Toward a Philosophy of Engineering: The Role of Representation

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According to an old Chinese proverb, "If you want to feed a man, give him a fish. If you want him to be able to feed himself, teach him how to fish." In engineering education today, we are doing a great job feeding our students vast amounts of information. Through mathematics courses, they learn how to calculate, in computer courses they master the art of programming, and they cram facts and theories into their heads in their science classes. But are we, as engineering educators, teaching our students how to fish, to use the knowledge we give them? Do we provide our students with a framework to guide how they organize and utilize the knowledge they acquire in their undergraduate education? I would argue that the true hallmark of a professional is that he or she possesses intellectual autonomy; while a professional may work with others, he or she must be able to decide for themselves exactly how to apply theory and information to solving problems. In engineering education, we need to be sure that our students learn to fish, to think for themselves.

Hence, a key task for humanities and social sciences in engineering education is to give students insight into the ways in which knowledge about technology is generated, validated, and organized. Engineering students need to learn how engineers, inventors, and other technologists learn about the material world and how they use this knowledge to analyze situations, solve problems, and design new devices. It is not enough to know the equation; to use the equation; one needs to know how equations represent the natural world. In other words, undergraduate students need a theory of engineering--or more precisely, a philosophy of engineering.

In teaching a first-year communications course to engineering students at the University of Virginia (UVa), I have developed a theory that argues that engineers gain insight into the material world by representing it using pictures, numbers, words, and computer simulations. This theory is based on ideas several fields including philosophy (John Locke), science studies (Bruno Latour), history of technology (Eugene Ferguson), and cognitive science (Donald Norman). In this paper, I will outline this theory by developing six propositions. In laying out these propositions, I will touch on the ways in which this theory helps us to define engineering as a distinct profession and I will provide examples from my course.

Before turning to the propositions, let me offer a word about my communications course. All undergraduate engineers at UVa are required to take TCC 101, Language Communications in a Technological Society. In my sections, I challenge the students to think about the nature of engineering by having them build a robot car kit and then prepare a series of writing and speaking assignments related to the robot. The writing assignments include maintaining an idea notebook, revising the kit's assembly instructions, and preparing an illustrated technical description. The students also work in teams to design an improved robot, draft a patent application, and prepare a proposal for manufacturing and marketing their improved versions. To hone their speaking skills, the student teams present their patents and manufacturing proposals before the class. By combining this hands-on exercise with communications assignments, this course helps students to appreciate the range of activities (design, analysis, patenting, and cost calculations) that constitute engineering, and it prepares them to appreciate the variety of courses they will take over the remainder of their undergraduate education. (Carlson and Peterson, 1996)

I. To represent is to know/To know is to represent

Within this course, my approach to philosophy of engineering starts with a model of human understanding. Like the English philosopher John Locke (1632-1704), I would argue that humans know the material world because of the sensations we experience through our five senses. However, unlike Locke, I do not think that these sensations are automatically converted into information about the world; instead, we convert incoming sensations into reliable knowledge by comparing them with information or representations stored in memory.

Notably, many cognitive scientists today would argue that humans make comparisons between sensations and stored information by visual and not verbal means. In order to make sense of incoming sensations, individuals generate some sort of picture in their minds--a mental model--and then try to fit the incoming sensations to that model. This mental model does not have to rigorous or formal--in many cases, it is a fleeting image--nevertheless, these mental models are what we use in thinking.

In this view of human understanding, memory plays a key role in relating incoming sensations with mental models. But as we are well aware, human memory can be weak and faulty. As a result, Locke advocated that humans enhance their memory by using external aids--notebooks, sketches, and models. By writing things down or drawing pictures, individuals can store information that can then be studied and analyzed. Ryan Tweney (1991) has argued that Locke's ideas about notebooks inspired Michael Faraday to maintain a series of notebooks through his career as an experimenter. For Faraday, to know something about electricity meant that he was able to represent it in his notebooks; he had a mental model of the experimental phenomenon when he was able to capture it in a notebook entry.

I phrase this proposition as duality to suggest that there are two points about human thinking. First, as argued above, thinking involves the process of using representations to convert sensations into reliable knowledge—representing is knowing. However, once we have created representations out of the sensations, we able to continue thinking by changing and altering the representations in our mind. We are able to take action in the world because we can use knowledge to represent the world in a variety of ways—knowing is representing.

