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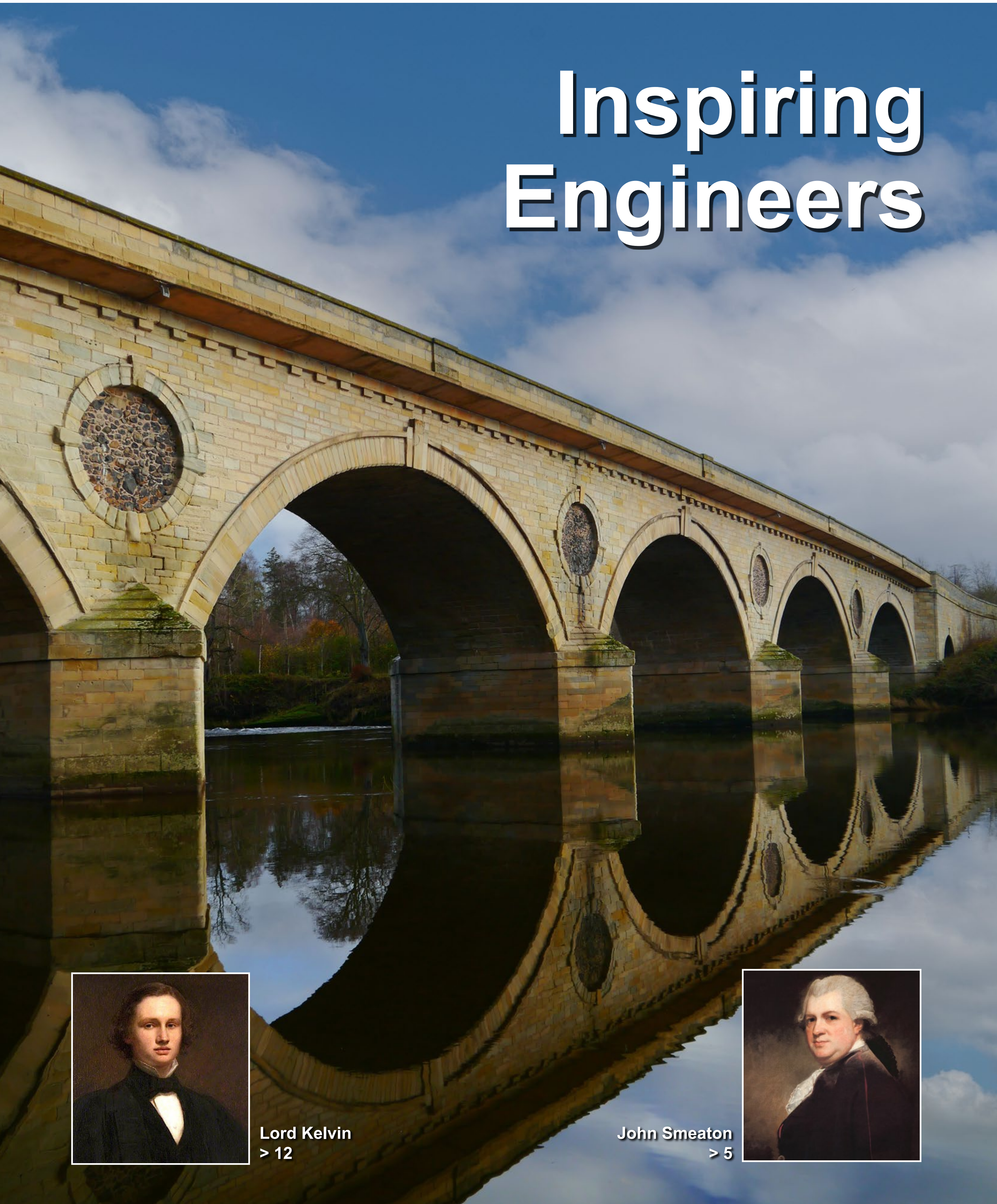

Inspiring Engineers

Lord Kelvin
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John Smeaton
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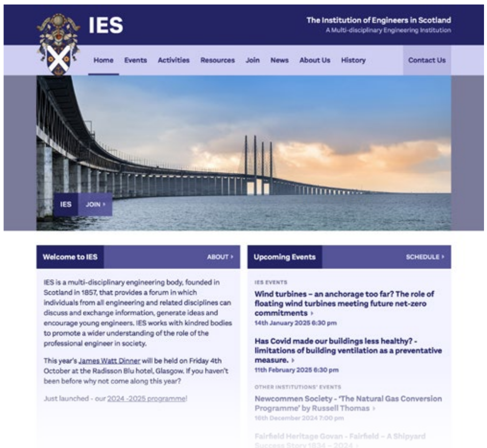

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The papers express the opinions of the authors and do not necessarily reflect the views of IES.

Copies of the journal may be obtained from the secretary for £60 inclusive of postage and packaging. Any advertising enquiries please send to the above address.

The editorial team for this edition was: Laura Clow and Andy Pearson.

The articles that were presented at an IES evening meeting have a QR code in the heading that links to the YouTube recording of the talk.

The articles in this edition of the Institution of Engineers in Scotland Journal are mainly drawn from the presentations delivered to the Institution's evening meeting in the preceding session. These are augmented by two significant milestone celebrations, the 300th anniversary of the birth of John Smeaton, recognised as the first person to describe their profession as "Civil Engineer", and the 200th anniversary of the birth of William Thomson, better known to the world as Baron Kelvin of Largs, who served as Professor of Natural Philosophy at the University of Glasgow for more than fifty years.

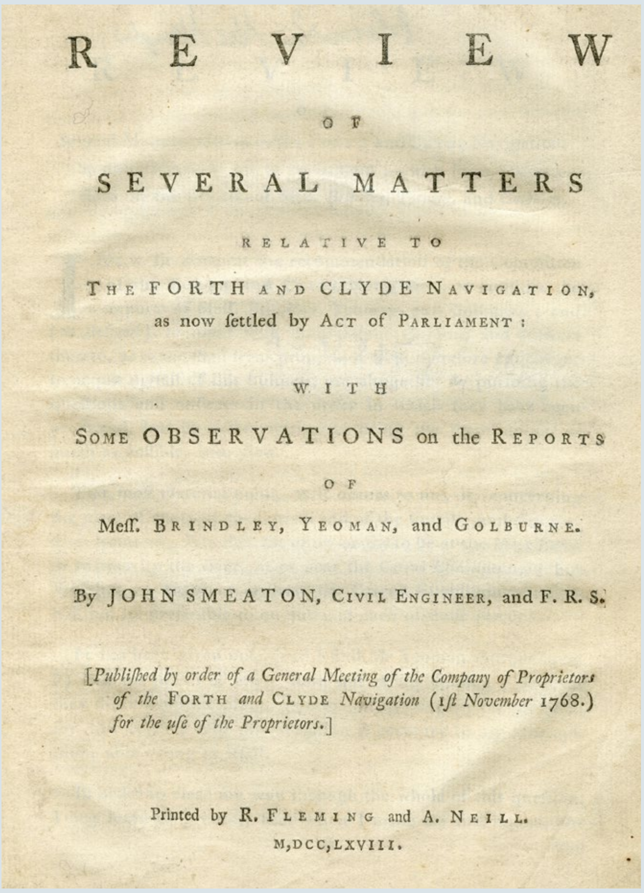
Thinking about these two giants of the engineering world in the context of the evening talks last session led naturally to the theme of this year's Journal – "Inspiring Engineers". Smeaton and Kelvin, as pioneers in a variety of fields, have inspired generations of engineers who saw what they had achieved and used that as the springboard to further development. Kelvin's range of academic interest was incredibly broad but he was also a gifted musician (a founder member of the Cambridge Musical Society) and a keen oarsman with a love of language and a highly developed sense of mischief. Smeaton, too, covered a wide range of topics including the design and construction of lighthouses, canals, bridges and harbours, but he also investigated improvements in the efficiency of Newcomen's steam engine and studied the relative performance of overshot and undershot water mills and windmills.

The accounts here of the evening talks show inspiration in several other forms, including bioinspired engineering which draws on the lessons we can learn from the natural world, presented by Professor Adam Stokes, and an account of the truly inspirational Crossrail Project, now known as The Elizabeth Line, given by the former CEO of Crossrail, Mark Wild. The intersection of the worlds of engineering and mathematics is explored by Professor Chris Dent who demonstrates that mathematical thinking can provide inspirational insights to engineers, often by making things simpler rather than more complex. Professor Raffaella Ocone, who is President-elect of the Institution of Chemical Engineers, presented a challenging and thought-provoking lecture on Engineering Ethics, drawing inspiration from the last 3,000 years of philosophical thought but also keeping the subject up-to-date and relevant by drawing on recent examples from the present day.

Looking to the future we also have a short piece by Jemma Quin, one of the Institution's Council members, who has self-published a series of illustrated story books for young children that explain to a young audience how she was inspired to follow her career as a Chartered Civil Engineer specialising in temporary works.

To maintain the spirit of the Institution's transactions, which date back to 1857, we have tried to capture the essence of the discussion that followed each of the evening talks, in a question and answer session. This is often the most fascinating part of reading our transactions from 150 years ago or more as it gives an insight into the way the audience thought about the subject and can show what motivated them to develop new ideas. We hope that readers of this volume of our transactions will still find inspiration in 150 years' time. In the shorter term you are invited and encouraged to attend next season's lectures because being present for the discussion is definitely more powerful inspiration than reading a sterile account of it long after the event.

Andy Pearson


REVIEW

OF

SEVERAL MATTERS

RELATIVE TO

THE FORTH AND CLYDE NAVIGATION,
as now ſettled by ACT of PARLIAMENT:

WITH

SOME OBSERVATIONS on the REPORTS

OF

Meſſ. BRINDLEY, YEOMAN, and GOLBURNE.

By JOHN SMEATON, CIVIL ENGINEER, and F. R. S.

[*Publiſhed by order of a General Meeting of the Company of Proprietors of the* FORTH *and* CLYDE *Navigation* (*1ſt November* 1768.) *for the uſe of the Proprietors.*]

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IES Journal of Engineering, Vol 163, 2024, Paper 1719
The Institution of Engineers in Scotland

John Smeaton – an Engineer who transformed Scotland

Professor Gordon Masterton

Professor Gordon Masterton served as President of IESIS (now IES) from 2010-12. He is Professor Emeritus of Future Infrastructure of the University of Edinburgh; a Past President of the Institution of Civil Engineers, Past Master of the Worshipful Company of Engineers, Past Chairman of the Construction Industry Council, and was a Director of Babtie Group and then Vice President of Jacobs Engineering until his first retirement in 2015. He founded the Scottish Engineering Hall of Fame in 2011, has chaired the ICE Panel for Historical Engineering Works since 2013 and is a member of the Smeatonian Society.

Introduction

Material for these reflections on John Smeaton's influence on the engineering of Scotland has drawn freely from various talks and seminars held across the country during the 300th anniversary year of his birth, in particular:

On 4th June, a talk on Smeaton's engineering in Scotland was given to IES at Firhill Stadium by Chris O'Connell, Heritage Manager of Scottish Canals and Professor George Fleming, President of the Institution of Civil Engineers in 1999-2000 and President of the Smeatonian Society in 2023. It was chaired and introduced by IES Past President, Andy Pearson.

On 4th September, a Smeaton300 Symposium was held at Heriot Watt University with a talk given by IES Past President Gordon Masterton on "Smeaton's Enduring Influences: Science, intellect and experimentation".

Professor Gordon Masterton

On the 8th June 1724, John Smeaton was born in Whitkirk, Leeds. He was to become one of the foremost engineers of his era, across a broad range of applications in what we choose to regard today as different engineering disciplines. But in Smeaton's time, all engineering that wasn't military engineering was simply known as "civil engineering".

John Smeaton was the first to describe himself as a "Civil Engineer" in his reports in the 1760s, and confirmation that a new profession had emerged came when the Society of Civil Engineers was formed in 1771, with Smeaton present at its first meeting in the "Kings Head", Holborn in London.

After Smeaton's death, the esteem in which he was held as the "father of civil engineering" by its members was confirmed when they renamed the Society, "the Smeatonian Society of Civil Engineers". Samuel Smiles included him in "Lives of the Engineers" (a shorter chapter than Brindley, Watt, Rennie, Telford and the Stephensons).

John Smeaton

Images courtesy of Institution of Civil Engineers Library and Archives except where noted otherwise.

Perth Bridge – image courtesy Simon Armstrong. Creative Commons Attribution-Share Alike 3.0 Unported license.

A 1981 volume of articles edited by Skempton, remains his only modern biography. His light has not shone as brightly through the years, unjustly so.

He was born in Yorkshire, educated in Leeds and London, and his very early practice and projects were in England. Yet much of Smeaton's output was for improving the infrastructure of Scotland. This paper gives some insights into those projects.

Smeaton's first major engineering project (having practised initially as a scientific instrument maker) was Eddystone Lighthouse (constructed 1756-59). He had been recommended for the commission by the President of the Royal Society, Smeaton having caught his attention as a new Fellow in 1753 (at the age of 28). It was an inspired recommendation and Smeaton did not disappoint. His scientific approach optimised robustness against extreme wave forces through the shaping of the tower and interlocking of the individual stone blocks. This became the prototype for all future nearshore and offshore lights, and it is a tribute to Smeaton's work that the Stevenson family, for four generations the pre-eminent lighthouse designers in the UK (and mostly built around the coastline of Scotland) evolved their increasingly impressive structural designs and details from that pioneered by Smeaton. Eddystone lighthouse was in continuous use until 1877 when replaced. The top section was dismantled and rebuilt on Plymouth Hoe as "Smeaton's Tower".

That Smeaton spent so much of his professional career in Scotland is partly because the infrastructure of Scotland at the time was far less mature than in England, yet Scotland's natural resources, particularly coal, had untapped potential to fuel the industrial revolution. Infrastructure was also seen as a military imperative. The Jacobite rebellion was only a 17-year-old memory when Smeaton began work on the Forth & Clyde canal. Strategic roads in Scotland were still being upgraded for military as well as civil purposes. Smeaton's journeys in Scotland had to be made for the most part on horseback.

The involvement of Smeaton in improving the navigation of the River Clyde goes back to his reports in 1755 and 1758, the second report proposing widespread dredging, but with a dam at Marlin Ford below Whiteinch and a bypassing river lock. That scheme was abandoned in favour of deepening alone without the need for a river lock, and later completely overtaken by John Golborne's suggestion of constructing groynes into the Clyde to encourage self-scouring, with highly successful results, later improved further by Rennie then Telford.

The Forth & Clyde Canal, arguably his greatest project after he made his name with Eddystone Lighthouse, occupied Smeaton for ten years from 1763 until 1773, the last five years of which he was Engineer in Chief for its construction, with Robert Mackell as a very capable resident engineer. Unlike the government sponsored Caledonian Canal, the Forth & Clyde Canal, the first sea-to-sea canal to be constructed in the world, was financed by public subscription. 1500 shares of £100 each were issued to raise the estimated £150k capital required. In the event, the funds raised lasted until 1777 by which time only Grangemouth to Stockingfield and the branch to Glasgow had been completed. (The final section to join Stockingfield to the Firth of Clyde at Bowling was resumed under Robert Whitworth in 1786 and opened in 1790.)

The canal was built to facilitate trade through the transport of goods, mainly coal, iron and grain. The canal helped facilitate the rapid growth of industrialised coal extraction. The canal transported 24,000 tons of coal in 1800 that increased to 500,000 tons in 1870, a 20-fold increase, also helped by the connection to Edinburgh through the Union Canal. Scotland's main cities had grown dramatically in the same period and were huge consumers of coal for the populace and the industries that were established to take advantage of skilled and unskilled labour. Passengers also took advantage of the canal's "Swift" boats to travel from Glasgow to Edinburgh in only seven hours.

Industry flourished in Glasgow with the completion of the canal, and numerous foundries, tradesmen, craftsmen and warehouses clustered canalside to take advantage of a speedy route to market. These provided the employment and wealth that led to Glasgow becoming the Second City of the Empire. At the eastern end of the canal, the Carron Ironworks near Grangemouth grew into a major industrial exporter, using the canal for transporting raw materials inwards and finished goods outwards.

The canal served Scotland well until custom declined in the 20th century, and it was closed to navigation on 1st January 1963, and was almost scheduled for infilling. By then it had been in continuous use for 173 years.

