Research Methods: Why we can trust the results

Online supplement for "The Making of an Expert Engineer" by James Trevelyan

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1. Introduction

This technical appendix explains aspects of the research contributing to the material in the book.

It is my intention that any reader who has taken the trouble to access this appendix document will be reasonably satisfied that they can trust most of the material in the book. It is not my intention for this document to present a rigorous account of the research methods used. Peer reviewed publications such as journal articles, Ph.D. theses by my students and, to a lesser extent, conference papers are the widely accepted means by which research methods are subject to critical review and assessment.[1]

A book provides an opportunity to describe a coherent set of ideas. Many ideas in this book have not been published before. Therefore, the trustworthiness of many parts of this book can only be assessed after some time, when readers have had the chance to contest the ideas. Inevitably, therefore, there has to be debate and discussion, and maybe the need for further editions and revisions.

The original motivation for this research emerged between 1997 and 2002 when I worked with Pakistan-based engineers on the development of experimental technologies for landmine clearance ("demining") in Afghanistan. Even though these engineers were intelligent and well educated, there was a marked difference in their ability to produce practical results compared with my experience of engineers working in Australia.

During this time, I had acquired some proficiency in the use of qualitative social science research methods. For example, one of the research questions that we addressed required us to interview experienced deminers, both at the management and organisational level and also at the working level, to elicit ideas on technologies that would improve the overall process. The most common response was "design a better mine detector." However, analysis of the qualitative data yielded a more insightful result, the notion of a "no mines" detector. This concept is a device that would indicate that a given area of land could be confidently declared "free of explosive devices". Then there would be no need for the tedious process of clearing the vegetation (with the possible risk of unintended explosions) and then meticulously checking every square centimetre of ground for the possible presence of explosive devices. Eventually, candidate solutions emerged from appropriately equipped research laboratories, including improved mine detection dog training methods and explosive trace detection methods that could survey large areas of ground rapidly without having to

[1] All our publications and most of the theses can be accessed at our web site: http://www.mech.uwa.edu.au/jpt/pes.html.

remove vegetation. This is still a work in progress. However, we can be confident that there have been significant advances on the traditional manual demining techniques that were the preferred methods for dealing with explosive remnants of conflict contaminating land required for human habitation and agriculture at that time.[2]

This experience with social science research methods provided the confidence to address questions relating to the apparent performance of engineers in a different environment from Australia.

Anticipating that there would be plenty of data on how engineering work is performed in industrialised countries, I took the opportunity of an extended stay in Pakistan to start interviewing engineers. Drawing on the connections that I had in the country, I was able to access engineers in both government and private employment, in both large and small enterprises.

As I collected detailed observations, I became aware that the costs of performing engineering in Pakistan were quite different from my expectations. I had to adjust my initial naïve understanding that engineering would be much less expensive in Pakistan because, on average, the people involved were paid 20 – 30% of the equivalent salaries they would have received in Australia.

Often it is possible to get work completed at what appears to be minimal cost. However, this can be deceptive. The time and trouble required to find someone who could do the work, arrange for them to be available, supervise its execution, and check the results, all add considerable indirect costs that can be difficult to perceive at first. It can be difficult or impossible to find suppliers, appropriate tools and equipment to work with the best quality materials. All these have to be imported, with transport and import charges adding to the cost. While local workers are extremely capable, they still need extensive training and supervision to work with high quality materials, adding further costs for training and skill development.

Subsequent and more widely based observations in engineering enterprises in the larger South Asian community revealed large measurable performance differences such as, for example, the extremely high (mostly indirect) cost of safe drinking water, an essential community service provided by large engineering enterprises.[3] Similar but less extreme cost differences are apparent in electric energy. In making these comparisons, it is essential to compare the total direct and indirect cost required to achieve a given result rather than the official metered rate for supplying electricity. There should be strict equivalence for service quality: what is it cost to obtain the equivalent product or service at the same level of quality?

These observations motivated a search for explanations, including the possibility that differences in engineering practices could account for at least part of the large differences observed.

Subsequent research revealed only a handful of prior studies of engineering practice in industrialised countries that could provide detailed understanding about the different ways that ordinary

[2] The following references provide further reading: Trevelyan(1997); Trevelyan(1998); Trevelyan(2000); Trevelyan (2001); Trevelyan(2002b); Trevelyan(2002a); Trevelyan (2004)

[3] Sections of Chapter 1 and Chapter 13 in the book provide my most recent analysis: Chapter 13 is based extensively on analysis published only this year (Trevelyan, 2014b), which also draws on results reported in Vinay Domal's PhD thesis (Domal, 2010).

engineers were performing their work.[4] Much more data would be required to explain practice differences between Australia, Pakistan and other countries. Furthermore, a coherent model of engineering practice would be needed to understand how the observed differences in practice contributed to such large differences in outcomes.

Over the next ten years of so, I was fortunate to work with a team of postgraduate and final year undergraduate engineering students who had developed an interest in exploring engineering practice. Working together, we were able to accumulate a large body of qualitative data, much of which has been shared and re-analysed in order to build a coherent account of engineering practice.

In the next section, I will summarise the important aspects of the qualitative techniques that provided most of the findings. Later sections provide additional background material for each of the chapters to explain some of the additional sources of research information used in compiling them.

