Biomimicry: Using Nature as a Design Inspiration

A. Course Description and Audience

Sustainable Construction is a technical elective for seniors and graduate students (primarily Civil Engineering majors). We expect that this module would also be appropriate across the range of engineering disciplines.

B. Placement of Lesson in the Course Design

Students in *Sustainable Construction* learn about the environmental, economic and social impacts brought about by the construction industry. In this course, methods and tools are introduced to help students find more sustainable solutions to problems they encounter as engineers and in their personal life. A primary objective of this course is for students to develop skills for life-long learning about sustainability in the built environment as the field evolves. Specifically the "Biomimicry" section of the course is intended to teach students a method to identify sustainable solutions to engineering and construction problems by using nature as a design inspiration. **This module introduces biomimicry to help students add this concept of using nature as a design model to their problem-solving approach.**

C. Lesson Learning Objectives

After this class session students will be able to:

- Define biomimicry as it relates to sustainable construction and engineering.
- Practice applying biomimicry to real world engineering problems to arrive at sustainable design solutions.
- Explain biomimicry to a variety of audiences in a clear and concise manner.
- Assess lifelong problems using a biomimetic mindset.

D. ABET Criteria 3a-k Addressed in the Lesson

Students will have the opportunity in this course to meet a number of ABET criteria education competencies. In particular, this module should support the following competencies ("Criteria for Accrediting," 2009):

(a) The ability to apply knowledge of mathematics, science, and engineering towards the design of a sustainable solution to human problems while using biomimicry as a tool.

(c) The ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability with the mindset of using nature as a design inspiration.

(d) The ability to function on multidisciplinary teams by using resources and references from biology, life sciences, and multiple engineering disciplines.

(e) The ability to identify, formulate, and solve engineering problems by using nature as a mentor for design concepts.

(g) The ability to communicate effectively by presenting their biomimetic designs in group and class discussions.

(h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context by realizing that biomimetic design has the potential to influence all four of these sectors.

(i) A recognition of the need for, and an ability to engage in life-long learning by understanding that biomimetic design, like nature, is an evolving concept that continuously improves as design standards advance.

(j) A knowledge of contemporary issues by using a biomimicry search engine as a reference tool for their biomimetic design concepts.

E. Description of the Topic

Background

The word biomimicry originates from the Greek words bios (life) and mimesis (imitation) and its theory has existed since the beginning of human evolution. Early human civilizations were critically dependent on the natural world and therefore their lifestyles, culture, and religion were all entwined with nature. These preindustrial societies relied on nature to harvest crops, produce medicine, provide clothing, build shelter, and clean up waste. In contrast, today's society depends on the industrial world to manufacture similar results. According to Janine Benyus, a biological science writer and leading scholar of biomimicry, we are much farther removed from nature compared to our ancestral beginnings, which is one reason our world is starting to show signs of weathering (1997).

Biomimicry shifts our present day ideology closer to nature by using nature as a design inspiration to sustainably solve human problems. As opposed to humans, nature solves its problems using methods that do not require high temperatures, high pressures, and chemical treatments. Additionally, nature solves problems with locally available resources and without generating unusable waste (Benyus, 1997). Biomimicry links the built environment to the natural world by striving to use Mother Nature as a *model*, a standard of *measure*, and a *mentor* (Figure 1). The rationale for this approach is that "the more our world looks and functions like this natural world, the more likely we are to be accepted on this home that is ours, but not ours alone (Benyus, 1997)."

