciences curriculum, courses bridging the gap between the arts and engineering have been created. "Nature's Designs" was one course created by this initiative. Using biological examples to explain engineering principals, students were introduced to the fields of fields of engineering and biology. Student evaluations from four semesters of the course show that students have enjoyed the class and found it to be relevant to their art and design work. Through interactions with guest lecturers and field trip guides the students are introduced to scientists and engineers and gain an understanding of what individuals in these professions do.

Acknowledgements

The authors would like to thanks the students who have participated in this course. We would also like to acknowledge the guest lecturers whose presence greatly added to the success of this course.

[1] Snow, C.P., *The Two Cultures and the Scientific Revolution*, New York. NY: Cambridge University Press, 1959.

[2] Dollens, D, "Design Biomimetics: An Inquiry and Proposal for Architecture and Industrial Design," 2005. Available: http://www.tumbletruss.com/DesignBiomimeticsSurvey.pdf.

[3] Vogel, Steven, *Cats' Paws and Catapults: Mechanical Worlds of Nature and People*. New York, NY: W.W. Norton & Company, 1998.

[4] Talks can be found at http://www.ted.com/tedtalks/. As of 1/2/06 some of the talks mentioned in this paper have not been released to the web. However, new talks are posted every week.

[5] Benyus, J, Biomimicry: Innovation Inspired by Nature. Harper Perennial, 2002.

[6] Autumn, K., Liang, Y., Hsich, T., Zwaxh, W., Chan, W.P., Kenny, T., Fearing, R., and Full, R.J. 2000. Adhesive force of a single gecko foot-hair. Nature. 405, 681-685

[7] A. Martinoli, K. Easton, and W. Agassounon, Modeling of Swarm Robotic Systems: A Case Study in Colloborative Distributed Manipulation. International Journal of Robotics Research, 23(4):415-436, 2004.

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