

Philosophy of Engineering: What It Is and Why It Matters

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Abstract: Philosophy of engineering is a growing field whose ideas should be considered by the engineering community. Because of the heuristic nature of engineering practice, philosophical thinking, including reflection, is an important way to enhance engineering judgment. This paper reviews a broad range of sources to give the reader a place to start when considering philosophy of engineering. Topics addressed include how engineering education and practice are different from other fields, how designers of non-prototypical engineered systems deal with a significant amount of uncertainty, and how aesthetics fit within an overall notion of engineering quality, among other topics. The references in this paper are not inclusive of all writings on philosophy of engineering, but they are a significant sampling that should help the reader begin delving into the relevant literature, and from there to go as deeply or as broadly as desired.

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Introduction

The Structural Engineering Institute (SEI) of ASCE established its Engineering Philosophy Committee in 2009. Since that time, the Committee has worked toward its mission to “advance and serve the structural engineering profession by exploring and expounding its philosophical foundations and implications.” This paper is part of the effort to perform that mission. The objective is to introduce engineers to philosophy of engineering, especially as it applies to the theory and practice of design of *non-prototypical* engineered systems, for which prototype testing is not possible and thus uncertainties are significantly increased (Blockley 1980).

With this objective in mind, we will approach the philosophy of engineering from a relatively pragmatic standpoint. History of engineering will appear only as necessary to explain specific philosophical ideas, and we will mention the philosophy of science only in passing. We hope to contribute to the development of a philosophy of engineering that looks at *how* we do engineering and *why* we do engineering the way we do. In the end, a philosophy of engineering must help to advance engineering practice, including the process of engineering design.

In this regard, the public view of engineers is often that we are not reflective; we just do what needs to be done and then move on to the next project. There is much truth to this view, but the fact that SEI sanctions an Engineering Philosophy Committee shows that there is some recognition that engineers benefit from being more reflective and philosophical. Consequently, if this paper ultimately leads the reader to find just one of the references and read it, then we will have succeeded in achieving our modest initial objective.

It is our belief that a reflective and philosophical engineer will be a better engineer. Schön (1983) has argued that practitioners in a range of fields can become better at what they do by incorporating reflection into their professional lives. We are not talking here about continual reflection, but reflection at appropriate points while work is in progress and about work that is already complete. Upon finishing a project, engineers should think back on what they did, how they did it, and what they could have done better. Certainly most of us do this at some level, but making it a regular practice can prove useful in enhancing our performance as engineers. Such reflection may also lead to deeper thinking about the fundamentals of our engineering practice, examination of our implicit philosophy of engineering, and an opportunity to make it more explicit.

Today there is not yet a well-established discipline known as "philosophy of engineering," although there is progress in that direction (e.g., Goldman 2004; McCarthy 2008), and there are certainly writers, both engineers and non-engineers, who are writing about engineering in a philosophical way; e.g., Florman (1987, 1994, 1996), Layton (1971), Petroski (1982, 1994, 1997, 2006, 2010), and Vincenti (1990). This paper will introduce many of these writings, within the limits described above. Our discussion is structured by dividing engineering philosophy into a series of overlapping subtopics, beginning with the basic question of how engineering should be demarcated from other fields, and ending with a discussion of what constitutes quality in engineering. While this arrangement is by no means absolute, we hope that it will resonate with the reader's personal experience.

One branch of philosophy that is largely omitted from this paper is ethics, primarily because engineering ethics is – somewhat paradoxically – a much more mature field than philosophy of engineering in broader terms. There are already several textbooks in widespread use (e.g., Fleddermann 2011; Harris 2014; Martin and Schinzinger 2005), and an entire journal is dedicated to *Science and Engineering Ethics*. Nevertheless, the ideas discussed in this paper have certain ethical implications that should not be neglected (e.g., Schmidt 2013a).

Hopefully this paper will stimulate and enhance how engineers think about the philosophical basis for their own practice. Engineers are nothing if not practical, and the members of the Engineering Philosophy Committee sincerely believe that examination of engineering philosophy will have positive practical ramifications.

Demarcating Engineering

Engineering uses the knowledge provided by science, but despite the widespread assumption to the contrary, engineering is not simply applied science. Moreover, the aims of engineering are different; while science aims for knowledge, engineering aims for useful change. Specifically, Goldman (1984, 1990, 2004) points out that science is supposed to be concerned with necessity, certainty, universality, and abstractness. It seeks objective *knowledge-that* of timeless truth that is based on reality, for the purpose of intellectual contemplation and understanding. By contrast, engineering is characterized by contingency, probability, particularity, and concreteness. Engineers rely on subjective *knowledge-how* and opinions that are derived from personal and historical experience, with the goal of willful action and use.