Research Method

We have adopted grounded theory approaches for data collection and analysis of data following well-known techniques.[5] There are several engineering-related case studies that provide models for students to follow with detailed guidance.[6] Some quantitative data and mixed methods approaches have also been used. Sule Nair also used narrative enquiry methods for her analysis, and Leonie Gouws invented her own techniques based on multi-criteria decision theory for working with hundreds of different codes.[7]

By working with research students to build a large qualitative data set over time, the author was able to access a far greater variety of engineering disciplines, workplaces and practice settings than would have been possible even with a generously funded research study. The graduate students brought insights from more than 100 years of practice experience between them. Final year undergraduate research students contributed more than 20 studies of engineering education and practice. A sufficient degree of commonality between these studies enabled a significant proportion of the data and analysis results to be used for the author's larger undertaking, providing a greatly expanded source of data.

In total, 337 interviews were conducted with engineers of which 83 were conducted by myself, and the remainder by my students. My own analysis included 119 interviews though most of the qualitative analysis was focused on a subset of 35 interviews with the remainder used for checking the findings and content analysis.[8] I focused on a further subset of 25 interviews and two field studies collected in India and Pakistan for the material presented in Chapter 13. In addition, with my students, we conducted participant observation field studies, and we obtained quantitative survey

[4] It took several years to search through social science, business and management journals, conferences and books (Trevelyan & Tilli, 2007). This would not have been possible without the sustained effort of Sabbia Tilli, my research assistant. Even after a thorough literature search, many research grant reviewers remained skeptical that such an obvious gap in the literature existed.

[5] There is a wide choice of texts describing these methods (e.g. Bryman, 2012; Huberman & Miles, 2002; Miles & Huberman, 1994; Patton, 1990; Strauss, 1987; Walter, 2006).

[6] Mintzberg (1973, p. Appendix), Zussman (1985), Orr (1996), Bechky (2003), Bailey and Barley (2010).

[7] Sule Nair, unpublished manuscript, 2010; (Gouws, 2014)

[8] Appendix 4 lists the interviews used for analysis

data from a further 381 engineers. Of these a subset of about 120 engineers provided repeated survey data for our longitudinal study collected every four months over a three year period.

Table 1: Summary of research data collected

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			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			
Naijiao Bo	U	14	(+11 students)		
Henry Tan	U	5	(+2 students)		
Johannes Scholz	M	4	(+6 students)		
Total		**337**		**381**	**12**

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

Table 2: Countries in which interviews were conducted with engineers

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

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

Countries

Australia	8
Brunei	1
India	2
Pakistan	1

Most of the analysis was required to support specific research publications and student theses. One exception to this was the analysis of different aspects of technical knowledge described in chapter 5. The explanations on technical knowledge have been published for the first time in this book. However, the same qualitative analysis techniques have been used.

Methodological challenges

Creating a model of engineering practice that could provide satisfactory explanations in most engineering disciplines and practice settings requires qualitative data from many different situations in which engineers work. Engineering disciplines represented in our studies so far include chemical, civil, electrical, electronic, environmental, manufacturing, materials, mechanical, mechatronic, software and telecommunications engineering: we have also accumulated a list of about 260 different disciplines.[9] Practice settings have included industrialised countries, low income countries, manufacturing, consulting, construction, utilities, maintenance, continuous process plants and others. Given that the data had to be collected by a team of researchers working over an extended time period, the main challenge has been to maintain sufficient consistency and quality to be able to work towards reliable conclusions.

Bishop (2009), in a discussion of qualitative data archiving, reminds us that there are methodological and ethical issues that arise when qualitative data is reused for subsequent secondary analysis. She also pointed out that historians re-analyse texts, often leading to different interpretations from earlier studies. Hinds, Vogel & Clarke-Steffen (1997) describe four different approaches that involve secondary analysis of qualitative data:

i) Shift in focus of analysis by the original researchers who collected the data.
For example, analysis of interview data focused on understanding supervision relationships in engineering practice revealed that most social interactions experienced by engineers occurred outside direct supervision relationships. 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).

ii) Extract a subset of cases for similar but more focused analysis relative to the primary study.
Subset selection can be based on shared characteristics or processes that distinguish the subset from the larger sample. In this study I focused most of the analysis on a subset of 35 interviews because nearly all of the variation in the data was represented by this sample. I then verified the findings by using the remaining interviews to find if there were issues not discovered in the analysis: very few additional issues were discovered.

iii) Reanalyse 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.

[9] Chapter 2 presents a list.

For example, when I discovered that value perceptions might play an important role in understanding engineering practice, it was useful to reanalyse earlier interview data to find the different contexts in which the words “value” and “benefit” were used by the participants (Trevelyan, 2012). Another was the discovery that engineers engage in a variety of teaching performances (Trevelyan, 2010a). By being able to reanalyse earlier 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.

iv) Use a pre-existing qualitative data set 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. In the early stages of their projects, students were asked to read transcripts of interviews collected from earlier studies. The main purpose was for them to understand what was expected in a qualitative research interview. This experience helped them focus on specific issues of interest and motivated them to pursue new research directions. In several cases, they researched specific aspects of engineering practice that opened up new lines of thinking. One example was a study to understand why engineers seem reluctant to engage in error-checking in design (Mehravari, 2007; Trevelyan, 2010b).

The fundamental question is the degree to which secondary analysis can differ from the rationale for collecting the data in the first place without compromising the validity of the findings.

