ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #35327

Changing the Mindset of Engineering Education through Biomimicry

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Abstract

For much of industrialized society, products have been engineered to "control" nature. We condition the air inside our buildings to our liking with enormous amounts of energy. We mass-produce single-use plastics for our convenience without a successful strategy to collect and make use of them at their end of life. We use harmful pesticides to protect our crops but do not fully understand the damage they may be doing to our bodies and the environment. Nature does none of these things yet has been able to provide for countless species throughout Earth's history. Why not learn from Nature? Why not make use of the billions of years of engineering that took place before humans even existed?

Biomimicry is the application of natural phenomena to solve engineering problems. This method of design is not necessarily new and many common and historic designs are biomimetic. This includes the invention of Velcro® by noticing how burrs stick to a dog's fur, to bullet trains in Japan that draw inspiration from the kingfisher's beak to reduce noise and improve energy efficiency. These incredible solutions and many others were discovered by observing the natural environment all around us. Biomimicry is an invaluable tool that can be employed by engineers to continue to improve the lives of people and advance humanitarian efforts.

The Biomimicry course taught in Villanova University's Sustainable Engineering program provides students the opportunity to assess current engineering solutions in areas they are most concerned. These topics have ranged from issues associated with current approaches to energy systems, building practices, and agricultural landscape. The course structure allows students to understand the benefits and issues associated with their chosen topic, observe and analyze nature for examples of relevant and successful designs, discover biomimetic projects that are currently underway, and experiment with biomimetic strategies to better solve the problems by achieving the benefits without the issues. This curriculum helps change the mindset and foster creativity in the next generation of engineers who will be tasked with solving the problems of the future. This paper will explain the course in greater detail, and how its approach differs from conventional engineering education. It will provide perspectives from students of different disciplines who have taken the course, co-instructed in the course, and are currently applying their changed mindset to their research and jobs.

Introduction

Teaching the next generation of engineering students to solve problems created by current designs while accounting for sustainability requires a new learning mindset. As Ricco et. al **[1]** have described in their recent paper named "Exploring the Engineering Mindset" the topic of mindset has "remained nearly untouched" and most authors have focused on "fixed" vs. "growth" mindsets. These mindsets refer to the engineering student's ability to either be constrained (fixed) in their ability to engage new engineering problems and solutions, or to be capable of going beyond their knowledge and skills to take on and successfully master new challenges and solutions (growth). Others have reported on an entrepreneurial mindset that brings the business perspective into engineering solutions **[2]**. In this case, again the focus is on the engineer and how the engineer applies his or her knowledge or skills to the solution. Figure 1 depicts how humans can interact with the rest of the ecosystem in either an egocentric way in which they look to exploit the rest of the ecosystem for their benefit, or in an ecocentric way in which they recognize parity and harmony as members, not exploiters of the ecosystem **[3]**. The conventional engineering mindset unfortunately aligns more with how humans have traditionally engaged as a member of our ecosystem in an egocentric way, in which the education focus is on the engineer to provide the knowledge skills and abilities to develop solutions with the rest of the ecosystem providing resources.

Figure 1.An Egocentric vs. Ecocentric view

In this paper we report the results of our research covering over 7 years of teaching a course designed to change the mindset of engineering education from a totally different perspective. Not one anchored to the pedagogically acquired knowledge and skills of the student but one influenced by what the student experiences. Specifically, by what the student has experienced in learning from nature, also known as Biomimicry. Janine Benyus **[4]** coined the term “biomimicry,” literally meaning imitation of life. She introduces it as three major ways to influence engineering solutions, using her words:

1) Nature as a model. Biomimicry is a new science that studies nature’s models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf.

2) Nature as a measure. Biomimicry uses an ecological standard to judge the “rightness” of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts.

3) Nature as a mentor. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it.

Today there is a Biomimicry Institute, cofounded by Janine Benyus, that produces a user friendly website “AskNature” **[5]** that can quickly provide examples of biomimicry by simply asking how nature would perform a function. Two of the most cited examples are Velcro® and bullet trains. Velcro® was invented from observing how the hooks on cocklebursz cling to the loops in a dog’s fur. As for the latter, the shape of the kingfisher's beak enables it to pierce water with minimal disturbance that helped the designer of the bullet train solve an early disturbance issue as it entered a tunnel by modeling its nose after the kingfisher's beak.