The National Academy of Engineering (NAE) puts it as follows (NAE 2005):

Science had its origins in the work of scholars supported by wealthy patrons and in the personal work of wealthy aristocrats who looked to the stars to understand the origins of the universe and life or who were intrigued to understand the natural physical, chemical, or biological world around them. Engineering had its origins in the trades, in the effort to make and implement something useful, first for military purposes and later for civil purposes.

Even engineering science is different from science. The primary reason is that engineering science was developed to assist in the design of engineering artifacts (Allen 2008). For example, one significant way that thermodynamics taught as physics differs from thermodynamics taught as engineering science is that design requires the use of control volumes, whereby the artifact of interest is separated from the rest of the world (Vincenti 1990). At the design stage, we are interested in the behavior of our artifact, and we are not interested in the region outside our design except as far as it produces effects on our artifact that we need to consider in our design. Thus the only connection to the world is at the input and output points. Similarly, a control volume from engineering mechanics is a free-body diagram (Bucciarelli 2003).

Furthermore, statics and mechanics of materials were specifically developed for the design of artifacts: “From the earliest times when people started to build, it was found necessary to have information regarding the strength of structural materials so that rules for determining safe

dimensions of members could be drawn up” (Timoshenko 1983). From the outset, statics and mechanics of materials were meant for design (engineering), not for gaining knowledge about nature (science).

Regarding the engineering process, the popular perception – even among engineers themselves – is that engineering is the rational solution of technical problems. However, it is rarely so straightforward in practice, because the formulation of engineering problems and their solutions is inherently indeterminate. They tend to be ill-structured (Simon 1973) or even "wicked" (Rittel and Webber 1969), which means that they do not yield definitive answers just by following rigid rules. Instead, engineering involves reconceptualizing a complex situation to facilitate analysis; it includes problem definition, not just problem solution. Engineers must convert all the relevant design criteria — which are often dictated by clients, codes, and other external authorities — into the language, so to speak, of engineering.

Because of the goals involved in engineering, the knowledge required is also unique. For example, Vincenti (1990) identified six categories of engineering knowledge:

- Fundamental design concepts - the operational principle of a device and the normal configuration that is commonly agreed to embody it best.
- Criteria and specifications - the specific, quantitative objectives for a device that have been derived from its general, qualitative goals.
- Theoretical tools - mathematical formulas or calculative schemes, whether grounded in nature or based mainly on successful past experience.
- Quantitative data - universal constants, properties of substances, physical processes, operational conditions, tolerances, factors of safety, etc.
- Practical considerations - information learned mostly on the job and often possessed unconsciously, rather than in codified form.
- Design instrumentalities - procedures, ways of thinking, and judgmental skills by which the process is carried out.

The distinction between knowing-how to accomplish specified goals, in contrast to knowing-that something is true, was first popularized by Ryle (1945) and one of the types of knowing-how is engineering judgment. As Davis (2012) puts it, "One who otherwise knows what engineers know but lacks 'engineering judgment' may be an expert of sorts, a handy resource much like a reference book or database, but cannot be a competent engineer." Nelson (2012) and Schmidt (2012) further discuss how engineering differs from other disciplines.

Engineering Education

Another distinction is manifest in how engineers are educated (Bulleit 2012b). Ferguson (1992) and Seely (1999) note that engineering education has changed noticeably over the past century. Prior to World War II, engineering still exhibited much of its origins from the trades. Engineering students had shop classes and had to do a significant amount of drafting. Engineering science was secondary to art and practice. That was beginning to change even in the early 20th century, and the process accelerated after World War II. By 1965, most engineering programs had moved away from the art and practice of engineering and made engineering

science the primary basis of engineering education. More recently, this trend has begun to reverse, and art and practice have been brought back into the curriculum; e.g., introduction to design relatively early, and a capstone design project near the end.

All but a few engineering programs are accredited by ABET, which defines the types of knowledge needed by an engineer. These include science and mathematics, but there is an increasing proportion of non-technical content and a requirement for a capstone design experience. Reflecting the growing importance of non-technical skills, the ASCE Body of Knowledge 2 (BOK2) identifies nine non-technical areas versus eleven technical areas (ASCE 2008). BOK2 demands a deeper level of achievement in the technical areas, but the relative importance given to non-technical areas is a strong sign that the profession believes that an engineer should be much more than a person with strong technical skills. Partly because of the addition of non-technical skills, BOK2 now suggests a master's degree or equivalent for an engineering trainee.

