Is There More to Engineering than Applied Science?

Thesis/Project work submitted in partial fulfilment of the requirements for the MSc in Human Factors and System Safety

Martin Downey

Lund University
Sweden

Date of submission: 2012-06-09

IS THERE MORE TO ENGINEERING THAN APPLIED SCIENCE?

Martin Downey

Under supervision of Hans J. W. G. M. Houtman
and James M. Nyce, PhD

ABSTRACT

This thesis examines the idea that engineering is an applied science, and what it means for the practice of engineering, particularly in the context of complex socio-technical systems. It traces the social history of engineering as a profession in the Anglo-Saxon context and the development of a 'scientific ideology' in engineering education which replaced the practice based learning of the shop-taught engineers. The success in the application of reductionist approaches to engineering analysis of complicated designs has reinforced the belief that engineering science provides an understanding of the world as it is. In the context of complex systems, this over-confidence in the epistemology of engineering science poses a risk in itself. Paradoxically, acknowledging the uncertainty, subjectivity and methodological imperfection in our approach to assessing the risks inherent in technology may provide most benefit.

TABLE OF CONTENTS

INTRODUCTION

The question of what engineering 'is' and what constitutes an engineer eludes a simple answer. A review of engineering syllabi, points to an epistemology based on the application of physics and mathematics to real world problems. Engineers are seen as providing a link between scientific research and the creation of new products. If engineering is understood to be purely the application of scientific principles, the epistemology of engineering would be seen as positivistic and 'value-free'. From this standpoint, any discussion of engineering failure could be seen as a failure of the engineer to apply robust scientific principles. Moreover, taking a view that engineering is based on a solid universal set of physical laws may leave the engineer with a strong sense of confidence in his methods and approach, a mechanistic view of cause and effect which underplays the influence of weak interactions. This view holds that risk can be quantified by analyzing a system under the assumption that the safety of a system can be assessed by quantifying the reliability of each component.

This thesis will examine the epistemology of engineering in an Anglo-Saxon context, and attempt to address the question: 'Does the belief that engineering is an applied science help engineers understand their profession and its practice?'

CHAPTER 1: SCIENCE AND ENGINEERING

A scientist discovers that which exists. An engineer creates that which never was.
Theodore von Kármán[1]

The Age of Reason

The intellectual movement that came to be known as "The Enlightenment" emerged in 17th century Europe, seeking to understand the natural world (and man's place in it) on the basis of evidence and reason, where previously man's concepts of the world were largely governed by religious belief and superstition. There can be little doubt that the practice of engineering has been transformed and enlightened by the Laws of Science uncovered in Europe during the period (described as the Age of Reason) spanning the 17th through mid 19th Century. Newton's and Euler's Laws of Motion transformed our understanding of mechanics; Coulomb, Faraday and Ampere formulated laws describing electromagnetism. Writing this thesis two centuries after many of these scientific discoveries were first postulated, it is easy to take this understanding for granted, however such Scientific Laws revolutionised how we as humans see ourselves in the world. Areas of knowledge that were shrouded in superstition and mysticism were explained in rational terms, and moreover, these laws had strong predictive effect – the motions of the celestial bodies could be accounted for, and more importantly, *predicted,* in relatively simple terms.

Typically, the laws had a mathematical simplicity and elegance; an aesthetic appeal that for some reinforced the idea of an Intelligent Creator – the Universe was perceived as a place of order – unexplained phenomena were understood and explained for the first time. It was a time of great social and religious upheaval, where scientific knowledge came head-to-head with religious dogma. The discoveries of science both supported and denied the existence of an intelligent creator – on one hand Rene Descartes insisted that science was simply discovering 'laws that God has put into nature', Newton attributed the laws of nature to the 'counsel and dominion of an intelligent and powerful Being' (Brooke, 1991, p. 19). On the other hand, findings of geologists and palaeontologists brought into question the Biblical creation story, and the refutal of the geocentric model by Copernicus, Galileo and Kepler somehow diminished man's importance as he was no longer at the centre of the universe. These Enlightenment scientists walked a fine line – Descartes drew a distinction between mind and body to lessen conflict between science and religion (Garber, 1998, 2003), and Newton left the door open for God's intervention through miracles – the laws of science came from God, and therefore He could choose to circumvent them at His will (Harrison, 1995, p. 531).

The Scientific Method

Descartes proposed an analytical, systematic, logical mode of inquiry which became known and accepted as the 'Scientific Method'.

> Those long chains of very simple and easy inferences that geometers customarily use to arrive at their most difficult demonstrations had led me to think that all the things that human beings can know are inter-deducible in that same way, and that nothing can be too remote to be reached

[1] Quoted by Young (2000).

> eventually, or too well hidden to be discovered—just as long as we refrain from accepting as true anything that isn't, and always keep to the order required for deducing one thing from another (Descartes, 1637, pp. 9-10).

Since then, this form of deductive reasoning proposed by Descartes has formed the basis of much of the scientific inquiry. It is the belief in a science consisting of a collection of Laws that are 'certain, universal and true' that is at the heart of this thesis, a belief in an ontological certainty arrived at through an analytical approach – by literally pulling apart and atomizing the artefact or system we wish to understand – reducing the whole into a 'long chain of very simple or easy inferences' (Descartes, 1637).

Enlightened Engineers

The findings of science certainly found practical applications, providing engineers with methods by which their designs could be analysed. Knowledge of physics and mathematics could be applied to engineering problems – the tacit practical knowledge which comes from producing physical artefacts could be married with the explicit theoretical knowledge derived from analytical methods, giving rise to an area of knowledge termed Engineering Science.

The advent of high speed digital computing brought the Cartesian vision even closer to reality. During the second half of the 20th century, the development of the finite element method (FEM) enabled engineers to analyse complex structures by dividing a complicated[2] object into small and manageable pieces. The behaviour the physical quantities of interest for each of the small pieces (finite elements) can be described mathematically and the elements may then be assembled at nodes to form an approximate system of equations that describe the whole structure. The system of equations is then solved numerically for the unknown quantities at each node (for example displacements), allowing in turn for stresses and strains to be calculated. In the past 10 years, such numerical modelling has become routine – what could only be done by expert modellers using state of the art supercomputers can now be done with relative ease with fully integrated Computer Aided Engineering packages that will run on a desktop PC. All design and modelling from the initial concept, design, analysis and manufacturing can be done within a single software environment. In theory, and often in practice, the entire design and validation process can be carried out in a virtual micro-world which as an output provides the instructions for manufacture using computer numerical control (CNC) machine tools. Thus there are situations within engineering where up to the point of manufacture, the product is entirely virtual. In the case of software engineering, the engineered artefact is entirely virtual – a stream of binary 1's and 0's. Moreover, engineering services are often delivered electronically – the engineer may never have any physical contact with the engineered artefact, which becomes an abstraction rather than a physical reality. Nothing could be further from the origins of the early engineers, which will be discussed in the next chapter.

Against this background of increased distance between the engineer and his work, and the development of sophisticated computer aided design and modelling technologies, it is understandable that the view exists that engineering is merely the application of science, and that it rests on a solid epistemology rooted on hard scientific laws, elaborated by robust and rigorous mathematics. Products are engineered in virtual environments fully described by the laws of physics –the entire engineering process up to the point of manufacture may be accomplished in a

---

[2] A 'complicated system can have a huge number of parts and interactions between the parts but is, in principle, exhaustibly describable' (Dekker, 2011, p. 149). A complex system is essentially irreducible (Dekker, Cilliers, & Hofmeyr, 2011).

virtual environment, by its nature defined mathematically. This is perhaps the strongest argument that engineering is an applied science. This view is appealing to the engineering institutions who promote engineering as a white collar profession – as distant as possible from the domain of wrenches, oily rags and boiler suits.

CHAPTER 2: THE PROTO-ENGINEERS

Engineering with a Capital E.

It could be argued that engineering in its broadest sense has existed for millennia – the evidence can be seen in examples such as the Pyramids of Giza, Roman viaducts and sewerage systems and ingenious machines such as those documented in early Muslim civilisation by Al-Jazari in 13th century (Hill, 1996; McCarthy, 2009). It may come as a surprise that Engineering (with a 'capital E') only emerged as a discipline (within the French Military) in its own right in the late 17th century – apparently in tandem with the Scientific Revolution. This chapter provides an insight into the background of Engineering as it exists today in Anglo-Saxon society, and its evolution from an activity that was learned by practical apprenticeship to one largely based on abstract theories taught as part of a university education.

Masons, Millwrights and Mechanics

Prior to the Scientific Revolution, the predecessors of modern engineers were to be found amongst the ranks of tradesmen such as mechanics, stonemasons and millwrights. Tradesmen were educated through a process of apprenticeship, whereby the master tradesman employed young people as inexpensive labour for a period of typically seven years, and in exchange they would be provided board and lodging and a formal training in the craft. The apprentice would be indentured for the period of his apprenticeship, and would typically become a Journeyman[3] (or Jack) for a period of time, typically 3 years, to gain experience working with others in his trade, until eventually being accepted as a master by his guild. The tradition still remains in Germany where young tradesmen go on the Waltz for a period of 3 years and 1 day, as itinerant tradesmen wearing distinctive attire specific to their trade. During the Waltz they never come within 50km of their hometown except to attend the funeral of an immediate family member.

The knowledge was gained through hands-on experience, which differs from the abstract theoretical knowledge that characterises current engineering education. These men were not necessarily craftsmen, working alone in their workshops, but rather tradesmen, behind the construction of what we would today consider to be engineering projects. These tradesmen certainly possessed some knowledge of geometry and mathematics – there can be little doubt that the builders of medieval gothic cathedrals were able to produce complex forms, something that required geometry to be combined with a deep knowledge of the properties of the materials they were using. The fact that many of their buildings are still defying gravity almost 1000 years after their construction is a testament to their skill and mastery, and piles scorn on the notion that prior to the scientific revolution the practical arts were a matter of trial and error.

Highly ornate pinnacles and flying buttresses drawing the eye towards heaven ensured that the masonry always remained in compression, even though concepts such as action/reaction symmetry first formalised in Isaac Newton's Philosophiæ Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy, 1687) and stress and strain had not been described formally by Thomas Young until the early 19th century. In fact the manner by which any inanimate object resisted a load worried 17th century scientists Hooke and Galileo (Gordon, 1976, pp. 27-28).

---

[3] The term Journeyman originates from the French word for day, journée, as a journeyman the tradesman would be considered of suitable skill to demand a day's wage for a day's work.

Building Bridges

Arch bridges which were constructed in medieval times when horse-drawn wagons were the heaviest things on the road now carry motor vehicles – this is seen as evidence that the bridge builders did not really know what they were doing, and the bridges were overdesigned. This view is rather unjust; in constructing a masonry bridge the greatest load carried by the bridge is the weight of the bridge itself. The weight of the live load – the passage of people, animals or vehicles crossing the bridge – would be negligible in comparison. The thought that bridges were made more massive as a means of dealing with limited understanding of bridge-building, demonstrates a limited understanding of bridges - the more massive the bridge was made, the more weight it would have to carry, and thus the greater the engineering challenge!

A common metric for bridge building efficiency is the ratio of rise to half-span (a semicircular arch has a ratio of unity).The smaller this ration becomes, the lower and flatter the arches, using less materials and with fewer piers. The present Ponte Vecchio Bridge in Florence Italy, built in 1345 has a central arch of 98 ft long with a rise of only 14.5ft (Hill, 1996, p. 72). This provides a rise/half-span ration of 0.296. It is made more remarkable that the bridge has shops built along it. When Brunel's Maidenhead railway bridge was completed in 1838, still holding the record for worlds flattest brick arches (128 ft with a rise of 24 ft – a rise to half span ration of 0.375) the board of the Great Western Railway had such little confidence in the flatness of the arches, that they refused to allow Brunel to remove the wooden formwork. Brunel lowered the formwork slightly to give the appearance that it was still in place, and it was only when the formwork was washed away in floods that the board accepted strength of the arches (A. Vaughan, 2006). The design of Brunel's bridge had been analysed scientifically, and was considered to be uniquely daring (A. Vaughan, 2006, p. 98), however, more daring arches had been constructed almost 500 years earlier using the practical know-how of Medieval Italian stonemasons – knowledge that was encapsulated both in the skills and experience of the stonemasons, and in the artefacts they produced.

