Developing Innovation Capabilities and Competencies for Undergraduate Engineering and Technology Education

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Abstract

Given the exponential factoring of knowledge due to scientific and technological advance, solving complex global problems will require a different way of thinking than was used to create them. No longer are solutions bound within a domain, science or technology. Instead, solutions require a highly integrated approach across many domains, sciences, or technologies. Albert Einstein stated "We can't solve problems by using the same kind of thinking we used when we created them." Einstein was emphasizing that one's knowledge and understanding are limited by one's own experience, education, and research and that the advancement of knowledge and science required more. The authors of this paper build a strong case, from the literature, that calls for using biomimicry innovation capabilities and competencies in undergraduate engineering and technology education programs to prepare students with this type of thinking to solve complex global problems to produce a sustainable world. To better prepare students to become more effective citizens and problem solvers in our increasingly interconnected, globalized world, the kind of thinker who contemplates complex global problems, the engineering and technology education curriculum must move to a more global educational model, and in particular, one that embraces integrating innovation capabilities and competencies that develop this new way of thinking about global problems.

The authors of this paper present an initial study for what key innovation theorist believe are the innovation capabilities and competencies necessary for future leaders to be equipped to solve the critical global problems facing our society. The authors challenge traditional approaches, for example, utilizes "systems-theoretic" approaches to studying global problems that relate to the dynamics of science, technology, and innovation and their relationship to economic growth, as being limited in their usefulness for solving global problems. The authors focus on undergraduate engineering and technology education programs utilizing biomimicry innovation capabilities and competencies as a means for preparing their students to solve complex global problems.

Four key research questions are discussed in the paper by the authors. The questions addressed are:

1. What are the necessary knowledge and sufficient conditions to solve complex global problems?
2. What are the sources of knowledge about nature that are most applicable?
3. How is that knowledge about nature structured and limited?
4. What do key innovation theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society?

In this paper, the authors present a valuable perspective of the capacities identified as essential for addressing current and emerging global issues. An in-depth literature review of biomimicry, biomimicry innovation, concepts and characteristics of nature, and biomimicry innovation capabilities and competencies are presented, analyzed and discussed. The authors' analysis of these proficiencies has wide application for all facets of engineering and technology education as an integral component of continuous program improvement.

Keywords: Innovation capabilities, innovation competencies, undergraduate education, engineering technology education, technology education

Introduction

Given the exponential factoring of knowledge due to scientific and technological advance, solving complex global problems will require a different way of thinking than was used to create them. No longer are solutions bound within a domain, science, or technology. Instead solutions require a highly integrated approach across many domains, sciences, or technologies. Albert Einstein stated "We can't solve problems by using the same kind of thinking we used when we created them." Einstein was emphasizing that one's knowledge and understanding are limited by one's own experience, education, and research and that the advancement of knowledge and science required more. Sagarin[1], Palfrey and Gasser[2], Friedman[3], Senge, Smith, Kruschwitz, Lauer, and Schley[4], McDonough and Braungart[5], and others have called for this type of thinking to solve complex global problems to produce a sustainable world.

The authors of this paper present what key innovation theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society. More specifically, the authors focus on a problem-centric curriculum approach developing the key innovation capabilities and competencies necessary to solving complex global problems by providing a novel way of answering the questions of what are the necessary knowledge and sufficient conditions to solve complex global problems, what are the sources of knowledge about nature that are most applicable, and how is that knowledge structured and limited. Using this type of thinking can greatly enhance the opportunities to solve, manage, or control the major complex global problems facing society.

Problem

If the U.S. will exist in the future as a world power, America must immediately invent a new research and innovation paradigm to study and solve the major issues challenging its existence. This new paradigm, through its ability to create and commercialize new products and services, will create new jobs, help reduce high U.S. unemployment, and increase cash flow back into the economy. The new innovation paradigm, by its very nature, adapts by reinventing itself to address emerging and future problems facing the country.

The U.S. is fighting an economic war, a war that unless addressed differently, will not be won, and the U.S. will be relegated to being controlled by the nations that buy its debts. These nations will benefit from U.S companies moving their technology oversees and from controlling key energy and other resources. Time is running out, or in some cases has run out, to solve critical problems that will determine how the U.S. will be positioned as a world power in the future. In other cases, the complexity of critical infrastructures or systems makes problems too costly to fix or causes the workable solutions to take too much time to successfully implement. Tomorrow is too late to create a new innovation model for the U.S. We must start today.

Higher education must reassess its role in preparing future leaders to address this crisis. In order to better prepare students to address this crisis by becoming more effective citizens and problem solvers in our increasingly interconnected, globalized world, the kind of thinker who contemplates complex global problems, the engineering and technology education curriculum must move to a more global educational model. In particular, the engineering and technology education curriculum must embrace integrating innovation capabilities and competencies that develop this new way of thinking about global problems.

The authors examine innovation capabilities and competencies of how scientists and engineers imitate nature, biomimicry, to solve complex global problems. More specifically, the authors identify the innovation capabilities and competencies necessary for developing sustainability solutions by integrating and applying knowledge of how organic systems (systems of nature) work with human systems, the nexus between problem solving (deductive reasoning) and scientific inquiry (inductive reasoning). It also focuses on the necessary innovation capabilities and competencies for understanding how relationships between two metabolisms, biological (cycles of nature) and technical (cycles of industry), provide a knowledge of systems of nature, how phenomena in nature exist, and how humans think those environments ought to be. The concept deals with the integrative relationship of how science starts with a problem and is guided by theory, while technology results in discoveries which lead to theories.

Purpose

Vincent, Bogatyreva, Bogatyreva, Bowyer, and Pahl[6] suggest that there has not been any general framework or method for searching the biological literature functional analogies for biomimetics. Most biomimetic solutions have focused on a single product, without application complex global problems. For example, Qualcomm commercialized a display technology based on the reflective properties of certain morpho butterflies, using interferometric modulation to reflect light to control the desired color for pixilation display. The Swiss Federal Institute of Technology has incorporated the biomimetic characteristics of self-diagnosis and self-repair in their adaptive deployable tensegrity bridge design[7]. However, biomimetics not only provides analogies for single-focused products, but also provides many opportunities for building mental models for solving complex global problems.

