James Trevelyan

THE MAKING OF AN EXPERT ENGINEER

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The making of an expert engineer

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The making of an expert engineer

How to have a wonderful career creating a better world and spending lots of money belonging to other people

James P. Trevelyan

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Cover photo: Engineers discuss the implications of vibration measurements at SVT Engineering Consultants head office in Perth, Australia, photographed by the author.

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Dedication

Dedicated to Joan Trevelyan, Begum Sarfraz Iqbal and Malik Muhammad Iqbal Khan

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Table of contents

Acknowledgements

So many people have contributed to the research for this book that it is not possible to name all of them.

Between 2001 and 2011 Sabbia Tilli supported me as we searched through hundreds of journals, conference proceedings and research books, gradually discovering, with a degree of dismay, just how little had been published describing systematic research on the details of engineering practices in different settings. Sabbia conducted the longitudinal study to follow the early careers of 160 engineering graduates from the University of Western Australia.

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To all, I owe an immense debt of gratitude.

List of tables

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List of figures

Preface: Engineering practice has been invisible

I am fortunate to be an engineer, an inventor, a teacher, and a researcher. I am lucky enough to have received international awards for my research, patents for my inventions, and awards for my teaching. I have seen my designs built and used by satisfied people, and I have had a wonderful career. I have spent enormous amounts of money that belonged to other people to do achieve all that. Determination played a part. So did persistence, good fortune, plenty of encouragement, and being in the right place at the right time.

In the most recent part of my career, I have researched engineering practice: what engineers do and how they do it. For my first 30 years as an engineer, I took the notion of engineering practice for granted. Although I was aware that my daily work was only distantly related to what I had learnt in engineering school, it never occurred to me that this was unknowable to anyone who was not already doing it. Somewhere, someone would have studied what engineers do, surely.

Around 2003, faced with unanswerable questions about engineering practice issues, I started to interview and observe engineers at work. Gradually, I came to realise, with a creeping sense of shock and amazement, that much of engineering practice seemed not to have been understood before and described in ways that made sense to me as an engineer. As I analysed hundreds of pages of interview transcripts and field notes, I surprised myself with the hitherto hidden complexity of what I had been doing myself, and observing others doing. Persistent patterns started to emerge to give this complexity a coherent form that could be understood.

Many of the engineers I met started by telling me how they hardly did any real engineering work: design, calculations, and the solitary technical work that they learnt to do in engineering school. Instead, their lives seemed to be filled with what one described as "random madness", seemingly trivial and routine paperwork, meetings, phone calls, frustrations, confusion, and misunderstandings. In the words of Dilbert, the cartoon engineer created by Scott Adams, "My job involves explaining things to idiots, who make decisions based on misinterpreting what I said. Then, it is my job to fix the massive problems caused by the bad decisions."

Some of the engineers I met and observed were clearly in a class of their own: they were experts in their own fields of practice, acknowledged by their peers to be exceptional performers. In time, I came to understand a little about what distinguished their performances, and I decided to write this book to help engineers and students who would like to become more expert in their practice.

Many work as engineers, but simultaneously wonder why the work is not what they thought it was going to be: why it seems dull, mundane, and does not challenge the technical abilities that they learnt in engineering schools. Many aspiring young engineers graduate into little more than disappointment. Many never even manage to find an engineering job to start off their careers. Many older engineers seem to lie trapped in dead-end careers by assumptions, myths, and misconceptions that are reinforced by endless unquestioned repetition. Much of this disappointment arises from misconceptions about engineering practice, misconceptions that persist in the absence of a comprehensive written account.

Anyone who has graduated from an engineering school has the capacity to become an expert engineer. However, much of what they need to know is neither taught, nor even known, in most engineering schools.[1]

I am confident that the ideas in this book can transform the careers of engineers, both young and old. As far as I know, most of this material has never been presented in a single book like this and some has never been described until now. Most of the ideas and concepts have emerged from research conducted over the last decade to gather material for this book. Through this research, I realised that engineering practice, what we engineers do every day, has been largely unknown even to us. We simply do the work without thinking much about what we are really doing. Only a tiny number of earlier research studies revealed any details before I started, and even then, they only did so in exotic high-technology engineering that only a tiny number of engineers encounter in their careers.

Engineering has been invisible to nearly all of its participants.

I want to change that by explaining the ideas that led to this book, and change the world through the engineering that my young readers will be able to perform with the help of these ideas.

I believe that this book can lead any engineer to a rewarding and exciting career. Engineering is a wonderful profession. With some learning from experts, any engineer can not only enjoy spending lots of other peoples' money, but in doing so, also provide great value, and earn more for themselves in the process.

A minority of people in the world enjoy comfortable lives because engineering enterprises in their regions have been able to provide services and products in an efficient and economical way. In Australia, the driest continent, copious amounts of potable water – clear, clean, and safe to drink – flow from kitchen taps 24 hours a day at a total cost of about $2 per tonne. In much of the world today, potable water costs between $20 and $100 per tonne. Getting the bare minimum needed for survival takes up to a quarter of the economic resources of poor families, more than 10% of the GDP in a country like Pakistan. Good engineering can change that staggering reality for billions of people who live in misery at the moment.

We also know that we are consuming too much of the world's resources, partly because engineering has not yet provided the means for people to use our resources efficiently. While a minority lead comfortable lives, it is only reasonable for the poor majority to aspire to the same living standards. Yet, if everyone on the planet consumed at the same rate as the comfortable minority, the remaining resources of this planet would be exhausted in a short time.

Therefore, the ultimate challenge for today's young engineers is to find a way for all people to live in affordable comfort and safety within the limitations of this planet. To achieve that, we need tens of millions of expert engineers.

Today, there is no single course of study from which you can learn to be an expert engineer. I do not know of a single engineering school or college that enables you to do this.

Part of the frustration encountered by graduates arises because these institutions claim to teach engineering. They do teach engineering science, which is an important part of engineering, but graduates need to learn much more to become experts. That is the part that has largely been invisible. I hope this book will change that by removing Harry Potter's cloak of invisibility that perhaps he carelessly left lying over the secrets of engineering practice. This book provides guidance on how to acquire this critical know-how for engineering.

Why is so much of engineering invisible?

You can see the results of engineering all around the planet. Phones, buildings, roads, vehicles, and aircraft: the list of engineering achievements is almost endless.

However, therein lies the trap: these are all objects, some of them vast systems of man-made structures, while others are almost too small to see.

Why is engineering invisible in these objects?

Engineering is a human performance: it is performed by people. Extraordinary people, in some cases, but most of them are entirely ordinary people. The creation of engineering systems and artefacts relies on human actions; therefore, feasibility is limited by human capabilities, as well as the laws of physics.

It is the evidence of their performances, the objects and the information left behind, that we associate with engineering.

Engineering artefacts, drawings, objects, documents: each represents for the most part what is to be, or what has been built – the finished objects. What they do not represent is the human process that led to their creation and the creation of the objects that they represent.

One of the great controversies of the ancient world concerns the techniques used to construct the great pyramids of Egypt. Even with the prolific hieroglyphic writing that litters the remains of the entire ancient Egyptian empire, no one has been able to find an account that explains how the pyramids were built. Engineers today are no different from their Egyptian forebears. The documents and artefacts we create represent the endpoints of our performances. How these artefacts came into being, the human engineering process, is no more likely to be written down now than it was 4,500 years ago. It remains as it always has been – practiced, yet simultaneously invisible.

Here, I would like to introduce the first important idea about engineering practice. I have labelled each of the main ideas in the book as 'Practice Concepts' in bold headings.

Practice concept 1: The landscape of practice

We can conceive of a map that includes all the engineering possibilities that could provide effective solutions for a particular project and we can also imagine contours of difficulty. The low contours surround possibilities that are easier to achieve, while the high contours include more difficult possibilities, and the boundaries mark the limits of feasibility. What determines this landscape? Which factors shape the contours of practice?

The contours are partly determined by the laws of physical sciences, which are almost always expressed in the language of mathematics. For example, thanks to Shannon's pioneering work on telecommunication theory,[2] we know that carrier frequency bandwidth determines how long it will take you to download a 10-gigabyte high-definition movie. The strength of steel and concrete and theories of fibre-matrix bonding stability determine the height of our tallest buildings.

Even with all that knowledge in place, there are many other factors influencing these contours, factors that only become apparent once you start working as an engineer.

The rights to use certain intellectual property, or the need to protect it, the distribution of human know-how, how much we can remember in our heads, how reliably and how fast we can learn more, how effectively we can explain this to others, technical collaboration capabilities, the time available to complete the project, local, national and international regulations, your reputation as an engineer, how much finance investors are willing to make available, their risk appetite, the capabilities of the people on hand, how they are organised, the state of the local and international economy, political stability, and attitudes of the local community and end users: these are all factors that shape this landscape of practice.

As an engineer, your job is to navigate this complex landscape, steering an engineering project away from the peaks of difficulty towards the plains of practicality. Engineering decisions reflect the shapes of these contours.

Now ask yourself, how well did your engineering degree course prepare you to navigate this landscape?

In this book, along with introducing key concepts that help to explain the landscape of practice, I also point out misconceptions that make it more difficult to appreciate the landscape. These are mental blockages, blinders over our eyes, which get in the way of a clear, unimpeded view of the landscape of practice.

Here's the first.

Misconception 1: These are all non-technical issues

What do we mean by 'non-technical'? Often, this term is used to label any idea beyond the world of objects that we, as engineers, can think about comfortably.

