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Chapter 7

Engineering Science as Opposed to Natural Science and Applied Science

Eugene Coyle, Mike Murphy, William Grimson

Abstract. In exploring the epistemology of engineering science we propose a *model of engineering*. This model incorporates the goals of engineering, the approach to engineering (also called the engineering method) and the role of experience in engineering. The basis for understanding the nature of engineering science will be explored, and will be contrasted with natural science. To begin, a large-scale engineering project that was successfully completed in Ireland many years ago is discussed - specifically, the development of a megalithic passage tomb as an exemplar of the engineering method in structural design, project management and aesthetics. This exemplar firmly demonstrates that engineering method existed before the development and understanding of the relevant natural science. We next contrast the nature of engineering or engineering science and natural science. This discussion will further develop the engineering model, but will contrast the philosophical differences between engineering and science. We then return to build upon the 'engineering model' through the modern day exemplar of the development of the jet engine, demonstrating that invariably multiple factors, including creative design initiatives from different sources, global, political, economic and cultural circumstance, and the passage of time contribute to the evolution and success (or failure) of large sustainable scientific and engineering projects. In conclusion, the engineering model is mapped to a philosophical model demonstrating that philosophy is as relevant to engineering as it is to other fields.

1. Introduction

Engineering has been carried out by mankind over many thousands of years; in earlier times by peoples adapting to their environment and generally providing shelter and means by which food could be grown and stored. In more modern times the concerns are the same basic ones but others have been added. It is appropriate therefore that this chapter starts with an example of engineering from the Neolithic period. Many wonderful examples of engineering from pre-history times, through Minoan, early Greek, the Egyptian and Roman periods, up to the Middle Ages, could be recounted. What remains a distinguishing feature of all the activities is that there was a definitive purpose and knowledge of ‘how to’ was gained and retained by generations of early engineers, but alas, as often as not the knowledge gained was subsequently lost. It was not until much later with increased travel and mobility of craftsmen, such as stonemasons, together with written records that knowledge started to be retained. Another feature of the progression of engineering through the centuries was that scientific and mathematical knowledge became more important if not however indispensable to engineers. Hence in time the engineering profession was founded with formal university level education programmes delivering a minimum level of knowledge and skill to graduates. Not surprisingly in all of this the difference between applied scientists, engineering scientists and engineers has been clouded and this topic is addressed in the central sections of the Chapter, where a model of engineering is presented. A 20th century engineering example follows before some concluding remarks are made.

2. Exemplar – A Successful Large-Scale Engineering Project

One thousand years prior to the construction of the Pyramids in Egypt, mankind had demonstrated an ability to solve mathematical problems, design and construct robust engineering buildings and monuments, and create items of both practical use and artistic beauty. In the latter half of the twentieth and early years of the twenty first century, there has been increased academic and public interest in post ice age Mesolithic (8000-4000 BC) and Neolithic (4000-2500 BC) archaeology and civilisation, in an endeavour to gain a greater understanding of ancestry together with an appreciation of mankind’s innate survival instincts and creative abilities.

Significant archaeological discoveries of remains across Europe, from Stonehenge and Avebury in England, to Maes Howe in the Scottish Orkney Islands, to Gavr’inisin in the Morbihan of Southern Brittany, and to the rich archaeological heritage of the Boyne Valley in Ireland, have revealed that early mankind had a scientific and observational understanding coupled with advanced engineering design capability, which enabled the creation of astronomical structures such as those used to mark sun and lunar seasonal annual cyclical alignments (Burl, 2005).

The United Nations Educational, Scientific and Cultural Organisation (UNESCO) has designated Bru Na Boinne, an area in Ireland rich in ar-

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chaeological remains, incorporating passage tombs at Newgrange, Knowth and Dowth, situated within a bend of the river Boyne, as a world heritage site. Constructed by a thriving farming community using simple tools of wood and stone during the Neolithic Age, these buildings are about 5,000 years old. The people who constructed them nevertheless had within their society expertise in architecture, engineering, geology, art and astronomy. So, what is Newgrange, and why do we make this claim?

Newgrange is a large mound or cairn, constructed of stone and covered in grass. The internal 19 metre southeast facing passage leads into a chamber with three semi-circular recesses. A cleverly designed corbelled roof covers the chamber. To construct the roof, the builders overlapped layers of large flat stones until the roof could be sealed with a capstone. The mound, constructed over 5,000 years ago, with carbon dating estimates of year of construction at 3,200 BC, is remarkable in many respects, not least that the passage tomb remains completely intact and as a result of clever design in drainage and construction techniques, rain water has never leaked into the mound and it remains dry to this day. The flat-topped cairn covering the chamber is almost 0.5 hectares in extent. Materials used in construction of the mound were transported considerable distances from both the Wicklow mountains to the south and the Mourne mountains to the north.

