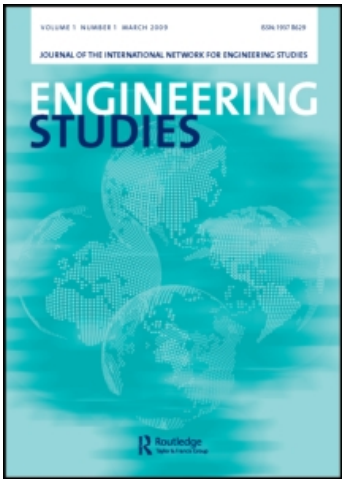

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Reconstructing engineering from practice

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Reconstructing engineering from practice

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Using data from interviews and field observations, this article argues that engineering needs to be understood as a much broader human social performance than traditional narratives that focus just on design and technical problem-solving. The article proposes a model of practice based on observations from all the main engineering disciplines and diverse settings in Australia and South Asia. Observations presented in the article reveal that engineers not only relegate social aspects of their work to a peripheral status but also many critical technical aspects like design checking that are omitted from prevailing narratives. The article argues that the foundation of engineering practice is distributed expertise enacted through social interactions between people: engineering relies on harnessing the knowledge, expertise and skills carried by many people, much of it implicit and unwritten knowledge. Therefore social interactions lie at the core of engineering practice. The article argues for relocating engineering studies from the curricular margins to the core of engineering teaching and research and opens new ways to resolve contested issues in engineering education.

Keywords: engineering practice; engineering education; engineering identity; distributed expertise

Introduction

This article draws on a large body of empirical data from interviews and field observations to show how some engineers tend to hide the social dimension of their work behind a technical facade, and, in doing so, marginalize important aspects of their work. Extensive first-hand experience has influenced the selection and analysis of data. The article proposes a model that helps to expose the social core of technical engineering practice. While the model is based on the full body of empirical data, this article can only present a small part of the evidence behind it.

Most existing descriptions of engineering practice have emphasized technical problem-solving and design. The need for an improved description arose from first-hand experience of employing engineers in Pakistan to design and construct prototype equipment for landmine clearance. These engineers were unable to meet expectations based on experience with similarly experienced mechanical and electrical engineers in Australia. Neither the level of qualification (bachelor or master degrees) nor the country in which it was gained (Pakistan, UK) appeared to make any difference. Interactions with industrial firms led to the realization that one

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has to adopt a different level of expectation in order to make realistic performance predictions for engineering work in South Asia. However, it was very difficult to explain the differences when compared with Australia. Pakistani and Australian engineers had experienced similar engineering education curricula. However there was a large difference in aspects that one might describe as 'practical skills,' the ability to produce practical, working results, but it was very difficult to articulate exactly what this term meant. The research behind this article originated from this challenging observation.

As explained later, there are remarkably few published accounts of systematic research examining the work of ordinary 'everyday' engineering in industrialized countries and there were none from the developing world at the time. This lack of research evidence led to a decision to include an investigation of engineering practice in Australia in order to provide a baseline for comparison. Gradually, the objective became clearer: a model of engineering practice that could explain performance observations in different settings and disciplines. At first it was difficult to see how so many different styles of practice, language, and thinking adopted in different engineering disciplines and practice settings could be accommodated into a concise framework for analysis. A single setting such as metal component manufacturing engineering that exists in both Australia and South Asia became a useful way to focus on the differences, but a broader sample was needed for a model with wide validity. Even though the data came from a variety of different settings and locations, a remarkably consistent and extensive pattern of common practice gradually became apparent. Engineers tend to share an identity mainly framed in terms of the solitary technical: problem-solving and design. As explained later, a model of engineering as a combined human performance, in which expertise is distributed among the participants and emerges from their social interactions, exposes the social at the core of technical practice.[1] We may need to refine the technical/social dualism by which engineers partition their work into mainly solitary technical work on the one hand and all the other seemingly mundane work they do with other people on the other hand.[2] Engineers also relegate many critical aspects of their technical work that rely on distributed expertise, such as checking and review, to secondary status. The article presents evidence revealing how these aspects often are the ones that create the real value that emerges from engineering practice, and how some engineers seem to miss these connections. The theoretical model presented in this article also provides insights that could help resolve some contested aspects of engineering education.

The model has also provided some preliminary answers on the differences in engineering practice between South Asia and Australia, and these will be reported in a future paper.

[1]There is a remarkable similarity between our observations and those reported in Brown et al., *Distributed Expertise in the Classroom*, 1993, 188–194. Several other informative discussions of distributed cognition in education appear in the same book. Distributed cognition in a naval context was also discussed in Roberts, "Some Characteristics of One Type of High Reliability Organisation," 1990; and Roberts, Stout, and Halpern, "Decision Dynamics in to High Reliability Military Organisations," 1994.

[2]Faulkner, "Nuts and Bolts and People," 2007; Lagesen and Sorensen, "Walking the Line?," 2009.

Studies on the work of engineers

In the 1970s and 1980s, there were detailed studies of engineers using the job analysis method revealing survey data showing, for example, that engineers spent about 60% of their time interacting with other people.[3] The aim of job analysis had more to do with establishing relativities in pay and responsibility than understanding engineering practice. These studies, therefore, were not designed to provide a coherent view of engineering practice. However, they provided useful data on particular firms.

