# Mind the Gaps: Engineering Education and Practice

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***Abstract**: Efforts to reform engineering education by improving the relevance of learning for engineering practice have not yet been very successful. Analysis of published literature demonstrates that engineering education is predominantly based on a model of engineering practice represented by technical problem-solving and design. However, this model cannot explain many observations of engineering practice like the amount of time that engineers interact with other people. This paper presents a description of engineering practice based on detailed observations of engineers. The new description sees engineering as a human performance that relies on distributed expertise. The paper briefly discusses how changes in pedagogy, assessment and accreditation are needed to close the gap between engineering education and practice.*

## 1. Introduction

This paper starts by reviewing reports of misalignment between engineering education and practice, and then explores why this apparent misalignment is a major problem. Analysis reveals that academics seldom understand engineering practice beyond design and technical problem-solving. A comprehensive model based on extensive observations and interviews with engineers reveals many hitherto invisible aspects of engineering practice. This model can explain why, for example, engineers remain involved with projects long after the design and problem-solving has been finished. The last part of the paper shows how the model explains the gap between engineering education and practice and points to education changes which will be needed to reduce it.

## 2. The gaps between engineering education and practice

Employers and others have described the gaps they perceive between engineering education and practice (Dillon, 1998; Florman, 1997; Pascail, 2006). Limited studies on the perceived effectiveness of novice (early career) engineers have shown weak if any support for the notion that grades awarded in engineering courses could predict effectiveness (Harvey & Lemon, 1994; Lee, 1986; Newport & Elms, 1997). The large gap between education and practice can also be traumatic for young engineers contributing to decisions by many to seek alternative occupations (Edward & Middleton, 2001).

Similar concerns led to fundamental changes to engineering education in the late 1990s. Completely new, outcome-based accreditation criteria were introduced worldwide based on the EC2000 model developed by ABET(2008). However, while these changes have provided some modest improvements, the apparent gap between education and practice seems as wide as before. In a survey to assess the effects of these accreditation changes, only about 50% of American employers thought that engineering graduates understood the context and constraints that govern engineering, and there was a majority assessment that graduate understanding had declined in the last decade (Lattuca, Terenzini, & Volkwein, 2006). This agrees with persistent feedback from employers in Australia that graduates lack appreciation of fundamental knowledge and engineering courses are misaligned with industry needs. Professional societies are currently pursuing further education reform agendas, mainly in response to these findings. For example, the American Society of Civil Engineers (ASCE) recently published an extensively revised Civil Engineering Book of Knowledge (or BoK)(American Society of Civil Engineers, 2008a) prompted by extensive consultation and surveys of their members(American Society of Civil Engineers, 2008b).

Detailed surveys of working time perceptions of novice engineers reveal that they report spending 60% of their time explicitly interacting with other people (Tilli & Trevelyan, 2008), of which about 32% is verbal (face to face and telephone calls) and the remaining 28% is in writing. These results agree well with several earlier research reports (Kilduff, Funk, & Mehra, 1997; Tenopir & King, 2004;

Youngman, Oxtoby, Monk, & Heywood, 1978, pp. p7-9). Given that young engineers are likely to spend more time listening than speaking, especially in training sessions and meetings, we can deduce that they spend between 20% and 25% of their time listening. Most written communication takes the form of requests or instructions to specify engineering work to be performed, for example the production of work packages and technical specifications. Only part of the need for writing is represented by formal technical reports. Technical presentations are relatively rarely reported in our fieldwork and interviews. Thus while engineering practice is dominated by informal listening and speaking, these communication skills are seldom even mentioned in engineering courses (Bauer & Figl, 2008).

## 2.1 How engineering educators see practice

Nearly all the literature on engineering education and practice reveals an overwhelming belief that engineering is all about solitary technical work: technical problem-solving and design. For example, Sheppard, Colby, *et al*(2006) in their article "What Is Engineering Practice?" argued that engineering "is focused on resolving an undesirable condition through the application of technologies" and therefore "the central activity of engineering work is solving problems" (p430). From this point, their discussion and comparison is centred on engineering as problem-solving. This reflects their respondents (academics and students) who said that engineering is about solving problems and therefore changing the world. Pawley (2009) recently reported similar results.

Tenopir and King presented a model of an engineer as an information processor in their book on engineering communication(2004, figure 3.1, p28). Inputs include time, information received, support staff time, computing equipment, instrumentation, facilities etc. Outputs include information created, information communicated (recorded information, interpersonal information), knowledge gained, etc. Unfortunately we learn little about why engineers adopt certain communication patterns from this simple model. For example, it would be useful to understand when and why engineers use certain kinds of specifications.