Based on the problem and lack of focus for biomimitics to solve complex global problems, four research questions were defined:

5. What are the necessary knowledge and sufficient conditions to solve complex global problems?
6. What are the sources of knowledge about nature that are most applicable?
7. How is that knowledge about nature structured and limited?

8. What do key innovation theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society?

Method

This paper is the initial study for identifying the key biomimitic innovation capabilities and competencies necessary to solving complex global problems using as a problem-centric curriculum approach. This descriptive study used a literature review and was limited to scholars who imitate nature to solve single-focused problems and those who imitated nature to solve complex global problems.

The authors conducted an exhaustive literature review of innovation curriculum theorists who have defined innovation capabilities and competencies that are necessary for developing sustainability solutions by integrating and applying knowledge of how organic systems (systems of nature) work with human systems, the nexus between problem solving (deductive reasoning) and scientific inquiry (inductive reasoning). The authors also reviewed the work of the innovation scholars. A comparison was made to gain an understanding of what common capabilities and competencies exist and which are unique among the types of innovation curriculum theorists and scholars.

Literature Review

Engineering and technology education undergraduate programs must focus on new and innovative curricula to better prepare their students to address and solve complex global problems. No longer is just using a traditional problem solving process to develop physical, mechanical, and electronic solutions good enough. Solving complex global problems requires a different way of thinking that is not bound within a domain, science, or technology. Today, the undergraduate engineering and technology education curriculum must integrate how to imitate and emulate nature as a component to teaching students how to solve complex global problems. This type of curriculum requires an interdisciplinary approach that incorporates engineers and scientists collaborating and teaching together.

This type of curricula model is applicable to any engineering and technology education undergraduate program. It includes systems thinking, design, materials, communication and information, energy, tools, and human systems. What is different from traditional engineering and technology education curricula is that the knowledge base and associate capabilities and competencies are designed around how nature's systems and cycles function naturally and how one can use this knowledge of nature to draw analogies and metaphors that create novel solutions to complex global problems.

Many scholars, such as Markman and Wood[8], Carlson and Wilmot[9], Kelley and Littman[10], and Vincenti[11], have looked at innovation capabilities and competencies. However, few scholars have identified innovation capabilities and competencies as they relate to biomimicry, especially as defined by the authors of this paper. In her seminal work, *Biomimicry: Innovation Inspired by Nature*, Benyus[12], provides the foundation reference for understanding how science imitates nature to solve problems. Other scholars, including Sagarin[1], Barnes[13], Lenau and Mejborn[14], Koutsouris[15], Madni[16], Vincent, Bogatyreva, Bogatyreva, Bowyer, and Pahl[6], Vincent[17], and Vincent and Mann[18], have built on Benyus's work to define capabilities and competencies necessary to study specific or complex global problem by imitating nature.

Applying this type of thinking about complex global problems, such as energy supply and demand, climate change, biodiversity loss, energy poverty, water scarcity, food scarcity, waste storage, health, or critical infrastructure problems, provides fresh and sustainable solutions. However, it is important to understand what biomimicry capabilities and competencies are the most importance and appropriate for studying complex global problems.

First, it is important to gain an understanding of biomimicry innovation and of what is meant by concepts and characteristics of nature that provide the foundational knowledge innovation that theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society. From these understandings, the authors specifically address the four research questions. The authors reviewed innovation literature of scholars who define capabilities and competencies as 1) imitating nature to solve single-focused problems, and 2) imitating nature to solve complex global problems.

Biomimicry innovation

While the disciplines of biomimicry and biomimetics are considered emerging field of study, in fact, humans have been using concepts of nature to solve complex problems since the beginning of time. For example, da Vinci and the Wright Brothers both studied birds to gain an understanding of human flight. Biomimetics was originally defined by Schmitt[19] to describe the transfer of biological ideas to technology. The MacMillan Dictionary[20] defines biomimetics as the study of systems and substances used in nature in order to find solutions to other human and technical problems. Benyus[12] defined biomimicry as a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems.

In this paper, biomimetics focuses on how relationships between two metabolisms, biological (cycles of nature) and technical (cycles of industry), provide an understanding of systems of nature, how phenomena in nature exist, and how humans think those environments ought to be in order to design sustainability solutions by integrating and applying knowledge of how organic systems (systems of nature) work with human systems. This relationship creates new technological solutions, based on inspired biological engineering that includes nano-scales and macro-scales. Applying this type of thinking to complex global problems, such as energy supply and demand, climate change biodiversity loss, energy poverty, water scarcity, food scarcity, waste storage, health, or critical infrastructure, provides fresh and sustainable solutions.

Concepts and characteristics of nature

The world of biomimicry offers a new universe of discovery and one that opens the door to a new world of innovation. Nature provides the largest laboratory ever created and provides the greatest knowledge base and opportunity for finding novel solutions to complex global problems. Unfortunately, scientists and engineers have, for the most part, only used concepts and characteristics of nature to solve specific, single-focused problems.

There are key concepts and characteristics that govern how nature's systems and cycles have functioned and survived since the beginning of time. Nature systems and cycles naturally take care of themselves. Nature fits form to function. Nature has evolved. It has experimented with its own systems and cycles to refine the living organisms, processes, and materials of nature. In nature, one by-product is the nutrient for another system. Nature's ecosystems can also transform nutrients from one form to another. Nature's energy source is solar radiation. The same energy powers all systems and cycles of nature − land, sea, and atmosphere. It is a totally energy efficient system, using only the energy it needs. Nature self-relates, with its systems and cycles cooperating with one another. In nature there is neither shortage nor scarcity; it curbs excess. The relationships between the systems and cycles of nature depend on diversity. In nature, there is a cradle to cradle concept, where there is not any waste, instead waste is eliminated by the very concept of design[4,12,21].