The hypothesis of this work lies in the ability to change students' problem-solving mindset through the course design of Biomimicry which is exemplified in their work after course completion. By designing a biomimicry course that is based on first understanding the benefits and issues associated with today's systems of livelihood, and then focusing the course on enabling the students to experience nature and develop improved engineering solutions based on those experiential learnings in a focused, project based educational process, we would change the conventional engineering educational mindset and see the results of that in how they apply their learnings in designing and implementing engineering solutions after having taken this course. Using experiential learning had been previously reported **[6]** to help change the fixed mindset challenge of leaders to a more open growth mindset.

Our methodology involved designing a project based experiential course suitable for all disciplines of engineering, surveying the effectiveness of the course in bringing new knowledge and capabilities to the students, and then waiting to engage students, years after they have taken the course, to provide examples of how these learnings are being used in their current engineering research and occupations. We selected a diverse set of students comprising three engineering discipline backgrounds (chemical, mechanical, civil) and one non-engineering, neuroscience background who now works in sustainable engineering with completion of the master's degree in this area.

We describe below how a graduate level course in Biomimicry has been developed to change the mindset of engineers by: Assessing our critical systems of livelihood to understand the great benefits they provide as well the daunting issues that the past egocentric mindset have created; Analyzing the capabilities of nature to understand the myriad of ways form and function have been engineered in nature over billions of years to solve multiple problems; and then applying these learnings to develop improved solutions to critical issues in our current systems. We then go on to share the examples from the above-mentioned engineering students who have taken the course over the past six years to show how their mindsets have been changed in their research and occupations, as well as their general livelihood.

Evidence for changing mindset from a biomimicry course experience

Biomimicry, a fifteen-week graduate level course at Villanova University taught through the Sustainable Engineering program in the College of Engineering, explores nature's inspiration behind science and engineering designs. Students from cross-disciplines of engineering and science engage in weekly lectures and critical thinking activities to assess situations from a whole systems perspective. Figure 2 below shows a representation of the undergraduate backgrounds of students enrolled in the Biomimicry course since 2019, which has been consistent with the previous years.

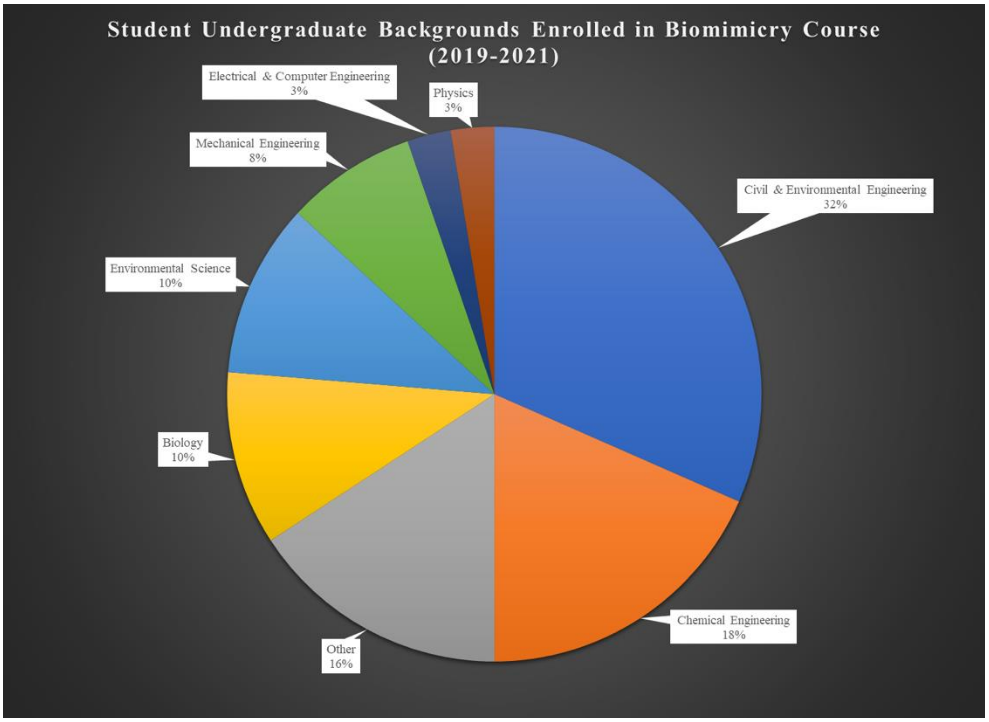

Figure 2:. Undergraduate backgrounds of students who have enrolled in the Biomimicry course at Villanova University between the years of 2019 and 2021.