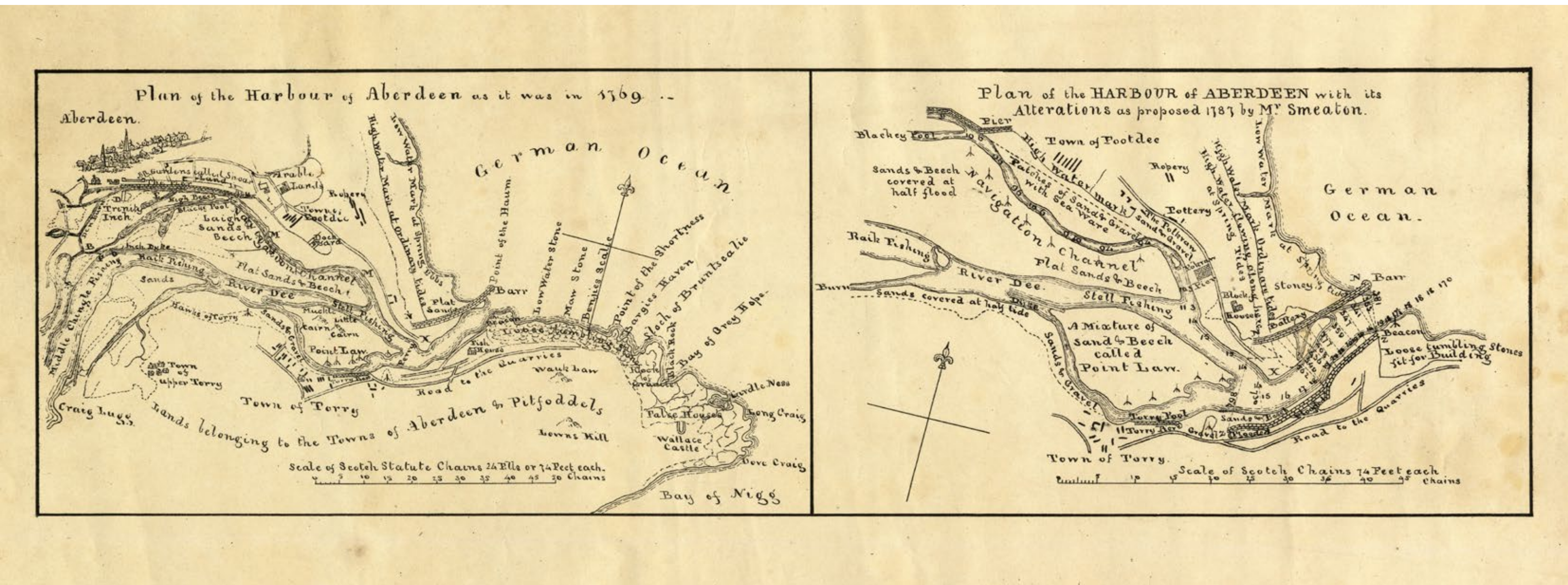
The canal's designation as a Millennium Project allowed the Forth & Clyde and Union Canals to be restored to navigation, linked by the Falkirk Wheel, and Smeaton would have been delighted to hear of the revival of its role as a piece of critical infrastructure as part of Glasgow's surface drainage and flood defence strategies, and as an attractive investment for utility corridors and property development. Tow paths are now active travel routes, making the canal useful in different ways to what Smeaton and the original proprietors had intended in the original "business case". This is a testament to the resilience of the design and construction methods used by Smeaton.

Most of the bridges designed by Smeaton were for Scotland and all of those that were built survive: Coldstream (1763-67), Perth (1763-71) and Banff (1772-79). All of them were multi-span masonry arch bridges, of similar appearance, even their decorative features such as the roundels above the piers faced with contrasting stone.

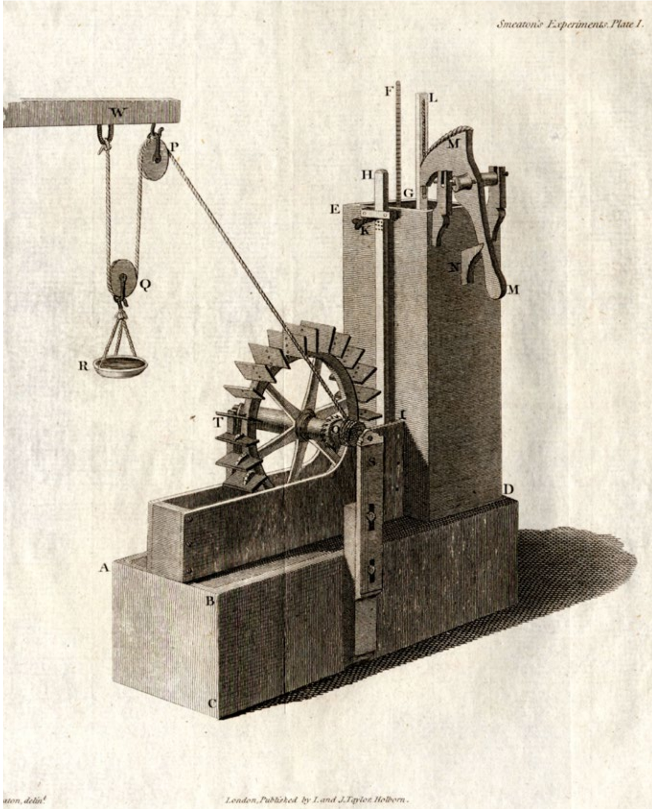
Smeaton's approach to pier foundations was generally consistent – timber piles driven inside cofferdams capped to create a platform for the masonry – and its success, even for fast flowing rivers prone to flooding, is evident from the bridges' longevity. But for his bridge over the Tyne at Hexham (1777-80), Smeaton believed the riverbed was good enough to allow foundations without piles. This led to a failure due to scour in a severe flood soon after completion. Smeaton wrote to his resident engineer "All our honours are now in the Dust! It cannot now be said, that in the course of 30 years' practice not one of Mr Smeaton's works has failed. Hexham Bridge is a melancholy witness to the contrary."

Smeaton reported on improvements to Scottish harbours at Portpatrick (1771-78), Aberdeen North Pier (1775-80) and (1788-91), Peterhead (1775-81) and Cromarty (c1781-83).

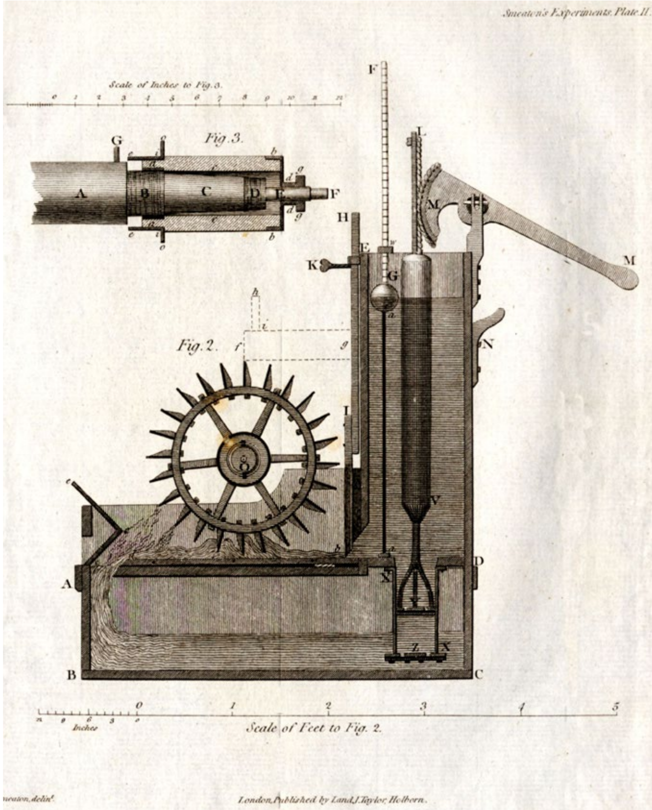
Mills and millwork were another of Smeaton's regular fields of work throughout his life. His most significant scientific paper had been published in 1759 on experiments on different configurations of water wheels, which won him the Royal Society's Copley Medal. He tested efficiency *at the wheel* of overshot and undershot wheels, measured by distance through which a weight was raised in a minute. His finding that overshot wheels were 66% efficient and undershot wheels only 30% efficient, was not previously understood.



Aberdeen Harbour – before and after Smeaton's alterations



Smeaton's Machine for research into water power



Smeaton's Machine – Cross-section

Millwork featured in Scotland in his work for the Carron Ironworks, for whom Smeaton had been regularly commissioned from 1769 for "blowing engines, dams and boring mills, etc".

Another Scottish connection with Smeaton arises not from projects, but from his close encounters with the younger James Watt. Smeaton had deployed his experimental method to improve the efficiency of the Newcomen engine, which had been the only steam engine available for pumping water out of deep mines. In 1770, he built a full-scale experimental engine and followed the same thorough experimental method as his wind and waterwheel tests – optimising the controllable variables. Over the next two years he carried out130 tests varying one factor at a time. He could vary piston loading, valve timing, form of injection nozzle, insulating the piston, use of hot-well tank as a feed-water heater, different types of coals.

Tests on his improved engine in May 1774 showed an increase in efficiency of 25% over the most efficient Newcomen engine built till then, a huge achievement that looked likely to earn him the grateful thanks of the nation, and many commissions.

Unfortunately for Smeaton, James Watt's partnership with Matthew Boulton was about to come to fruition and Watt's patented steam engine proved 3 times more efficient than Smeaton's best attempts. The slow, lumbering and inefficient Newcomen pumping engine had been in use for fifty years before these two engineering geniuses made these simultaneous breakthroughs, both impressive in their own right. But Smeaton's improvements were achieved by incrementally optimising the variables in the original engine, whereas Watt's invention of the separate condenser was an intellectual breakthrough that totally transformed the system efficiency to a far greater degree.

There was a short period when Smeaton tried to keep his engine designs competitive, and in that time he also resorted to denigrating the Boulton & Watt engines. He does seem to have temporarily strayed from his high standard of professionalism at this time, resorting to anonymous letters to the *Newcastle Courant*. But after all, he had just spent two years perfecting an engine that was immediately virtually obsolete, except where coal was so cheap that it could be profligately burned. When his measurements proved to him just how much more efficient the Boulton & Watt engines were in operation, he acknowledged the superiority of Watt's invention and they were to become friends in later life, Smeaton nominating Watt for membership of the Royal Society and the Society of Civil Engineers. Smeaton was also an occasional visitor to the Lunar Society, and we know that Watt met him there at least once.

Smeaton's work has also influenced aeronautics. His 1759 experiments on millwheels included a series on windmills testing the efficiency *at the wheel* of varying sail angle and sail area. From this he was able to derive the relationship

$$D = k.V.^2A.Ci$$

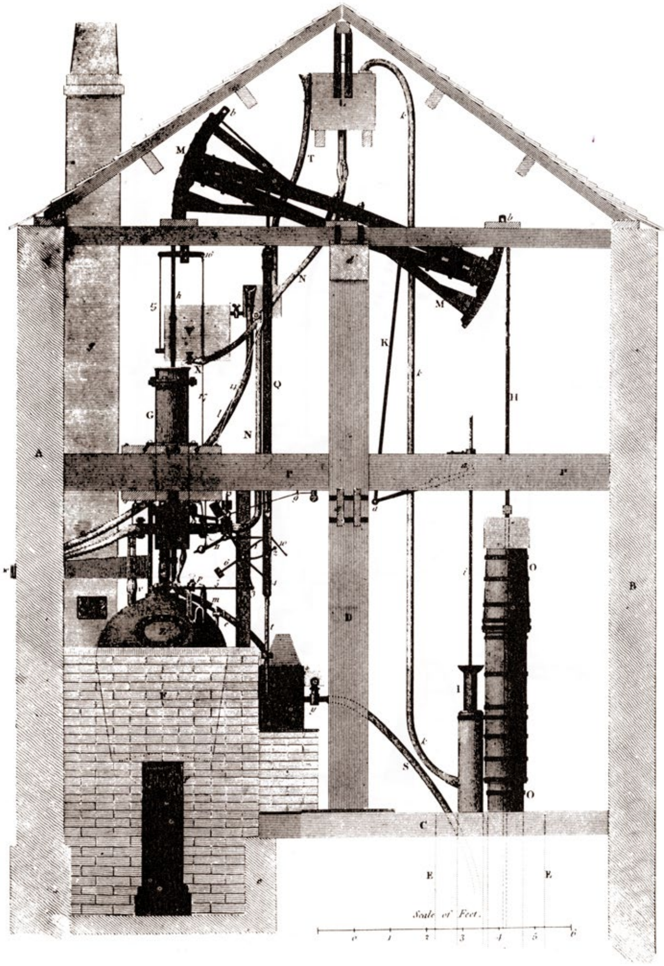
where:
D is Drag Force (lbs)
k is the Smeaton coefficient (lbs/(mph^{2}ft^2))
V is velocity (mph)
A is area (ft^2)
Ci is drag coefficient (reference condition of 1.0)

In 1759, Smeaton's experimental data led him to a value for k of 0.005; in 1902 the Wright brothers in their experiments on gliders leading up to "The Wright Flyer" taking flight, estimated k as 0.0033 and in modern times NASA have refined k to 0.00327. It is still termed the "Smeaton coefficient".

Smeaton was one of the first consulting engineers making a living from commissions from private or public clients at a daily or weekly rate. The young Smeaton charged fees that would be considerably less than a modern equivalent (though to be fair, he had significantly fewer overheads!) but as his experience and reputation grew, so did his charges, and eventually they bore a reasonable comparison with modern fee scales. He also practised some basic ways of working that have endured. He regularly described himself as a "professional man" giving an opinion in his reports. He set a daily rate for his services. He would refuse to comment on or criticise the work of other professional men. He set out the roles and responsibilities of himself as designer and his resident engineer as overseer and manager of the Works. His reports use the first recorded use of "civil engineer" in the 1760s.

As a "professional man", Smeaton also gave evidence in Courts from time to time, and a case (Folkes v Chadd) heard at the Norfolk Assizes in 1782 is widely regarded as the first acceptance by the Courts in English Law of what is now known as the "Expert Witness". The case related to the siltation of Wells Harbour, and a dispute on what had caused it. Smeaton's evidence had initially been rejected by Justice Henry Gould since it was based on opinion, not facts.

On appeal, Lord Mansfield found that Smeaton's opinion had been deduced from facts, and "in matters of science no other witness may be called. Such men as Mr Smeaton alone can judge." With Mansfield's ruling on 21 November



Smeaton's Experimental Engine

1782, the court formalised that expert testimony was not just proper evidence, but the best kind of evidence for the court to consider in matters of science.

The Smeatonian Society of Civil Engineers changed its name in 1830 and still meets 6 or 7 times a year in the Institution of Civil Engineers, maintaining the tradition of dining together to discuss and debate engineering issues of the day, much as Smeaton and his fellow members did in 1771.

John Smeaton has many legacies, many of them nurtured through the projects he was responsible for in Scotland. He was the pioneer of a lighthouse design that has become so familiar to us because of its many later adoptions. He was an exceptional canal designer and oversaw the world's first sea-to-sea canal. He designed elegant bridges still surviving today, proving, with the one exception in his career, at Hexham, that he made good decisions on pier foundations and scour prevention. He became the authoritative expert in harnessing energy from wind and water wheels. He improved the efficiency of the Newcomen engine, and where used, would have reduced coal consumption and pollution significantly. He derived the Smeaton coefficient later used by the Wright Brothers and NASA. He reinvented concrete and modern-day Portland cement for Eddystone lighthouse.

His peers, successors and biographers thought very highly of him. Here is a short selection:

"Smeaton is the greatest philosopher in our profession this country has yet produced." (Robert Stephenson, 1858)

"Civil engineering has to be both an art and a science, and the engineer's responsibility is to develop both aspects to the limit of his powers in order to fulfil the clients' requirements as safely and economically as possible. Smeaton steadfastly based his practice on this principle, to the immense benefit of his country and profession." (A.W. Skempton, 1981)

"In justice to him we should observe that father Smeaton lived before Rennie, and before there were one-tenth of the artists there are now. Suum Cuique, his example and precepts have made us all engineers" (James Watt, writing to Sir Joseph Banks)

In summary, he was a man of science who applied himself to the practical, quality-of-life enhancing projects that allowed him to contribute his knowledge and professional skill as a means of effecting improvements. Evidence obtained through research, reading and experimentation formed the basis of his scientific approach. He was one of the first in the UK to bridge academia and industry.

He was motivated by the common good with strong ethical principles. He had a conscience and he was human, and the prospect of him having wasted two years refining the Newcomen engine brought out a natural reaction until he made his peace with himself – and James Watt!

He created the operating model and raised public expectations for the standard of professional civil engineers who followed him like Mylne, Watt, Jessop, Rennie and Telford. He is rightly regarded as the father of the profession of civil engineering through his science, his intellect, his professionalism and earning the respect of those who knew him.