In contrast to the cradle to cradle philosophy, the industrial age philosophy was based on maximizing efficiency, a cradle to grave concept. Instead of zero-waste, the products of the industrial age are designed with built-in obsolescence, with 90 percent of the materials used to produce those goods becoming immediate waste[5]. Unlike systems and cycles of nature that produce more energy than they consume, the production of industrial age products uses more energy than is produced. Using this type of thinking can greatly enhance the opportunities to solve, manage, or control the major complex global problems facing society.

Biomimicry innovation capabilities and competencies

The literature focusing on biomimicry innovation capabilities was examined by reviewing biomimicry researchers, institutes, and universities who offer courses in the field of study. A description of the body of work is presented and summarized in Table 1.

Benyus[12] in her seminal work, *Biomimicry: Innovation Inspired by Nature*, emphasized that scientist and engineers need to emulate nature to solve human problems. She organized her work six key problem areas: 1) food, 2) energy, 3) production, 4) medical cures, 5) computing, and 6) business. Although Benyus defines specific knowledge for each of the problem areas, she draws four key steps that bring unity to these problem areas:

1. Quieting: Immerse ourselves in nature
2. Listening: Interview the flora and fauna of our own planet
3. Echoing: Encourage biologists and engineers to collaborate, using nature as model and measure
4. Stewarding: Preserve life's diversity and genius (pp. 287-95).

Passino[22] examined how to use biomimicry to solve optimization, control, and automation problems encountered in the construction of high technology systems. Besides knowing biological processes, Passaino identified the need to know mathematical stability analysis, mathematical modeling of technological operations, and computer simulation in order to manage large data sets and construct solution models that imitate and emulate nature.

Yahya[23] in his book *Biomimetics: Technology Imitates Nature*, discusses how biomimicry capabilities and competencies can be utilized for scaling design solutions for strengthening and improving products that provide both single-focused and complex global problem solutions. He emphasized the need to understand the material science or structure of nature's materials and apply those characteristics to design and construct products with superior properties than the electromagnetic, physical and mechanical properties of traditional products. He also stressed the importance of understanding the systems and cycles of nature and how they can be applied to design, architecture, artificial intelligence, and robotics. Yahya discussed that one should know how to use the waves and vibrations of nature in order to design single-focused and complex global problem solutions. As did daVinci and the Wright Brothers, Yahya sees the importance of understanding the principles of flight of birds and insects in order to design future aircraft. Equally important, Yahya identifies the importance of knowing the organs, characteristics, and capabilities of animals in order to design advance products with superior qualities to today's products. He finally illustrates the importance of understanding the technology that exists in living creatures and how it can be applied to solve problems.

Reap's[24] dissertation explored the key question, "*How can biomimicry guide environmentally benign engineering?*" Reap focused his research based on an environmentally benign design and manufacturing framework (EBDM) which encompasses the entire product life cycle. Six biological principles were identified by Reap for biosphere sustainability: 1) biodiversity, 2) ecosystem engineers, 3) webs of life, 4) metabolic limit, 5) relationship between hydrophobic micro/nanostructured surfaces and particle adhesion, and 6) succession. Reap also identified five biologically inspired guidelines for sustainable engineering; 1) industrial diversity, 2) ecosystem engineers, 3) weaving eco-industrial webs, 4) energy consumption limits, and 5) succession.

Sagarin[1] discussed the biomimicry in terms of imitating nature to find solutions for complex global problems, such as fighting terrorist attacks, natural disasters, and disease. He identified ten capabilities or competencies necessary for solving complex global problems using biomincry principles.

The Biomimicry 3.8 Institute[25] developed a biomimicry taxonomy that is organized under eight categories: 1) move or stay put, 2) maintain physical integrity, 3) maintain community, 4) modify, 5) make, 6) process information, 7) break down, and 8) get, store or distribute resources. The categories provide the classification network for biomimicry capabilities and competencies needed to solve complex global problems. The Biomimicry 3.8 Institute offers a master's level professional certificate program. Program completers develop 15 biomimicry capabilities and competencies for developing innovative and sustainable solutions for complex global problems[26].

Kleinke, Weaver, and Lynch-Caris[27] identified two key competencies needed for biomimicry innovation: 1) bio-function, and 2) bio-TRIZ. Bio-function, as it relates to biomimicry, deals with the connection between biomimicry and function mapping. Bio-TRIZ is a problem solving method based on the Russian theory of inventive problem solving, TRIZ[28], that integrated human-made and biological examples of inventive principles to resolve contradictions.

Researchers at the Biomimetics-Innovation-Center in Bremen, Germany (Biomimetics-Innovation-Center) utilize an integrative and interdisciplinary approach to studying biomimetic questions to develop novel technical solutions for sustainable products and applications, biomimetic/biokon study. The five areas of biomimetics/biokon study − 1) locomotion/transportation systems, 2) functional surfaces, 3) biological materials, 4) construction/optimization, and 5) organization/logistics − provide a comprehensive look at how scientists and engineers can imitate and emulate nature to develop novel technical solutions for sustainable products and applications. Each area of study defines specific capabilities and competencies necessary to realize these solutions[29].

The Kompetenznetz Biomimetik Network in Baden-Wuerttemberg is an interdisciplinary collaborative of scientists from many disciplines working with business and industry partners to create new products and technologies based on biomimetic principles and concepts. Their research areas define ten specific capabilities or competencies required for biomimicry innovation[30].

In a sustainable construction course at Syracuse University, entitled *Biomimicry: Using Nature as a Design Inspiration*, students develop eight competencies in a number of ABET criteria. This course was specifically included in the literature since it was directed linked to ABET criteria[31].

Barnes[13] defines a biomimcry problem-centric approach to solving complex global problems by integrating and applying knowledge of how organic systems (systems of nature) work with human systems. He identified six resources of sustainability: 1) networks or systems, 2) life cycles, 3) sustainability factors, 4) designing environments, 5) applications of nature, and 6) funding sources. In addition, Barnes identified six restraints on sustainability: 1) scarcity, 2) lack of understanding of nature, 3) lack of integration, 4) unwillingness to change, 5) waste, and 6) risk levels.