The course reviews nature's mechanisms and designs and their application for reducing or eliminating daunting issues derived from human development. There are three pillars to the Biomimicry course consisting of today's systems, nature's systems, and biomimetic solutions for present day problems. The systems examined throughout the course include food and agriculture, energy, information and communication technology (ICT), materials, and medicine. The course is delivered through a combination of readings, lectures, guest lectures, class projects, assignments, and site visits. Students can expect to 1) assess the holistic benefits and issues of current engineering solutions, 2) analyze fundamental capabilities of relevant natural systems for potential applications, and 3) create better solutions by applying learnings from nature to achieve the same or similar benefits of current systems while minimizing issues from a whole systems perspective.

Class lectures provide the foundational knowledge of systems associated with maintaining and developing society, as well as the benefits they provide and the issues they foster. The STEEP (Social, Technological, Economic, Environmental, Political) framework, used in other core courses in the Sustainable Engineering program, is the main methodology for assessing situations holistically in Biomimicry **[7]**. STEEP allows students a complete view of the benefits and obstacles associated with designing new systems. To supplement the course fundamentals, guest lectures conducted by subject matter experts in their respective fields are arranged throughout the semester. Guest lectures enrich learning through in-depth explanations of biomimetic designs realized by an alternative mindset. During these lectures, students are encouraged to engage with presenters about topics from the holistic perspective. At the end of lecture class sessions, the final half hour is dedicated to a Critical Thinking Exercise (CTE) related to the main topic(s) of the lecture. During the CTE, students form small groups to solve a complex problem. The CTE is often posed as a free-form design challenge or a debate; however, another CTE structure is under development in the form of an open-ended engineering challenge (similar to a hack-a-thon) that requires student groups to recruit a more technical skill set to develop a potential solution. The CTE has often been cited in end of the semester surveys as a key learning element and encourages a changed way of thinking.

The main deliverable for the course is split into three interconnected projects where students are asked to identify and investigate a system of their choice throughout the semester. Students are asked to 1) identify the benefits and issues of the current infrastructure implemented within their system of choice, 2) identify natural systems able to address the identified issues, and 3) develop/design a biomimetic solution to solve the problems identified in part one.

In years past, students enrolled in the course had the opportunity to attend field trips to local areas that offer insight for biomimetic inspiration. Around the greater Philadelphia area, students visit Longwood Gardens and the Philadelphia Zoo during the middle of the semester. These field trips allow students to make observations of natural systems within the plant and animal kingdom that may assist with their respective projects.

A new mindset is instilled in students during the Biomimicry course, one encompassing the whole systems perspective as well as looking for solutions in natural behaviors surrounding them. The interactive classroom trains students how to investigate their chosen topics for class projects, asking full bodied questions and searching for the answer among reputable sources. The ability to select a topic each student personally identifies with provides breadth to the course, allowing the class as a whole to think critically about subjects in fields different from their own.

Surrounding the entire course is the theme of discovering and applying solutions observed from nature, usually the main reason students take Biomimicry. Throughout the course, students develop observational skills from watching videos of natural behaviors in addition to taking field trips to gardens and zoos for first-hand observation. The mindset of students changes to include the services nature provides rather than just their physical consumption. It is quickly realized amongst the students that nature has endured for billions of years, far longer than human existence, and has evolved effectively and efficiently to thrive on Earth. Students come to accept nature as a respectable entity, a teacher, in a changed mindset that complements the conventional role of the professor. The student surveys conducted at the end of the course have shown that the students learned the most from nature while pulling it together in their project. This resonated in an end of the semester survey where the overall rating of "value of the course in terms of recommending to a colleague" has consistently averaged above 4.5 out of 5.

Evidence for mindset changing from biomimicry influencing research and work

There have been many examples of students at Villanova University grasping the design principles taught in the Biomimicry class and applying them in their work outside the course. We selected the notable examples described below from a cross-discipline group of students who had taken this course over the past six years and are now applying the learnings in research on: a decarbonized and circular supply chain of phenolic resins, a biomimetic battery based on membrane potentials across electrocytes in the electric eel, improving the resilience of bridges located in marine environments, and applying the learnings from the course to an occupation in professional consulting that incorporates these practices on a regular basis. This section will provide more detail of these projects and how the student's mindset was changed from the Biomimicry course to solve problems in their respective fields.