3. Winter Solstice at Newgrange

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One of the more significant features noted during archaeological excavations of the Newgrange Megalith in the nineteen sixties was a small window-box shaped opening located above the tomb entrance (O'Kelly, 2003). In time it became apparent that this opening is exactly positioned so that at dawn on winter solstice, December 21st, a shaft of light penetrates the opening and creeps along the passageway. For some minutes, as the sun rises in the early morning sky the beam of sunlight entering broadens and moves down the passageway, welcoming daylight from darkness into the central chambers for a few short minutes, before retreating again leaving the chamber in darkness for another year. The alignment is extremely accurate, showing that the architects and engineers who constructed the monument had full knowledge and capability in achieving their intended objective.

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To the Neolithic farmers the winter solstice marked the start of a new year, a sign of rebirth promising renewed life to crops. It is also suggested that it served as a powerful symbol of the inevitable victory of life over death, perhaps promising new life to the spirits of the dead. A further significant feature of the megalith is that of the highly decorative art work to be seen on

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many of the monument stones, with the greatest decoration to be seen on the large stone located immediately before the entrance to the chamber. Circles are the most common motifs. Spirals and tri-spirals of differing types are also to be seen, together with geometrical, curvilinear and rectilinear shapes. Interpretation of meaning in the art work is open to question, however it is believed by many that the drawings are not for decorative purposes alone, being of symbolic and perhaps hieroglyphic importance.

The Neolithic people who created this and other such monuments had clearly not received an education as we would know it, nevertheless they demonstrated ingenuity, creativity, and acquired knowledge in the use of tools and in the transportation of large and heavy stones over long distance, by sea, river and land. They had a philosophical outlook on life, with an innate understanding of astronomical phenomena and in particular they paid homage to the sun and celebrated important calendar events such as the winter solstice, with the knowledge that from this point the days would now get longer and the seasons of spring and summer would again return to replenish, feed and nourish the inhabitants of their land. In short by observation of the relative movements of the earth and the sun, followed by carrying out some form of calculation and accurately measuring distances, these Neolithic people were able to construct this impressive monument.

The creators of the megaliths were most definitely intuitive engineers. The sheer implementation of a project as large as Newgrange demanded great competence in planning, design and management. Materials had to be sourced, perhaps quarried and transported over large distances and challenging terrains. Flint and other tools suitable to the task in hand would need to have been adapted, and creative and reliable rolling and floating platforms would have been conceived and constructed to transport the large stone monoliths. It has been calculated that in addition to the 97 slabs forming the kerb (none weighing less than a tonne) and a further 450 large structural stones used to form the passage, chamber and roof, the monument consists of some 200,000 tonnes of stone. The correct alignment of the roof-box to achieve the penetration of the rising sun at winter solstice and to the illumination of the rear of the chamber, entailed considerable observational, recording and architectural skills, and was a spectacular feat. How did such a monument come into existence? It has been conservatively estimated that the entire monument could have been constructed by a well organised work force of some 400 people, abandoning their agricultural activities for some months after their spring sowing over a period of up to twenty years (Flanagan, 2003).

One could argue that the creators of such monuments were empiricists, their knowledge being derived from experience and reflection over several decades if not hundreds of years and passed from generation to generation. Were they pragmatists, demonstrating that a proposition is measured by correspondence with experimental results and its practical outcome? They most definitely had a philosophical outlook upon life, the hereafter, the forces of nature and the mysteries of existence. Indeed one could readily compare and draw parallels between the Neolithic passage tombs and the historically more recent creations of the world's most famous temples, mosques, synagogues, cathedrals, and other places of worship, from the Pantheon in Rome to the Blue Mosque (Mosque of Sultan Ahmet I) in Istanbul, the Cathedral of Notre Dame in Paris to Gaudi's Sagrada Familia in Barcelona.

In addition to seasonal movements of the sun, early Neolithic people grappled with gaining an understanding of the intricate cycles of the moon's movements, a field of study which later occupied the mind of the great Sir Isaac Newton (1642-1727), albeit with more profound scientific importance to the accumulation of humanity's knowledge base, proffering an explanation of and describing planetary motion and the complexities of the universe. What we note here is that their engineering achievements far outweigh their scientific achievements, and indeed that such engineering achievements preceded the scientific understanding of the nature and movements of the earth, moon and stars.

As an endnote, and striking a particular resonance with what has just been described, it is worth noting that by the year 1500 AD, builders would still construct remarkable structures without what today we would think of as a scientific underpinning to their methods. Consider for example the very beautiful vaulted roof of King's College chapel in Cambridge, England. The span of the roof is approximately 15 meters and the thickness is a remarkable 10 centimetres only: an amazing eggshell-like tour de force. Even today structural engineers are trying to fathom the secrets of the stonemasons who could carry off such a feat. John Ochsendorf, a structural engineer at Massachusetts Institute of Technology, using computer methods and graphics can now provide the engineering science justification – but some 500 years after the event (Ouellette, 2006). Another outstanding example would be the creation by Brunelleschi of the dome of the Cathedral of Florence, see Chapter 1.

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4. A Model of Engineering

Philosophy aims to make sense of the world we live in, whilst engineering aims to work with what knowledge is available to achieve society's goals, a point stressed in Chapter 4. Good engineering practice is built on the experience of applying existing knowledge together with suitable design paradigms or heuristics to produce 'outcomes' which in time contribute to 'experience' leading to knowledge refinement. This could be called evidence-based engineering.

