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The Role of Design in Materials Science and Engineering*

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Learning to apply the design process can be the key to understanding the blending of Materials Science with Engineering. Design is a method that involves both inquiry and innovation but it is also constrained by such practical factors as time-to-market and cost-effectiveness. Engineering students must learn to recognize the similarities and differences between the scientific and design methods. Both can be looked at as systems for solving problems; however, the input for the scientific method is a theory with the output being increased knowledge, while the input for the design method is an application with the output being a device or process. Introducing design through project-based learning activities will enable students to see how the fundamental concepts of science and math can be applied to solve complex engineering problems. It is imperative that students be exposed to the design process throughout their undergraduate education and this article will recommend methodologies for accomplishing this task.

Keywords: design method; systems engineering; project-based learning; critical thinking; teaming.

INTRODUCTION

AGENCIES LIKE THE Accreditation Board for Engineering and Technology in the United States have identified and highlighted the need to emphasize the incorporation of design into the Engineering curriculum. [1] Moreover, learning to apply the design process can be the key to understanding the blending of Materials Science with Engineering. It is widely recognized that students need to be exposed to the design process early in their undergraduate education [2, 3]. Doing so enables them to see how the fundamental concepts of science and math are applied to solve multi-faceted engineering problems. Design is a process where the functional requirements of an application must be clearly established and then translated into design solutions. Students can learn to practice the design process through project-based learning activities based on authentic and practical design applications. By employing a top-down approach when practicing design, problems should first be broken down to the fundamental levels of technology that will be required to solve the problem. The principles of science, engineering and math required to solve the problem can then be identified and brought together to form a design solution. In addition, by creating a team-learning environment during this process, students will learn to develop a shared vision and a holistic outlook towards solving problems. Integrating these practices through their undergraduate learning experience will ensure that students become equipped with the skills necessary for success in their professional careers.

THE GOAL OF DESIGN

Design is a method of inquiry and innovation. It is an iterative decision-making process that applies the basic principles of science, mathematics and engineering to solve a problem. The dictionary defines *design* as 'a process to create, fashion, execute, or construct according to a plan.' The U.S. Accreditation Board for Engineering and Technology (ABET) defines it as 'a process of devising a system, component, or process to meet desired needs.' Design has been characterized as the process of applying engineering and scientific principles for the purpose of formulating a device or a process. [4] In summary, design should produce a device or process that meets a specific need defined by functional requirements that enable it to be put into practice. The goal of design is also to satisfy all of the functional performance requirements within a minimal number of iterations. This will minimize time-to-market and increase the likelihood of a product's commercial success. Understanding how to effectively apply the design method should be a critical component of every engineer's education.

SCIENTIFIC VERSUS DESIGN METHODS

Design is the glue that binds Science with Engineering. It is a method that involves inquiry and innovation but is also constrained by practical

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factors such as time-to-market and cost-effectiveness. Engineering students must learn to recognize the similarities and differences between the scientific and design methods. Both can be looked at as systems for solving problems; however, the input for the scientific method is a theory with the output being increased knowledge, while the input for the design method is an application and the output is a practical device or process [5, 6]. The goal of the scientific method focuses on the process of establishing fundamental truths from theories that have been proven by extensive observation, testing and analysis. The goal of the design method is to produce a device or process that satisfies the functional requirements derived from a customer or market application. The similarities and differences of these two approaches are outlined in Fig. 1.

Throughout the process of learning the fundamentals of Materials Science, undergraduate students are immersed in the scientific method but are often not exposed to design until their capstone senior project. It is imperative that students be exposed to the design process earlier in their education, preferably during their freshman year. Doing so will enable them to see how the fundamental concepts of science, math and engineering are applied towards solving problems. Moreover, it will enable them to perform successfully as engineers and empower them to make significant contributions to society at large once they graduate.

Typically, students are introduced to the scientific method in high school chemistry or physics classes. It begins with the development of a theory or hypothesis for a solution to a problem. Experimental methods are then carefully defined to test the validity of the theory. Data is collected and the results are analyzed. Hopefully, the results enable the scientist to formulate clear and concise conclusions regarding the correctness of the theory. The results are then communicated to the technical community with the identification of a scientific truth as the underlying goal of the process. Time and cost should not influence the outcome. Most pure research activities employ the scientific method and the value of the effort is measured by the increase in fundamental knowledge that is achieved.