Decarbonization of the phenolic resin supply chain

A main purpose of structural polymers such as phenolic resins is their durability and resistance to degradation over time, the exact opposite of ideal materials in the circular economy. Yet, polymers do occur naturally in the forms of lignin, cellulose, proteins, and DNA **[8]**. Observing natural polymer structures and lifecycles at the molecular level inspired a mindset transformation of the phenolic resin supply chain, a new proposed lifecycle is shown in Figure 3. Specifically, renewable sources for material feedstocks and site targeted degradation as a form of recycling were inspired by polymers in nature. The use of feedstocks that can be regenerated and/or are waste products from other systems is based on the circularity of the carbon cycle **[9]**. Using readily available and continuously producible sources replicates the idea of growth in plant matter and using by-products of other systems is based on nature's principle that all matter, main product or by-product, is created for a purpose. Completing the circle, recycling by breaking targeted bonds in phenolic resin's structure would revert the polymer back into monomers. While this part of the project is in its infancy, the idea was derived from nature's ability to transform "waste" into valuable materials similar to the way enzymes in fungi degrade cellulose into nutrients **[10]**. Overall, the carbon cycle creates the foundation for material circularity within the phenolic resin supply chain.

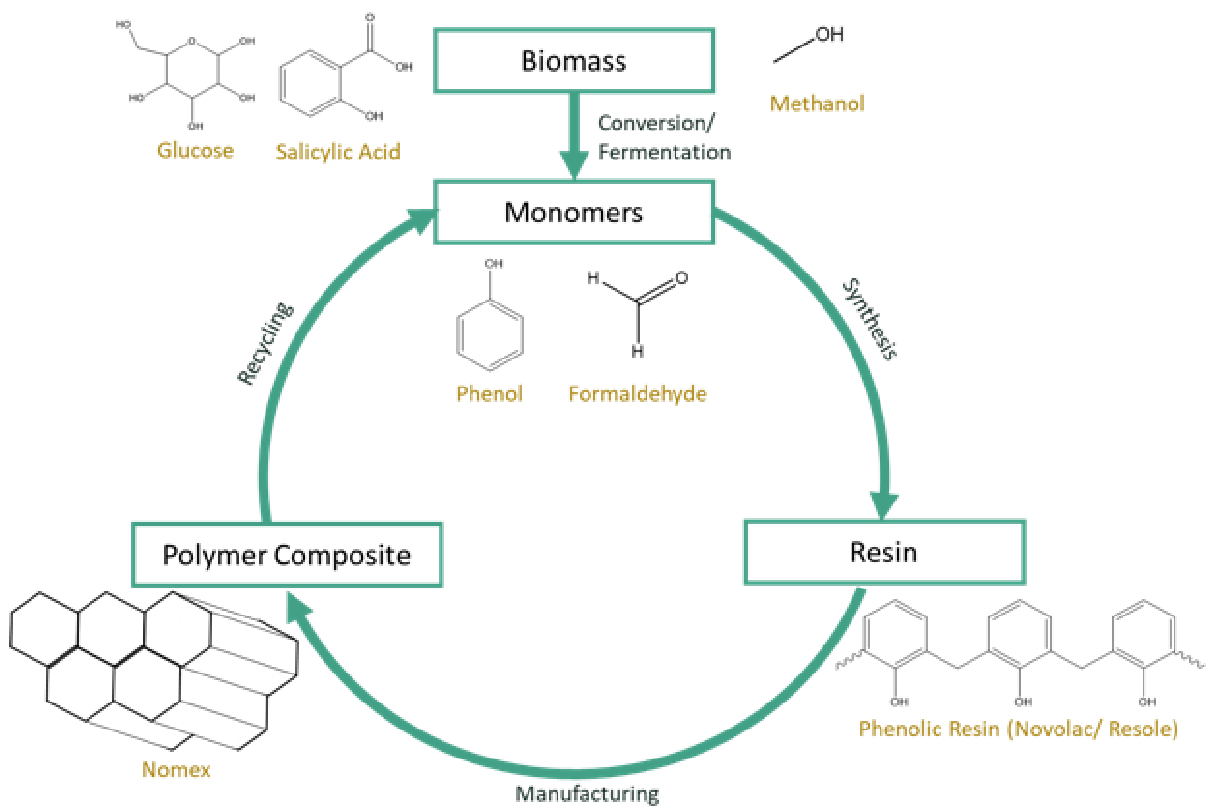

Figure 3. Proposed circular economy of phenolic resins incorporating transformed mindset brought about through the Biomimicry course at Villanova University. Incoming biomass allows increasing demand for phenolic resins when recycling cannot meet current demands and is involved in the circular carbon lifecycle.