He wasn't perfect, but he set a very high bar, with no precedent to guide him.

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Gordon Masterton. Smeaton vs Watt: The race to improve the steam engine. ICE, 2024

Ric Parker. John Smeaton mechanical engineer – rotating machinery, history and legacy. ICE Smeaton Lecture 2024.

Alexander M Aizenman. How John Smeaton helped transform expert testimony. ICE, 2024

Explore the projects of John Smeaton in the ICE PHEW google mymap of Smeaton projects

Professor Masterton features in a Youtube video commissioned by the Smeatonian Society and sponsored by the Institution of Engineers in Scotland to mark the 300th anniversary. It can be seen by clicking the play button on the left.

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The Institution of Engineers in Scotland

Images of Kelvin

some stories from the life of William Thomson to celebrate his bicentenary

Andy Pearson

Dr Andy Pearson is past President of the Institution of Engineers in Scotland and currently serves as the Institution's Company Secretary and Journal Editor. He has a keen interest in the history of engineering and science, particularly from the beginnings of the industrial revolution through to the Victorian era. He has written several historical accounts of this time including an investigation of the Chicago fire of 1893, the life of David Boyle of Johnstone who pioneered the use of ammonia for refrigeration in the United States, the history of Star Refrigeration which was founded in 1970 but could trace its roots back to 1874 and The Rankine Songbook, published by IESIS to celebrate Professor Rankine's bicentenary in 2020.

Introduction

Most people, when Lord Kelvin is mentioned, are liable to visualise the grand old gentleman shown in Figure 1. This is Baron Kelvin of Largs at the age of about 75, taken in about 1900, standing with his maritime compass, which had recently been adopted by the Royal Navy as their standard instrument for iron and iron-clad ships. Of course he didn't always look like this. Figure 2 shows Professor Sir William Thomson at the age of about 55, taken in about 1880, when he was settled into his new teaching and research facilities at Glasgow University's new campus on Gilmorehill in the West End of Glasgow.

Dr Andy Pearson

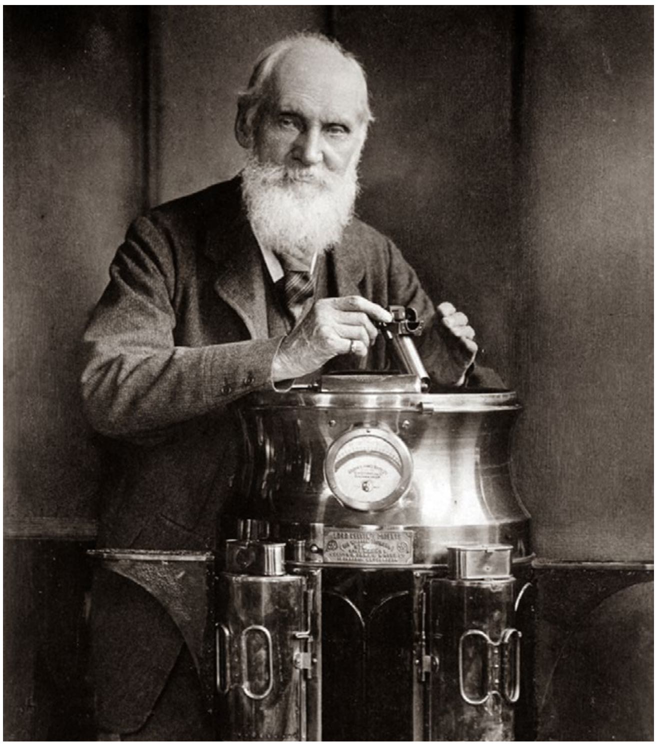

Figure 1

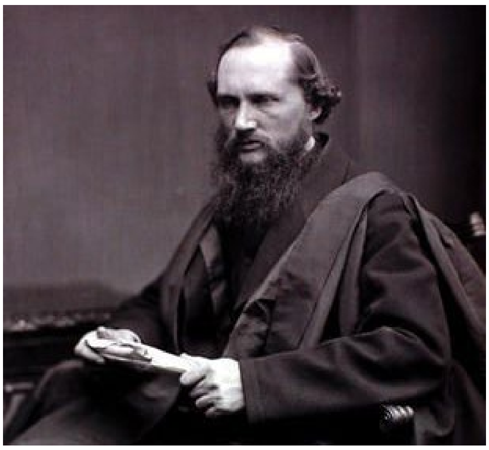

Figure 2

Figure 3 shows his lecture theatre in the new University and Figure 4 shows his laboratory.

Sir William was knighted by Queen Victoria in 1866 to mark his contribution not only to the design of the transatlantic telecommunication cable but also the engineering of the signalling and recording apparatus necessary to make it functional.

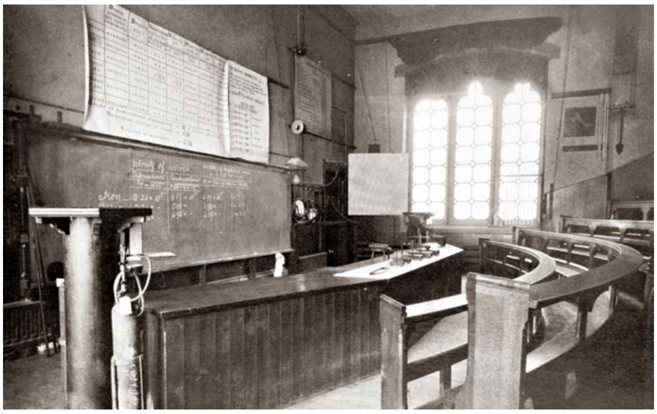

Figure 3

Figure 4

In Figure 5 we see Professor William Thomson in a picture taken around 1860 at the age of about 35. The caption below the picture, in his own handwriting, says "W Thomson reading a letter or letters from Fleeming Jenkin, about experiments on submarine cables probably about March 1859 – K, 24 Hamilton Terrace, London Nov 23 93". Thomson worked with the Atlantic Telegraph Company on several attempts to design, manufacture and deploy a suitable cable for transatlantic communication from around 1857 until the cable's successful installation in 1866.

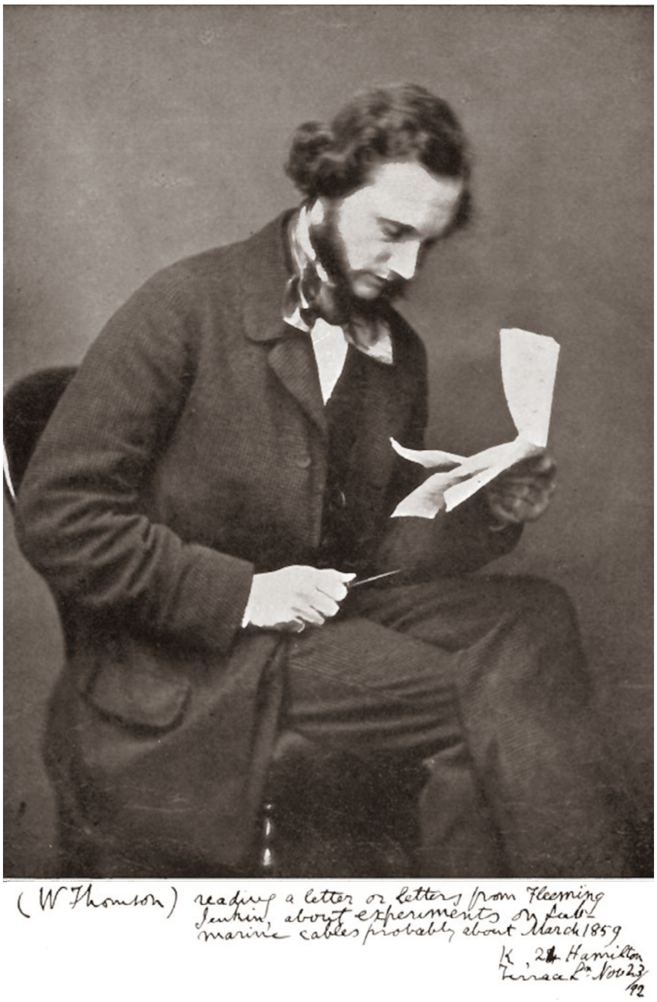

Figure 5

The Thomson family were gifted in many ways; William's elder sister, Elizabeth, was a talented artist and many of their family experiences were recorded as sketches by her, or later by her daughter, Agnes. Figure 6 is a sketch, by Elizabeth, of young William Thomson, aged about 15 and drawn in about 1840. It was about this time that he enrolled at Cambridge University.

Figure 6

In 1845, after graduating with a BA in Mathematics, Thomson spent a year in Paris working in the laboratory of Victor Regnault and when the chair of Natural Philosophy became vacant in 1846 the young scientist was appointed by the University Senate unopposed, much to the delight of his father, James Thomson, Professor of Mathematics at Glasgow. The younger Professor Thomson is shown in the portrait in Figure 7.

Figure 7

Figure 8

Figure 9

Sadly, his father contracted cholera in an epidemic in 1849 so the two Professors Thomson did not have long working together, but his death created the opportunity for William's close friend Hugh Blackburn to be appointed as James' successor. Hugh had been a student at Cambridge with William, coming fifth in the Mathematical Tripos examinations when William came second. His wife, Jemima, was also a gifted artist, particularly of animals and is said to have been an inspiration to Beatrix Potter who named Jemima Puddleduck after her.

Figure 8 shows Hugh and William in the Blackburn's garden at Ardmillan in Ayrshire (Jemima has sketched herself into the background with their son, named William after his godfather.

Figure 9, also by Jemima, shows the two Williams, godparent and godson, on the beach at Ardmillan and is titled "Teaching Projection".

It is something of a mystery why Professor Sir William Thomson adopted the title of Lord Kelvin when he was elevated to the peerage. His niece, Agnes King, described the excitement of the initial announcement in her diary in 1892, saying of the discussion of a possible title "We were all full of brilliant ideas: Lord Compass, Lord Cable, Lord Netherhall. Uncle William himself suggested that Lord Tom-Noddie would be nice." On another occasion

Figure 10

both Lord and Lady Kelvin mentioned that the title had been selected for the sake of association "with the University and the city of Glasgow" and for "not being too territorial". However it must have pleased Kelvin greatly when the University moved to its new home on Gilmorehill in 1872 because his grandmother, Elizabeth Pattison had lived from her birth in 1790 to 1806 in Kelvin Grove House, a mansion on the banks of the River Kelvin which at the time of his elevation to the peerage was used as a museum. It served this purpose from 1876 until the Kelvingrove Art Gallery and Museum was opened in 1902, at which time the old mansionhouse was demolished. It is shown, in a picture by Thomas Annan, in Figure 10.

The name Lord Kelvin seemed to catch the imagination of the general public almost immediately, and William Thomson took to calling himself "Kelvin" even when writing to members of his immediate family. Not everyone understood the change of name however: one European scientist wrote "I suppose it is still considered an honour to sit in your House of Peers; but why, as a penalty for doing so, should my friend Sir William Thomson, whose reputation belongs to Europe and not to England alone, bury his illustrious identity in an unknown title?" and another complained "Who is this person, Kelvin, who claims to have invented the galvanometer that all the world knows to have been invented by Sir William Thomson?"

Further reading

Kelvin the Man, Agnes King, Hodder & Stoughton, London

Lord Kelvin's Early Home, Elizabeth King, Macmillan and Co, London

Life of Lord Kelvin Volumes 1 and 2, Silvanus Thomson, Macmillan and Co, London

Jemima: Paintings and Memoirs of a Victorian Lady, Jemima Blackburn, Canongate Publishing

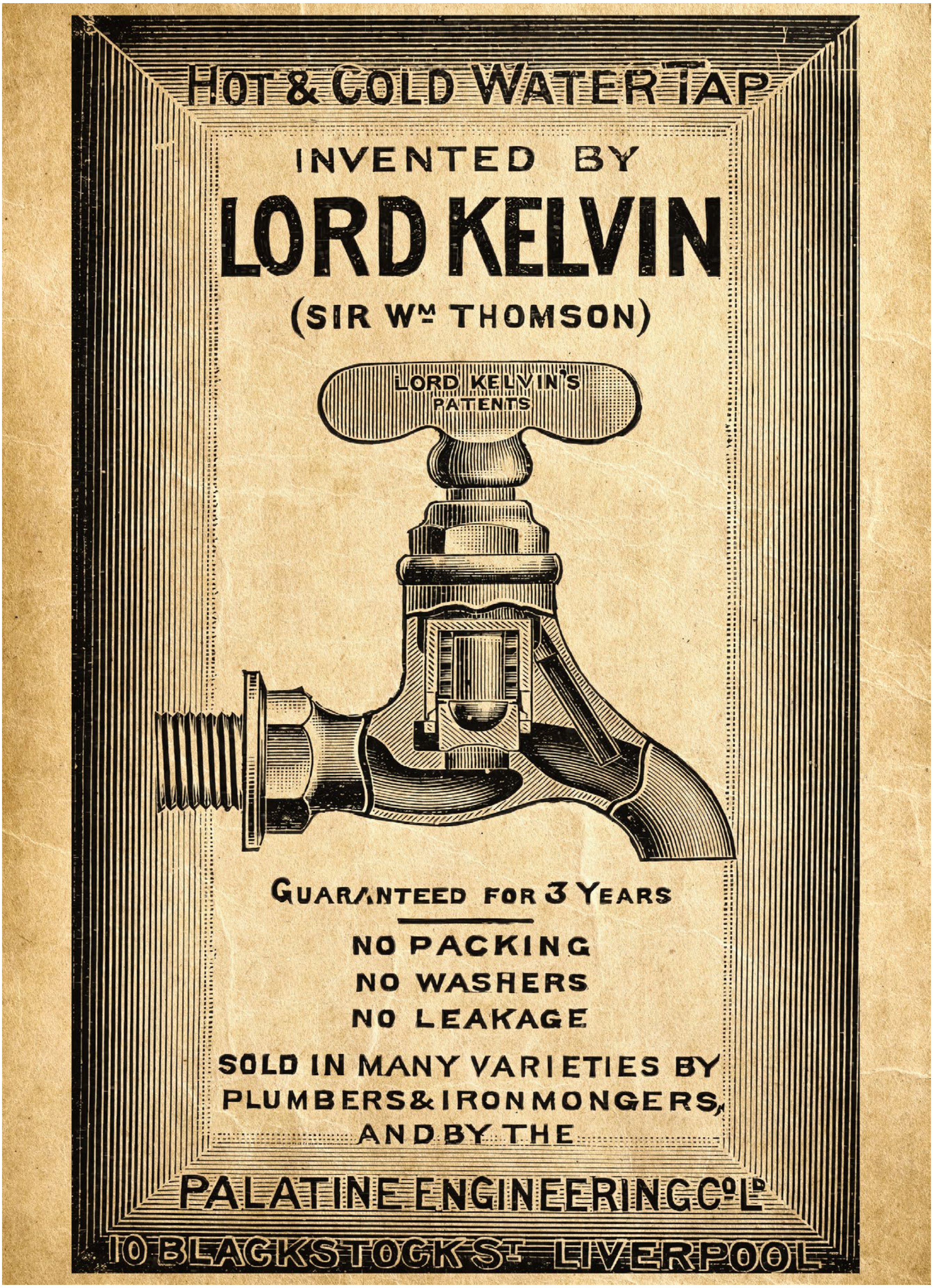

Figure 11 – The name Kelvin caught the imagination of the general public

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The Institution of Engineers in Scotland

Bioinspired engineering

Adam Stokes, University of Edinburgh

Presented to the Institution of Engineers in Scotland, 5th December 2023, University of Strathclyde.

Adam A. Stokes is Professor and Chair of Bioinspired Engineering in the School of Engineering at The University of Edinburgh where he is Head of The Institute for Bioengineering. Adam holds degrees in engineering, biomedical science, and analytical chemistry. His pioneering research in Soft Robotics and Soft Systems has received over 7000 citations, with publications in leading scientific journals. He is a founding Co-Lead of The National Robotarium, the UK centre of excellence in robotics. He is the Deputy Director and founding member of the Edinburgh Centre for Robotics. Adam leads a team of approximately 20 people in his interdisciplinary research laboratory – The Soft Systems Group – where the focus is on the intersection of next-generation robotics technology, bioelectronics, and bioinspired engineering. Outside of the academy, Adam is a founder of several companies in the health-tech and robotics fields and serves as Academic in Residence with Archangels Investors Ltd.