The ASCE BoK was written by a large panel consisting of academics and industry representatives: the former comprised a clear majority. There is only an implied problem-solving model of engineering practice in the document since there is no explanation in the document about what graduate civil engineers are expected to do in their daily work. Nor is there any mention that engineers deliver tangible results: engineers instead "develop ways" to do this "economically". Someone else, by implication, reads the documents and drawings and thus meets human needs.

Many who have contributed to design literature argue that engineering and design are almost synonymous. Even if engineering is more than design, there is a common perception that design is more important than other aspects, more complex, more difficult, and that everything in engineering starts from design (Coley, Houseman, & Roy, 2007; Dym, Agogino, Eris, Frey, & Leifer, 2005; Eckert et al., 2004; Ferguson, 1992; Petroski, 1994; Schön, 1983; Vincenti, 1990; Vinck, 2003).

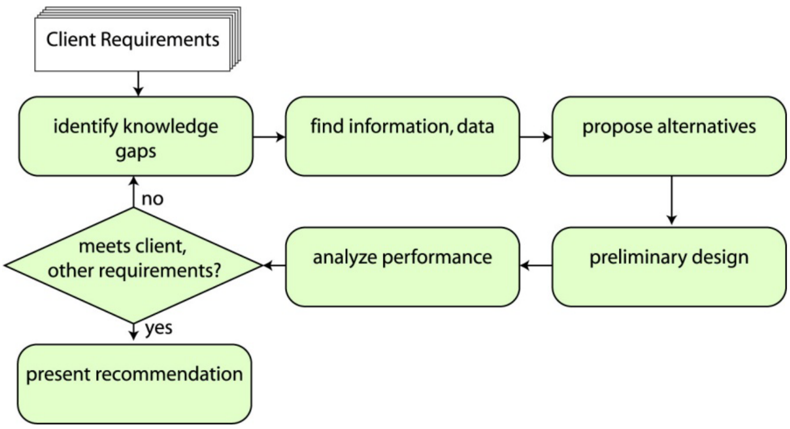


Figure 1: Example of engineering problem-solving approach, starting with a statement of client requirements. 'Other requirements' includes standards and regulations and, according to some, social needs and environmental constraints.

Many advocates of problem-based learning explain their approach as an analogy of engineering problem-solving which starts with the client requirements (Heywood, 2005; Savin-Baden, 2007). The instructor allows students to explore possible solutions and identify needs for further information. The students, working collaboratively, each perform their own research to fill the information gaps and then analyze the alternative solutions until one solution has been confirmed to meet the client requirements. The students then write a document presenting their recommendation and the analysis supporting their conclusions (Hadgraft, 2008). Just as there are those who claim that engineering education is supposed to educate designers, there are others who claim that engineering education is all about educating people to solve problems (Jonassen, Strobel, & Lee, 2006).

What we learn from this brief review is that there is a widely understood model of engineering practice among engineering faculty. This model sees engineering in terms of design and technical problem-solving. The end point for engineering is communication of the design or problem solution (both verbal and written) to 'the client', and sometimes to society at large. Social interactions and communication lie at the periphery of the core technical issues and, as a result, cling precariously to the curricular margins of engineering education.

## 2.2 Technical problem-solving model cannot explain practice

There are several weaknesses which are inherent in the technical problem-solving model. The first is that engineers can only change the world (Sheppard, et al., 2006, p430) if they also *deliver* the artefacts represented by their problem solutions and designs.

Many academics would see this as implicit and obvious, yet their model of engineering practice does not explicitly include this step. Another difficulty is that the model does not explain how engineers manage to eliminate most if not all errors from their solutions and still deliver the results on time when they can seldom do this in their university studies.

Another difficulty is that the technical problem-solving and design model cannot easily explain the consistently large proportion of time spent interacting with other people, and the relatively small proportion spent on solitary technical activity such as designing, technical problem-solving, or performing analytical calculations. The interesting observation that novice engineers spent the same proportion of their time on social interactions as more experienced engineers also presents a difficulty.

Here is a young mechanical engineer telling us about her contributions to the design and construction of an offshore oil and gas platform:

> *"My main task is the preparation of installation work packages for an offshore oil and gas platform near India. This involves gathering drawings, preparing procedures like welding, painting etc. Not the major installation jobs. Our team does all the completion bits, not heavy lifting such as installing the jacket and the top sides. We install cables, pipework and other minor items. This is multidisciplinary work – I have to prepare structural drawings, structural welding instructions and even electrical diagrams and cable documentation. I have to (describe in) detail everything that we need to tell the subcontractor to undertake the work. The latest area I have been looking at is cabling. I have to prepare specifications like the inspection and test plans."*

This work does not sit comfortably in the problem-solving model. Yet without this contribution, the platform would not be built in the way its designers intended and therefore could be noticeably more costly, hazardous, less productive and less effective than its owners expected. This is unquestionably the work of engineers, and no model of engineering practice can be complete unless this, and each of all the other aspects of work performed by engineers, can be recognized for their contributions to the whole.