The NAE has considered the possible state of engineering in 2020 and the implications for engineering education now (NAE 2005). The NAE speaks to all branches of engineering analyzing current conditions and historical trends in engineering education. Being a high-level report, the NAE does not provide details like BOK2, but rather guiding principles and ideas that universities, professional organizations, and accreditation agencies can use to reform engineering education. Three major changes that the NAE identifies as important in the future are: (a) engineers will have greater involvement in the civic arena; (b) system-level perspectives will become more important, such that engineers will need to break out of their subspecialties; and (c) engineering is a rapidly changing field requiring engineers to be able to learn new skills and acquire new knowledge continually. BOK2's emphasis on non-technical skills and advocacy of a master's degree as a baseline requirement are consistent with these recommendations.

These efforts recognize that an engineering education can never teach the graduate all that needs to be known (knowing-that), nor can it teach the graduate all the aspects of the craft that will be useful in practice (knowing-how). It seems that the best approach is to provide a foundation of fundamental knowledge while cultivating the engineering way of thinking. Through a career of professional practice, the engineer will fill in the necessary knowledge gaps and develop the necessary engineering judgment.

While no student can be expected to graduate with the judgment of a senior engineer, an education that provides each student with meaningful practice with these skills will allow them to develop such judgment subsequently and progressively. For example, *heuristics* (Koen 2003), discussed later in the paper, can be introduced through codes of practice (Bulleit 2012b). Some aspects of the code may be different from the concepts learned in the fundamental engineering science courses. Students need to interact with these parts of the code in order to become comfortable with applying these potentially unjustifiable rules.

Visualization also forms a strong component of engineering education. Ferguson (1992) describes three kinds of sketches that are useful for students to master: the thinking sketch, the prescriptive sketch, and the talking sketch. The thinking sketch is how an engineer visualizes ideas for designs. These sketches are intended only for that individual, and are not typically

shared with others. For example, much of what we know about the ideas of Leonardo da Vinci comes from his notebooks, which consist primarily of thinking sketches. A prescriptive sketch, which may be drawn to scale, is used to transmit detailed information to the person who is preparing the actual plans for the artifact. These sketches can be drawn by hand or created using software, but however they are prepared, they must convey everything necessary to create final plans for the design. The talking sketch is used to transmit ideas back and forth between engineers who are discussing ideas related to a design. Engineering students are expected to be able to draw prescriptive sketches as design summaries in homework and projects, and they are exposed to talking sketches almost daily once they enter their engineering courses.

Models

Arguably, we cannot access reality directly or even “mirror” it in an exact way. Instead, both philosophically and cognitively, our interaction with reality is always mediated by models. The form of a model may be conceptual, mathematical, computational, or physical, and all of these forms are used in engineering (Alvi 2013a). All models are simplifications of reality, incomplete and abstracted representations of phenomena that emphasize selected features of reality and deemphasize or ignore others (Weisberg 2013), analogous to the various types of maps that we develop to suit various purposes.

Some key goals of modeling in engineering include *explaining*, *predicting*, and *controlling* the behavior of engineered systems; developing *intuition* and associated engineering judgment; *instructing* in both academic and practice settings; *designing* and *evaluating* engineered systems; and providing a context for *experimenting* and *collecting data* in order to develop models further. These diverse possible goals make it clear that there will rarely be a single, one-size-fits-all model that is best for all objectives for a given engineered system. Instead, a range of possible models can typically be developed, so explicit modeling goals need to be specified, including priorities assigned to goals in order to guide the tradeoffs that must be made. All of these considerations highlight the fact that models are essentially heuristics (Koen 2003).

In terms of their development, models are based on objective empirical phenomena and aim to represent them, so discovery is involved. However, as modelers we choose the form and goals of our models, and we likewise evaluate our models according to criteria of our choosing; so a creative and subjective element is involved as well. This has the implication that due to *bounded rationality* (Simon 1957) – limited availability of information, limited cognitive capacity, limited time to complete tasks, and a variety of associated cognitive biases – instead of optimizing or striving for “perfect” models, in practice we *satisfice*, continuing our modeling efforts only until “good enough” results have been achieved (Simon 1996). Indeed, it can be argued that satisficing necessarily applies to all aspects of engineering practice, including design.