Take communication and collaboration, as an example. As we shall see in later chapters, engineers communicate and collaborate constantly, and most of the time, there are technical issues that frame communication and collaboration. Technical issues influence much of the risk faced by investors, making it easy or difficult to comply with regulations. Technical issues also determine intellectual property constraints and appropriate collaboration arrangements. Political issues, the state of the international economy, and local community attitudes are factors that we could discuss without recourse to any engineering technical understanding, yet they inevitably shape the technical constraints within which we engineers have to work. Furthermore, innovative technical solutions can often create new space and ease these constraints once we can understand the issues.

Most factors that shape the contours of the landscape of practice have technical implications or dependencies. Two of the main attributes that distinguish expert engineers are their abilities to perceive how technical factors and social interactions shape the landscape of practice and their skill at influencing people working with them to preserve the technical intent through multiple reinterpretations by other people.

Practice concept 2: Socio-technical factors shape the landscape of practice

Therefore, to understand engineering, we need to understand human capabilities and social behaviour, as well as the laws of physics. We have to watch what people do, listen to what they say, and understand some of their feelings, both those of frustration and pride. Only by making these actions and feelings visible can we begin to understand. That's the job of researchers, to make visible what was previously hidden and subsequently provide as concise and readable descriptions as possible so that you, the readers, can share their insights.

In the field of science and technology studies, researchers have coined the terms 'socio-technical' and 'heterogeneous' to describe this intrinsic link between people and engineering. In engineering, the social and technical are intertwined, inseparable realities of practice.

Unfortunately, engineering schools rarely help you learn about people and this concept of socio-technical factors. You will be lucky if you can find one that includes any study of people in the core curriculum.

That's precisely why graduates get so frustrated. Engineering schools are only enabling them to learn part of the picture: the other part has remained hidden.

Engineers like to see themselves as agents of change who can shape the future of the world with technology. Engineers produce new technology and technology can change the world . . .

. . . but only if people, particularly other engineers, adopt the technology, which requires people to change. Engineers can only change the world if they can influence their colleagues, the technicians who translate ideas into reality, and the financiers who provide the money: it is people who change the world through the technologies they choose to create and use.

Engineering schools don't explain this to graduates . . . yet. They help students learn some elements of engineering physical science and abstract thinking about objects. While all engineers need these capabilities, they are insufficient by themselves for a person to become an expert engineer.

That's why I'm writing this book.

As an engineering student, a novice engineer, or even an experienced engineer, you still have a lifetime of learning ahead of you. Until recently, however, it has not been clear what you needed to learn. Engineers talk about this simply as "experience" and "practical skills" but have not been able to explain exactly what they have meant by this, only that it is something that has to be learnt "on the job", something that you cannot learn in a formal academic setting. With the help of research, we can now describe much more clearly what you need to learn beyond the engineering school curriculum: engineering practice.

Until the 1950s, engineers learnt engineering by emulating their teachers, either in classes or in the workplace. This practice-based education made it difficult for engineers to keep up with and apply the huge scientific advances of the 20th century. Physical sciences and mathematics came into the curriculum and have now entirely displaced practice. The extraordinary technological advances we have seen in the second half of the 20th century have come from the ability of engineers to exploit fundamental advances in science, mathematics, and computation. This ability was seen as critical when engineering curricula were reformed in the 1950s.[3] Education founded on science and mathematical theory has created this ability: theories enable you to quickly learn what you need to know, exactly when you need it.

Engineers today are still learning practice by trial and error, on the job, and many have never learnt very much that way.

Now, in the 21st century, there are fundamental advances in many other fields, such as the humanities, economics, psychology, learning sciences, social sciences, organisational science, linguistics, even philosophy and history, that can be applied to help engineers learn about most of the human factors that shape the landscape of engineering practice. Complementing these advances, we now have ten years of detailed research on what engineers do every day.[4] This book builds on these advances, and a good portion of it will involve some difficult and challenging reading. You will need to open your mind and understand ideas and theories that may be new and seem baffling at first.

However, just as mathematics and physics theories made it easy for you to learn engineering technical principles quickly when you need them, social and human science theories make it easier for you to learn about socio-technical factors.

These are the ideas in this book that have the potential to help you become an expert engineer much more easily than before.

Many engineering graduates find themselves in a frustrating position: you may be experiencing this for yourself right now. They find that nearly every engineering job advertisement requires applicants to have "experience", but they can't get that experience without being in an engineering job.

Learning with the help of this book cannot completely replace engineering experience. However, by working through the prescribed exercises and practicing the skills, you can prepare yourself and make the process of finding an engineering job much easier. When you start to work as an engineer, you will be able to learn much more from your experiences faster and with less frustration. I am confident that your talents will be greatly appreciated by any enterprise in which you can apply these ideas.

This book can only be a guide for your future learning. Apart from a few basic skills, this book does not contain what you need to learn. Instead, it shows you how to learn from your surroundings. Most of what you have to learn is right there in front of you, even today. You simply need to learn to see it, to pull aside the 'cloak of invisibility'. You will have to do the learning, although other people can certainly help you.

Engineering can be a wonderful career, full of intellectual stimulation and challenges, financial rewards, and fantastic fun.[5] All of the engineers that I've interviewed as part of the research for this book have immensely enjoyed their careers. Many have faced extraordinary frustrations at times, for which the material in this book might have been helpful, had it been available at the time.

This book has been built on extensive research across many disciplines, but it is meant to be a practical guide for engineers. Notes link the text to research publications mainly to help future researchers improve on what is already here. Several of the explanations presented in the book have grown out of valuable philosophical discussions to which I was kindly invited.[6]

Experienced engineers will find useful material in this book: most will find that at least some parts of the book have new ideas that could help them improve their performance. The book can also provide guidance for experienced engineers who are helping younger engineers to develop practice skills. Human resources professionals can benefit from this book: no previous book has provided a comprehensive and research-based description of what engineers really do in their work. Over 200 interviews and extensive field observations by myself and my students provided the data for this research.[7] My own professional work experience over four decades framed the interpretations that were checked and refined by discussing the results with many of the participants. To help the reader, particularly researchers and students, I have also provided notes throughout the book listing references and publications from other researchers that corroborate, amplify, or extend my interpretations and data.

This book is only a start point: it is only a guide to help you learn more from expert engineers. If you read it all at once, you may find some sections repeat earlier material. Each chapter is designed to be read more or less on its own, and so has to summarise relevant ideas from earlier ones. By the end of your lives, I hope, you will have learnt much more than I did. Maybe one or two of you will write even better books than this one. It is my aim that before then, you will have helped to improve the lives of billions of people, allowing most people on this planet to live in reasonable comfort and safety.

NOTES

1. The reasons for tenuous knowledge of practice within engineering schools are explained in Trevelyan (2014b).
2. Shannon (1948).
3. The Grinter Report (1955) advocated that engineering education be founded on mathematics, physics, and chemistry, as well as a set of engineering sciences, such as materials science and thermodynamics. However, at the same time, the report argued that about 20% of the curriculum should be on social sciences, a recommendation that has been almost completely ignored.
4. Trevelyan (2014b), also in the online appendix on research methods.
5. Sam Florman (1976; 1987; 1997) wrote several books on the pleasures of engineering that are still relevant today.
6. I should acknowledge some of the many contributions on philosophy relevant to engineering and technology that helped inspired these explanations (Downey, 2009; Foucault, 1984; Heywood, 2011; Heywood, Carberry, & Grimson, 2011; Koen, 2009; Marjoram, Lamb, Lee, Hauke, & Garcia, 2010; Nussbaum, 2009).
7. Described more fully in the online appendices.

Chapter 1

Why engineer?

What do engineers actually do? The truth is, even many engineers find this question difficult to answer.

Many of the students whom I've taught think that engineers mostly work alone, designing and solving technical problems, while looking forward to a 'practical, hands-on' profession.

Many engineers, perhaps a majority, often think that the amount of 'real engineering' they do is rather small. In fact one engineer suggested that only a small part was engineering and 'the rest would just be random madness'. From their perspective, it often seems that they spend a lot of time focused on what they consider to be non-technical issues and administration.

One of the aims of this book is to help engineers answer this fundamental question by providing new concepts and ideas to explain what exactly it is that they 'do'.

However, first and foremost, I would like you to think about something far more important and fundamental, something that seems to have been forgotten in the majority of engineering schools. It seems so basic that we all tend to take it for granted: **why do we do engineering and why is it so valuable?**

For most of my career, I never thought to question why engineering might be valuable. Until recently it had always seemed self-evident to me. It was only when I started to think a bit deeper about the question that I realised the answers are far from obvious.

Students in law school and medical school have no difficulty explaining the value of their professions. Lawyers and judges help people get out of trouble, provide access to justice, and protect human rights. Doctors heal the sick and help people live longer, healthier lives. On the other hand, when I ask engineering students about the 'value' of engineering, they usually hesitate for a moment before tentatively offering 'new technology' as the underlying value of their future career. 'And how does that help people?' I ask. Most engineering students find that question quite hard to answer.

As engineers, most of us don't get to develop new technology, although finding practical applications for it is something we do all the time. However, if we're not actually *developing* new technology, then what is the value of what we do?

Hence, the title of this chapter: **Why Engineer?**

Try and answer these simple questions (see practice quiz 1 below):

Why should a company employ me as an engineer?
How can I help the enterprise?
What value can I create for an enterprise and my community?