The historical approach taken by engineers to arrive at an engineering solution to a problem, however large or small, has been to develop a model of the required system. The solution, of course, cannot be divorced from the ‘purpose’ and general objectives of the enterprise. To be equipped with the required skill set to solve the problem, or design and implement the system, a knowledge base is required. This knowledge base will most likely by necessity be multidisciplinary and, depending on the nature of the problem to be addressed, may need to be regularly enhanced and improved upon. Having the required body of knowledge, the engineer is equipped to implement or develop the design tools necessary to achieve the required outcomes for the project in hand. Through time, experience is gained enabling knowledge to be refined which will further enhance system design capabilities (Figure 1).

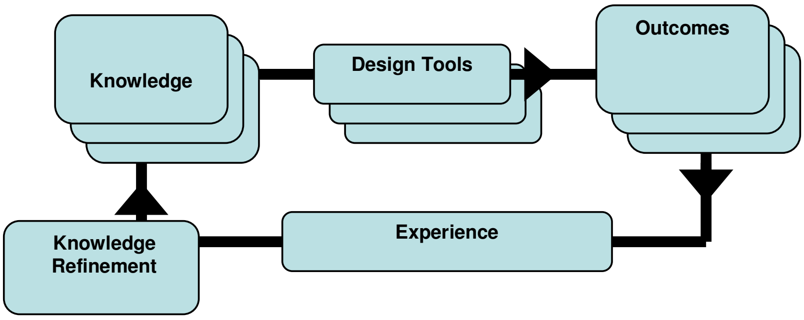

Figure 1 A Model of Engineering

As is pointed out later, whilst knowledge can be viewed as being central to the design process the context in which that knowledge is selected and used is also of necessity a function of many other philosophical aspects including ethical and aesthetical considerations.

5. Association of Science and Engineering Science

The word ‘engineer’ is derived from the Latin *ingeniatorem* meaning one who is ingenious at devising, whilst the word ‘science’ is derived from the Latin word *scire*, meaning to know. The term ‘science’ is of multivaried connotation and has universal acceptance in today’s world. On the one hand, science refers to the system of acquiring knowledge, based on empiricism, experimentation, and methodological application. Science further refers to the organized body of knowledge humans have gained by applied research. Engineering on the other hand is generally concerned with the creation and use of technology to the solution of practical problems. An illustrative quotation attributed to Theodore Von Karman (1881-1963), the esteemed aerospace engineer, highlighting the fundamental difference between the scientist and the engineer proffers that "scientists discover the world that exists, whilst engineers create the world that never was." At its core, the scientist asks and answers the question ‘why’ whereas the engineer will ask and answer the question ‘how.’ Engineers are interested in science to the extent that it can illuminate the methods by which problems can be analysed or modelled in order to offer an approach to a solution. Engineering science then is that part of science which provides the engineer with the physical and mathematical basis to solve engineering problems.

The pursuit and publication of scientific knowledge has purposely developed in such a way that there is little ambiguity in the meaning and verification of scientific statements. There is an accepted objective approach to both the language of science and its notation. Further, scientific method ensures that scientists know the right method or procedure to verify the statement, usually by collecting and analysing evidence that either supports or refutes the statement (Wilson J, 1968). Hence the development of the “scientific method” to elicit scientific knowledge, or truth. According to Einstein “the development of Western Science is based on two great achievements, the invention of the formal logical system (in Euclidean geometry) by the Greek philosophers, and the discovery of the possibility to find out causal relationship by systematic experiment (Renaissance)” (Price, 1975).

6. Historical Evolution of Engineering

The evolution and development of engineering has been closely aligned to fundamental developments in mathematics, in the first instance by eminent scholars such as Jean Baptiste Joseph Fourier (1768-1830), Leonhard Euler (1707-1783) and David Hilbert (1862-1943). Ingenious techniques were developed which could be applied to the solution of practical problems and in so doing would further explain the underlying nature of natural phenomena. These mathematicians developed powerful new analytical tools which were applied to elicit scientific truth.

In the more specific evolution of electrical and mechanical engineering, developments by James Clerk Maxwell (1831-79) and Sir Joseph John (J.J.) Thomson (1856-1940) in the science of electromagnetism and electrodynamics were to be of significant importance. These theoretical scientists developed applied mathematical concepts and provided the necessary tools to later mathematicians, physicists and engineers who would advance conceptual knowledge and understanding in electrical and electronic engineering one hundred fold. There also developed a need for an important category of electrical engineering scientist who ‘translated’ theory into understandable language that the inventors and empiricists could then exploit (Weber E, 1994).

These engineering scientists, or rather what we call today theoretical engineers, were the people who could bridge the gulf between the theoretical scientist and the literate, practical engineer. For these theoretical engineers, mathematically demonstrated truth takes precedence over practical considerations or experience. They perform a scholarship of integration (Boyer, 1990). Examples include Oliver Heaviside (1850-1925), Charles Steinmetz (1865-1923), and Dennis Gabor (1900-71).