Because models are always imperfect representations of phenomena, modeling is also subject to uncertainty. To help reduce uncertainty, models can be tested and calibrated against empirical data over some domain, but such testing will always be finite and generally will not cover all cases for which a model may be used, and may not even include the full model – just certain components of it. In other words, we generally cannot avoid going from the known to the unknown, and we are faced with the philosophical *problem of induction*: no series of observations can *causally prove* that a particular observation will follow – there is always an

assumption, “an act of faith,” in making such an inference (Popper 1959). In civil and structural engineering, a further challenge is that designers rarely get feedback on how well their models represent the specific full-scale projects that they have designed. It may be argued that adequate performance of those projects, both individually and collectively, validates the associated models; but substantial safety factors prevent models from truly being put to the test and thus “falsified” unless they are highly inaccurate.

These issues present a genuine challenge with regard to evaluation and validation of models, but some pragmatic steps can still be taken (Alvi 2013a):

- Treat models as “guilty until proven innocent.”
- Identify the assumptions underlying a model explicitly and in writing.
- Conduct independent peer reviews and checks during and after model development.
- Evaluate models against experience and judgment.
- Use visualization tools.
- Perform sensitivity studies of model parameters.
- Compare results from multiple diverse models and investigate any substantial discrepancies.
- Develop and apply a strong understanding of engineering theory.
- Understand the assumptions and limitations of computational models, rather than using them as “black boxes.”

Further pragmatic suggestions related to modeling are provided by Alvi (2013a), MacLeod (2005), Dym (1997), and Dym and Williams (2012) for structural modeling; Wood (2004) for geotechnical modeling; and Wainwright and Mulligan (2013) for environmental modeling.

Uncertainty

Much of what is required for design of non-prototypical engineered systems is driven by the way practicing engineers must deal with the significant uncertainties that are inherent in the process (Bulleit 2008). These uncertainties can be separated into two broad categories: *aleatory*, related to luck or chance, and *epistemic*, related to knowledge (Der Kiureghian and Ditlevsen 2009). Elms (1999) looks at the problem as the “three enemies of knowledge,” which are *ignorance*, lack of technical knowledge that a designer should know; *uncertainty*, essential knowledge that is missing, but whose absence is recognized; and *complexity*, which means that there is no reliable way to predict behavior. The impact of complexity on the design of non-prototypical engineered systems is also discussed by Bulleit (2013b).

Any of these categorizations has an impact on how engineers cope with the various types of uncertainty and the way we think about each type. Bulleit (2008) used the first broad category above and then considered five broad sources of uncertainty – time, randomness, statistical limits, modeling, and human error – to examine the way in which structural engineers deal with it. Some uncertainties are explicitly addressed by codes of practice (e.g., Ellingwood et al. 1980; Galambos 1992; Allen 1992), some through quality control measures, and others in implicit ways that we often do not think about much, such as heuristics (Koen 2003). Vick (2002) has discussed the use of subjective probability in engineering decision-making. This approach,

employing expert opinion as well as formal analysis, is necessary where uncertainties are great, such as large geotechnical projects and complex systems, and engineers need a better understanding of the concept of complexity as it relates to engineered systems. For example, many non-prototypical engineered systems are complicated, but not complex. Bridges and buildings are examples of complicated systems, but the effects on these systems may be driven by complex systems interacting with them (Bulleit 2013b).

One type of complex system involves human interactions in the operation of the system (Alvi 2013b), and typically system responses are tightly coupled. This means that small failures in the system can lead to actions, both human and automatic, that cause more small failures and more compensating actions, which eventually lead to cascading failures causing system collapse (Perrow 1999). Examples of this type of system include petrochemical facilities, the power grid, and nuclear power plants. Examples of failures of these types of systems include the Three Mile Island nuclear plant failure in 1979 (Perrow 1999); the Space Shuttle Challenger disaster in 1986 (Delatte 2009); and the Midwest power failure in 2003, caused by a tree contacting a local power line in Ohio. In many of these cases, safety devices that were supposed to reduce the possibility of a failure were instead part of the cascading event.

Complex adaptive systems are a second type. These systems are defined by interactions among agents, as well as interactions between the agents and their environment; the agents are also adaptive, allowing the system to evolve (Alvi 2013b). Large organizations, human societies, and the human/natural environment are examples of complex adaptive systems, which can exhibit behaviors that have come to be called "black swan" events (Taleb 2007), which have large but unpredictable impacts, but are rationalized in hindsight to have been foreseen. Two examples are the attack on the Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma on April 19, 1995, and the destruction of the World Trade Center on September 11, 2001. In the same vein, as early as 1921, Knight (1948) discussed the effects of "unmeasurable uncertainties" on the investment community, and a recent U. S. Secretary of Defense spoke of "unknown unknowns." The division between complicated and complex is a gray region, but whenever an engineered system becomes an interacting part of human society, the possibility of unpredictable – and thus highly uncertain – events becomes very real (Pool 1997; Taleb 2007; Alvi 2013b).