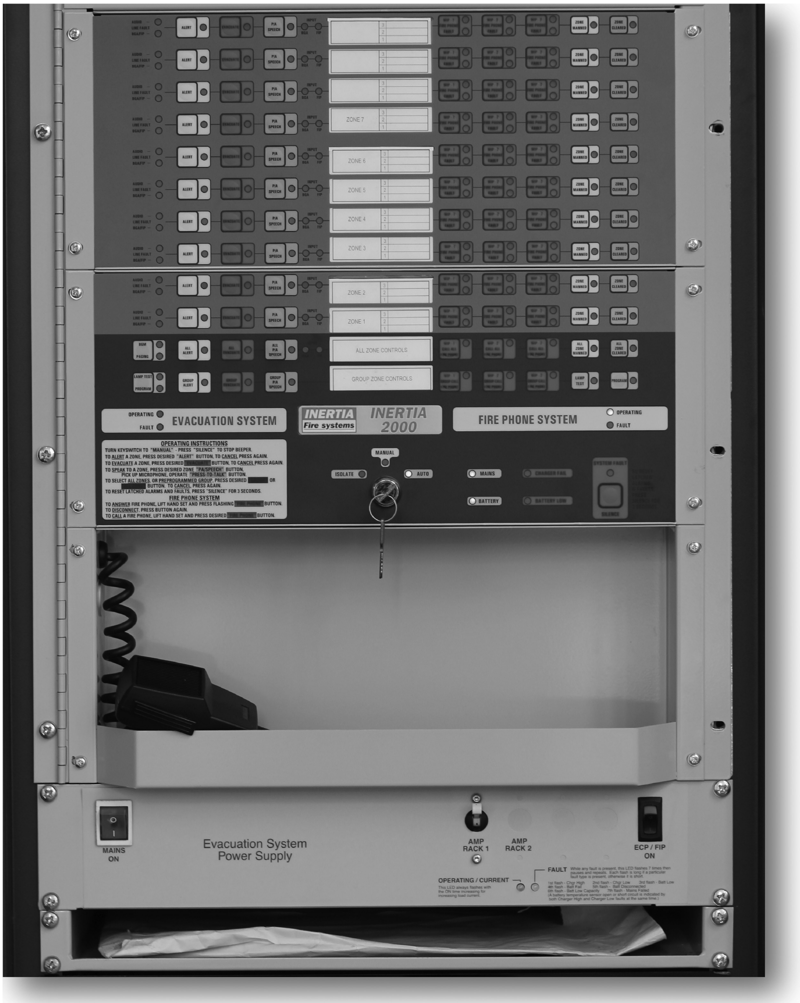

Figure 1.1 Fire alarm panel installed in the entrance of the building where my office is located.

Recently, I was approached by a novice engineer; she was a recent graduate who had obtained her first job with a small family company that employed about 20 other people. The company owner had asked her the same questions. She came to me a few days later explaining that she had been completely unable to answer these simple questions. Somewhat baffled, she asked for my suggestions.

I would like you to try and answer her questions before proceeding any further with this book. First, you need to know a little more about the company in question.

At the time, the company manufactured electronic panels for fire alarm systems. Electronic smoke detectors and other fire sensors fitted to buildings are all wired to a fire alarm control system panel. Electronic circuits in the panel respond to a smoke alarm and cause a fire alarm to sound as a warning to people in the building. The same circuits also automatically raise the alarm with the local fire brigade, providing the address and directions so they are able to reach the building quickly. The panel contains a public address system with a microphone, enabling the fire brigade to make announcements throughout the building when they arrive. The panel provides internal wiring connectors for the smoke detector sensors, a public address amplifier, switching circuits, and communications circuits.

The company manufactured the panels using both locally sourced and imported components. The owner started the company approximately 20 years ago, utilising his practical electrical wiring and circuit board assembly skills. Other members of his family worked for the company in administrative and accounting positions.

Practice quiz 1

If you don't feel comfortable answering the questions for this particular company, think of any other company, enterprise, or organisation that you would like to work for and answer the same questions in that alternate context.

If you have access to the online site for this book,[1] you can find the quiz there: please type your answers in the electronic quiz. Otherwise, write brief notes here for future reference. This first quiz should take 30–90 minutes to complete.

Q1: Why should the company employ an engineer?

1. ______________________________
____
____

2. ______________________________
____
____

3. ______________________________
____
____

Q2: What value would an engineer create for the company that will justify the cost of employment? You don't have to calculate a financial value; a qualitative description is sufficient.

1. ______________________________
____
____
____

2. ______________________________
____
____
____

3. ______________________________
____
____
____

4. ______________________________

5. ______________________________

Use this space for additional comments or questions that might have occurred to you to ask the owners of the enterprise.

Now that you have written your answers, I would like you to self-evaluate your responses.

Evaluating question 1 responses

Perhaps you suggested this for the first question:

> 'I can design a better fire alarm system for you. It would utilise new technology and work more efficiently.'

Another response might have been:

> 'I can solve technical problems affecting your existing systems. For example, if a similar issue often occurs after your panel has been installed in a building, I could work out the underlying cause and rectify the problem by redesigning your system.'

Here's another:

> 'I can improve the efficiency and quality of processes and practices used in the company.'

Or even this:

> 'I work hard and I can offer new insight into old problems.'

Give yourself one point for each response that resembles one of these examples, and then consider this reply from the company:

> 'Solutions on paper and hard work are not much use to us unless they lead to tangible results. We need problems fixed without redesigning our panels. What do

we have to do so problems are no longer an issue for us? How can we retrofit all the systems that we have already installed so similar failures don't occur in those as well?'

For each of your responses that answers one or more of these reasonable requests from the company, award yourself two additional points.

Evaluating question 2 responses

Each of your answers needs to describe the *value and other benefits for the company derived from employing an engineer*.

Carefully compare your responses with the ones below.

Give yourself one point for every response similar to the ones below *and two extra points* if your response described the value to the company, at least in qualitative terms. Notice how each of the responses below includes a description of the value created – in the first few responses, this section is in italics.

Product and process improvement, research and development, and anticipating future developments:

- Work on an application to justify a large proportion of the cost of employing an engineer as research and development, thereby gaining tax concessions. Value: *significantly reduces the cost of making technical improvements to products*.
- Prepare designs for an upgraded product that could be manufactured in the event that a competitor enters the market with a better quality product at a similar price. Also, evaluate the likelihood of this happening. Value: *reduces the risk that a competing product will take a significant portion of the existing market share*.
- Prepare designs for a cheaper product with a similar performance standard and quality that could be manufactured in the event that a competitor enters the market with a similar quality product at a significantly cheaper price. Value: *reduces the risk that a competing product will take a significant portion of the existing market share*. This strategy also helps if the local currency rises in relative value, thereby enabling imported products to cost less in the local currency.
- Improve workforce skills to provide better service to clients in a timelier manner. Value: *improves client satisfaction and customer loyalty*.
- Introduce design modifications to allow for easily installed expansion in panels to minimise the cost when customers need to extend their fire alarm systems. Value: *increases profitability or improves price competitiveness*.
- Investigate self-powered and wireless sensor technology in fire alarm systems in order to lower the cost of installing cabling at new customer sites. Value: *increases the company profitability or improves price competitiveness*.
- Reduce internal power consumption of panel electronics by eliminating ventilation fans. This will reduce dust accumulation inside the panel. Value: *reduces maintenance costs and improves company profitability by reducing warranty and service costs*.

Business development research and understanding customer needs:

- Research competitors' products, product announcements, and sales information in order to anticipate changes in the market. Value: *allows the company to respond accordingly in a timely fashion, thereby reducing the risk of lost market share*. Explore technical similarities that might suggest effective partnerships with other manufacturers.
- Understand client needs so that the company can diversify sales to its existing customers, which will increase customer satisfaction. Value: *strengthens the company's market position*.
- Prepare a feasibility study for the company to manufacture building security systems (or to purchase a competing company). Value: *increases market opportunities by providing a more comprehensive service package to existing customers*.
- Work with fire insurance companies and demonstrate the company's product compliance with international and commercial fire safety standards. Value: *opens new market opportunities by reducing customers' insurance premiums*.
- Work on a design for a low-cost, reliable fire alarm system that can be installed in vulnerable down-market boarding houses to reduce the risk of significant casualties in the event of a fire. Consider working with local authorities so that these affordable alarm systems will eventually become mandatory. Value: *significantly increases the overall size of the market for the company's products and improves the safety for less affluent members of the community*.

Cost monitoring, control, and reduction:

- Reorganise manufacturing processes with a more systematic workflow so that existing products can be tailored more effectively to client needs. Value: *significantly increases profit margins*.
- Investigate and, if necessary, help to rearrange the company's accounting systems to ensure that the different costs of manufacturing electronic panels, the costs involved in servicing and maintaining products installed at customer sites, and the costs of maintaining or replacing production and service facilities and equipment can be accurately monitored. Value: *accurate monitoring of, costs enables the company to identify where technical improvements could provide real value, and demonstrates which previous improvements have provided real benefits in order to improve cost-efficiency.*
- Introduce systematic inventory and configuration management systems. Value: *reduces the number of spare parts held in stock, thereby reducing the need for working capital and storage space*.