The design method begins with a careful evaluation of the application as a system with inputs and outputs along with the technologies required to address the application. A minimum set of independent functional requirements that completely satisfy the performance goals of the application must be established. Concept maps are tools that engineers can utilize to develop and analyze the outline of a design architecture that can achieve the functional requirements [7]. They enable the engineer to 'brainstorm' and optimize the architecture of the design solution and diagram a pathway for translating the functional requirements into design specifications. From these specifications a prototype of the design solution can be fabricated and tested to verify if it meets the target performance requirements. The results of these tests must be clearly reported to the engineering team and management before any commercialization decisions can be made. This requires engineering students to develop effective written and oral communication skills.

A SYSTEMS APPROACH TO DESIGN

Design requires the ability to think holistically, to view the big picture and approach a problem from a systems perspective. Systems thinking emphasizes seeing the whole and establishing a framework for seeing inter-relationships rather than individual things; it requires seeing patterns of change rather than static conditions [8]. Many educators have identified the need for this type of pedagogy in design [9, 10, 11]. A systems approach to design involves learning that simply optimizing individual components cannot optimize complex systems. It requires an in-depth knowledge of how the components interact with each other [12]. It also requires the engineer to design with five basic considerations in mind [13]:

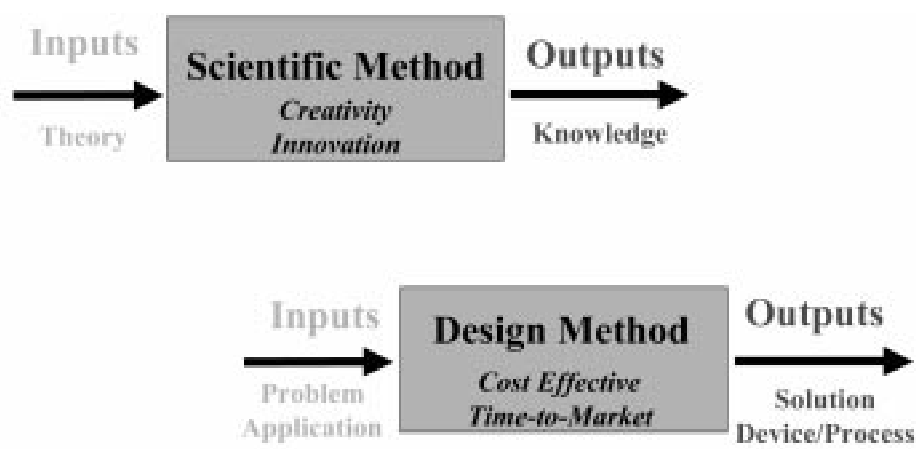

Fig. 1. A systems view of the scientific and design methods.

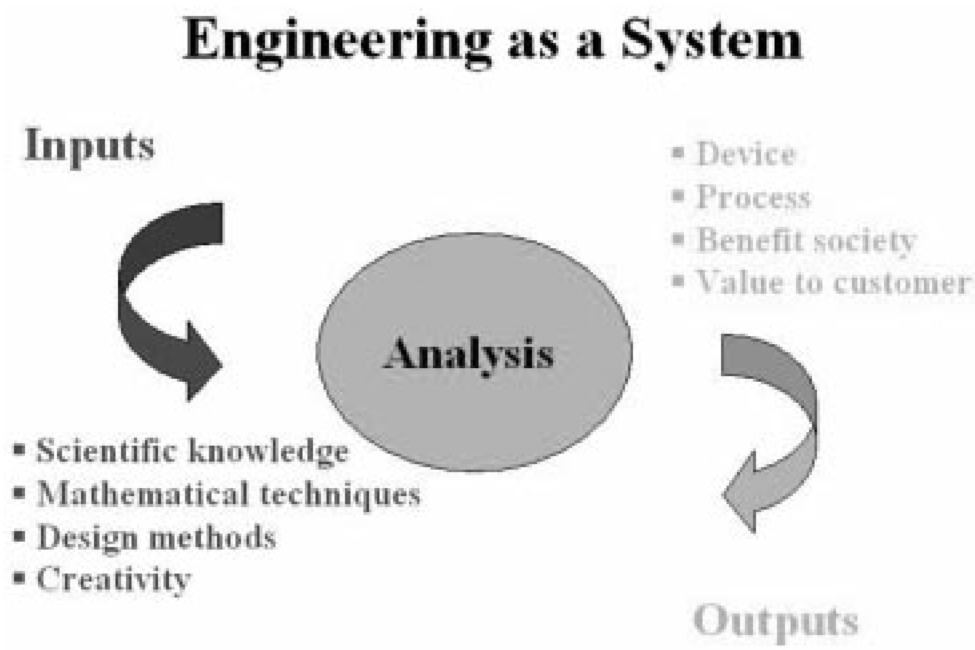

Fig. 2. Engineering as a problem-solving system with inputs and outputs.