Biomimetic battery based on the electric eel

Emerging osmotic power generators are being developed that use a salt gradient to convert ion migration into useful electrical energy. These systems are still under development, but the general premise for their operation involves the use of ion-selective membranes that mimic how cell membranes exchange ions to allow the formation of an action potential under various concentration gradients. One common biological example is the electric eel (*Electricus electrophorus*), which has electrocytes that act as tiny batteries that can discharge on command to allow the eel to defend itself or to hunt for prey **[11]**. The electrocyte of the eel has an asymmetric structure on one side, as shown in Figure 4. On one side, the electrocyte has an innervated membrane that allows ion flux to occur and the formation of the action potential ($+\mathbf{65\ mV}$), while on the other side lies the non-innervated membrane, which remains at its resting potential ($-\mathbf{85\ mV}$). Even though the voltage across a single electrocyte is only $\mathbf{150\ mV}$, when these cells are connected to form the main electric organ, the electric eel has the capability of discharging at $\mathbf{600\ V}$ **[11]**.

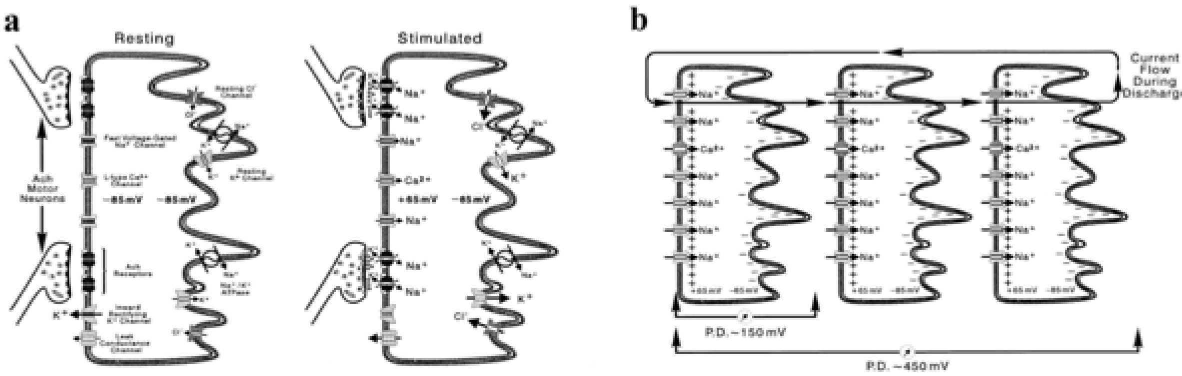

Figure 4: (a) Electrocyte in the electric eel in the resting and stimulated states and (b) series-connection of electrocytes to form the total electric organ discharge [11].

To date, research has focused on developing ion-selective membranes to allow ion transport in the presence of a concentration gradient to mimic the action potential that is realized in electrocytes and lead to power generation. These ion-selective membranes are starting to show promising power densities of $\mathbf{5\ W/m^2}$ and above **[12]–[14]**, indicating that this biomimetic concept can be deployed in future power generation applications. The research approach being pursued at Villanova University involves the investigation of ion-selective membranes that can potentially be deployed in emerging energy storage devices, which involves the examination of the joint resistive and capacitive nature of these biomimetic membranes. The proposed research involves the use of common electrochemical techniques such as conductivity testing and electrochemical impedance spectroscopy (EIS) to characterize this behavior in ion-selective membranes. With this research approach, ion-selective membranes can be compared to various types of electrocytes that serve various functions in nature, and how those function translate to emerging energy storage devices.

