Integrating Complex Systems Study into the Freshmen Mechanical Engineering Experience

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Introduction

According to the president and a member of the National Academy of Engineers (NAE), William Wulf and George Fisher, "many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems."[1] Unfortunately, the traditional engineering curriculum is a series of courses that teach simple systems. There is no emphasis on the true complexity of these systems—how they interact with other systems. "Engineers normally will not spend their lifetimes solving purely technical problems. Most engineering problems span a wide range of both technical and non-technical areas. The non-technical include environmental, political, economic, social, regulatory and corporate factors that are usually interrelated in a complex fashion."[2] There is a need to engage students in a new way of thinking about the problems that they will encounter in their careers. To change the trend in thinking, it is necessary to change the way that courses are taught throughout the engineering curriculum.

The American Society of Mechanical Engineers (ASME) promotes a "shared vision of the future of mechanical engineering education in the context of new and rapidly emerging technologies and disciplines, national and global trends, societal challenges for the 21st century, and associated opportunities for the profession."[3] We are at the threshold of what is considered to be the century of biology. The ASME vision recommends reconsidering the traditional recognition of chemistry and physics as the only basic science courses.

We designed and taught a course for first semester honors engineering students for three semesters to address this needed change from a simple systems approach to a more complex systems approach by including biology in an engineering course. This course was designed to emphasize both the simplicity and complexity of the problems that they will encounter as engineers. The Shewhart Cycle was used as a tool for continuous learning and improvement in the design of this course.[9] The Shewhart Cycle consists of four continuous steps: Plan, Do, Check, Act, and then repeat as necessary. If we discovered that the students did not learn what was intended in the check portion of the cycle, we would move through the cycle again under slightly different conditions. The syllabus reflects the Shewhart Cycle, because it leaves room for change by keeping the subjects somewhat vague, such as "Pit and Pit'um Laboratory" or Complex Systems (see the class web page at http://www.me.sc.edu/courses/U101E/). This allowed room in the course for some flexibility depending on what teaching methods worked well for the students.

Complexity needs to be incorporated throughout every engineer's educational development. The freshmen learning experience discussed in this paper took place in a College of Engineering section of University 101, "The Student in the University." We used many different vehicles to introduce systems study into this course. The students were introduced to biology, teaming exercises, experiential learning activities, technology, and communication in order to integrate the systems perspective into this course. The most unique portion of this course was the inclusion of biology in a discipline that does not value biology as a fundamental course. In order to incorporate biology into the course the students read "What is Life?" by Lynn Marguilus and Dorion Sagan. This book provided a way to introduce the complexities of designs that exist in the natural world.

The focus of this paper will be on the inclusion of biology in an introduction to engineering course. The student's comments concerning the ways that this book will help them in their engineering education and career will be analyzed thoroughly. Possible ways to integrate biology into other courses throughout the mechanical engineering curriculum will be discussed briefly. Finally, the student's perspective of whether simple systems or complex systems will be dealt with in their education, career, and life will also be looked at closely.

Discussion

The freshmen learning experience discussed in this paper took place in a College of Engineering section of University 101, "The Student in the University." This course recently received recognition from U.S. News and World Reports as the number one program for first-year students in the country.[5] The "university" part of this course introduces and exposes the students to living and learning opportunities such as sex education, alcohol and drug abuse education, the library, and the career center.

This section will describe in detail the experience of introducing the students to biology in an engineering course, possible ways to incorporate biology into other engineering courses, and the understanding that the students gained about the concepts of complex and simple systems (actual student comments will be given with anonymous attribution and year).

Biology through What is Life?

A report from a workshop organized by the Big-Ten-Plus Mechanical Department Heads in January of 2002 emphasizes the importance of including "new material on atomic and molecular physics, quantitative biology, comprehensive (organic) chemistry, micro fabrication, and modern computing" in a mechanical engineering curricula.[6] ASME has also emphasized the importance of including biology in addition to the traditional science core classes (chemistry and physics).[3] By having the students read *What is Life?*, we were attempting to introduce the students to the complexities of life, including both living systems and engineered systems that interact with living systems. Because of its length, content, and the presentation of ideas, we thought it would be best to hold class discussions about the book two chapters at a time. This way we could observe student comments and reactions to the book as they read it, and not just when they finished it. After reading the first two chapters, most of the class agreed that they did not need to be reading this book. "Why do engineers need to read a book about biology?"

One student, Laura, loved this book from the beginning. She wants to be a biomechanical engineer and never thought that she would be reading something like this in her first semester of college. She is a soft spoken student that responded to this question of why engineers need to know about biological systems in class.

> *"What is Life? discusses the great complexities and amazing capabilities of life. It shows us how we as engineers have a great deal to learn from the perfected complex systems of life. A striking example is found on page 92: 'Ancient bacteria mastered nanotechnology. Already miniaturized, bacteria control specific molecules in ways of which human engineers can only dream. Far more complex than any computer or robot…' The author then goes on to describe the flagella of bacteria that are made of 'rings, tiny bearings, and rotors' and that spin about '15,000 rpm.' Today in the 21st century with all of the extensive advanced technology available, humans have not come close to designing something so complex, so miniaturized as bacteria. In fact the search is on for a living computer chip. This example of the bacteria only scrapes the surface of the amazing complexities and systems of life that engineers can only hope to mimic."*
> ***Laura, 2002***

This question of "Why study Biology?" reappeared every time that a class discussion was held. Only after completing the book did the students start to understand the relevance of "living complexity" to their future careers as engineers.

