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Extending Engineering Practice Research with Shared Qualitative Data

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ABSTRACT

Research on engineering practice is scarce and sharing of qualitative research data can reduce the effort required for an aspiring researcher to obtain enough data from engineering workplaces to draw generalizable conclusions, both qualitative and quantitative. This paper describes how a large shareable qualitative data set on engineering practices was accumulated from 350 interviews and 12 field studies performed by the principal investigator and by students conducting PhD and capstone research projects. Ethical research practice required that sharing and reuse of qualitative data be considered from the start. The researchers' interests and methods were aligned to maintain sufficient consistency to support subsequent analysis and re-analysis of data. Analysis helped to answer questions of fundamental significance for engineering educators: what do engineers do, and why are the performances of engineering enterprises so different in South Asia compared with similar enterprises in Australia? Analysis also demonstrated the overwhelming significance of technical collaboration in engineering practice. Conceiving engineering practice as a series of technical collaboration performances requires a more elaborate understanding of social interactions than is currently the case in engineering schools. Another finding is that global engineering competency could be better described in terms of "working with people who collaborate differently". Research helped to demonstrate that formal treatment of technical collaboration in an engineering curriculum could help avoid student misconceptions about engineering practice that hinder their subsequent engineering performances.

Key words: engineering education, shared qualitative data, engineering practice, technical collaboration performance

INTRODUCTION

Research on engineering practice is scarce, even within the engineering education community, and aspiring researchers face significant challenges in gathering data, both qualitative and quantitative, from engineering workplaces. This paper demonstrates how an alignment of students' and researchers' interests and sharing of qualitative data gathered in PhD and capstone research projects helped to accumulate a large sharable qualitative data set. Students also supplemented analysis capacity in a research project that has yielded several engineering practice research findings of fundamental significance, especially for engineering educators.

The principal research aim was to understand the reasons for large apparent performance differences between engineering enterprises in Australia and South Asia. First-hand observations suggested that differences in engineers' workplace practices might provide explanations for these differences. Extensive literature research at that time (2002-2005) revealed a scarcity of detailed qualitative research on engineers' workplace practices that could have been used to provide reference data for comparisons (Barley 2005). The research aims, therefore, had to be widened to investigate engineering work practices in both Australia as well as South Asian countries. Final year engineering students joined this research, motivated by curiosity to discover more about the realities of their chosen career paths. PhD students with prior engineering work experience also saw opportunities in this research to resolve puzzling observations from their workplace experiences. Through this fortunate alignment of interests, it was possible for the research students to contribute shared qualitative data from limited scope research projects to the much broader over-arching investigation of engineering practices. In doing so, it was possible to build a large enough data set to provide satisfying explanations, and, at the same time, significantly add to the body of available research on engineering practice.

There are other reasons to study engineering as it is actually practiced in real workplaces.

Engineering education curricula are mostly based on understandings of the knowledge, skills and abilities (KSAs) required of engineers. Rather than describe the KSAs in detail, accreditation agencies such as ABET have relied extensively on brief statements of learning outcomes (such as ABET's outcomes a-k) and exposing students to engineering practice through internships (e.g.Prados, Peterson, and Lattuca 2005, ABET 2008, International Engineering Alliance 2013, Seron and Silbey 2009). Engineering educators aim to build graduate capabilities (Bowden 2004) that address these learning outcomes enabling graduates to overcome only partly foreseeable workplace challenges. The learning outcomes can also be seen as competency descriptors. However, Shipmann *et al.* (2000) have pointed out the weakness of brief competency descriptors: they require intimate knowledge of practice to be interpreted appropriately. Unfortunately, the practice knowledge needed for interpretation has been weakened in engineering schools because few engineering educators with appropriate experience of practice remain (Cameron, Reidsema, and Hadgraft 2011). Practice knowledge carried by engineering educators is largely anecdotal and unwritten, and reflects only the range of workplaces experienced by individuals. Therefore, research is needed to build written, generalizable knowledge of engineering workplace practices to address the decline in appropriately experienced faculty members.

Therefore, it is not surprising that some of the findings of this research have revealed significant gaps in engineering educators' appreciation of engineering workplace practices and corresponding curriculum gaps. The research revealed student misunderstandings flourishing in these gaps, misconceptions that can persist through decades of practice, limiting the ability of engineers to meet the needs of their employers and societies, especially in low-income countries.

This paper explains how capstone student research projects on engineering practice topics could help close these gaps and reduce misunderstandings among future engineering graduates. It is possible that reducing the level of misunderstanding could eventually help to transform many low-income economies, eliminating poverty and significantly improving global energy and resource utilization.

Student projects, even at PhD level, can rarely accumulate sufficient qualitative data to support conclusions beyond a narrow set of circumstances in one or two workplaces: even then, the conclusions are typically tentative and require further critical analysis. Building generalizable knowledge of engineering practices requires much larger data sets than is feasible for students. However, by paying close attention to data gathering methods, students can contribute data to a much larger data set that can then be used for qualitative analysis leading to well-supported generalizable conclusions.

The focus of this paper, therefore, is on maintaining sufficient qualitative data consistency and quality in student research projects so that their data can inform a much broader analysis of engineering practices in many different workplaces in different countries and industries.

In the research described in this paper, student contributions extended well beyond the gathering of research data and the paper will describe some of the most helpful. The paper starts by describing the origins of the research project and briefly addresses a selection of relevant literature to explain why a thorough investigation of engineering work practices was necessary. The paper describes some aspects of the research interview questionnaire which was adopted by most of the research students as a template for their own investigations and thus framed the collaborative research effort. A description of the alignment of student interests with the principal research aims was a critical factor in attracting students to the project and leads to a discussion on some of the factors that need special attention when sharing qualitative data, including ethical approvals. Some of the significant research findings are discussed in the context project publications, focusing on curricular gaps and graduate misunderstandings, and the paper concludes with a discussion on how engineering educators could build on this research and help to reduce misunderstanding among future graduate cohorts.