Codes of Practice

Codes of practice are one of the key ways that engineers of non-prototypical systems reduce uncertainty in design (Bulleit 2008, 2013b; Bulleit and Adams 2011). Codes provide a link between technology and society (Allen 1992), and a way for society to help ensure its safety (Elms 1999). However, the level of complexity of a code of practice has an impact on the uncertainty in the design (Elms 1999), because an overly complicated code can lead to errors in interpretation and implementation by designers. On the other hand, a code that is too simple increases the probability of conceptual errors, particularly errors in which relevant aspects of the system are ignored or are inadequately considered in designing the system (Addis 1990).

From an information theory perspective (Shannon and Weaver 1949), the provisions in a building code can be viewed as an encoding of some portion of the design knowledge space. The designer's job is then to decode this encoded design knowledge. Viewed this way, it is

apparent that enhancements to a building code can come from doing a better job at encoding the design knowledge, enhancing the decoding process, or a combination of the two (Bulleit 2012a; Bulleit and Adams 2011). Many arguments for simplifying design codes simply advocate reducing the portion of the design knowledge space that is encoded (Hess 2009).

Over the years, codes have become more explicit, and implicit provisions are often overshadowed. Explicit requirements are also called prescriptive requirements, and implicit requirements are often called objective-based requirements. Certainly implicit directives are more difficult to enforce, but a large amount of explicit requirements does not necessarily lead to safer structures. It is often difficult to decide how heavily to weigh the importance of these two elements (Shapiro 1997; Coeckelbergh 2006). If building codes are too explicit, innovation can be hampered, and engineers may be viewed as simply instruction-following technicians (Coeckelbergh 2006). Furthermore, too many explicit requirements, facilitating relatively straightforward use of the knowledge base, make it difficult to legitimize the profession (Shapiro 1997). Also, as the number of explicit requirements increases, so does the noise in the code (Bulleit 2012a). On the other hand, if codes are too implicit, then proper enforcement of construction requirements for safe structures can be difficult to perform, and the likelihood of a structural failure may be increased (Elms 1999). Codes of practice place a limit on the range of the judgment space in which professionals can work (Shapiro 1997), and this judgment space requires both explicit and implicit requirements. The appropriate balance between them is difficult to maintain due to the different constituencies that established the code in the first place and affect its ongoing evolution.

Writing over twenty years ago about design codes, Galambos (1992) reached a conclusion that may be even more true today: “In the opinion of this writer, the present generation of codes has probably reached the limit of tolerable bulk and complexity. More of this complication will make the codes a modern dinosaur. Future design codes should concentrate on providing general principles and deemphasize detailed requirements.” The present code structures are generally complicated encodings that force an engineer into a difficult decoding process, thus increasing the chance of human error.

Heuristics and Judgment

As described previously, science is different from engineering in a number of attributes. Just as science is widely perceived as an especially systematic approach to *knowing*, so engineering could be conceived as an especially systematic approach to *willing* (Schmidt 2013b). This becomes evident by simply comparing the scientific and engineering methods.

Scientists observe natural phenomena, propose hypotheses in an effort to explain them, and conduct careful experiments to test their theories. Although the will is implicitly involved, the *intellect* is primary, because the goal is ideal: additional knowledge that is supposed to be objective. By contrast, engineers use "state-of-the-art heuristics to create the best change in an uncertain situation within the available resources" (Koen 2013). Although the intellect is implicitly involved, the *will* is primary, because the goal is pragmatic: a particular outcome that is usually subjective.

Heuristics are thus central to engineering practice. In this context, a heuristic is "anything that provides a plausible aid or direction in the solution of a problem but is in the final analysis unjustified, incapable of justification, and potentially fallible" (Koen 2003). Familiar examples include rules of thumb and factors of safety, which usually work even though they do not constitute timeless truth embedded within the essence of reality. Heuristics cannot be "proven" in the absolute sense, but their use is legitimately warranted, frequently on the grounds of successful past implementation (i.e., induction).

Each individual engineer has a unique collection of relevant heuristics at his or her disposal, along with "meta-heuristics" for selecting which heuristics are most appropriate in a given set of circumstances. When these are combined, they constitute what Addis (1990) calls a *design procedure*, which is analogous to a hypothesis in the scientific method. However, the term is somewhat misleading, because a design procedure does not lead inevitably to a particular outcome. In fact, Addis notes "that it is possible to produce very similar structural designs using different design procedures and that similar design procedures can lead to significantly different structures – there is no logical connection between the two."