Risk management and reducing uncertainties:

- Increase compliance with international standards for all aspects of the product, as well as company operations, in order to increase the likelihood that future company expansion will be financed by the company's bank (rather than family capital) with a lower cost of capital. Banks closely inspect a company's operations when a company requests bank financing. Banks employ trained engineers to perform these investigations. Value: *banks are more likely to provide financing for projects that are well managed and produce reliable outcomes*. Demonstrating compliance with standards often (but not always) indicates sound management practices.

- Develop systematic procedures and an organisational method for maintaining the production and service facilities to ensure that there are no costly interruptions in manufacturing or company service activities caused by equipment breakdowns or the need to repair buildings or equipment. Value: *saves on the cost of lost production due to breakdowns and preventable disruptions.*
- Develop systematic quality assurance procedures for purchasing supplies and components that will ensure that incoming products are thoroughly checked and inspected, even tested, if necessary, in order to eliminate the possibility that a defective component might cause a costly panel failure. This could include working with the company's suppliers to develop customised quality assurance procedures. This will also improve customer perceptions of product reliability. Value: *improves customer loyalty and increases future market opportunities.*
- Automate testing of manufactured panels to eliminate current haphazard manual testing, which is known to be inefficient. Value: *reduces the incidence of panel defects discovered after installation, thereby reducing service and warranty expenses.*
- Increase the reliability of in-house manufacturing processes so that senior staff members can go on holidays without having to worry about what is happening at the factory. Value: *staff member morale improves due to time off, therefore making them more productive upon their return.*
- Increase imported components of the electronic panel systems to balance the effects of changes in international currency exchange rates. Value: *reduces the effect of exchange rate fluctuation on company profitability.*

Here are two completely different, but equally good, responses:

- 'I think that the decision to employ a graduate in this position could be a mistake for both the graduate and your business. It might be much more valuable to consider employing an experienced engineer who would be able to provide guidance on compliance with fire protection standards, quality requirements for components and assembly, design and documentation management, and issues such as product quality assurance systems and factory acceptance testing.' Value: *an experienced engineer would provide significant, measurable value to the company much faster than a graduate*. Also, an experienced engineer would be able to pass on high-quality training and professional development to a subsequently hired graduate engineer. This might be very difficult (if not impossible) for the staff members currently employed by the company (Bonus – 10 points).
- As an alternative, insist on an arrangement in which a young and relatively inexperienced engineer receives 2–3 hours of mentoring and guidance each week from an experienced engineer, including daily telephone access. The company would need

to pay for the mentoring and advice, in addition to the engineer's salary. Value: *the engineer becomes more effective and productive much faster* (Bonus – 10 points).

If you managed to devise another way to demonstrate the value of employing an engineer that is different than the responses above, award yourself 10 bonus points and please send us the suggestion.

How did you score?

Less than 10 points out of a possible score of more than 60 points?

Don't panic. Most engineers, even those with several years of experience, might also find these questions hard to answer.[2]

You are an exceptionally smart person: anyone who can pass through a university-level engineering course has to be intelligent. Your family is probably immensely proud that you are an engineer or are preparing to graduate from an engineering school. That's no small achievement, so don't forget to congratulate yourself!

On the other hand, you may be concerned that you found answering these questions harder than you expected.

Perhaps you are beginning to think just like one young engineer that I met recently. He told me that he had been seconded to an engineering firm undertaking a major expansion project for his employer, a large multinational corporation. He described his frustration that he was not doing any 'real engineering work', which is what he had expected the job to entail.

I asked him what he was doing in this position, since he wasn't doing 'engineering work'.

He said, 'They just send me out to check whether contractors have installed electrical junction boxes in the right places, or put the right culverts under the roads where they were supposed to. When it rains, I have to go and watch to see if the water flows through okay. Then, I have to fill in a stack of paperwork back at the office. It's not engineering work at all, definitely not what I expected. I'm also not learning anything that's going to help me in my engineering career.'

I answered with complete honesty, telling him that the work he had described *was* engineering work. In engineering, it is vital to check that the contractors have completed all their assigned work in compliance with the requirements in the contract documents before they are paid.

I said, 'It's just that your engineering lecturers forgot to tell you about the dozens, if not hundreds, of very important elements of engineering work, which are just as important as performing structural design calculations.'

Once the contractors have been paid, it can be very difficult to get them to come back and fix mistakes without additional payment. It can be even more expensive to pay someone else to fix the mistakes, and it usually requires high-level engineering knowledge to spot those mistakes.

This young engineer was contributing value by reducing the chances that mistakes had been missed, as well as avoiding the risk that extra money would be needed to fix them.

You can empathise with another of our graduates who reported feeling 'completely incompetent' in his first job working for a major multinational oil company. He told me that he did not know enough to do anything useful for the firm without having to ask other people a plethora of questions.

Don't forget that you are standing at the start of a lifelong career; it takes time to become an expert engineer. A degree confirms that you an intelligent and talented novice engineer.

If you described a multitude of ways for our young engineer to contribute additional value to the firm, then you may already be well on your way to becoming an expert.

Practice concept 3: Why engineering provides value and what this means for you

Now we can return to the question from the start of the chapter: what do engineers really do?

Looking at the sample responses for the fire alarm panel company's questions, we can see many of the ways in which engineers provide value for their clients, employers, and communities.

Engineers contribute value in two main ways:

- In the time available and to the greatest extent possible, engineers minimise the human effort and the consumption of materials and energy needed to achieve a desired result.
- Engineers provide a reasonably accurate forecast of the technical and economic performance, cost, and time required for a given project, while also being reliably capable of delivering results within these expectations.

A frequently cited quote on this issue reads, 'An engineer can do for one dollar what any fool could do for two'.[3] However, this adage misses the value contributed by the relative certainty of an engineer's predictions and the ability to deliver, compared to other people. In fact, an engineer's solution may actually be more expensive, but it is also more predictable and reliable. Chapter 11 discusses this in more detail.

There are many ways to do this. Engineering might provide a small productivity or reliability improvement in the short term without having to spend much money, or perhaps a much larger improvement in the future that requires more upfront expense. Maybe the improvement is small, but relatively certain, while another improvement might be larger, but less certain. Therefore, engineers can also help people decide how to invest their money in terms of making these improvements.

- Engineers seek to understand, discern, and explain the needs of a client, firm, or community in terms of engineering possibilities.
- Engineers conceive achievable economic solutions and forecast their performance, benefits, and costs to help with investment decisions.
- When investors decide to proceed, engineers arrange, organise, and manage the predictable delivery, installation, and operation of reliable artefacts (man-made objects, materials, and information systems).
- Engineers think ahead to reduce or eliminate risks and uncertainties that could have negative consequences. While many events are intrinsically unpredictable, engineers can help to make sure that negative consequences are minimal or at least

reduced as much as possible. At the same time, engineers are also prepared to take advantage of unpredictable opportunities.

More specifically, especially in the company case study above:

- Engineers can help improve a product or service, which will subsequently improve the way that customers experience the product or service, thereby increasing the apparent and actual value for a customer.
- Engineers can find ways to reduce or eliminate uncertainties, particularly mistakes caused by human error. Mistakes can cause delays or lead to wasted materials and energy; introducing systematic methods to consistently eliminate uncertainty results in a reduction of perceived risk.
- Engineers can reduce the material and energy consumption required to achieve a given outcome without reducing performance.
- Engineers can find ways to save time. Time always has a value, even if it is time for which people are not normally paid.
- Engineers can improve customer confidence by improving the reliability of artefacts and products.
- Engineers can anticipate future costs and benefits of alternative courses of action, providing information with an established level of reliability and uncertainty to better guide decision-makers.

TECHNICAL EXPERTISE

Scanning the contents of this book, it would be easy to get the impression that engineering science and technical knowledge are not considered sufficiently important enough to even have a chapter devoted to them. However, this impression is categorically incorrect. This book explains how expert engineers have integrated technical thinking with all the other important aspects of engineering practice.

The ability to conceive and design a practical achievable solution and predict its technical and economic performance is a critical component of the value contributed by engineers. On the other end of the spectrum, predicting failure is equally valuable. The techniques needed to do this are covered extensively in university courses, engineering science texts, patents, and hundreds of thousands of new journal articles and conference papers published every year.

It is this technical knowledge that distinguishes engineers as an occupational group. Therefore, I would ask you, the reader, to remember throughout this book that technical knowledge remains the primary qualifying attribute that defines an expert engineer.

There is just one other issue concerning technical knowledge. While this knowledge is used for analysis and diagnosis, more than anything else, engineering science knowledge is mostly applied directly when making accurate predictions. These are crucial in establishing an engineer's reputation for foresight.

The advanced engineering science and mathematical techniques learnt at university are rarely applied directly in the workplace. They are most often used indirectly: analysis software packages used by engineers incorporate these techniques and make them available for convenient application. The software packages often originate in universities. Once their practical utility for engineers in commercial practice has been demonstrated, the software is often acquired and reworked by specialist engineering software companies to make it easier to use and more tolerant of the typical mistakes made by users. These companies can also supply high-quality documentation, user manuals, and even training courses.