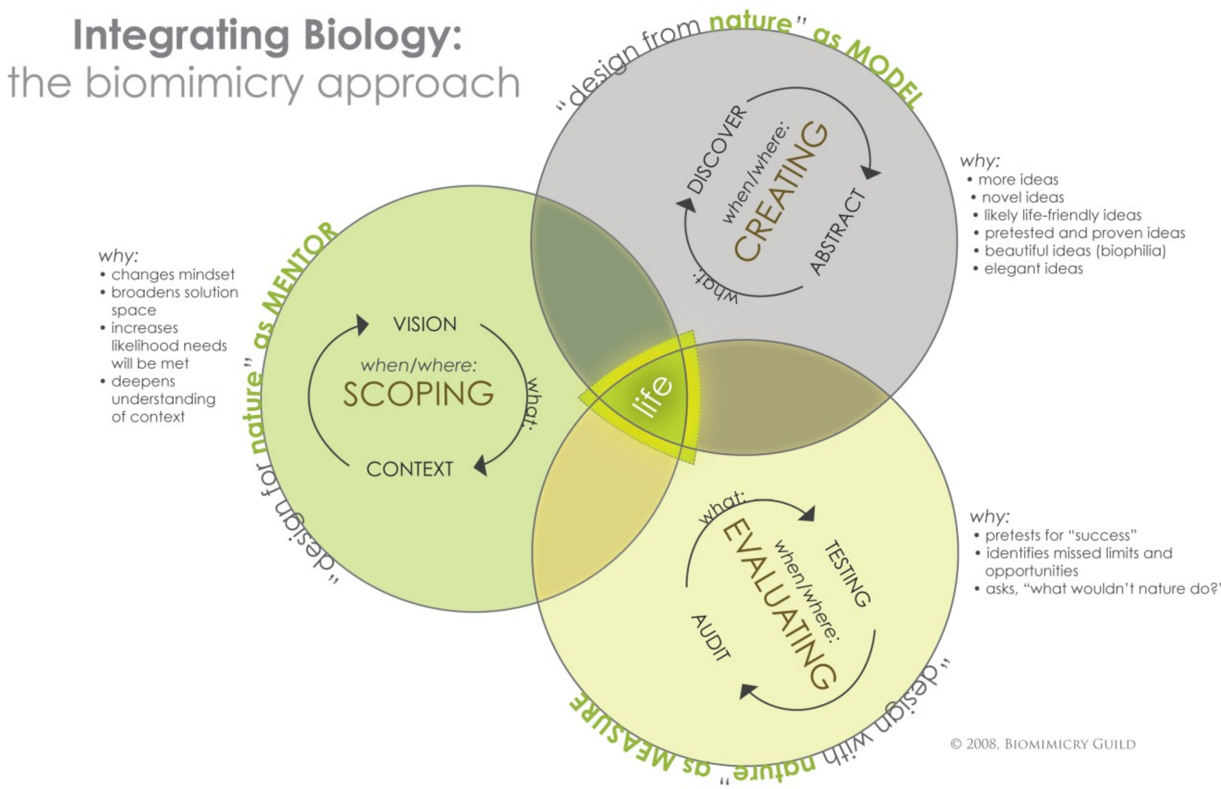

Figure 1. Viewing nature as a design model, measure, and mentor ("Curricula," 2009)

Nature as a Model

Biomimicry studies nature then imitates its designs and processes to identify potential solutions to human problems. Through close study of how nature functions, it appears that many of mankind's inventions are present in nature; however, they exist in more elegant forms that are less harmful to the planet (Benyus, 1997). For example, in order to heat and cool a building, humans invented the central heating and air-conditioning systems. In contrast, West African termites solve this same problem without technology that expends energy and natural resources. These insects create mounds that passively maintain a consistent temperature of 86 degrees Fahrenheit despite a dynamic non-equilibrium African climate (Doan, 2007). A vertical chimney cuts through the center of the termite mound and leads to a large air space called the cellar where cool air is stored. As hot air rises through the chimney, cool air is pulled in via porous ridges found in the interior and exterior walls (John et al., 2005).

Using nature as an inspiration, the Eastgate Centre building located in Harare, Zimbabwe, introduced a design similar to African termite mounds that uses passive cooling instead of the conventional air-conditioning methods (Figure 2). The energy and cost savings from this design are outstanding. The building uses less than ten percent the energy of a comparable building; the owners initially saved 3.5 million dollars simply from eliminating the need for central air-conditioning (not including annual energy savings); and because the building cost less to construct, the tenant rent is twenty percent lower than those in the surrounding buildings (Doan, 2007).

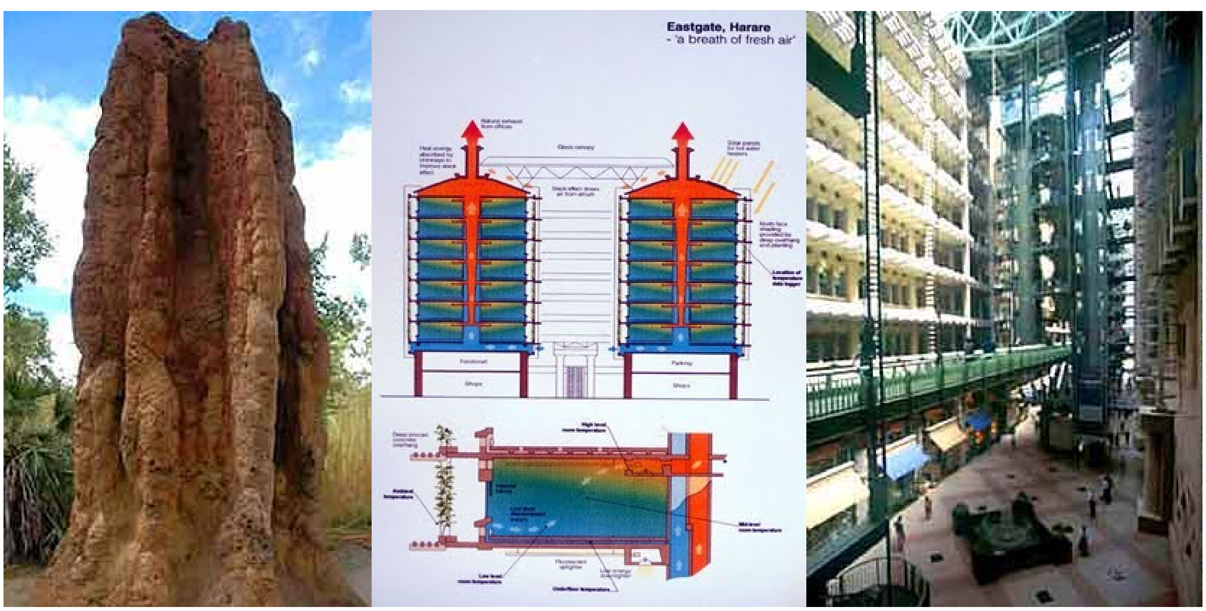

Figure 2. The Eastgate Centre building design inspired by African termite mounds (Doan, 2007)