# 3. Engineering Practice Beyond Technical Problem-solving

We have conducted extensive qualitative research studies on engineers in their workplaces. Full details appear in earlier publications (e.g. Domal, 2010; Han, 2008; Mehravari, 2007; Trevelyan, 2007; Trevelyan, 2010b). Data for analysis has come from over 120 interviews with engineers in all disciplines in Australia, India, Pakistan and Brunei. Triangulation data has come from several participant observation studies, published research on engineering practice, and quantitative surveys.

This research has lead to a new description of engineering practice that can explain observations such as the large proportion of time that engineers spend on social interactions.

The research revealed engineers organizing and coordinating production of the products and services that sustain nearly the entire human population of the planet: clean water, sanitation, shelter, long-lasting supplies of processed food, transport and telecommunication systems. It is the reliable and predictable delivery of products and utility services that creates social and economic benefits that sustain the raison d'être of engineering.

The engineers that we observed had little hands-on involvement in making products or providing services. The value of their work, therefore, was indirect, and emerged through the work of other people who do that. The ultimate value is obtained by the people who use the products and services. In other words, the value that arises from the contributions of engineers is created only through the actions of many other people, often far removed from the setting in which engineers perform their work.

Many of the engineers were providing information in the form of reports and designs, especially performance predictions or diagnoses. These contain information that reduces the level of uncertainty in the knowledge required to decide on some future course of action. With less uncertainty, there is less need to allow for additional resources or material to guarantee performance in the worst-case scenario.

## Engineering: A Human Performance

The main finding of the analysis, though much of the detailed evidence remains to be published, is that we can better understand engineering practice by reframing engineering as human social performance (Trevelyan, 2010b). We can only fully understand engineering if we understand how people think, feel, act, and interact as they perform it.

Taken together, the participants' accounts of their work coalesced into the following description of the overall performance through the process of detailed coding, analysis, re-reading, and synthesis. Each participant provided a view on their own part of the whole: none could provide a coherent description beyond their immediate experience.

Engineers think about physical and abstract objects governed by laws of science often described using mathematical formulations. Their aim is to re-arrange the objects so they perform some required function with desirable properties, yielding economic or social benefits for people. We can describe this thinking as 'technical'. Thinking is human and we need to recognize that even technical accomplishment is limited by human capabilities.

Engineers rely on interactions with other people: practice is based on distributed expertise. Engineering involves more than 150 different aspects of practice and specialized knowledge, even within one discipline, most of it unwritten and difficult to transfer to others. Learning about all of this is beyond any one individual in a working lifetime: there is not enough time. Instead, engineers develop cooperative relationships with other people so they willingly and conscientiously contribute their expertise. Sometimes there is little or no overlapping understanding at the start, so helping others to learn and learning from others is always a part of practice. Translation and negotiating shared meaning to enable understanding across different areas of expertise is part of this as well. Much of the expertise is contributed in the form of skilled performances. Engineering, therefore, is a combined performance involving, among others, clients, owners, component suppliers, manufacturers, contractors, architects, planners, financiers, lawyers, local regulatory authorities, production supervisors, artisans and craftspeople, drafters, labourers, drivers, operators, maintainers, and end users. In a sense, the engineer's role is both to compose the music and conduct the orchestra, without relying on formal authority. The distributed nature of expertise provides an attractive explanation for the large proportion of time spent on social interactions.

Engineering performance, like most human performance, is time, information and resource constrained. In engineering practice therefore, people have to allocate time and attention to satisfy many diverse demands. Seldom is there complete information available, and the information always comes with some level of uncertainty. One cannot predict nature completely (though we are getting better at it.) Rarely, if ever, did the engineers who participated in our study have extensive uninterrupted time to think and reflect. Engineering performance means seeking the best use of personal time and material resources.

Engineers have to be teachers. They need to ensure that everyone involved in producing products or providing utility services has sufficient understanding of the essential features that will create value to ensure that they are faithfully implemented and reproduced by other people through planning, detailed design, production, delivery, operations and maintenance. The people who use the products and services need to make effective use of them to gain their full value. In other words, engineers have to explain, often at a distance and through intermediaries, how the products of their work need to be designed, built, used and maintained most effectively.

We observed that every engineering venture follows a similar sequence. Engineers we interviewed were usually working on several projects at the one time, each one at a different phase of the sequence.