This inevitably leads to discussions on research rigour, but we need to consider the purpose of research to assess the degree of rigour required. For example, if we need to check whether a particular refrigerator would fit in a kitchen recess, measurements of width, depth and height with an accuracy of 1 centimetre would normally be sufficient. On the other hand, if we need to check whether a new door will fit on an old refrigerator, we would many more measurements with a much greater degree of accuracy. The degree of rigour depends on the research questions and the quality and trustworthiness demanded in the answers.

In our studies of engineering practice, we have been mostly at the explanatory stage, generating knowledge and understanding of a domain that has largely been unexplored until now. Since we were more concerned with the discovery of different aspects of engineering practice rather than, for example, evaluating their relative significance in particular practice settings, reanalysing qualitative data did not pose significant methodological challenges.

Some of the studies had to be conducted more or less independently of the larger dataset to protect commercial interests of the participating firms. However, it was still possible to draw on the findings of these independent studies to inform the larger research effort on engineering practice.

The main research study and all of the student research studies have been conducted within the host university’s human research ethics framework with individual approvals for each one. 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.

Interviewing engineers in their workplaces poses special challenges. 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 days ahead at any one time. All these factors make it difficult to access engineers for workplace studies. Therefore, sharing data gathered by students has been important in order to accumulate sufficient data to enable the research results to be generalised with some confidence across several different disciplines and practice settings. All students used sample interviews from the main study as examples to guide their interviewing technique and for preparing transcripts. Some students also used selected transcripts from our library for their own projects, but all of the students strongly preferred to conduct and analyse their own interviews whenever possible.

Workplace studies on professional engineers require consent from their employers, who also contribute their engineers' time for this research. Gaining this consent can be difficult, especially in the case of smaller companies who have not been involved with similar research studies before. Pre-existing relationships with companies established by my students through their professional practicum internships or previous employment in the case of postgraduate students made it much easier to gain the required consent.

Controversies on grounded theory

In evaluating the results from this work, it is important to take into account recent discussions that have questioned the intellectual foundations of grounded theory research methods. One issue concerns the influence of prior knowledge or observer bias on both data gathering and analysis. Glaser and Strauss have emphasised the importance of avoiding such influences.[10] On the other hand, Strauss and other researchers have since taken the view that it is impossible to avoid such influences and it is better to expose them through systematic methods. More recent criticism has focused on claims relating to theory building.

Undergraduate students can act as relatively naïve researchers, often taking a completely fresh view of data and sometimes emerging with novel and creative interpretations. As a practising engineer, the my own analysis is inevitably framed by my experience of practice.

Recent debates on grounded theory methods have called into question many of the underlying assumptions that students need to make in order to complete their research studies within the prescribed time limits. For example, Thomas and James (2006) argue that grounded theory methods do not, by themselves, create new theories, nor can the researchers "neutrally and inertly lay some cognitive framework over the data they collect to allow them to draw 'theory' dispassionately from this data, this ground." Instead, they argue, the details of coding and analysis required for grounded theory can interfere with description, sense-making and enlightened insight and new researchers "risk losing the best of qualitative enquiry." Harry, Sturges and Klingner (2005) reflect on "years of conditioning to seek larger numbers for greater reliability" and conclude that the logistical and organisational demands required to collect large dataset actually limited the researchers' ability to devote sufficient time for examining emerging interpretations of the data. On a smaller scale, this same issue manifested itself with many of the undergraduate research studies that were restricted in time to just a few months.

[10] Glaser and Strauss {, 1967 #1379}

Another controversy that affects researchers working with grounded theory methods is the degree to which their prior experiences, particularly of engineering practice, will affect the way that they read and interpret the data from interviews and field observations. The principal researchers (the author and graduate students) all brought perspectives formed by substantial yet diverse industry experiences. Given that engineers can be remarkably economic with their own descriptions, hiding a mass of technical complexity behind just a few words (Trevelyan, 2014a, p. 83), a degree of insight from engineering practice is helpful for interpreting the data. This insight can be necessary for helping undergraduate students who have only a few weeks of internship practice experience.

Some student researchers starting out with a grounded theory approach faced discomforting criticism from other social science researchers insisting that they adopt a conventional "theoretical framework" before even starting their data collection. Latour (2005, pp. 141-157) provides some reassurance on this point, emphasising the overriding need for description and interpretation.

Even though the overriding objective of the author's research was to develop a coherent model of engineering practice that would help explain differences in practice outcomes between different settings, the students could complete their own research projects by focusing more on description and localised interpretation than theory development. It was sufficient, for example, for an undergraduate student to focus on a smaller group of engineers working within a single discipline in a single firm, such as project managers within the construction firm, and produce a description of the diversity in their careers, work roles, and future aspirations based on no more than five to ten interviews (Han, 2008). Obviously, graduate students were expected to create higher level abstractions based on much more extensive and detailed analysis of their data. By focusing more on description and less on model-building and theorising, students could avoid having to engage with ongoing debates on grounded theory and qualitative research methods. In our research we have focused on interpretation of the data with the aim of discerning regular patterns of social interaction. The main challenge has been to reduce the immense complexity in tens of thousands of pages of transcripts to just a few patterns of technical collaboration behaviour that can explain much of the landscape of engineering practice (Trevelyan, 2014a, Preface; 2014c). Such explanations provide potentially powerful ways to enable engineers to see meaningful patterns in what, to most, is seldom acknowledged as real engineering work.