Another way in which engineering science and mathematics is applied in the workplace is in the form of tacit knowledge and understanding.[4] For example, Julie Gainsburg described structural engineers trying to decide if a simplified two-dimensional mathematical model of a building structure would be sufficient to predict its behaviour when the building is subjected to horizontal loads, for example from an earthquake or strong winds. They were asked to investigate whether the forces in the fasteners that secure the floor of the building to the structure would be within allowable limits. The engineers had a choice of several modelling techniques, including a full three-dimensional model that would have been much more accurate. However, it would have taken much more time, and therefore expense for the client, to prepare all the data so that the building would be accurately represented in this more complex modelling method. By choosing simpler methods that are known to be conservative (in other words, the forces are likely to be overestimated), the engineers were able to perform the calculations in much less time. Choosing which method to use, without having completed a full and detailed analysis, requires judgement based on tacit understanding of the relevant mathematics, conventional practices in structural engineering, and the engineers' personal experience and familiarity with the different techniques.[5]

An expert engineer will be continually building a personal repertoire of engineering science knowledge and techniques, and is likely to be familiar with a growing range of engineering software applications.

In the end, however, technical expertise is not sufficient by itself. In the words of an experienced engineer, 'No amount of reliability calculation achieves anything until maintenance technicians use their tools differently'. As we shall see throughout this book, engineering is a collaborative effort; what really counts is how an engineer uses technical expertise when working with other people.

There is no better illustration of this than the problem of supplying drinking water to a large number of people. Most of the detailed technical problems have been solved long ago. However, as we shall see in the next section, the essential factor is the ultimate economic cost for people to access the drinking water.

AN INDICATOR OF ENGINEERING PRACTICE

In my opinion, there is no better illustration that demonstrates the value of good engineering practice than the economic cost of potable water (safe, clean drinking water). Water supply has been the responsibility of engineers since the earliest urban civilisations. Water is heavy to move or transport, and is therefore not traded on the world market. Engineers design and organise the construction of water supply systems that enable water to run in pipes to any location where it is needed. However, many of these water supply systems don't work as intended. In the megacities of many countries like Haiti, India, Pakistan, and even parts of Europe, water flows from supply pipes for just an hour or so each day and can sometimes be unsafe to drink. When you need safe, clean drinking water in these cities, you usually have to prepare it, carry it to your home, or pay someone else to bring it to you, which can be very expensive.[6]

The economic cost of supplying potable water in many developing countries is very high compared to industrialised countries. A woman wearing colourful clothing and carrying water from a well to her house is often the subject of romantic paintings or photographs from developing countries. A typical earning rate for such a woman might be around USD $0.50 per hour, which sounds like a very low rate of pay. Now consider that she can probably make one round trip to a well in an hour and carry home about 15 litres of water. Assume that she needs another hour to boil and properly sterilise the water.

She does not have to pay cash for the water, but there is an opportunity cost because her water-carrying work prevents her from doing other work that could earn income or save expenses, such as growing food or caring for animals (she does have to pay for the stove and fuel to boil the water, as well as containers to boil, store, and carry it in).

An opportunity cost represents the income that has not been earned because the opportunity to earn the income was lost, either intentionally or unintentionally. Opportunity cost associated with unpaid time can also be referred to as 'shadow-priced cost for unpaid labour' or 'value of time'. It can include things such as waiting in a queue or traveling to and from work, or unpaid time off from work due to injury or illness. In low-income countries, the opportunity costs incurred from domestic work roughly equates to two-thirds of the local female earning rate. In other words, the time-consuming nature of domestic labour prevents women in low-income countries from gaining greater earnings through paid work.

This measure can be determined by making a large number of observations on decisions that people make, for example, when they decide whether to walk, take public transport, or hire a taxi. The difference in cost, when averaged over a large number of such instances, represents one measure of people's 'value of time'.

Once we account for this opportunity cost, the real economic cost of potable water is around USD $40 per tonne. In Australia, the driest continent, copious quantities of potable water come out of a kitchen tap at a cost of about USD $2 per tonne, including the connection charges of basic plumbing. Good-quality water and sanitation costs around 2% of the average family income in Australia, whereas getting barely enough water to survive can take 20–40% of a family's economic resources in a low-income country. Furthermore, sanitation services are often non-existent. If people don't drink clean water, they take an equivalent economic penalty: they get sick and lose several weeks of earnings every year, and also can lose years of life expectancy. When the real economic costs and penalties are taken into account, acquiring the bare minimum of daily drinking water consumes 10% or more of the GDP (Gross Domestic Product) of a country like Pakistan, whereas the cost in an advanced, industrialised country is less than 0.1% of GDP.

Few people realise that the cost of water for families in many low-income countries is this high. Officially, about one out of every six people in the world lacks access to an 'improved' water supply.[7] However, well over half of the world's population lacks continuous, piped, potable water supplies to their homes: these people have to either carry potable water themselves or pay someone else to perform the task.

What we can learn from this simple analysis is that the value of engineering in the industrialised world lies in the enormously reduced cost of essential services like potable water. I would even go so far as to suggest that the real economic cost of obtaining potable water is an indicator of the effectiveness of engineering practices in any given region of the world.

Engineers not only find ways to reduce the cost of products and services, but they also organise and arrange the reliable delivery of these products and services so that people can effectively use them. The value from engineering, therefore, emerges from *reducing* the human effort and resource consumption needed to provide the product or service, which in this case is a supply of reliable, safe, clean drinking water. A reliable water supply in the home liberates women and children from endless backbreaking labour, without which survival is impossible. Women can then provide education for their children and earn supplementary income for themselves.

I will leave further explanations for the failure of public water supply utilities for Chapter 13. The main lesson to learn from this example is the social and economic value of engineering. We see people in low-income countries paying far more for essential services, in equivalent currency terms, than those of us lucky enough to live in wealthy, high-income countries where engineering functions more effectively.

I was shocked when I first realised how expensive essential services and commodities are for the poorest people on our planet. There is no denying that we take them for granted in wealthy countries.

Later, I realised that this issue presents a new generation of expert engineers with wonderful opportunities by creating effective utility services that work well. Chapter 13 explains these opportunities in more detail.

While many engineers see themselves as technical problem solvers, simply finding a solution for a technical problem may not provide any useful value by itself. The value only arises when the technical solution is implemented and applied so that people in the community can experience the benefits. Engineers take part of the responsibility for this; otherwise, their work may be of little intrinsic value.

One of the most important observations arising from our research is that engineers almost always have to rely on other people to implement the results of their work and reliably deliver products and services to the people who are going to use them. Engineers, by themselves, perform very little, if any, hands-on work. Most engineers rarely even meet the people who make use of their products and services. Therefore, the value of engineering work arises indirectly through the actions and behaviour of people other than engineers.

Given this situation, engineers need to be able to influence the behaviour of the people who deliver their products and services if their work is to result in lasting value. In the same manner, the only way that this book will result in any value for humanity is through you, the reader. This book will only achieve any useful value if the techniques that I suggest work out in practice and you choose to adopt and use them.

Therefore, in a sense, an expert engineer has to be an expert educator. Such an individual needs to educate and influence other people to reliably deliver the artefacts and services as the engineer intended in order for others to make effective use of them.

There is one additional, important step in this discussion on the value of engineering. I need to take you through a short argument based on economics to do this, but you will soon appreciate why this is critically important for you, the reader.

DISCOVERING EXPERT ENGINEERS

Labour market economics demonstrates that, in a stable market that responds well to information about supply and demand, employee remuneration reflects the employee's marginal product. In other words, employees are paid in proportion to the additional value that their work creates. At least in theory, your pay as an engineer will reflect the value you create for your employer and clients.

In reality, however, your pay depends on many factors, only a few of which reflect the value created by your contributions. First, as we have seen, the value of engineering work arises indirectly and depends on the contributions of many other people apart from engineers. This makes it difficult to measure the real value created by engineers. Second, and partly because of this, engineers are often paid according to a broadly agreed upon set of conventions. Third, valuable engineering ideas often arise, seemingly by chance, from social interactions with other people, making it even harder to identify any one individual's contributions.

That being said, our research has produced strong supporting evidence for this principle by comparing experts and other engineers in developing countries.

In India and Pakistan, our research revealed that most engineers are paid about one-third of the salary that engineers receive in advanced industrialised countries like the USA, Canada, Germany, and France. The same research demonstrated a critical shortage of engineering skills in India and Pakistan, as evidenced by widespread performance shortfalls in water supply and many other industries. The extraordinarily high economic cost of water reflects this shortage. These two observations seem to contradict one another. If there is a shortage of engineering skill, then why is the price of engineering labour so low when compared to industrialised countries?

The answer lies in what we consider to be engineering skill. Engineering students in India and Pakistan learn much of the same information in their university courses as students in any industrialised country. However, few of them have the real world opportunities to learn the kinds of skills necessary to become an expert engineer, the skills to which this book introduces you. In an industrialised country, novice engineers have more opportunities to learn from engineers with more skills, although this is often due more to chance than intentional design. Many of my former students left engineering in frustration because they ended up in jobs where they were expected to learn by themselves, without expert engineers to imitate or provide guidance.

We found a small number of engineers in India and Pakistan with the kinds of skills that made them experts in their fields. Their skills were recognised and rewarded by their employers, in some cases government-owned organisations. Their employers knew that these individuals could move to highly paid jobs in engineering firms in the Gulf region or even in Europe, Canada, and the USA. They were being paid well above the salary level that they could earn elsewhere, in equivalent currency terms. At the time (2004–2007) they were each earning the full-time equivalent of USD $90,000–150,000, salaries that most engineers in Southern Asia could not even dream of earning.

What were their skills that were recognised as so valuable?