1. The total system's objectives or performance of the whole system
2. The system's environment or fixed constraints
3. The resources required by the system
4. The measures of performance for each component in the system
5. The management of the system

Systems thinking is particularly important for design engineers, as it requires careful attention to the process of developing a balanced solution rather than a single, 'correct' answer. When making decisions in the design process, an engineer is required to balance inherent trade-offs. Design problems are multi-faceted with many inputs and outputs that must be carefully balanced and optimized to achieve a solution with acceptable risks, in the shortest period of time and at the lowest cost.

Engineering itself can be thought of as a problem-solving system, where technical methods are applied to meet stated performance objectives. As with every system, there are inputs that are acted upon (processed) and produce outputs (results). For engineering, the inputs are scientific knowledge, mathematical techniques, design methods and creative problem-solving techniques. These inputs are put through an analysis process that

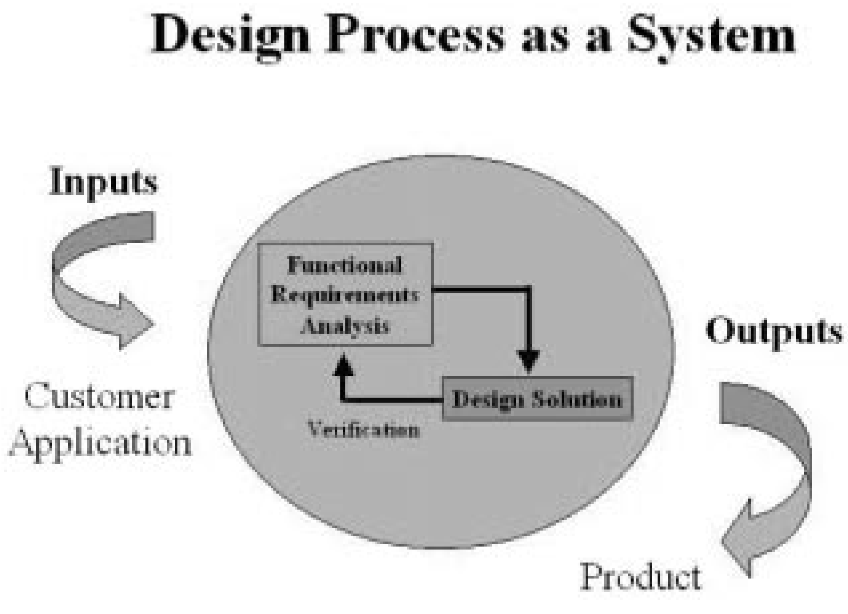

Fig. 3. The design process is a system with inputs and outputs.

results in outputs such as a device or process that has value to a customer and a benefit to society, as illustrated in Fig. 2.

The engineering design process itself can be looked at as a system that has inputs based on the requirements of a customer's application. These requirements are analyzed and a design solution is developed that will produce performance results that match the customer's application, as illustrated in Fig. 3. Design is also an iterative problem-solving process that draws upon whatever technology is necessary to meet the performance requirements. Importantly, the performance results must be verified before the product or process can be carried through to commercialization. In addition to technical performance, the design process must be carefully planned and managed to meet schedule and budgetary requirements.

At the heart of this cycle is the design solution, which can also be looked at as a system. There are many inputs to the design solution analysis including functional requirements, integration of technology (e.g. hardware, software and science), reliability, costs, technical and business risks and market timing. All of these inputs must be optimized and balanced to achieve the level of performance required to satisfy the application. It is important that students develop the ability to see engineering as a problem-solving system with constraints. They should also realize that developing a design solution often requires them to have cross-disciplinary skills.

Taking a systems approach to developing a design solution is a skill that can only be developed through practice. Engineering students can achieve this by completing progressively more complex design activities throughout their undergraduate curriculum. Examples of how to integrate design into the curriculum will be addressed later in this report.

THE DESIGN PROCESS

Design begins with identifying the needs of a specific application and defining the performance of a device or process that would satisfy that need. Most undergraduates are only familiar with facing clearly defined problems, whereas most design problems have vague objectives and performance requirements that are not always clearly spelled out. This can lead to a design solution that does not satisfy the requirements of the application; therefore, the first task is to clearly define the functional requirements for the design problem.