Introduction

I was born in Paisley and spent my early years in Erskine where my Dad was a minister, both of my parents are graduates of The University of Edinburgh and prior to bible college my Dad had studied physics. I was far more interested in the materiality of the world than the spirituality of religion. I was always asking questions and taking things apart to see how they worked.

Prof Adam Stokes

Towards the end of my degree I was involved in a very interesting project looking at the intersection of microelectronics and biology. At that time a new degree was just starting up, a joint venture between Edinburgh, Glasgow, Dundee and Strathclyde, so I spent four years doing that. The first year was a conversion into biological science and afterwards I moved into doing a PhD in Analytical Chemistry. After that I went to the United States and worked with an outstanding Professor – George Whitesides – in the department of Chemistry and the Wyss Institute for Bioinspired Engineering at Harvard University. I thought that I would be working with him on point-of-care diagnostics but I ended up researching robotics, materials science, and optics.

Throughout my training I was approaching this science from an engineering perspective and in particular systems engineering. We start with a requirement and partition it to look at individual components and then integrate these components to produce a system with various feedback stages to refine the requirements. Typically in robotics we build systems from the stable sub-systems that we already know, things like motors and rotary elements, to create an overall system that meets the desired requirements. If we want high precision and high accuracy to do dull, dirty, dangerous things repetitively this is the approach we take. Robotics has progressed in leaps and bounds because of this approach. When the requirements change, the system can also change, with better encoders, bigger robots, bigger motors. One of the questions that led me on this journey was "what happens when the available sub-system components don't meet the overall requirements?" So the challenge that I was set when we moved to the States was "how can we create a robot that can replicate the behaviour of an octopus?" An octopus trapped in a box with a very small exit hole will find a way to squeeze itself through the gap to escape. From an engineering perspective I would say "I don't know how to do that. I don't know how to combine encoders, motors, bits of metal and bits of plastic and build something that is able to do that." Often we think as engineers that if we just think hard enough about something we will be able to figure out how to do it but often we can find guidance from the ways in which natural systems do things differently. This bioinspiration is not really anything new, it is basically science. It's what people have been doing in science for ever. Leonardo Da Vinci's quest was to learn more about the natural world, how to explain it and how to understand what's going on. We like to put names on these things so we talk about biology, chemistry and physics but they are all just different lenses that can be used to understand the natural world. I teach electronics and electrical engineering and it is interesting to note that electronics came out of observation of bio-electricity. People knew about bio-electricity before they knew about electricity, so by observing the natural world they were saying "I don't know how muscle moves, I don't know why if I zap it with a lemon and some bits of metal it will move, I don't know why this happens". The quest for bioinspiration is about understanding. Bioinspired engineering is slightly different. It is about taking what we know about the natural world and using it to turn materials and knowledge into products that will fit in the marketplace. In this talk we will look at both bioinspiration and bioinspired engineering but it is important to note that "bioengineering" and "engineering biology" are two different things. Engineering biology is about using engineering principles to be able to build with biological systems. Bioengineering is about how you combine different substances together, some of which are biological in nature, to build products that fit into some sort of market.

Professor Julian Vincent

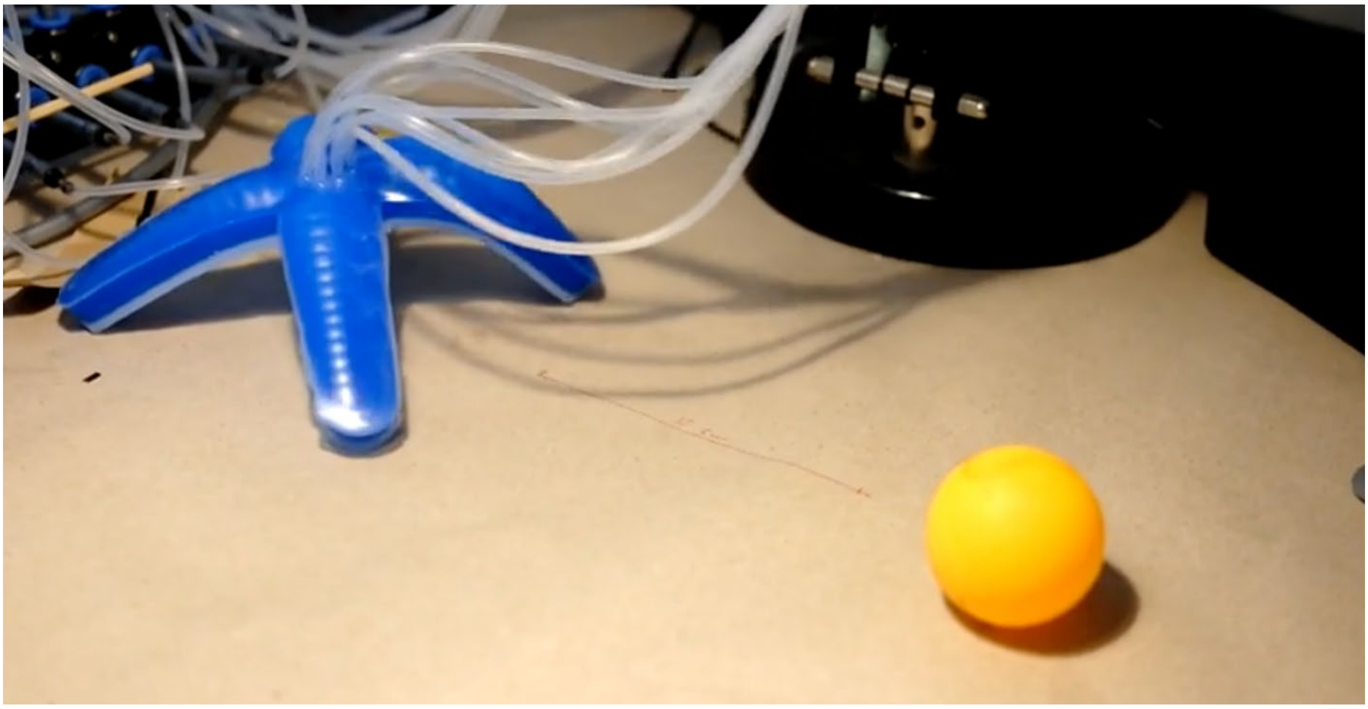
One of the key figures in bioinspiration, or biomimetics as it is also known, is Professor Julian Vincent of Heriot Watt University. He has worked in this field for a very long time and has identified the linkage between biology and engineering as a trade-off. Common trade-offs are speed versus accuracy or strength versus weight or exploration versus exploitation. A lot of our work in engineering is addressing and solving these trade-offs. There are a few different approaches that you can take: preference for one solution over another, adaptation to suit prevailing external conditions or compromise between two competing factors. Compromise will look at the balance between the two factors, such as speed and accuracy, and explore the many intermediate positions, creating a Pareto front of solutions to identify the most suitable combination. Professor Vincent has for many years been developing a disciplined approach to biomimetics and has created a huge database of the ways in which these compromises are addressed in the natural world. The database can be searched to find solutions to particular compromises, provided the query can be phrased in a suitable way. This has been built by using some of the principles of Triz; a problem solving technique that is generally taught to design students but not to engineers. It was developed from a study of patent literature which found that there are only about 40 ways in which anyone has ever solved a problem. Looking at biology you can see that problems are solved in very similar ways.

Prof Julian Vincent

Some examples from the work at Edinburgh University

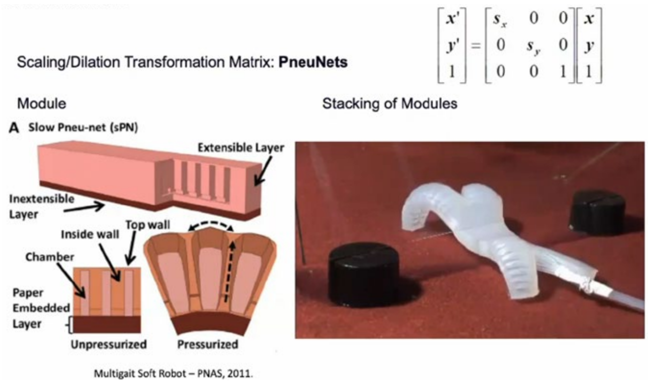
One example from Prof Ignazio Maria Viola at Edinburgh University is the Dandidrone, inspired by the way that dandelion seeds are dispersed. The seeds fly in a previously unknown manner and this is being used to develop extremely low cost sensors. Another example from Dr Francesco-Giorgio Serchi is the variable stiffness tentacle, inspired by the movement of an elephant's trunk, which can move in three dimensions. This work is supported by the North Sea oil and gas industry and can be used to inspect undersea pipelines. Another example is a pneumatically actuated soft plastic robot that can be taught to walk through reinforcement learning. This is bioinspired but is not biomimetic, which means that it doesn't look like anything that you would find in nature, but it is certainly inspired by nature.

In Greek creation myths Prometheus and Athena created man (and all the other animals) out of boredom, simply to give themselves something to do. In contrast the giant statue of Talos was constructed by Hephaestus to defend the port of Crete; a very specific purpose. Some of the work we have been doing at Edinburgh looks a bit like Talos – it has been done with a very particular reason in mind. It follows the specification of requirements, decomposing the system and then building something that meets the requirements. A lot of the other things, however, are more like Prometheus; playing around and seeing what happens, and then seeing what you can do with it. This is the opportunistic idea of having some creativity, having some play in science, and then seeing what you can do with the results when they come out. I think that's an important point because we often don't do that in science. We don't do a lot of playing or messing around. We do it as children – children are great at just playing with stuff – but as scientists and engineers we take ourselves very seriously. Science is a function of how much money you have, or how big your lab is, or how many Nature papers you have published, but not a lot of it is just looking at nature, playing with things and seeing what happens.



A starfish playing football. From research by Stokes and Marowski.

The central thesis of the work at Edinburgh is that "soft systems" are adding value to robotics. This challenges the ways in which robots are normally built, how they are built, the materials that are used and the ways in which they are used. Soft systems are just like any other system in several respects. They need to have sub-systems that enable them to move and to sense the environment around them. They need a control system to enable them to process the inputs and generate outputs and they need to have a physical embodiment of all these features. We naturally tend to envisage humanoid robots because that's what we see in films and other media, built in our own image, but most of the robots that we work with at Edinburgh are not like that. Robots are often required to work in places that humans don't go doing dirty, dangerous or repetitive tasks. We asked the question "what if we build systems in a different way but to perform the same function?" For example think about a 6-axis robotic arm or an octopus tentacle. Essentially they perform the same function; they can pick something up, move it and put it back down again. They have some actuators in there, some sensors in there but they are built in a very different way. From an energy point of view and from a task point of view they do the same thing but they do it in a different way. From a complexity point of view they are very different. The octopus tentacle is an enormously complicated system, although nature does a great job of hiding complexity and making it look simple. A key question is "why would you want to build something looking more like an octopus tentacle and less like a robotic arm?" We have taken a very reductionist viewpoint, saying that you can take all robotic movement and split it down into two simple two-dimensional transformational matrices for translation and rotation. The ways in which a 6-axis arm looks and moves are determined by the ways in which it is modelled in the mathematics. This is not complex, although it might be complicated. There are only six motors and the maths behind it is very simple. By contrast, soft robotics in addition to translation and rotation requires scaling and shearing. Scaling represents what happens when the robot changes volume, which doesn't happen with conventional robots. Shearing represents what happens when the form is distorted, for example when a square becomes a parallelogram. Scaling and shear enable soft robots to be created based on a balloon structure, constrained on one side so that when it is inflated it tends to arch and when it is deflated it flattens. This can produce a device that is capable of forward motion and can change its gait to get past obstacles, like the octopus in the box.



A pneumatic soft robot simulating the octopus in the box

When these sorts of system were first produced about ten years ago and papers were submitted to academic journals they elicited the response "I don't know what that is but it is not robotics". Since then the field has grown with tens of thousands of researchers, with international conferences and it changes the use case for robotics, particularly in proximity to people. It is also very low cost – it is essentially disposable. When robots become that cheap it opens up many new opportunities.

Another example of a very cheap robot is the Arthrobot, made from drinking straws, balloons and rubber bands. It is built up from elements which bend in one axis around a revolute joint and can be configured to mimic four legged walkers, ants, water-boatmen, spiders and similar creatures. This is just a way of playing with things but it asks the serious question of "what happens when you build systems from different materials and at different price points?" This puts us at a different point on that Pareto front of speed vs accuracy. There is no denying that these are machines that do something. Whether they do something useful is another question. The quest then becomes for utility, to find a purpose for these interesting developments. In the early days of these devices there were no simulators to mimic the complex processes with the thermodynamics of gases, or the unknown properties of the elastomers and what happened when they went to really high strain rates. There were all sorts of things that challenged what we could do with these systems.

We noticed that the dominant paradigm for what we were doing was that we were looking at the one-to-one mapping of control inputs to actuators and so we started to investigate how we could move off that line to create something that was more capable with less control input or alternatively something that has higher levels of redundancy. In terms of increasing capability, if we compare a 5-axis robot arm with five actuators it needs five inputs whereas something like an octopus arm with a thousand actuators needs a thousand control lines and a thousand valves with a thousand tubes and all of the controls to run that sort of thing so it becomes unwieldy. The scaling doesn't work, but it doesn't work because that's not how nature builds things. The control system and the actuation are not separate; they are all in there from the start. We started looking at the trade off between capability and redundancy and considered how we would embed control into the system so that we would have the benefit of the soft actuators but in a more controllable form. This is all about actuators. It is interesting to note that there are no actuators that work in the same way as biological muscle. Albert Szent-Györgyi, who won the Nobel prize, did a lot of pioneering work in this area. He discovered vitamin C but also spent most of his life trying to understand biological muscle to work out how muscles worked. There is a complex interaction between two proteins, actin and myosin, which provide a sort of ratchet mechanism as the fibres in muscle slide over each other to build up a huge hierarchical assembly to form a biological actuator. Nothing that we make approaches this. The key observation from this is that it is the properties of the materials that you build from that give the overall system its characteristics, not just in terms of the amount of strain that it has or its mechanical properties, but also things like cost and where the materials come from.

Two key questions are how do we simulate and predict what the actuators are going to be able to do and how do you improve the efficiency of the network. There are no simulators for this sort of thing, but the work of Henry Paynter at MIT in the 1950s looking at the modelling of energy flows in hydroelectric dams to improve efficiency is instructive. The BigDog robot from Boston Dynamics is a good example. Why does it take 12 horsepower to do a one horse job? To put it another way, where do the other 11 horses go? The answer is that robots are a bit like animals in that they are non-equilibrium systems, not in balance with their environment, and they are dissipative, meaning that they have to take energy in and then transform it to do useful work. Power is transmitted through the system by effort and flow variables. In electrical engineering these key parameters are voltage and current but there are equivalences in mechanical engineering and chemical engineering in terms of what carries the effort and what carries the flow. We have been using port-based modelling to study these flows and to work out the efficiency of the system. If we consider one of the bending actuators for example, in terms of efficiency all we need to know is how much energy goes in and how much useful work is done. Modelling this can be very complicated using computational fluid dynamics and finite element analysis, but it is also possible to measure the energy input and useful work and then to approximate the transaction mechanisms. We noted that all of the actuators that we use in robotics have the same form; they have an energy source, an energy sink, some sort of mechanical domain where they do useful work and some way in which energy is transduced through a series of junctions. We have been able to take many of the types of actuator that we have built and model the ways in which they store energy capacitively, the way that they store energy inductively and the way in which the dissipate energy, which is basically resistively. This is derived from analogues of electrical engineering where the effort leads the flow or the flow leads the effort in the same way as voltage leads current or current leads voltage, as in a typical phasor diagram. All of that information can also be applied in the chemical domain or the mechanical domain, in pneumatics or hydraulics. The reason for this approach is to inform the choice of actuators for particular function. The key to understanding "why" is the energy flow in the system which in robotics, especially field robotics is the main point of interest. How do I select an actuator for a particular job? How do I model how much energy it is going to use? How long will the system run, given the available energy source, which might be a tank of petrol or a lithium polymer battery? This leads to the question of optimising efficiency in order to extend the operating time. When we look at any of the quadrupeds or other mammals that we typically mimic when we build robots we find that they have lots of modes of movement, depending on their purpose. Some of these modes are for capturing prey, or for moving long distances efficiently, or for covering short distances very fast. In robotics we do the same thing but we look at the emergent properties of the system and we describe them rather than designing the control system to optimise for particular aspects. An example is the soft starfish type of robot shown earlier. In this project the controller didn't have any information on what the robot looked like but was programmed to learn to move and then to kick the ball. This is an interesting mix of robotics, artificial intelligence, reinforcement learning and reward for behaviour. In this case the reward was for getting close to the ball but it could also have been for moving in the most efficient way possible. In that scenario the movement would evolve to minimise energy use. This is a radically different approach to the traditional translational and rotational commands used to move from A to B.