This proposition applies obviously to engineering. For the most part, engineers do not wrestle directly with the forces of Nature (Unlike Superman, they do not bend steel with their bare hands). Instead, engineers are able to understand and control forces because they are able to picture or represent them. (Ferguson 1992) By manipulating these representations--which may be numbers, symbols, pictures, or words--engineers are able to identify the patterns in natural forces and to predict the behavior of these forces. Significantly, representations offer a real advantage to engineers (or other professionals) in that representations are easier to manipulate than actual objects or forces in the world; it's a lot easier to change a set of equations representing, say an airplane, than it is to build an entirely new plane. Thus, what makes an engineer different than technician or craftsmen is that the engineer is able to generate and manipulate abstract representations of the material world.

II. There are many different kinds of representation--using words, pictures, and numbers—and all offer valid insights.

It is important to recognize that humans can use a variety of different representations to make sense of the world. To understand, say, a rose, we can use words to write a description or poem, we can visually represent it using photographs, sketches, or diagrams, and we can make all sorts of measurements using numbers. We can even make a virtual rose by modeling it on the computer. What is important here is that different types of representations can convey different kinds of information about the material world, and all of this information is valid. While our engineering students must develop a high degree of skill in manipulating numerical representations of the material world, they need to be aware that numerical representations—either data or equations-- do not always capture everything we need or wish to know about a particular phenomenon.

In discussing this proposition with my students, I often point out that different professions use different kinds of representation to make sense of the world. Lawyers, for instance, depend primarily on words to understand the law and society while architects rely heavily on drawings. Indeed, what makes engineers unique among the professionals is that they must be able to work fluently with words, pictures, and numbers. For an engineer in different situations, he or she must be able to do the calculations, prepare diagrams or plans, and write reports.

III. We gain insight when we use two or more representations together.

Another characteristic of human cognition is that humans seem to do better when they get more than one representation of something in the material world. A picture may be worth a thousand words, but human understanding jumps by an order of magnitude when we get a picture with a few well-chosen words.

On a sensory level, we often learn more from a live performance because we are both hearing and seeing the presentation; we are receiving input from both our ears and our eyes. In terms of documents, it is apparent that humans frequently absorb more information when there are pictures to accompany the text; one negative example is how frustrating it is to try and assemble a kit using text-only instructions. And in technical drawings, we often need to see several views--top, profile, and plan--in order to visualize an object in our mind's eye. These examples underline the importance of using several representations when we are communicating technical information.

Moreover, in the field of science studies, Bruno Latour (1987) has argued that scientists and engineers often make discoveries by collecting and representing data in a variety of ways. They gain new insights by looking at where the different representations coincide and where they deviate from each other. As Thomas Kuhn (1970) observed years ago, new science often springs up around the anomalies--where the new data doesn't match the prevailing theory or framework.

IV. All representations are incomplete, but this provides an advantage.

This proposition takes us to the essence of representations in human thinking. At first glance, it may seem that human cognition should be enhanced by complete representations. Would we not be able to understand more, analyze more, if our representations were complete?

To think about this proposition, I ask my students if they would like to have a full-scale map of the world. After a few moments, most students decline the offer, realizing that a full-scale map of the world would be the same size as the world and that they would not be able to store or handle it. The students quickly realize that what makes a map a useful representation of the world is that certain information has been left out. In order to scale the map down to manageable proportions, the mapmaker has had to leave out all kinds of details, but in so doing, the mapmaker is able convey essential information about the relationship between geographical features.

In his studies of how people solve problems, Donald Norman (1993) has found that a key to problem solving is to identify a representation that allows the individual to strip away distracting details and to think about the relationship between different elements. As an example, Norman describes how people can use pencils to explain an automobile accident; with the pencils serving as the cars, people can focus on the direction and speed at which the vehicles were moving. What is powerful about representations, then, is that they allow us to concentrate on selected aspects of a problem. Representations are useful because they allow us to sift through the details and identify the key pattern, the pattern that makes sense of the problem at hand. As Herbert Simon (1981) once said, "Solving a problem simply means representing it so as to make the solution transparent."

V. Representations are used for both communications and thinking (cognition); hence they are both shared and personal.

Clearly, representations using words, pictures, or numbers are the coin of the cognitive realm. We use them to capture information from the outside world and to make sense of that information.