Nature as a Measure

Life on Earth has evolved throughout its 3.8 billion years of existence. In comparison, humans have been present for only a tiny fraction of this time period. Excluding humans, Earth's inhabitants have endured billions of years of life without consuming their ecological resources. Species alive today hold the secret to survival. These species have learned how to survive, evolve, and adapt to their surroundings throughout time. Creating a built environment that functions more like the natural world may address human caused problems such as the depletion of natural resources, global warming, pollution, overpopulation, starvation, etc. (Benyus, 1997).

To achieve a sustainable ecosystem, nature lives by several vital principles. "Life's Principles" (Figure 3) are interrelated and various species of plants and animals depend on each other for survival. This is how nature operates; waste from one organism is used as resource for another, ultimately forming an efficient, self-sustained ecosystem. In Kalundborg, Denmark, engineers designed an industrial ecosystem inspired by how nature integrates waste from one system as a resource for another. In essence, a series of businesses consisting of a coal fired power station, an oil refinery, a pharmaceuticals plant, a plasterboard manufacturer, a water, electric, and heat distributor, and a farm all use by-products from one process as a low cost input for another process. For example, Figure 4 demonstrates how treated wastewater from the oil refinery is recycled as cooling water for the power station. Meanwhile the refinery and the pharmaceuticals plant both purchase steam produced as waste from the coal fired power station to run their engines. In addition, excess heat from the power station contributes to the warming of 3,500 homes in the neighboring area, as well as 57 local fish ponds (Reed, 2004; "Kalundborg," 2007).

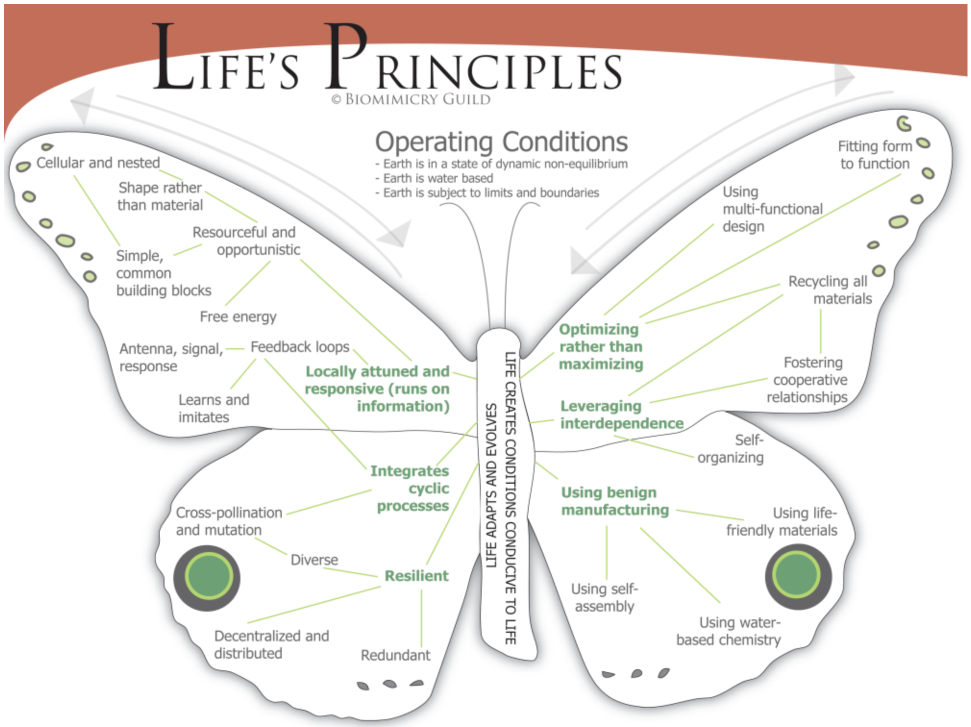

Figure 3. Life's Principles illustration ("Curricula," 2009)