Framing qualitative data collection: the questionnaire

All the students joined the research effort with similar motivations. The undergraduate students all expressed a curiosity about the kinds of work they would be performing as graduate engineers, and some thought that studying practice in detail would give them a head start in seeking employment opportunities. The postgraduate students all had practice experience (ranging from two to more than 30 years) and brought their own versions of the questions that motivated the larger project outlined at the start of this paper. For example, two postgraduate students were consultants and were curious as to why clients failed to take the recommended measures to capture the potential benefits from their work, and why there seemed to be little visible impact of their recommendations on the client's processes three or more years later. They both accepted that it was unclear what the clients' engineers were doing in their work, and therefore difficult to understand why these difficulties were occurring. Another two graduate students took on the challenge of comparing practice in their home countries with Australian engineering practice. Another was puzzled by the consistently low ranking of consulting engineering firms in surveys of service quality. Another realised that consistent reports of poor data quality in computerised maintenance management systems, an issue that seemed to persist despite technological, training or organisational 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.

With this fundamentally common goal, it was possible for most students to adapt the author's original qualitative questionnaire (Appendix 2) for their own projects. The first few questions were therefore common in nearly all the student questionnaires.

The questionnaire commences with demographic questions on the individual (education background, locations for education, years of experience) and estimates of the numbers of engineers and other employees in the organization. Some "warm-up" qualitative questions on the individual's education experience precede the main interview questions below.

> *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 how you now rate the quality of your studies at university or college - in comparison to other colleges or universities that you have heard of (either in your own country or other countries).*
>
> *Tell us about the costs of your education, if you can (cost of tuition, living expenses, tools, materials, books, computers, etc.)*
>
> *Tell us why you chose engineering work in the first place. (Tell us if the prospect of working in another country influenced your choice of education, and what difference this made.)*

The next three questions produced long responses (with appropriate probes such as "*Could you explain a bit more about* ____") and often took up to half of the interview time. The responses were often the most interesting and informative.

> *Please tell us about your career so far.*
>
> *Please tell us about your current position: (your role here, and your responsibilities).*
>
> *Tell us about the technical aspects of your duties in your current position.*

Depending on the kind of work being performed, and the responses to the first three questions, many of the later questions either had already been answered or yielded relatively short responses. The following are samples only:

> *Tell us about any planning or estimating work that you have to do.*
>
> *Tell us about any marketing or sales promotion work that you do.*
>
> *Tell us what you enjoy about your work.*
>
> *Tell us how do you decide what to do each day? How much does your boss decide for you?*

As a supervisor for all of the students, I provided initial background reading and training in qualitative research methods and interview techniques. Most practiced their interview techniques with myself or experienced graduate students before they interviewed practicing engineers. Most transcribed their own interviews though undergraduate students often found that they did not have time to fully transcribe every interview. I also listened to recordings (when they were available) to check transcription quality and to review completed transcripts.

Validating the findings

The research findings have been validated in several different ways.

First, as explained earlier, the intention was to gather data for analysis from a wide range of settings and engineering disciplines. Data was collected through semi-structured interviews, field studies and also in quantitative studies with moderately large samples of engineers. Data was collected in six different countries, mostly in Australia, India, Pakistan and Brunei. Most of my own analysis was focused on a subset of interviews and I used the remaining interviews and quantitative data to triangulate the findings. My own engineering experience, which continued throughout the time of this research, also provided a means to validate the findings. Obviously, my understanding of my own practice changed considerably as a result of performing this research. While my research was framed by my prior experience, and this must have affected the findings, that same research (and continuing practice) provided me with a reference point for comparing the research findings of my students who worked mostly independently.

Second, each of the individual studies performed by students has been conducted with careful attention given to validation through triangulation. Ph.D. theses and journal publications, in particular, have been subjected to rigorous peer review.

Third, all of the findings have been widely discussed, partly with engineers who participated in the study, and partly with other engineers in countless casual encounters, often as a result of asking about the research. The findings in India and Pakistan have been validated through my own continuing contacts and encounters with individual engineers and engineering organisations in those countries.

Fourth, the chapters in the book have been read by experienced engineers who have provided detailed feedback and comments to help with preparation of the final text.

Fifth, the explanations in the text have been developed progressively through my work with undergraduate and postgraduate students, and also through my experiences in having to explain the research to so many people of different backgrounds. I hope that these explanations are mostly sufficient in themselves. However, I expect the conversations to continue for some time yet and I have created an interactive website at http://JamesPTrevelyan.com to enable this to happen. I don't expect all of the findings to be accepted without debate and discussion. Not all of the findings have been supported by research that I would regard as complete and rigorous so I am open to reinterpretation and the necessity to revisit my findings in the light of future discoveries.

Chapter 1: Why engineer?

This chapter draws extensively from a discussion on understandings of value in engineering practice.[11] Two independent lines of investigation led to the finding that most engineers have difficulty understanding how engineering leads to commercial and social value creation. This has fundamental implications for the profession as a whole. A profession that has difficulty explaining its "raison d'être" (the principal reason for its existence) is likely to be in trouble, an issue that Rosalind Williams has drawn our attention to in her essay "Education for a profession formerly known as engineering."[12]

As explained in the chapter, my experiences in Pakistan and India transformed my appreciation of the value of engineering. However, few engineers have this opportunity. I had practised as an engineer for three decades before I personally confronted this issue: the value of engineering was something I had taken for granted since many different employers were willing to pay me to do it.