These engineers were highly sought after because they had the capabilities needed to produce high value for their firms. Just as I have explained above, these firms recognised their capability of producing value indirectly, *through the skilled contributions of many other people*. They were no more intelligent than engineers employed for a small fraction of their salary. However, they had learnt how to tailor their engineering performance to deliver consistently valuable results for their firms. By studying their work, I started to understand how they achieved that. Some, but not all, had gained their engineering qualifications in Europe, Canada, or the USA. Some, but not all, had actually worked in Europe or the USA, although not necessarily in the best-managed firms. Some, but again, not all, had studied in business to supplement their engineering qualifications. Some others had none of these opportunities, yet they had still managed to acquire 'expert' engineering capabilities. What they had in common was a combination of determination to succeed, a belief that they could succeed, and an understanding that they could only achieve their own success through the successful contributions of many other people. Helping others to succeed was the critical factor in their own success. Most also explained their contributions in terms of the value created for their employers, which justified their high salaries.

In other words, these select few 'experts' had realised that success in engineering means creating economic and social value by working with and through other people: it cannot come solely from individual technical excellence, no matter how brilliant and insightful it happens to be.

If you live in a developing country like India or Pakistan, this should demonstrate that you can, in fact, succeed and become an expert engineer without having to leave your home country. You can also look forward to earning a salary at least equal to the best in the world. Of course, that all depends on you learning how to become an expert engineer.

If you live in a country like Australia or the USA, this lesson is just as relevant for you. Surveys of engineers have revealed that a large majority are dissatisfied with their earnings, responsibility levels, and opportunities for advancement. American civil engineers reported this in a large survey in 2004.[8] They complained about being passed over for leadership responsibilities and promotions in lieu of people without engineering qualifications. They complained about working with project managers who had little or no technical understanding and less experience, yet they were denied opportunities to lead projects themselves.

Here, then, is the answer to the question in the title of this chapter, 'Why Engineer?' Engineering is a wonderful career, partly because you can have great fun spending lots of money that belongs to other people. However, you need to remember that these people are investing in you, and your ability to consistently provide valuable results. Investors, by and large, don't understand much about engineering, but they spend their money on you (and others) in the expectation that it will result in sufficient value for their shareholders. Your ability to attract their money, confidence, and trust (as well as their patience when things go wrong), depends on your capacity to build relationships and deliver results . . . almost entirely through the actions of other people.

There is a social justice issue here as well: who gets to share the benefits of an engineering investment? While the economic benefits of reliable piped water to the home undoubtedly go to the householder's family, the benefits may not be so evenly distributed with every example of engineering success. Ultimately, if the benefits are not shared fairly and reasonably, people may intervene and bring even the best-planned engineering project to a halt. We will see this in Chapter 12, which discusses sustainability.

You cannot do engineering completely on your own, of course. No single person has all the required knowledge, skills, and capabilities to achieve engineering success without other people. Therefore, what counts is your ability to win the willing and conscientious cooperation of others who have complementary skills to yours. This ability, above all others, is what will underpin your success as an expert engineer.

I hope this explanation will show you that the real challenge as an engineer is to be able not only to devise wonderful technical solutions, but also to make sure that these solutions are delivered predictably, and that they provide real value for other people, both your clients and the people that they serve.

You might be thinking that all of this has to do with management, something that will only become relevant later in your career, at least not until after the first few years. You might think that you can learn all of this by studying for an MBA degree when you feel the need, can afford the fees, and are willing to face the prospect of studying hard once again.

You can see for yourself how much of the material in this book is included in an MBA programme: most is specific engineering material.

Our research demonstrates conclusively[9] that all of this will be relevant in the first year of your first job. Novice engineers find themselves relying on skilled contributions and help from many other people right from the start of their career. Understanding this, and building on this understanding by learning the skills described in this book, can get your engineering career off to a flying start.

PRIOR LEARNING

We're not quite done yet.

In fact, there is a long way to go. Learning has to start with an exploration of what the learner already knows when they begin. If I ask you to learn something that you already know, you will probably put this book down and never read the rest of it. Equally, if I ask you to learn something that relies on some prior knowledge that you don't yet understand, then no amount of explanation is going to be sufficient for you to learn it.

Throughout this book, there are many references to further reading if you need to build up your prior knowledge.

One of the main aims of this book is to provoke you into thinking more about engineering practice. There are many misconceptions about practice that can interfere with the quest to become an expert engineer, so it can be helpful to gauge how much you may have to shift your own perceptions to remove some obstacles to learning.

These are not small issues.

In all, this research has revealed more than 80 significant aspects of engineering practice that are missed by texts and conventional university engineering courses. These omissions allow myths and misconceptions to persist, mainly through unquestioning repetition. The texts were written by engineering educators, so it is quite possible that you unknowingly developed similar knowledge gaps from your experiences at an engineering school.[10]

Practice quiz 2

This quiz consists of a series of propositions that engineers talk about in the context of discussions on engineering practice. Respond to each question by indicating your current beliefs on the proposition. Select one item from the responses provided, ranging from 'strongly disagree' to 'strongly agree'.

Each proposition has been addressed by research that has contributed to this book. When you assess your responses (or receive feedback from the electronic version of the quiz), you will be able to see how well your beliefs align with the results of this research.

The evaluation guide in the online appendix also provides explanations for the scoring: read this carefully to learn more. Your score will provide some indication of the extent to which you need to study this book to help you on your way towards becoming an expert engineer.

Q1: An engineer who achieved higher grades at university tends to perform better in engineering work.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q2: As an engineer, it is critical that you accumulate sufficient technical knowledge by yourself to solve any problem that you are likely to be confronted with.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q3: Engineering is a hands-on practical occupation.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q4: In engineering, many decisions are made on the basis of perceptions that can be inaccurate or incorrect.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q5: Being a successful engineer depends primarily on your technical expertise.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q6: Facts are more objective and unbiased when stated in terms of numbers rather than words.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q7: The ability to build collaborative relationships with more experienced engineers, suppliers, and site supervisors has more of an effect on workplace performance in engineering than academic ability.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q8: Most of what an engineer needs to know is learnt in the workplace.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q9: You can only learn communication skills by practice; they cannot be taught.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q10: In engineering, decisions are almost always based on technical facts, computation, analysis, results, and logic.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q11: Engineers often have to work with vague verbal statements of requirements from their clients.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Q12: Graduate engineers, on average, spend just as much time interacting with other people as senior engineers, who often have management responsibilities.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

How did it go?

What did you get out of a possible 120 for the second quiz?

Even if you scored less than 60, you're doing okay. However, you still have a lot to learn. If your score was better than 90, consider yourself well on the way to being expert: congratulations!

Practice concept 4: What does it cost to employ you?

The second question asked of my recent graduate at the start of this chapter related to the cost of employing an engineer. Most engineering students, and many working engineers to whom I have explained this, are very surprised when they learn just how much it costs to employ an engineer.

Naturally, the exact costs depend on the particular company and its respective circumstances. The figures below indicate the approximate costs in Australia at the time of writing but will vary from place to place. However, in any given setting, the costs will be more or less similar in proportion.

Obviously, the first cost is the salary that a firm pays you.

Other costs include the following, expressed as an approximate percentage of your salary, although the actual amount will vary from place to place.

The last item (business development) represents the proportion of your time that will be needed to support business development, winning contracts for the firm, helping to write proposals, and tender submissions to gain new work.

With four weeks of annual leave and a nominal 37.5-hour working week, you will be at work for a maximum of 1800 hours each year. Allowing for one week of sickness, time for personal hygiene, work breaks, and moving from one location to another (200 hours), business development activities (200 hours), and training and guidance from supervisors (300 hours), approximately 1100 hours are available for 'billable' work, which are projects for which a client will pay. In practice, it is difficult to achieve this because there are times when there is insufficient work to keep everyone

Table 1.1 Additional employment costs.

Payroll tax, employer's liability insurance	5%
Superannuation/pension contribution	10%
Annual leave	10%
Office accommodation rent (approximately)	15%
Administrative support	15%
Supervision and assistance from senior engineering staff, approximately one hour per day for the first year and about 30 minutes per day thereafter	33%
Health insurance contribution	2%
Electricity, water	3%
Travel, accommodation, visits to engineering sites, attendance at conferences, sales seminars, etc.	15%
Engineering software licence fees	10%
Subscriptions to databases, libraries of standards, and other sources of information	5%
Business development, preparing proposals, and presentations by other company staff	25%
Total	148%

occupied. Let's optimistically assume that a young engineer would be assigned to work on projects for 1000 hours annually. That means that the cost of employment has to be recovered on 1000 hours of work for which the firm is paid by the clients.

With a monthly salary of $5,000 ($32.50 per hour pay, before tax is deducted), the hourly rate needed to cover your salary and all the other costs listed above will be at least $150. After allowing for a profit margin, the cost to a client will be about $170 per hour.

You need to understand this. The important issue here is that, as an engineer, you need to create sufficient value through your work to justify the cost that a client will be asked to pay for your services. You need to think very carefully about how you do your work because the cost can rise very quickly.

Most graduates and many engineers have never seen this simple calculation and therefore find it difficult to understand why their managers might be concerned about the way they spend their time. Recent research has shown that young engineers find it very difficult to describe the precise value created by their work, and most engineers only consider the direct salary cost of employment, not the overhead costs listed above. To be an expert engineer, and also to enjoy your work, you need to be confident that you are creating at least as much value as it costs a client to obtain your services. Adapting designs and plans that have provided value for previous clients is often the best way to create value for new clients. You also need to charge clients a fee that covers your costs and a reasonable profit margin. It is easy to underestimate both of these costs.