One of the main findings in this paper is that engineering, particularly access to essential technical knowledge, relies on specialized technical collaboration performances. The prevailing social culture in which engineers work influences their collaboration performances, and this seems to explain many of the differences in engineering enterprise outcomes between Australia and South Asia. This suggests that global engineering competency could be better described in terms of "working with people who collaborate differently" rather than knowledge representational differences that have been emphasized in earlier literature. This critical aspect of technical collaboration has been missing from earlier descriptions of engineering and the paper proposes a new description recognizing this omission.

GENESIS

The questions that inspired this research emerged from the author's experience between 1997 and 2002 working with Pakistan-based engineers on the development of experimental technologies for manual landmine clearance in Afghanistan (Trevelyan 2002). Even though they were intelligent and well educated, these engineers were much less able to produce practical results compared with expectations based on experience with engineers working in Australia. Many engineering enterprises in the larger South Asian community were experiencing similar practical difficulties with their engineers and, at the same time, were performing well below their Australian counterparts in terms of service quality and total cost (and still do so today). For example, the provision of safe drinking water is an essential service provided by large engineering enterprises. In Australia drinking water is supplied to homes through pipe networks at about US$3 per ton including basic plumbing connection costs. In South Asian communities, utility networks are operated in a way that renders the water unsafe for drinking. Therefore, almost all safe drinking water has to be prepared and carried at a cost of $50-$150 per ton, taking direct and indirect costs into account such as the imputed economic value of unpaid labor (Trevelyan 2013a). Anand and Coelho in separate studies have also described the low service quality in South Asian water utilities and attributed this to interference from local social power structures (Coelho 2006, Anand 2011, Coelho 2004) though they did not address engineering practices, nor the very high indirect costs imposed on end-users through low service quality. First-hand experience and other observations in a variety of engineering enterprises raised the possibility that differences in engineering practices could account for at least part of the large apparent performance differences between South Asian and Australian engineering enterprises. These observations, therefore, prompted the first research question: "Are there differences about the way that engineers in South Asia work compared with engineers in Australia, and if there are, could these differences explain large apparent performance differences between engineering enterprises in Australia and South Asia?"

Research work started in 2002 with the assumption that engineering practices in industrialized countries would have been researched in depth and that reference data, observation methods and appropriate theoretical approaches would be readily available.

It turned out to be very difficult to find detailed studies of engineering practice that could provide detailed insight into engineers' workplace practices, as Barley had found about the same time (Barley 2005, Trevelyan and Tilli 2007). Most of the relevant literature contributed a combination of personal opinion and anecdotal reports (e.g. Vincenti 1990, Ferguson 1992), and some empirical evidence from quantitative surveys (e.g. Youngman et al. 1978). The quantitative surveys available at that time appeared to be based on preconceived notions of engineering work rather than systematic qualitative field work. Most of the papers in the literature that referred to engineering practices aimed to provide evidence for changing engineering education or evidence to support a particular set of engineering competencies and did not contribute useful comparative data that could help answer the research question.

A few researchers had conducted detailed and systematic qualitative studies of engineers (e.g. Bailyn and Lynch 1983, McCormick 2000, Meiksins and Smith 1996, Fletcher 1999, Bucciarelli 1994, Faulkner 2007, Kilduff, Funk, and Mehra 1997, Suchman et al. 1999). However their research aims reflected contemporary concerns with gender and social power structures in industrialized societies, rather than the details of day to day work practices. To the extent that Bucciarelli and others examined the details of how engineers performed their work, nearly all studies focused on advanced technology and software engineering (Bucciarelli 1994). Barley (2005) conceded that little was then known about the reality of ordinary everyday engineering work. Much more was known about technicians, partly because their work is easier to observe: they perform numerous and visible technical tasks as they interact with machines (Barley and Bechky 1994, Orr 1996). Exceptions included a series of studies providing detailed insights into engineering design work and some isolated comparative studies in software engineering and manufacturing (Perlow and Weeks 2002, Sandberg 2000, Lam 1996, Vinck 2003). Another concerned the work of sales engineers (Darr 2000). However, design and sales are only two of many aspects of engineering work and there did not seem to be studies that examined the totality of engineers' workplace activities. Much more data would be required to explain practice and enterprise performance differences between Australia, Pakistan and other countries (Domal 2010). Furthermore, a coherent model of engineering practice would be needed to understand how the observed differences in practice contributed to such large differences in enterprise outcomes.

Therefore, the research project had to be broadened into a study of engineering practices in Australia, India, Pakistan and eventually other countries with a second deceptively simple research question: "What do engineers really do?" Without detailed qualitative data gathered from numerous workplaces in these countries, it would much more difficult to draw conclusions about differences in workplace practices to answer the first research question.

The first research question had to be framed carefully because it was apparent that South Asian engineers who had migrated to Australia and other industrialized countries worked just as effectively as Australian-born and educated engineers in their home environment. Subsequent investigation of census data has revealed some differences in South Asian migrant engineers' employment outcomes compared with native born Australian graduates, but insufficient evidence of the large systematic performance differences that prompted this investigation (Trevelyan and Tilli 2010).

Experience employing engineers in Pakistan had not revealed any apparently significant differences in explicit technical knowledge. Engineering education curricula are relatively standardized and Australian graduates interviewed for engineering jobs did not appear to remember significantly more details than their South Asian counterparts remembered from their courses. These observations highlighted the importance of studying the social and cultural environment in which engineers work. National cultural differences have been addressed in a large body of earlier literature some of which has focused on explaining the apparent relative success of Japanese industrial enterprises in the late 20th century compared with USA and European counterparts. For example, Lynn and colleagues focused on specific Japanese workplace cultural practices yet argued that explanations based on culture differences were untested and seemed to be contradicted by the relative portability of practices once thought to be rooted in national culture (Lynn 2002, Lynn, Piehler, and Kieler 1993). These research efforts aimed to explain differences in terms of enterprise organization and avoided studies on engineering work practices at the individual engineer level.

Even though literature research continued for some time after the research questions were proposed, it seemed unlikely that a satisfactory combination of one or more theoretical frameworks, observation methods and comparative data would eventually be found, pointing to the need for qualitative research with interpretive data analysis (Huberman and Miles 2002, Miles and Huberman 1994, Patton 1990, Strauss 1987, Bryman 2012, Walter 2006). Several prior engineering practice studies informed this research, providing models for data gathering and analysis methods (Zussman 1985, Orr 1996, Bechky 2003, Bailey and Barley 2010, Sandberg 2000, Lam 1996). For example, Zussman (1985) gathered qualitative data in order to compare engineers' career patterns, political attitudes and identity in two US manufacturing firms, yet little data on day-to-day detailed work practices. Even with this limitation, however, these contributions provided effective guidance to help gather data that could answer the research questions described above.