A summary of innovation capabilities and competencies by researcher, institute, or university is outline in Table 1.

Table 1

Innovation Capabilities and Competencies by Researcher, Institute, or University

Researcher, institute, or university	Innovation capabilities and competencies
Benyus	Knowing how to use analogies and metaphors to understand how to imitate nature to solve problems Understanding life that preceded us, understanding nature's history Knowing systematic, a deep knowledge of particular groups of organisms Knowing how to match nature's designs and processes to the needs of

	technologists and engineers to solve problem. Need for engineers and biologists to work on the same teams Learning nature's survival principles to screen for viability Understanding how to scale based on nature's design, processes, and diversity. Knowing how to apply good stewardship principles to nature's habitats (287-95)[12]
Passino	Systems theory Problem solving Mathematical stability analysis Mathematical modeling Technological operations Computer simulation Biological processes[22]
Yahya	How to scale design solutions Understand the material science of nature Understand the structure of nature's materials Understanding the systems and cycles of nature Understand the waves and vibration that occur in nature Understand how animal organs function and are similar to humans Understand the technology that exist in living creatures[23]
Reap	Biodiversity Ecosystem engineers Webs of life Metabolic limit Relationships between hydrophobic micro/nanostructured surfaces and particle adhesion Succession Energy consumption limits[24]
Sagarin	Understanding how nature's systems are redundant and multifunctional Understanding how nature uses symbiotic relationships to extend its own adaptive capabilities Applying biological ideas to societal needs Understanding how organizations have the capacity to learn, like in nature where learning occurs at multiple levels of the organization Understanding that centrally controlled organizations do not thrive in nature Understanding the adaptability of nature Knowing how systems of nature survive and thrive in a constantly escalating world Understanding why variation is a fundamental building block of nature Knowing how to use uncertainty to your advantage

	Understand the ubiquity of symbiosis[1]
Biomimicry 3.8 Institute	How biology can be incorporated into the design process How to integrate biomimicry into design and bring nature's genius to the design table How to work in interdisciplinary teams How to integrate biomimicry into an engineer's process How to communicate biomimicry with engineers and business people How biologists gather and research information and how that information can inform other disciplines What considerations go into a successful business plan What are the fundamentals of business design and decision-making Understanding intellectual property issues Applying biomimicry methodology Developing presentation skills Developing facilitation skills Understanding life principles Developing systems thinking Understanding about enabling technologies[26]
Kleinke, Weaver, and Lynch-Caris	Bio-functioning Bio-TRIZ[27]
Biomimetics-Innovation-Center	Locomotion/transportation systems Functional surfaces Biological materials Construction/optimization[29]
Kompetenznetz Biomimetik Network	Form-structure-function relationships in plants, animals, and plant-animal-interactions Mechanical testing and technical biology Surfaces and interfaces Lightweight construction and materials Optimization Fluid dynamics Energy Fiber-based materials and composite materials Architecture Transfer into technical applications on laboratory and pilot plant scale, and scaling up to industrial level[30]
Syracuse University	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 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 The ability to function on multidisciplinary teams by using resources and references from biology, life sciences, and multiple engineering disciplines The ability to identify, formulate, and solve engineering problems by using nature as a mentor for design concepts The ability to communicate effectively by presenting their biomimetic designs in group and class discussions 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 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 A knowledge of contemporary issues by using a biomimicry search engine as a reference tool for their biomimetic design concepts[31]
Barnes	Knowledge of how organic systems (systems of nature) work with human systems Knowledge about cycles of industry Understanding networks or systems Knowledge about life cycles Understanding sustainability factors Understanding how to design environments using biommicry principles Knowing how to apply nature Knowledge about funding sources Problem solving Knowing how to use mental models to integrate systems of nature with systems of technology[32]

Analysis and Findings

Based on the evidence presented, the findings were analyzed under four questions:

1. What are the necessary knowledge and sufficient conditions to solve complex global problems?
2. What are the sources of knowledge about nature that are most applicable?
3. How is that knowledge about nature structured and limited?
4. What key innovation theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society?

What are the necessary knowledge and sufficient conditions to solve complex global problems?

Examining the relationship between two different cycles, such the biological metabolism of nature and the technical metabolism of industry, is central to biomimetic problem solving. Through this exploration, humans can begin to construct their own understandings of natural phenomena and of how to create an ideal environment for themselves. Unlike the traditional engineering approach to solving problems by applying scientific theories or the technological approach resulting in discoveries, this biomimetic approach requires integrative thinking. To solve complex global problems using biomimetic thinking, humans need to look at adapting systems and cycles of nature to the technical, human systems of the world[6,17,18]. Mimicking nature's systems is a complex endeavor. One needs to have keen observations skills to grasp how natural systems function and a vision of how to apply these observations in a technical system that yields an optimal solution. Problem solvers often call upon cognitive tools and mental models to help them evaluate how a natural phenomenon could provide inspiration for solving a complex global problem. Analogies, patterns, trends, and metal simulations can be constructive, but useful problem solving requires input from other informants. Networking with engaged stakeholders and experts in a transdisciplinary, collaborative environment is key to successfully solving complex global problems (Barnes, Barnes, & Dyrenfurth[32], Koutsouris[15]; Lenau & Mejborn[14]; Madni[16]). Specific examples of knowledge related to undergraduate engineering and technology education program examples are found in Table 2.

