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Review Article

Engineering Epistemologies

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Abstract: The basic point made here is there is no such thing as engineering knowledge *simpliciter*. What engineers need to know depends on what subfield of engineering they are working in? There is, however, a commonality among the various subdisciplines of engineering; it is a method revolving around the use of feedback loops. I argue that the use of feedback loops is common to all forms of human reasoning and it is the hallmark of rationality.

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1 Introduction

Engineering is not a single, unified field. But, across the many sub-disciplines of engineering such as civil, chemical, computer, etc., there are some commonalities, such as a focus on design, concerns about the production process, the use of theoretical principles and knowledge drawn from the sciences, and efficiency, among others. Each of these requires a special kind of knowledge such that it is incorrect to talk about engineering knowledge *simpliciter,* hence, the title of this essay. With a little reflection, it is not hard to see that what one needs to know in order to design an artifact is not the same as what one needs to know how to produce the artifact. We also hear a lot about how engineers are problem-solvers and practical. Well, many disciplines are engaged in problem-solving and a lot of theoretical work in engineering has little to do with being practical. Now that all that is out in the open, let's turn to epistemology.

2 Epistemology

"Epistemology," as used in philosophy, is a term that identifies the area of philosophy concerned with knowledge. Epistemologists attempt to answer such questions as: What is knowledge? What are its identifying criteria? Who has it? The history of epistemology in the West goes back to the ancient Greeks. Within that history a long-standing battle has played out between two different accounts of knowledge, one as certainty, the other as justified true belief. There are other accounts, but these two have dominated the scene for over 2000 years. There are, clearly, problems with both traditions. For example, can you ever be certain about anything? What does it mean to be certain? On the other side, how does one justify a belief? Do you need to know the belief is true or is it enough for it to be true whether you are aware that it is or not? What is a belief? One of the major problems common to these two older traditions was the focus on knowledge as the product and possession of an individual. In an attempt to avoid dealing with this issue, i.e., do individuals produce and possess knowledge, the pragmatist tradition (interestingly, founded by C. S. Peirce, a chemical engineer by profession) distinguishes between an individual's internal epistemic state and the conclusions of a community of investigators. Whether or not Jones knows something can be determined by whether or not Jones is successful in his actions based on the claims he makes. What counts as Knowledge with a capital K, on the other hand, is what the community of investigators comes to agree on. This account can be understood by analogy with the peer review system. A paper is submitted to a journal where it is then sent out for review by experts in the field. The experts send their evaluations to the editor who decides whether to publish it or not. If the paper is published, its finding and methods are open to the scientific community for critique. If the dust finally settles, and all objections are met, the results of the paper are added to the body of Knowledge in that field. This account also accords with the view that science is a self-correcting system, allowing for revision of both the content of knowledge and the criteria by which a claim is admitted to the house of Knowledge. Knowledge, then, is the product of a social process, one constantly undergoing revisions as new techniques, instruments and materials come on line.

3 Engineering knowledge

The question of what constitutes engineering knowledge is not new. It has, however, become increasingly of interest as philosophers and engineers have started coming together to discuss topics of mutual interest, most recently under the rubric of the Forum on Philosophy, Engineering, and Technology (fPet). As philosophers, engineers, and others come to a greater understanding of the domains of each other's disciplines, learning their vocabularies and methodological approaches and the kinds of problems each is interested in, more sophisticated discussion of questions like "What is engineering knowledge?" have begun to take place. Several different accounts of engineering epistemology have emerged. For instance, there are attempts to find out what engineers think engineering knowledge is by interviewing individual engineers. There are attempts to codify engineering knowledge by engineering discipline, e.g., civil engineering. There are philosophical attempts to define "engineering knowledge" in the abstract. In the context of engineering education, the question becomes "what do engineering students need to know?", both by discipline and in the abstract. These issues are considered in depth in Part II of *Engineering Identities*[1] There is some consensus regarding engineering as a problem-solving activity. There is some consensus on the need for some scientific knowledge in some engineering projects, there is no consensus on engineering method. Positions range from Billy Koen's "All is heuristics"[2] to Vincenti's big-problem-is-a-set-of-little-problems approach (see below)[3].

3.1 Systems engineering

In *Designing Engineers*[4], Larry Bucciarelli opens the topic of engineering knowledge with some musings on the question "Do you know how your phone works?"

> *Indeed, from my own observations, I can claim fairly confidently that there is no single individual alone who knows how all the ingredients that constitute a telephone system work together to keep each of our phones functioning. There is no one "maker." Instead, inside each firm, there are different interests, perspectives, and responsibilities - corporate planning, engineering research, production, marketing, servicing, managing - and consequently different ways in which the telephone "works." (p.3)*

Bucciarelli sees the telephone, not as an object, but as a system, hence systems engineering. While each of us may have some command of a part of the system, no one has control of the entire system. But, by approaching the question "Do you know how your phone works?" this way, he plays into the hands of those who conceive of knowledge as something possessed by individuals, since the question concerns what *you*, the actor charged with solving this part of the puzzle, know. However, he also, at the same time, seems to be buying into the sense of knowing as successful action – for to know your part in the system is to be able to do something particular to your role. But, and this is now our question, is this approach appropriate to understanding engineering epistemologies? In short is the systems approach helpful? Yes, it is if we are buying into the pragmatist account of knowledge and knowledge construction, where individuals don't create knowledge by themselves, knowledge is the product of a complicated community process. Individuals may *use* the knowledge that the system has produced, but can only be said to know something metaphorically.