Last but not least, ‘practical’ engineers have applied their creative skills, seeking to find practical solutions and applications, with inventiveness their driving goal. Pioneers such as Thomas Edison (1847-1931), Nikola Tesla (1856-1943), Lee de Forest (1873-1961) and Jack Kilby (1926-2005) applied both theoretical and exhaustive trial-and-error approaches to the solution of problems, paving the way to the advanced technological age we are part of today.

It would be fair to say that science and engineering have developed as interdependent activities and today there is a strong symbiosis between the disciplines. Beven argues that “*science is dependent upon technology to develop, test, experiment, verify, and apply many of its natural laws, theories and principles, whilst technology is dependent upon science for an understanding of how the natural world is structured and how it functions*” (Beven, 1996). Snow in his classic treatise on the different cultures associated with science and literary intellectuals, suggests that engineering is a ‘branch of science’ in that “the scientific process has two motives; one to understand the natural world, the other to control it” and he refutes the attempt to draw a line between pure science and technology arguing that an engineer designing an aircraft “goes through the same experience – aesthetic, intellectual, moral – as though he were setting up an experiment in particle physics” (Snow, 2004). Beven on the other hand contends that “technology is much more than applied science and science is quite different to applied technology” (Beven, 1996).

The eminent physicist J.J. Thomson made a clear declaration of the independent importance of scientific research when he declared “*by research in pure science I mean research made without any idea of application to indus-*

trial matters but solely with the view of extending our knowledge of the Laws of Nature" (Weber R, 1973).

Science is the discovery of knowledge, a framework to discern the 'laws of nature,' and there is only one such set of laws to discover. On the other hand, the engineer, using the engineering method, is free to create any solution that meets the design requirements and constraints. The 'output' of the engineer is therefore more arbitrary.

The term 'applied science' is at times introduced to explain how engineering and science are linked. The approach usually taken is to argue that engineering takes the knowledge discovered by science and applies it to solve problems for the benefit of society. Snow argues that industrialization, which enabled mass job creation, was the result of the 'applied science' of engineering (Snow, 1998). Hendricks on the other hand suggests the engineering science is not literally nor solely 'science applied', but constitutes a field of its own, with its own methods that produces its own knowledge independent of natural science or applied science. Hendricks further suggests that there is a difference in the epistemological and ontological assumptions between pure science and engineering science partially based on a difference in cognitive values governing their respective enterprises (Hendricks, 2000). Chapter 4 also points out the 'wider than science' characteristic of engineering.

Snow considers that engineers are applied scientists. He is of the view however that while pure and applied scientists belong to the same scientific culture, the philosophical gaps between them are wide, to the extent that pure scientists and engineers often totally misunderstand each other. "*We prided ourselves that the science we were doing could not, in any conceivable circumstances, have any practical use. The more firmly one could make that claim, the more superior one felt*".

Science is the discovery of knowledge, a framework to discern the 'laws of nature,' and there is only one such set of laws to discover. For example, the second law of thermodynamics is the second law of thermodynamics independent of the discoverer. Had Einstein not developed his theory of relativity, then the credit for the same discovery would eventually have rested with another physicist. Thus "*even if science is philosophically a process of generalisation and invention of laws, nature appears very strongly to act as if there were only one world to discover*" (Price, 1975). On the other hand, the engineer, using the engineering method, is free to create any solution that meets the design requirements and constraints. The output of the engineer is therefore more arbitrary.

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10 · *Engineering Science as Opposed to Natural Science and Applied Science*

Engineering science is different than science for three principle reasons. Firstly, there is a different purpose in what the scientist seeks to do, compared to what the engineer seeks to do. For engineering science the only criterion is that it be adequate for the underpinning or understanding of the relevant discipline, whereas science demands accuracy and precision to determine which of competing theories should be preferred. Secondly, the presuppositions for science are different than they are for engineering. Science is the discovery of knowledge and science presupposes that there is only one such set of laws to discover. Engineering presupposes that nature is capable of manipulation and modification. Thirdly, economic and social considerations play a much more important role in engineering than in science (Rogers 1983).

From a scientific perspective, engineering certainly stands alone as its *own* discipline, and may be characterised by an extension of the paradigm concept of the influential philosopher Thomas Samuel Kuhn (1922-1996) to that of a technical matrix, which sets the standards and authority for legitimate engineering work. In development of his paradigm concept, Kuhn points out that a mature science experiences alternating phases of ‘normal science’ and ‘revolutions’. In normal science the key theories, instruments, values and metaphysical assumptions that comprise the disciplinary matrix are kept fixed, whereas in a scientific revolution the disciplinary matrix undergoes revision, in order to permit the solution of the anomalous puzzles that disturbed the preceding period of ‘normal’ science (Kuhn, 1970). Considering science as an entity, Kuhn contends that the engineer is working within a specific technical matrix and is practicing engineering, subject to engagement in and operation of a defined set of conditions, including:

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1. procedures and methods for delimiting a set of research objects
2. epistemic and ontological assumptions
3. theoretical structure
4. experimental structure (and experimental techniques)
5. methods
6. values
7. exemplars and research competence

An engineering matrix is substantially ‘externalistic’ and may stem from either: (1) new theoretical discoveries either adopted from pure science or engineering science itself, (2) practical challenges while constructing new artefacts (like bridges), and (3) possibilities linked to new tools (like powerful computational abilities).