Several studies of engineers explored social relationships between engineers and the wider structures of industrialized societies.[4] The rapid economic ascent of Japan relative to other industrialized countries during the 1980s motivated a series of comparative studies.[5] Sociologists interested in the details of daily practice have described many difficulties in studying engineers, such as technical jargon and the intellectual nature of critical aspects of the work that cannot be directly observed.[6] The interests of organizations with the capacity to fund research tend to confine the focus to design, innovation,[7] and software engineering[8] with only a few representing everyday engineering.[9] Technicians and engineers with more hands-on content in their work are slightly easier to understand and several informative studies have appeared.[10] Most studies have been written for Science and Technology Studies (STS) specialists and few are easily accessible for engineers or their educators, our primary constituencies.[11] While these studies have contributed to our understanding

[3]Youngman et al., *Analysing Jobs*, 1978, 7–9.

[4]E.g. Bailyn and Lynch, "Engineering as a Life-Long Career," 1983; Meiksins and Smith, *Engineering Labour*, 1996; Suchman, "Organising Alignment," 2000.

[5]E.g. Kilduff, Funk, and Mehra, "Engineering Identity in a Japanese Factory," 1997; Lam, "Engineers, Management and Work Organization," 1996; Lam, "Embedded Firms, Embedded Knowledge," 1997; Lynn, "Engineers and Engineering in the US and Japan," 2002; McCormick, *Engineers in Japan and Britain*, 2000.

[6]E.g. Whalley and Barley, "Technical Work in the Division of Labour," 1997, 34; Zussman, *Mechanics of the Middle Class*, 1985, 28.

[7]E.g. Bucciarelli, *Designing Engineers*, 1994; Eckert et al., "What Designers Think We Need to Know About their Processes," 2004; Kidder, *Soul of a New Machine*, 1981; Kunda, *Engineering Culture*, 1992; Leonardi and Bailey, "Transformational Technologies and the Creation of New Work Practices," 2008; Vincenti, *What Engineers Know and How They Know it*, 1990; Vinck and Blanco, *Everyday Engineering*, 2003, 13–28; Wilde, "The Skills and Practices of Engineering Designers Now and in the Future," 1983.

[8]E.g. Kogan and Muller, "Ethnographic Study of Collaborative Knowledge Work," 2006; Perlow, "The Time Famine," 1999; Sonnentag, Niessen, and Volmer, "Expertise in Software Design," 2006.

[9]E.g. Faulkner, "Nuts and Bolts and People," 2007; Faulkner, "Doing Gender in Engineering Workplace Cultures," 2009; Korte, Sheppard, and Jordan, "Early Engineering Work Experiences," 2008; Yun, "Technical Workers in a Newly Industrialising Economy," 1991.

[10]E.g. Barley and Bechky, "In the Backrooms of Science," 1994; Barley and Orr, "Between Craft and Science," 1997; Bechky, "Sharing Meaning across Occupational Communities," 2003; Horning, "Engineering the Performance," 2004; Mason, "Production Supervisors in Britain, Germany, and the United States," 2000; Orr, *Talking About Machines*, 1996; Zabusky and Barley, "Redefining Success," 1996.

[11]Some readers might see engineering studies as a niche in a cathedral of social science studies. As an engineer I see this differently: a more pragmatic approach in which engineering studies illuminates the core of engineering practice, as I argue in this paper. Engineering studies scholars, therefore, can argue for the attention of engineers and their educators as a primary constituency in which social science offers pertinent insights.

of engineering practice, our knowledge of technical occupations remains tenuous[12] and there is still no concise and comprehensive understanding of engineering practice with validity in a wide range of disciplines and settings that provides satisfactory explanations for the issues outlined in the Introduction.

Even though these reports have exposed the rich diversity of social interactions in engineering practice, it is debatable whether they have begun to displace the widely held view in the engineering community that these aspects are 'non-technical' and are peripheral to the core technical discourse, particularly design and technical problem-solving. Downey recently explained that engineering educators are attempting to emphasize 'professional skills, practices *beyond the core* of technical problem-solving'[13] (emphasis added). Most social researchers have long recognized that the social and technical aspects of science, technology, and engineering are intertwined and cannot be separated.[14]

The research for this study exposed the critical lack of literature presenting data from South Asia, particularly the difficulties in satisfying critical social needs in water supply, sanitation, transport, and energy. There are few reports that help us understand how issues in engineering practice might have contributed to these problems.[15]

Engineering faculty who help students construct the discipline centre their view of practice on problem-solving and design. An extensive study of faculty and students at several American universities revealed that they describe engineering practice in terms of:

(1) problem-solving, a systematic process that engineers use to define and resolve problems, often ill-defined ones,
(2) specialized knowledge, both theoretical and contextual, and
(3) integration of process and knowledge to resolve some particular problem, involving judgment, creativity and uncertainty.[16]

A more recent study revealed similar themes: applied science and mathematics, problem-solving and making artefacts, drawings, or models, and the vague notion that engineers are involved in building the human environment.[17] Another way to discern notions of practice is to examine prescriptions for undergraduate education outcomes. The Engineering Professors Council in the UK recently proposed education outcomes to prepare graduates for practice that included eliciting client needs, mathematical and physical modeling, design, and technical performance review.[18] Professional societies representing engineers have also provided lists of