Table 2

Examples of Knowledge Related to Undergraduate Engineering and Technology Education Program Examples

Program examples	Examples of knowledge
Architectural Engineering Technology	Oyster shells as a model for design light, sturdy roofs[a]
	Understanding how nature fits form to function[b]
	Understanding leaf structures to design buildings[a]
	Understanding large termite mounds to design ventilation systems for buildings[a]
	Understanding honeycombs to design earthquake structures[a]
	Understanding sea creatures for designing large scale architectural structures[a]
	Understanding spider webs for designing load-bearing systems[a]

Manufacturing Engineering Technology	Understanding bird flight and shape to design aircraft[a]
	Understanding the flight of flies to design gearboxes[a]
	Understanding the propellant force principle of squid and octopus to design jet engines[a]
	Understanding the inner shell of the abalone as a analogy for designing stronger and more ceramic products and armor on tanks[a]
	Understanding spider silk as an analogy for designing more structurally sound products[a]
	Understanding the adhesive used by mussels to fasten themselves to rocks[a]
	Understanding how the crocodile skin was used in fiberglass design[a]
	Understanding how steel-cable technology for bridges was inspired from tendons[a]
	Understanding insect shells and exoskeletons as a means for increasing surface hardness[a]
	Understanding plant structure as a means for improving car design[a]
Energy Technology	Understanding the process of photosynthesis as an analogy for design energy efficient systems[a]
	Understand how plant leaves function like solar panel[a]
	Understanding how nature's ecosystems can also transform nutrients from one form to another[b,e]
	Understanding that nature is totally energy efficient system, using only the energy it needs[b,e]
Health Technology	Understanding coral reef as a self-generating organism to grow more compatible organs for transplants[b]
	Understanding biodiversity as a defense against disease outbreaks[c]
	Understanding DNA as a means for building redundancy in systems[c]
	Understanding how nature's decentralized networks function as a defense against disease outbreaks[c]
	Understanding that nature systems and cycles naturally takes care of themselves[b]
Intelligence and Security Technology	Understanding plants that give off alarm signals[a]
	Understanding how nature adapts to changes in it environment[c]
	Understanding how patterns in nature appear similar across different levels of biological organizations[c]
	Understanding that nature's complex processes are derived from the four basic molecules of DNA[c]
	Understanding that good ideas of evolution are similar across many different organizations and evolve independently multiple times[c]
	Understanding that change and variation rule everything in nature[c]

Note. [a] Adapted from *Biomimetics: Technology imitates nature*, by H. Yahya, 2006, Istanbul: Global Publishing. [b] Adapted from *An epistemological problem-centric approach to solving complex global problems*, paper presented by J. Barnes, S. Barnes, and M. Dyrenturth at the Forum on Philosophy, Engineering & Technology (fPET-2012), The Graduate University of the Chinese Academy of Sciences (GUCAS), Beijing, People's Republic of China. Manuscript submitted for publication. [c] Adapted from *Learning from the octopus: How secrets from nature can help us fight terrorist attacks, natural disasters, and disease* by R. Sagarin, 2012. New York: Basic Books. [d] Adapted from *How science imitates nature* by M. Gandhi , 2010. [e] Adapted from *The necessary revolution: How individuals and organizations are working together to create a sustainable world,* by P. Senge, B. Smith, N. Kruschwitz, J. Laur, and S. Schley, 2008. New York: Doubleday.

What are the sources of knowledge about nature that are most applicable?

The two key sources of knowledge about nature that are important to building the mental models used to design novel solutions to complex global problems are a comprehension of how nature's systems and cycles function and a appreciation of how those systems and cycles work with human systems. The key knowledge or observable elements in nature's systems and cycles that are most applicable to designing undergraduate engineering and technology education curricula are found in Table 3.

Table 3

Sources of Knowledge

Nature's systems and cycles	Applicable knowledge
Hydrological cycle	Terrain characteristics
	Areal extent of standing water
	Soil moisture
	Vegetation moisture
	Balancing the water budget
Biogeochemical cycle	Marine biosphere-ocean-atmosphere exchange
	Terrestrial biosphere-atmosphere exchange over land
Plant canopy	Plant structure
	Particle adhesion
	Adaptability
	Waste elimination
Carbon cycle	Understanding how plants absorbs carbon dioxide from the atmosphere
	Understanding how carbon atoms are incorporated in the photosynthesis process
	Understand how animals use carbon to build their own tissues and for other needs
	Understand the concept of respiration
Energy cycle	Photosynthesis
	Energy consumption
	Solar radiation
	Distribution
	Transport
	Transformation
Ecological cycle	Biodiversity
	Habitat loss
	Succession
	Webs of life
	Glaciology
	Hydrology
	Vegetation science

	Oceanography Geology Adaptability Waste elimination Scarcity

How is that knowledge about nature structured and limited?

Typically, in engineering and technology education undergraduate programs, knowledge is structured within a domain, science, or technology. Only a few programs design their curriculum as an integrative model. Thus, innovation capabilities and competencies are addressed in a traditional way, such as mechanical, physical, or electronic solutions.

Markman and Wood[8] identified that analogical innovation is limited in two ways. "First, the team is limited to the knowledge possessed by its members. Second, even if the relevant analogous solution is within the knowledge base of its members, the people with that knowledge may fail to retrieve it" (pp. 92-93). Sagarin[1] suggests a biological framework because it can be applied consistently across a wide variety of platforms.

Barnes[32] further identified six factors that constrain thinking about nature and thus restrain sustainability solutions based on biomimicry: 1) scarcity, 2) lack of understanding of nature, 3) lack of integration, 4) unwillingness to change, 5) waste, and 6) risk levels. The first of these restraints, scarcity, is based on a simple principle which states "everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment"[33]. Assembling an interdisciplinary team of scientists and engineers is fundamental to imitating and emulating nature to design solutions to complex global problems. The lack of integration refers to the stakeholders and experts failure to create analogies and mental models of systems and cycles of nature and to apply them to technical and human systems. Regrettably, some scientists rebuff the work of engineers and some engineers refuse to work with scientists. An unwillingness to change is a restraint that describes a community's reluctance to accept a sustainable solution. This disinclination to change could be the result of social or cultural values or political volatility or corruption. An unwillingness to change can also refer to scientists' and engineers' reluctance to give up traditional approaches to explore the innovations in science and technology. The waste restraint refers to the lack of ability to move towards a satisfactory level of waste or to reach zero-waste for the naturalistic sustainable solution. The final restraint, risk level, refers to the obstacle that naturalistic sustainable solutions cannot be safe enough to implement or that the community will not accept the solution due to a pre-conceived belief of the risk level of the proposed solution.