The term engineering embraces a wide church in today's world and each discipline of engineering contains an extensive body of knowledge associated with that discipline. Some knowledge may be related to an underlying science which supports the discipline. Other knowledge may be based solely on theories developed from engineering practice; a good example being control systems engineering. In all cases the application of the body of knowledge should enable the engineer to design a solution to a problem in their discipline (Rogers, 1983).

One form of knowledge, called the engineering method, relies on heuristics (from the Greek word 'to find') to guide in the engineering design process. Since the core of engineering is the design process, such heuristics are therefore of high importance to the engineer. This point is also made in Chapter 5 where 'design is considered to be the central activity that defines engineering and distinguishes it from science.'

With the development of engineering disciplines, engineers have added many important 'heuristic tools' to the engineering toolbox. These tools include:

- Engineering judgement
- Failure analysis
- Risk assessment (see Chapter 12)
- Impact assessment (not just environmental)
- Trial and error
- Standards and Codes and Factors of Safety
- Rules of Thumb and Orders of Magnitude

As with the creative inventions of early Neolithic craftsmen and throughout historical time since those eras, engineering science has relied on heuristics to both simplify and enhance the engineer's design work. Heuristics used may on occasion be in conflict, may lack accuracy and may indeed lack solid underpinning of scientific justification. However, the heuristic combined with the engineering judgement borne of experience of when that heuristic can be applied provide an important tool to the engineer. Here the engineer is supported by the collective experience of all the engineers who went before. To quote the French author Albert Camus (1913-1960): "*You cannot acquire experience by making experiments. You cannot create experience. You must undergo it*".

The question is sometimes raised as to whether science and engineering science contain the same ethical challenges for scientists and engineers. Ethics, the study and philosophy of human conduct, at first consideration might appear to pose greater challenges to those who apply scientific knowledge (engineers), than to those who seek that knowledge (scientists). Either way, as Chapters 11, 12 and 13 illustrate, ethics certainly is of huge importance to engineers and engineering.

Technological development has been one of the greatest single engines for change and development within society. Technology affects society in two ways: firstly through the means of production adopted by that society and secondly through the devices that technology puts at the disposal of society (Rogers, 1983). An example of the former would be clean room technology and an example of the latter would be integrated circuits that enable the storage and transmission of huge amounts of data. We must distinguish here between the collective ethical problems faced by society and the professional ethical problems faced by the individual engineer. Society's use, or non-use, of the devices that technology puts at its disposal is part of the set of collective ethical issues. Koen proposes that the engineering method, rather than the use of reason, is the universal method, in that it is the "strategy for causing the best change in a poorly understood situation within the available resources". Koen goes further and suggests that "to be human is to be an engineer" (Koen, 2003). The individual engineer however, in following the engineering method to solve a problem, has responsibilities to his/her employer, profession and to the public, and must be cognisant of the ethical issues attaching to and emerging from the fruits of their endeavours. In short, ethical considerations must be added to the list of constraints with which the engineer must grapple in arriving at a solution.

7. A Second Exemplar – The Development of the Jet Engine

As discussed earlier 'engineering' is a complex set of activities that an individual, but more often a team, undertakes in order to achieve a goal. To build long span bridges, develop and make operational satellite communications systems, introduce a new jet aircraft, produce ever more powerful computing resources, design and manufacture controllable artificial limbs, by way of example, all require a huge investment of intellectual effort if the objectives are to be satisfactorily met. The effort involves the judgement as to what knowledge is required – the knowledge typically would include but not exclusively a combination of science, technology, mathematics and what might be termed engineering 'know-how'. And in many cases new knowledge must be acquired if the 'project' is to proceed.

This then is the start of the process! Within the design phase many other factors might have to be taken into account, be they financial, environmental, aesthetical, sociological, or the urgency of finding a solution in face of a threat or competition. It is here that engineering is akin to a juggling or a balancing act requiring a marshalling of knowledge and effort whilst working within a set of constraints. Following any implementation evaluations are carried out. Even if and when there has been a total or partial failure, valuable information accrues from having performed an evaluation.

The knowledge so gained might be primary knowledge such as a hitherto unknown behaviour of a material or it might be knowledge as in an improved design heuristic or a more refined approach to dealing with constraints. All of this might be termed evidence-based engineering: a phrase borrowed from medicine which it may be said has many of the characteristics of engineering. There is though another aspect that might be mentioned where a new paradigm is invented or introduced. Thomas Kuhn in 'The Structure of Scientific Revolutions' surmised that it was the young or those new to a field who introduced new paradigms being either uncommitted or unfamiliar with conventional and established views and therefore 'free' to make new rules (Kuhn, 2003). Kuhn also stressed that scientific and technological developments had impulses that were sociological in nature. One example that briefly illustrates all of the above is the invention of the jet engine.