FRAMING QUALITATIVE DATA COLLECTION: THE INTERVIEW QUESTIONNAIRE

30 years of experience working as an engineer positioned the lead researcher as an insider in the context of this research: part-time professional engineering work continued through the duration of the research. While experience provided a wealth of personal observations and helped appreciate gaps in the available research literature on the one hand, outsider perspectives had to be sought elsewhere, for example from academic colleagues in the social and business sciences. Engineering work experience helped in constructing a research interview that could help explore the totality of an engineer's workplace activities needed to address the second research question.

Discussions with research colleagues in the social science and business disciplines helped strengthen the focus on necessary aspects of the social and cultural environment needed for the first research question. Locating the study in a comprehensive research university with complementary research strengths helped immensely.

One of the challenges in exploring engineers' work activities is their instinctive questioning of much of their work by labelling it "non-technical" or "not real engineering": technical work is often privileged (Bailyn and Lynch 1983, Perlow and Bailyn 1997, Perlow 1999, Trevelyan 2010b) and only a restricted range of activities are associated with the term "engineering". Other activities are often referred to as "management", "admin", "fire-fighting" or "non-technical" even though engineers explain that specialized knowledge is needed: these cannot usually be delegated to non-engineers. The anticipated importance of social and cultural factors in answering the first research question required the investigation of all workplace activities that might be influenced by these factors, as well as some aspects of social life outside the workplace.

Another challenge is the sheer diversity of engineering work in different disciplines (e.g. civil, electrical, environmental, manufacturing, mechanical and about 255 others (Trevelyan 2014, Ch2)) and settings (e.g. consulting, manufacturing, construction, military, maintenance, sales and many others). Restricting the investigation to a single discipline, setting, or even a given level of experience might have reduced data collection and subsequent analysis efforts. However, narrowing the scope would also have limited the findings and the potential to generalize across engineering disciplines and settings. To maximize the chances of distinguishing differentiating factors, participant sampling emphasized settings where large apparent enterprise performance differences had been observed, for example in manufacturing, process industries, power and water utilities, and construction, and one setting in which South Asian performance equaled or even surpassed Australia: mobile telecommunications (Trevelyan 2014, Ch13).

Building on sampling diversity, therefore, the first analysis step was to understand and classify all the different activities that engineers reported in interviews and were observed performing in field studies. Assuming that engineers from different disciplines and settings would be engaged in at least some broadly similar types of activity, thematic analysis and interpretation would help to evolve activity descriptions that were independent of discipline and setting. Engineers from other disciplines and settings participated when suitable opportunities arose to help test the emerging work activity descriptions to help ensure that they could be used in a wide variety of disciplines and settings.

Flexibility and the importance of following up unexpected interview narratives led to a semi-structured research interview design. A pilot series of interviews showed that participants were interested and keen to contribute to the study, and would readily provide up to two hours of their time.

The interview questionnaire commenced with quantitative demographic questions on the individual (education background, education locations, years of study and work experience) and estimates of the numbers of engineers and other employees in the organization. Some open-ended "warm-up" questions on the participant's education experiences preceded the main interview questions below. While these would yield only indirectly useful data, the aim was partly to help the interviewer and participant become accustomed to each other proceeding with the most relevant questions:

Tell us about the good features and the deficiencies, as you now see them, of your studies at university or college for your first engineering qualification (degree, diploma, trade certificate).

Tell us why you chose engineering work in the first place. (Probe question, if needed: Tell us if the prospect of working in another country influenced your choice of education, and what difference this made.)

The next questions were designed to yield rich narratives on workplace activities without first pointing to any specific ones (with appropriate probes such as "*Could you explain a bit more about that?* ") and took up to half of the interview time. The responses were often the most interesting and informative because the conversation followed the interests of the individual participant.

Please tell us about your career so far.

Please tell us about your current position: (your role here, and your responsibilities).

The next question opened up activities that engineers tended to identify with more strongly in the technical domain:

Tell us about the technical aspects of your duties in your current position.

In retrospect, replacing "duties" with "activities" might have made a difference to the responses but in practice, the interviewer would often add a clarification, such as "… what you do each day."

In order to be able to answer the research questions, within limitations imposed by a 90 minute target time for a workplace interview, it was essential to explore the totality of an individual engineer's workplace experiences. Later questions served as prompts to help participants describe aspects they could have missed in the responses to earlier questions. Depending on those earlier responses, some of the later questions either had already been answered or required only brief responses. The following are samples only:

Tell us about any planning or estimating work that you do.

Tell us about any marketing or sales promotion work that you do.

To the extent that they were needed to expand on what participants had already related, further questions explored each engineer participant's social relationships:

Who do you report to, and for what? Do you have to report to more than one person, and if so, for what?

Who, if anyone, reports directly to you?

Tell us about any supervision responsibilities you have from time to time.

Tell us about any subcontract responsibilities: work that you are responsible for that is actually performed by subcontractors.

With the benefit of hindsight, these questions would have been designed differently. Some of the earliest findings revealed a complex web of informal, yet critical, social relationships outside formally designated workplace reporting relationships. Narratives describing these relationships emerged partly in responses to the earlier questions, and partly because many engineers had no formal supervision responsibilities, yet spent much of their time monitoring performance of multiple simultaneous tasks performed by other people. Some people were in the immediate work group but many others were not, and were often in completely different organizations (Trevelyan 2007). A question that might have exposed this more directly could have been:

Tell us about the interactions you have with other people in your daily work here.

With a question like this, further probe questions would be needed to elicit responses about each of the people the participant interacts with.

Some questions were included to explore engineers' values, motivations and expectations to provide some insights into social identity and help understand how engineers prioritize particular aspects of the work and their relative level of autonomy. It was expected that significant differences between Australia and South Asia would emerge in the responses to these questions in particular.

Tell us what you enjoy about your work.

What are the lasting effects of your work? (the contributions which will remain after you leave)

Which part of your job makes you think hardest?