In addition to these constraints and limitations, the ability to appropriately scale solutions must be factored into the problem solving equation. Friedman[3] identified three key supply issues relative to solving complex global problems: 1) scale of demand, 2) scale of the investment needed to produce alternatives at scale, and 3) scale of time it takes to produce alternatives. Demand is based on the exponential factoring of the global population. At about seven billion today, the world population is being projected to 9.3 billion by 2050. The ability to scale complex global problems at the local, regional, or global level has been complicated, if not impossible.

Other considerations that must be factored into the design equation are the immediate impacts and long-term consequences of the new solutions. Resolutions to problems can create both beneficial and harmful impacts, both immediate impacts and long-term consequences. The impacts and consequences can be personal, social, cultural, political, and environmental. Regardless of the best intentions, the considerable knowledge, and dedicated attempts to solve complex problems by a transdisciplinary group of stakeholders and experts, they cannot know and control for all of the potential impacts and consequences. Sometimes the science or technology support the solution, but the impacts and consequences may not be realized until decades later.

What key innovation theorists believe are the necessary innovation capabilities and competencies necessary for future leaders to solve the critical global problems facing our society?

Culminating biomimcry innovation capabilities and competencies identified by the researchers, institutes, and university programs resulted in an extensive list. By analyzing the identified items, the authors were able to reduce the list based on commonly identified capacities. A summary of this consolidation is found in Table 4.

Table 4

Summary of Biomimcry Innovation Capabilities and Competencies

Biomimcry innovation capabilities and competencies
Ability to imitate and emulate nature
Understanding nature’s cycles and systems
Understanding the concept of adaptability as it applies to nature
Understanding the structure of nature’s organisms and species
Understanding how nature scales itself
Understanding sustainability factors
Understanding biomimicry principles
Understanding how to use mental models to translate nature to design solutions to complex problems
Ability to think critically
Ability to use biomimicry problem solving concepts
Understanding complex systems
Understanding systems thinking
Understanding structures of nature
Understanding material science of nature

Discussion

Paul Romer[34], the American economic expert and Senior Fellow at Stanford's Center for International Development and the Stanford Institute for Economic Policy Research is credited with the famous quote: "A crisis is a terrible thing to waste" in response to the economic downturn of 2007-2009. Romer's quote parallels Albert Einstein's quote, "We can't solve problems by using the same kind of thinking we used when we created them."[35] Einstein was emphasizing that one's knowledge and understanding are limited by one's own experience, education, and research and that the advancement of knowledge and science required more.

The United States (U.S.), historically, has responded to a crisis by reinventing itself to successfully resolve the crisis. The U.S. gallantly rose to the challenge to address the 9-11crisis to combat terrorism. Now the U.S. is facing the largest economic crisis in its history, a true economic war. Unfortunately, today the ability for the U.S. to create the type of innovation needed to solve critical problems is hindered by complexity and convoluted by lobbyists, politics, and a higher education system unwilling to change from tradition. The challenge that the U.S. is unwilling to face is taking responsibility for creating a new way of thinking and conducting basic research necessary for developing a national innovation strategy.

If the U.S. will exist in the future as a world power and not as the largest third world country, America must immediately invent a new research and innovation paradigm to study and solve the major issues challenging its existence, such as critical infrastructure and energy supply. This new paradigm, through its ability to create and commercialize new products and services, will create new jobs, help reduce high U.S. unemployment, and increase cash flow back into the economy. This new innovation paradigm, by its very nature, would adapt by reinventing itself to address emerging and future problems facing the country.

A traditional approach, for example, utilizes "systems-theoretic" approaches to studying global problems that relate to the dynamics of science, technology, and innovation and their relationship to economic growth. However, while these complex system dynamics approaches are attractive, they are also limited in their nature for solving global problems.

Olson[36] emphasized the increasing complexity of engineering problems, those that transcends boundaries and disciplines. Koenig[37] emphasized that undergraduate engineering and technology education programs enhance their focus on cognitive, interpersonal, and intrapersonal skills as man integral component of the curriculum. The undergraduate engineering and technology education programs must change their curricula to better prepare students to become more effective citizens and problem solvers in our increasingly interconnected, globalized world. They must address preparing students as the kind of thinkers who contemplate complex global problems. The engineering and technology education curriculum must move to a more global educational model, and in particular, one that embraces integrating innovation capabilities and competencies that develop this new way of thinking about global problems.

One key way to enhancing the way undergraduate engineering and technology education programs must prepare future students is to focus more on the design component of the program, which includes greater emphasis on critical thinking and complex problem solving. Paramount with this critical enhancement is the inclusion of utilizing the development of mental models using critical thinking techniques such as analogies, metaphors, and other analysis techniques to understand new knowledge. Mental models greatly aid students in gaining an understanding of new environments by applying knowledge from a similar environment where they have an existing familiarity. Integrating biomimicry innovation capabilities and competencies unto the undergraduate engineering and technology education curricula will greatly facilitate developing the necessary critical thinking and problem solving skills necessary for the future scientist and engineer.

Nature, itself, provides robust examples that can provide excellent mental models that can be applied in these new environments to solving complex global problems. Nature provides the largest laboratory ever created and provides the greatest knowledge base and opportunity for finding novel solutions to complex global problems. Unfortunately, traditional undergraduate engineering and technology education programs focus on solving single-focused problems, producing a better widget, not on a holistic approach to solving complex global problems. There are not many integrative and interdisciplinary models where engineers and scientists team together in this context. Where biomimicry curricula typical exists are in architecture, environmental science, and biotechnology, not in the typical engineering and technology education programs.