The Engineer

The etymology for the word 'engineer' is said have its roots in the Latin word *ingenium* meaning *ingenuity* with *ingeniatorum*, meaning *one who possesses or exercises ingenuity* (Auyang, 2006, p. 14; McCarthy, 2009, p. 4), and the term was in usage as early as the 12th Century (Auyang, 2006, p. 14). Throughout the Middle Ages ingeniators worked with the military on producing 'engines of war' such as cannons and trebuchets. The word engineer derives directly from the French word ingénieur. In France the ingénieur was a formally educated technical officer in the French Army with responsibility for the creation and maintenance of the engines of war. In 1676 the French Army established Corps de Génie, who received special training in the construction of military infrastructure (roads, bridges and fortified positions) in addition to the machinery of war. The establishment of the Corps de Génie is considered to be a turning point in the engineering profession, where engineering became a discipline in itself, and engineers were trained and developed through a process of apprenticeship carried at specialised military camps. The Corps des Ingénieurs des Ponts et Chaussées (engineering corps for bridges and roads) was founded in 1716 with the purpose of establishing a national network of roads in France. In 1747, the École des Ponts et Chaussées was formed for the purpose of training civilian engineers (as opposed to military engineers). It was the establishment of the École Polytechnique in 1794 (then known as the École Centrale des Travaux Publics) that saw the introduction of an engineering education similar to that existing today (McCarthy, 2009, pp. 6-7).

The establishment of West Point Military Academy in 1802 saw the adoption of the French approach of principled engineering education (with the assistance of French educated officers), and the approach lead to the establishment of numerous engineering schools by the 1830's

(Auyang, 2006, p. 120). The United Kingdom was slow to follow, and the French approach to engineering education was generally viewed with distain – I.K Brunel expressed himself rather succinctly on the subject in 1848 in a letter to a young man hoping to become an engineer:

> I must strongly caution you against studying practical mechanics among French authors - take them for abstract science and study their statics dynamics geometry etc. etc. to your heart's content […]. A few hours spent in a blacksmiths and wheelwrights' shop will teach you more practical mechanics-read English books for practice-There is little enough to be learnt in them but you will not have to unlearn that little (Buchanan, 1978, p. 220).

Brunel trained his engineers in his own office in the manner of apprentice craftsmen, with the emphasis on practical experience. Brunel demanded 'immensely hard work, gentlemanly conduct, and common sense' as much as technical skills (Buchanan, 1978, p. 220). Brunel remained opposed to abstract theories, and was more interested by theory that was related to practice.

Despite the reticence exhibited by Brunel and many of his generation of British engineers (Buchanan, 1989, pp. 164-165), there was a proliferation of Schools of Engineering being established in British universities in the second half of the 19th century (Buchanan, 1989, pp. 172-173). In 1886 the Institution of Municipal Engineers introduced a requirement for would-be members to demonstrate an adequate level of theoretical knowledge by way of its 'Testamur' examination. By 1897 the Institution of Civil Engineers (ICE), at the time the largest British engineering institution, accepted that it was desirable that applicants should have academic qualifications in engineering, and by 1909, university qualifications were required. Professor Unwin, the first professor of engineering at University of London has strongly promoted the benefits of a formal university education stating that 'it is more a more recognised that although an engineer cannot be made in college, yet a college education is an essential part of the training of an engineer' (Buchanan, 1989, p. 174).

The other professional engineering institutions eventually adopted the approach of the ICE, and by 1914 a university education was a generally accepted and required part of the formation of a professional engineer in Britain (Buchanan, 1989, pp. 174-175).

Having emerged as an activity in its own right, the next chapter will examine the process by which British Engineering in particular attempted to emerge as a recognised profession with a power base of its own.

Chapter 3: The Emergance of a Profession: Consolidation, Institutionalisation and Fragmentation

A Gentlemanly Pursuit?

Engineering and its close association with production and manufacture to this day produces status problems – in Victorian Britain (as is still the case today) making things was considered to be the pursuit of the working classes and not the concern of Gentlemen . It is against this background that the early British Engineers sought to organise themselves into a recognised profession (Buchanan, 1983; Whalley, 1986).

Larson (1977) defines a Professionalisation as:

> a process by which producers of special services [seek] to constitute *and control* a market for their expertise [...];
> a collective assertion of special social status and as a collective process of upwards social mobility [...];
> an attempt to translate one order of scarce resources – special knowledge and skills – into another – social and economic rewards (Larson, 1977, pp. xvi-xvii).

It would appear that, in Britain, engineering had the makings of a strong profession, however, after a promising start it failed to establish a power base of its own, and this disunity has been put forward as a reason why modern British engineering lacks a strong professional identity and direction (Buchanan, 1985).

Achieving Royal Recognition

The organisation of the emerging discipline of engineering into a profession in the United Kingdom can be traced back to the establishment of the Society of Civil Engineers (latterly known as the Smeatonian Society of Civil Engineers) in 1771 by John Smeaton, who was the first to describe himself as a 'civil engineer'. (Armytage, 1976, p. 100). Although today Civil Engineering is associated with the built environment (engineering of roads, bridges, dams and buildings), at the time, the term 'civil' denoted engineering of a non-military nature. The society, from the outset, was little more than a highly exclusive dining club for senior engineers – but it did demonstrate the benefits of collaboration. The society met informally over dinner, and although there were some early technical meetings, and a library, the exclusivity of the society was a frustration to younger engineers, and it offered little in way of encouragement to the next generation (Buchanan, 1989, pp. 50-51). Today the Smeatonian Society of Civil Engineers lives on as a dining club with an exclusive membership of 50 senior engineers and 12 Gentleman Members, including HRH The Duke of Edinburgh (Roberts, 1995, p. 1).

It was against this background that the Institution of Civil Engineers (ICE) was established in London in on 2 January 1818. The meeting was called by H.R. Palmer who lamented that 'there was a deplorable lack of professional education for civil engineers and of contact between members of the profession' (Buchanan, 1989, p. 61). Palmer's opening speech gave the following description of the engineer:

> The Engineer is a mediator between the philosopher and the working mechanic, and like an interpreter between two foreigners, must understand the language of both, hence the absolute necessity of possessing both practical and theoretical knowledge (Armytage, 1976, pp. 122-123).

The members of the institution approached Thomas Telford in January 1820 appealing to him to step in and lead the institution (Armytage, 1976, p. 123; Buchanan, 1989, p. 63). Telford was leading engineer of his generation, who was conspicuously absent from the membership the Society of Civil Engineers, probably due to personal differences between himself and John Rennie who was at the time an influential member of the Society (Buchanan, 1989, p. 61).

In their appeal to Telford, the members of the ICE identified issues with the emerging profession that persist today:

> It is unnecessary to remark to you on the business of an engineer; all admit the difficulties of it, and its indefinite character; and that by want of definition, its respectability is less than its due, that public confidence which is indispensable, is much weakened by the presumption of unskilled and illiterate persons taking upon themselves the name. Engineering, indeed, in England, is taught only as a trade, and this is an essential cause of the evil complained of [...] (Buchanan, 1989, p. 63).

They stated the aims of the institution:

> To facilitate the acquirements of knowledge in engineering; to circumscribe the professions; to establish in it the respectability which it merits, and to increase the indispensable public confidence [...] (Buchanan, 1989, p. 63).

Thomas Telford was installed as president in March 1820, and the Institution gained strength under his leadership, being granted a Royal Charter in 1828, by which the British Monarch gave a written grant of rights to the institution recognizing engineering as a profession. The 1828 Charter provided this definition of civil engineering:

> Civil engineering is the art of directing the great sources of power in Nature for the use and convenience of man; being that practical application of the most important principles of natural philosophy which has, in a considerable degree, realised the anticipations of Bacon, and changed the aspect and state of affairs of the whole world... (Buchanan, 1989, p. 64).

The Beginnings of Fragmentation

Whereas, at its inception the ICE appeared to meet the requirements of all non-military engineers, the emergence of specific areas of knowledge resulted in a proliferation of other engineering institutions, starting with the Institution of Mechanical Engineers (IMechE) in 1847. George Stephenson, who was renowned as ‘Father of the Railways’, was its first president. Stephenson was not a member of the ICE – he had faced opposition to his railway schemes from its leading members, and he had taken the request to provide an essay to the ICE showing evidence of his capabilities as an engineer as an affront, considering that he had developed the steam locomotive, and been at the helm of most of the railway schemes of the time (Armytage, 1976, pp. 130-131; Buchanan, 1989, p. 81).

The IMechE was followed by the Institution of Naval Architects (1860), the Institution of Gas Engineers (1863), the Royal Aeronautical Society (1866), the Iron and Steel Institute (1869), the Institution of Electrical Engineers (1871) and so on, each institution serving an emerging specialism or niche within engineering and seeking to establish its own influence and prestige (Buchanan, 1985, pp. 48-56). The British engineering profession grew rapidly from less than 1,000 engineers in 1850 to over 40,000 by the outbreak of the First World War in 1914, by which time there were 17 distinct engineering institutions (Buchanan, 1985, p. 43).

Compared to other professions such as the medical or legal professions which had a comparable expansion in this period without the proliferation of institutions, much of the institutional diversification in engineering was associated with being on the forefront of innovation and technological upheaval, with the development of new areas of specialised expertise that was not being well accommodated within the existing institutions (Buchanan, 1985, pp. 58-59). Buchanan (1985, p.60) attributes the 'persistent professional inferiority complex' within British engineering as a negative legacy of the disunity brought about by the proliferation of institutions in the mid to late 19th Century.

Attempts to Reconsolidate

By the mid 20th century, government concerns about the absence of a central body to agree educational and professional standards lead to the establishment of the 'Joint Council of Engineering Institutions' in 1964 (later known as the Council of Engineering Institutions') (Engineering Council, 2012) however, this failed to satisfy criticism of the lack of uniform standards. A Royal Commission lead by Sir Monty Finniston was convened in 1977, growing from the Committee of Inquiry into the Engineering Profession in response to complaints from industry about a shortage of qualified engineers. The outcome of the Commission was the publication of the Finniston Report 'Engineering our Future' in 1980 (Finniston, 1980). Among the recommendations was that universities should offer engineering degrees (BEng, MEng) rather than science degrees (BSc). Also, based on recommendations from the Finniston Report, the Engineering Council was established in 1982 as the national representative body of the British engineering profession, at the time overseeing 54 separate institutions. The Engineering Council set about regulating the professions of Chartered Engineer (CEng), Incorporated Engineer (IEng), Engineering Technician (EngTech) and Information and Communications Technology Technician (ICT*Tech*), meaning that these specific titles are protected by law, and entry was governed by a set of Standards and Routes to Registration (SARTOR). Nonetheless, in Britain (unlike most other European countries), anyone can call themselves an engineer (or even confusingly a professional engineer or registered engineer) and many semi-skilled trades still do. In 2002 the Engineering Technology Board (now known as EngineeringUK) was split away from the Engineering Council with the specific responsibility for promoting engineering, while the Engineering Council retained responsibility for the standards of professional registration (Engineering Council, 2012).

In December 2003, in response to continued concerned about the standards of professional engineering, after consultation with the member institutions the Engineering Council published a new standard for professional engineers – United Kingdom Standards for Professional Engineering Competence (UK-SPEC) replacing the previous SARTOR. The UK-SPEC specifies required areas of competence and commitment to be developed throughout the engineer's career rather that objectives which are achieved once. For Chartered Engineers, a Masters degree (MEng) is required for registration, where previously an Honours Bachelors Degree had been the minimum requirement for registration.

As of 2012 there are no fewer than 36 licensed professional engineering institutions qualified with the Engineering Council to assess candidates for registration and monitor the continued professional development and conduct of their registrants. Rather than the strong unified profession envisaged by Telford, the British engineering profession remains fragmented, poorly protected and lacking coherent direction and leadership. The fragmentation is exacerbated by the fact that quite low numbers of graduate engineers are actually registering as Chartered Engineers. Approximately 180,000 engineers have registered with the Engineering Council as Chartered Engineers, although the number of professional engineers is estimated at 600,000 (EngineeringUK, 2011) – so less than one third of those in 'professional engineering' positions are registered with professional institutions. This suggests that the British engineering institutions are struggling for relevance in an industry where standards of professionalism are defined by employers.