Tell us how do you decide what to do each day? How much does your boss decide for you?

Many engineering enterprises provide 'scripts' that prescribe how people interact in the form of procedures and partly circumscribe autonomy. This question evoked some surprising responses and opened up some of the first clues about differences between South Asian and Australian workplaces:

Tell us about any fixed procedures that you are expected to follow, such as purchasing, design change control, defect reporting, etc.

Further questions explored financial and organizational awareness, job security, continuing education, promotion, procurement, information resources and dishonesty. Flexibility was needed to include questions on issues not addressed in the questions about past and current work activities, and there was neither need nor time to pose every question.

Data gathering was not restricted to semi-structured interviews, however. Notes on interesting aspects of casual conversations before and after the interviews provided a rich source of insights to follow-up later. Field study notes (by students) helped to validate interview responses, confirm that the interviews covered the full gamut of workplace activities in sufficient detail, and some provided rich narratives that were ultimately critical in answering the principal research questions. Quantitative studies were also an important part of the project, helping to provide triangulation data as well (Trevelyan and Tilli 2008, Robinson 2013).

FINDING PARTICIPANTS

Interviewing engineers in their workplaces poses special challenges for any researcher. Unlike engineering education studies for which every year brings a new cohort of participants seated in the researcher's classes, practicing engineers are much less accessible. Many work in remote locations. Many work behind a veil of commercial or government secrecy, and most work under time pressure with schedules that are difficult to predict more than a few hours or a day ahead at any one time. All these factors can make it difficult to access engineers for workplace studies. Inevitably this requires consent from their employers, who also contribute their engineers' time for research. Gaining this consent can be difficult, especially in the case of smaller companies who have not been involved with similar research studies before. Even in a larger company, without a friendly and influential champion on the inside, it can be difficult to gain official approval for a research study.

Students engaged in professional practice as employees or interns can be very helpful in overcoming these barriers. In this project, students' relationships within one or more particular firms pointed to individuals through whom the lead researcher could gain the required consent for the students to conduct research interviews or field observations, and often the lead researcher was able to accompany the student for some interviews. PhD students with extensive prior work experience were particularly helpful in negotiating access to engineers in new firms for research interviews. All the firms in this study were happy with the confidentiality provisions of the university's human research ethics procedures (National Health and Medical Research Council 2007) and none requested additional confidentiality provisions apart from publication restrictions in two cases. These relationships with firms also helped the lead researcher access engineers for his own interviews.

None of the firms involved in this study expressed significant reluctance in making their engineers available. However, practical difficulties were often encountered in arranging interview times as many engineers experienced frequent schedule changes and interviews were often cancelled or postponed with little advance warning.

In South Asia, considerably more persistence was needed in opening relationships with firms and high level contacts were often essential (Domal 2010). Local university faculty were helpful in arranging access to these contacts. The idea of participating in a research interview was new for many South Asian engineers, and some expressed a degree of initial confusion thinking that they were being interviewed for some new position in the company.

COLLABORATION AND DATA SHARING

Collaboration with students supervised by the lead researcher was critical in successfully completing this research with a sufficiently large shared qualitative data set. However, this could only succeed if the interests and objectives of the students in their research projects were sufficiently well aligned with the principal research questions. Hinds, Vogel & Clarke-Steffen (1997) draw attention to one of the fundamental challenges in sharing qualitative data: the need for close alignment in the research purposes in gathering the data. They explained how the purpose of secondary analysis needs to be sufficiently aligned with the rationale for collecting the data in the first place to avoid compromising the validity of the findings.

The question “What do engineers really do?” attracted the attention of undergraduate and masters students looking for intellectually challenging capstone research projects, and for others offered a way to learn more about a career as an engineer before finally deciding whether to embark on one after graduation. Several chose the topic because they thought (correctly) that many potential employers would value a deeper understanding of engineering practices in the workplace when hiring graduate engineers.

Out of an annual department capstone cohort of 200-220 students, between one and four students chose engineering practice research each year. All the prospective students were warned that selecting a relatively unconventional research project for an engineering school could compromise dissertation grades awarded by academic colleagues who mostly had little understanding of social research methods, let alone qualitative research and a few students chose other topics after hearing this.

The research questions attracted the interest of six PhD students in five years, all with engineering work experience (between 2 and 30 years, total >100 years). Each brought challenging observations from their work experiences. Two were curious as to why clients failed to take the recommended measures to capture the potential benefits from their maintenance consulting work. They both accepted that it was unclear what the clients’ engineers were doing in their work, and researching a detailed understanding of practice might help explain their observations. Another two compared engineering practices in their home countries with Australian practice, one in manufacturing and another in telecommunications. Another was puzzled by the consistently low ranking of consulting engineering firms in surveys of service quality. Yet another realized that consistent reports of poor data quality in computerized maintenance management systems, an issue that seemed to persist despite technological, training or organizational changes, suggested that searching for a sociological explanation might be helpful. They all saw the need to develop better quality, detailed understandings of workplace practices in order to answer their chosen research questions.

All of the students therefore, had interests that aligned with the over-arching project objectives, and developed limited scope projects with similar aims. In this way, the challenge of aligning the reasons for gathering qualitative data can be addressed adequately (Hinds, Vogel, and Clarke-Steffen 1997).

Bishop (2009), in a discussion of qualitative data archiving, has reminded us that there are ethical issues that arise when qualitative data is reused for subsequent secondary analysis. Her discussion mainly focuses on the ethical issues and particularly the balance between respecting the rights of the participants who have contributed what is often personal and confidential information, and the expectations of the wider community for trustworthy research conducted with minimum inconvenience. Qualitative data collection is time-consuming for both participants and the researchers and, she argues, data should be available for reuse whenever it is feasible and has been collected with the appropriate ethical safeguards.

In this project, the ethical issues were addressed by ensuring that all of the student research studies have been conducted within the host university's human research ethics framework with individual approvals for each one (National Health and Medical Research Council 2007). It would have been possible to conduct most of the studies with a single research ethics approval covering the acquisition and analysis of qualitative data over an extended time. However, the process of applying for ethics clearance is itself a valuable educational experience for students, even though approvals were sometimes received after long delays. By working within the author's prior ethics approval, the students could still proceed with their own data collection without having to wait for their own applications to be approved. A consistent approach was adopted by all students to ensure that the identity of participating companies and individual engineers would be protected. Pseudonyms or data identification numbers were used in publications.