Benyus[12] sentinel work provides an excellent structure that aligns well with engineering and technology education curricula. Her work was organized around six core areas: 1) food, 2) energy, 3) production, 4) medical cures, 5) computing, and 6) business to provide a structure for how scientist and engineers could emulate nature to solve human problems. Passino's [22] work that uses biomimicry to solve optimization, control, and automation problems encountered in the construction of high technology systems also matches well with the future needs for preparing engineering and technology education undergraduate students. As Barnes[32] pointed out there is a logical and symbiotic relationship between the cycles of nature and the cycles of industry.

The research of Yahya[23], Reap[24], Sagarin[1], the Biomimicry Institute 3.8[25] support these relationships, which provide an excellent integrative structure for the future engineering and technology education curricula needs. Understanding about the knowledge of systems of nature, how phenomena in nature exist, and how humans think those environments ought to be is analogous to how one thinks about systems of industry and technology. The foundation of this approach is an integrative relationship in which science starts with a problem and is guided by theory, while technology results in discoveries which lead to theories. These concepts are at the heart of innovation, not just creativity or the invention of a new gadget, but a process of creating solutions that produce a continuous value for improving society and quality of life on local, regional, and global scales.

Dyrenfurth, Murphy, and Grimson[38] called for engineering and technology education programs to consider changing their goals to better address the future needs of their students. Angeles et al.[39] proposed a set of core ideas of a design-centric curriculum that would foster a more holistic understanding of how to solve problems. Incorporating biomimicry principles of how to imitate and emulate nature in the design process would provide a wellspring of knowledge for a holistic approach to solving complex global problems. This type of curricular thinking is what Pellegrino and Hilton[40], Brewer and Stern[41], and the National Academy of Engineering[42] called for in its benchmark publications, *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century*, *Decision Making for the Environment: Social and Behavioral Science Research Priorities*, and *Educating the Engineer of 2020: Adopting Engineering Education to the New Century*.

Conclusion

Undergraduate engineering and technology education programs provide the future technical workforce. Will this workforce be prepared to think about problems differently, with a holistic approach that includes biomimicry or will they be prepared in traditional programs? Understanding systems of nature, how phenomena in nature exist, and how humans think environments ought to be will provide analogies and mental models to create innovative solutions to either solve complex global problems or at least to slow down the progression of those problems. To better prepare students to become more effective citizens and problem solvers in our increasingly interconnected, globalized world, the kind of thinker who contemplates complex global problems, the engineering and technology education curriculum must move to a more global educational model, and in particular, one that embraces integrating innovation capabilities and competencies that develop this new way of thinking about global problems.

It is paramount that undergraduate engineering and technology education programs include biomimicry innovation capabilities and competencies to prepare students to solve complex global problem that are facing society. Being able to understand systems of nature and how they can be applied to complex global problems will greatly help future leaders to create novel solutions to those problems. Biomimicry innovation provides an additional toolkit that transcends traditional disciplinary boundaries of engineering and technology education programs. It provides an ideal means for scaling complex program. No longer are solutions bound within a domain, science or technology. Instead solutions require a highly integrated approach across many domains, sciences, or technologies.

By integrating and applying knowledge of how organic systems (systems of nature) work with human systems, the nexus between problem solving (deductive reasoning) and scientific inquiry (inductive reasoning), undergraduate engineering and technology education will be able to design naturalistic sustainability solutions to improve the quality of life for societies. This greater ability to understand how relationships between two metabolisms, biological (cycles of nature) and technical (cycles of industry), provide an understanding of systems of nature, how phenomena in nature exist, and how humans think those environments ought to be will provide innovative solutions to either solve complex global problems or at least so down their progression.

The result of this integration is a problem-centric curriculum approach that develops the key innovation capabilities and competencies necessary to solving complex global problems by providing a novel way of answering the questions of what are the necessary knowledge and sufficient conditions to solve complex global problems, what are the sources of knowledge about nature that are most applicable, and how is that knowledge structured and limited. Using this type of thinking can greatly enhance the opportunities to solve, manage, or control the major complex global problems facing society. Applying this type of thinking to critical global problems such as energy supply and demand, climate change biodiversity loss, energy poverty, water scarcity, food scarcity, waste storage, health, or critical infrastructure problems provides fresh and sustainable solutions. The lapse is in the failure of undergraduate engineering and technology education programs to make this change. The question is how much longer can undergraduate engineering and technology education programs wait to make this change?

References

1. Sagarin, R. (2012). *Learning from the octopus: How secrets from nature can help us fight terrorist attacks, natural disasters, and disease*. New York: Basic Books.

2. Palfrey, J., & Gasser, U. (2012). *Interop: The promise and perils of highly interconnected systems*. New York: Basic Books.

3. Friedman, T. (2008). Hot, flat, and crowded: Why we need a green revolution – and how it can renew America. New York: Farrar, Straus, and Giroux.

4. Senge, P., Smith, B., Kruschwitz, N., Laur, J., & Schley, S. (2008). *The necessary revolution: How individuals and organizations are working together to create a sustainable world*. New York: Doubleday.

5. McDonough, W., & Braungart, M. (2002). *Cradle to cradle*. New York: North Point Press.

6. Vincent, J., Bogatyreva, O., Bogatyreva, N., Bowyer, A., & Pahl, A. (2006). Biomimetics: Its practice and theory. *Journal of the Royal Society Interface, 3*(9), 471-482. doi:10.1098/rsif.2006.0127

7. Korkmaz, S., Ali, N., & Smith, I. (2011). Determining control strategies for damage tolerance of an active tensegrity structure. *Engineering Structures 33* (6), 1930–1939. doi:10.1016/j.engstruct.2011.02.031

8. Markman, A., & Wood, K. (Eds.). (2009). *Tools for innovation: The science behind the practical methods that drive new ideas*. New York: Oxford Press.

9. Carlson, C., & Wilmot, W. (2006). *Innovation: The five disciplines for creating what customers want*. New York: Crown Publishing Group.

10. Kelley, T., & Littman, J. (2005). *The ten faces of innovation: IDEO's strategies for beating the devil's advocate and driving creativity throughout your organization*. New York: Doubleday.