[12]Barley, "What We Know (and Mostly Don't Know) About Technical Work," 2005.
[13]Downey, "What Is Engineering Studies For?" 2009, 69.
[14]Lagesen and Sorensen, "Walking the Line?" 2009, 132, also works such as Bijker, *Of Bicycles, Bakelites, and Bulbs*, 1995.
[15]E.g. Bennell, "Engineering Skills and Development," 1986; Coelho, "Of Engineers, Rationalities and Rule," 2004; Domal and Trevelyan, "Comparing Engineering Practice in South Asia with Australia," 2008; Kirmani and Baum, "The Consulting Profession in Developing Countries," 1992.
[16]Sheppard et al., "What Is Engineering Practice?" 2006.
[17]Based on extensive qualitative analysis at a single institution: Pawley, "Universalized Narratives," 2009.
[18]Maillardet, "What Outcome Is Engineering Education Trying to Achieve?" 2004.

competencies and recognition requirements for their members. Recently, a panel of the American Society of Civil Engineers, with a large majority comprising teaching faculty, updated their Body of Knowledge (BoK) and specified no fewer than 24 education outcomes. They called for a broader education and more emphasis on sustainability, globalization, public policy, and business administration.

The BoK stated that 'Civil engineers are fundamentally applied scientists' and described civil engineering as,

> ... the profession in which a knowledge of the mathematical and physical sciences gained by study, experience, and practice is applied with judgment *to develop ways to utilize*, economically, the materials and forces of nature for the progressive well-being of humanity in creating, improving and protecting the environment, in providing facilities for community living, industry and transportation, and in providing structures for the use of humanity[19] (emphasis added).

Several aspects of engineering practice are missing or are inconspicuous in these accounts. The words 'human' and 'people' were rarely mentioned in the BoK or research on faculty notions of engineering practice, except in a distant sense such as 'providing structures for the use of humanity'. Second, there was little explicit mention of involvement by engineers in delivering tangible results: engineers instead 'develop ways' to do this 'economically.' Other people, by implication, create structures that meet human needs.

This brief survey of the scarce available literature reveals a significant difference between the notions of engineering practice in the social research literature as a discipline with intertwined social and technical aspects, and the views of engineering writers and engineering faculty that place problem-solving and design at the centre and people at the distant periphery of the discipline.[20]

I turned to engineers themselves to reconstruct a description of engineering practice. By seeking a description with broad validity, we can discern the effects of different settings and possibly make predictions about the way people are likely to think and behave in different settings. We can also discern relatively invariant aspects of practice that are common between different settings, beyond the universal principles of science and mathematics. For this reason, data from Australia, South Asia, and other countries are valuable to base the analysis on a wide range of settings.

Methodology

Qualitative research has been preferred for many systematic investigations of engineering practice[21] and is appropriate for constructing a qualitative description based on interviews with engineers and workplace observations. Semi-structured interviews lasting 90–120 min explored participants' engineering careers, all aspects of their current work, and perceptions related to job challenges and achievement satisfaction. Some interviews included questions on dishonest behavior (of others), checking, and mistakes (Appendix B, online). In some instances, circumstances

[19]American Society of Civil Engineers, *Civil Engineering Body of Knowledge for the 21st Century*, 2008, 50.
[20]E.g. Ferguson, *Engineering and the Mind's Eye*, 1992; Petroski, *To Engineer Is Human*, 1985.
[21]A useful and detailed example is provided by Zussman, *Mechanics of the Middle Class*, 1985.

required small focus group discussions with up to three participants instead of interviews. Transcripts were prepared from recordings (with participants' consent) or notes (checked by participants). Several students contributed interview data using the same protocol with minor variations to suit their research. Some also contributed field study data to triangulate the interviews. Training, joint interviews, and reviews of the recordings and transcripts helped ensure consistent data.

The sampling was partly opportunistic and partly purposeful for maximum variation to include engineers in all major disciplines, experience levels, and types of business (except defense, Appendix A, online). Six per cent were females and most had engineering degree qualifications.

Analysis followed standard ethnographic analysis techniques[22] and also drew on the author's extensive first-hand experience of practice. Some recently published accounts also helped triangulate data.[23] Repeated listening to recordings and reading of 20 Pakistani and 25 Australian transcripts yielded an initial list of 70 codes describing different aspects of practice and 38 codes describing specialist technical and generic business expertise. All code descriptors were independent of specific discipline contexts. Selected participants reviewed the codes and suggested some changes.

Detailed analysis of the 25 Australian transcripts refined and extended these codes and descriptors. A surprisingly large proportion of quotations mentioned social interactions in which the participant was relying on others to perform some work or provide information. The term 'coordination' seemed more appropriate as most interactions involved clients, peers, people in other parts of the same organization, superiors, contractors, and outsiders. These were mostly one-on-one situations with little or no formal authority. The absence of formal authority in most reported interactions led to the conclusion that securing willing and conscientious cooperation is an important part of coordination.[24] Little further elaboration emerged from the analysis after a further 10 transcripts. This onset of saturation helped to confirm that the sample size was sufficient, and triangulation data helped confirm that the codes provide a detailed qualitative description of engineering practice.[25] Finally the descriptors were grouped in categories (Appendix C, online).