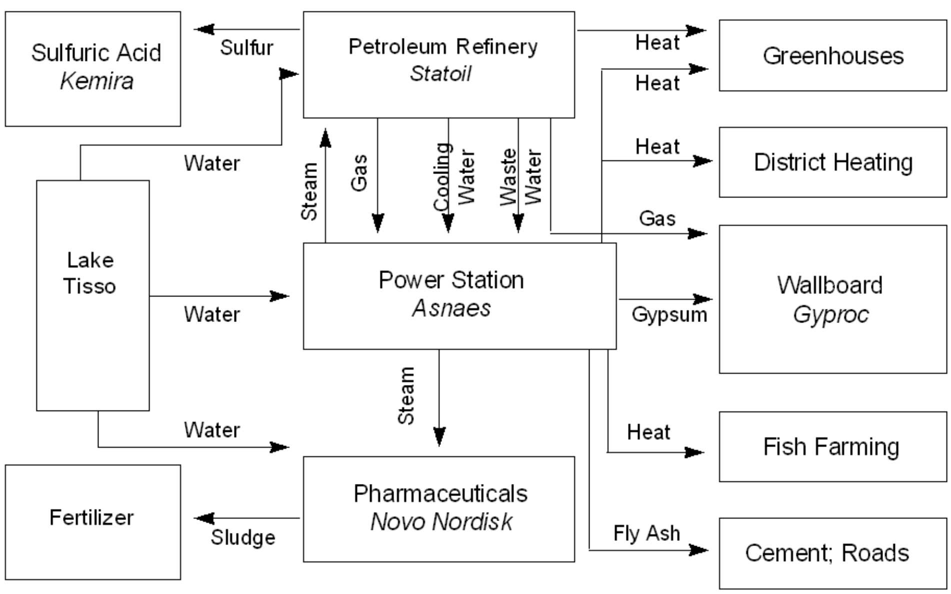

Figure 4. Schematic diagram of the industrial ecopark located in Kalundborg, Denmark (Allenby & Graedel, 1994)

Nature as a Mentor

Biomimicry is an innovative way of viewing nature. It repositions the mindset of designers from "*what can we extract from the natural world?*," to "*what can we learn from it?*" By examining nature's materials and processes, humans can formulate new ideas and methods with the potential to affect the way crops are harvested, materials are made, energy is harnessed, medications are produced, information is stored, business is conducted, building are constructed, and much more (Benyus, 1997). Biomimicry teaches engineers that, "there is more to discover than to invent… nature, imaginative by necessity, has already solved the problems we are struggling to solve. Our challenge is to take these time-tested ideas and echo them in our own lives (Benyus, 1997)."

Applying Biomimicry in Engineering Design

Through understanding the natural processes and their relations with human needs, designers can improve the materials, mechanisms, and risks associated with the built environment. Many innovative sustainable engineering techniques are obtainable from mimicking how the natural world efficiently consumes energy, produces low impact materials, and generates waste valuable to other organisms.

One of the learning objectives addressed in this module is students will practice applying biomimicry to arrive at sustainable design solutions. To accomplish this objective, students must understand that utilizing biomimicry as an instrument is more complex than simply viewing one aspect of nature as a design model, measure, and mentor. Since nature functions as a whole structure with many different interconnected elements, biomimetic designs must use an integrated systems thinking approach to include disciplines such as biology, biophysics, and material science (John et al., 2005). Systems thinking, as opposed to siloed thinking, views a complicated problem in terms of the components and their relationship to the problem as a whole (Nikou and Klotz, 2009).

Like systems thinking, the biomimetic design process is a continuous progression towards an ultimate goal; once one challenge is accomplished, a new one arises, therefore beginning another round of the design. This repetition of design stages continues until new challenges cease to occur and the final goal of the project is met. The application of biomimicry in the design process can be simplified into eight useful steps which serve as a thought rubric:

1. ***Identify*** a real world challenge

2. ***Interpret*** the design brief
3. ***Discover*** nature's models
4. ***Abstract*** design principles
5. ***Brainstorm*** potential applications
6. ***Emulate*** nature's strategies
7. ***Evaluate*** against Life's Principles
8. ***Repeat*** steps 1-7

First, innovators must ***identify*** the basic functions of a real world challenge by asking 'What do you want your design to do?' For example, *I want my design to produce energy at a low cost*. The next step is to ***interpret*** the design brief from nature's prospective. This step asks the question 'How does nature do this function?' Specifically, one must determine how nature performs the function within its climate, nutrient, social, and temporal conditions. Building on the previous example, *nature produces energy through the plant process of photosynthesis which captures solar energy and converts it into chemical energy* (Photosynthesis: Cooke's koki'o, 2009). After interpreting the design brief, one must ***discover*** nature's models by determining which species perform this function the best. This step asks the question, 'Whose survival in nature depends on this function?' If the function is common throughout many species, such as photosynthesis, the designer must search for the species that executes this function in the most extreme living conditions, yet is unaffected by the variables ("Biomimicry: A tool for innovation," 2009). For example, penguins are a group of aquatic birds that must survive in the extreme climate of the Antarctic. Their ability to withstand variables such as the cold climate and scarcity of food proves that their survival relies on their thermal insulation and energy consumption. The penguin's thick, air-filled, windproof coat consists of two layers of evenly packed overlapping feathers that help reduce heat loss and moderate the external environment (John et al., 2005). Biomimetic designs inspired by the penguin's dynamic coat may lead to innovative building and pipe insulation techniques.