CHAPTER 4: THE SCIENTIFICATION OF ENGINEERING, 1918-1969.

Back in the Summer of '69

1969 was a milestone year for engineering. In February Boeing's 747 took to the air for the first time, followed in March by the first flight of the Anglo-French Concorde. In July, the world watched in awe as US Astronaut Neil Armstrong set foot on the surface of the moon. Forty-two years later, supersonic flight is the preserve of military pilots, there is no US manned space programme and changes to commercial jets have been evolutionary rather than revolutionary.

Within a lifetime, aviation had been transformed from being the preserve of brave and adventurous pilots flying machines fashioned from wood and fabric to a routine activity where passengers could travel twice the speed of sound at the very edge of space, while being fed and entertained in comfort. Engineering had been transformed from a workshop-based activity to being the concern of nations as during the Cold War technological achievements became a measure of the relative success of capitalist and communist ideologies.

Vannevar Bush (1890-1974)

Vannevar Bush was a remarkable engineer, and had a great influence on the research and development boom that occurred after World War II. As a boy he liked to tinker; as a student at Tufts College he secured his first patent in 1912, and his last (49^{th}) was secured in 1974, the year he died (Zachary, 1995). Bush graduated with BSc and MSc degrees from Tufts College in 1914. He entered the Massachusetts Institute of Technology (MIT) in 1915 where he completed his doctoral thesis in engineering in one year (Weisner, 1979). In 1919 he joined the Electrical Engineering Department at MIT, where he became a professor, and was Dean of Engineering and vice president of MIT from 1932 to 1938. In 1922, he founded the company that was to become Raytheon which achieved great commercial success (Weisner, 1979; Zachary, 1995). His contributions in the application of computing to engineering problems (taking problems from the physical world to and into a virtual world) and his influence on the development of a science based ideology were to shape the development of science and technology in the latter half of the 20^{th} century.

The Development of Analogue Computing

The increasing complexity of electrical power transmission networks spurred Bush's interest in computing machines, and through the late 1920's a series of more elaborate mechanical computers were developed under his supervision. By 1931, under Bush's leadership, an advanced mechanical analogue computer called the Differential Analyser was completed, which could solve up to sixth order differential equations. These early machines were cumbersome to use, and required a lot of preparation before a problem could be solved. Development of analogue computing continued at MIT under Bush in part financed by the Rockefeller Foundation, and in 1941 it culminated in the Rockefeller Differential Analyser. This machine weighed 100 tons and had 2,000 vacuum tubes and 150 motors. Three shifts of workers operated the machine day and night throughout the remainder of World War II on critical calculations such as Navy range tables and artillery fire control problems (Weisner, 1979).

Digital vs. Analogue – Increasing Levels of Abstraction

Bush's analogue computers were eventually surpassed in terms of computing power and speed by the advent of digital electronic computers – such as the ENIAC which was developed in secret for the US Army and was unveiled in 1946. Analogue and digital computers differ in a fundamental way – analogue computers such as Bush's differential analysers physically modelled the processes that were under investigation using electromechanical wheel and disc integrators where the data was entered by tracing input curves. Analogue computers did not perform calculations by mathematical processes, but rather by simulation of the system behaviour – the simulation remained closely related to the engineering problem, and a good feel for the nature of the engineering problem was needed before it could be modelled. Digital computers on the other hand approximate physical behaviour by breaking down complex behaviour into a series of addition and subtractions – applying brute force and approximation to handle complexity by breaking it down analytically into a format that a digital computer can handle - a binary state – 0 or 1 (Owens, 1986).

Engineers of Bush's generation thought in tactile, physical and graphical terms – a type of engineering that was still in intimate contact with the workshop. The development of high speed digital computing in the second half of the 20th century facilitated a change of character within engineering towards a more mathematical and abstract way of thinking and viewing the world. It could be surmised that Bush's involvement in early computers hastened this process of abstraction, however, it is worth reflecting that Bush modelled complex processes using complex elements, and far from being a matter of posing a question and turning a handle, using these early analogue computers required a good measure of intuition and an intimate knowledge of the processes being modelled.

'Science won the War'

Bush played a pivotal role during the WWII as director of the Office of Scientific Research and Development (OSRD). The OSRD was behind developments such as nuclear weapons, sonar, radar and the Norden bombsight – technologies considered critical in the Allies winning the war. In 1941, Bush secured the approval from US President Franklin D. Roosevelt to develop the atomic bomb, and he controlled the Manhattan Project until 1943 when it came under control of the US Army (Weisner, 1979).

As the dust began to settle after the end of the WWII, there was an appreciation that 'science had won the war'. The awesome destructive power of the nuclear weapons unleashed on Hiroshima and Nagasaki on the 6th and 9th of August 1945 (respectively) hastened the end of the war by prompting a Japanese surrender some 3 months after the hostilities had ended in Europe. For a brief moment scientists and engineers were the darlings of the world.

'Science: the Endless Frontier'

In November 1944 President Roosevelt approached Bush for his recommendations in four key areas of government policy:

- Diffusion of scientific knowledge gained during the war effort for the purpose of stimulating new enterprises,
- the 'war of science against disease',
- aiding public and private scientific research
- 'discovering and developing scientific talent in American youth' (Weisner, 1979).

Bush responded with his report titled 'Science The Endless Frontier' that was delivered to President Harry Truman on 25 July 1945. At the heart of Bush's response was an ideology that unleashed a boom in all areas of science and technology, given added momentum by the proliferation of nuclear weapons, the Cold War and the so called Sputnik Effect.

Bush argued that :

> [W]ithout scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world. [...]
> There must be a stream of new scientific knowledge to turn the wheels of private and public enterprise. There must be plenty of men and women trained in science and technology for upon them depend both the creation of new knowledge and its application to practical purposes. [...]
> Basic research is performed without thought of practical ends. It results in general knowledge and an understanding of nature and its laws. This general knowledge provides the means of answering a large number of important practical problems, though it may not give a complete specific answer to any one of them. The function of applied research is to provide such complete answers. The scientist doing basic research may not be at all interested in the practical applications of his work, yet the further progress of industrial development would eventually stagnate if basic scientific research were long neglected.
>
> Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.
>
> A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill. (Bush, 1945).

The Proper Concern of Government

The US Government responded to Bush's report by establishing the National Science Foundation (NSF) in 1947. The effect of the resulting research was to produce powerful bodies of generalisable systematic knowledge that was to transform the nature of engineering and engineering education. Sustained engineering research on a national scale saw engineering develop extensive theories of its own, and be transformed into a science of manmade systems. Engineering had moved from a 'workshop based culture' to a culture of applied science. It seemed that we never knew more about the world around us, and the gap to be spanned in the course of an engineering education never appeared greater. Engineering educators faced new challenges in taking an engineering student from first principles in engineering to the frontiers of rapidly developing technology. The next chapter discusses the development of engineering education, and the widening gap between engineering education and engineering practice.

CHAPTER 5: ENGINEERING EDUCATION VS. ENGINEERING PRACTICE

Mind the Gap

An aspect of engineering education which has prevailed from the introduction of formal university training is the gap between engineering as practiced and engineering as taught. To draw comparison between the engineering and medical professions, medicine is for the most part taught by practicing senior medical professionals – a professor of surgery will, generally speaking, be an eminent surgeon, thus minimising the gap between what is considered best professional practice and what is being taught to the medical students. In addition to being a practicing professional, the professor would have typically proven his credentials through medical research – the relevance of which would be boosted by the close association with practice. In the case of engineering, it is less common for engineering lecturers to have a background in professional engineering.

In a US study of engineering education performed in 1918 (Mann, 1918), an important distinction is highlighted, referring back to the origins of professional education. The medical and legal professions were originally based on an apprenticeship system, and as the professions grew, for sake of convenience, the apprentices were gathered into a class for instruction by a well qualified practitioner. These classes formed the basis of schools of law and medicine which were under the management and control of practitioners who gave the instruction on a part-time basis in parallel with their own professional practice. Schools of medicine and law at universities retained their status as practitioners' schools, and were not fully assimilated into the university. The curricula taught in these schools were drawn up by those with daily contact with their professional work (Mann, 1918, p. 55).

The apprenticeship system existing in engineering did not develop into engineering schools – rather a split generated between shop-trained and university trained engineers. The original engineering schools in the US were founded by colleges, with college-trained professors and a curriculum drawn up by college faculty with little input from practicing engineers. These early schools had a hard time proving (to a largely shop-trained engineering profession) that engineering was something that could be taught in schools (Mann, 1918, p. 55).

The Struggle for Relevance

Concerns about the relevance of university engineering education persist. Young (2000) highlights the old concern that lecturers of engineering design struggle to remain relevant to the practice of engineering. Even in the case that universities require intensive industrial experience as a prerequisite to lecturing in engineering design, Young contends that the level of currency with industry practice declines the longer the lecturer is away from industry (both through being left behind by industrial developments and the dulling for previously finely honed skills and knowledge). Although over time the pedagogical skills of the lecturer improve (his presentation and delivery improves with experience as a lecturer), the overall quality of the teaching is undermined by the disconnect from engineering practice (Young, 2000, pp. 213-214).

According to Young, talented engineers are discouraged from entering academia by the increasing requirement that academics have a PhD – which is at odds with gaining industrial experience in the first place. Universities also place a high emphasis on the number of academic papers published as a measure of success, and this has the effect of drawing the design lecturer's emphasis away from design and into areas of study (such as materials science) that lend themselves better to the acquisition of research funding and publication of papers (Young, 2000, p. 214).

Young suggests that industry should become more involved with university design projects, and welcome students for work experience placements. He suggests that universities should recognise industrial experience as being of equal value as experience in research, that design lecturers shall spend time in industry every 5-8 years on (compulsory) sabbatical, that teaching quality should be balanced against 'paper count', and that more use of practicing engineers should be made in the teaching of design (Young, 2000, pp. 214-215). Engineering education continues to be hounded by the question of relevance, with Young's concerns echoing those voiced in the Mann report of 1918.

A Well-Rounded Engineering Education?

Another area of concern is the near absence of humanities[4] and social science[5] subjects within engineering education. It is evident from the Mann report (1918) that 'humanities' content in the MIT engineering curriculum had reduced from about 31% in 1867 to about 18% in 1914 (Mann, 1918, p. 24). The reduction was accounted for by time pressure due to the 'extraordinary growth in science and industry' meaning that there was more to teach, with increasingly specialised courses (Mann, 1918, p. 25), thus pushing aside learning of a more general nature.

The Society for the Promotion of Engineering Education published two committee reports examining the changing needs in engineering education in the USA. The reports were prepared under the chairmanship of H.P. Hammond in 1940 and 1944 (SPEE, 1940, 1944), and are referred to as 'The Hammond Reports'. The 1944 Hammond report highlights that the 'cultivation of creative ability' was an aspect that was missing from engineering education and that it should be integrated into all engineering instruction. The report suggested that courses incorporating design projects were a useful means of encouraging originality and initiative (SPEE, 1944, p. 601). This report also highlights that the 'art of engineering' and the application of the engineering method to problems was being lost through subdivision of knowledge – learning the 'tools of engineering' though did not necessarily 'constitute ability to practice engineering'(SPEE, 1944, pp. 598-599).

The Hammond report of 1940 called for a reorganisation of engineering curricula to develop the 'scientific-technological' and 'humanistic-social' aspects of education in parallel to provide a broader base of instruction to sustain a 'rounded educational growth which will continue into professional life' (SPEE, 1940, pp. 562-563). The emphasis should remain on engineering and science, but humanistic-social aspect was 'fundamental and vital' and should comprise the equivalent of one full year of study; 25% of a 4 year degree (SPEE, 1940, p. 565; 1944, p. 595). It was considered that the integration of a humanistic-social stem would assist the student to acquire 'the ability to understand, to analyze, and to express the essentials of an economic, social or humanistic situation or problem and to appreciate the relationships of such problems to the life and work of an engineer' (SPEE, 1944, p. 597).