Conceiving engineering in terms of rearranging components, materials, and abstract data to produce products with economic or social benefits yielded a manageable framework in which to code expertise. Aspects of specialized technical expertise included, for example: knowing a particular product, how it works, and how each component contributes to appropriate function, qualitative and detailed quantitative knowledge of the components and materials, processing, combining

[22]Huberman and Miles, *The Qualitative Researcher's Companion*, 2002; Miles and Huberman, *Qualitative Data Analysis*, 1994; Patton, *Qualitative Evaluation and Research*, 1990; Strauss, *Qualitative Analysis for Social Scientists*, 1987.

[23]Useful data came from accounts such as Bucciarelli, *Designing Engineers*, 1994; Darr, "Technical Labour in an Engineering Boutique," 2000; Orr, *Talking About Machines*, 1996; Vinck, *Everyday Engineering*, 2003; Winch and Kelsey, "What Do Construction Project Planners Do?" 2005.

[24]Elaborated in Trevelyan, "Technical Coordination in Engineering Practice," 2007.

[25]Note that any coding scheme depends on the approach taken by the investigator: Button and Sharrock, "Occasioned Practices in the Work of Software Engineers," 1994; Garfinkel, *Studies in Ethnomethodology*, 1967.

them, and bringing them together, standard and specialized working techniques to achieve this predictably with reliable results, and selling the product to different kinds of customers. In an engineering organization with several products, therefore, there is a 'layer' of equivalent expertise for each product. Different clients, engineering disciplines, or application areas, even geographic regions might lead to further layer subdivision. Some products may be grouped with similar manufacturing methods, technologies, modeling methods, and fields of application. With multiple expertise layers, generic aspects of expertise subdivide into hundreds of different kinds of specific technical expertise. In this quote from a young engineer, she demonstrated the necessity to learn about components (pumps and valves in this instance), how foundations are installed, and sources of expertise:

> Practicality, how it all works, what a valve looks like, how you pull a pump apart. The next most important thing is where they fit in. ... As the scheduler I had no idea how long it took to put in foundations. I had to ask somebody and figure out who to ask. I had a terrible lack of knowledge of actual 'stuff.'

To further triangulate the field study and interview data, we conducted a longitudinal study of 180 novice engineers, about 50% of the 2006 graduating cohort from The University of Western Australia.[26] We wanted to find out what they are doing and how they acquire their expertise. The practice descriptors guided construction of on-line surveys. The responses confirmed that the descriptors were meaningful to young engineers in the majority of disciplines, and also contributed some minor revisions. While there were significant differences in the proportion of time spent on different technical aspects between different engineering disciplines, the overall pattern was remarkably consistent. A surprising finding was that novice engineers in their first year of practice spend about 60% of their time interacting directly with other people. This figure is remarkably consistent with the interview and field study data from more experienced engineers, and also with several earlier studies.[27] A recent survey using the same method revealed almost the same result (62%) from a sample of 59 novice engineers in Portugal.[28] It is noteworthy that the average proportion of time spent interacting with other people should be so remarkably large and constant, irrespective of experience level and discipline.

This detailed framework provided a foundation on which to synthesize a more concise, higher level description of practice. As described above, the first component to emerge was technical coordination of other people outside lines of authority: this was the predominant aspect of practice for most of the engineers we interviewed or observed. Re-reading all transcripts from Australia, India, and Pakistan, searching for missing aspects of practice, reflecting on the data, the language and meanings, and discussing the main themes emerging from the analysis with some of the Australian study participants helped to validate or refute aspects of the analysis and distil the essential features. This last activity was one of the most helpful in leading to the findings that follow.

[26]Tilli and Trevelyan, "Longitudinal Study of Australian Engineering Graduates," 2008.
[27]Trevelyan, "Engineering Education Requires a Better Model of Engineering Practice," 2009, 5.
[28]Work in progress by Bill Williams at Instituto Politécnico de Setúbal.

Off the record: hiding aspects of practice

Many engineers instinctively question the validity of much of their daily practice. Several participants, when I told them I am researching engineering practice, what engineers really do, responded like this one who said, 'Oh, I can't help you much, I hardly do any engineering.' I asked him what he actually did when he was 'doing engineering.' He replied, 'Calculations, design, technical stuff.' His response strongly evoked the technical/social binary in engineering and revealed how the technical is often privileged over the social in the minds of engineers. The data in this study provide evidence that it is not just the social that is marginalized.

The following excerpt from an interview with a young engineer with 5 years experience reveals how technical work involving social interactions is given a technical label, hiding the social interactions beneath. The engineer had earlier described his 'software upgrade' work to replace an outdated process control system with a modern one programmed in a different language. He had talked about this work in terms of designing specifications for programmers writing the new replacement software code. He explained that the old software was poorly documented. Many of the gaps had to be filled by talking to the plant operators, some of whom had made the changes to the legacy software.