Some of the arguments in this chapter are based in development economics, particularly the concept of the value of time.[13]

Data on the cost of employing engineers has been drawn from formative experiences throughout my career preparing budgets for consulting engineering projects.

Practice quiz 2 was developed with the initial idea that it might be possible to use these questions as a way of monitoring the development of ideas about engineering practice and the way they change with experience. However, a quantitative study by Sarah-Jayne Robinson cast doubt on this idea because her data suggests that the responses from engineers do not seem to change very much with experience.[14]

However, this quiz can still be used to gauge the extent to which individual engineers (and students) conceive engineering in a way that matches the findings of this research. The indicative scores are based on the findings of Robinson's study.

Chapter 2: What type of engineer?

The list of engineering disciplines in table 2.1 and the comparison between main disciplines in terms of workplaces, thinking and safety implications in table 2.2 have been drawn from analysis of our interview data and field study results, combined with published occupation lists. I expect that there are disciplines that we have missed and would be grateful for further contributions.

Chapter 3: Flying start, no wings, wrong direction

Much of this chapter is devoted to fundamental misconceptions and practice concepts that set the stage for readers to appropriate[15] the material that comes later in the book.

[11] Trevelyan(2012)
[12] Williams(2003)
[13] For example, Ahmed(2006) and IT Transport Ltd(2002)
[14] Robinson(2013)
[15] A verb used in learning science literature roughly translated as "to learn and comprehend".

It is well known that the transition from formal education to engineering practice can be a discomforting experience for many young engineers.[16] Through our interviews, surveys and informal encounters we learnt that many young engineers find it so discomforting that they leave the profession within five years of graduation. Many even never find an engineering job to start with. The introduction to this chapter attempts to describe why this occurs and also to explain, mostly to younger readers, why it is so important for them to understand the ideas in the book.

The ideas in this chapter emerged from a field study with a medium-sized engineering consultancy in Australia. I was asked to explain some of the ideas from our research to a group of early career engineers with up to 8 years of experience.

It was this experience, more than anything else, that made me start writing this book. I found that I needed a coherent explanation that linked all of the ideas, a book that students could read at their leisure, when they were ready to confront new ideas. Verbal explanation alone was insufficient.

At the same time, however, I encountered a further significant difficulty. Some concepts were resisted by these engineers, no matter how hard I tried, over several weeks of explanation and practice exercises. Reflecting on my notes taken during the discussions, I began to realise that there are some significant misconceptions in the minds of young engineers. As I was unaware of these at the time, I did not realise that my explanations simply didn't fit with the conceptions of practice that they started out with.

As a result of my experiences working with these young engineers, recorded in notes and informal interview transcripts, I started to accumulate a list of conceptual misunderstandings (or misconceptions) about engineering practice. This grew from an initial list of about 20 to a combined list of 85 practice concepts, 17 common misconceptions and two additional general concepts listed in appendix 5. I analysed 19 introductory texts that aim to provide young readers with descriptions of engineering practice and I found that the practice concepts I had identified were almost entirely missing from these accounts, and many of the misconceptions were either reinforced or not countered with evidence.[17]

I have tried to develop the practice concepts as a step-by-step introduction to the ideas in this book.

The misconceptions seem to present learning barriers for many of these practice concepts. Anyone attempting to disseminate these ideas among young engineers is likely to encounter these barriers. I have received many informal reports from workplace educators about their difficulties with engineers in learning about the fundamentals of collaboration in a business environment. Gradually, I realised that many of the misconceptions arise inadvertently through a combination of existing texts and our current approaches to formal education for engineers.

[16] Martin, Maytham, Case and Fraser (2005) provide one of the best descriptions.

[17] (American Society of Civil Engineers, 2008; Auyang, 2004; Beakley, Evans, & Keats, 1986; Brockman, 2009; Burghardt, 1995; Dowling, Carew, & Hadgraft, 2009; Gabelman, 1996; Hansen & Zenobia, 2011; Holzapple & Reece, 2003; Horenstein, 1999; Jensen, 2005; J. C. Martin, 1993; Millar, 2011; Project Management Institute, 2004; Saeed & Johnson, 1995; Skakoon & King, 2001; Wells, 1995; Wright, 2002; Yuzuriha, 1998)

So far, this list of misconceptions and practice concepts is my own creation which has not been previously published in its entirety.[18]

It is perhaps coincidental that my first list of the different kinds of activity in which engineers can be observed produced from the initial analysis of interviews around 2007 contained about 85 different items[19], the same number as enumerated practice concepts in the book. I had hoped that subsequent analysis would bring simplifications, but I have had only limited success with that aim.

Even though, in the book, I have managed to describe a large proportion of engineering practice in terms of a few collaboration performances, it is not possible (so far) to avoid the need to confront complexity in engineering practice.

The choice of defining these misconceptions and practice concepts depends on one's starting point and I expect that this will need revision in future.

I have found that young engineers and students are much more prepared to accept that engineering is different to what they initially expected once they have seen quantitative research data. Our longitudinal study of engineering graduates was particularly valuable in providing data is that engineering students can readily identify with, particularly because the data was collected from our own graduates emerging from the 2006 cohort.

Chapter 4: Becoming an expert

In contrast to most of the other chapters, this one mainly draws on comprehensive research on expertise that has emerged in the last two decades, and published reports about C. Y. O'Connor. However, the research insights provided a framework for interpreting the findings from these sources.