Another set of recent studies has been looking at ways of using the characteristics of hydraulic controllers to embed the control directly into the system. This can enable motion control to be embedded in the system without any moving parts. This makes it possible to build a moving robot from one material, in this case polylactic acid, which can be easily constructed by additive manufacturing and is completely biodegradable.

We have also looked at how we can build control systems borrowing ideas from microelectronics. We took the way in which transistors are incorporated into microprocessors and created a similar network using fluidic transistors. This was originally developed by Professor Stephen Quake in the United States. The fluidic transistors can be stacked to create logic gates, memory and processors, and can then be embedded into the soft robots. It has been possible to create simple logic gates with no metals and no electronics which opens up a whole range of applications, such as working in high explosion risk zones or high magnetic fields for example MRI machines, or highly radioactive areas. These stacks can do sequential or combinational logic, enabling complex systems to be built from these sub-components. This development has been greatly accelerated by the development of software tools to characterise the different components and enable design choices and simulations using a fluidics hardware description language. This enables us to do synthesis by describing at a behavioural level what we want the system to do and then synthesise the layout and build systems that perform those functions.

One example is a system for biochemical analysis using enzyme kinetics. This was constructed from analogues of the microelectronic components and was 3-D printed using just one material to precisely control the fluid flows in the analyser. We also created an exoskeletal robot to move a hand which is used with stroke patients to restore the link between intention and action. This has now been developed by a spinout company called Bioliberty at the Robotarium at Heriot Watt who produce actuated gloves that can extend and contract a movement-impaired hand but with no sensors at the business end of the robot. The robot is inherently safe because it is pneumatic.

A third example is a robotic gripper used for handling delicate food products such as whole fish, fish sticks, salmon fillets, crab legs and chicken portions. The compliance in the soft fingers at the end of the actuator means that the robot can move very rapidly and instead of spending a lot of time accurately positioning, it can just grab at the food as it moves along the process line without damaging it. This avoids the hazards associated with using suckers to lift the food, where particles of food or bacteria may get sucked into the mechanism.

A fourth and very different example is a self-assembling access track used for decommissioning nuclear power plant. This structure can move into place without any electronic control and is sufficiently robust to withstand the harsh environment for long periods. This development arose from the original question of "how do we control soft systems without electronics?" which led to this system for autonomous control of hard robots through hydraulics. The power and data are both transmitted through the track structure, which can be used to enable a small, fast robot to traverse difficult terrain quickly. Most of the time in robotics is spent working out how to get the robot from one place to another. In this case that is very easy.

The Future

The future of robotics is in hybrid systems. This sounds like a familiar concept from movie plotlines with living tissue over a metal endoskeleton. In the real world however the hybrid is a combination of hard robots to do precise positioning with the benefits of compliance, speed and low cost that come with soft robotics. New materials and new fabrication methods offer some interesting opportunities in this respect. Another emerging technology is exemplified by another local company – Konpanion – who use soft robotics to build a companion robot.. The companion has been co-designed by end users and both responds to and provides effective touch. It looks a bit like a cushion but you can stroke it and it responds by making noises and snuggling in to you. It is definitely bioinspired, but not biomimetic. In some cases companion robots are made to look and respond like animals – this is not the case here, the companion robot doesn't have eyes or feet but you can be nice to it and it will be your friend.

Another recent development has been the concept of tunable stiffness. Some soft bodied animals such as jellyfish move by resonating at particular frequencies which enables them to conserve energy. Leo Micklem in the group at Edinburgh has built robotic fish which operate at specific stiffnesses and resonate at different frequencies so they are enormously efficient because they mimic the way in which fish move. From an engineering perspective if you can give people a greater energy budget to play with by improving efficiency then there are many opportunities for new applications.

Conclusion

Soft robotics is the future of robotics. We will end up with bio hybrid systems very soon. Natural systems have been around on earth for 3.8 billion years and have overcome lots of adversity based on what we see alive today. There is a lot that we can learn if we ask the right questions about how they have solved particular problems. For example we have been looking at some of the dead-ends of evolution and considering what would have happened if they had progressed. Bioinspiration is essentially just science: looking at the way the natural world is, trying to understand it and then trying to do something with it. You can't really do that in the lab. When we look at complex systems we can see insights into the way that nature has evolved over the last few billion years and some of the tradeoffs that it has been able to solve with the approaches that have persisted and the things that they have been able to do.

Questions

Q: How did the robot that was picking up bits of fish from the conveyor belt know where to go?

A: The system used a vision system to spot the product but it didn't need to do it in a very accurate way. It just needed to find the centroid of the mass approximately and then move the robot to that point to pick something up. Vision is actually a much easier problem to solve in robotics than touch. There is another company based in the Robotarium called Touch Lab and they are solving the problem of the amount of information that we get from touch and from touching things. Most of the vision systems that are used for the robotics that we work with are now well developed and relatively simple.

Q: How do you cope with unpredictability?

A: It depends what you are doing. If it is not relevant to the grasp or the pose then it doesn't really matter. For example if you had a piece of fish that is oddly shaped and the robot tries to grab it but it doesn't work then it will pass to the next robot. If that also doesn't work then it will be caught by a human further down the line. The point is that it is not trying to do really precise pose estimation with accuracy and precision; it is just wildly grabbing at things. Sometimes it works and sometimes it doesn't but as long as it works more times than it doesn't then you get the job done.

Q: What about the precision and accuracy required for a robot to open a door?

A: The key is that the way hard robots and soft robots are built is very different. If you remember the robotics challenge where we had all these robots trying to open doors and missing the handles and then falling on the floor the problem was with the approach taken, which was to try to model as much as you could about the system and then put it into the software, do everything in the computer and then try to run it back in the real world. We don't do that. We don't learn how to pick things up by reading books about how to pick things up, we just learn by doing it. A robot can't learn by doing if it is really expensive or there's a risk that it might break in the process or it might damage the person or thing that it is working with, so soft robotics changes the way that we do the research. Humans mess up all the time when performing tasks but this is the way that we do things. When we build traditional robots the design approach is to make it as precise as possible and this is very different to just letting it start and learning along the way. There is a hybrid approach. When humans pick something up they typically collide with the surface first and then slide along it to the object. We don't model everything we know about the system and work out the position of our fingers in Cartesian coordinates. That is the way that robotics has been taught but it is not the way that natural systems interact with the environment. A few years ago we presented a paper in a session that was called "Avoiding collisions in robotics" and our paper was called "Embracing collisions in robotics" because we asked "why do we spend all this time stopping robots from bumping into things?" We learn a lot by bumping into things: is it a soft or hard material, is it slippery, is it hot.

Q: How do you deal with the safety problem when the object weighs several tonnes?

A: I'm not suggesting that we would replace automation robots used, for example, for building cars in factories. Those robots work, they do a great job. What we are doing is adding value to robots by opening up many places where robots couldn't currently be. So you wouldn't use an octopus tentacle to do the sort of manipulation done at Clansman but you also wouldn't use a Clansman manipulator to provide healthcare to an elderly grandmother in a hospital, although you could do that with a soft robot.

Q: Can you say a bit more about the integration of control and embodiment?

A: This is a philosophical question that is not unique to robotics. It is the sort of question that Descartes was asking about Cartesian Dualism. Is it the body or is it the brain? It's similar in robotics; if you separate out the control from the embodiment then you can miss an opportunity. This is common in robotics; design the body first and then create a controller to work with it, then design the way in which the combination interacts with the environment. All three need to be co-designed and co-evolved to make a system that is useful for performing its task in its environment. Animals that are observed in nature have evolved in their environment with the materials around them to do what they do. A common problem in robotics is that we try to start with the most difficult problem first, creating a general purpose robot, perhaps humanoid, to do all manner of tasks in all situations. When you change the design approach you can abstract a lot of the control into the physical dynamics of the system and then use a model of that to provide the control. For example our robots that have legs to walk around, we only give them a high or low signal to do what they are doing. We don't give it a whole series of kinematic instructions and control loops and feedback. So our controller is really simple. We can build controllers using fluidic transistors because the input is simple, even though the output is complicated.

Q: Are there any bioinspired control mechanisms designed for use with soft sensors and actuators?

A: Neural networks are a good example of this. These were originally bioinspired systems but have now been abstracted so far from that original development that they are widely used without ever thinking about neurons and the way in which the brain works.

Q: How can we incorporate variable stiffness in modelling and control?

A: The control parameter that we modulate to control stiffness is the pressure in the hydraulic or pneumatic circuit. That produces a different bending stiffness of the beam that we are modelling. When a system is designed to operate at different speeds the peak efficiency can be maintained by adjusting the pressure to vary the stiffness.

Q: Many of your examples had an umbilical connection to something off-screen providing the processing power required to make it work. How far are we from having an independent system with all the processing power onboard?

A: We have built completely untethered systems with all the processing power onboard but they are not very advanced at present. We are not trying to replicate what has been done in electronics; we are trying to provide options for cases where electronics wouldn't work. Systems with independent power based on hydrogen peroxide with a platinum reactor have been produced to provide independent movement with fluidic logic to route the pressure to different parts of the system. They are functional but at present not useful: they are very interesting and usefulness will follow. Very often the quest for utility starts with something that is just interesting.

Q: Professor RV Jones said "Fortune favours the trained observer" and observation is central to all that you have described. What is the best way to introduce engineers to this field?

A: This is where I come into conflict with people who describe themselves as "roboticists". People like to have a label but it's all just stuff. Alex, who works in the group at Edinburgh has a background in fashion and design and came into a PhD in robotics from that starting point. It is not surprising that he is able to make things that nobody has done before in robotics. One of the difficulties in our education system is that we make people specialise early on and we continue that until they become experts. My mission in life is to actively resist becoming an expert in anything.

Q: Can you explain the role of 3-D printing in your work?

A: Additive manufacturing is great. When I started as a faculty member at Edinburgh eleven years ago I bought the first 3-D printer in the department and now everyone has one. It is reminiscent of the aphorism that if all you have is a hammer then everything that you see is a nail. People use 3-D printing to make things that really shouldn't be 3-D printed but we try to produce things that could only be made by 3-D printing. The key is the design, build, test, fail, learn loop. We can do that really quickly, making lots of failures along the way. Being able to fail quickly is essential and this often is what limits people in the speed at which they progress. The things that Elon Musk is doing at the moment are failing all over the place, but he learns a lot when he fails. This is another aspect of the education system that we need to buy into: the creativity of playfulness, learning by doing and learning by failing. 3-D printing lets us get things wrong lots of times but we can do the classic revisionist thing when we write it up as a paper: this is what we wanted to do, this is how we did it and here are the results. It is much more useful to be open and honest about the failures along the way.

Q: How do you get funding for such loosely defined goals?

A: I suppose when we talk about things that are broken in science and engineering, one of them is funding. If you only ever do the things you are funded to do then you never make progress because you can only get funding if you have already done it. So often you get the funding in to do the thing that you have already done and then you work on the next thing. This is a strange way to do things and what it does is to favour people who have large labs and lots of funding. When we try to de-risk science and engineering to the point where you know it's going to work and therefore you put the money into it, it makes it not worth doing. That is the balance that needs to be struck in research funding and I am pleased to see that some of the new mechanisms that are coming out in the UK around higher risk, higher reward funding are addressing this. The criteria for European research grants such as the ERC starter are that they will only fund the research if you don't know how to do it and nobody else knows how to do it. The value is then created in the unexpected things that happen, sometimes by accident. Some of the greatest examples I;ve seen are when somebody messes something up in the lab, they make a mistake, and immediately they say "Ah, I got that wrong but it's quite interesting." That sort of facilitating serendipity in scientific research is what I try to do by bringing in strange people from strange places and making them work on strange projects that they don't know anything about. It's something I've always done and I quite like it because experts will do things the right way and what we want is for people to do things in a different way. I think that's why bioinspiration is a good model for scientific research because it allows people to do research without looking stupid. They can say "this thing does this but I don't know how" and so you can ask lots of questions about it, construct a hypothesis – "I think it does it this way" – and when it turns out that it doesn't do it that way that's still OK because you have learned something by doing it. You can do hypothesis led research by saying "this is my best guess as to how it works", then when you find out that's not how it works you have learned something, and that's great.

Q: Can you describe the functionality of the companion robot and how it is manufactured.

A: The skins that Alex makes for Maaa use a 3-d knitting machine which means that you can customise the yarn and the weave and build in sensing elements, optics, conducting fibres and other pieces, enabling the product to be customised. The first thing everybody does when they buy an iPhone is to get a cover for it because then they know it's their phone. When you buy a robot they all look the same. That's fine for research, but when you own an object that you want to interact with, or that lives in your house and you want to show off then you want to have something personalised and customised to you. Enabling that in the design process is something I never thought of before Alex came to work in the department and it is now embedded in a lot of what we do. "How do you make something which is desirable?"

Q: Where will bioinspired engineering take us in ten years time? Do you have a specific goal in mind?

A: One example, currently being developed in the United States, is the building of soft robotic systems directly from cells. This is being led by Mike Levin and Josh Bongard who have made robots from cell tissue that can move and navigate, and more recently that can self-replicate. Their primary function is to find suitable cells and push them together to make copies of themselves. This has been done successfully with frog cells and more recently with cells from human trachea. This moves us from bioinspired engineering to engineering biology. It goes back to the playfulness of the Greek creation myths, using the biological building blocks of life at multiple different length scales and making systems that have utility, that are functional, that are built from materials that are readily available around us and that don't require import or export. In ten years time I think that robots will disappear into the background in the way that mobile phones did, so that you don't even notice that they are there. These will be service robots and will just be an accepted part of everyday life. The frontier science that will be done will be building entirely new life forms that are previously unknown to science and can do all kinds of interesting things. As to "why?" we will have to work that out as we go along.

IES
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The Institution of Engineers in Scotland

Encouraging the next generation

Jemma Quin Member of IES Council.

Jemma Quin

Introduction

Since I joined the engineering industry back in the noughties I've been told that we are facing a shortage of engineers across all sectors.

According to the Institution of Mechanical Engineers[1], 120,000 engineering professionals will have retired by 2026. In 2023 they estimated that by 2030 there will be a shortfall of one million engineers. With all these people retiring we need to replace them with new people entering the industry. So how do we do this? Children pick their careers based on what they are exposed to, with the biggest influences being their parents, school and popular culture. According to a survey by joblist.com "48% of people felt that their parents strongly influenced their career path"[2]. So what barriers or misconceptions are putting children (and their parents) off engineering? These are:

- lack of awareness of engineering careers
- bias/ negative stereotype – that it is boring or "just for the boys"
- perception that there is no work (especially in Scotland)
- lack of apprenticeships or routes into engineering

How can we encourage children to pursue STEM subjects and go into engineering careers? The solution at first glance seems simple. We expose kids to the many engineering options in a fun and engaging way and destigmatise some of the misconceptions like "it's just for boys." Then they will fall madly in love with engineering and choose it as their career, which I assume most of the people reading this, like me, did.

There are many organisations and volunteers following this approach by going into schools and running fun activities with children. One organisation that the Institution of Engineers in Scotland supports is Primary Engineer, who run competitions like "If you were an engineer – What would you do?"

This is the direct approach which works well. However, not every school has the opportunity to receive these activities.