Civil infrastructure materials for resilience

In addition to applying practices employed by nature to directly solve engineering problems, natural design principles can be more broadly applied to nearly any type of project. One example is civil infrastructure and how bridge design can be improved to create more resilient structures, especially in harsh, marine environments. The American Road and Transportation Builders Association (ARTBA) found that more than one-third (231,000 spans) of the bridges in the United States are in need of repair work **[15]**. A breakdown of the type of work required on these bridges can be seen in Figure 5 below:

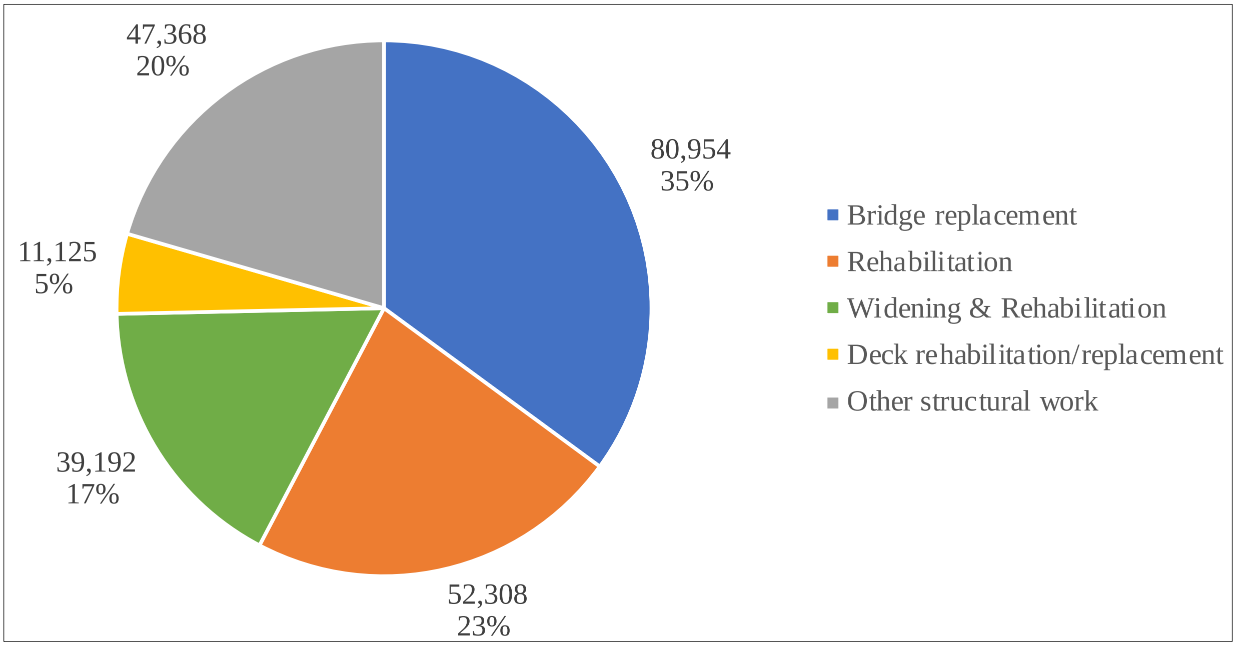

Figure 5. Number of bridges in need of work by types of repairs required [15].

Of those, about one-fifth (46,000 spans) are classified as "structurally deficient," and in urgent need of repair or replacement. Many of these bridges are located in in northern areas of the country or along the coast, where they are typically subject to the presence of corrosive salt solutions from the use of de-icing salts or by direct exposure to salt water in marine environments. A common reason for the structural deficiency of these bridges is corrosion of the steel reinforcement in the structure from the presence of these salts. There are many methods employed to prevent the salt from coming in contact with the rebar (epoxy-coating, galvanizing, stainless-steel), but ultimately the salt solution will penetrate any protective coatings and the reinforcement will begin to deteriorate.

In learning from nature, continuing to build with these materials for these applications seems unsustainable. Nature is able to create and apply the most appropriate materials to a variety of settings, instead of continuing to attempt to use the same material for the wrong application. A student was inspired by this idea and came across the company Advanced Infrastructure Technologies (AIT) who design and build bridges using fiber-reinforced polymer composite materials to circumvent these problems **[16]**. These materials are more resistant to the salt present in these environments and are an example of applying nature's guiding principles of material selection to a civil engineering problem. The student is now working with the company to perform a Life Cycle Assessment (LCA) on their product to determine the potential impacts of this innovative new bridge design and possible improvements.