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Frank Whittle and Hans von Ohain are generally acknowledged to be the two independent inventors of the jet engine and they came to prominence via two very different routes. Frank Whittle was born in Coventry, England, and joined the Royal Air Force, in the UK, as an apprentice in 1923. Apart from becoming a good mechanic he learnt to fly and was rated as an above average pilot. Subsequently he was selected for, and passed with distinction, the Officer's Engineering Course in 1933 and thence to Cambridge University where he was awarded a First Class Honours in Mechanical Sciences in 1936. The route taken by Whittle was exceptional and indicated that the RAF had spotted a special and young talent. Hans von Ohain on the other hand was born in Dessau, Germany and studied Physics at the University of Gottingen where he graduated with a PhD in 1935 and then became a junior member of staff at the university. What is of some significance in how events in the development of the jet engine would unfurl, particularly from a commercial perspective, was that Whittle and von Ohain were on opposite sides during World War II.

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A point that should be stressed is that ideas seldom come out of a vacuum – others will generally have made some contributions along the way. Of note is the work of Sir Charles Parsons (1854-1931) who revolutionised marine transport through his work on steam turbines. His first and influential experimental boat, the Turbinia could travel at 34 knots, and this was in 1897. The working fluid might have been steam but an important contribution had been made. And of course there were others too – the work of the Norwegian

Jens William Ægidius Elling (1861-1949) being one almost forgotten contribution.

8. Types of Jet Engine

To set the context a brief description of the main types of jet engines follows. The commonly used classification is to consider five engine types: Turbojets, Turboprops, Turboshafts, Turbofans, Ramjets (Bellis). Very briefly, the Turbojet consists of an opening for the intake of air at the front of the engine, the air is then compressed by a vaned rotating compressor following which fuel is added, and the air-fuel mixture ignited in a combustion chamber and exhausted at high speed through a nozzle via a turbine which provides the power through a shaft to operate the compressor. The thrust or reaction is a function of the mass flow and speed of the exhausted hot gas or jet. The underlying scientific principle regarding this thrust being Newton's Third Law. In the case of Turboprops the turbine is connected by a shaft to a propeller which provides the thrust and is used mostly for small aircraft operating at low to medium altitudes.

Turboshafts are similar to Turboprops but are usually associated with helicopters where the shaft connects via a gearbox to rotors for propulsion and lift. Ramjets are the simplest of all with no moving parts. Air is taken in, thus requiring the engine to be already moving at some considerable speed relative to the still air, following which by constriction the air is compressed, fuel added and ignited to produce a hot and fast exhaust stream. The Ramjet is largely confined to experimental and military operations. The most important jet engine now, commercially, is undoubtedly the Turbofan type. The major difference between the Turbojet and the Turbofan is that the latter has an additional element which is a fan, often very large, at the intake which facilitates improved air intake. The power for the fan is provided through a shaft driven by the engine's turbine. So, in summary, with a Turbofan the air is taken in with the aid of a fan, compressed, then has fuel added and ignited in a combustion chamber. The hot gas is then directed through turbines which power the compressor and fan, and is finally exhausted at both a high temperature and speed in a jet stream through a nozzle thus providing the thrust. Of course there are variations on the above themes such as adding fuel at the final stage – afterburn – to provide additional thrust, and the use of a bypass whereby not all of the hot exhausting gas is directed through the turbines. Nevertheless what has been described sums up the main features of the operation of jet engines. But to produce a working jet engine, and subsequently throughout an extended period of time gradually improve its performance, is a story of engineering endeavour laced with politics, commercial cut-and-thrust and of course the interactions between a range of influential personalities. Frank Whittle was one of the key personalities involved.

9. The Engineering Challenge

The problems in moving from the initial concepts that Whittle had articulated to having a useful engine were manifold but they were almost entirely engineering rather than scientific. What were these challenges? The key challenges were first to build a satisfactory compressor and then a turbine that could operate at both high rotational speed and high temperatures. When all the engine components were brought together in a logical linear arrangement the earliest designs were considered too long: the problem was that of maintaining stability of the shaft linking the turbine to the compressor together with some thermal expansion related issues. Whittle's solution was to propose a radial or centrifugal rather than an axial compressor which resulted in a shorter engine length, but at a cost. The manufacture of a centrifugal compressor including its housing was intrinsically more difficult as the design required forcing the air through a number of bends necessitating difficult and hence highly skilled metal work. The high temperature problem for the turbine and its blades also needed to be addressed both by the use of new materials and through the use of holes providing a cooling stream of air. And the high rotational speed of the turbine meant that the mechanical design and the subsequent manufacturing problems were challenging. Against this background, work in thermodynamics, compressibility (of the fluid - air), aerodynamics, suitability of fuel, not to mention lobbying to provide the finances and resources to undertake the overall project, continued in what was now a country preparing for war.