> *Engineer:* There were things like schematics on the plant so those had to be ... it was getting information out of the plant guys for what was sitting behind those schematics and what equipment they were reading off. It was a lot of work trying to get that information out of them.
>
> *Interviewer:* That's an interesting remark. Could you just expand on that?
>
> *Engineer:* When I joined the team, the guy I was working with I guess he was - he didn't have the best relationship with the point of contact we had on site and it got to the point where he actually left the project and I carried on myself. But I guess the positive that I took from that for my own personal development outside of the engineering was my ability to work with this guy and actually bring him back on board. By the end of the 12 months that I was there we were sort of working quite well as a team again and the Woodley[29] site ended up being pretty much ahead of schedule almost in terms of getting information to the programmers to be able to do their thing and get the code working there.

His work depended on gaining the cooperation of plant operators so that they could contribute their knowledge and experience. Then, with this information, the engineer could write code specifications for programmers. This is an example of how the critical importance of developing cooperative relationships lies off the record in the language that engineers use to describe their work. This excerpt also reveals how engineers rely on expertise distributed among participants, and how engineers often need to codify implicit knowledge as written documents adapted for other people to use them effectively. This illustrates distributed expertise in engineering practice.

It is not just the social that is being relegated in this excerpt. The engineer's work has a highly technical aspect: his job is to decide the exact functions that the new process control system must perform. His work involved writing specifications rather

[29]Fictitious place and project names have been used in some quotations.

than performing the software design and coding. Persistent probing was needed several times before the excerpt above to get beyond the superficial description of his work as upgrading software to discover that the work involved not writing and installing software, but writing specifications based on incomplete, outdated schematic diagrams of the old software, and filling the gaps with socially enacted knowledge carried by plant maintainers and operators. This step, with its social components, lay off the record, even though it is undeniably technical.

In the next excerpt, we hear from a young quality assurance (QA) engineer in a large offshore project with 2 years experience in that role. His work was to make sure that technical documents were reviewed and checked by appropriate engineers, and that all comments and changes were archived.

> *Interviewer:* ... At the beginning of this interview you said 'I'm not an engineer. I don't work in engineering ...'
>
> *Engineer:* When I look at engineering I think of the hardcore design and the modeling that the guys are doing so that is why I say I'm sort of disconnected I guess from the engineering ....
>
> *Interviewer:* Are most of them engineers here, most of the people?
>
> *Engineer:* No probably just under half I'd say.
>
> *Interviewer:* What are the rest of the people doing?
>
> *Engineer:* There would be half engineers, a quarter of the team would be construction guys ... The construction group - there is basically one guy for each part of the job so there is a subsea guy, there is an offshore pipelines guy, there's a person responsible for the shore approach and ... logistics, yes.
>
> *Interviewer:* These are not engineers?
>
> *Engineer:* Yes they are in fact ... three quarters of the team is.
>
> *Interviewer:* Three quarters of the team now and the rest?
>
> *Engineer:* The rest is made up of HES,[30] project controls ... there's a mix there. There are environmental scientists, obviously there are safety guys in there so there are safety advisors ...
>
> *Interviewer:* The project group?
>
> *Engineer:* Project controllers. These are the schedulers.
>
> *Interviewer:* How do they know how to schedule if they don't have engineering expertise?
>
> *Engineer:* That is another interesting one because our previous planner was actually a chemical engineer as well. He was a year younger than me.

In this exchange, we can see how this engineer not only classified his own work as 'non-engineering' but also grouped all the work required to convert the design into a usable source of oil and gas – construction, procurement, commissioning, health, safety and environment protection and project management – into the non-engineering category.

The next interview excerpt came from an experienced marine engineer and illustrates once again how social interactions hide behind a technical facade. Intermediate prompts and requests for clarification have been represented by

[30]Health, Environment, and Safety.

ellipses: some persistence was needed to encourage this detailed explanation. Asked about the *technical* aspects of his work, he replied:

> *Engineer:* Well, I'm responsible for the technology qualification process, ... identifying technology gaps with the equipment required to execute the Narrakine project.
>
> *Interviewer:* So tell me what you do to do that?
>
> *Engineer:* ... What we do is we look at the technology, identify the technology gaps ... We either go out to the known vendors and say, this particular field, there's only one ... maybe two people who can supply the equipment to the industry. So we speak to those guys, issue a request for information, see what they've developed in the past, and if there is a known technology gap then we document that one on a technology qualification plan ... So basically, they input our specifications, data sheets, etcetera, and review them and then tell us what the technology gaps are for their particular systems.
>
> *Interviewer:* Okay. So you specify the requirements and they then analyse to find the gaps and then report back to you.
>
> *Engineer:* Then report, yeah ... So in there we risk them, we develop our individual technology qualification plans for each piece of equipment, but we also identify a fall back strategy or contingencies measures also in that plan. We also evaluate the probability of success based on the degree of step-out etc.
>
> *Interviewer:* Okay. Tell me more about that, estimating the degree of probability, of success.
>
> *Engineer:* Well, I mean it's making an engineering judgment really from ourselves internally and asking the suppliers of this equipment how confident are they that they can extend the existing design and modify – keep the existing design and modify materials, etc., depending on what the step-out is. We ask them to say what the probability of success is in their opinion and likewise, we look at that internally, review internally as well ...
>
> *Interviewer:* So can you describe in detail to me your own involvement in this? You write contract documents, what else do you do?
>
> *Engineer:* I co-ordinate the work; basically, you could essentially say I project manage it. For each technology gap, we assign a lead to that, who's normally the lead in whatever field that may be: wells, controls, pipelines, subsea. So he's directly responsible for producing the engineering documents and giving technical response as necessary.
>
> Then I will oversee and co-ordinate this activity to make sure that we initiate this work to meet the overall schedule for the project. I assign a budget for the work, track the project, track the progress. So it's essentially a project management position that I'm filling. I chase the individuals to give us responses and coordinate the work, as needs be.