The publication of the 'Report on Evaluation of Engineering Education' ('The Grinter Report') in 1955 (Grinter, 1955) was retrospectively seen as a turning point in a move towards the

---

[4] The academic disciplines collectively known as 'The Humanities' seek to gain insight into the human condition by means of methods that are of analytical, speculative or critical in nature. Conversely the natural sciences rely on a mostly empirical approach.

[5] Social science refers to the group of academic disciplines concerned with the study of human behaviour and society. Methods used range from quantitative/positivist (similar to natural sciences) to qualitative/interpretive.

inclusion of more science in engineering education. The report recommended an integrated approach to the study of analysis, design and engineering systems, improved oral, written and graphical communication skills and a reinforcement of the position of social sciences and humanities in engineering programmes. The net result, however, was more science in engineering, with an associated trend toward more graduate programmes and PhDs in engineering science (Dym, 2004, p. 305; National Research Council Panel on Engineering Graduate Education Research, 1985, p. 11). Whilst the Grinter Report gave a more balanced integrative view of the needs within engineering education, reflecting on the legacy of the Grinter report 40 years on, Peden asserted that the academic community read the report rather selectively and she neatly sums up the way that engineering education developed in the years that followed:

> Not anticipated were the downstream imbalances in academe that emphasized engineering science and analysis to the point of reductionism at the expense of design and integration, faculty research at the expense of teaching and curriculum innovation at universities with graduate programs, publication and grantsmanship at the expense of other evidences of scholarship at those same institutions, and the impact of federal support for research on academic priorities. (Harris, 1994, p. 71)

Same-Same, But Different

The observations of 1918 (Mann, 1918) and 1940-1944 (SPEE, 1940, 1944) are as true today as they were then, in current engineering education there is a very strong emphasis on science and mathematics, to the neglect of social science, design and practice. It could be argued that the science and mathematics are the easiest to teach, but on the other hand serves as an unhelpful barrier to entry into the profession, as it is only one aspect of the practice of engineering and it is argued that the overemphasis of a certain positivistic epistemology handicaps, or even extinguishes the types of divergent thinking linked with creativity (McGilchrist, 2010).

A review of a undergraduate engineering syllabi at two universities (University of Limerick, 2011; University of the West of England, 2011) shows that almost all of the subjects taught have a 'hard' scientific epistemology. Even the non-technical subjects could be characterized as 'management science'. Rophol provides robust criticism of contemporary engineering education as providing a set of 'prescribed recipes' providing a 'one best way' to solving contextless predefined problems producing the 'illusion that technological practice is completely value-free' (Ropohl, 1991, p. 289). The fact that engineering syllabi at different universities are broadly similar should not come as a surprise. University courses are aimed at awarding engineering qualifications that are recognized by the professional institutions, and as such the course syllabi are accredited by the relevant institution(s) – in the United Kingdom, the Engineering Accreditation Board administers this on behalf of the Engineering Council (Engineering Accreditation Board, 2010). The Washington Accord provides the framework in which engineering qualifications (academic and professional) are mutually recognised in the signatory countries, which this in turn has imposed a certain uniformity (Hanrahan, 2011).

The view of engineering as applied science seems to be most prevalent among engineering academics, which is hardly surprising, as it provides justification for engineering research (Pawley, 2009). Scientists would also appear to support that view, as it provides a justification for scientific research – as a way of generating practical applications for the findings of basic research (Goldman, 2004, p. 164).

In response to growing concerns from industry about the relevance of engineering education, the Washington Accord members are in the process of transitioning to an 'Outcome Based' approach to learning, where rather than stipulating what goes into an engineering education, they focus on what comes out – for example from 2012 in Ireland, the first professional degree will be a Masters of Engineering , and the criteria apply a greater emphasis on 'creativity and innovation', 'design and development' and 'social and business context' (Engineers Ireland, 2007, p. 20). The proposed changes are hoped to close the gaps in engineering education, however, the opposite may be taking place. One course leader described the initiative to me as "a load of hocus-pocus dreamed up to justify the existence of administrators who like to pretend that they are instigating 'change'"[6] Understandably, the universities are not approaching curriculum reform as a blank canvas, but are shoehorning the existing syllabi into the new framework, and the broader holistic concepts (such as creativity and innovation, and social and business context) are being atomised into lists of attributes that then can then be micromatched against the existing programmes of study. Ironically, the outcome has been the incorporation of more advanced computational and theoretical methods into the extended MEng programmes – rather than filling the gaps in the programmes, the universities have taken the opportunity to fill the additional year with more of the same, as can be seen, for example, in the syllabus for the University of Limerick Master of Engineering in Aeronautical Engineering programme (University of Limerick, 2010).

McCarthy highlights that the situation persists in the United Kingdom where few engineers study the social sciences, which seems to be at odds with the how engineering is portrayed as a profession focussed on human needs (McCarthy, 2009, p. 14). This theme is echoed by Ropohl (who writes from a German perspective) who argues strongly for the inclusion of social science within engineering training, he proposes an arbitrary ratio of 20% as an initial minimum objective, and that the social science content should be targeted in such a way as to be integrative rather than additive so as to underline its relevance (Ropohl, 1991, p. 291). Petersen, Nyce and Lützhöft similarly suggest that there is a need for social science, anthropology in their case, to adapt their message to demonstrate its relevance and usefulness (Petersen, Nyce, & Lützhöft, 2011, p. 12).

'Nice Tools, But Can You Use Them?'

The unfortunate conclusion is that engineering education in Anglo-Saxon society provides plenty in the way of analytical tools, but misses the target in terms of integrative associative learning, and failing to prepare students for professional practice. The divergence between academia and practice can be traced back to the origins of university engineering education, and the same sorts of issues relating to the relevance of education to practice and the need for an approach which is integrative and applied, rather than abstract and reductionist.

[6] My correspondent discussed this on the basis of strict anonymity.

CHAPTER 6: THE APPLICATION OF HEURISTICS?

The Engineering Method

Billy Vaughn Koen[7] describes a heuristic based system of reasoning used by engineers which marries the theoretical and practical aspects of engineering (Koen, 1985, 2003). Koen's view takes a radically sceptical standpoint towards engineering knowledge (be it 'scientific' or otherwise) by which all knowledge is fallible – and is better considered as heuristic, or rule of thumb. Koen (1985, p.6) defines the engineer not in terms of the artefacts he produces, but rather as someone who applies the engineering method, which he describes as 'the strategy for causing the best change in a poorly understood or uncertain situation within the available resources.' (Koen, 1985, p. 5). Koen argues engineering consists of the application of heuristics, rather than 'science' and 'reason'. A heuristic, by Koen's definition is 'anything that provides a plausible aid or direction in the solution of a problem, but is in the final analysis unjustified, incapable of justification, and fallible.' (Koen, 1985, p. 16). Koen (1985) provides four characteristics that aid in identifying heuristics (p.17):

- 'A heuristic does not guarantee a solution
- It may contradict other heuristics
- It reduces the search time in solving a problem
- Its acceptance depends on the immediate context instead of an absolute standard.'

He contends that the epistemology of engineering is entirely based on heuristics, which contrasts starkly the idea that it is simply the application of 'hard science':

> Engineering has no hint of the absolute, the deterministic, the guaranteed, the true. Instead it fairly reeks of the uncertain, the provisional and the doubtful. The engineer instinctively recognizes this and calls his ad hoc method "doing the best you can with what you've got," "finding a seat-of-the-pants solution," or just "muddling through". (Koen, 1985, p. 23).

State of the Art

Koen (1985) uses the term 'sota' ('state of the art') to denote a specific set of heuristics that are considered to be best practice, at a given time (p.23). The sota will change and evolve due to changes to the technological or social context, and the sota will vary depending on the field of engineering and by geo-political context. What is considered as sota in a rapidly industrializing nation such as China will be different from that in a developed western democracy.

It is impossible for engineering in any sense to be considered as 'value-free'[8] due to the overriding influence of context, which sets it apart from 'science'. Koen (1985) emphasizes the primacy of context in determining the response to an engineering problem, and the role of the engineer is to determine the response appropriate to the context. To the engineer there is no absolute solution, at the core of practice is selecting adequate solutions given the time and resources available. Koen proposes his Rule of Engineering:

---

[7] Emeritus Professor of Mechanical Engineering at University of Texas at Austin.

[8] 'Value free' in this context refers to ideal of the Scientific Method; remaining purely objective and without 'contaminating' scientific inquiry with value judgements.

> Do what you think represents best practice at the time you must decide, and only this rule must be present (Koen, 1985, p. 42).

Koen characterizes engineering as something altogether different from 'applied science'. Indeed he provides the following heuristic:

> Heuristic: Apply science when appropriate (Koen, 1985, p. 65).

He highlights the tendency for 'some authors […] with limited technical training' to become mesmerized by the 'extensive and productive use made of science by engineers', and elevate the use of science from its status as just one of the many heuristics used by engineers. He states that 'the thesis that engineering is applied science fails because scientific knowledge has not always been available and is not always available now, and because, even if available, is not always appropriate for use' (Koen, 1985, p. 63).

The Best Solution

Koen's position points towards a practical, pragmatic experience based epistemology – flexible and adaptable. Koen's definition of 'best' is highly contingent something can be the best outcome within available resources without necessarily being any good, in a universal, objective sense. Koen gives the example of judging whether a Mustang or a Mercedes is the better car. Although, objectively the Mercedes may be the better car, the Mustang could be considered as the best solution to the given problem statement and its constraints (Koen, 1985, p. 10). Koen's viewpoint takes 'scientific knowledge' as provisional, and judges it in terms of its utility in arriving at an engineering solution in the context of other available heuristics.

Koen's discussion of how the engineer arrives at a 'best' solution involves trading off the utility characteristics which are to a large extent incommensurable and negotiable – engineering judgement prevails, and it is the ability to achieve a solution under constraint that lies at the heart of the engineering approach to problem solving:

> Theoretically [...] *best* for an engineer is the result of manipulating a model of society's perceived reality, including additional subjective considerations known only to the engineer constructing the model. In essence, the engineer creates what he thinks an informed society would want based on his knowledge of what an uninformed society thinks it wants (Koen, 1985, p. 12).

Trade-Offs Under Constraint?

On the face of it, Koen's approach to arriving at the best solution under constraint sounds rather similar to Erik Hollnagel's ETTO Principle (Hollnagel, 2009), however any similarity is superficial as Koen and Hollnagel appear to hold very different philosophical positions. Hollnagel takes an abstract view that human action balances two commensurate criteria: being efficient or being thorough. Hollnagel proposes a principle where trade-offs are made between efficiency and thoroughness under conditions of limited time and resources, which he terms as ETTO (Efficiency Thoroughness Trade-Off) (Hollnagel, 2009, p. 16). He suggests that people 'routinely make a choice between being effective and being thorough, since it is rarely possible to be both at the same time' (Hollnagel, 2009, p. 15). Using the analogy of a set of scales, Hollnagel proposes that successful performance requires that efficiency and thoroughness are balanced. Excessive thoroughness leads to failure as actions are performed too late, or exhaust available resources, excessive efficiency leads to failure through taking action that is either inappropriate, or at the expense of safety – an excess of either will tip the scales towards failure (Hollnagel, 2009, p. 14).

Hollnagel (2009) defines the ETTO fallacy in administrative decision making as the situation where there is the expectation that people will be 'efficient and thorough at the same time – or rather to be thorough when in hindsight it was wrong to be efficient' (p.68). He redefines safety as the 'ability to succeed under varying conditions' (p.100), and proposes that making an efficiency-thoroughness trade-off is never wrong in itself. Although Hollnagel does state that ETTOs are 'normal and necessary', there is an undercurrent of scientific positivism running through his book. In essence the approximations that are used in ETTOs are in his view driven by time and resource pressures – uncertainty is a result of insufficient time and information. Putting time and resource considerations to one side, there is the inference that greater thoroughness would be an effective barrier to failure – *the right answer is out there if we care to be thorough enough in our actions*. This, superficially, is not unlike Reason's discussion of 'skill based violations' (Reason, 2008, pp. 51-52). Indeed Hollnagel suggests (Hollnagel, 2009, pp. 141-142) that for a system to be efficient and resilient ETTOs must be balanced by TETOs (Thoroughness-Efficiency Trade-Off) – having thoroughness in the present allows for efficiency in the future.