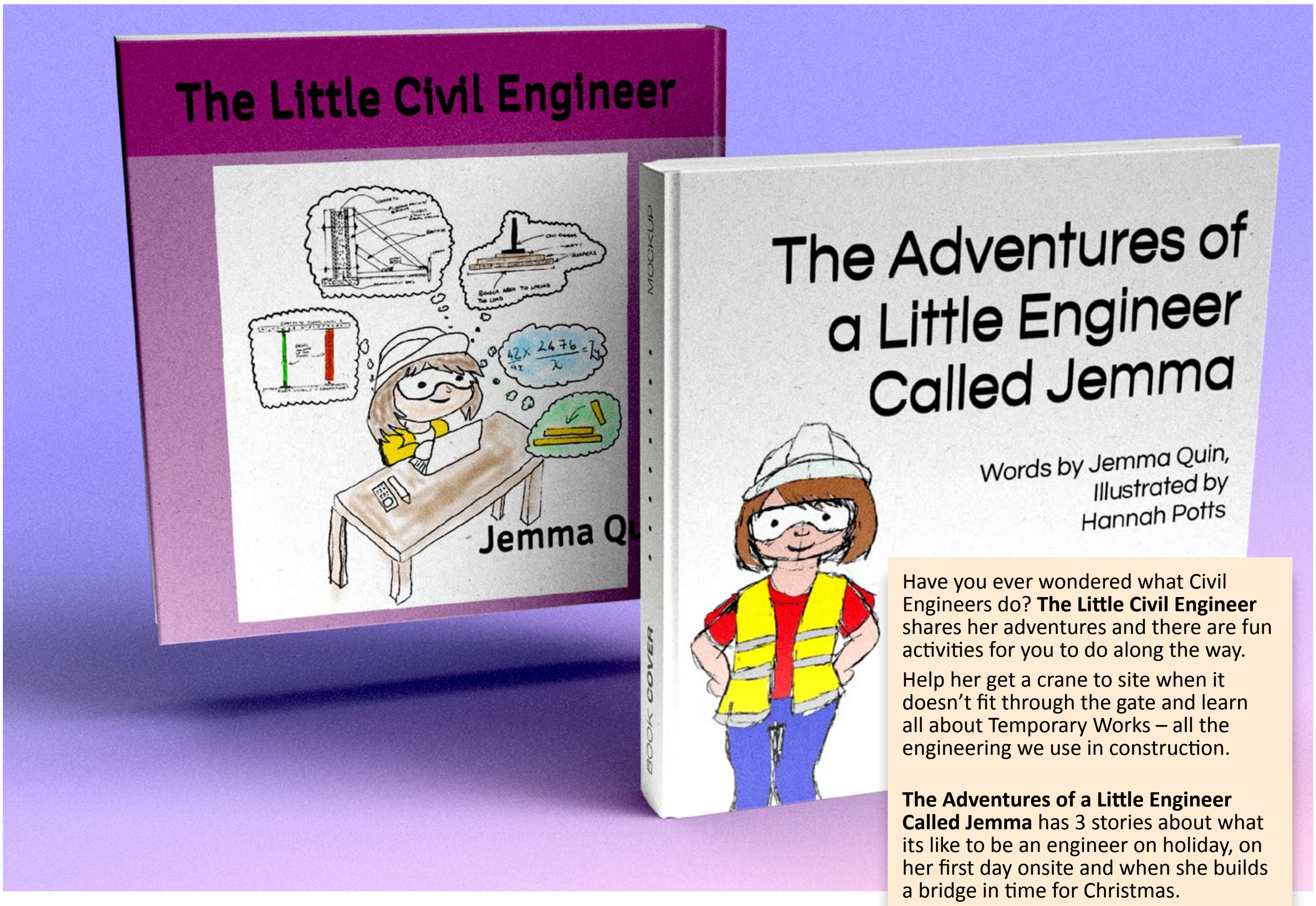
So, if not in the classroom, where else can children get their inspiration?

Looking back on my route to engineering I consider what I wanted to be when I was little. It changed every week, based on what TV show I watched. After ER I wanted to become a doctor. After Doctor Who I wanted to become an adventurer. So perhaps we could have some engaging TV programs to encourage engineering?

Growing up in the 90's my first memory of engineers on television was from the various versions of Star Trek, including "Scotty", Geordi La Forge, Chief O'Brien and B'Elanna Torres. They toiled away in the engine room making sure their captains had "warp speed" and could "create an inverse tachyon pulse" at a moment's notice. My favourite was B'Elanna because she looked like me (the short dark hair, not the forehead ridges) and she was allowed to be angry on screen. She was respected by her crew and ended up saving the day on more than one occasion. Looking back, she was one of the unconscious reasons I became an engineer later in life.

1 https://www.imeche.org/news/news-article/shortfall-of-1m-engineers-threatens-uk-infrastructure-projects

2 www.joblist.com/trends/the-impact-of-parental-influence-career-edition



Have you ever wondered what Civil Engineers do? **The Little Civil Engineer** shares her adventures and there are fun activities for you to do along the way.

Help her get a crane to site when it doesn't fit through the gate and learn all about Temporary Works – all the engineering we use in construction.

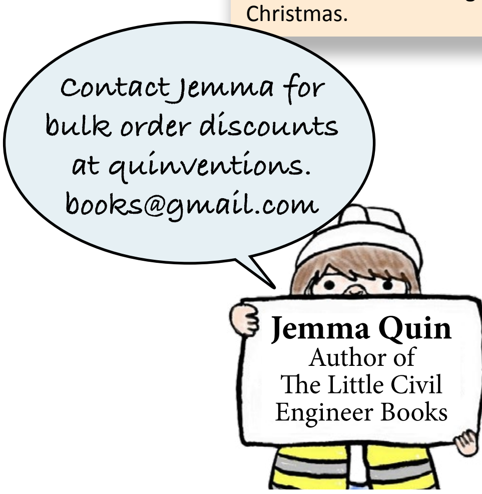
The Adventures of a Little Engineer Called Jemma has 3 stories about what its like to be an engineer on holiday, on her first day onsite and when she builds a bridge in time for Christmas.

She has a rubbish first day on site but doesn't let that deter her from pursuing her dreams of being an engineer. Then by the 3rd story a village asks her to fix their broken bridge in time for Christmas.

I would love to produce a TV show/sitcom which shows the real life of engineers. Think "Downton Abbey", but on a construction site with operatives vs engineers in the office, or "The Office", but in a factory. However, I haven't quite figured out the script or how to finance such an adventure.

The other big influence in my life is reading. I decided to write about my own adventures in engineering, hoping they will one day inspire future engineers. The books have short snappy rhyming stories about things which happened to me. The first is "The Adventures of a Little Engineer Called Jemma" and it describe her first day on a big project. It shows how everything was overwhelming, but she carried on anyway. Then, by the end of the book, she builds a bridge in time for Christmas. The second book shows problem solving (how to get a crane to site when it doesn't fit through the gate) and has activities for kids to follow.

The final question is "What more can the IES do to promote engineering to the next generation?" I am setting up a working group to look at this very topic. If you would like to join me please contact Laura Clow at IES and let her know that you are interested. Jemma's books are available on Amazon and at other outlets. They can be ordered by clicking the red play button opposite.



Both are available in Kindle and paperback format on Amazon.

Jemma is a STEM Advisor and offers interactive sessions with schools, after school clubs and local community groups where you can find out more about the real-life engineering that inspired her books.

Discounts are available for bulk orders. Please contact quinventions.books@gmail.com for more information.

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The Institution of Engineers in Scotland

What Have Mathematicians Ever Done for Us?

An Exploration of Industrial Mathematics in Engineering

Professor Chris Dent

Presented to the Institution of Engineers in Scotland, 24th October 2023, University of Strathclyde.

Prof Chris Dent is a Chartered Engineer, and an academic in the School of Mathematics at the University of Edinburgh. His research interests are in data and model-based decision support in energy, infrastructure and government. He has long experience of working with industry; including analysis underpinning the electricity capacity market for the National Grid ESO; Technical Lead on the National Digital Twin programme Climate Resilience Demonstrator; and a current knowledge exchange project with an internatonal consortium of power system operators.

Chris is a Turing Fellow at the Alan Turing Institute, a Fellow of the IET, IES and OR Society, and is Standards Officer for the IEEE Power and Energy Society Analytical Methods for Power Systems Committee.

Introduction

Mathematics underpins all that engineers do, but this is not fully recognised, particularly where the mathematical approaches used have become very long-established. This paper gives a number of examples of where the kind of thinking that is specific to the mathematical sciences can be helpful in thinking about questions of planning or operating engineering systems.

Professor Chris Dent

I was asked to give a talk on the subject partly because of my job title of "Professor of Industrial Mathematics". In the School of Mathematics at the University of Edinburgh this title has no great philosophical implication – it essentially means that to be considered candidates must have had some effect on the world outside academia! Many other understandings of the term exist, though I am very happy with a meaning that presupposes nothing other than work relevant to genuine industrial or societal issues (as opposed to the made-up versions that academics have been known to work on).

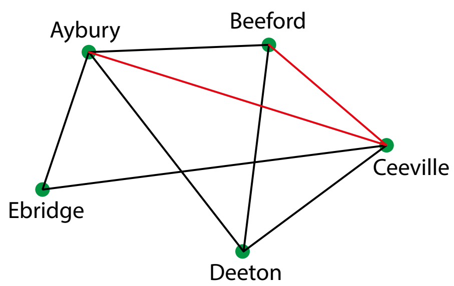
The key point will be that the relevance of the mathematical sciences is not simply about carrying out bigger, harder or more detailed calculations.

Network Control

A good example of the relevance of mathematics is the decentralised operation of complex engineering networks, where the system is simply too large to permit scheduling by a central computation, as the resulting calculations would be intractable, and it might even not be feasible to bring the relevant data together centrally.

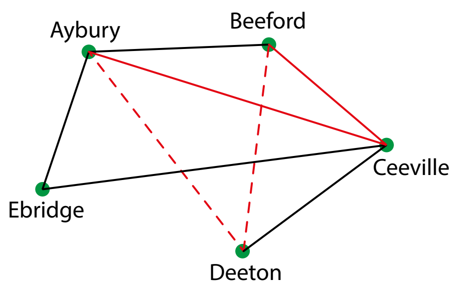
Indeed the mathematical field of stochastic networks has developed in tandem over the years with the field of communications engineering. Over 100 years ago Erlang studied the requirement for phone lines to a village, using what is now known as the Erlang distribution. Fast-forwarding to the the 1980s, there was a need to re-develop the call routing system for the national trunk network for long distance calls. As the number of calls on the national network increased, the central computation for routing was becoming intractable. A simplified version of the problem is shown in Figure 1 with a five node network of towns, called here Aybury, Beeford, Ceeville, Deeton and Ebridge.

Ideally a call between two neighbouring towns, for example Aybury and Beeford, would be routed directly. If that link is full because network traffic is heavy then an indirect path may be required in order to connect the call, but using two links places a greater burden on the network at a time when it is already congested – for instance the map in Figure 1a shows a call from Aybury to Beeford being routed through Ceeville. It is possible for this to lead to a "congestion collapse", where a tangled spaghetti of too many indirect calls significantly reduces the overall network capacity to carry calls.



Network map showing calls from Aybury to Beeford being routed through Ceeville.

Figure 1a Routing trunk calls on a network
Graphic Credit www.plus.math.org



Network map showing change in route from Ceeville to Deeton.

Figure 1b Routing trunk calls on a network
Graphic Credit www.plus.math.org

The solution found by Frank Kelly and Richard Gibbens at the University of Cambridge developed an approach called "Dynamic Alternative Routing" which relied on two very simple rules. First, some capacity is always reserved on each link for direct calls ("trunk reservation"). If despite this there is no further capacity for a direct link then the system remembers the last route that worked between the two points and seeks to use it again ("sticky routing"), and if that is also not available then subsequent options are tried until a connection is made.

Such algorithms for network control can often seem almost comically simple like this, but the mathematical contribution that Kelly and Gibbens made was to prove mathematically that these simple rules perform essentially as well in solving a relevant optimization problem that can be written down in principle but cannot be solved in practice. In particular, trunk reservation is key to avoiding congestion collapse.

Data Transmission on Networks

Another example, on which Frank Kelly has also worked, is the control of transmission rates of data on a network such as the internet, for the management of congestion given finite capacity. Again it is not feasible to manage this centrally, and there may also be issues with varying network configuration, data privacy and other constraints. Each source increases the rate of transmission linearly until a data packet is lost, and at that point the data transmission rate is multiplied by a factor (for instance halved), with the linear increase then repeating. Again this can be shown to solve a central optimization problem that is not tractable in practice.

One feature of both of these examples is that there is no overlaid additional communication system for control signals, with the control being intrinsic to the task at hand. In the first example it was "can you route a call?" and in the second it was "did you lose a data packet?"

Control of Power Systems

In alternating current power systems, the frequency of ac current and voltage oscillation is used as a measure of the balance of supply and demand; again the signal is intrinsic to the system and so there is no need for any overlaid communication system.

AC power networks are not just an electrical systems, but rather electromechanical systems with conventional turbine generators rotating at the same synchronous frequency as the oscillations of the ac current. If the available supply is below the demand, then additional power is drawn into the grid by slowing down the rotation of the generators. If supply exceeds demand, the opposite happens and the frequency rises.

Use of this signal depends on different circumstances. Supply-demand balance is maintained continuously through generators adjusting their outputs slightly in response to any imbalance indicated by changes in frequency. If there is a sudden large drop in frequency arising from a sudden loss of infeed to the systems, then more dramatic intervention is triggered – for instance, fast ramping generating capacity might come on line, such as pumped storage hydro units at Dinorwig in Wales which can ramp from zero to 300MW output in about 10 seconds. If the frequency goes even lower then emergency load shedding might be initiated, disconnecting a limited proportion of customers in order to prevent collapse of the whole system.

The events of 10th August 2019 give a good example of this. After a lightning strike large generating units disconnected in quick succession, causing a drop in generating infeed and consequent drop in frequency far greater than the system was designed to handle without customer consequences. Figure 2 is extracted from the National Grid Electricity System Operator's report "Technical Report on the events of 9 August 2019" which was published on the 6th September 2019, less than a month after the incident.

The frequency was initially close to its nominal value of 50 Hz, but with the initial loss of infeed it dropped suddenly. This initial loss of infeed was within the range that the system can handle, and the frequency drop was arrested and frequency stabilised at 49.2 Hz. After a further loss of infeed, the frequency again dropped suddenly, and at 48.8 Hz the first tranche of under-frequency load shedding was triggered. This produced the required recovery of frequency because there was then a significant surplus of generation versus the reduced demand. Over a slightly longer timescale additional generation capacity was brought online, and frequency recovered within 5 minutes with all demand being reconnected soon after.

The only significant longer-lasting effect was on a particular class of train on the Thameslink network, which shut down after the outage, and could only be restarted through an engineer visit. This is often how the most severe after-effects of power outages occur, when something somewhere connected to the system fails to respond as expected and doesn't follow the rules laid down for it. Indeed the lightning strike that triggered the power system disturbance was an innocuous event, and the two large generators that disconnected should under the Grid Code have been able to ride through the fault event.

A topic of present interest, where there is direct analogy to the telecoms questions discussed earlier, is decentralised operation of future power systems. Historically the operator of the Great Britain power system has interacted directly with a few hundred large entities (mainly power stations), instructing changes in their output or demand to balance the system. In future we envisage the majority of customers having electric vehicles or heating, and coordinating their demand with the system, resulting in tens of millions of individual

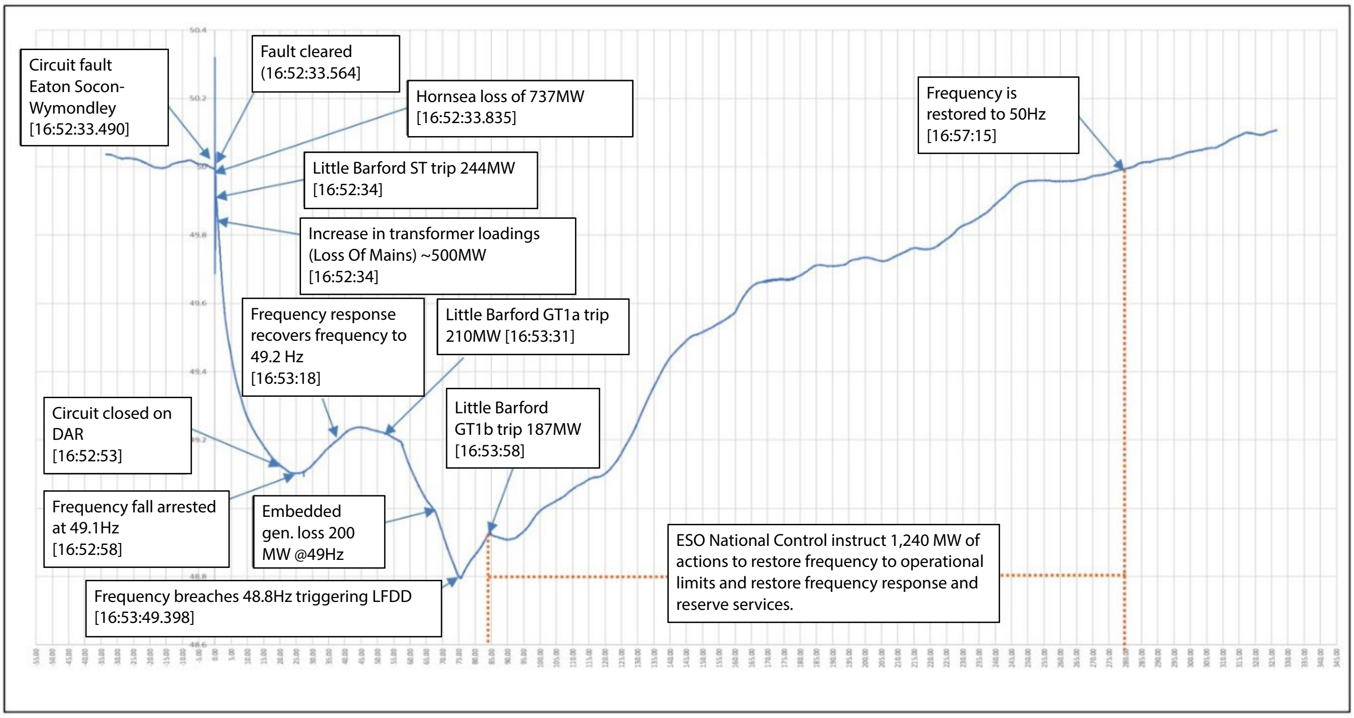


Figure 2 Sequence of events 9th August 2019 *Graphic credit National Grid ESO*

entities which in some way need to be scheduled. Central scheduling of such a complex system is clearly not possible, and so some kind of principled architecture, or set of rules, for decentralised operation is required.