He had no organizational authority: no one reported to him. His 'technical' role largely depended on his ability to coordinate expertise distributed among the 'leads', senior expert engineers in the organization, and engineers from potential suppliers, to form a collective judgment on the degree to which new technology would be required for this offshore gas project. Social interactions enabled the necessary expertise, yet he described all this as the technical aspects of his work.

In the next interview excerpt from the chief executive of a technical consultancy, we hear another instance of this tendency to dismiss a critical aspect of the product delivery side of engineering: controlling scope, deciding exactly what technical work has to be performed. If this is not clearly defined, it is not possible for engineers to know whether the work they are doing is necessary or not. Once the scope is agreed upon, engineers will only be paid for work that is 'within scope.'

> *Engineer:* The engineers had no real link to, or definition, a competently prepared scope of work. I feel that the engineers do not have a sense of responsibility to the organization. Controlling the scope is not seen as part of an engineering problem.

In the next instance, we hear from a software project manager with 15 years experience who formerly called himself a software engineer. His work was to coordinate and manage a team of people who set up and configure large software systems to store data for companies. Although the engineer explained that no new software code needed to be written, configuration changes are a form of software coding, even if it is only changing the way that the software appears to work for different users.

> *Engineer:* I'm not an engineer any longer: I'm a project manager for my company. I don't write code and I don't design software any more.
>
> *Interviewer:* Can you give me an example of the kind of project that you manage?
>
> *Engineer:* Installing a data system for a new company, that's a good example. It's just the application of software we've already built.
>
> *Interviewer:* So, could someone with no technical understanding in software engineering do your job, do you think?
>
> *Engineer:* No, definitely not. They would find it very tough to do that. You need that engineering know-how just to run the project. In fact there's a lot of engineering in project management. You lose the respect of a lot of people who think that you're only an engineer if you are seen to be writing code or doing software design. They say you're not an engineer any longer, you're just a project manager.

Without configuring the software for a particular client, the software code would not provide any useful value: it could even make office work more tedious and difficult instead of eliminating unnecessary work. What we see here is an example of how some technical work is privileged over other technical work. The work that is privileged is creating software which makes the data system function in the first place. The work that is 'off the record' for 'software engineers' embraces all the other steps needed to ensure that the software will be useful for the ultimate users and that often involves much more work than the design and coding of the original software.

In another interview at a company engaged in mining and refining employing more than 2500 people, the engineering manager explained, 'We only have fifty-five engineers in this company. They sit over there [pointing to an open plan office with cubicles]. They do analysis for us.' He went on to explain that the company employed a large number of people with engineering training as its production supervisors, managers, production schedulers, the entire operational excellence team, the maintenance leads, and so on. But only 55 were labeled as engineers.

Fourteen interviews in one company and five in another (with a student who also conducted a field study in the second company) explored error checking in design in addition to the standard questions. Analysis of data from both companies revealed a similar pattern: engineers were often 'too busy' to perform more than cursory checks. Later, when the mistakes were eventually discovered, costly redrafting or even on-site changes were needed to fix them. Both companies operated strict comprehensive QA processes that required that every document pass through a

Figure 1. How do the fluorescent tubes get changed?

rigorous checking procedure: numerous engineers were required to 'sign-off' the documents to indicate that they had checked the contents for accuracy and completeness. Audits of these systems had revealed 100% compliance: every document had the required signatures. The senior engineers were proud of the process: they offered us sample documents that had passed through the QA process. Yet these documents contained mistakes obvious from a casual reading, such as missing or unreadable diagrams and incomplete sections of text. Even though all the engineers acknowledged document checking to be critical, they still saw document checking as an interruption and were observed to delegate the work to the most junior person available or, in some instances, sign the document with only the most cursory checking. One engineer remarked, 'When things land on people's desks, there is just too much of a mentality of them saying, oh no, I don't have time for this right now.' Another reported, 'There is an inbred mentality of not doing checks or peer reviews. The right culture isn't there.'[31] Technical review relies on distributed expertise – the reviewers are often from different disciplines, sometimes from external organizations, and complement the authors' expertise.

The data reveal many other technical aspects of practice which are either relegated to inferior status, or are even off the record or unseen in the context of design and problem-solving, and yet they are critical in obtaining useful value when the engineered products or services reach their ultimate users (e.g. Figure 1). Maintenance provides prolific examples: Figure 1 illustrates a recent advanced technology installation in Australia where technical reviews exposed the need for people to reach the lights to change the fluorescent tubes. By the time the issue was noticed, space that could have been used to provide a movable maintenance platform

[31]Mehravari, "Systematic Checking in Engineering Design," 2007, 39–40.

had been allocated for ventilation service ducts. Many similar oversights emerged in the data.