The next step is to ***abstract*** design principles from the species then find any repeating patterns or processes within nature that are successful. In this stage, the intention is to select the principles from nature that are most relevant to the original design challenge. Then, ***brainstorm*** potential applications of nature's models in an engineering mindset. The designer must search for multiple solutions by researching literature, studying nature, and consulting biologists for a more distinct perspective. Then, step six requires the designer to ***emulate*** nature's strategies and develop design solutions based on nature's models; the principal concept is to mimic nature's form, function, and ecosystem ("Biomimicry: A tool for innovation," 2009). Continuing on the photosynthesis example and applying it to step six, *conventional silicon-based solar panels capture, separate, and transport light energy and have a high solar energy conversion ratio inspired from how nature produces energy through photosynthesis* ("Photosynthesis: Cooke's koki'o," 2009). Although the creation of solar panels is an innovative idea inspired by nature, it can still be improved on through the final steps of the rubric.

After nature's strategies are emulated, the next step is to ***evaluate*** the design against "Life's Principles" (Figure 3). Questions the designer must answer are: 'Does your design adapt and evolve?', 'Does your design create conditions conducive to life?', and 'How can you improve your design?' This step is meant to identify further ways to advance the design and develop new questions to explore, essentially adapting and evolving the design similar to how nature would function. Upon answering these questions for the solar panel example, one would determine that, *solar panels are manufactured from one material that requires large amounts of energy, toxic solvents, and bulky infrastructure* ("Photosynthesis: Cooke's koki'o," 2009).

Although photovoltaic solar panels are a revolutionary method of generating renewable energy, their design can still be improved. This illustrates why biomimetic design is portrayed as a continuous loop and why the last stage of the rubric is to ***repeat*** steps 1-7. The repetition of these steps allows improvement and expansion of the design. By repeating steps 1-7 for the solar panel example, one would discover that, *dye-sensitive solar cells use photosensitive dyes and flexible materials that are less harmful to the environment and can be incorporated into architectural elements such as window panes, building paints, and textiles. Also, they have a higher overall power collection potential due to low-cost operability under a wider range of light and temperature conditions* ("Photosynthesis: Cooke's koki'o," 2009). A biomimetic design concept experiences multiple iterations of the thought process to adapt, evolve, and develop into a sustainable solution for a human problem.

F. Lesson Plan

This lesson plan extends throughout two class periods and covers the introduction, overview, and application of biomimicry as an engineering design approach. The first class begins with the instructor briefly introducing the learning objectives for the class. This introduction is followed by a presentation describing biomimicry that elaborates on background information provided in the preceding sections. At the end of the presentation, the instructor assigns homework to be included in the next class as an interactive learning task.

Biomimicry Homework Assignment

1. Choose an engineering material or system (e.g. ductwork, steel, traffic controls, etc.) and identify its basic functions (e.g. move air, provide structure, organize movement, etc.).
2. Provide an example from nature that performs these same functions.
3. How could you draw on the example from nature to better perform these functions?
4. Use the 8-Step rubric introduced in class in order to formulate a sustainable design inspired by nature for your basic function.
5. Use http://www.asknature.org/ as a reference.
6. Be prepared to present your design to the rest of the class

The second class period begins with a brief review of the previous class. Then, students are engaged in an in-class activity that allows them to share and receive knowledge about biomimetic design in a short period of time.

Biomimicry Homework Assignment Example

1. **Choose an engineering material or system and identify its basic functions.**
   Engineering material or system: Building exterior finishing surfaces such as vinyl siding.
   Basic functions: Protect the building enclosure from external elements such as wind, water, and debris. Satisfy requirements such as aesthetics, insulation, ease of installation, durability, and life-cycle cost.
2. **Provide an example from nature that performs these same functions.**
   The "Ask Nature" search engine provides an example from nature that repels water (hydrophobic) and is self-cleansing as well. The lotus plant (*Nelumbo nucifera)* is capable of resisting both water and dirt while living in an aquatic and typically muddy

environment. The leaves of the lotus plant use a combination of papillose epidermal cells (microstructures that create a roughened surface) and wax crystals that reduce adhesive forces on water and dirt particles ("Hydrophobic surface allows," 2011).