1) Engineers attempt to understand and at the same time shape clients' perceptions of their needs, and work with clients to articulate requirements.
2) Engineers conceive different ways to meet the requirements economically, propose solutions using readily available components, and design special-purpose parts when needed.
3) Engineers collect data and create mathematical models based on scientific knowledge and experience to predict the technical and commercial performance of different solutions so that sensible choices can be made. Stages 1, 2 and 3 may be repeated with progressively more certainty, particularly in large projects, until prediction uncertainty can be reduced to match investors' expectations (Cooper, 1993, p. 109).
4) Once 'project execution' starts, engineers prepare detailed plans, designs and specifications of the work to be performed and organize the people and resources that will be needed.
5) Engineers coordinate and manage the work while it is being performed.
6) Engineers arrange for the decommissioning, removal, reuse, and recycling at the end of a product's life span.

The term 'engineering problem-solving' is often used in a sense that embraces phases 2 and 3.

Understanding that engineering is a human performance, we need to accept that human performance always involves a level of unpredictability, like nature. Given that the aim is predictable delivery of products and services, engineers need to know how to ensure that countless unpredictable performances by individual people produce results in a predictable way. Assessing risks and uncertainty, checking and review, technical standards, organization, training and procedures, coordination and monitoring, survey and measurement, teamwork, configuration management, planning, testing and inspection all form parts of engineers' techniques to contain human and natural uncertainty.

## Bridging the Gaps: Educational Implications

Any agenda for change has to build on current conceptions of engineering practice: trying to persuade engineering faculties or even students to adopt a different model is unlikely to succeed. An entirely different approach is needed. In the model of engineering practice presented in this paper, problem-solving and design remain as an important element of a much more complex process where the distribution of expertise and interactions between people constrain the solution space just as much as technical considerations. At the same time, the investment business context with risks and delayed returns shapes decisions based on engineering analysis. It is reliable delivery of tangible results for clients and investors that earns money and, while nearly all of this work is performed by other people, engineers have to provide the guidance and oversight necessary to achieve the predicted results. This requires three attributes:

1) Engineering relies on applied engineering science as well as rules of thumb to make accurate prediction and reduce uncertainty in predictions. Reducing risk and uncertainty enables safety allowances and contingencies to be reduced, reducing the overall capital and material requirements. Engineers, therefore, need to be able to apply business and engineering science effectively.

2) Engineering practice relies on 'tacit ingenuity' in order to make use of natural and man-made resources, components and materials and to exploit business opportunities. This, in turn, relies on extensive tacit knowledge and unwritten know-how carried in the minds of engineers developed through practice and experience.

3) Engineering practice relies on an ability to achieve practical results through other people, coordinating peers, negotiating shared understandings with peers, clients, contractors, suppliers, operators and end users. Engineers work as much or more by leveraging and coordinating the expertise of others as they contribute themselves. To do this, engineers need to be good listeners, learners, teachers and leaders.

Examination of any contemporary engineering education curriculum reveals that practically all of the formal instruction effort is devoted to engineering science, with little attention to business aspects. The other two attributes receive little more than token acknowledgement, and are often labelled as skills that cannot be taught at a university. The present curriculum, therefore, provides graduates with only one of the three required attributes and even that is incomplete: a three legged stool with only one partially completed leg.

One way to re-balance the education agenda is to recognise that attributes 2) and 3) above are not only valuable for engineering practice: they can immeasurably strengthen learning for engineering and business science.

A close examination of social interactions between engineers in the workplace reveals that there is a remarkable similarity with interactions reported in early studies of classrooms using cooperative learning methods (Brown et al., 1993). By adopting formal cooperative learning methods, engineering educators can improve learning in engineering science and develop social interaction skills that build the third essential attribute above. However, it is necessary to devote formal classroom time to develop the social skills needed for cooperative learning to work effectively (Johnson & Johnson, 2009). Training students to teach their peers will not only help them become effective engineers, but can also multiply the teaching potential within an engineering school (Trevelyan, 2010a).

Simple hands-on practical work in the context of formal learning can help students overcome their conceptual misconceptions with less need for feedback from faculty. By exploiting opportunities to link hobbies and part-time work experience with formal learning, students can learn to value tacit ingenuity and unwritten knowledge. Part-time work, in particular, with structured links to formal coursework, can provide a practical introduction to business science that is essential for engineering practice.

An exciting prospect emerges from this analysis. Building a deep understanding of engineering practice into the curriculum has the potential to greatly strengthen engineering education, particularly learning of the essential technical framework that distinguishes engineers without extra resources or study duration. However, faculty will need help to master what, for most, will be completely new approaches to learning. That will make engineering schools much more exciting and rewarding places to be in, and will help faculty become better and more effective teachers and researchers at the same time.

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