We began with the assumption that there are multiple practices under the heading of "engineering". We are also advocating a pragmatist approach to epistemology, where Knowledge is the product of the endorsement of a community of investigators, making the production of Knowledge a social process. Individuals do not possess knowledge *per se*, they act on the basis of habits formed over time[5] using an iterative process involving background beliefs, values, goals and a feedback loop for the purpose of updating these various components[6]. No matter what the job, people are usually trained to do their part (except perhaps college teachers who are rarely given any pedagogical training before being thrown into a classroom).

3.2 Problem solving

In his seminal *What Engineers Know and How they Know It*[3], Walter Vincenti, originally trained as an aeronautical engineer, lays out a fairly general schema for how engineers approach their projects. Essentially, the project is conceived of as a big complicated problem. The first step in solving this problem is to break it down into smaller problems, each of which requires a specific kind of expertise to solve. Problem solving in this text is a team activity. Each team starts with a set of background knowledge and a goal and then proceeds to lay out strategies to accomplish the goal - and when a line of attack fails they employ a feedback loop to go back and check their background knowledge, their assumptions, etc. and try again. When each group finishes solving their problem, they start rebuilding the project and should a solution to one sub-problem fail to fit with the others, up comes the feedback loop.

3.3 Feedback loops

Elsewhere[7] I have argued that this approach to problem-solving is the basic form of reasoning we employ when trying to solve any problem. If there is such a thing as the scientific method, this is it, and it is also how I deal with finding the proper product when I am grocery shopping. If I can't find an item on the shopping list, I ask myself what it to be used for is and can I find an appropriate substitute. Not being averse to substituting items requires some background knowledge and the willingness to gamble a bit. If I return home and am told "No, No! I need X specifically", then I realize my background knowledge was incomplete and I head out to return the item and find another store which hopefully has the right thing. It might even be argued that this way of thinking is the commonality that links engineering epistemologies, if there are such. The main differences among them are two. First, what is the level of abstraction at which the subject is being approached? Second, what is the subject matter?

3.4 Levels of abstraction

In the field of Engineering Science, the level of abstraction is very high. Further, the range of areas studied vary greatly.

Areas of specialization available vary from one institution to another. In general, areas of specialization available may include, but are not limited to, aerodynamics, biomechanics, bio nanotechnology, biosensors and bioelectronics, composite materials, continuum mechanics, data mining, electromagnetics of complex materials, electronic materials and devices, experimental mechanics, fluid mechanics, laser-assisted micro manufacturing, met materials, micro fabrication, microfluidic systems, micro electromechanical systems (MEMS) and micro-opto-electromechanical systems (MOEMS), nanotechnology, neural engineering, non-destructive testing or evaluation, nonlinear dynamics, optoelectronics, photonics and plasmonics, quantum mechanics, solar-energy-harvesting materials, solid mechanics, solid-state physics, structural health monitoring, and thin films and nanostructured materials.[8]

As the name suggests, this area attempts to develop the science of engineering in these areas, which to many seems odd. Isn't there a significant difference between science and engineering? Isn't trying to develop a science of engineering similar to trying to develop a science of art? But the key point here is that Engineering Science is conceived of as an interdisciplinary field, using the principles of various sciences to frame investigative principles for engineering purposes, i.e., for the purpose of making things. This means that the scientific principles must be presented in a manner that makes applying the feedback loop method available.

The second area in which the feedback loop method suggests commonalities among the different engineering fields, is that it is not restricted to one field of engineering. Vincenti uses examples from aeronautical engineering because he was trained as an aeronautical engineer, but he clearly thinks this method applies across the board.

This, according to Vincenti, is how engineers go about solving problems. Once they solve the problem, they may be said to know how to solve that problem - but it is a funny kind of knowledge since it is really consists of a set of fragmented problem solutions, each requiring its own solution. In short, this is an account of one kind of *method* engineers employ to solve problems and it seems to be a general kind of method. So, the question here is whether or not possessing a method constitutes knowledge? And this brings us back to the old distinction between knowing how and knowing that, a distinction first introduced by Gilbert Ryle[9].

Surely, the method Vincenti relates is a case of knowing how - specifically, knowing how to attack a problem. But this form of knowledge, in order to be usable, requires background knowledge involving a lot of knowing that. For example, if you are a structural engineer being asked to complete the specifications for a very *avant guarde* museum, think of the ceilings in the main area of the East Wing of the National Gallery of Art in Washington, D.C., you need to know, first, that different materials can handle different stress loads, e.g., that steel is not good for bridging long spaces without support.