Hans von Ohain's solution to the compressor problem was also to adopt a centrifugal compressor but he positioned the turbine directly next to the compressor. This resulted in an engine that was very large in diameter but short along the thrust axis (*see* Wikipedia, *Hans von Ohain*). The end result, at that stage, for von Ohain was that the engine based on his work powered the Heinkel He 178 machine and this was the first jet powered aircraft to fly on August 27, 1939.

Returning to Whittle, what was to work to his advantage was that he had both a good idea and a personality that helped win over sceptics. As recounted by Nahum in his book *Frank Whittle – invention of the jet,* the complex discussions that took place between the inventor, the RAF, the Air Ministry, the Ministry of Aircraft Production and later with commercial organisations that included Rover, Rolls-Royce and de Havilland, would have scuppered anything other than a genuinely good potential enterprise (Nahum, 2004). After much maneuvering Whittle succeeded in establishing a company called Power Jets Ltd. However this company did not have the resources or experience necessary to be able to go into the production of jet engines. Eventually the British Government acquired the assets of Power Jets Ltd in 1944. In due course engines based on Whittle's designs powered the Meteor and proved more reliable than their German counterparts; additionally the British engine had superior maintenance characteristics, as well as markedly better power-to-weight ratio and fuel consumption figures. As a result Whittle's input turned out to be more influential. Subsequently, even though von Ohain could claim a 'first', by dint of hard work and powerful lobbying Whittle's designs and their 'children' combined with 'Britain's superior high-temperature alloys and engineering expertise resulted in engines that led the world in performance for the next decade' (*see* Wikipedia, *Frank Whittle*).

Continuing the story of the engineering aspect of the 'enterprise', unknown to Whittle the Rover engineers had decided to abandon the concept of the centrifugal compressor and instead developed an axial compressor. This work involved much ingenuity involving finding solutions to the very problem that Whittle had sought to circumvent, namely the length of the shaft coupling the turbine to the compressor. The secrecy in which this work was carried out did not help collaboration and the subsequent dispute was settled on the basis that the W.2B engine based on Whittle's design and the Rover engine using an axial compressor could both be produced. History records that the axial solution was the winner. Subsequently when Rolls Royce became the main producer, taking over the Rover Plant, the main effort went into the 'straight-through' version. In time and partly because of the events in the 1940's Rolls-Royce became a key provider of engines and in 2006 is the World's number one supplier of large turbofans and the number two engine maker overall. In some respect, therefore, they were the main beneficiary of Whittle's invention. But companies in the US were also to benefit.

10. The Commercialisation of the Jet Engine

Two factors contributed to a major shift in utilizing the expertise in jet engines that had been gained by the end of the war and applying it to civilian use. First, the British, as part of the pre-cursor to the Lend-Lease agreement of 1941 by which the US provided much needed war material to Great Britain, had shared with US engineers the design specifications of their jet engines (essentially the Whittle inspired design). This provided an important impulse to proceedings in the US where it was recognized that the quickest way forward was to make use of the hard earned engineering experience gained by

Whittle and others in England. Great Britain ended the war in an exhausted state whereas the US was in a better position to capitalize on technologies developed in the 1940's having been in a somewhat dormant state throughout the Depression. Second, the lead that Britain had or could have had was effectively eliminated due to the Comet disaster. The Comet aircraft had Rolls-Royce turbojet engines, built by the de Havilland Engine Company, and these engines were based on Whittle's designs. The aircraft entered service with BOAC in May 1952 as the first commercial jet airliner (*see* RAF museum, 2006).

Within two years of commencing service two Comet aircraft disappeared, the fleet was grounded and an investigation launched. It transpired after a careful investigation that the cause was metal fatigue causing a crack that had grown with the repeated cycle of cabin pressurisation and de-pressurisation in each flight. There were lessons to be learned and passed on to other aircraft manufacturers. Whilst the jet engines were not the cause of the disaster the impact on engine design and the manufacture of jet aircraft in Great Britain was profound and leadership passed to the US. With commercial power now in the hands of companies in the US, Rolls-Royce found it difficult to sell its engines into an American dominated market. In time, though, and after being rescued by direct State intervention, Rolls-Royce Engines survived and grew to its present impressive position in modern jet engine design and manufacture.

Currently some of the preoccupations of jet engine design engineers reflect environmental and sociological aspects in terms of fuel efficiency and noise reduction. The direct descendent of Whittle's designs in the form of the turbofan jet engine with its large fan, very obvious to all air travellers, and the near optimum use of a turbine bypass, have certainly made engines more efficient and quieter. What is astonishing in many respects is that a systems sketch of a modern jet engine is so similar to ones of over sixty years ago.

Regarding the fuel, to some extent the early jet engines were insensitive to the type of fuel, but as time marched on a number of factors influenced choices. Factors that had to be considered included: losses due to evaporation at high altitudes; risk of fire during handling on the ground; fire risks following a crash. Kerosene-type fuels are now the most common types throughout the world, though there are some exceptions such as in very cold climates (*see* Chevron 2006). This is a typical aspect of engineering where additional constraints have to be taken into account brought about by wider considerations, mostly related to safety in this particular case.