Similarly to the communications systems examples, it is easy to write down a set of rules that seems generally sensible, but it is much more difficult develop the kind of mathematically rigorous analysis need to provide that the rules will work (i.e. give the intended outcome in a stable way) in a wide range of situations. One difference between the examples of power systems and communications systems is that the commodity flowing in the power system is the physics of the system; in communications, when we are dealing with data packets or telephone calls we are already abstracted away from the physics.

Another challenge in power systems is the nature of congestion management. In communication systems it is accepted that occasionally calls cannot be routed, or that at busy times connections might be slower. The equivalent in power systems would be involuntary disconnections, which is counter to the present paradigm that when people flip the switch they get exactly what they want when they want it. However, this may change in the future, where large new domestic electricity demands such as heating and transport are intrinsically flexible in a way that most present large demands are not.

More detail on this challenge may be found in a recent report for the Energy Systems Catapult by the author and colleagues.

Conclusion

This paper has presented a number of examples of where mathematical thinking can help with control of engineering systems, based on a talk the author gave in the Institution of Engineers in Scotland's 2023-24 series. For those interested in learning more about applications of mathematics in engineering, there are many articles on the excellent "plus.maths" website, including a podcast interview with the author and his colleague Lars Schewe. A number of other general-readership articles by the author may be found on his School's website. A recent journal article, written for a general engineering audience, was the basis for the section of the IES talk on electricity security of supply, which is not included in the present article.

Questions

Q: In terms of the approach used in assessing large infrastructure projects what would you do differently?

A: The budget allocated to the early strategic analysis underpinning large projects is typically not commensurate with the capital costs in play. A few years ago Gordon Masterton, I and others ran a scoping network for the Centre for Digital Built Britain on planning complex infrastructure. I made this point in one of the associated workshops, expecting some slightly controversial debate, but actually people just agreed and it went in the report.

Given the amount of money we're spending on such capital projects it is worth just putting more effort into the initial strategic decision of what it to be built build, what size, etc. It would also be helpful see these early assessments and decisions better documented in order to assist with reappraisal. For instance, when there is large uncertainty associated with the benefit analysis, in order to be able to take logically well-founded decisions the assumptions and judgments made need to be clearly stated. Even if the project goes well it might not be commissioned for maybe 10 to 15 years, and may have a lifetime of half a century or even longer, so appraisal of the quality of analysis may need to study the process rather than the results.

One specific issue is that for line items that do not start out as cash flow and have to be monetised, there may be no single generally accepted framework, even in specialist methodology communities such as the statistical uncertainty quantification world – in particular, expert and reasonable people might differ not just as to the numbers but the way that monetisation is conceptualised.

Another mathematical/statistical issue is that we are often dealing with one off events or projects, and thus one cannot sensibly use a frequentist understanding of probability in terms of the average of a large number of trails. Philosophical ideas about the interpretation of probability then become very practically relevant, and I have gained a lot from my interactions over the years with the field of what one might call "applied philosophy" (not everyone assumes that such a field exists!)

Q: The decision making process for large infrastructure projects takes many years. Societal changes, for example modal shifts in transport and a greater emphasis on decarbonisation, change the ground rules during that process. How different would recent analyses be if these had been taken into account at the start?

A:* It's pretty fair to say that there would almost certainly have been much more emphasis placed on carbon benefits. I don't think there was very much mention of that at all even back in about 11 years ago when the main appraisal of the HS2 project was done. Other recent examples of really big ticket appraisals in the £10 billion bracket include the Lower Thames Crossing and the tunnel under Stonehenge. The Lower Thames Crossing is at risk and a huge amount of effort has been placed on that analysis. The Stonehenge tunnel was objected to and went through the courts before it was finally given approval. All of those discussions were about environmental impact and in the case of Lower Thames Crossing how efficient is it in terms of net zero carbon so those issues are much more relevant today than they were 11 years ago. I suppose the other one which is not that recent now because they've spent an awful lot of time building it is Hinkley C looking at new build nuclear power they're in the low tens of billions again one of the issues that always rather baffles me there is that again it's another one of these things which has nothing to do with the analysis but with Hinkley C why on earth if you're going to buy one you buy it from the French when they spent the last decade proving that they can't build one in Finland and France and it does seem to have gone up cost a little bit from the original estimates but I think it's likely that the biggest shift in emphasis would have been the carbon emissions aspect.

Q: it seems that a lot of the difficulty in what you're describing is in making rational decisions based upon a scarcity of information. Either there's not an awful lot of it about or you're having to plug the gaps and fill in between the knowledge that you do have. Do you get frustrated in seeing the way that people do this because they make the same mistakes over and over again or do you think that we've got that just about right?

A: Yes, I think one of the key issues (and a recurring theme in this talk and Q+A) is simply that insufficient resource is allocated to these assessments. Often, with additional effort uncertainties can be reduced, or at least understood better.

One challenging aspect about the future is that one cannot have direct data (because it's the future!), must accept that either explicitly or implicitly a lot of the numbers come from some form of human judgment (e.g. by technical experts or decision makers).

One particular frustration I associated with government, though perhaps less so with industry, is that the government does big capital projects government, uses single annual cycle consulting projects, and basic research falls under the research councils – but there isn't a standard mechanism directly in government for multi-year innovation agendas on matters such as improvement of analysis practices. There are exceptions, for instance under DEFRA in areas of environmental science where there are government research labs.

Q: It seems that the maths isn't really the problem because if you feed in poor assumptions and poor data then what you are going to get out is what you decided you wanted in the first place, but you did say that you thought that if people invested more in upfront analysis this might improve things. Can you quote any examples where that's actually proven to be true?

A: It is certainly easier to find examples where things have run into trouble. There is an excellent book by two political scientists called The Blunders of Our Government, where their thesis was essentially that British government is particularly prone to a certain kind of blunder precisely because there commonly is not enough deliberation consideration of different options.

A:* An example that unfortunately is perhaps perceived as less than successful but deserves greater credit is Crossrail, now called the Elizabeth Line. In terms of the analysis that went into the assessment of whether there should be an east-west link across London for full sized trains this was first investigated in the post war era. It was revisited in the 1980s and the 1983 review said that it wasn't justified so it was then analysed again in the 1990s and finally the 2008 hybrid bill succeeded. Every time that the previous analysis failed there were still people working on maintaining the concept and revisiting it and therefore honing and looking at the wider economic benefits.

The other positive examples I can think of are generally ones with narrower scope, where the analysis sits in a more conventional realm of science. A good instance was the estimation of the number of people in modern slavery where the then Chief Scientific Advisor at the Home Office, Bernard Silverman, was a statistician working closely with the relevant minister, who also had a scientific background. Silverman gave a great talk about this where the punchline was that when the Minister presented

* *This response was provided by Professor Gordon Masterton*

the findings, she explained it better than he could have done. It's not impossible to find good examples, but in the majority of cases, particularly in relation to large scale projects or policy analyses, there simply isn't enough resource devoted to this kind of analysis; there also is a lack of mechanisms for the innovation agendas needed to make major improvements in how this kind of analysis is done.

Q: In the Gulf Cooperation Council of Saudi Arabia, Kuwait, Qatar, Oman and UAE, they initiated projects for three separate rail tracks; high speed rail between the member countries, the Silicon Road initiative balancing the Chinese corridor and the economic corridor to Europe. How can consultancy firms such as McKinsey or Bain manage to run the mathematical analysis for these projects within that two year timescale yet it is much slower in Britain?

A: I don't know about this specific case so can only speak about the British experience, but I can recall that one of the major issues facing the energy industry in Britain is how long the various permission processes take. The issues in play are pretty simple: There is the national benefit of doing the project and you the local objections. It is important to treat the objections as fairly as possible but often the issues that will arise are obvious without any consultation. A public adversarial process is often not fair because it produces extreme asymmetry of resources between the proposers and the objectors. Arguably one could devise a process that would be a lot quicker and would look after the interests of the objectors better through a regulatory approach with a very robust "red team" exercise to identify limitations of the project's justification.

Q: Is there a role for industrial mathematicians in the early appraisal of projects such as the Queensferry Crossing?

A:* Yes, like any large infrastructure project a lot of the analysis will benefit from an analytical approach, but particularly so in the ongoing operation of a bridge like the Queensferry Crossing. One example that comes to mind – not actually the Queensferry Crossing but the Forth Road Bridge – was work done at the University of Strathclyde by the statistics group in the Management School. It is a good example of a tricky reliability problem in areas where inspection is difficult or expensive. They looked at the condition assessment of the suspension cables with the idea of making an overall system assessment based on the limited number of measurements that can be taken.

Q: I have read that experts are so expert that they believe that there is very little error in their judgement, so they are likely to come up with a plus or minus 2 percent or 5 percent on their estimates whereas the lay public, who know much less about the project are more likely to have a broader range. In practice the final answer is likely to be within the public range but outside the experts' one.

A: Yes, there has been some work on overconfidence. One of my colleagues, Kevin Wilson from Newcastle University has a good example where he would ask an audience to estimate the distance between two cities and place a margin of error on their figure. In England he would typically use Glasgow and Edinburgh. The audience always tend to overestimate and are too confident in their uncertainty bounds. He goes on to talk about how to get realistic uncertainty estimates when working with a group of experts by confronting them with each others' estimates and refining the individual figures with a group assessment.

Q: Has there ever been a case in a public infrastructure project where the "minus" in the concept of "plus or minus" has ever come good?

A: It is certainly fair to say that the distribution inevitably is skewed towards the plus side, simply because there isn't a bound on that side – there is a limit to how good things can be but no limit to how wrong things can go! I think the Queensferry Crossing is a good example of a project that was pretty much on target and Crossrail is another example where given the size of the project it wasn't a terrible result in terms of either cost or schedule. The problem there was that the project team didn't admit to delays until a few months before the scheduled opening.

* *This response was provided by Professor Gordon Masterton*

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The Institution of Engineers in Scotland

Hedgehog or Fox?

Exploring Ethics in Engineering

Professor Raffaella Ocone, Heriot Watt University

Presented to the Institution of Engineers in Scotland, 16th April 2024, University of Strathclyde.

Raffaella Ocone OBE FREng FRSE is the Chair of Chemical Engineering at Heriot-Watt University and Guest Professor of Multiphase Multiscale Systems at RUHR Universität, Bochum, Germany. At RUHR Universität she was awarded the first "Caroline Herschel Visiting Professor" in Engineering (July-November 2017) in recognition of her work in ethics in engineering. She is an authority on complex reactive systems and their application in the energy industry. She has co-authored a Royal Academy of Engineering report, funded by the UK government, on the biofuels industry. Her research team have recently announced a £1M research partnership under the PETRONAS Centre of Excellence in Subsurface Engineering and Energy Transition (PACESET), to advance techniques to use thermochemical reaction to produce hydrogen from biomass and other waste materials.

Introduction

It is difficult for an engineer to present a subject without any equations or data to show. When discussing ethics it is useful to have some context and give some background to the subject. The presentation can then pose some questions but it does not aim to provide answers to the questions, because there are not usually simple answers to these types of question. Instead the paper presents some scenarios and hopefully leads to some discussion of the issues that they raise.

Engineering students sometimes are reluctant to address philosophical questions but it is important to appreciate that in ancient times ethics was more a way of living than an abstruse concept, so we need to go back to the ancient philosophers if we want to understand the way forward with modern challenges.

Professor Raffaella Ocone

Aristotle wrote in his Nicomachean Ethics (in 1142 BC) that ethics is simply "practical wisdom", and he observed that young people seemed to be interested in studying geometry and mathematics but that "prudent young people do not seem to be found". Becoming prudent, in this sense, means gaining the practical wisdom that helps them to understand the implications of their geometry and mathematics. In parallel with the ancient philosopher we should also consider the ancient engineer. In his 1963 book by that name Lyon Sprague de Camp describes the development of engineering from about 3000 BC up to the time of Leonardo. On the last page it concludes that "Civilisation is a matter of power over the world of nature and skill in exploiting this world. It has nothing to do with kindness, honesty or peacefulness". Sprague de Camp goes on to say "No doubt it would be a good thing if they were universal, but the engineer is not the man to ask this of. He can heat your house, dam your river, or build your space ship, but it is hardly fair to expect him also to make you love your fellow man." In reality modern engineering is not like this. Engineers work in society, they have to be creative, they have to have core knowledge, but they also have to be aware of society. Their technology needs to be sustainable and it needs to be inclusive, so engineers in the modern world need to be concerned about these ethical questions.

Introducing the hedgehog and the fox

The twentieth century philosopher Isaiah Berlin wrote an essay called The Hedgehog and The Fox in 1953, contrasting writers who focus on one big idea (hedgehogs) and those who draw on a wide range of experiences to frame their thinking (foxes). The term comes from the Greek poet Archilochus who wrote "the fox knows many things, but the hedgehog knows one big thing." Engineers for many years have

been like hedgehogs but we ought to behave more like foxes. Ethical considerations in engineering are not in fact new. In the sixteenth century the German metallurgist, Georgius Agricola, known as the Father of Mineralogy, produced a beautiful book, De Re Metallica. He wrote "mining is a perilous operation to pursue and there is no compensation which should be thought great enough to equalise the extreme dangers to safety and life." However, he goes on to write "since things like this rarely happen, and only in so far as workmen are careless, they do not deter miners from carrying on their trade and no more than it would deter a carpenter from his." This seems to be the first mention of worker safety with regard to working practices. Now it is important not to confuse safety and ethics, although it is possible to consider safety from an ethical point of view.

One example of this comes from the Apollo XIII mission, famous for the phrase "Houston, we have a problem". The problem was that, due to a fault in the electrical supply, the module that was to serve as support for the mission (the command module) lost power and oxygen. The crew had to transfer into the lunar landing module and use it like a lifeboat to return to earth. In this case good management of the problem made the rescue mission a success. However a very different scenario occurred in 1986 during the launch of the space shuttle. Just 73 seconds into the launch, and live on television broadcasts all round the world, the shuttle disintegrated. This was very much an engineering problem with an impact on safety because it was all to do with data. The root cause of the explosion was that an O-ring in the fuel system broke down and allowed hot gases to recirculate into the fuel stream, ultimately causing the explosion. This is a good example of an engineering ethics case study because there were many factors in play in the background. The NASA engineers knew that there were problems with the O-rings when the temperature was low – and indeed on the day of the launch the weather was very cold. However they were also under pressure on several fronts. Congress were unhappy with NASA because they were not delivering results and launches were often being postponed. There was competition from the Russians which intensified the pressure to go ahead. So they took some high temperature data, extrapolated it and concluded that it would be OK to launch. It was not OK and people died.

The problem of data

Today in engineering we are still surrounded by data but now we might face additional issues, such as hallucinations. Artificial Intelligence, for example Chat GPT, can provide quick answers to seemingly complex questions. Sometimes the answer is good, indeed sometimes it is very good, but if you drill down with information that you know to be true you can sometimes find that the plausible answer from the large language model is a fabrication – a hallucination. For example, I know that the majority of the oil extracted in the UK is not refined in the UK so I asked Chat GPT the question "What percentage of oil extracted in the UK is refined in the UK?" The answer was presented in a beautiful way with figures for the amount extracted and the number of refineries in the UK, leading to the conclusion that all the oil extracted was refined here, but that is simply not true. This simple example illustrates a very significant point. In the modern world we are frequently manipulated by data-driven decision making which is very unethically based around data monetisation. However much of the basis for the decision making could be bult on false foundations.