The bottom line is that engineering is not deterministic; it routinely requires setting priorities and selecting the best way forward from among multiple options when there is no one "right" answer (Addis 1997). Consequently, attempts to apply a theory of *rationality* to engineering are likely misguided (e.g., Kroes et al. 2009); *intentionality* seems like a more appropriate concept (Schmidt 2013b). Tradeoffs are inevitable, and not just for technical reasons — there are often budget constraints, legal restrictions, or political considerations that come into play. These kinds of tradeoffs – both technical and non-technical – are at the heart of the design process, and therefore constitute the essence of engineering intentionality (Goldman 2010, Alvi 2013b).

This being the case, how do engineers ultimately make good decisions that are not simply arbitrary? Presumably, they exercise the faculty that they constantly take for granted but rarely try to explain: engineering judgment, which is "the *disposition* (including the ability) to *act* as competent members of the discipline act" (Davis 2012). It is neither arbitrary nor algorithmic, and the reference to peers as the benchmark is consistent with the legal notion of the standard of care: "that level or quality of service ordinarily provided by other normally competent practitioners of good standing in that field, contemporaneously providing similar services in the same locality and under the same circumstances" (Kardon 1999).

Engineering judgment can be viewed as a specific form of practical judgment – what the ancient Greeks called *phronesis* – which gives it an ethical dimension, as well as technical. It is manifested as "the cultivated capacity to make [particular judgment 'calls'] resourcefully and reliably in all the complex situations that they address," as well as "an ability to recognize situations, cases or problems ... and to deal with them adequately and appropriately" (Dunne 2005). It also constitutes "a reliable capacity to respond to risk with the appropriate attitude" (Ross and Athanassoulis 2010).

If we think of the heuristics just described as *engineering* heuristics, with which most engineers are comfortable working, then we also need to consider other kinds of heuristics—the ones that are innate to us as humans. For example, Kahneman (2011) describes a model in which humans

have two thinking modes: System 1, in which we think quickly, also called intuition; and System 2, in which we think slowly, also called analysis. Since humans over history have often lived in dangerous environments, System 1 tends to take precedence if we do not consciously apply System 2. If the bushes move in the jungle, it is better to run than to stand and think about running). Those who ran often ran from nothing, but those who stopped to think about running eventually got eaten. System 1 uses heuristics to do its job, and these heuristics can produce biases. Furthermore, these biases cannot typically be avoided unless System 2 is consciously activated. Thus, unlike engineering heuristics, which are visible, System 1 heuristics work automatically and unconsciously (Bulleit 2013a).

To make matters even more challenging, System 2 is lazy and defaults to accepting System 1 decisions. An implication is that engineers must be careful when working in environments that are new – intuition works no matter what, and you will feel confident in your intuition even when you should not be confident. As Kahneman (2011, p. 212) says, “Subjective confidence in a judgment is not a reasoned evaluation of the probability that this judgment is correct. Confidence is a feeling, which reflects the coherence of the information and the cognitive ease of processing it.” Ferguson (1992, p. 193) similarly states, “If we are to avoid calamitous design errors as well as those that are merely irritating or expensive, it is necessary that engineers understand that such errors are not errors of mathematics or calculation but errors of engineering judgment – judgment that is not reducible to engineering science or to mathematics.”

In contrast to the somewhat pessimistic “heuristics and biases” model of Kahneman and others, which tends to focus on errors in judgement and decision making, Gigerenzer et al. (1999) present a more optimistic model of “fast and frugal” heuristics, emphasizing the adaptive utility of heuristics for efficiently and effectively dealing with the complexity of real-world environments. From this perspective, heuristics are not merely a suboptimal means to cope with “bounded rationality” and satisfice, but can even sometimes enable *better* decisions than are attainable using the rational analysis of System 2, through selective use of the information that is most relevant and useful in each context.

The relative merits and empirical foundations of these models of heuristics continue to be debated among researchers, but key conclusions for engineering are that use of heuristics is clearly unavoidable, and that such use entails both benefits and risks.

Competence and Expertise

Extending our discussion of engineering education, how do engineers learn the heuristics that are essential to their practice and develop the judgment to use them properly in a given set of circumstances? One study determined that at least two-thirds of the knowledge used by structural engineers on a daily basis is “practice-generated,” rather than “historically established”; i.e., gained by means of experience instead of formal education or reference materials (Gainsburg et al. 2010). Consequently, the ongoing trend toward ever more detailed and prescriptive codes and standards seems like a well-meaning but ultimately misguided attempt to ensure competent engineering by providing an increasingly elaborate set of instructions. Can engineering really be reduced to rule-following all the way down?