IDEAS FROM ECONOMICS

If you are going to spend lots of money, particularly money that belongs to other people, you need to have a basic idea of how money works.

Money has evolved as a means of exchange for goods and human services. The price of goods reflects both their perceived value to the purchaser, their relative scarcity, and the amount of human effort and other resources required to produce them. This much is common knowledge.

Money, therefore, is an approximate measure of human labour.

As an engineer, you will probably be paid an agreed amount for each hour or day that you work, but not everyone works on this basis. A contractor often gets paid an agreed upon amount for completing a task.

Two fundamental difficulties arise in both of these situations.

The first is that what a person can achieve in a given amount of time is highly variable. If the person is focused on the task, free from interruptions, well rested, keen, motivated, and finds the work intrinsically rewarding and satisfying, then that person will often achieve a great deal in a short time.

If, on the other hand, the same person is tired, working in a noisy environment with frequent interruptions, unable to concentrate, thinks the work is seemingly of no consequence, like a report that no one will read or that will be simply filed away forever, then much less will be achieved in the same amount of time.

The same applies even in the case of a person who is working on a 'piece rate' and gets paid an agreed upon amount for completing a task.

If the person is focused on the task, free from interruptions, well rested, keen, motivated, and finds the work intrinsically rewarding and satisfying, then that person will not only finish the task earlier, but will also 'put their heart and soul into the task', working conscientiously to make sure that there are as few faults or defects as possible.

So even though the amount of money paid is predetermined, the quality of the work performed and the amount of work performed by people can be highly variable.

The second difficulty is that the value of money itself changes over time and, more importantly, with human perceptions of value.

Most of the time, the prices of goods and the salaries that people earn slowly increase all the time: this is known as inflation. Most government economic regulatory agencies aim to keep annual inflation rates between 2% and 3%. Because of inflation, the value of money changes with time. Normally, when the inflation rate is low, the effect on the value of money is quite small.

However, much larger changes occur in the value of money because much of it is invested in shares in business enterprises.

The value of shares fluctuates daily, sometimes by a large percentage. It is not unusual for the price of shares in a firm to go up or down by more than 5% in a single day. Yet, on most days, the firm occupies the same buildings, with the same clients, the same customers, and basically the same volume of sales. Why then does the share price rise and fall so much? And why is this important for you, particularly if you do not even own any shares?

The reason why the share price rises and falls so much is because the share price depends not so much on the day-to-day business conducted by the firm, but rather by what prospective buyers of the shares think is going to happen to the share price over the next 6 to 12 months, even over the next few days. What this means is that they are trying to figure out what prospective buyers of the shares are going to think in future, and the future, as we are constantly reminded, is entirely unpredictable. It is like trying to forecast what other people think will be in fashion when they attend next year's fashion parades.

Many people think that a house built from bricks and mortar, constructed on a block of land, and unable to be moved easily, is a rock-solid, reliable investment. Some of the time, house prices change very little from one day to the next. However, this is not always the case. There have been many times when buyers have believed that by offering a price well below what the seller is demanding and then waiting, the seller will eventually compromise and reduce the price. This happens when it is hard to obtain money from the banks to buy houses, particularly in uncertain economic times. The real value of a house, what a buyer will actually pay for it, can be very hard to predict and can fluctuate just as much as the shares in a business. Barring any unforeseen disasters, the house remains exactly the same: it does not change. The only things that change are the expectations of the buyer and the anxiety of the seller to conclude a sale.

As I explained before, engineering depends on spending lots of money that belongs to other people. Those people are investors. They borrow much of the money through investment banks, but if the engineering does not work as expected, many will have to sell their shares, and even their houses and land, to repay the loans from the banks. The banks protect their interests well: they will hire other engineers to analyse the proposed venture in order to ensure that the engineering and market studies have been done thoroughly. Banks pass on risks to other investors. The investors only take on the risk because they are confident that, eventually, the engineering work will provide products or services that are valuable for other people, and that these other people will buy enough products and services at sufficiently high prices so that the investors will get their money back with an additional profit.

Notice, therefore, how much depends on human perceptions of value.

Investors who are providing money for engineering depend on other investors to buy the shares and houses that they sell to raise capital.

The same investors would not be providing money for an engineering enterprise, part of which will pay your salary, unless they (and their bankers) were confident that you and the other engineers involved will be able to deliver the products and services at the expected cost. Nor would they provide money unless they were confident that other people will buy enough of the products and services at high enough prices for them to eventually make a profit.

Investors usually know very little about engineering. While they may hire consulting engineers for advice, in the end, they rely on their own judgement, which is based on their perceptions that the enterprise will succeed.

Therefore, their willingness to spend money, and furthermore your opportunity to perform engineering work for them, critically depends on the perceptions of investors and many other people. In the same way, the cost of engineering work and the quality with which it is performed depends to a large extent on the perceptions and feelings of the people performing the work.

Now, all of this can be very difficult to accept and understand, particularly when one has been taught for several years to work with predictions based on accurate computer models, precise laws of physics, and repeatable experiments. Many engineers yearn for the unerring certainty and feelings of precise control that come from writing their own computer software: once it works, it works every time. Furthermore, if it does not work, the only mistakes are your own and no one else's.

However, within the real world of shifting human perceptions and emotions, engineering becomes much more challenging . . . and interesting. Like a ship at sea, human emotions move and change all the time. Just as the ship's bow may be momentarily submerged by a large oncoming wave, seconds later it will soar above the oncoming trough. In the same way, when a person feels a temporary loss of confidence, when even the smallest obstacles seem overwhelming, you can be confident that this dark depression will soon be forgotten and displaced a few days later by humour, excitement, and optimism.

Among all of this social fluctuation and change, one of the most attractive attributes of an engineer is the ability to clearly distinguish the essential engineering functions needed to satisfy human desires and requirements, especially for end-users, the people who ultimately use the engineered products or services. This means understanding and listening to the client, end-users, and other stakeholders, something that we will explore in greater detail in the coming chapters. However, it also means perpetual dialogue, a continuing conversation to educate the client and other stakeholders about feasible engineering possibilities.

At the same time, an engineer will be searching for the most cost-effective ways to achieve the required function, considering ways that bypass unsolved technical problems and uncertainties, adapting what has been done before, and thinking ahead – how could this be misused, abused, or neglected? Can we line up reliable people to do the work at the time they will be needed? What is the situation facing our preferred contractors that have experienced similar situations before? Are they going to be overcommitted with other work, or at risk of financial default?

At the same time, in the search for feasible choices for the client, an expert engineer will be instinctively thinking ahead and planning for risks and uncertainties to minimise the effect of unpredictable events on the ability to deliver results earlier than required, safely, with better quality, and at a lower cost. Simultaneously, the engineer will need to reassure the client and help build a trusting relationship so that the client feels confident that the engineer can deliver. This takes time and experience in working with people.

You might think that this is something that will await you after several years in your career. Our research proves otherwise: even engineers in the first few months of their employment find themselves dealing with apprehensive and anxious clients, often indirectly through their employees or representatives, which makes it all the more difficult to understand what's actually happening.

Did I know any of this when I started as an engineer?

No, not in the least . . . none of this. I was shy and apprehensive, and also quite confident that I was one of the least equipped people to deal with human relationships, business, and finance. I focused instead on my technical skills, where I had reasonable confidence in my abilities.

Gradually, I came to appreciate my dependence on other people: no amount of technical expertise could isolate me from the need to work with other human beings. The skills and insights in this book could have helped me understand so much more than I was able to at the time. They could have helped me become an expert engineer much sooner and with less frustration than I alternatively experienced through ignorance.

Even now, I am still learning about people. I admit it: I can be a slow learner. With the help of this book, you will be able to learn far faster than I did, and it will help you become an 'expert' engineer in a few years from now.

NOTES

1. Access to online quizzes and practice exercises is available through the online appendix for this book.
2. Trevelyan (2012b).
3. Wellington (1887).
4. Goold (2014).
5. Gainsburg (2006).
6. Trevelyan (2014a).
7. An 'improved water supply' is a term used in the context of UN projects and discussions on meeting the 'Millennium Goals' for human development, meaning a water supply that does not require people to go to the nearest river, water hole, or other natural water source. It includes water supplies such as wells and piped water supplies, but does not imply safe, clean, potable water. Piped water does not have to be continuous: intermittent service for an hour or so every few days, possibly contaminated by water seeping into the pipes

through broken connections when the pressure is low, still counts as an 'improved water supply'.

8. Reported in American Society of Civil Engineers (2008).
9. We conducted an extensive study of the work and careers of a cohort of 160 engineering graduates from the University of Western Australia (Trevelyan & Tilli, 2008).
10. See online appendix for details.

Chapter 2

What type of engineer?

When I tell people that I am an engineer, the first question they always ask is, 'What type of engineering do you do?' I tell them that I'm actually an engineering academic and that I teach young engineers. The conversation moves on predictably from there.

'Yes, but what type of engineer are you? Are you mechanical, civil, or electrical?'

'That's a difficult question,' I often reply. 'Most of my career has been in mechatronics and robotics. I graduated as a mechanical engineer and moved into aerospace and human factors engineering at the start of my career. Now, I teach design and sustainability and commercialise new air conditioning technology.'