3. **How could you draw on the example from nature to better perform these functions?** Integrate the micro-topographical features that allow the lotus plant to repel water and self clean into modern day exterior finishing surfaces such as vinyl siding.
4. **Use the 8-Step rubric introduced in class in order to formulate a sustainable design inspired by nature for your basic function.**
    1. Identify a real world challenge. Typical exterior finishing surfaces constantly collect organic dirt particles, grime, and moss. Such surfaces require maintenance and cleaning that expend energy, water, and may use environmentally harmful chemicals. Consider a design that eliminates the need for maintenance of exterior surfaces through self cleaning techniques.
    2. Interpret the design brief. Many of nature's leaves have hydrophobic surfaces that are rinsed clean from organic dirt particles by raindrops running across their surface.
    3. Discover nature's models. Although most plants with leaves repel water and self-clean, the lotus plant is recognized as a superhydrophobic plant because of its high contact angle with water. Since the lotus plant demonstrates impressive water repellent traits, particles that contaminate the leaves of the lotus plant are completely removed by water droplets that roll off the surface, otherwise known as the "Lotus Effect." The combination of surface roughness, reduced particle adhesion, and water repellency is the key to the lotus' self-cleaning abilities (Barthlott and Neinhuis, 1997).
    4. Abstract design principles. The design principles that make the lotus plant hydrophobic and self-cleaning are a combination of micro-topographical features. According to Neinhuis and Barthlott (1997), "water-repellency is based on surface roughness caused by different microstructures (trichomes, cuticular folds and wax crystals), together with the hydrophobic properties of the epicuticular wax… rough, waxy leaves are not only water-repellent but anti-adhesive with respect to particulate contamination."

5. Brainstorm potential applications. The AskNature website provides a few example of how the lotus plant's hydrophobic surface inspired biomimetic designs for self-cleaning textiles, clay roofing tiles, fabrics, and paints ("Hydrophobic surface allows," 2011). Given vinyl siding as the engineering material, the new design will incorporate a roughened microscopic surface to vinyl siding (similar to the lotus plant's microstructures) that will reduce the adhesive force of water droplets and dirt particles. Ultimately, this technology will eliminate the need for power washing houses with potentially harmful chemicals.
6. Emulate nature's strategies. Figures 5a and 5b illustrate how the new design will emulate nature's strategies. Figure 5a shows the smooth surface of typical vinyl siding and how particles are only redistributed by water droplets rolling across the surface. However, Figure 5b depicts the surface of the new proposed vinyl siding design and how the microstructures prevent water and particles from adhering to the surface.

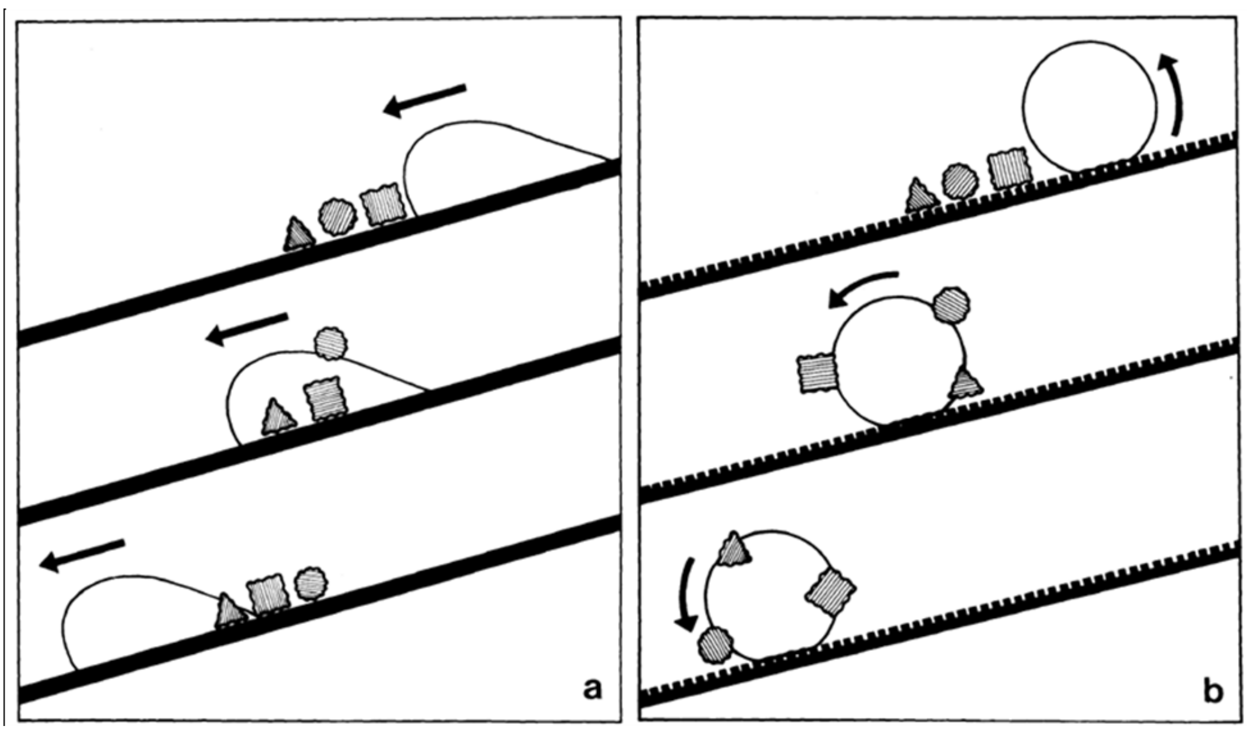

Figure 5a, b. Depiction of how the "Lotus-Effect" occurs on rough surfaces (Barthlott and Neinhuis 1997)

7. Evaluate against Life's Principles. This is a multi-functional design yet it does not adapt, evolve, or create conditions conductive to life. The new design can be

improved by using benign manufacturing techniques that utilize sustainable life-friendly materials.