There Are No Right Answers, Only Best Answers

The engineering method as defined by Koen (recall: 'The strategy for causing the best change in a poorly understood or uncertain situation within the available resources'(Koen, 1985, p. 5)) superficially bears the hallmarks of an ETTO, however, Koen would argue that there is 'no one right answer out there', and that in effect 'all is heuristic' – science is essentially a succession of approximations (Koen, 2003). Hollnagel's ETTO Principle, understood on a superficial level, is unhelpful in understanding how safety is generated in an engineering context. It relies on hindsight and outcome knowledge, and simply asks at each critical decision point (which in itself is only defined with hindsight) 'where could the engineer have been more thorough', on the basis that being more thorough would have brought them closer to the 'right answer'. If you accept, as Koen would assert, that there is no 'right answer', only the 'best' answer, then any assessment of engineering accountability reduces to a discussion as to whether the engineer used a set of heuristics that were considered at the time (and place) of the decision to be 'state of the art', in the context of the constraints of the engineering problem faced. This ethical discussion goes beyond the agency of the individual engineer or engineering team insofar as the constraints imposed (time, materials, budget, weight...) mean that the best is not good enough. The 'wisdom' to know when a problem is over-constrained, and the power to change the constraints need to go hand-in-hand. This decision is confounded by the tendency for the most successful systems to be optimised at the boundary of failure – too conservative and failure will come from being uncompetitive (too heavy, too expensive, too late...); too ambitious and you may discover where the boundary between successful operation and functional failure lies.

And Why is All This Important...?

The view that engineering is based on the application of heuristics in face of uncertainty provides a useful framework in which engineers can consider risk and the limitations of the methods used to assess system safety. The appearance (illusion?) of scientific rigour can blind engineers to the limitations in the ability of engineering models and abstractions to represent real systems. Over-confidence or blind acceptance of the approaches to risk management leave the engineer open to censure for presenting society with the impression that the models used are somehow precise and comprehensive. Koen's way of defining the Engineering Method promotes a modest epistemology – an acceptance of the fallibility of the methods used by engineers, and a healthy scepticism about what constitutes 'scientifically proven fact' can paradoxically enhance safety. A modest approach encourages us to err on the side of caution and think more critically about the weaknesses in our models of risk.

CHAPTER 7: ADDING VALUE, MAINTAINING VALUES.

Value Free or Value-Added?

It is when one examines the social context in which engineering activities are performed that one encounters the greatest challenge to the idea that engineering is an applied science. Engineering is first and foremost a productive activity, with an intimate relationship between the technical and commercial aspects which are mutually intermingled. David Noble, charting the history of engineering in the USA (using Marxist rhetoric), describes this relationship seeing engineers fulfilling a role as agents of capital in the quest for further capital accumulation:

> The technical and capitalist aspects of the engineers' work were reverse sides of the same coin, modern technology. As such, they were rarely if ever distinguishable: technical demands defined the capitalist possibilities only insofar as capitalist demands defined the technical possibilities (Noble, 1977, p. 34).

Engineering is portrayed in idealistic terms as 'serving humankind', elevating standards of living and meeting human needs, and certainly those outcomes are possible, under the proviso that it is profitable to do so. If engineering was the mere application of scientific principles, then worldly concerns such as business success and shareholder value would have little influence on the engineering process. Koen's definition of the engineering method encapsulates the context by incorporating a catch-all 'within the available resources' (Koen, 1985, p. 5), acknowledging the external constraints; physical, political and economic (Koen, 1985, p. 8). This is not to imply some sort of universal amorally calculative Machiavellian drive towards profit, even though that may lay at the heart of some management strategies. Engineering concerns are primarily businesses, and business success is generally measured in monetary terms; you can be the 'best' or the 'safest', but unless you are making money you won't stay that way for very long.

Professional Servants of Power

Perrucci argues that engineers 'do not constitute an independent power base which shares in decisions governing the uses to which engineering talents are put'(Perrucci, 1971, p. 494). Although he recognized the increasing importance of engineers in society, he saw it as increasingly unlikely that engineering would develop as a 'genuine profession committed to the service of man'.

Perrucci highlights how the profession was becoming increasingly specialized and fragmented at all levels; in terms of education, professional institutions and careers within organizations. This fragmentation was undermining the possibility for engineering to emerge as a profession with a sufficiently strong power base to enable it to shape its direction and activities, and creating divisions amongst engineers that inhibit the emergence of a strong unified profession (Perrucci, 1971, p.504-505). Perrucci summarizes the status of the engineer:

> Given such limited autonomy over their work, control over who may and may not practice engineering, and doubts over how their talents are being used, engineers find themselves with a body of specialized knowledge that is for sale to any client who seeks to hire them. (Perrucci, 1971, p. 498).

Perrucci characterizes engineers as employees rather than professionals – the relationship is an employer-employee relationship rather than a professional-client relationship, and engineers serve their employers rather than human welfare (Perrucci, 1971, p. 498).

Whalley (1986) characterizes engineers as 'simply the professionals who apply knowledge and expertise to the production process' (Whalley, 1986, p. 5). As 'trusted workers' who have 'little opportunity for setting up as self-employed consultants', they 'sell their expertise to powerful corporate clients who reserve for themselves the right to judge an acceptable performance' (Whalley, 1986, p. 5).

It might be expected that the story would be rather different in cases where engineers are providing services on a consultancy basis, either as self-employed consultants, or as part of an engineering consultancy firm – where the relationship is closer to one of professional/client. Rather than providing an independent view, these hired guns may strive to provide precisely what the client wants, performing the engineering task in the manner prescribed by the client.

Engineering/Management

Diane Vaughan captures the tension between 'engineers' and 'managers' in the discussions on the night before the ill-fated Space Shuttle Challenge launch, exposing the powerlessness of the engineering professional in an organizational setting. The famous 'hat' comment, where the Senior Vice President at Morton Thiokol (Mason) encourages the Engineering Manager objecting to the launch (Lund) to take off his 'engineering hat' and put on his 'management hat' (D. Vaughan, 1996, p. 366), could be seen as epitomising the power relationship faced by engineers when raising concerns, but it also illustrates one of Koen's heuristics 'always give an answer' (Koen, 1985, p. 49). Mason's remark only gained significance in the aftermath of the Challenger disaster, and marked the transition from a technical discussion to finally making a decision.

Ben Powers, an engineer at Marshall Space Flight Centre at the time that the Challenger Launch Decision was made, rationalized his involvement in the launch decision by his interpretation that the limitation of responsibility of the engineer was to report the concerns up the 'chain of command':

> "You don't override your chain of command. My boss was there; I made my position known to him; he did not choose to pursue it " - "at that point, it's up to him; he doesn't have to give me any reasons; he doesn't work for me; it's his prerogative" (Bell, 1987, p. 51).

Morton Thiokol and NASA were subsequently portrayed as having taken a calculated risk under production pressure and lost (D. Vaughan, 1996, p. 32). Ironically, the launch was carried out at an ambient temperature that was a few degrees lower than the design operating envelope of the Solid Rocket Booster, a fact which appears to have gone unnoticed in the discussions on the eve of the ill-fated launch. The un-noticed reality that the design operating envelope was being exceeded could have been sufficient grounds to delay the launch. Instead the discussion became one of tasking the engineers with proving that it was not safe to launch; that the joint would fail when operating at the lower ambient temperatures.

Being the Bearer of Bad News

It is not easy being right, as Roger Boisjoly demonstrated – particularly when you are only proven right in the aftermath of a disaster. Roger Boisjoly was the staff engineer at Morton Thiokol who had been most vocal in raising concerns about the SRB field joint performance, and had raised the issue unequivocally in the year prior to the disaster – predicting the catastrophic loss of a flight, personnel and launch pad facilities. An engineering task force was set up to investigate the issue, but was strangled by bureaucracy, and the management focus appeared to be on getting a quick partial fix with further improvements coming over a period of years (D. Vaughan, 1996, pp. 447-455). Another aspect that becomes clear from reading the engineering memoranda written prior to the event (D. Vaughan, 1996, pp. 447-455) is the way Boisjoly appears to have created a rod for his own back by raising the issue. Although the issue was recognized, and an informal task force set up, all this work was to be done in parallel with the teams existing workload. Boisjoly resented 'working at full capacity all week long, and then being required to support activity at the weekend that could have been accomplished during the week' (D. Vaughan, 1996, p. 455). This creates a double-bind – often the issue is only evident to those who are close enough to understand the implications, and this understanding puts the specialist in the best position to enact an improvement – as in the case of Boisjoly, the issue was reflected back to the originator to resolve, and within the existing time and budgetary resources. The author has experienced this double bind on several occasions, and it was found to have a strong inhibitory effect on raising issues – at its most banal level, do you highlight that a procedure is incorrect or obsolete, knowing that you will have to spend several hours, or indeed days getting an approved revision in place (while balancing a heavy workload), or do you turn a blind eye to it, muddle through, and hope that another of your colleagues will fix it. When it is made difficult for the person raising an issue, even if that difficulty stems from 'empowering' them to resolve the issue without additional resources to do so, less reporting can be expected.

Cutler (1967) lays down the moral duties of engineers:

> Engineers have a responsibility that goes far beyond the building of machines and systems. We cannot leave it to the technical illiterates, or even to literate and overloaded technical administrators, to decide what is safe and for the public good. We must tell what we know, first through normal administrative channels, but when these fail, through whatever avenues we can find.
> Many claim that it is disloyal to protest. Sometimes the penalty – disapproval, loss of status, even vilification can be severe. The penalty for neglect of this duty can be much more severe (Cutler, 1967, p. 47).

Cutler's call for engineers to exhaust all avenues to alert the public of safety concerns elicits a strong sense of moral righteousness. On the other hand, there are the practical, pragmatic considerations of putting clothes on your back and food on the table. How far could you expect a staff engineer to go to highlight his safety concerns? Is it worth them potentially sacrificing their career by making a stand – going outside their company management hierarchy – perhaps escalating the matter to a regulatory agency, on the back of a concern that is often tacit and unquantifiable, but nonetheless feels very real?

Koopman (2006) outlines four options that the engineer faces. Firstly they can present the problem to their leadership as clearly as they can, if possible providing a potential solution, and then accept whatever decision their management make as being the right decision. This does rely on the decision makers understanding the nature of the problem – something which is difficult to ascertain if it relates to a specialist area. A second possibility is to make a stand, and escalate the issue above the direct management or through another route such as a corporate safety department or regulator. This can be a no-win situation for the engineer – even if the concerns are justified and management back down, they can face personal censure, and such negative outcomes can suppress further reporting.

A third approach would be to ignore the problems, and if you do happen to find them, don't inform your management. This amounts to shirking professional responsibilities and jeopardising your company and its customers. Finally, the ultimate choice is to leave the job, or seek transfer to a different project. This approach may have a high personal cost, but allows the engineer to (partially) preserve their personal integrity, if the cost of making a stand is too great – you may not be part of the problem, but you are not part of the solution either (Koopman, 2006).

Koopman (2006) sees the ideal situation being one where 'management views problem finding as a healthy part of the engineering profession', but engineers also need to make the effort to understand the non-technical factors that influence decision making so as to make effective risk trade-offs. He does accept that there will be time when it is not possible to reconcile management direction with the engineer's professional and personal interests.

Claus Jensen, in his analysis of the Challenger accident, accounts for the real world constraints on authority faced by engineers working in 'extremely large and complex systems' – and proposes that rather than calling for moral heroics, the efforts should be directed at 'reinforcing safety procedures and creating structures and processes conducive to ethical behaviour'. He reflects, however, that when systems threaten to set 'their own agenda' beyond the control of human intervention, the need for individuals to show courage, integrity and good judgement is at its greatest (Jensen, 1996, pp. xiii-xiv). Whereas Jensen's suggestions certainly may provide a useful framework for facilitating individuals involved in safety critical operations to raise concerns, it ultimately comes down to the ability to decipher and make sense of mixed signals and be in a position to make what could be an unpopular (and ultimately rationally unjustified) decision on the basis of uncertain and incomplete information. In this respect, the assumption that engineering is somehow an exact science is unhelpful – seeking the strongest, most explicit evidence in making critical no-go decisions has a Newtonian element, and it denies the role of less explicit ways of knowing – experience, judgment, intuition and gut feel. Indeed, in the case of NASAs 'science based, positivistic and rule based system', 'observational data backed with intuitive argument' was not acceptable (D. Vaughan, 1996, p. 221). Robert Boisjoly had been 'chastised [...] for using words "I feel" or "I think"' as they were not 'engineering supported statements, but they [were] just judgemental' (D. Vaughan, 1996, p. 222). A reliance on evidence that fits into the framework of existing rational beliefs limits our capability to deal with complex systems, something which will be discussed further in the next chapter.