We can observe from these accounts that engineers tend to frame their identity in terms of technical problem-solving and design, and marginalize other aspects of practice that lie outside. As has been recognized before, people tend to devote more effort to activities congruent with their current identity.[32]

One way to understand the data in a coherent way is to see engineering in terms of a combined performance of many different people, with the necessary expertise distributed among them. The next section of the article synthesizes observations from the data and presents a consistent common pattern of engineering practice that emerged from the accounts contributed by the participants in different disciplines and settings.

Engineering: a human performance

The main finding of the analysis, though only part of the evidence has been presented here, is that we can better understand engineering practice by reframing engineering as human social performance.[33] 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 this description of the overall performance through the process of detailed coding, analysis, re-reading, and synthesis described above. Each participant provided a view on their own part of the whole: none could provide a coherent description beyond their immediate experience.

Engineers use their special knowledge of materials and physical and abstract objects to work out how to rearrange them 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.

None of the participants in our study worked on their own. To a greater or lesser extent, they all relied on interactions with other people: their practice was based on distributed expertise.[34] The first stage of analysis revealed that engineering involves a large number of different aspects of practice and specialized knowledge, most of it unwritten, developed through years of practice,[35] and difficult to transfer to others. Learning about all of this is beyond any one individual in a typical project timeframe or even a working lifetime: there is not enough time. Instead, engineers informally coordinate with other people so they willingly and conscientiously contribute their expertise. Sometimes they start with little or no overlapping understanding, so helping others to learn and learning from others is always a part of practice.

[32]Ashforth and Mael, "Social Identity Theory and the Organization," 1989, 25.
[33]Evans and Gabriel, "Performing Engineering," 2009, suggested the term "performance." Petroski, *To Engineer Is Human*, 1985, demanded "human" to be tightly associated with engineering.
[34]Jonassen, Strobel, and Lee, "Everyday Problem Solving in Engineering," 2006, 144; Korte, Sheppard, and Jordan, "A Qualitative Study of Early Work Experiences of Recent Graduates in Engineering," 2008, 9–11.
[35]Ericsson, "The Acquisition of Expert Performance as Problem Solving," 2003.

Translation[36] and negotiating shared meaning to enable understanding across different areas of expertise is part of this as well.[37] Most 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, laborers, drivers, operators, maintainers, and end users. In a sense, the engineer's role is both to compose the music and conduct the orchestra, working outside lines of formal authority.

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 the study have extensive, uninterrupted time to think and reflect. Engineering performance requires rapid and difficult choices on the use of personal time and material resources.

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. Therefore, an engineer has to ensure that everyone involved 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.[38] The people who use the products and services also need understanding 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, maintained, and disposed of.

The participants' accounts reveal that engineering projects follow a similar sequence. Many participants narrated their careers in terms of projects they had worked on. Each participant provided a view of the projects they were currently engaged in and many were contributing to several projects at the same time, each one at a different phase of the sequence presented here.

(1) At the start, engineers attempt to understand and at the same time shape clients' perceptions of their needs, and work with clients to articulate requirements. Helping the client to see their issues in terms of engineering possibilities is part of an engineer's work. Gaining clients' and investors' trust and confidence is essential because much of the money will be spent and much time elapses before anyone gains benefits and money is repaid to the investors. Engineers also sustain their own businesses by helping clients anticipate future needs.

[36]In a wide ranging discussion Collins and Evans referred to this as interactive expertise, though they seem to reserve the term for STS researchers, Collins and Evans, "The Third Wave of Science Studies," 2002, 252.
[37]See also, for example, Darr, "Technical Labour in an Engineering Boutique," 2000, 208.
[38]Sonnentag, Niessen, and Volmer, "Expertise in Software Design," 2006, 380.

(2) Engineers conceive different ways to meet requirements economically, propose solutions using readily available components, and design special-purpose parts when needed. Much of the design work involves re-arranging elements drawn from a vast memory of design fragments and piecing them together.[39] Engineers solve technical problems, though many of the engineers observed in this study avoided technical problems as much as possible through a combination of shaping client expectations, foresight, experience, careful planning, and effective organizational methods.
(3) Engineers collect data and create mathematical models based on scientific knowledge and experience to analyze and predict technical and commercial performance of different solutions so that sensible choices can be made. The level of precision depends on investors' acceptance of risk and uncertainty. Engineers usually describe uncertainty qualitatively, occasionally quantifying it, accounting for incomplete data and uncertainty in available data and from external uncontrolled events. They also diagnose perceived performance deficiencies (or failures), conceive and design remediation works, and predict how well the modified system will perform. They also negotiate for appropriate approvals from regulatory authorities.

Phases 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.[40] The term 'engineering problem-solving' is often used in a sense that embraces phases 2 and 3.[41]

(4) Using the engineers' predictions as a starting point, the client, investors, regulatory authorities, and contractors decide whether to proceed with the project. The work up to this point is often called 'front end engineering.' Once 'project execution' starts, engineers prepare detailed plans, designs, and specifications for the work to be performed and organize the people and resources that will be needed for construction, commissioning, operations, and maintenance.
(5) Engineers coordinate, monitor, and evaluate the work while it is being performed, adapting plans and organization to circumstances, explaining what needs to be done, making sure that the work is performed safely, to an agreed schedule, within an agreed budget, and within negotiated constraints such as regulatory approvals, effects on the local community, and the environment. Although engineers carry these responsibilities, they are reluctant to use formal authority (and it is only rarely available to them). Instead they rely on informal technical coordination. The aim is to deliver the intended products and utility services with the predicted performance and reliability.