Chapter 5: What engineers know

This chapter forms one of the main intellectual foundations for the book. It presents evidence that shows how much of the knowledge used by engineers is shared by verbal discourse. Much of the sharing occurs through the contribution of skilled performances rather than by attempting to transfer the knowledge.

I think it is necessary to update our contemporary understanding of what we mean by "engineering" in the light of the research in this book and many other contemporary reports. Collaboration and influencing have to become central ideas in this new definition. Bill Williams, with encouragement from Dominique Vinck, suggested that I write an introductory chapter providing a framework for theories that could help understanding engineering practice.[20] I adapted the ideas in this chapter to elaborate on a new definition of engineering in the context of an "engineering enterprise."

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[18] Some of the initial ideas appeared in Trevelyan (2011).

[19] Later, in analysing different kinds of specialised knowledge that engineers can be observed using (from our interview and field study data), this list of items was further extended as shown in Appendix 4.

[20] Trevelyan(2014c)

The discussion on definitions of engineering and knowledge owe much to discussions on the philosophy of engineering to which I was kindly invited by Russell Korte and John Heywood.

While many philosophers would find this material rather elementary, I have found it is necessary to explain some basic ideas about knowledge to help engineers understand the relevance of a philosophical discussion. It is necessary to understand the different kinds of knowledge that contribute to their work. Understanding the different kinds of knowledge is important because we can then understand some of the difficulties inherent in transferring that knowledge.

I chose to draw on published accounts of engineering practice to build the foundation for the maps of specialised engineering knowledge presented later in the chapter because they draw on a much larger body of data and experience than I could analyse myself. They add considerably to the breadth of settings and disciplines and I think they provide some fascinating insights for the reader, beyond what my own data would have been able to provide.

The classification scheme for specialised knowledge emerged from my analysis of interview data and field studies. I used published accounts of engineering practice to triangulate my own analysis, to make sure that I had not missed any important kinds of specialised knowledge. Published research on the kinds of knowledge that engineers use also provided further triangulation data and helped identify some categories that I had missed.[21]

The last part of the chapter then links the critical observation that engineers seem to spend about the same amount of time (averaging about 60% from many observation) on direct social interactions with peers, regardless of their career experience level. The best explanation I have for this observation is the idea of distributed knowledge and cognition. This leads to the conclusion that the technical knowledge that lies at the core of engineering expertise depends on social interactions and relationships. In other words, for engineers, influencing and social relationships are as fundamental as the technical knowledge that is normally regarded as pre-eminently important in engineering schools.

This finding sets the stage for the rest of the book.

Chapter 6: Three neglected skills: Listening, seeing and reading

The foundation for this chapter is the observation from research on experts that has identified their perception skills as being a critical component of expert performances, as explained in chapter 4.

This chapter draws extensively on my own experiences with material that I have used for teaching final year engineering students.

Having identified that listening forms such a significant part of practice (approximately 25% of the time for novices), I adapted material derived extensively from Robert Bolton's book "People Skills". While engineering students are not particularly keen to learn listening initially, once they evaluate the own listening skills using the procedure on page 174, many realise that they need to improve, and be able to take accurate notes. Contemporary teaching techniques that provide students with

[21] Gainsburg, Rodriguez-Lluesma and Bailey (2010), particularly early drafts of the initial manuscript provided by Dianne Bailey, and Vincenti's book (1990) were particularly valuable for triangulation.

on-line lecture notes, online recording of lectures, textbooks and PowerPoint slides can easily undermine students' listening skills. Another way I have used to encourage students to acquire listening skills is to work on the frustration that many experience trying to explain their ideas to their peers. By getting the students to learn how to observe when their peers are not listening, they can begin to recognise similar traits in themselves and improve their own listening practice. When I meet with students, I remind them take notes and, if they don't, ask them to demonstrate that they can remember exactly what I have said. When they find that they cannot remember, they begin to realise more about the value of note taking.

In 2012 I checked with the Australian Council on Education Research (ACER) to see whether anyone had developed some kind of listening skills assessment for university students, using relevant subject material, apart from techniques used in the IELTS and TOEFL tests. These latter tests have been carefully designed to assess listening capabilities of students whose first language is not English. They use multiple choice questions (MCQ) about a recorded speech that the students listen to. MCQs provide cost-effective means of assessment but they test different skills from the kind of listening that engineers need. ACER were unable to suggest an alternative to the exercises on page 174 of the book.

In my own career, I have found that the most valuable information is only encountered in conversations: often it is too sensitive or too inconvenient for the speaker to transcribe into text.

The techniques described for practising reading are based on methods that I have seen being used by engineering firms, with the addition of a scoring system to enable students to assess their progress as they practice.

As explained in the text, the material on visual perception, drawing and sketching is not new or unique. It is derived from well-known texts and material that I have used in classes since 1992.

Chapter 7: Collaboration in engineering

This chapter is extensively based on analysis of interview data and quantitative surveys that provide complementary evidence on the significance of social interactions and collaboration processes in engineering practice.

The misconceptions presented in this and other chapters are framed using actual quotations from students and young engineers.

The idea that communication is critically important in engineering practice is not new. However, most discussions on communication in engineering education literature seem to emphasise skills such as report writing and oral presentations. The focus on communication skills hides the broader context in which these skills are used. Field study data has been particularly valuable in exposing the context in which engineers communicate with each other and with others. In looking for a coherent way to describe our observations, I came across the notion of a performance that describes a sequence of interactions involving two or more people. This seemed particularly helpful in describing collaboration as a series of performances that can be observed in the workplace. This chapter presents the idea for the first time in this form, based on observations that engineers are engaged in a number of identifiable performances such as teaching, discovery learning, technical coordination, project management and negotiation. Each is a complex series of performances in itself and I have tried to present these in an organised framework, showing how they can be conceived in terms of combinations of simpler performances.