CHAPTER 8: DISCUSSION

"Does the Belief that Engineering is an Applied Science Help Engineers Understand Their Profession and it's Practice?"

In some ways engineering is the opposite of science – where science makes observations in the 'external world' and generates an abstraction – a theory to account for these observations, broadly speaking engineering starts with an abstraction – an idea – and creates a change in the world. Science tests its theories by predicting behaviour and making sense of observed behaviour in the frame of the theory, engineering tests its theories empirically by creating artefacts based on its abstractions. Engineers have gained utility from insights gained through the application of the Scientific Method, but an understanding of engineering as applied science is misleading and unhelpful.

Rational and Tacit Knowledge – Show Me the Evidence!

Engineers spend rather a lot of time at University being inculcated with basic sciences, engineering sciences and mathematics. The dominance of quantitative, objective ways of approaching the world subjugates the qualitative and tacit to something unreal and subjective. Unquantifiable qualities are dismissed – as they are incommensurable with objective quantities. In engineering, a lot can be predicted and explained by the application of engineering science which ultimately reduces to putting the required numbers in the appropriate equations. Engineering science is not a language which contains words like 'feel', 'think', 'reckon' or 'expect' and decisions tend to be 'evidence based'.

Modelling of complicated structures and systems has become *very, very, good.* We can test scenarios that we would not or could not test physically (such as aircraft crash landings or nuclear explosions); we can go through multiple iterations of a design with minimal cost impact, 'testing' the design at each step – using software that requires minimal user expertise. It is the quality and representativeness of the abstractions that are in use that poses a risk to engineers and a barrier to learning. Complicated, intricate designs can be analysed to great accuracy, and this carries the risk that we make the assumption that everything around us can be analysed in this way. There is a fine line between having a healthy scepticism about the limitations of models, and being branded a neo-luddite, but this is the line that engineers must negotiate as they tend towards ever higher levels of abstraction. With more being done virtually, less development testing of physical systems is being carried out – arguably there are less opportunities to shake out unwanted interactions that are a result of the 'imperfect behaviour' of the physical world – friction, vibrations, electromagnetic interference –mundane environmental effects such as dust and moisture can vary the assumptions made in models greatly. Even something as banal as determining wiring harness lengths from three-dimensional digital models have humbled the engineers constructing the Airbus A380 – resulting in substantial production delays as each aircraft had to be rewired on the production line. The mere announcement of the delays in 2006 knocked over 26% off the parent company's share price, and the delays were expected to reduce profits by US$ 2.5 billion (Clarke, 2006).

Boeing were not immune to problems getting from Computer Aided Design (CAD) model to a physical reality on the B787 programme – with the first aircraft being delivered to All Nippon Airways some 3 years later than originally planned – much of the delay due to the time taken to develop the know-how required to manufacture the aircraft. Boeing had not only gone for a composite structure, but also outsourced much of the production to subcontract companies – effectively offloading the risk of learning the new production methods to its subcontractors (Ostrower, 2011; Teresko, 2007).

Risk

So much can be described and predicted using engineering science that we may assume that everything can be determined by this Newtonian-Cartesian approach – an approach which denies subjective, tacit, qualitative ways of knowing. This shapes our attitude towards risk – the more confident we are in our models, the more likely we may be to engage in hazardous activities. A simple mathematical formula underlies much of the thinking in risk management:

Risk = Frequency x Consequence

Each individual hazard can be assessed in relation to its consequence, and then the expected frequency of the hazard estimated providing a measure of the risk. Analytical methods may be used to decompose a system so that it can be transformed to an abstraction of hazards and associated probabilities. Indeed the airworthiness authorities certifying aircraft type designs (e.g. FAA and EASA) require the use of analytical methods to demonstrate that the probability of catastrophic failure conditions are extremely improbable. Helpfully, the FAA defines catastrophic as a failure condition that would prevent continued safe flight and landing (FAA, 1988, p. 5) or more explicitly EASA defines 'Failure Conditions, which would result in multiple fatalities, usually with the loss of the Aeroplane' (EASA, 2011, pp. 2-F-43). 'Extremely Improbable failure conditions are those having a probability on the order of 1 x 10^{-9} or less' (EASA, 2011, pp. 2-F-44; FAA, 1988, p. 15). EASA also uses qualitative terms – 'those [failure conditions] so unlikely that they are not anticipated to occur during the entire operational life of all aeroplanes of one type' (EASA, 2011, pp. 2-F-43). If a system that can constitute a Severe Major or Catastrophic hazard is deemed to be complex then qualitative and quantitative assessments are to be performed as appropriate (FAA, 1988, p.17). Unfortunately a rather circular definition of 'complex' is given by the FAA:

> Complex: A system is considered to be complex if structured methods of analysis are needed for a thorough and valid safety assessment. A structured method is very methodical and highly organized. Failure modes and effects, fault tree, and reliability block diagram analyses are examples of structured methods (FAA, 1988, p. 4).

EASA provides a slightly different definition, which merits discussion:

> Complex. A system is Complex when its operation, failure modes, or failure effects are difficult to comprehend without the aid of analytical methods (EASA, 2011, pp. 2-F-40).

EASA concedes that a complex system is difficult to comprehend without the aid of analytical methods. This contains that the inference that it can be comprehended with the aid of analytical methods. This ideology contrasts starkly with the views of complexity put forward by Dekker, Cilliers and Hofmeyr (Dekker, Cilliers, & Hofmeyr, 2011) where complex systems are by definition irreducible. It could be argued that the problem is merely a question of semantics, the airworthiness authorities are not making the distinction between *complex* and *complicated*, where a 'complicated system can have a huge number of parts and interactions between the parts but is, in principle, exhaustibly describable' (Dekker, 2011, p. 149). The concept of a complicated system may sit better with the airworthiness authorities' world view, but by taking this position is to deny the possibility of complex interactions in highly integrated aircraft systems, or at the very least substantiate the belief that complexity is something that can be analysed, tabulated and controlled, and expressed as a probability in the allowable range.

Gone are the days when fuel was simply that, the source of power for the engines – in modern jet aircraft it is used to cool electrical generators, as a hydraulic fluid for actuators, it provides wing bending relief and is used to actively control the centre of gravity of the aircraft. The wing is no longer merely a structural component sticking out each side of the aircraft generating lift. In the case of the Boeing 747-8, on an existential level, the wing is also made up of electronic components in the avionics compartment, and lines of software code. During flight testing the wing exhibited an excessive 'Limit Cycle Oscillation'[9] in some flight conditions[10]. The certification rules prohibit such levels of aeroelastic instability, however, a solution was proposed and accepted which used elements of the 'fly by wire' flight control system to provide active damping using the outboard ailerons – thus providing a direct interaction between the wing structure and aircraft systems. This required the regulations to be adapted, and the safety of the damping system had to be demonstrated in analytical probabilistic terms (FAA, 2011, pp. 39765-39768). The engineer credited with developing the system was declared Boeing Engineer of the Year (Gates, 2011), in recognition of developing a solution to the problem that 'which required no physical modification to the wing and no added weight'. Not wishing to take away from the achievement, it does raise some philosophical concerns when one considers that issues found during testing which previously would have prevented certification of a product can be circumvented by the addition of a little more technology, and rewriting the rules. The requirement for inherent structural aero-elastic stability (an emergent property of the aircraft structure) was abandoned and replaced by what is effectively a piece of software. Moreover, the software is designed to damp the oscillations seen in the flight regimes specified in the certification requirements and in effect simulates stable behaviour in these (fairly arbitrary) cases. Do we believe that if we engineer stability into the places we then go looking for it, that it is an inherent property? A cynic could liken this to 'proving that the Easter Bunny exists' by depositing chocolate eggs around the garden and guiding the children in their quest. Added to that, through careful reframing, what, in a previous era, would have been considered a disastrous design failure was portrayed as an engineering triumph.

Contained in the approach to system safety analysis is implicit belief that quantitative methods are superior to qualitative methods – Minor and Major hazards may be assessed qualitatively, quantitative analysis is advised for Severe Major (termed Hazardous by EASA) and Catastrophic failure conditions. The entire analysis process is bounded by the imagination and creativity of the system designers. To a large extent, the system designer needs to be able to think the unthinkable. Events with a frequency of one in a billion hours are suitably improbable to be implausible, and in my experience the designer of system can easily adopt a mindset centred about how the system is designed to work, not the unusual ways that it can fail. A billion flight hours translates to an individual aircraft spending over 100,000 years in the air– ample opportunity for Murphy to foil the best laid plans.

The engineer faces an uphill struggle when attempting to have a critical dialogue about the precepts of aircraft certification. A challenge to the epistemological basis of the Acceptable Means of Compliance specified by the Airworthiness Authorities tends to elicit a dismissive (and entirely understandable) response of the form 'So *you think you know better* than the FAA *and* EASA?' In raising in service airworthiness concerns to the aircraft manufacturer, a stock answer is 'the safety objectives are still met'. In reality what is being said is that the System Safety Assessment has been checked, and even with a much higher than expected failure rate of a sub-

[9] Traditionally referred to as 'flutter', but 'flutter' to aeronautical engineers is 'the seven letter 'F' word', so it is not used in polite company.

[10] It is not unusual to have such findings on flight test, but they are typically resolved by stiffening the wing structure, changing the aerodynamic profile or adding a mass to change the natural frequency of the structure – indeed 'flutter' encountered on the original 747 flight test programme in 1969 was resolved by these more conventional means (Sutter & Spenser, 2007, p. 181).

system, the impact on the analysis does not increase the calculated probability of the associated failure condition to a level beyond that acceptable. Analytical abstraction has a greater air of authority than an empirical experiential assessment of risk and hazard; appearing more robust and scientific than 'that doesn't look right...' or 'I have a bad feeling about...'. Engineering judgement is delegated to a subsidiary role, even though the identification of hazards, potential failure interactions and indeed the definition of the certification plan are driven by the voices of experience. Indeed many of the certification requirements are in essence Koenian Heuristics – factors of safety, and apparently arbitrary values and operational requirements that have no basis other than reflecting what has been found to be successful in the past.

The Paradox of Safety Science

There can be little doubt that the types of analysis required for the certification of complex aircraft systems has lead to an increased level of safety. The methodical and systematic approach to the analyses has allowed engineers to gain a better understanding of the strengths and weaknesses of their systems (despite being bounded by their ability to imagine the implausible and constrained by the strait-jacket of a Newtonian-Cartesian world view). Inherent in the analysis are a lot of 'equals signs', which pose a challenge to the engineers to see beyond the mathematical abstractions and through to the contingent nature of the analysis.

It would be tempting to believe the safety analyses are an objective representation of the system – such a belief would legitimate the use of high risk technology. Conversely it could be argued that the non-believer would be knowingly employing imperfect means to justify the exposure of the public to a level of risk above that which is deemed acceptable by society, or their proxy, the safety regulators[11]. The desire for ontological certainty when potentially exposing third parties to catastrophic risk can blind engineers to the uncertain epistemology of safety analyses, such as those done to achieve aircraft certification.

A more modest, provisional approach to the analytical methods used to quantify risk, while on one level would be unsatisfactory to the creators or guardians of the hazardous activity, would, I believe, enhance safety by accepting the provisional nature of our understanding of our systems, and prompt us to seek alternative approaches to risk assessment and keep an open mind in relation to the revision of past assessments. It could well be that this modest epistemology with relation to risk analysis could prompt a rethink on the societal acceptability of high risk activities, an acknowledgement that our ability to produce complex risky technology has surpassed our ability to grasp their complexity and manage their catastrophic potential. I would be much happier for society to decide on the basis that our assessment of risk is uncertain and provisional rather than believe that the risks have been accurately assessed and quantified.