Functional requirements are the minimum set of independent requirements that completely characterize the performance of the design in order to satisfy the application. It is imperative that all of the functional requirements are clearly identified, characterized and prioritized. They are usually the answers to the 'what' question. What performance must the device or process achieve to satisfy the application's requirements? Keep in mind that functional requirements should only tell the engineer what to do but not how to do it. The objective tree method described by Haik provides an effective format for organizing functional requirements [14]. It utilizes a diagrammatic form for showing the inter-relationships and hierarchy of the functional objectives.

It is important to identify whether functional requirements are coupled or dependent on each other. It is easier to design a solution if the functional requirements are decoupled. For example, some faucets have two separate knobs to control the hot and cold water. If the functional requirement is to achieve a constant water temperature regardless of water flow rate, then this design will have problems, since the temperature and flow rate of the water are coupled. It is difficult to change the temperature without affecting the flow rate of the water. A better design would be a single lever faucet, which employs a control mechanism that can vary the balance of hot and cold water while maintaining a constant flow. The functional requirement of achieving a constant temperature at varying flow rates can now be achieved because the parameters (flow rate and temperature) are decoupled; each can be established independent of the other. It is best to try to minimize the number of coupled functional requirements as they often lead to conflicting design requirements.

Concept maps and design specifications are the next step and this involves creating potential system architectures for the device or process that will satisfy the functional requirements. Conceptual design solutions can be developed using the concept mapping process. This is where the creativity of the students can be developed. Begin by encouraging students to sketch out ideas while keeping a focus on the top-level requirements. Do not get bogged down in the minutia but challenge students to participate and embrace alternative ideas. A functional analysis and optimization of the concept map should identify the inter-relationships of technology (e.g. hardware, software and process). The concept map should outline the overall system architecture of the product and identify key sub-systems and components [15]. Now is the time to question functional requirements and consider design criteria such as geometry (size), kinematics (motion), forces (weight), energy (heating and cooling), materials (thermal conductivity), controls (electronics), safety (regulations), assembly (automated/manual), reliability (uptime), service (repair time and routine maintenance) and ergonomics (user and service). Attention should be paid to any physical limitations on the use of the design introduced by human capabilities. The user's body size, strength, reach, visual acuity, average manual dexterity, sensitivity to shock, noise and vibration along with tolerance to environmental conditions such as temperature and humidity must be considered [16]. It is also important to complete a preliminary life cycle analysis evaluating the natural resources required and environmental impact of the device or process from development on into manufacturing and finally end-of-life [17].

Next, clearly translate the functional requirements into *design specifications* that can be measured. Make sure that tolerances are included for each. It is imperative that all design specifications have tolerances that can be tested and measured. Design specifications typically answer the 'how' question. How will the device or process achieve the functional requirements? Overall system level specifications can be broken down into sub-systems and ultimately components. Once a conceptual design has been established, it is time to develop a fully detailed design solution. In industry, the design solution must address 10 key issues:

- Detailed part or component drawings
- Material selection
- Make vs. buy decisions
- Verification of performance through modeling
- Fabrication processes
- Reliability analysis
- Safety compliance
- Environmental impact analysis
- The protection of core intellectual property
- Project schedules and design reviews

Building and testing is next and students need to recognize that this is an iterative process, where the design's performance is improved based on preliminary testing and a balance or compromise must be reached between the time available for iterations and the optimum performance of the design. In addition, the cost effectiveness of the design is usually very important. Unlike the scientific method, if the design method does not solve the problem (application) within a prescribed cost, the design is not considered successful. First, test components, then sub-assemblies and finally the entire system. It is important that your tests are capable of leading to conclusive answers. Tests that generate lots of data but do not provide conclusive evidence that the design is actually achieving the critical performance requirements are of no value.

PROJECT-BASED LEARNING ACTIVITIES

The best way for students to learn to apply the design process is through a project-based pedagogy. Moreover, Springer, Stanne and Donovan [18] as well as Colbeck, Campbell and Bjorklund [19] have found that interactive-learning classroom techniques promote 'deeper learning.' Through 'deeper learning,' students retain concepts and are more likely to apply the concepts to unfamiliar situations. That is, they develop 'cross-cognitive abilities' by applying concepts to a context outside the one in which it was originally learned, thereby enabling them to develop a more holistic way of approaching the solutions to problems. Many engineering curricula approach learning design by packaging problems along with a few principles into a cookbook-type format; however, leaders in engineering education feel that engineering and science curricula have too many courses where problems are presented to the students as a 'tidy application of a few principles' [20]. William Wulf, President of the National Engineering Academy, has recommended that students be asked to develop a design given a limited number of constraints [21]. Accordingly, it is important that the functional requirements of a design problem be clearly defined, but the implementation of a design solution should be left to the creativity and innovation of the student.