> *"I was rather surprised how a topic so seemingly different from engineering as biology would have so many connections to such a technical field."*
> ***Cathy, 2002***

A goal of studying complex systems through reading *What is Life?*, was for the students to start to understand how complex systems study will show up in their careers and in everyday life.

> *"Later in life I can turn to the examples of the interconnected systems of the Earth, study of the formation of coal, or the relationship between man and nature and be reminded how important team dynamics and symbiotic relationships are for success."*
> ***Thomas, 2004***

Another goal of reading *What is Life?* was to introduce the students to looking at the 'bigger picture.' We would like the students to begin to see how their designs and work as engineers could effect the environment, while the environment will simultaneously effect their designs.

> *"With me living more aware of nature and how nature interacts I can be more aware of man altering or tempering with nature."*
> ***Robert, 2004***

> *"If the number of bacteria in my mouth is equal to the population of the world, how much life must exist in a plot of land where a building may go up? How many other living things must be affected by the construction of a building? How*

will they react? These are questions I will need to consider."
Dave, 2002

We also wanted our students to leave this course with a desire to think outside of the box.

"Sagan and Margulis in the last chapter discuss that despite this vast knowledge we have of life there is still so much more left to be discovered. This is perhaps the most significant concept in the book—the idea of pushing, asking, improving—all qualities of an engineer."
Lee, 2002

This book challenged many of the beliefs of the students. While most of them had taken a biology course in high school, they were not prepared to have some of their fundamental ideas challenged.

"I also learned to view humans not as dominating over the world, but as being another component in the world's ecosystem."
Sean, 2003

"I also remember the authors saying that humanity can't destroy the world because the biosphere checks itself—so on one hand I'll be environmentally conscious because humans want to survive, but on the other I won't care because if we mess up our situation and go extinct it'll be our own fault."
Vanessa, 2003

"The final chapter put medicine into perspective, as human life is trivial to the existence of Earth."
Tara, 2004

After reading this book, an objective was for the students to leave with an appreciation for designs in nature. Engineers are beginning to look toward nature for inspiration in their designs.

"Engineers must look to living systems to gain inspiration. Specifically, a useful aspect of living systems is that they are self renewing and self maintaining. Another thing that is useful is that bacteria are not programmed to die, if we can utilize this characteristic, who knows what we can accomplish."
Joe, 2002

"I learned the importance of adaptive solutions from bacteria. p. 92 "…because their survival led to their inventing every kind of metabolic transformation."… I learned from plants that oftentimes internal structure leads to overall strength."
Jim, 2002

"We as engineers can learn from the close to flawless design of organisms to construct new and improved systems for our own lives. We also learned from the book that if you stick with it and adapt, problems can be overcome. One good

example of this is the bacteria who, when introduced to large amounts of oxygen, used the oxygen to help them instead of letting it destroy them. Similarly in engineering, we must look at problems as ways of improvement instead of destruction."
Pam, 2002

"Since life systems have been here so long and often can fix themselves, we could model designs for things after them."
Theresa, 2002

Most of the students left the class with a good understanding of the value of reading *What is Life?* in an engineering course. Their writing demonstrates an understanding of the connections between engineering and biology.

"Humans, to us, seem to be "top of the game" on Earth, however What is Life? reminds us that humans have been around for so short a time, it may be we place too much importance on ourselves; whereas bacteria, so small and "insignificant" effectively run every complex action, situation, and process on Earth. This is important to remember as another example (from class, not the book) shows that through planning and design for an engineering process is only 5% of the cost, it is 70% of influence. What is Life? highlights the importance of complexity and the idea that influence is not always as it seems in the traditional paradigm.
Dan, 2003

"The book also points to the importance of the laws of thermodynamics in biology as well as other areas (namely, engineering). In discussing the myriads of ways in which all life is interconnected, the book emphasizes the importance of viewing everything as a complex system, not bound to simple deterministic rules."
Keith, 2003

A major objective of reading *What is Life?* was for the students to leave with an appreciation of biology for today's mechanical engineer. This is in line with the vision that the American Society of Mechanical Engineers put forward.[3]

"Biology and the engineering field work together in many ways and the future of engineering may be in biology. What is Life? explains how many different organisms and processes work, and much of that can be used in engineering to build better and more efficient products."
Robert, 2004

"I will be on the verge of the new technology and the collaboration of engineering with biology. Engineering is taking on a biological shape (ex. Computers made from living molecules)."
John, 2002

"I think that What is Life will help me later in my engineering education and career because now engineers are having to know more about biology and how life works."
Theresa, 2002

This book, while challenging to honors freshmen engineering students, was very worthwhile for the students to read. While many of the students met the objectives that were set forward, some will not appreciate the importance of reading this book until they are further along in their education and careers.