A practical difficulty lies in the fact that risky technologies exist, and are widely deployed on the basis that we have assessed and quantified the risks as being acceptable. A revision to these assessments would be problematic to powerful interests, so it seems that there is a strong tendency to resist change, particularly if it would point towards the abandonment of technologies which society has come to depend upon (such as nuclear power). As Francis Bacon surmised: 'A man is more likely to believe something if he would like it to be true' (Bacon, 1620, p. 10).

---

[11] Recall, Catastrophic failure conditions must be 'Extremely Improbable' having a probability on the order of 1×10^{-9} or less'. (EASA, 2011, pp. 2-F-44; FAA, 1988, p. 15). This is the level of risk which is deemed acceptable by the regulators – whether or not such an explicit level of risk exposure is acceptable to society is another matter entirely. That said, it should be evident to most members of the travelling public that climbing into thin metal or reinforced plastic tube which moves almost at the speed of sound in a partial vacuum some 8 miles above the ground is an inherently risky activity.

Always Give an Answer

In the case of modern Anglo-Saxon engineering education, which for the most part lacks learning which is equivocal or uncertain, generally speaking there will be an answer, and it will be found just to the right of an 'equals' sign. Engineers may not be developing the types of critical thinking prevalent in the social sciences (such as psychology or sociology) or philosophy. I feel that the absence of even a rudimentary appreciation of philosophy handicaps engineers in gaining critical thinking skills. The engineering sciences are taught as 'fact' wrapped up in method – leveraging mathematics and the 'laws of nature' to form useful representations of the system or artefact under inquiry. Phrases such as 'maybe' or 'we don't really know' are not really part of the vocabulary in engineering discourse, and when used, draw a response of 'well, find out then!', with the expectation that uncertainty, equivocalness and ambiguity can be eliminated through application of the correct method to the correct dataset. More diversity in the *types* of subjects studied by engineering students would help greatly in their ability to reason in situations where there is not one right answer; where the quality and clarity of the reasoning is paramount. The inclusion of social sciences and humanities subjects as a core element of engineering education would not only help engineers with the social context of their profession, and understand the human element to their practice, but it would also develop skills in dealing with uncertainty and assessing critically the multiple views that prevail in subjects such as philosophy.

Social Context

As described in chapter 7, engineers lacking an independent power base, typically operate under the constraints of their employers. Casting aside any idealistic notion that engineers operate for the benefit of mankind (they can do, but this has more to do with the motivations of their employers rather than the engineers themselves), it is an inevitable reality that engineers are employed to generate value of some tangible nature, usually monetary. The idea that engineering is merely the application of science does not stand scrutiny – the science being developed takes a direction motivated by the demands of capital, and is applied in a manner which seeks to maximise returns (even if 'safety is the number one priority').

In parallel to engineering becoming more 'scientific', business administration has followed a similar path, with an expectation that business decisions are made rationally and on the basis of objective evidence. Management science has deified the concepts of evidence-based decision making, to the point that calls for decisions to be made on 'robust and scientific' grounds have become the unquestioned norm – and it is hard to argue against such an approach in rational terms. What is clear, at least in my experience, is that what passes as 'evidence' would not stand close scrutiny in an academic context. All too often evidence-based decision making could be more accurately described as 'decision-based evidence making'.

Decision-Based Evidence Making

In an environment in which decisions must be justified in rational terms, there is plenty of opportunity for the rationality of the justification to be subverted – knowingly or unknowingly. A typical example of how the process is knowingly gamed is in the case of cost-benefit analysis. When engineering teams in airlines propose a modification to in-service aircraft, it is typical that the airline demands a payback period in the order of two years. This means that the cost of not doing the modification (over a 2 year period) should exceed the cost of doing the modification. Angell and Demetis point out that 'Numbers are like people; torture them enough and they'll tell you anything' (Angell & Demetis, 2010, p. 81), something we could well bear in mind when performing quantitative analyses with an end in mind. There is an expectation in some areas that modifications with significant safety impact are rendered mandatory by the Airworthiness Authorities. In the absence of an Airworthiness Directive (AD) engineers have an uphill battle appealing on the grounds of safety alone – if it is so important, where is the AD?

Modifications which in the judgement of the engineer provide a perceived, but ultimately unquantifiable, safety benefit tend to be difficult to justify commercially over such a short payback period, so engineers often resort to imaginative methods to construct the required business case – down playing the cost and talking-up the benefits. This apparently harmless approach has two unhelpful outcomes – it reinforces and legitimises the cost-benefit analysis methodology (on one level), but in the medium term degrades confidence in the engineers' decision making process if the anticipated tangible benefits are not realised. This in turn makes it more difficult to justify modifications in future.

The second scenario is more insidious – where evidence to support a decision acquires an inherent bias – a case of finding what you set out to look for. When setting out to find evidence to support in increased aircraft maintenance task interval, for example, the evidence is created, and is created in a specific way specified in procedures governing maintenance task interval evolution. There is an assumption that any deterioration or adverse effect from the task interval increases will be gradual and linear, however, the first evidence of an over-extended maintenance task interval can have catastrophic effects (Dekker, 2011, pp. 31-33).

Essentially, All Models Are Wrong, but Some Are Useful[12]

The 'problem' of ontological uncertainty which arises through an acceptance of the fundamental uncertainty of our risk models could lead one into a state of despair – why bother modelling if we accept that they are essentially wrong, and we have no real way of determining just how wrong they are (at least until we have the 'benefit' of hindsight[13]). I believe that this issue can be, at least partially, addressed by more modelling – taking Karl Popper's approach to Science – testing the thesis that 'This System has Acceptable Safety' from as many angles and using as many methods as possible. Whilst accepting that no one model is true, the lessons derived from the different modelling approaches will say something about the robustness and resilience of the system as a whole. An acceptance of science (in its many forms and abstractions) as provisional and falsifiable rather than universal and true would benefit the practice of engineering. It would make space for multiple, approximate, fallible and at times contradictory approaches to safety assessment (including methods aimed towards dealing with complex systems such as STAMP (Leveson, 2004) or FRAM (Hollnagel, 2004)), without the need for *one true method*. Rather than measuring the safety of a system in terms of a single quantitative probability value, the safety and robustness of a system could be elucidated in terms of its behaviour in the face of a diverse assembly of partially true assessments.

Remaining in denial concerning the fallibility of the approaches currently in use will not make the uncertainty go away. A perfect method of risk assessment will (probably) never exist (and if it did exist, how would we ever know?). In the mean time, I believe that strength lies in diversity, and an approach in which multiple imperfect incomplete views are taken would provide an improved means of understanding the conditions in which our technologies succeed or fail.

---

[12] Box and Draper (1987, p. 424).

[13] Hindsight may not inform our model-making, particularly if it is possible or expedient to attribute the failure to 'human error'.

CHAPTER 9: CONCLUSIONS

'All I Know is that I Know Nothing'[14]

The systems of knowledge and abstraction developed through the application of the Scientific Method have formed the basis for the development of engineering science, and engineering science has proved to be of utility in the development of much of the technology in use today. In face of such utility, a 'scientific ideology' has permeated contemporary engineering, particularly in the second half of the twentieth century – as a result of widespread government involvement in research and development, and the desire of the emerging engineering professions to distinguish themselves from their 'shop taught' predecessors.

The effectiveness of engineering science in the analysis of complicated systems has reinforced the illusion that scientific knowledge is approaching 'truth'. This is manifest in the approach that engineering has taken towards the quantification of risk through analysis of systems – through deconstruction of the system into its constituent components, and then having assigned a reliability value, reconstructing the system to assign a numerical value to the probability of future occurrences.

How Confident is 'Over-Confident'?

I argue that an over-confidence in the epistemology of engineering science poses a risk in itself. How do we operationalise 'over-confidence'? Arguably, the concept of over-confidence is an ex post facto judgement – we can only define over-confidence retrospectively – well founded confidence becomes over-confidence within the space of an '*ohno*second'[15]. A more useful way of thinking of over-confidence is challenging ourselves as to whether we are gambling as if we cannot lose, and asking ourselves how much are we staking on our quantification of risk being accurate. Any unquestioning belief that we have definitively quantified risk, is in my opinion over-confidence. We are well advised to take Dekker and Lundstrom's (2006) advice to keep "a discussion about risk alive, even when everything looks safe" (Dekker & Lundstrom, 2006) . Friedrich Nietzsche reminds us that "that which convinces is not necessarily true [...], *it is nothing more nor less than convincing*" (Nietzsche & Levy, 1933, p. 18) – over-confidence stems from mistaking something we merely find convincing for absolute truth.

Although a quest for certainty appears to underpin the Newtonian-Cartesian scientific ideology, paradoxically, acknowledging the uncertainty, subjectivity and methodological imperfection in our approach to assessing the risks inherent in technology may provide most benefit. An admission of the persistence of doubt with relation to the safety of high risk technologies may not be what society wants to hear, but it is certainly a dialogue that deserves to be heard.

Knowledge/Power

A belief in engineering as applied science may have the effect of suppressing minority opinion. The process of creation of scientific knowledge is coupled with demand, and demand is deeply intertwined with power. Arguments which are counter to the status quo may be dismissed, particularly if they are not well reasoned – rationality (in the strictest sense) takes primacy over reasonableness. We can easily lose sight of the fact that the generation of knowledge and theory is not value free, and is a reflection of the history of power and ideologies. In this respect,

---

[14] This quotation is commonly attributed to Socrates, but fittingly even that is not by any means certain (Taylor, 2000, p. 46).

[15] An *ohno*second is the miniscule period of time it takes to realize that things are not working out as you expected.

Vannevar Bush's appeal for basic science to be performed without any direct expectation of utility becomes very relevant – potentially providing an opportunity for utility and ideology to be decoupled from inquiry.

The Utility of Reductionism, and its Constant Companion, Human Error

Engineering science remains essentially reductionist and linear – non-linear processes (such as fluid dynamics) are either simplified in analysis to the point that they can be treated as linear, or approximated using computational brute-force. It would seem remarkable that much of the development of this reductionist epistemology occurred after Einstein published his General Theory of Relativity (1915), or Heisenberg's formulated the Uncertainty Principle (1927) (Salam, Dirac, Evans, & Watts, 1990). The linear reductionist view was fatally undermined in Physics almost a century ago, but is still alive and well in engineering science. The reason appears to be one of utility – the Cartesian-Newtonian world view is useful, or indeed useful enough, most of the time. An assumption of linearity, cause-effect symmetry, and that past performance will provide an accurate depiction of future events is akin to driving a car ever faster down the road while only 'looking in the rear-view mirrors at the road behind' (Angell & Demetis, 2010, p. 37) – something which works well so long as there are no bends ahead. When a (metaphorical) bend is reached, as tends to happen when a system is optimised on the edge of chaos – as Rasmussen would term at the 'boundary of acceptable performance' (Rasmussen, 1997, p. 190), the typical reaction is not to question the core beliefs – but rather to assign the residual uncertainty to a helpful catch-all such as human error. Prior to the adoption of Enlightenment Thinking, concepts such as God's Will, Evil Spirits or even plain old Bad Luck fulfilled this role.

The scientific ideology within engineering (and arguably ubiquitous in the western world) appears to go hand in hand with categories such as human error – it would appear to be psychologically adaptive to explain unexpected and unwanted outcomes in terms of human error rather than question the essential truth of the scientific doctrine.

'Merely Complicated?'

Earlier in this thesis, a distinction was drawn between 'complicated' and 'complex' and as a means to differentiate those systems which could be described, *for all intents and purposes*[16], in linear deterministic terms, and those which could not. In reality, this is a false distinction – even the simplest mechanical systems (such as a spring and a pendulum) can possess complex, non-linear and unpredictable behaviour (Gleick, 1988). We need to bear in mind that the scientific endeavour is largely about finding order in the world, which has the intrinsic effect of making disorder, chaos or complexity unobservable. Concepts such as complexity theory may not (almost by definition) yield models with useful predictive value, however, may provide a useful contribution in shaking the foundations of the Newtonian-Cartesian paradigm, and encouraging a more modest, provisional approach to our models and theories.