This is particularly important as we enter the nanotechnology age, where design problems are often cross-disciplinary in nature and require creative new approaches and solutions. Nanotechnology is truly multi-disciplinary in its foundations and requires an approach to solving problems based on the integration of atomic physics, molecular biochemistry, mechanical, electrical and biomedical engineering. Mihail Roco of the U.S. National Science Foundation has recommended a technique referred to as 'reversing the pyramid of learning' and he believes that it is a means for expediting the development of a nano technology workforce [22]. By utilizing this reverse pyramid or top-down approach when practicing design, problems can be broken down to their fundamental levels and students can more clearly recognize the connection between the fundamentals of materials science and applied engineering.

An example of a *top-down approach* to a design solution for a SmartChip bio-sensor might be as follows: a functional requirement might be to detect parts-per-billion of a specific pathogen. The design solution might involve a microfabricated cantilever actuator employing capacitance sensing. This would require the team to learn about chemical etching, film deposition and patterning of thin films to produce the cantilever. In addition, they would need to study molecular organic coatings and surface biochemical reactions. The team might also need to explore cell biology and protein synthesis mechanisms. The functional requirements of the design problem can be broken down into the fundamental technologies required to achieve the targeted level of performance by employing a fishbone diagram technique (see Fig. 4). Now students can see the connection between the science and engineering principles that they have studied and their application to a practical design problem.

Critical thinking is also an important part of *active learning*; it encompasses the entire process of obtaining, comprehending, analyzing, evaluating, internalizing and acting upon knowledge and values [23]. A person who thinks critically can

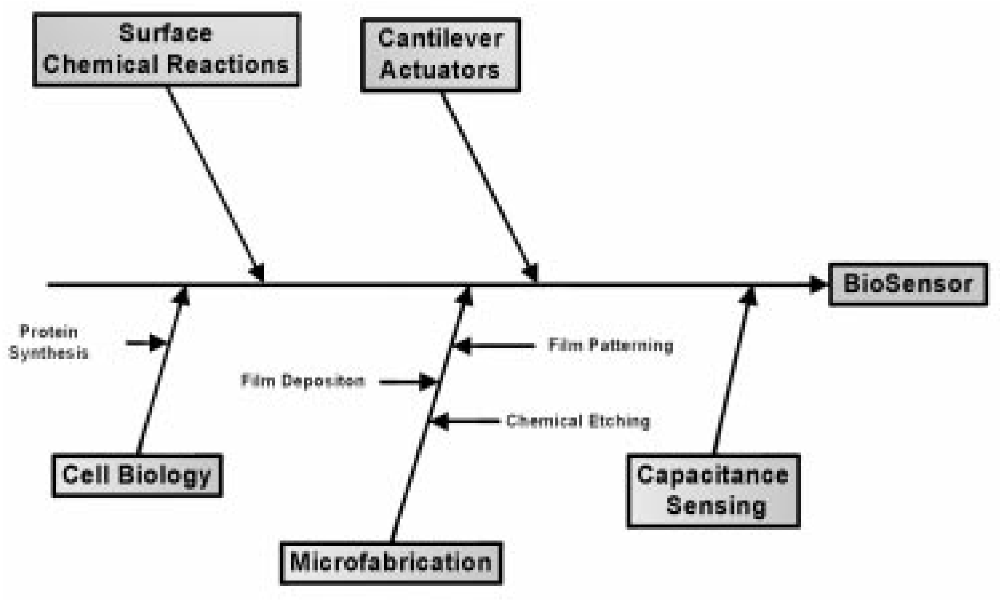

Fig. 4. Fishbone diagram relating engineering principles to a design problem.

ask appropriate questions and gather relevant information. They must then efficiently and creatively sort through this information, reason logically and come to reliable and trustworthy conclusions. Some of the key components of critical thinking include:

- Identifying problems and clarifying issues
- Focusing on relevant topics and methods
- Manipulating data and statistics
- Analyzing arguments and identifying assumptions
- Using logical reasoning and avoiding logical fallacies
- Considering your teammate's point of view
- Anticipating the consequences of one's actions

Overall, the design team should apply critical thinking throughout the design process. This will provide students with the opportunity to assess the impact of their design solutions on society and consider the benefits versus the risks. In addition, the global social and ethical impacts of technology should be discussed along with their environmental impact [24].