Evidence for mindset changing from biomimicry influencing an occupation centered perspective

As previously mentioned, one of the common themes seen among students taking Biomimicry at Villanova University is the diversity of thought and the variation of disciplines. Coming from a neuroscience background, it was difficult to bridge the gap between the study of the human nervous system and sustainability; at the surface, these seem like strikingly distinguished fields and it was challenging to figure out how to synchronize both of these academic backgrounds in a way that would allow for a successful career as a sustainable engineer. Biomimicry teaches a whole-systems approach to problem solving that helps students more efficiently assess critical systems, identify issues, and outsource solutions from nature and other disciplines to help them develop an innovative mindset. The whole systems thinking approach from this course helps students break down a system to understand how the smaller parts make up the whole and how these parts interact with each other to affect the system. In the field of biomimicry, whole systems thinking helps us see how elements such as water, sun, soil, air, plants, animals, and humans interact and support one another within a greater system. Similarly, neuroscience, the study of the human nervous system, seeks to understand how cells, neurons, chemicals, proteins, lipids, and more form a conglomerate of individual parts that comprise the network that makes up the human brain and defines the human mind. Completing this course was enlightening because it demonstrated the cross-functionality of this method of thinking; it brought clarity to past academic experiences and thus provided the confidence to be successful as a consultant.

The primary work of a sustainability consultant is to perform life cycle assessments for a wide range of companies to assess the life cycle environmental and human health impacts of a product/process. Whole systems thinking is helpful for this line of work because the lifecycle is broken down into its various stages and investigated in more detail; this process leads to successful outcomes with clients who want a deeper understanding about their products and the root causes of their impacts. The result of clearly assessing a critical system answers the following questions: 1) what are the impacts of a product? 2) where along the supply chain do these impacts come from? 3) what about the product make it have impacts? With answers to these questions, one can effectively and efficiently communicate findings to companies, manufacturers, and stakeholders.

Furthermore, just as biomimicry seeks nature for inspiration, we can seek other disciplines for inspiration to increase the chances of finding innovative solutions. With people in the sustainability field coming from so many different backgrounds, it is a melting pot of disciplines. We can take the biomimicry teachings of mimicking nature and apply it to the professional world by bridging gaps and opening channels through which ideas can be exchanged. As biomimicry has proven, reaching to other sources for inspiration is an effective approach.

As someone with a diverse academic and professional background, it was important to identify a widely applicable thinking and problem-solving methodology. The Biomimicry course introduced the whole-systems approach and the practice of turning to nature for inspiration; these have proven to be reliable tools that lead to successful outcomes and innovative solutions in the professional world.

Analysis and Conclusions

The overview of the Biomimicry course and examples of biomimetic designs outlined above provide evidence of the changing mindset in engineering education using design principles inspired by nature. The Biomimicry class provides the foundation in understanding nature's systems and allows students to apply these ideas through Critical Thinking Exercises and class projects. The lasting impact of this change in mindset is apparent in the exciting examples presented here from students who were influenced by this course to come up with polymer systems that are designed to be circular, batteries that are designed to use only ions like those found in nature, bridges that are designed to perform in their natural environment and not be corroded by it, and the confidence to tackle the diverse and challenging cross-discipline problems in consulting. While the examples for the most part correlated with their specific disciplines, the insights revealed a common ecocentric mindset of learning from nature to enable an improved engineering solution or capability. In addition to these specific examples of how the traditional engineering education mindset has been changed in their approach to engineering solutions, there are also impactful statements from former students whose approach to critical aspects of their jobs and livelihoods have been changed:

From coauthor Manuela Toro, a neuroscientist by training:

> The Biomimicry course put whole systems thinking into a different context; it was enlightening to see how this method of thinking is not unique to a specific field and it was fascinating to uncover the commonalities between two of them: neuroscience and sustainability.

From former student Ashlee Beyer, a chemical engineer working with a pharmaceutical company:

> It's becoming more apparent to me that my passion lies in doing something intimately connected to nature. I am so passionate about finding sustainable solutions in my own life and feel that improving the planet - somehow, some way - is my calling.

Now more than ever, as we are faced with the daunting challenges of climate change, increasing population, vulnerabilities to pandemics, resource shortages, etc. as we meet and exceed our planetary boundaries largely through the conventional engineering education mindset of the past…it is time for an engineering education mindset for the future that embraces and learns from nature.

Acknowledgements

We acknowledge all the efforts of past and current students, guest lecturers, collaborators in our biomimicry course. All of the coauthors are former students of this course. We give special thanks to former student Ashlee Beyer for allowing us to quote her and to our Sustainable Engineering Program Director William Lorenz for his support and encouragement in developing and integrating this biomimicry course into the sustainable engineering graduate program.

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