The word 'type' in this context means 'discipline', a specialisation within the field of engineering. This is a relatively new concept; until the middle of the 19th century, there were only two types of engineers: civilian engineers and military engineers. However, by the end of the 19th century, the three main disciplines had emerged. Civil engineers, the original civilian engineers, were responsible for most engineering projects at the time. They designed and organised the construction of railways, roads, water supply and sanitation systems, canals, ports, and buildings. The Industrial Revolution in the 18th and 19th centuries led to the proliferation of manufacturing and machines; mechanical engineers specialised in the design and manufacture of machines, as well as the rapidly growing number of consumer products. The invention of electric machines in the 19th century naturally resulted in the development of electrical engineering as an engineering discipline in its own right. In the early years of the 20th century, the industrialisation of chemical science necessitated the development of chemical engineering as a further major engineering discipline. In the late 20th century, as computer programming increasingly became a significant focus of development, software engineering emerged as another new discipline. Growing concern about the need to maintain the quality of our environment and reduce the destructive impact of human activities, particularly in terms of engineering activities, has recently given rise to environmental engineering as a distinct discipline as well. A vast range of other disciplines have emerged in the last half-century, making it important to take stock of the situation and pose an important question:

What is, and what is not, an engineering discipline?

My research notes have provided me with a list of about 260 engineering disciplines, labels that engineers use to mark out the particular specialised knowledge on which they base their practice. What is the difference between each of these disciplines? What distinguishes an electrical engineer, for example, from an electronics engineer? What characterises a ship engineer, an aerospace engineer, a fire protection engineer, and a machine designer? What defines an electrical power network engineer? Along with what separates these disciplines, what do they have in common?

The research for this book demonstrated that the work performed by engineers in many different disciplines is remarkably similar. Even from a technical point of view, practically all engineers rely on the same basic concepts in engineering science:

- **Equilibrium:** Things stay the same and only change in response to an external influence.
- **Mathematics:** Provides the underlying mathematical logic in which the laws of engineering science are framed.
- **Systems Thinking:** Engineers define a boundary around a cluster of interacting objects and artefacts and then think about what must cross the boundary and what remains inside.

Disciplines other than software engineering also build on two other basic concepts:

- **Conservation Laws:** Energy, momentum, charge, and mass must be conserved. Except in the context of certain nuclear reactions, mass remains constant, which means that Einstein's famous law relating mass and energy stays out of the picture.
- **Continuity:** The notion that what goes in must come out, somewhere. It can't disappear.

Most engineering students learn these fundamentals in their first two years of study, while much of the mathematics and science required for engineering disciplines has already been learnt in high school.

What makes up the rest of an engineering discipline is a language of ideas, confidence in learning about technical issues quickly, and an appreciation of supporting resources, practices, and ideas in a given area of technical specialisation, along with a wealth of detailed technical knowledge; we will learn more about this in Chapter 5.

This book is mainly about ideas that are common to all engineering disciplines, particularly the socio-technical concepts that underpin collaboration, which is an essential feature of all engineering pursuits. It is paradoxical that these ideas seem to have been largely forgotten in engineering schools. Perhaps it is simple to understand what distinguishes us from other academic disciplines like the humanities and social sciences, but it is not so easy to see what is common for all engineers.

As we shall see in the next chapter, collaborating with other people and coordinating technical work takes the majority of the time and effort in real world engineering practice. Remarkably, these practices are common to all disciplines of engineering that we have studied so far. There are only very minor differences in certain disciplines. It is this, the major part of engineering practice, which the rest of this book is all about.

Your university education provides you with the technical language, ideas, and methods used for one of the main engineering disciplines: civil, mechanical, electrical, environmental, chemical, or software/IT. Yet, graduates from these disciplines then go on to enter two to three hundred different areas of engineering practice and disciplines! At the end of this chapter, Table 2.1 lists the disciplines that we have encountered in our research. This table shows which of the main disciplines that engineers in each more specialised discipline may have migrated from. Migration is an appropriate word in this context. While you might start out as a civil engineer, over the course of your career, you may gradually migrate from one discipline to another, often by chance as opportunities arise.

Many, if not most, engineers end up practising in a completely different area from the one they expected to enter at the time of graduation. That is nothing to be concerned about; while the technical knowledge in a particular discipline is always important, it can be learnt remarkably quickly because of the practice that you have had at university. What is common to all engineering disciplines is much harder to learn because it involves concepts and issues that you have not learnt much about at university.

This book is all about these common issues, those challenging ones that take time and real world experience to learn. We will understand more about why they are so difficult to master in the next chapter.

While most of the work that engineers perform is remarkably similar, even in technically very different disciplines, there are different places that engineers need to go to and ways that engineers need to think. Table 2.2 lists some of these fundamental differences. It compares some aspects of the main engineering disciplines, but it is a simplification of reality. Columns in the table describe the following aspects:

Where, apart from the office
Most engineers spend much of their time in offices, while many others spend a lot of time travelling. Working on-site takes you to the other locations listed in this column.

What you can see, feel, smell, and touch
This column briefly lists aspects of the materials and artefacts that you work with that you can perceive with your senses.

What you cannot perceive, where abstract thinking is required
Lists some of the aspects for which abstract thinking is needed, often with the help of mathematical analysis and computer modelling.

3-D spatial thinking
In some disciplines, it is an advantage to be able to think in three dimensions, to be able to visualise three-dimensional objects portrayed with two-dimensional diagrams and sketches. However, this specialised skill is not essential in any discipline.

Predicting hazards and anticipating failure
Being able to forecast possible material and artefact failures is an essential critical thinking ability for engineers. Being able to perceive the early signs that indicate the likelihood of failure is a valuable attribute that will save time and enhance safety.

Public health and social risks
Engineering work in most disciplines, but not all, can have a large influence on public health, as well as social stability and cohesion. For example, the failure of a water supply system can have catastrophic public health and social stability consequences.

Is this something I can show my children?
For many engineers, this is a powerful motivator. 'I helped to build that big ugly ship you can see in the picture!' However, in many aspects of engineering, the contributions of an individual engineer are more difficult to see.

CHOOSING A DISCIPLINE

When students have asked me about different disciplines, usually when they are trying to make up their mind about which discipline to specialise in, they usually ask the following (or similar) questions:

Which discipline has the most jobs for engineers?

There is no simple answer to this question. Which of more than 200 diverse, dynamic disciplines do you think has the most jobs for engineers? Employment opportunities for engineers are nearly always good, but there are large fluctuations in some areas of engineering. Engineering depends on people spending money long before the benefits are received: engineers spend money that investors are willing to provide. In times of economic uncertainty, investors are usually much more cautious, which means that there is less money to spend on engineering, thereby limiting job opportunities. However, engineers are always in demand, to a certain degree, in order to keep things running. People always need water, food, energy, shelter, transport, communications, and sanitation and there are plenty of opportunities for engineering to provide these necessities. As long as you are prepared to be flexible and have the skills to work on different aspects of engineering at different times, there will always be jobs available for you.

Which discipline is going to be in demand in the future?

I once went to a lecture by an electronic engineering professor who claimed that his was the only discipline worth studying. All the other disciplines had reached the end of their intellectual development, so all that was left to do was incremental refinement. All the excitement, he claimed, had vanished from the other disciplines. He was clearly mistaken in his belief. True, there are some engineering disciplines that have receded in relative prominence, for example, mechanism design. However, there are still endless opportunities for intellectual advancement in even the oldest disciplines of engineering. There is no reliable way to forecast future developments in engineering, just as in most aspects of human activity. All that one can be sure of is that engineers, in every discipline, will be in demand for the foreseeable future.

What's common between the disciplines?

Read the rest of this book and find out. Most of what engineers do is common between all of the disciplines. This helps to explain why most engineers are able to change disciplines during their careers, some more than once.

Which disciplines are special, involving something that no other engineers do?

> None of them. That's the fascinating thing about engineering. Everything that is done in any one discipline is also done by some people in other disciplines. There is no such thing as a 'standard' mechanical or civil engineer. Every engineer has unique abilities that are different from every other engineer. Even in a specialised discipline such as fire protection engineering, you will still find ordinary mechanical or electronics engineers working in fire protection without calling themselves fire protection engineers. There are usually many more mechanical, electrical, and instrumentation engineers working in the oil and gas industries than there are petroleum or oil and gas engineers. The same applies in the aerospace discipline, where mechanical, mechatronic, and electrical engineers typically outnumber aeronautical and aerospace engineers.

Which industries provide employment opportunities and where?

> There are obviously links between certain industries and specific disciplines. For example, a road engineer is less likely to be working in aerospace than a materials engineer. However, a road engineer that acquires high-level commercial and project delivery skills could successfully migrate into mine development, and from there into mineral processing systems. By recognising that there are as many, if not more, similarities as differences between engineering disciplines, and also learning these common engineering practice skills, you will have far more opportunities in a wide range of industries.
>
> Also, many industries employ engineers simply for their analytical and mathematical abilities, as well as for their ability to work with abstract ideas. The most common destination where these skills are directly applicable is probably finance. For example, almost all the engineering graduates from one of the prominent London universities end up working in financial institutions.

In summary, then, my recommendation is to always follow your interests, knowing full well that your interests will change and, at the same time, keep watching for opportunities in areas that you might not have considered. In the end, it does not matter which discipline you choose. All the engineering disciplines offer exciting and rewarding careers and each of them offers the chance to become an expert engineer. Every choice on the diverse spectrum of specialties will give you the chance to improve the world, while also making a reasonable income to support your family at the same time. The most essential things you need to learn in order to become an expert engineer do not depend on which discipline you happen to find yourself in at any one time.