Some companies demanded that the research reports not be published and some reports contained discomforting findings for the sponsors. The interview transcripts from these studies, therefore, had to be quarantined from the shared data set. However, research supervision discussions enabled the insights from these confidential studies to be shared and important generalizable findings have since been disseminated in other publications, with appropriate permission when needed.

Apart from aligning the rationale for data collection and providing guidance to ensure ethical research conduct by students, the next important methodological issue was maintaining data quality and consistency.

In the early stages of their projects, students were given selected readings on qualitative research methods and interview transcripts shared from earlier studies to understand what was expected in a qualitative research interview. Reading transcripts also helped students focus on specific practice issues and often motivated them to pursue new research directions.

Several student projects opened up new lines of investigation, for example a study to understand why engineers seem reluctant to engage in error-checking in design (Mehravari 2007). This is an instance of an approach described by Hinds and her colleagues (1997): using pre-existing qualitative data as one data source while continuing to refine the study purpose, questions and data collection processes. The dataset generates additional hunches, research questions or hypotheses.

As each student project had a different focus and scope, students would replace some of the questions in the second half of the interview with their own so the interviews could be adapted for the aims of their particular project.

In this way, at least the first half of each interview was consistent across nearly all the student projects.

To achieve a high level of consistency with interviews, each student practiced their interview technique with the lead researcher (also their supervisor) before starting field work. To help maintain consistency through each project, students provided recordings (when available) and draft transcripts for checking and to provide the supervisor an opportunity to suggest improvements in their interview techniques.

None of the students had significant difficulties in achieving satisfactory interview proficiency, though there were differences in the quality of the interviews and transcripts. Most transcribed their own interviews though some undergraduate students found that they did not have time to fully transcribe every interview. Tables 1–3 summarize the shared data collection.

REUSING QUALITATIVE DATA

In a discussion on the possible reuse of qualitative data set for secondary analysis, Hinds, Vogel & Clarke-Steffen (1997) described several different approaches that involve secondary analysis of qualitative data. All these techniques were used in this project.

One technique is a shift in focus of analysis by the original researchers who collected the data. For example, analysis of interview data on understanding supervision and reporting relationships in

Summary of Interviews Conducted	Researcher level*	Engineers interviewed	Notes	Quantitative Survey Participants	Field studies
James Trevelyan	Academic	83	10 with others	221	2
Adrian Han	U	8			
Devid Mehravari	U	5			1
Michael Crossley	U	7			
Sanji Sivabalan	U	5			
Tim Maddern	U	6			1
Marcus Peterman	M	5			1
Leonie Gouws	P	31			
Adrian Stephan	P	30			
Sule Nair	P	10			1
Emily Tan	P	26			
Vinay Domal	P	29			3
Siong Tang	P	34	(data quarantined)		1
Sarah-Jayne Robinson	U			160	
Ron Jacobs	U	13			
James Concannon	U	5	(+6 students)		
Emma Hamsma	U	4			1
Gerarda Westcott	U				
Sheena Ong	U	15			1
Chris Brown	U	6			
Japleen Kaur Bhatia	M	7			
Ravinderpal Singh	U	7			
Naijiao Bo	U	14	(+11 students)		
Henry Tan	U	5	(+2 students)		
Johannes Scholz	M	4	(+6 students)		
Total		**351**		**381**	**12**

* Student classifications: U = undergraduate, M = masters, P = PhD

Table 1. Summary of research data collected. Note that several investigators also interviewed students for comparative purposes.

engineering practice revealed that most social interactions occurred outside organizational reporting lines. This prompted a secondary analysis of the same data that yielded the idea of technical coordination, an informal performance that seems to dominate engineering practice with high degree of consistency between different practice settings and disciplines (Trevelyan 2007).

Another technique possible with shared data is to extract a subset of cases for similar but more focused analysis relative to the primary study. Subset selection can be based on shared characteristics

Countries	
Australia	236
Brunei	29
China	2
Germany	2
India	48
Pakistan	20

Table 2. Countries in which interviews were conducted with engineers.

or processes that distinguish the subset from the larger sample. Subsets of interview data have been used to explore issues specific to a particular setting or discipline, for example, patterns in sharing technical knowledge within a particular firm.

A third technique is to reanalyze all or part of the dataset by focusing on a concept that seems to be present but was not specifically addressed in the primary analysis. For example, when we discovered that value perceptions might play an important role in understanding engineering practice, it was useful to reanalyze earlier interview data to find the different contexts in which words such as "value" and "benefit" were used by the participants. Questions with responses providing insight into value systems and motivations were re-analyzed (Trevelyan 2012). Another instance was the discovery that engineers engage in a variety of teaching performances (Trevelyan 2010a). By being able to reanalyze shared interview data, it was possible to draw on a much larger dataset that would have been possible in a single focused study of limited time duration.

VALIDATING FINDINGS

Several techniques helped to validate research findings. While few of the undergraduate students managed to independently triangulate their findings, all of the PhD students were expected to.

Countries	
Australia	8
Brunei	1
India	2
Pakistan	1

Table 3. Countries in which participant observation field studies were conducted.

Findings from the principal study have been validated in several different ways. First, several of the student projects contributed independent interview data using similar questionnaires that enabled gaps in activity descriptors to be identified (Trevelyan 2008). Published literature mentioned earlier with qualitative data on engineers' activities was used as a further source for validation data. Quantitative studies reaching a large sample of engineers also helped validate qualitative findings (Trevelyan and Tilli 2008). Several field studies performed by students (table 1) provided further data to compare with interview data in the same firms (e.g. Petermann et al. 2007, Domal 2010). Finally, the lead researcher discussed findings in detail with several participants, some on repeated occasions, helping to refine and simplify descriptions of the findings.