Research into the nature of genuine competence suggests otherwise. Dreyfus and Dreyfus (1986) used a phenomenological approach to study "unstructured" problem areas that, like engineering, "contain a potentially unlimited number of possibly relevant facts and features." They produced a plausible model of skill acquisition that includes five distinct stages: novice, advanced beginner, competent, proficient, and expert. The higher levels can only be attained through extensive experience and are characterized by less rational deliberation and greater emotional involvement.

The Dreyfus model is consistent, up to a point, with Koen's heuristics (Koen 2003) and Addis's design procedures (Addis 1990), as well as use of heuristics in general. Formal education primarily imparts rules for the novice, such as how to calculate the maximum moment on a simply supported, uniformly loaded beam. Engineer interns become advanced beginners during the first few years of their careers by picking up on maxims such as "least weight does not equal least cost" and their implications. Over time, engineers develop conscious and unconscious ways of decomposing and solving problems based on what has and has not worked for them. These are not necessarily processes that the engineers can communicate in words; they have become integral to who they are and how they operate. Competence is achieved when an engineer is capable of focusing intuitively on what really matters and converging relatively quickly on a viable solution.

However, an important constraint to acknowledge is that competence is domain-specific. Even experts inevitably revert to the behavior characteristic of novices and advanced beginners when confronted with unfamiliar circumstances. They must fall back on more formal rules and maxims, because they lack the kind or amount of experience that would enable them to discern the appropriate course of action on their own. The challenge is that humans have a natural tendency to overestimate their own capabilities (i.e., overconfidence bias) – a cognitive deficiency, not an ethical one – which can lead them to undertake assignments in areas where they are not genuinely competent (Kruger and Dunning 1999).

Quality

When engineers develop options for consideration or make a decision based on a certain amount of information, how do they choose the best option and make the best decision? Billington (1983) has described how the best structural designers of the past achieved a balance of efficiency, economy, and elegance. Considerations such as durability, constructability, and other constraints could be added to these three. One other term that is often used is *quality*, which – depending on one's viewpoint – may comprise all or some subset of these criteria.

Quality can be thought of in two ways: the end (the system itself) or the means (the design process). We can say to ourselves, "I want quality in the form of the structure and the assemblage of materials," or "I want to design well, I want quality engineering decision-making." These may overlap. For example, how does the description or idea of the final artifact as "quality" create a path for working towards it? After all, civil and structural engineers are typically designing one new and novel artifact.

Consider what the philosophers of antiquity thought on the subject of quality, along with beauty and art. These concepts generally fall under the branch of philosophy called *aesthetics*. Aristotle (1976a) believed that one has to have a clear picture of the system first (the end) and simply work towards that: “He starts by forming for himself a definite picture, in the one case perceptible to the mind, in the other sense of his end – the physician of health, the builder of a house – and this he holds forward as the reason and explanation of each subsequent step he takes.” Furthermore, “Art indeed consists in the conception of the result to be produced before its realization in material.”

Aristotle continues, “The plan of the house has this or that form; and because it has this or that form, the construction is carried out in this or that manner. For the process of evolution is for the sake of the thing finally evolved, and not this for the sake of the process.” But how does one conceive of an end first? How does one know ahead of time that something will be good, correct, and well-proportioned, or efficient and economical? Here we learn from Aristotle that good design is done by those who can take a complex task and split it up into smaller and simpler problems.

Plato believed that what is central to the production of beautiful artifacts is one’s ability to understand the nature of *measure*. When good engineers have a vision, or an end at which to aim, they have a command of measure, what we now may think of as proportion. For example, the structural engineer, according to Plato, must know the nature of measure or proper proportioning of structures (artistic as well as scientific): “Basic to any art, is the art of measure without which there can be no art at all” (Hofstadter and Kuhns 1976). To know the proper size of a column, the proper proportion of a window, or “the proper organization of language in a poem, is to command the art of measurement” (Hofstadter and Kuhns 1976).

Measure is thus essential to quality and is the fundamental principle that defines quality. “There are accomplished men, Socrates, who say ... the art of measurement is universal, and has to do with all things” (Plato 1976). So if we think that we have succeeded in achieving the proper form by creating something well-proportioned, how do we know that we are right? How do we judge quality?