So whilst the basic idea of the jet engine has stood the test of time the 'invention' and ingenuity of engineering has focused on improving designs, using new materials such as ceramics in the hostile turbine environment, adopting new manufacturing techniques, reducing the maintenance downtime, and extracting as many benefits as possible from the use of computers in modelling the controllability as well as the thermodynamic and aerodynamic behaviour of the engine. The story of the development of the jet engine reinforces the model of engineering as one in which science, mathematics and technologies are brought together with the objective of producing some physical system through applying practices that have been proven in the same or other similar fields. And improvement comes following careful evaluation of the systems so designed and produced to a set of criteria that as often as not grow in time.

Rolls-Royce inherited a great idea from Whittle and turned it into a commercial success. The manufacturers in the US also inherited the same great idea and they have always acknowledged the role played by Whittle. Following early visits to the US by Whittle the American engineers expressed their gratitude for his open and constructive discussions in which a number of technical problems were solved or at least progressed. Much later, in recognition of his contribution Whittle was made Professor at the U.S. Naval Academy and with von Ohain was awarded the Charles Stark Draper Prize of the National Academy of Engineering in 1991. In 1977 Whittle had been invested in the International Aerospace Hall of Fame eventually and deservedly followed by Hans von Ohain in 1982.

11. The Engineering Model Re-Visited

As portrayed in the story of the jet engine, there are many factors that contribute to the evolution and development of large scale engineering design projects. Considering again the outline engineering model described in Figure 1, one may further link this Model of Engineering to one of Philosophy. Epistemology, indeed Logic, Ethics and Aesthetics are fundamental to the creative design processes essential to good engineering practice. Knowledge in engineering, science and technology has grown through the additions of the activities of engineers, not alone in the increasingly shared global experience of recent decades, but over hundreds and indeed in some instances thousands of years, as with the creative methodologies applied by Neolithic people, outlined earlier. Logic is a fundamental tenet of engineering subject matter, and of mathematics and science, forming the basis of rational calculation and acting as a foundation for good design practice. Good ethical practice in the engineering and scientific professions is of increasing importance to every aspect of modern day living. However it is the design process that most heavily can be characterised in terms of Philosophical perspectives.

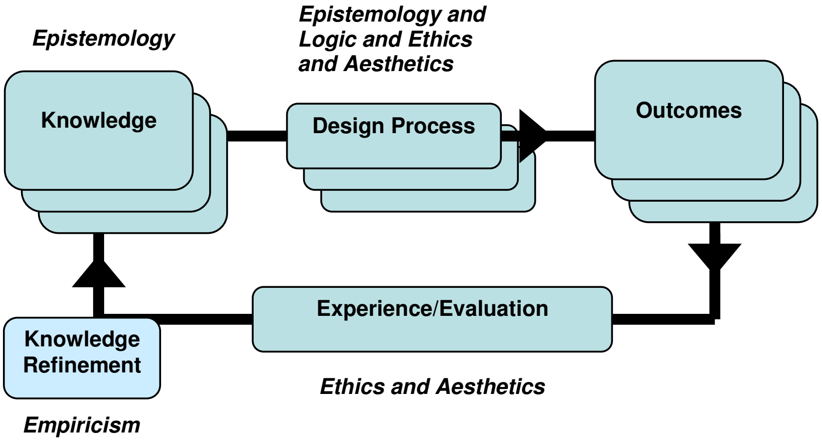

Figure 2 A Model of Engineering: Links to Philosophy

Sustainability, renewable energies, environmental impact, climate change, welfare of the planet, population increase: these are topics which impact at all levels on every nation and community in today's world. The engineering and scientific professions will be central partners to the core of the debate as to how these major humankind issues may be addressed, what solutions can be found and how best they may be implemented. Just as for ethical considerations, aesthetics is no longer a soft option or lip-service addendum to the engineering design portfolio. As with architectural design, aesthetic application and appropriate use of sustainable materials in the design process are both essential and fundamental to the teaching and practice of engineering.

12. Conclusion

Engineering, through its core activity of design, is heterogeneous in nature. It benefits from multi-disciplinary skills and yet it can also accommodate differences in approach to the same issue, such as for example different building codes in different countries, what Hendricks has termed poly-paradigmatic, whereas science is typically mono-paradigmatic (Hendricks, 2000). Over the last fifty years, engineering has strongly leveraged the tools of science and mathematics as its disciplines have become increasingly specialised. We have perhaps reached a nexus where society's problems demand that engineers exhibit horizontal multi-disciplinary skills rather than vertical specialist skills. Engineering educators respond with the concept of the renaissance engineer, or the entrepreneurial engineer. "In times of social stability, it is the specialist who best contributes to society by driving deeper into a given discipline. However, times of great flux call for those who can cross disciplines, who can see and understand the larger picture" (Akay, 2003).

Modern engineers are educated professionals to whom society entrusts the development of new technologies for the benefit of that society. Engineers accept that trust and conduct their enterprise through a range of ingenious activities, called the engineering method, while adhering to a code of ethics to themselves, their profession and to society.

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