Subsequently, the lead researcher discussed the findings in several firms, in some instances with the aim of helping with career development for younger engineers. These teaching experiences led to the discovery of many notions of practice among engineers that were significantly limiting their career development (Trevelyan 2011). For example, one engineer with three years of experience acknowledged her need to develop better communication skills by saying "I know my communication skills are poor, and I will need to do something about that when I am a manager." While she had earlier acknowledged that her communication skills were limiting her abilities to work with clients, she clung to a belief that better communication skills would only be needed once she commenced management responsibilities.

FINDINGS AND IMPLICATIONS

Fifteen final year capstone research projects have been conducted by students as part of this investigation, extending the shared qualitative data set well beyond what would have been possible with a single investigator project, or even with several PhD students working on the project. All these capstone research projects resulted in qualitative data that was used partly for qualitative analysis and partly for validation of the findings. One other capstone research project contributed validation data on conceptual misunderstandings from a quantitative survey with a sample of 160 engineers.

As well as enlarging the primary qualitative data set, these student projects resulted in relevant learning for capstone students, particularly engineering practice and social science research methods. They all learned to observe and appreciate the significance of human behavior in engineering enterprises. These students also discussed their work with peers, widening the impact of their learning in student cohorts. Research participants learned too: many gained new insights into their own practices by answering the research questions and some made comments such as "That was very interesting: through the interview I have come to understand what I do in different ways."

Students contributed original ideas for the principal research project, some from their own qualitative data analysis and others through discussions with research team members (e.g. Gouws 2014, Tan 2013, Tang 2012). Several students helped the lead researcher focus on particular engineering practice issues, such as error checking in design work (Mehravari 2007) and perceptions of commercial value by engineers (Crossley 2011). The shared qualitative data contributed by the students significantly extended the data set available for analysis and extended the data set to engineering disciplines and settings beyond those originally planned for the study.

There were some limitations in the quality of data collected by students, however. In some, but not all cases, the students were satisfied with relatively brief responses from participants, and did not necessarily see opportunities for probes that could have elicited valuable clarifying explanations. However, when this was pointed out to students in subsequent discussions and review of interview materials, some of the students approached participants by telephone and obtained supplementary explanations that provided some additional data. Since most students had projects with specific aims, and questions related to those aims, most of the additional data that would be directly usable for the principal study was provided in response to the first few (standardized) questions mentioned earlier. Therefore, each student interview provided less usable data than an equivalent interview conducted by the lead researcher. However, the students were able to conduct and transcribe many more interviews than the lead researcher could have in the same time period.

Some students transcribed only parts of their interviews, but provided the recordings for full transcription later.

Principal research findings

The findings of the principal research study contain some challenging findings for engineering educators. Space permits only a brief summary of the implications for educators and the reader is directed to earlier publications for more detail.

What do engineers really do?

The research findings identified around 85 different work activities and a similar number of different aspects of specialized knowledge (Trevelyan 2014, 2008) and descriptions of these activities that were meaningful in all the engineering disciplines represented in the study. Within the interview quotations mentioning interactions with other people, an intriguing pattern emerged. Most social interactions were outside formal reporting relationships and seemed to be associated with gaining the willing and conscientious collaboration of other people performing aspects of technical work, and monitoring the performance of the work to ensure it was completed on schedule: an informal version of project management, but largely undocumented. Since labelled 'technical coordination' this work appeared to take up 20-30% of an engineer's time, and was remarkably similar between disciplines and settings (Trevelyan 2007). Similar findings have been reported by other researchers (Engeström 2004, Blandin 2012, Anderson et al. 2010). A largely quantitative longitudinal study of a cohort of engineering graduates through the first three years of their careers revealed similar evidence, and the overwhelming predominance of work involving direct interactions with other people face to face, via telephone or through exchanging emails and documents, about 50-70% of the time (Trevelyan and Tilli 2008). Similar evidence comes from published literature (Kilduff, Funk, and Mehra 1997, McGregor and McGregor 1998, Youngman et al. 1978, Tenopir and King 2004, Williams and Figueiredo 2013). Surprisingly the proportion of time spent interacting with other people seems relatively invariant with career experience level, and one explanation for this appears to lie at the core of specialized engineering knowledge: knowledge is distributed in the minds of the participants and collaboration is the means by which engineers gain access to this knowledge (Trevelyan 2010b, 2014, Ch 5).

A complex series of technical collaboration performances critical for engineering practice has emerged from data analysis: discovery learning, informal teaching, technical coordination, project management and negotiation (Trevelyan 2014, Ch7-12). Not only are the performances complex in themselves, but they are specialized in the sense that preserving sufficient alignment between technical intent and interpretation seems to be a unifying thread, distinguishing these performances from more generic teamwork performances. Technical problem solving can be better understood as a social process (Jonassen, Strobel, and Lee 2006) and even as a negotiation (Itabashi-Campbell and Gluesing 2013, Trevelyan 2014, Ch12).

This strong element of collaboration does not seem to have received equivalent emphasis in earlier descriptions of engineering reflecting its apparent significance in practice (e.g.Layton 1991). Even though much is lost in reducing rich complexity emerging from analysis into a single succinct description of engineering, it may be helpful to attempt that here, using italics to emphasize parts that appear to be missing from earlier descriptions.

> Engineers collaborate with investors, clients, communities and end users, using their specialized knowledge and experience to discuss alternative futures in terms of technical possibilities. They devise and implement solutions that *create economic and social value by enabling people to do more while requiring less overall human effort, material resources, and energy with less uncertainty, environmental degradation and other harmful effects*. Engineers predict the technical and commercial performance of feasible solutions so investors and communities can decide with a degree of confidence whether the benefits

sufficiently outweigh the expected lifetime costs. *Engineers organize, manage and coordinate the collaboration of diverse actors to deliver chosen solutions while retaining sufficient technical and commercial alignment with the original intentions. Engineers aim to do this well enough for all stakeholders to receive their anticipated benefits in order to encourage repeat business in future.*

Communication between engineers and others underpins technical collaboration performances. Most of the uncertainty in engineering practice seems to arise from the differences of interpretation inherent in human communication (Collins 2010) and much of the coordination activity by engineers can be seen as maintaining sufficient alignment between original intentions and the diverse interpretations by individuals involved in both design and implementation (Trevelyan 2014, Ch10).