Class Activity: Student-Group Presentations (2-minute)

Each student is responsible for describing their design (from the homework assignment) in a two-minute presentation to a small group of students. The students must explain how their design is inspired by nature, how it qualifies as a sustainable solution to a human problem, and how it would impact the field of civil engineering as well as society as a whole. The class is divided into groups of four to five students and each student presents their design to their group in a two-minute time period. Each group member takes notes and evaluates their peers (see Figure 6). Once every student has presented to their group, each group will determine a "champion" from their group who has the most fascinating and innovative design. This activity will take approximately 20-25 minutes.

For the second half of this activity, each individual group "champion" presents their biomimetic design concept to the entire class. Depending on the size of the class, 4-10 students will present in this second round. Finally, the entire class will vote on which student presented the best overall biomimetic design concept. The winner, and the other members of their group, will win a prize the instructor decides on. This round should take approximately 10 minutes depending on the size of the class. At the end of the interactive activity, the entire class participates in a 10-minute discussion led by the instructor on the lessons learned from participating in the biomimicry activity. After the discussion period, final remarks will be presented (see the following section) and students will reflect individually through two minutes of low-stakes writing.

In-Class Activity: 2 Minute Student-Group Presentations			
Student Name:_________________________		Date:____________	
Content	**Presenter 1:_________**	**Presenter 2:_________**	**Presenter 3:________**
Design inspired by nature			
Sustainable solution to a human problem			
Impact to Civil Engineering and society			

----✂---

Peer evaluation:

Please evaluate each presenter on the criteria below from 1 to 3, with 1 being a poor delivery and 3 being an excellent delivery.

Criteria	**Presenter 1:_________**	**Presenter 2:_________**	**Presenter 3:________**
Content			
Verbal communication			
Clarity of the concepts			
Time management			

Figure 6. Student handout for in-class activity

Final Remarks

As this class activity will reveal, many of the human inventions throughout time already exist in nature, yet in a more fascinating form and at less cost to the planet. Students will realize that there is a lot to learn from nature. By the end of the two class periods, students should understand the fundamental concepts of biomimetic design and the potential of biomimicry to introduce sustainable engineering design solutions. This module is meant to inspire students to consider biomimetic designs in their future professional and personal endeavors.

Learning Styles Addressed

This module is constructed to appeal to a wide variety of student learning styles. Students will learn biomimicry through a range of teaching methods including a lecture-style presentation, homework assignment, interactive learning activity, and holistic discussion. The interactive learning activity encourages students to master key concepts by teaching and explaining their biomimetic design to other students in a cooperative classroom environment. The final discussion provides a holistic analysis of the topics covered throughout the two lessons and allows the students to ask questions. The two biomimicry lessons follow the proposed timetables depicted in Table 1 and Table 2 below. These timetables are adjustable based on the needs of the students and instructor.

Table 1: Learning Styles Addressed in Class I

Activity	Learning Styles Addressed	Time (min)
Introduction	- Global: present an outline where this topic fits into the course and relate biomimetic design to previous topics covered in class	4 - 5
Instructor lecture and presentation on Biomimicry	- Reflective: convey different resources to present the topic - Visual: show pictures and diagrams - Verbal: provide concrete examples of biomimetic designs - Active: involve effective communication in a short period of time - Intuitive: biomimicry is a new design tool that requires innovation	30 - 40
Conclusion	- Verbal: summarize the lesson and provide time for Q & A	5 - 10
Homework Assignment	- Reflective: promote students to think through a problem - Intuitive: allow students to use to real world problems - Active: encourage students to apply concepts learned in class	Varies

Table 2: Learning Styles Addressed in Class II

Activity	Learning Styles Addressed	Time (min)
Introduction	- Verbal: quickly review the concepts covered in the previous class	4 - 5
Two-minute student-group presentations	- Reflective: convey different resources to present the topic - Active: discuss and explain biomimetic designs to peers - Verbal: converse with peer groups about biomimicry	20 - 25
Student-class presentations	- Reflective, active, and verbal: same as above	10 - 15
Class discussion	- Global: summarize the implications of different perspectives - Verbal: discuss opinions and lessons learned - Inductive: build concepts based on students' research and designs	10 - 15
Reflection time	- Reflective: allow students to revise their notes after the discussion - Active: allow students to converse about final thoughts	6 to 8

G. Assessment Tools

Two different areas are evaluated after this class period. The first area is the effectiveness of various teaching methods. Depending on the creativity, excitement, and interest portrayed by students during their presentations, the instructor can judge how well students responded to various teaching methods. By collecting and reviewing the one-page written assignments from students, the instructor can document and assess each student's ability to understand the main concepts of the lecture and the assignment. This assessment will help the instructor determine which concepts need reinforcement during future class periods.