To facilitate thinking and problem solving, then, engineering students should obviously study and acquire a variety of representational techniques. They should learn how to represent problems using equations, diagrams, and computer models. They should acquire a mastery of the written and spoken word, and if I had my way, engineering students would still learn how to draw and sketch free-hand. In so doing, students should reflect on which representational techniques work best for them--do they gain more insight by making a sketch? Do they find some computer graphics packages more congenial than others? In studying inventors such as Alexander Graham Bell, Thomas Edison, and Nikola Tesla, Michael E. Gorman and I found that one secret of their creativity was that these men were continually honing their representational skills, looking for more effective ways of sketching their ideas or building models. These inventors sought representations that were congenial to their style of thinking. (Carlson, 2000)

Because they are intimately related to how an individual thinks, representations can get highly personal. Most art historians believe that Leonardo used his reversed writing to protect his ideas from the prying eyes of apprentices and rivals. Faraday's notebooks are filled with tiny, nearly indecipherable sketches depicting the relationships between electric and magnetic fields. As long as the representation works for the creative person, then it doesn't really matter if it makes sense to anyone else.

However, the creative act is not just about thinking profound thoughts in solitude; it is also about sharing the new discovery, invention, or design with others. Hence, as a creative person moves from thinking to sharing an idea, he or she must realize that others may not understand the representations they have been using. Thus the task in communications is often finding modes of representation that make sense to others, that are shared by both the creative person and the audience.

For engineers, it is crucial to be able to differentiate between personal and shared representations. For a new design to be accepted by others, it must make sense to various audiences. One telling example of this in the classroom comes with group projects. Frequently, as a student group discusses and modifies the robot car, they will develop drawings that reflect their discussions. Because they have reached consensus within the group about what the drawings represent, they then proceed to show the same drawings in their presentations to the whole class. Often, however, the group is dismayed to find out that what was obvious to them is not all apparent to the larger audience; their drawings do not convey the improvements on which they worked so hard. Hence, students need to learn not only how to think on their own with representations that they find congenial, but they must also learn which representations work with various audiences.

VI. Communicated representations work best when they utilize patterns that the audience finds familiar or can recognize.

A key task, then, of teaching communications to engineering students is help them to identify and use familiar rhetorical patterns. Humans are able to communicate complex ideas to one another not only because they have a shared language but also because we have shared ways of organizing information. From an early age, children in various cultures learn not only words but also the conventions by which stories are told, information is organized, and lessons conveyed. On one level, these patterns include such obvious things (for Westerners at least) as the fact that we read from left to right and top to bottom. On another level, these patterns include logic and evidence--that in engineering and scientific papers, we expect the argument to move from hypothesis through experiment to results to interpretation.

I suggest to my students that technical documents are often hard to read not because the information itself is inherently opaque but because the author has not employed patterns that make the information accessible to the audience. Instead of using obvious patterns that are familiar to the reader, the author employs patterns that force the reader to work harder to understand what is being said. Rather than reducing the cognitive load, poor writing frequently increases the load on the reader by forcing him or her to sift through the information and reorganize it in their minds. Hence, I work closely with my students not only to find the right words for their papers but also to employ effective patterns for presenting information in the text as well as in their illustrations.

Conclusion

All professions, I would argue, need to be engaged in the process of defining their philosophy. For a professional to exercise his or her expertise in the world effectively and ethically, they need to be aware of the nature of their knowledge. Professionals should have a conception of how they acquire reliable knowledge about the world and how they apply knowledge in the course of solving problems

What I have tried to suggest here is a first pass at what might constitute a philosophy of engineering. Like other professions, engineering gains power over the material world through representations. By being able to use numbers, words, pictures and computer programs, engineers are able to identify patterns in the forces of Nature and predict the behavior of those forces. Engineering is unique in that its practitioners must master all of these modes of representation and use them together in problem-solving design.

For engineering education, the idea of representation constitutes a significant opportunity at creating an overarching framework. For decades, students have taken a variety of courses in the engineering curriculum and we engineering educators have not offered them an explanation as to how all these pieces fit together. By introducing the idea that engineering is about using representations to make sense of the world, we provide the student with a framework that brings together their math, science, engineering, and communications courses since in essence all of these disciplines offer the student ways of thinking about and representing the world. The notion of representation might very well serve as a catalyst for focusing and revitalizing engineering education for the new century.

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