An explanation for enterprise performance differences has to encompass both the traditional engineering sciences and social sciences because engineering results depend on both the physical laws of nature and the ability of people to collaborate and retain sufficient alignment with original intentions. Just as engineering has drawn on intellectual developments in the physical sciences for innovation and improvement, there is also the potential to draw on corresponding developments in the social sciences (Trevelyan 2013b). Some of the most powerful explanations for the observed differences in engineering workplace practices lie in understanding the social culture of the society and the social power relationships within which engineering is performed. Disciplines such as anthropology and linguistics have informed the data analysis and have revealed fundamental factors that influence engineers' access to essential knowledge.

Engineering science principles are universal, to an acceptable degree of precision. However, the ways that people collaborate in an engineering enterprise that depends on technical expertise for success are dependent on the social culture in which the enterprise is embedded, and most engineers are ill-equipped to navigate the intricacies of social culture. In South Asia, we found several cultural factors that explain the relative performance difficulties for most engineering enterprises and also the undoubted success of mobile telecommunications. Understanding relative engineering enterprise performance, therefore, requires a sufficiently elaborate understanding of social behaviour in a technical setting.

One of the first differences to be identified emerged even before analysis of the qualitative interview data.

Contrary to the expectation that engineers in South Asia would less freedom to depart from fixed procedures than engineers in Australia, interview data showed that organizational procedures seemed to have much more influence on engineers in Australia than South Asia. Three South

Asian participant responses to a question on the influence of organizational procedures provide a representative selection:

> "No, they are not laid down at all."

> "No, the owner is a flexible man and has allowed me to establish the necessary procedures."

> "I don't have fixed procedures, just an outline of what I am expected to do based on my job description that I have shown you. Each person in this position will institute different procedures to suit himself."

Many South Asian engineers paid scant attention to a few extant workplace procedures, and did not see them as important. Technical issues were much more important to them than what they regarded as "administrative restrictions" on what they were allowed to do.

Most Australian participants, on the other hand, reported a myriad of documented organizational procedures that dictated many of their work activities. Most of these procedures choreographed collaboration between engineers and with other actors, for example laying out processes to be followed for checking technical documents and eliciting client requirements. Many successful engineering enterprises have learned the importance of these procedures to ensure that necessary collaboration occurs. Written procedures, along with learned patterns of collaboration, form much of the intellectual capital and provide significant competitive advantage for specialized engineering firms.

In contrast with other industries, it was notable that telecommunications engineers in South Asia worked with much more extensive organizational procedures inherited from US and European parent companies.

This research builds on earlier work that has demonstrated engineers' reliance on tacit and practical knowledge distributed in the minds of other actors such as technicians (Bechky 2003, Mukerji 2009, Trevelyan 2014, Ch13). Data from South Asia demonstrated the difficulties encountered by engineers in accessing this knowledge among technicians and operators. Deep social and cultural divisions and even one or more language barriers can stand in the way. Engineers were observed explaining technical objectives while technicians preferred to remain silent rather than asking clarifying questions, let alone challenging the engineer on the practicality of the objectives. To do so risked loss of face for the engineer, and loss of employment and family destitution for the technician. Engineers in manufacturing were almost completely unprepared for these difficulties (Domal 2010). However, technicians in the telecommunications sector were more likely to share a similar cultural background and language (English) with the engineers, significantly reducing the social divisions between them, and were more confident in their interactions with engineers (Trevelyan 2014, Ch13).

Perhaps the most challenging finding from this research for engineering educators is the overwhelming significance of technical collaboration in engineering practice and the challenges for engineers in collaborating effectively, not just with other engineers, but all the other actors involved in engineering enterprises. Conceiving engineering practice as a series of technical collaboration performances requires a much more elaborate understanding of social interactions than is currently the case in engineering schools.

There is a deeply embedded notion within engineering discourse that communication involves the transfer of information from one person to another (e.g.Galloway 2008, p26). An example from a research interview helps to demonstrate how this notion can be destructive in the context of collaboration. A senior engineer asked for the interview to be suspended after receiving a phone call from a very distressed client, complaining that they had heard nothing from the responsible engineers for several months. The engineer responsible for the work was summoned to the office and when he arrived, was asked why the client had not been kept informed about progress. "Well, there's nothing to report because the design isn't finished yet, and won't be for another few weeks. So there's nothing to tell them." Unfortunately, in a context where communication is considered to be information transfer, and there is no new information to transfer to the client, the young engineer was rightly thinking that there was no need to communicate. The idea that communication is only needed when information needs to be transferred is one of many fundamental misconceptions uncovered by this research: misconceptions that seem to persist many years or even decades into an engineer's career (Robinson 2013).

This short example can help us understand how misconceptions can arise in the absence of formal treatment of technical collaboration in the engineering curriculum: curriculum gaps allow students to develop misconceptions that are all the stronger because of the ways they are reflected in contemporary engineering education literature (Trevelyan 2011).

While teamwork and collaboration is acknowledged to be a part of engineering practice, it is seldom explicitly taught: students, more often than not, are expected to learn through practice alone and practice without evaluative feedback reinforces bad habits as much as good ones (Sheppard et al. 2009). Even when introduced in the context of design, collaboration and teamwork can evoke resistance from students, accustomed to an education model that implicitly rewards individual performances through individual grades (Paretti 2008, Leonardi, Jackson, and Diwan 2009).

Research revealed large curriculum gaps even at the components level of communication skills. Data showed that engineers spend 20-25% of their time listening yet listening is seldom if ever taught explicitly in engineering. Students using simple self-assessment instruments returned low listening and reading scores (Trevelyan 2014, Ch6), suggesting opportunities for significant improvement.

Curriculum gaps are emphasized by the contemporary focus by many engineering educators on technical problem solving, and some others on design (Sheppard et al. 2006, Jonassen, Strobel, and Lee 2006, Dym et al. 2005), and both have often been conceived as solitary cognitive tasks that "define" engineering. A strong theme emerging from this research is the relatively small component of engineering practice that can be characterized as solitary technical problem solving and design. Participants were able to recall relatively few specific problem-solving episodes, and many served as markers in their career, recalled in great detail. Problem-avoidance was preferred to problem-solving by following technical standards and by adapting previous designs and solutions for new clients. Naturally, the ability to apply engineering science to make accurate performance predictions for known solutions was critical in being able to avoid unnecessary problems. Furthermore, most reported problem solving episodes were collaborative, supporting similar published findings (Korte, Sheppard, and Jordan 2008, Jonassen, Strobel, and Lee 2006, Itabashi-Campbell and Gluesing 2013).