INTEGRATING DESIGN INTO THE CURRICULUM

Educators have established that there are considerable advantages when design activities are integrated throughout the undergraduate learning experience [25]. The challenge is to develop a systematic method for introducing design that parallels the skills that engineering students are assimilating as they progress through their undergraduate courses. During the first year it can provide a relational foundation for the math, chemistry and physics that students are often struggling to master [26, 27, 28]. Over their second and third years it can provide a vehicle for learning to apply the fundamental principles of engineering and in the fourth year it can be put into practice through their senior capstone project. Moreover, design cannot be effectively learned through short-term problems of limited scope that constitute the traditional one- or two-week laboratory experiments. Longer-term projects based on authentic and practical applications requiring students to collaborate to achieve solutions should serve as the foundation for applying the design process that has been outlined in this article. Importantly, assessing the ability to practice design is a difficult task, but tools are available, including portfolio assessment, cognitive maps and a 'freewriting' technique that captures the evolving design strategies employed by students [29].

Peter Senge (1990) says that the core disciplines necessary to build a learning organization are personal mastery, mental models, *team learning*, shared vision and systems thinking. He defines team learning as the process of aligning and developing the capacity of a team to create the results its members truly desire. It also builds on personal mastery, for talented teams are made up of talented individuals [30]. Team learning is vital because teams, not individuals, are the fundamental learning unit in modern organizations. Unless teams can learn, the organization cannot succeed. Teams transform their collective thinking; they learn to mobilize their energies and actions to achieve common goals and, thereby, draw forth an intelligence and ability greater than the sum of the individual members' talents. The team must identify the technology required to solve a problem and the design solution must reflect the collective expertise of all of the team members. Students should learn to discuss and debate to achieve a consensus before taking action; such dialogue can transform individual thinking into collective solutions. Design activities can serve as an excellent opportunity for students to learn and practice teamwork. In an effort to encourage students to learn more about teamwork, many courses are team-taught by a group of faculty. This often results in each faculty member merely conveying a set of different learning objectives; however, it is often left up to the students to try and correlate the information. A better approach would be to place students into a learning team, with faculty serving as guides and advisors to help direct them to the information required to solve their design problems. Faculty should only serve as facilitators, helping students to formulate practical solutions and challenging the results of their analyses.

At Cal Poly State University (San Luis Obispo, CA) we have embarked on a journey that incorporates a design experience into our Materials Engineering student's first year. During their first quarter, students are given a set of functional requirements for a vacuum system and they explore the process of developing a design solution and testing it to see if it meets their specifications. The fundamentals of pressure measurement and control are blended with the process of machining, welding and selecting commercially available components. During their second and third quarters, students study applications that involve *service learning* [31], where their design efforts will meet the needs of their local community on a voluntary basis. This process helps foster civic responsibility and enables them to see the impact of their design beyond the classroom. One such project involved the need for potable drinking water in rural communities around San Luis Obispo and, hence, the design of a water purification system. In a third-year course, students explore the optical properties of materials and are challenged to design fiber-optic cables that will be utilized in a system for evaluating the optical properties of various materials. They explore the fundamental principles of refractive index, total internal reflection, absorption, transmission and interference through traditional laboratory exercises. Then, as systems engineers, they integrate this knowledge into a design solution that includes the fabrication of fiber-optic cables which channel light from a remote source to a sample and send the resulting optical signal to a spectrometer for spectral analysis. Their design experience enables them to develop an understanding of cleaving, stripping, epoxy and polishing optical fibers along with a familiarity of tolerances associated with specifying the necessary materials and components. They learn to develop CAD drawings that are properly documented for the fabrication processes required. Design experiences such as these can be incorporated throughout many laboratory sessions associated with foundational materials science and engineering courses. They can provide both an opportunity to explore the design process as well as provide students with an opportunity to practice the principles of science, math and engineering.

In this paper, the design process has been characterized and contrasted with the scientific method. Design has been introduced as a complex decision-based activity with the common thread that requires the integration of science and engineering to produce a result. Pedagogies such as activity-based learning, team-learning and top-down learning practices have been recommended as tools that can enable students to learn to practice design. In addition, methodologies have been proposed for integrating design throughout the engineering curriculum.

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