11. Vincenti, W. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins studies in the history of technology.

12. Benyus, J. (1997). *Biomimicry: Innovation inspired by nature*. New York: William Morrow & Co. Inc.

13. Barnes, J. (2011). *Naturalistic sustainability: The nexus of biomimetic problem solving and scientific inquiry*. Harrisonburg: BTILLC.

14. Lenau, T., & Mejborn, C. (2011). Solving global problems using collaborative design process. *Conference Proceedings of the 18th International Conference on Engineering Design – Impacting Society Through Engineering Design, Vol. 1,* 310-320.

15. Koutsouris, A. (2010). Transdisciplinary and participatory development: A critical realist approach. *The International Journal of Interdisciplinary Social Sciences 5*(4), 253-264.

16. Madni, A. (2007). Trandisciplinarity: Reaching beyond disciplines to find connections. *Journal of Integrated Design and Process Science 11*(1), 1-11.

17. Vincent, J. (2003). Biomimetic modeling. *Philosophical Transactions of the Royal Society London, 358*, 1597-1603. doi:10.1098/rstb.2003.1349

18. Vincent, J., & Mann, D. (2002). Systematic technology transfer from biology to engineering. *Philosophical Transactions of the Royal Society London, 360,* pp. 159-173. doi:10.1098/rsta.2001.0923

19. Schmitt, O. (1969). Some interesting and useful biomimetic transforms. *Conference Proceeding of the Third International Biophysics Congress*, Boston, Mass., p. 297.

20. Biomimetics. (n.d.). *MacMillan Dictionary*. Retrieved from http://www.macmillandictionary.com/buzzword/entries/biomimicry.html

21. Gandhi, M. (2010, 19 September). *How science imitates nature*. Retrieved from http://www.peopleforanimalsindia.org/articles-by-maneka-gandhi/212-how-science-imitates-nature.html

22. Passino, K. (2005). *Biomimicry for optimization, control, and automation*. London: Springer-Verlag.

23. Yahya, H. (2006). *Biomimetics: Technology imitates nature*. Istanbul: Global Publishing.

24. Reap, J. (2010). *Holistic biomimicry: A biologically inspired approach to environmentally benign engineering* (Doctoral dissertation). Available from ProQuest Dissertations and Thesrs database. (UMI 3394452)

25. Biomimicry 3.8 Institute (2012). *Biomimicry taxonomy*. Retrieved from http://www.biomimicryinstitute.org/images//biomimicry_taxonomy.pdf

26. Biomimicry 3.8 Institute (2013). *Biomimicry professional certificate program*. Retrieved from http://issuu.com/biomimicry38/docs/professional_guide?mode=window&backgroundColor=%23222222

27. Kleinke, D., Weaver, J., and Lynch-Caris, T. (2012). *Biomimicry: Tools and techniques*. Littleton, CO: Innovations in Action, Inc.

28. Altshuller, G. (1996). And suddenly the inventor appeared: TRIZ, the theory of inventive problem solving. Worcester, MA: Technical Innovation Center, Inc.

29. Biomimetics-Innovation-Center. (2012). Research at the Biomimetics-Innovation-Center B-I-C. Retrieved from http://bionik.fbsm.hs-bremen.de/pages_english/re_general.html

30. Kompetenznetz Biomimetik Network. (2012). *Kompetenznetz Deutschland networking for innovation*. Retrieved from http://www.kompetenznetze.de/netzwerke/bionik_biomimetik

31. *Biomimicry: Using Nature as a Design Inspiration*. (2012). Syracuse University. Retrieved from http://lcs.syr.edu/centers/sustainableengineering/modules/10-17_Cattano.pdf

32. Barnes, J., Barnes, S., and Dyrenfurth, D. (2012, November). *An epistemological problem-centric approach to solving complex global problems*. Paper presented at the Forum on Philosophy, Engineering & Technology (fPET-2012), The Graduate University of the Chinese Academy of Sciences (GUCAS), Beijing, People's Republic of China. Manuscript submitted for publication.

33. United States Environmental Protection Agency. (2012). *Sustainability*. Retrieved from http://www.epa.gov/sustainability/basicinfo.htm

34. Romer, P. (n.d.). Retrieved from http://en.wikipedia.org/wiki/Paul_Romer

35. Collected Quotes from Albert Einstein. (n.d.) Retrieved from http://rescomp.stanford.edu/~cheshire/EinsteinQuotes.html

36. Olson, S. (Ed.). (2013). *Educating engineers: Preparing 21st century leaders in the context of new models of learning: Summary of a Forum*. Washington, DC: The National Academies Press. http://www.nap.edu/catalog.php?record_id=18254

37. Board on Testing and Assessment. (2011). *Assessing 21st century skills: Summary of a workshop*. Washington, DC: National Academies Press. http://www.nap.edu/catalog.php?record_id=13215

38. Dyrenfurth, M., Murphy, M., & Grimson, W. (2009). Implications of philosophy for engineering and technology bachelors programs. Presentation at the International Technology and Education and Development Conference, Valencia, Spain.

39. Angeles, J., Britton, R., Chang, L., Charron, F., Gregson, P., Gu, P., Lawrence, P., Stiver, W. Strong, D., Stuart, P., & Thompson, P. (2004). The Engineering Design Competency. In Proceedings of the Inaugural CDEN Design Conference, July 29-30, Montreal, QC, Canada.

40. Pellegrino, J. & Hilton, M. (Eds.). (2012). *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century*. Washington, DC: Washington, DC: National Academies Press. http://www.nap.edu/catalog.php?record_id=13398

41. Brewer, G. & Stern, P. (2005). *Decision Making for the Environment: Social and Behavioral Science Research Priorities*. Washington, DC: National Academies Press. http://books.nap.edu/catalog/11186.html

42. Committee on the Engineer of 2020, Phase II, Committee on Engineering Education, National Academy of Engineering. (2005). *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, DC: National Academies Press. http://www.nap.edu/catalog/11338.html