Educators' emphasis on problem solving can be seen in many discussions on curriculum. For example, Downey and colleagues have described global engineering competency as "Through course instructions and interactions, students will acquire the knowledge, ability and predisposition to work effectively with people who define problems differently than they do." (Downey et al. 2006) Yet, as an example of assessing global competency, they cite a hypothetical episode that explores cultural differences in collaboration, thus conflating collaboration with problem solving.

The differences between South Asian and Australian engineering practices observed through research interview notes and transcripts and field study notes in this study were all related to ways in which social culture influences technical collaboration performances. This suggests that global engineering competency could be better described in terms of "working with people who collaborate differently" while not underrating the significance of representational differences. A wealth of evidence emerged from this research that explained the large apparent differences in enterprise performances in ways that also explained the relative success of mobile telecommunications enterprises (Domal 2010, Trevelyan 2014, Ch13).

The research also revealed a small number of engineers who had stumbled upon, and could not necessarily explain, highly effective localized collaboration in their firms. These engineers were highly rewarded because their firms recognized the value of their work and provided significant financial incentives for them to stay. This finding suggests that if other engineers could learn similar performance techniques, large productivity improvements could be possible. If these practice improvements were adopted broadly within engineering enterprises in low income countries, even industrialized countries, we could see significant overall economic improvements as a result. For example, reducing the real economic end-user costs for power and water through improved engineering practices could be a significant step in eliminating poverty that has stubbornly persisted despite many other intervention efforts.

Open research questions

There are many further questions that arise from this project that could inspire further investigations. While this study has provided some insight into engineers' workplace practices, the range of settings and disciplines has necessarily been limited. Detailed studies in most countries of the world still lie ahead and many cultural issues that influence engineering collaboration practices remain to be discovered. Given that value perceptions significantly influence engineers' motivations, the next obvious research question is "Why do engineers do what they do?" While some of the data collected for this study is providing insights into engineers understanding of value (Trevelyan 2012, Crossley 2011) much more is needed to understand motivations and choices made by engineers in highly autonomous work settings. Recent work has built momentum for further studies on engineering practice that could help build understanding in this crucial area (e.g.Williams, Figueiredo, and Trevelyan 2013, Anderson et al. 2010), complemented by recent contributions in Engineering Philosophy (e.g.Davis 2015).

One pressing issue for engineering educators concerns the links between education and practice: how do different curricula and pedagogies influence practices by individuals or whole cohorts of graduates? The few available studies have indicated rather tenuous connections between academic performance and subsequent career performances (Lee 1994, Gibbs 1995, Gibbs and Simpson 2004) and more studies of engineers' early career experiences could help us better understand the connections between education and practice (Korte 2007, Korte, Sheppard, and Jordan 2008). Without such understanding, it is difficult to be confident in advocating improvements in education programs. Beyond studies on engineering practice further understanding is needed on how education experiences shape subsequent work practices, beliefs and value systems.

This paper has described how such studies could be pursued on a broader scale by engineering faculty, using shared data collected partly by students to build large data sets needed to explore these complex socio-technical issues.

Research is needed on pedagogies that enable students to learn effective collaboration techniques, and to see these as being as critical for an engineer as being able to apply engineering science to make accurate performance predictions.

The significance and stature of practice knowledge in relation to engineering science within the discipline is represented by the choice of research topics in an engineering school. It could be argued that this selection implicitly defines what constitutes legitimate engineering knowledge (Seron and

Silbey 2009, Quinlan 2002). In today's universities, this selection comprises mostly physical sciences, for example nanotechnology fabrication methods. Gradually, biology is establishing a foothold, for example nonlinear finite element modelling of brain tissue is a research topic in the author's school. However, beyond some presence in industrial engineering and project management, research on human behavior is seldom represented. Therefore, one way to help students attribute appropriate significance to the learning of technical collaboration techniques would be to encourage research on engineering practice, and this paper demonstrates how capacity for this research can be developed with modest resources.

Of course, it is also worth noting strong evidence for the effectiveness of collaborative learning techniques (Smith et al. 2005). Understanding the significance of technical collaboration in engineering practice might strengthen arguments to adopt these methods more widely to create classroom environments that more accurately reflect engineering practice. Part of this change probably has to include assessment methods that reward students for their contributions to the success of other students. This reflects practice where engineers are rewarded less for their individual performances than for the results they engender in other people who implement the technical ideas created by engineers.

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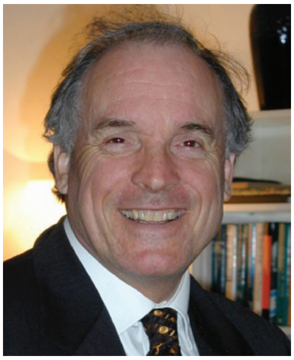

James Trevelyan teaches in the Mechanical and Chemical Engineering School at The University of Western Australia, is a Fellow of Engineers Australia, and practices as a mechanical and mechatronics engineer developing new air conditioning technology through his technology start-up, Close Comfort (www.closecomfort.com). His main area of research is on engineering practice and he has recently published a major book: "The Making of an Expert Engineer." He teaches mechanical design, sustainability, engineering practice and project management. He is well known internationally for pioneering research that resulted in sheep shearing robots (1975–1993). He and his students produced the first industrial robot that could be remotely operated via the internet in 1994. He was presented with the 1993 Engelberger Science and Technology Award in Tokyo in recognition of his work, and has twice been presented with the Japan Industrial Robot Association award for best papers at ISIR conferences. He has also received university, national and international awards for his teaching and papers on engineering education. From 1996 till 2002 he researched landmine clearance methods and his web site is an internationally respected reference point for information on landmines. He was awarded with honorary membership of the Society of Counter Ordnance Technology in 2002 for his efforts, and was also elected a Fellow of the Institution of Engineers Australia. Professor Trevelyan's web pages are at http://JamesPTrevelyan.com/ and http://www.mech.uwa.edu.au/jpt/ providing further information on his research and teaching.