The second area for assessment is students' ability to verbally communicate and present their design topics to classmates. For this area, the instructor will use peer evaluations provided at the bottom of the handout for note-taking. Using a scale from 1-3, with 1 being poor and 3 being excellent, students will anonymously grade their peers on performance during the two-minute student-group presentations. These evaluations allow each student to receive feedback from peers in four different fields: content, verbal communication, clarity of the concepts, and time management (see Figure 6). The instructor will collect these evaluations and use the results to count participation and, if desired, to provide constructive feedback for each individual student on how to improve their presentation skills.

Significance of this Lesson Plan

This module introduces biomimicry to help students add the concept of using nature as a design model to their problem-solving approach. Introducing this topic in the undergraduate engineering curriculum may teach students a useful method to generate sustainable engineering design solutions.

The written homework assignment, two-minute student-group presentations, and class discussion all promote active learning. In particular, the concept of peers teaching other peers is a proven effective active learning method for both the students doing the teaching and the students being taught (McKeachie & Svinicki, 2006). Concluding the lesson with a class discussion allows the instructor to cover unmentioned material, administer a holistic conversation by asking questions to the entire class, and bring the lesson to a close with any final remarks. The ultimate goal of this module is for students to value, apply, and share biomimetic concepts during their life-long approach to learning.

References

1. Allenby, B. R., and Graedel, T. E. (1994). Figure 6. A schematic diagram of the industrial ecopark located in Kalundborg, Denmark. In *Industrial ecology: Some directions for research*. Retrieved September 4, 2010, from The Rockefeller University website: http://phe.rockefeller.edu/ie_agenda/index.html
2. Barthlott, W., and Neinhuis, C. (1997). Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta, 202*, 1-8.
3. Benyus, J. M. (1997). *Biomimicry: Innovation Inspired by Nature*. New York: HarperCollins Publishers Inc.
4. *Biomimicry: A tool for innovation*. (2009). Retrieved September 4, 2010, from The Biomimicry Institute website: http://www.biomimicryinstitute.org/about-us/biomimicry-a-tool-for-innovation.html
5. *Biomimicry Guild*. (2008). Retrieved September 4, 2010, from http://www.biomimicryguild.com
6. Criteria for accrediting engineering programs. (2009). *ABET* (criteria 3: program outcomes) [Accreditation criteria]. Retrieved September 4, 2010, from ABET, Inc. website: http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2010-11%20EAC%20Criteria%2011-03-09.pdf
7. Curricula. (2009). *Biomimicry Institute*. Retrieved September 4, 2010, from http://www.biomimicryinstitute.org/education/university/curricula.html
8. Doan, A. (2007, December 10). Green building in Zimbabwe modeled after termite mounds. In *Inhabitat* [Article]. Retrieved September 4, 2010, from http://www.inhabitat.com/2007/12/10/building-modelled-on-termites-eastgate-centre-in-zimbabwe/
9. Felder, R. M. (1993). Reaching the second tier: Learning and teaching styles in college science education. *Journal of College Science Teaching, 23*(5), 286-290.
10. *Hydrophobic surface allows self-cleaning: sacred lotus*. (2011). Retrieved February 25, 2011, from The Biomimicry Institute website: http://www.asknature.org/strategy/714e970954253ace485abf1cee376ad8
11. John, G., Clements-Croome, D., and Jeronimidis, G. (2005). Sustainable building solutions: a review of lessons from the natural world. *Building and Environment, 40*, 319-328.
12. Kalundborg. (2007). *Business and sustainable development: A global guide* [Case study]. Retrieved September 4, 2010, from International Institute for Sustainable Development website: http://www.bsdglobal.com/viewcasestudy.asp?id=77
13. Klotz, L. (2008). Sustainable Construction Syllabus. Civil Engineering Department, Clemson University.
14. McKeachie, W. J., and Svinicki, M. (2006). Active learning: Cooperative, collaborative, and peer learning. In *Teaching tips* (12th ed., pp. 213-219). Boston: Houghton Mifflin Company.
15. Neinhuis, C., and Barthlott, W. (1997). Characterization and distribution of water-repellent, self-cleaning plant surfaces. *Annals of Botany, 79*, 667-677.
16. Nikou, T., and Klotz, L. (2010). Systems thinking in sustainable engineering and construction. *Center for Sustainable Engineering Electronic Library*. Retrieved from http://www.csengin.org (in review).
17. *Photosynthesis: Cooke's koki'o*. (2009). Retrieved September 4, 2010, from The Biomimicry Institute website: http://www.asknature.org/strategy/ee4e268a5a0fe3861f6d1f5ae21ea608
18. Reed, P. A. (2004, December/January). A paradigm shift: Biomimicry. *The Technology Teacher*, 23-27.

19. Valdes-Vasquez, R., & Klotz, L. (2010). Considering the social dimensions of sustainability during the construction project design. *Center for Sustainable Engineering Electronic Library*. Retrieved from http://www.csengin.org