3.5 Engineering education

How one acquires the necessary background knowledge forms the basis for much discussion in engineering education. And one would think that examining how engineering students are taught to think about the problems in the areas they are studying would reveal different kinds of knowledge. I teach at an institution with a large engineering school. When engineering alumni return and come see me they report that 90% of what they were taught in classes they took was irrelevant to doing the job they were hired to do. Their successes depended on finding good mentors with lots of real world experience who were willing to take the time to show them how it was done. This then raises the thorny questions of what they are taught in school and why. It also suggests that reviewing a variety of approaches to the question "What is engineering knowledge" is probably a waste of time.

What engineering students are taught is pretty much a function of what their instructors were taught, updated to accommodate relevant developments. In this respect their instructors are much like instructors in other non-engineering fields, with perhaps an unreasonable emphasis on mathematical rigor. What they are not taught is how to look beyond or outside the engineering parameters.

This is not to say that many involved in engineering education are not aware of this issue. Olin College has been a leader in instituting a liberal arts-based engineering curriculum and the use of teams. Larry BucciarelIi has spear-headed a nation-wide effort at curriculum reform using historical case studies to illustrate fundamental engineering principles. I have suggested that at my institution engineering students be allowed to take only one engineering course a semester for the first two years of their curriculum and the remainder be courses in the arts, humanities and social sciences.

Consider the following thought experiment. Assemble three 12-person teams of undergraduates and give them what is essentially an engineering problem to solve, let's say: design an automobile manufacturing plant to be built in Brazil. Have Team A be composed of only engineering students. Team B will have two parts, half engineering students and half drawn from the arts, humanities and social sciences. Team C will be comprised of only students drawn from the arts, humanities and social sciences. Give them six weeks to complete the project and then have a fourth team, D, composed of automobile company representatives select the winner after the solutions have been presented and defended. My guess is that Team B will be the winner.

Returning to the knowing how/that dichotomy, it seems that knowing how to apply the method Vincenti outlines may be the key to successful engineering, i.e., designing, building, etc. But that leaves open the question of how to get the job done. In the spirit of Bucciarelli, who recognizes that different steps in the manufacturing process, from concept formation to marketing, require different knowledge bases, it is not clear to me that asking an environmental engineer to develop a new eco-friendly automobile will result in a successful product. And that brings us back again to the notion of teams and why Team B will be the winner in the contest to design an automobile plant in Brazil.

One thing that is being emphasized in engineering education is the importance of teamwork. Unfortunately, engineering training in teamwork usually falls short of developing the kinds of skills engineering students will need on the job. The kinds of teams they are exposed to are usually teams of students in the same major working on a class or senior project. What they are not exposed to are interdisciplinary teams. Take the example above of asking an environmental engineer to design an eco-friendly automobile. No one should expect her to know how to do that all by herself. She is going to need a team composed of individuals with a variety of skills, some with knowledge of the factors involved in propulsion, others in the physicality of the machine, interior design, creature comforts such as Wi-Fi connection, aesthetics, etc. In the case of the automobile factory, members of the team will have to know how to site a factory, how to maximize the production process, what materials will be needed and how to obtain them, the availability of skilled labor, environmental impact, etc.

But more important than having various experts on the team is their ability to talk to one another. In some respects, a field of expertise is characterized by the language its practitioners use. Just because many of the members of the team are engineers doesn't mean they speak the same language. This is a direct function of the lack of homogeneity in the general area of engineering. What makes for a good team is the ability of the members of the team to communicate in meaningful ways across disciplinary boundaries. Just consider, as Bucciarelli notes[4], one member of the team may be out of the marketing department. Now that poses a communication problem, not just because he and the other members of the team speak different languages, but because they have different goals. The goal of the marketing individual is to make sure the product will sell while each engineer is interested in maximizing the features with which he or she is most concerned to make a maximalizing product.

If there is a single feature of engineering activity that stands out, it is the formalization of the feedback loop. Virtually every textbook on design has multiple diagrams illustrating the design process with distinct feedback loops. But the interesting thing here is that we all employ feedback loops in daily life. The height of irrationality is doing the same thing over and over again with failure the result each time. When an action results in something we didn't expect we usually step back and review why we thought what we did should have the result we expected, looking for bad assumptions, factual inaccuracies, poorly articulated objectives, etc., in short, we employ a feedback loop.

4 Conclusion

The bottom line here is that it is misleading to speak of engineering epistemologies. It is not that there are different ways of knowing, depending on what kind of an engineer you are. Different engineering specialties are individuated by what they know, not how they know. And, as we have noted, because of a myriad of factors, such as academic battles over which area of research is the most important, the level of abstraction gets confused with how to solve real world problems. Abstract knowledge is of no value if it can't be applied.

That is why good engineering and good science are so close to common sense. The most accurate account of scientific method is that science proceeds by trial and error. But that is how we make our way around in the world and that is what good engineers do. Once again, this does not speak to Knowledge, but to method. To speak of engineering epistemologies is to address what specific engineers need to know to successfully complete their job as part of a team. It is not so much a way of knowing as it is the specifics that can be utilized in solving a problem, much of which comes from hands-on doing. It is not different ways of knowing, but different things known, either individually or as a group. That is why it is not uncommon for an engineer to go online with "do you know how to ….?"

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