[39]Appropriate structural elements described in Gainsburg, Rodriguez-Lluesma, and Bailey, "A 'Knowledge Profile' of an Engineering Occupation," 2010; also in other disciplines, Sonnentag, Niessen, and Volmer, "Expertise in Software Design," 2006, 377.
[40]Often referred to as a project phase gate decision process, Cooper, *Winning at New Products*, 1993, 109.
[41]E.g. "The Engineering Method" in Dowling et al., *Engineering Your Future*, 2009, Ch. 3.

(6) Engineers conceive, plan, organize, coordinate, monitor, and evaluate decommissioning, removal, reuse, and recycling at the end of a product's life span, and also the rehabilitation, remediation, and restoration of the site and the local environment.

Since engineering is a human performance, we need to accept that the performers have unpredictable aspects, like nature. Given that the aim is *predictable* delivery of *reliable* products and services, engineers need to know how to ensure that *unpredictable* aspects of countless individual performances 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 are all parts of an engineer's repertoire for containing human and natural uncertainty.

Engineers are involved in training and development, not only of other engineers[42] but also all the other people who contribute to the process, including end users. Engineers also work on technology improvements and interpret technological possibilities to society, business, and government. They help ensure that policy decisions are properly informed and that the costs, risks, consequences, and limitations are understood.

Concluding remarks

Analysis of data from interviews and observations of practicing engineers has provided a description of engineering practice based on distributed expertise. The description reveals that human performance and social interactions lie at the core and constrain engineering outcomes just as material properties constrain the feasible height of buildings. The description captures many aspects of engineering practice omitted from contemporary narratives that restrict 'engineering' to design and problem-solving.

Many engineers would view human performance and social interactions as 'management issues.' However, the analysis demonstrates that technical knowledge is distributed in the minds of participants. This observation helps to explain why even novice engineers in roles labeled with a predominantly 'technical' focus (as opposed to more senior engineers with a more explicit managerial component in their work) devote an average 60% of their time to direct social interactions. This proportion does not seem to vary with experience level. The social discourse required to enact distributed expertise is necessarily technical, and therefore these interactions cannot be regarded as 'non-technical.' Distribution of expertise is an engineering issue, albeit currently outside what many practitioners might acknowledge as engineering.

Reframing engineering as human performance enables engineering studies researchers, currently sitting at the curricular margins of a discipline dominated by technical discourse, to relocate their research and its significance to the core of engineering practice. Nearly all the practitioners who have taken part in the study reported that the major failures they have encountered resulted from failures in

[42]Younger engineers need up to an hour of explicit help and guidance daily. See Bailey and Barley, "Teaching–Learning Ecologies," In review.

human interactions rather than errors in the underlying written technical knowledge. There may be interesting research here: how do the social interactions required to support distributed expertise and the languages through which they occur shape the expertise and influence predictable applications? There are grounds for optimism that a much stronger research focus on the way that people think, feel, act, and interact in engineering could lead to significant improvements in practice.

Researchers in engineering schools can build on the natural curiosity of students anxious to learn more about the profession they aim to join. Valuable data for this article came from students conducting their own research studies. Two graduate students, both practicing consultants with decades of experience, have been motivated by the desire to understand why their clients seem unable to use their advice effectively. Others have been motivated by the possibility of making original contributions to our understanding of engineering practice in different settings. The description provided in this article could provide a useful starting point for students wanting to pursue studies on aspects of engineering practice.

One aim of this article has been to present a clearer understanding of engineering than any of our participants were able to articulate on their own. For students in particular, the description demonstrates the central place of people in engineering practice and the necessity to understand how human interactions influence technical results. Students need to understand that communication in engineering practice is more than simply providing technical information to other people.[43] Developing cooperative social relationships and shaping the perceptions of other people are equally significant.

Engineering educators can also make use of this description of engineering practice that, like education itself, focuses attention on people. Education is a social process just as much as engineering practice. The traditional reaction from engineering faculty faced with the need to pay more attention to professional skills has been to point out the already over-crowded curriculum. However, improving the understanding of how people learn has close parallels with understanding the way that people interact in engineering practice. Therefore, we may be able to improve understanding of both and also improve technical learning at the same time. There has been an increased emphasis on scholarship in engineering education over the last decade and research methods appropriate for these studies are equally appropriate for understanding how people interact in engineering practice.

The observation that expertise is distributed among the participants in an engineering performance places social interactions at the core of the technical practice of engineering. This observation ties social skills to the technical identity most valued by engineers and also provides educators and students with a strong motivation to elevate the importance of social skills needed for effective collaboration. Developing the social interaction skills to handle distributed expertise in the classroom[44] could provide engineering students and faculty with a means to improve learning of both the technical – with which most young engineers strongly identify themselves – and the social at the same time in a common framework. At the same time, an understanding of how distributed expertise enables practice might help

[43]A common explanation for the role of communication in engineering, usually from the engineer to others, e.g. "The purpose of communication is to convey information." Galloway, *The 21st Century Engineer*, 2008, 26.

[44]Brown et al., "Distributed Expertise in the Classroom," 1993.

engineers to see the social as a central part of their technical identity, and revalue many aspects of practice that rely on distributed expertise.

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