In the research literature and our own studies, there is evidence that more experienced engineers and other employers are often critical of the communication abilities of graduate engineers, even university graduates in general. On the other hand, most graduates think that they have acquired sufficient communication abilities as a result of their school and university studies. One way to acknowledge the validity of both points of view is to understand that engineering and professional work require complex collaboration performances. Being able to communicate is not enough: graduates need to learn to enact these collaboration performances if they are to become effective as professionals.

Having described this framework of collaboration performances, the remaining parts of the chapter cover some fundamental ideas in communication required for these performances.

I am grateful to Sule Nair, one of my Ph.D. students, who introduced me to post-modernist philosophy and the earlier work of Goethe, the famous scientist, poet and playwright who anticipated Charles Darwin's findings by a century and the French post-modernist philosophers by two centuries. I realised that there are critically important ideas about the way we use language that have become pervasive among many contemporary university graduates, but engineers do not seem to have any exposure to these ideas. The short sections of this chapter hardly do justice to these ideas on communication but at least serve as an introduction to the notion that the meanings of words change with time and context, even with the same speaker and listener. Many engineers, on the other hand, seem to think that words have fixed meanings defined in dictionaries or technical standards.

Having exposed the significance of ideas about language in understanding collaboration performances, I have done my best to describe them in a way that is hopefully accessible for engineers. However, I have not so far attempted to teach these ideas since they are well beyond what it is feasible to teach in the context of a normal engineering school, either at undergraduate or master's level.

By combining these ideas with short sections on much more basic and practical skills, for example the use of email and calendars, I hope that engineering readers will appreciate their significance and take on at least some of the ideas I'm trying to convey. However, I'm happy to acknowledge that this material may need substantial revision for future editions in the light of actual teaching experiences.

Chapter 8: Informal teaching: More than an interpreter

Chapter 7 identifies teaching as an important collaboration performance in engineering practice and an important component of technical coordination, project management and negotiation. This chapter draws on contemporary education research to provide ideas for engineers who wish to improve their teaching practices. Readers familiar with contemporary discussions on engineering education will recognise many of the ideas and concepts presented in this chapter.

Of course, in engineering practice, teaching performances tend to be much more informal than the classroom situations that most education research aims to understand. Therefore, I have been selective in drawing on the literature to present material relevant for informal teaching.

Discovering more about other people is also an important element of teaching so this performance is also explained in this chapter.

Chapter 9: Technical coordination: Informal leadership

This chapter elaborates on ideas presented in my 2007 paper in which I first described observations of technical coordination in engineering practice.[22] Since that paper was written, I have found many other literature references to similar ideas and I have tried to present these in context. The interested reader can explore these references to see how similar ideas have been described in other contexts.

The chapter draws on teaching materials that I have used to explain technical coordination and informal leadership in engineering practice. It also includes detailed background material drawn from analysis of interviews with engineers to provide guidance for practitioners.

Chapter 10: Managing a project

Initially, I thought that I would be able to refer readers to plentiful contemporary literature on project management and cover large scale formalised collaboration performances in a relatively short chapter.

However, as I analysed field study and interview data, the shortcomings of contemporary project management literature became more and more apparent. Even though project management training has become almost universal for most engineers, and project management tools ubiquitous, it is still rare to find well managed projects in engineering. Data from other sources confirms our own interview and field study observations.

Reflecting on this, I realised that many engineers seem to overlook the distinction between written, explicit knowledge on paper and in documents, and knowledge in the minds of people that can influence behaviour. Further, analysis of project risk assessments shows the overwhelming attention given to foreseeable but unpredictable events associated with different interpretations of written information. For example, different people will have different ideas on the relative priorities of different activities in a project.

A further issue emerged as well: technical specifications. There were many references to difficulties with specification documents and test schedules in the interview data and field study observations, evoking memories of similar experiences through my own career.

Project management has emerged as a discipline in its own right, freed from the engineering contexts in which contemporary project management practice emerged. However, many aspects that are critical in engineering practice have been lost as a result. As explained in many places through the book, one of the really difficult challenges in engineering is to ensure that technical

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[22] Trevelyan(2007).

ideas survive sufficiently intact through successive interpretation by people who implement the ideas. Failure to achieve this will usually result in project performance that does not match the technical and commercial predictions made to justify the project in the first place. In other words, one cannot escape the inevitable connections between technical knowledge and human behaviour.

Therefore, this chapter is evolved as a complementary treatment of project management that still draws on contemporary literature but emphasises the critical importance of the issues described above in achieving reasonably predictable outcomes in engineering. It also builds on the idea that project management is a complex socio-technical collaboration performance and draws on material presented in the earlier chapters.

As in other parts of the book, I'm very grateful for the comments and suggestions made by expert engineers and project managers. It was reassuring to find that the final chapter based on our research required only a few minor improvements to bring it into line with the experience gained by these experts.