What is Life culminates with a discussion of biomimicry, which was explored further through a project in the 2004 class. Each team was required to find and research a case study of a designed product that is based on concepts of biomimicry. The student teams researched and presented the following case studies: a beer brewery that mimicked an ecological system, a Speedo swimsuit that mimics sharkskin, and airplane wings that mimic bird flight. The freshmen gained a strong understanding of the concepts presented in this book, imagine what would happen if biology was integrated throughout the curriculum.

Biology in other Engineering Courses

Engineering students could become prepared for their careers, by being exposed to biology and complex systems study throughout their education. This could occur by including a module that involves biology in every course that is taught throughout the curriculum. As with planning any course it is important to adhere to a continuous improvement loop. Some possible ways to incorporate biology into typical mechanical engineering courses will be briefly discussed.

In heat transfer, the students could be required to do a project to determine the heat transfer of a starfish to its surroundings. In microprocessors, the students could be required to determine the maximum number of atoms that could be held on a computer chip that is 1 centimeter squared. They could also be required to draw a flowchart to determine how a mouse finds the cheese in a maze. In a design course, the students could be required to design a part using principles of biomimicry. Even courses that teach mechanistic simple systems could use examples that incorporate biology into them. For a solids course, the students could determine the tensile strength of a spider web, or find the area of maximum stress on a tree.

Complex Systems

The overarching goal of this course was to introduce the students to simple and complex systems. This was done using a variety of activities from class readings to teaming exercises, experiential learning activities, technology applications, and communication-based activities in order to integrate the systems perspective into this course.

After participating in this course, some of the students thought that they would continue to study complex systems throughout their schooling. This was evidenced by their responses on the final exam to the question, "In school do you think that you will be dealing mostly with simple systems or complex systems? How about in work and life? Explain."

"I feel that, since this course introduced us to complex systems, much of our schooling would follow that path. In the real world, in work [and] in life, I am not so sure that simple systems really exist. There is always so much more to consider."
Guy, 2003

"In school I think that I will be dealing more with complex systems, because in work and in life I will probably deal more with complex systems. This is because in life, things are not as simple as they seem."
Theresa, 2002

Another objective of this course was for the students to understand the problems that can be encountered when reducing complex systems into mechanistic, simple systems. The mechanistic systems are important in order to learn how to analyze problems, and to break down very complex problems. However, there is often something lost by reducing a large system into many individual parts and then assuming that the sum of the parts is equal to the whole.

"The methods by which complex systems are reduced into simple systems (written on a page, or maybe a book) clouds the understanding of the intricacies of interactions."
Brian, 2002

One of the large hurdles of incorporating complex systems study in the existing curriculum is having the professors comfortable talking about systems that cannot be explained with a set of equations.

When people think of engineering, they think of equations and diagrams and everything being perfectly logical. I don't think an engineering class would normally talk about complex systems because engineers like order."
Vanessa, 2003

"In school, particularly in early, basic-level courses (an introduction physics course, for example), the emphasis will be on simple systems that are easy to teach, understand, test, and grade. ... It is also possible that a potential lack of understanding will lead to little education about complex concepts. In work and life in general, complex systems are much more prevalent, and thus will dominate my experiences."
Keith, 2003

However, as we move into sub-disciplines of engineering such as bioengineering and nanotechnology, some professors are becoming comfortable dealing with systems in which the there are a large number of components that act according to rules that may change and that may not be well understood.

"In school, I think that I will mainly be dealing with simple systems, but I'm sure that I will have to deal with some complex systems in some of my later classes.

Everything is fairly simple and understandable right now, but later we will probably get into complexity and uncertainty."
Robert, 2004

If students are challenged to look beyond the common system boundary lines and consider other ways that their designs may affect the world and people around them, they will be more likely to be attracted to the idea of being an engineer. We may be able to attract more females and minorities to a white, male dominated field if engineers are considered to positively impact the world and people as doctors and teachers do.

"But most likely, I will be working with complex systems because I would like a challenging career with complexity."
Robin, 2004

Complex systems study is laying the foundation for a revolution of all sciences to move beyond reductionism into holism.[7] This holistic approach involves not only looking at the technical aspects of a system, but the economic, social, cultural, global, and environmental aspects as well.

"To almost every simple system in this world there is a complex side which should not be ignored."
Lee, 2002

Conclusion

The complexities of the systems that we "engineer" are beginning to be understood because of the many breakthroughs in science. These complexities must be incorporated into engineering curriculum. Industry realizes the need for this change. Desmond Hudson, President of Northern Telcom Inc., said that, "My concern is for the students who come out of school suitably versed in mathematics, physics, and the sciences, but lacking an appreciation for literature, history, and philosophy. The view they have is that modern technology is a collection of components rather than an integral part of our society, our culture, our business environment."[2] There is a need for a change in the current engineering curriculum. The Accreditation Board of Engineering Training addresses this need in the current accreditation method, Criteria 2000.[8] It states that the graduates must possess the broad education necessary to understand the impact of engineering solutions in a global and societal context. This freshmen honors engineering class is a start to developing a complex systems oriented method of educating our future engineers.

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Biography

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