Aristotle believed that quality can be judged by the average of the many, the intermediate. “Every art does its work well – by looking to the intermediate and judging its work by this standard” (Aristotle 1976b). He agrees that science may have a hand in the judgment of art: “The chief forms of beauty are order and symmetry and definiteness, which the mathematical sciences demonstrate in a special degree” (Aristotle 1976c).

We know that the design of engineered systems combines objective knowledge (e.g., engineering science) with more complex and subjective decision-making (e.g., heuristics). Problems encountered by the engineers of non-prototypical systems are complex and nuanced, and require experience and judgment to sift through multiple design ideas. Engineering design is thus more of an art than a science (Ferguson 1992, p. 194):

Necessary as the analytical tools of science and mathematics most certainly are, more important is the development in student and neophyte engineers of sound

judgment, an intuitive sense of fitness and adequacy. No matter how vigorously a science of design may be pushed, the successful design of real things in a contingent world will always be based more on art than on science. Unqualifiable judgments and choices are the elements that determine the way a design comes together. Engineering design is simply that kind of process. It always has been; it always will be.

So the focus is on both the state of the art in science and the art of design; or as Allen (2008) says, “Design has to be completed by second-order thinking about perception, guided by stylistic practice and aesthetic feeling.”

Nelson (2013) has focused on the art of design with ideas on how to improve as an individual engineering designer. They range from the importance of drawing hand sketches to reasons why structural engineers should learn how to weld. He describes why physical models are important, why having materials in your hand is critical, and ideas for better communication. He also discusses the importance of worrying and why drawing at a one-to-one scale is meaningful. All of these ideas are intended to lead to quality design. Similarly, Addis (2000) has given two lists, one for “structural criteria of excellence” and one for “non-structural criteria of excellence.” His goal is to help engineers work toward a value system that includes excellence in design; i.e., quality.

All of these ideas are good, but how do structural engineers design beautiful works of “structural art”? We should turn to the best structural engineers of the 20th century for clues. Nervi (1956) states the importance of structural honesty or correctness: “Every improvement in the functionality and the technical efficiency of a product brings out an improvement in its aesthetic quality ... there is no doubt that any product of high efficiency is always aesthetically satisfying. In the field of architecture, in which functional, statical, and economic needs are intimately mixed, truthfulness is an indispensable condition of good aesthetic results.” Therefore, one answer among many is that structural honesty is necessary to create beautiful artifacts; not that anything that is efficient is beautiful, but that for something structural to be beautiful, it needs to be honest – efficient, economical, and/or elegant.

In the forward to Nervi (1956), Salvadori reminds the reader: “Nervi’s results are not achieved by consciously trying to meet aesthetic demands, but by tackling the fundamental structural problems from the outset, and giving them an obvious and clearly articulated solution. Beauty, says Nervi, is an unavoidable by-product of this search for satisfactory structural solutions.” This is similar to the idea that goals are not important to the designer since quality simply emerges from doing honest hard work (Nelson 2013).

Pirsig (1974, 1991) examines quality and builds an entire metaphysics around it. The metaphysics of quality, partially an alternative to Western culture’s ingrained subject/object dualism, creates a holism that links the designer to the material itself. While quality can only be defined after an artifact is judged, Pirsig suggests that quality is really only found in the present, by working with and being part of the material world – the difference between being a spectator and a person who engages the work thoughtfully and with complete attention.

How does one enter the right frame of mind to do quality work? It might be the time when the mind is at ease in the task at hand, such that it no longer feels like a task but an extension of ourselves; it becomes part of us, a feeling of closeness, connectedness. This state has been described as *flow* by Csikszentmihalyi (1988). There are moments while doing engineering that could be described as being in the flow state, such as modeling, sketching, or hand calculations. He describes how flow is exhibited by mountain climbers: "The mountaineer does not climb in order to reach the top of the mountain, but tries to reach the summit in order to climb," which means that climbing is intrinsically rewarding regardless of whether the goal is accomplished. Climbing is about the exhilaration of the task at hand, not some reflection on an accomplishment. Design is the same way, and it is through flow that quality can also come about.

Conclusions

Philosophy of engineering is a growing field whose ideas should be considered by the engineering community. Because of the heuristic nature of engineering practice, philosophical thinking, including reflection, is an important way to enhance engineering judgment. The authors have reviewed a broad range of sources to give the reader a place to start in considering philosophy of engineering. Certainly the references in this paper are not inclusive of all writings on philosophy of engineering, but they are a significant sampling. The reader can use the references as a way to begin delving into the relevant literature, and from there to go as deeply or as broadly as desired.

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