Chapter 11: Understanding investment decisions

Like chapter 1, this chapter has its roots in observations of expert engineers who were able to explain many of the important decisions they made in terms of creating commercial or social value through their engineering work. As explained earlier, analysis of interview data and field observations confirmed the view of many business owners, that many engineers struggle with the idea of creating commercial value and have lost sight of the social value contributed by engineering.

This chapter, therefore, is intended to help engineers develop a much better understanding of how engineering contributes value and how investors make decisions on engineering projects. Many of the interviews included comments by engineers that revealed a degree of frustration with decisions that affected resources for their projects. This chapter provides the explanations that might have helped these engineers understand more about these decisions, and reduce their levels of frustration.

Once again, I have not had the chance to gain experience from teaching most of this material. It has been checked by experts with both engineering and financial investment backgrounds.

The case study reported in this chapter was pieced together from several accounts of project failures described in interviews with engineers. While it is strongly based on one particular project failure, it incorporates observations on other project failures from the interview data in order to provide a realistic account for readers, and also to expose some of the important reasons why large projects can easily fail. Obviously, names and locations have been changed to protect the interests of the parties involved.

Chapter 12: Negotiating sustainability

Sustainability has become a critically important issue, not only in public discussions on climate change and depletion of the earth's resources, but also among engineers. Engineers have to confront this issue even though it manifests itself rather differently from public discussions. Much of the material in this chapter has been contributed through lengthy discussions with different people involved in major engineering projects, including bankers, investment advisors, union representatives, environmental NGO activists, conflict mediators, environmental regulators, and lawyers. Many contributed as guest speakers to a final year engineering course on sustainability and project management that I ran with other colleagues for several years.

This course included a role playing exercises that introduce engineering students to the challenges of managing an environmentally sensitive project and also negotiation skills. In our research interviews, most engineers described negotiations in the context of commercial discussions with clients, suppliers and contractors. Almost every interview with engineers contained references to negotiation.

Most sustainability issues ultimately have to be solved through negotiations. These negotiations can be more complex than commercial negotiations because of the number of stakeholders involved. However, I have found that appropriately prepared role playing exercises can give students a very realistic experience that helps them to prepare appropriate negotiation skills.

Thanks to recent research on the differences between successful and unsuccessful technical problem solving, while I was writing this chapter, I realised that negotiation also has to be presented as a technique that can be used for technical problem solving in the workplace. As I have encountered many times in my own practice, technical problem solving situations usually manifest themselves as disagreements between stakeholders, typically engineers from different disciplinary backgrounds and levels of experience. These disagreements occur because the choice of a particular technical solution will influence the amount of work (or revisions to existing work) that the individual stakeholders will have to contribute. Therefore, technical disagreements tend to involve conflicting issues of resources and time schedules.

As far as I can tell, the idea of presenting negotiation as a technical problem-solving tool is novel as I have not been able to find prior references to this in the engineering literature. Once again, it is an illustration of how collaboration performances in engineering can only be learned by understanding them as socio-technical performances. At the same time, one cannot escape the technical aspects of engineering practice.

A chapter on sustainability would not be complete without some discussion of climate change and related issues affecting the future of our planet. I have been very selective in drawing on particular research results and I hope the reader can forgive me for this particular selection. It is not a complete treatment by any means. My chosen selection is a means of drawing out certain issues that are relevant in a discussion on sustainability and I think that this will help readers to appropriate other ideas that they can find in the plentiful literature on this topic.

Once again, the industrial case study has been put together from interview accounts in a similar manner to the case study presented in chapter 11. Names and places have been changed to protect the interests of the parties involved. The intention is to provide a composite account that exposes important issues for engineers to appreciate.

The material linking beliefs by Aboriginal Australians to the discussion on sustainability is speculative and I hope readers understand that. I suspect that the persistent tendency by most human civilisations to over-exploit environmental resources is probably linked with underlying beliefs about the place that human beings occupy in the world. However, expert engineers have sufficient respect and social status to change those beliefs by influencing clients and wider society.

Chapter 13: Great expectations

Even though many industrialised country readers may regard this chapter as a peripheral matter, the material is critical for understanding the main themes of the book.

This chapter brings together many diverse observations and experiences from the research performed in India and Pakistan. Only part of the material has been published previously: this is the first time that all these ideas have been presented together.

The aim is to present an account that will inspire engineers in low income countries to become experts in their own domains, and reassure them that they can do this without having to have education and experience from the industrialised world.

As explained in the chapter and the introduction to this appendix, the research for this book started with observations of engineers in Pakistan and some of the key breakthroughs in understanding came with the chance discovery of highly paid expert engineers working in India and Pakistan.

Chapter 14: Seeking work

While this chapter draws on research observations, it is also a field tested practical guide for job seeking in engineering. Many of my students who have struggled to find engineering work during employment market downturns have followed the methods explained in this chapter. None came back reporting that they could not find jobs. There are two possible explanations. Either they did not follow the instructions and were too embarrassed to come back and admit that, or they managed to find satisfying jobs and did not need to come back.

As with other chapters, I am grateful to the expert engineers who read through this material and contributed valuable suggestions.

Chapter 15: Conclusion

This chapter is more of a challenge for other researchers to test some of the ideas through further research. I hope that it inspires researchers to take up this challenge and that it inspires engineers to try out the ideas presented in this book for themselves and report the results. I would like to hear from readers.

I hope that I will be able to continue this research. At the time of writing these notes, I have enthusiastic students testing some of the ideas in this book and I hope that their results present intellectual challenges that force me to rewrite parts of the book for a future edition.

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