A pragmatic engineer may ask whether it matters, and may promote taking a means-end approach – judging engineering methodology in terms of utility, accepting it's fallibility. In high risk activities, such a relativistic approach may not suffice – unacknowledged and unknown blind spots may exist. As Einstein pointed out to Heisenberg in 1926: 'whether you see a thing or not depends on the theory which you use. It is theory which decides what can be observed' (Salam et al., 1990, p. 99).

[16] The phrase 'intents and purposes' nicely reflects a utilitarian basis for the judgment of abstractions.

REFERENCES

Angell, I., & Demetis, D. (2010). *Science's First Mistake: Delusions in Pursuit of Theory*. London, UK: Bloomsbury Academic.

Armytage, W. H. G. (1976). *A social history of engineering* (6 ed.). London, UK: Faber and Faber.

Auyang, S. Y. (2006). *Engineering: an endless frontier*. Cambridge, MA: Harvard University Press.

Bacon, F. (1620). The New Organon or: True Directions Concerning the Interpretation of Nature J. Bennett (Ed.) Retrieved from http://www.earlymoderntexts.com/pdf/baconewo.pdf

Bell, T. E., Esch, K. . (1987). The fatal flaw in flight 51-L. *IEEE Spectrum, 24*(2), 36-51.

Box, G. E. P., & Draper, N. R. (1987). *Empirical model-building and response surfaces*. New York, NY: Wiley.

Brooke, J. H. (1991). *Science and religion: some historical perspectives*. Cambridge, UK: Cambridge University Press.

Buchanan, R. A. (1978). Science and Engineering: A Case Study in British Experience in the Mid-Nineteenth Century. *Notes and Records of the Royal Society of London, 32*(2), 215-223.

Buchanan, R. A. (1983). Gentlemen Engineers: The Making of a Profession. *Victorian Studies, 26*(4), 407-429.

Buchanan, R. A. (1985). Institutional Proliferation in the British Engineering Profession, 1847-1914. *The Economic History Review, 38*(1), 42-60.

Buchanan, R. A. (1989). *The engineers: a history of the engineering profession in Britain, 1750-1914*. London, UK: Kingsley.

Bush, V. (1945). *Science, the endless frontier: A report to the President*. Washington, DC: U.S. Govt. Printing Office.

Clarke, N. (2006, June 15, 2006). Airbus Delay On Giant Jet Sends Shares Plummeting. *The New York Times* Retrieved March 16, 2012, from http://query.nytimes.com/gst/fullpage.html?res=9A01E5DC1031F936A25755C0A9609C8B63

Cutler, C. C. (1967). Spectral lines - Duty to dissent. *IEEE Spectrum, 4*(6), 47.

Dekker, S. (2011). *Drift Into Failure: From Hunting Broken Components to Understanding Complex Systems*. Farnham, UK: Ashgate.

Dekker, S., Cilliers, P., & Hofmeyr, J.-H. (2011). The complexity of failure: Implications of complexity theory for safety investigations. *Safety Science, 49*(6), 939-945. doi: 10.1016/j.ssci.2011.01.008

Dekker, S., & Lundstrom, J. (2006). From Threat and Error Management (TEM) to Resilience. *Human Factors and Aerospace Safety, 6*(3), 261-273.

Descartes, R. (1637). Discourse on the method of rightly conducting one's reason and of seeking truth in the sciences. J. Bennett (Ed.) Retrieved from http://www.earlymoderntexts.com/pdf/descdisc.pdf

Dym, C. L. (2004). Design, systems, and engineering education. *International Journal of Engineering Education, 20*(3), 305-312.

EASA. (2011). *Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25 Amendment 11*. Koln, Germany: European Aviation Safety Agency.

Engineering Accreditation Board. (2010). The accreditation of higher education programmes. London, UK: Engineering Council.

Engineering Council. (2012). Engineering Council History Retrieved February 10, 2012, from http://www.engc.org.uk/about-us/about-the-engineering-council/engineering-council-history

EngineeringUK. (2011). Engineering UK 2011 - The State of Engineering. London, UK: EngineeringUK.

Engineers Ireland. (2007). Accreditation criteria for engineering education programmes. Dublin, Ireland: Engineers Ireland.

FAA. (1988). *Advisory Circular 25.1309-1A System Design and Analysis*. Washington, DC: Federal Aviation Administration.

FAA. (2011). *Special Conditions: Boeing Model 787–8 Airplane; Interaction of Systems and Structures, Electronic Flight Control System-Control Surface Awareness, High Intensity Radiated Fields (HIRF) Protection, Limit Engine Torque Loads for Sudden Engine Stoppage, and Design Roll Maneuver Requirement*. Washington, DC: Federal Aviation Administration.

Finniston, H. M. (1980). *Engineering our future: Report of the committee of inquiry into the engineering profession Cmnd 7794*. London, UK: HMSO.

Garber, D. (1998, 2003). Descartes, René. *Routledge Encyclopedia of Philosophy* Retrieved Jan 20, 2012, from http://www.rep.routledge.com/article/DA026SECT8

Gates, D. (2011). In Person: Fitzgerald's fix for Boeing 747-8 earns aviation honors. *Seattle Times* Retrieved 9 March, 2012, from http://seattletimes.nwsource.com/html/businesstechnology/2016583947_inpersonfitzgerald24.html

Gleick, J. (1988). *Chaos: making a new science*. New York, NY: Penguin.

Goldman, S. L. (2004). Why we need a philosophy of engineering: a work in progress. *Interdisciplinary Science Reviews, 29*(2), 163-176.

Gordon, J. E. (1976). *The New Science of Strong Materials: Or Why You Don't Fall Through the Floor* (Second ed.). London, UK: Pelican.

Grinter, L. E. (1955). Summary of the report on the evaluation of engineering education. ***Journal of Engineering Education***, *46*(1), 25-63.

Hanrahan, H. (2011). The Washington Accord Past, Present, Future Retrieved December 9, 2011, from http://www.ieagreements.org/Washington-Accord/Washington-Accord-Overview.pdf

Harris, J. G., DeLoatch, E.M, Grogan, W.R, Peden, I.C.,Whinnery, J.R. (1994). Journal of Engineering Education Round Table: Reflections on the Grinter Report. *Journal of Engineering Education, 83*(1), 69-94.

Harrison, P. (1995). Newtonian Science, Miracles, and the Laws of Nature. *Journal of the History of Ideas, 56*(4), 531-553.

Hill, D. R. (1996). *A history of engineering in classical and medieval times*. London, UK: Routledge.

Hollnagel, E. (2004). *Barriers and accident prevention*. Farnham, UK: Ashgate.

Hollnagel, E. (2009). *The ETTO principle: efficiency-thoroughness trade-off : why things that go right sometimes go wrong*. Farnham, UK: Ashgate.

Jensen, C. (1996). *No downlink: a dramatic narrative about the Challenger accident and our time*: Farrar, Straus & Giroux.

Koen, B. V. (1985). *Definition of the engineering method*. Washington, DC: American Society for Engineering Education.

Koen, B. V. (2003). *Discussion of the method: conducting the engineer's approach to problem solving*. New York, NY: Oxford University Press.

Koopman, P. (2006, 5/23/2006). On Being the Bearer of Bad News. *Online Ethics Center for Engineering* Retrieved March 26, 2012, from www.onlineethics.org/Topics/LegalIssues/LegalEssays/badnews.aspx
Larson, M. S. (1977). *The Rise of Professionalism: A Sociological Analysis*. Berkeley, CA: University of California Press.
Leveson, N. G. (2004). A new accident model for engineering safer systems. *Safety Science 42*(4), 237-270.
Mann, C. R. (1918). *A study of engineering education: prepared for the Joint Committee on Engineering Education of the National Engineering Societies*. Boston, MA: Merrymount Press.
McCarthy, N. (2009). *Engineering: a beginner's guide*. Oxford, UK: Oneworld.
McGilchrist, I. (2010). *The Master and His Emissary: The Divided Brain and the Making of the Western World*. New Haven, NY: Yale University Press.
National Research Council Panel on Engineering Graduate Education Research. (1985). *Engineering graduate education and research*. Washington, DC: National Academy Press.
Nietzsche, F., & Levy, O. (1933). *The Will to Power*. London, UK: Foulis Press.
Noble, D. F. (1977). *America by design: science, technology, and the rise of corporate capitalism*. New York, NY: Knopf.
Ostrower, J. (2011, Sept. 25, 2011). Boeing formally delivers first 787 to ANA. *Flight Global* Retrieved March 16, 2012, from http://www.flightglobal.com/news/articles/boeing-formally-delivers-first-787-to-ana-362515/
Owens, L. (1986). Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer. *Technology and Culture, 27*(1), 63-95.
Pawley, A. L. (2009). Universalized Narratives: Patterns in How Faculty Members Define "Engineering.". *Journal of Engineering Education, 98*(4), 309-319.
Perrucci, R. (1971). Engineering Professional Servant of Power. *American Behavioral Scientist, 14*(4), 492-506.
Petersen, E. S., Nyce, J. M., & Lützhöft, M. (2011). Ethnography re-engineered: the two tribes problem. *Theoretical Issues in Ergonomics Science, 12*(6), 496-509.
Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science, 27*(2-3), 183-213.
Reason, J. T. (2008). *The human contribution: unsafe acts, accidents and heroic recoveries*. Farnham, UK: Ashgate.
Roberts, G. (1995). *From Kendal's Coffee House to Great George Street*. London, UK: Thomas Telford Publications.
Ropohl, G. (1991). Deficiencies in engineering education. In P. T. Durbin (Ed.), *Critical perspectives on nonacademic science and engineering* (Vol. 4, pp. 278-295). Cranbury, NJ: Associated University Presses.
Salam, A., Dirac, P. A. M., Evans, J. M., & Watts, G. (1990). *Unification of Fundamental Forces: The First of the 1988 Dirac Memorial Lectures*. Cambridge, UK: Cambridge University Press.
SPEE. (1940). Aims and scope of engineering education. *Journal of Engineering Education, 30*(7), 555-566.
SPEE. (1944). Report of the committee of engineering education after the war. *Journal of Engineering Education, 34*(9), 589-614.
Sutter, J., & Spenser, J. (2007). *747: Creating the World's First Jumbo Jet and Other Adventures from a Life in Aviation*. New York, NY: HarperCollins.
Taylor, C. (2000). *Socrates: A Very Short Introduction*. Oxford, UK: Oxford University Press.

Teresko, J. (2007, Dec 1, 2007). Boeing 787: A Matter of Materials -- Special Report: Anatomy of a Supply Chain. *Industry Week* Retrieved March 16, 2012, from http://www.industryweek.com/articles/boeing_787_a_matter_of_materials_--_special_report_anatomy_of_a_supply_chain_15339.aspx?Page=4?ShowAll=1

University of Limerick. (2010). Master of Engineering in Aeronautical Engineering March 2010. Retrieved December 9, 2011, from http://www2.ul.ie/web/WWW/Services/Research/Graduate_School/Prospective_Students/Graduate_Programmes/Taught_Programmes/Science_%26_Engineering/Mechanical_Engineering

University of Limerick. (2011). LM077 - Bachelor of Engineering in Aeronautical Engineering course structure Retrieved December 9, 2011, from http://www3.ul.ie/courses/AeronauticalEngineering.php

University of the West of England. (2011). H404 - MEng Aerospace Engineering course structure Retrieved December 9, 2011, from http://courses.uwe.ac.uk/H404/2012#coursecontent

Vaughan, A. (2006). *Brunel: an engineering biography*. Hersham, UK: Ian Allan.

Vaughan, D. (1996). *The Challenger launch decision: risky technology, culture, and deviance at NASA*. Chicago, IL: University of Chicago Press.

Weisner, J. B. (1979). Vannevar Bush *Biographical Memoirs* (Vol. 50, pp. 89-118). Washington, DC: National Academy of Sciences.

Whalley, P. (1986). *The social production of technical work: the case of British engineers*. New York, NY: State University of New York Press.

Young, T. M. (2000). Aircraft design education at universities: benefits and difficulties. *Aircraft Design, 3*(4), 207-215. doi: 10.1016/s1369-8869(00)00014-8

Zachary, G. P. (1995). Vannevar Bush on the engineers role. *IEEE Spectrum, 32*(7), 65-69. doi: 10.1109/6.392806