The second example of an ethical dilemma affecting engineers does not at first sight seem to be about data. Imagine you are in charge of a gold mining company that wants to expand globally. The company knows that there is a new opportunity in Africa but they require a licence to commence operations. It is difficult for them to navigate the difficulties of negotiating a licence in a foreign country so they speak to the local mayor. The mayor suggests that the necessary paperwork can easily be issued if the mining company will fund the construction of a new hospital in town. Is this bribery? It is apparently in support of a good cause for the community but how can you judge whether the mayor will pass all the money on to the construction project and how can you tell whether the activities in the hospital will be above board – perhaps there will be organ trafficking in the new facility. The point here is that there is not a right answer. Often people do things in good

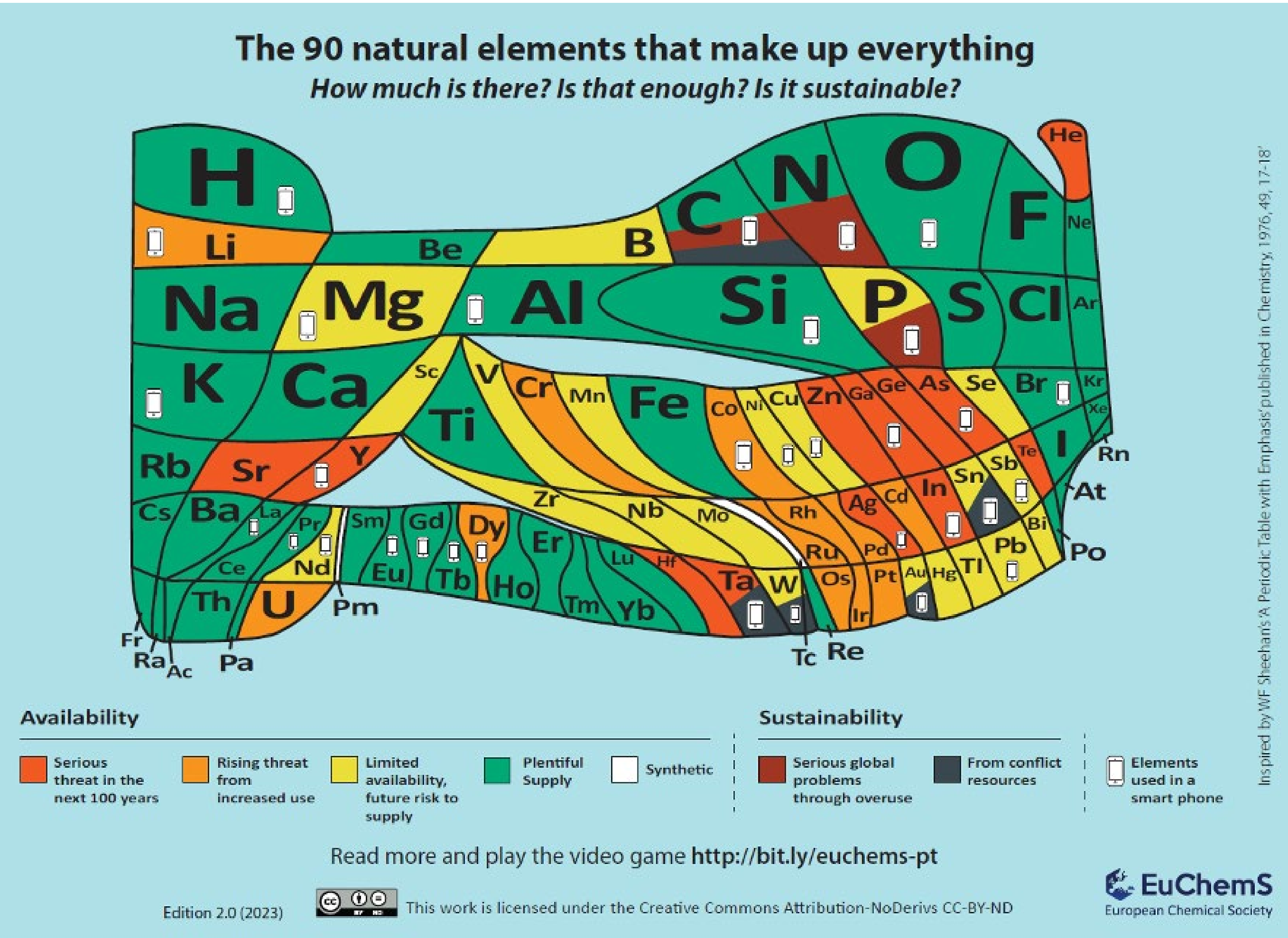

Figure 1 – The Periodic Table *Graphic credit The European Chemical Society*

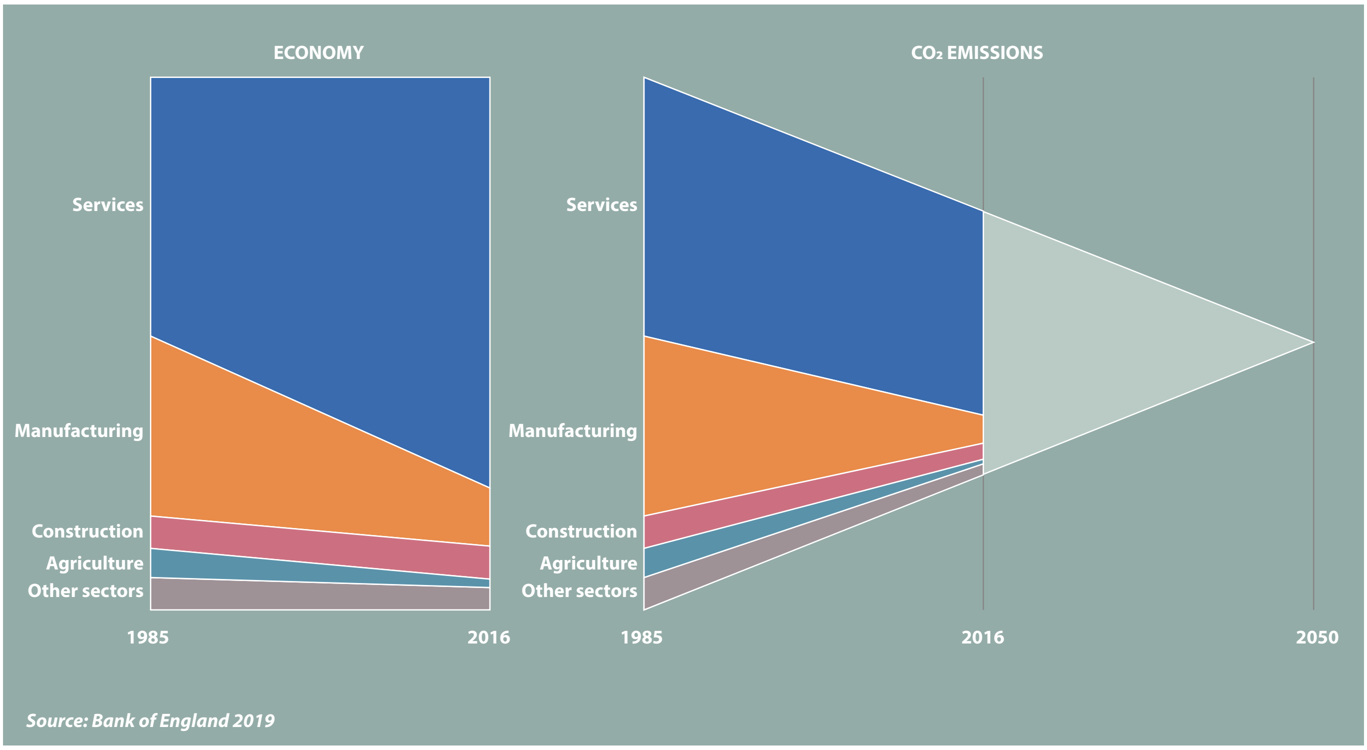

Figure 2 relative sector contributions to CO_2 emissions Graphic credit The Bank of England

faith but produce bad consequences because they don't look in detail at what is going on. For example, looking back to Georgius Agricola, the gold mining is potentially a hazardous operation so is it a good idea to fast-track a licence without ensuring that all the necessary safeguards are in place to protect the workers?

Ethical dilemmas facing modern engineers

The recent movie Don't Look Up, starring Leonardo di Caprio and Meryl Streep, tells the story of two astrophysicists who discover an asteroid heading straight for earth but are unable to get anyone to pay attention to them. Part of the problem was that big business identified that the asteroid contained many valuable minerals and the desire to exploit them overpowered the need to take care of humanity's wellbeing. This is based on a developing concern, illustrated by Figure 1. This is the periodic table but distorted to show how abundant the elements are and how freely available they are around the world. It also shows the elements that are used in the manufacture of smart phones and you can see that in some cases there is already limited availability with possible future risk to supply and in other cases there is a serious threat to availability in the next 100 years, even of common materials like zinc, silver and helium. The graphic also shows the elements sourced from "conflict resources" and this raises the ethical question "is it reasonable to change your mobile phone every second year?"

Is it ethically responsible to shift from oil refining to lithium mining? The sustainability issues for each activity are different but it is not simple question because it also shifts the geopolitical equilibrium and this has a huge impact on populations that also has to be considered when proposing such a change.

Another scenario that presents ethical challenges is the question of responsible manufacturing. This requires technologies that are competitive and agile, that provide environmental sustainability, that meet the customers' needs and fulfil the manufacturers' obligations to society. This means that the whole life cycle of the products has to be considered, including disassembly, material recovery, remanufacturing and pollution prevention. Can these requirements all be satisfied or are there tensions between them? Once again we need to take care to consider all the angles when we look at this question. On the face of it our CO_2 emissions have greatly reduced since 1986 as shown in Figure 2, despite the fact that the economy has grown in that time. However this is clearly because the proportion of goods consumed in the UK that are manufactured in the UK has greatly reduced. In other words we have been offshoring our emissions and we import more carbon intensive goods.

Remanufacturing raises additional ethical issues. It is very common in the automotive sector and can also be done with chemicals but there is a growing realisation that mechanical remanufacturing is limited in its application and chemical recycling, where waste is broken down into its constituent compounds which can then be reused as feedstock for new production. It is often forgotten that this is just a means of using more energy so we have to take care of what goes into the equation in terms of all the factors. Power to Food presents another relevant scenario. Imagine that emitted CO^2 could be captured and transformed through chemical or biological processes, powered by renewable energy, into food. This can already produce a microbial protein that can be used in animal feed and ultimately the technology could produce food for human consumption, further reducing the carbon emissions produced by intensive animal farming. Is manufacturing of food in this way at large scale ethical? The questions that this scenario prompts include whether the technology is responsible, whether cultural values, trust and business pressures would affect the ethical assessment, which areas of that assessment would be of particular concern to stakeholders and whether the location of the power to food plant would have a bearing on any of these considerations. Ultimately the question is "what is the role of ethics in technology development and manufacturing?"

We cannot stop technological progress and we must recognise that it will proceed whether we want it to or not. This follows a five step process from research and development through production to marketing and finally diffusion to society. Technologies that are at the production, marketing and diffusion stages are described as entrenched. If they are still under development then they are called emerging. Entrenched technologies could be classed as stand-alone, disruptive, incremental, enabling or pervasive. Artificial Intelligence is a very good example of a pervasive technology that we cannot expect to stop. This is a frightening prospect because most of us use the technology blindly. When we click on accept cookies on a website we are giving our permission for our data to be used in ways that we did not envisage. For example if I check the price of a blender for my kitchen on Amazon within seconds I am getting notifications on other sites, for example on X or on Instagram that there are beautiful blenders available to me. What are they doing with my data? Are they authorised to do so? Well, yes they are because I clicked at the bottom "accept cookies". I have authorised them to use my data. The data is a commodity and can be sold. In America there is less regulation and even facial recognition data has been traded.

Entrenched technology is already with us but should we be concerned about emerging technology and should we try to do something about it? Should we stop them or regulate them in such a way that we ensure that they are responsible? Would you stop the advancement of science? Could you stop it?

Science and technological advancement cannot be stopped. It will be done anyway so we need policies and regulation. Take stem cells for example. Nobody will be able to stop that development but it does have to be regulated. The problem we have at the moment is that the regulation varies from country to country and in some places it is not regulated at all. My personal view of this, which I am happy to debate with you, is that in the 21^{st} century the first decade was about converging technology, which is defined as nanotechnology, biotechnology, information technology and cognitive science. The second decade was more about the sustainable development goals and emerging technology. Now, in the middle of the third decade it is really about responsible technology, so that when we develop a technology we need to ensure that it is done in a responsible way. However, there is a huge ethical issue in the converging technology segment. This work was commissioned by the US National Science Foundation and the Department of Commerce who identified that these sectors were developing at different rates and were interconnected. This meant that the focus at that time was on engineering improvements to human beings. How should humans be manipulated or enhanced? What would you do and how would you judge whether it improved things or not? This development path, called transhumanism, presents many ethical issues. The challenges we now face are the climate emergency, the use of AI, the energy transition and global security; and all of these create ethical issues. This means that we need to become more collaborative, not just between engineers but engineers with wider society and engineers with policy makers. This means that we have to deal more and more with uncertainties and when we operate under uncertainties we start to feel less comfortable. Ethics will take us out of our comfort zone and that's why we are reluctant to address the issues. When the technology is emerging I believe that we have to do what I call anticipatory ethics. Up to now engineers have only done a little bit of ethics. We have looked at something that has already happened, we have analysed it and we have said what went wrong. With the space shuttle we looked back to what happened in the past and analysed what had been experienced. With these new technologies the important and difficult thing will be to imagine what is coming next and work out how I approach the ethics of something that I don't yet know. When we think about responsibility in emerging technologies we have to address many questions. Responsible to what? To society? To ourselves as professional engineers? The two problems with anticipatory ethics are that we have to work with speculative scenarios and we have to work with uncertainty. Who chooses which scenarios are used? Engineers are used to working with uncertainty but the context of ethical uncertainty is new and we don't teach our students how to handle it. Should we adopt a risk assessment type of approach? We are good at doing this for safety issues; there is always a risk because no activity is riskless. Should we develop a similar approach for ethical issues? In traditional risk assessment a hazard is a potential to cause harm but not every hazard results in a disaster. Hazard Identification (HAZID) is used as a high level, area driven assessment to identify hazards and to plan mitigation steps. The purpose is to obtain a list of hazards for subsequent evaluation and to perform a qualitative evaluation of the hazard and the associated risk reduction measures. An ethics assessment would consider unwanted consequences that could cause harm to individuals or the environment. The Ethical Issues Identification (ETHID) would be a high level, area driven assessment to identify ethical issues and to plan mitigation steps. This would create a list of ethical issues for subsequent evaluation and would perform a qualitative evaluation of the significance of the consequences and the risk reduction measures.

An effective ETHID would require a diverse approach to the identification of the risks because the situation needs to be viewed from all points of view. Diversity is not just about gender although the tech sector is heavily male dominated, but needs to consider diverse cultures and diverse ethnicity. However even with a diverse approach it will not be possible to do a complete ETHID, but we can identify some risks. Therefore ethics needs to be a modus operandi rather than being just an exercise in following rules or a bolt-on addition to the core subjects. We need to identify in every decision what the ethical element is, we need to understand the nature of the inherent responsibility, both professional and personal and we need to address the problems that arise from questionable practices by using appropriate assessment tools. To do this it will be necessary to develop critical thinking skills and judgment, to understand the practical difficulties of this approach and to use suitable techniques to lead towards better outcomes. Following this method will enable us to develop an ethical identity to carry forward in our working life. The Professional Engineering Institutions have a key role to play in ensuring that ethics is embedded in our teaching, not just in the formation of our students or professional engineers. They need to act with competence, comply with the rules and adhere to the codes of conduct. It is clear that merely complying with professional codes is not sufficient.

Teaching Ethics in Engineering

The first attempt to include an ethical approach in the teaching of engineering came not so long ago, in 1977, with the Daring Report, which said that there should be greater correspondence between engineering and social sciences at university degree level. Despite this, the teaching of ethics in engineering faculties is still relatively uncommon. However the current cohort of students seem to be more aware of ethical issues in the world, not because we are teaching them but rather because their knowledge of world affairs and the challenges we face is better developed. Teaching ethics is a challenge for engineers because the lecturer may say something that they believe to be ethical and appropriate but in practice is criticised on some basis they had not considered. When they present data from experiments or results from the lab they have greater confidence because the result can be tested and replicated but with ethical issues it is much less certain. To help with this reluctance a joint venture between the Engineering Professors Council and the Royal Academy of Engineering has created an Engineering Ethics Toolkit to help teachers address the difficult issues raised in discussing ethics with their students.[1] Even if you are not a teacher the resource provides useful case studies that can help engineers to open their minds and consider a broader range of issues than they have previously addressed. This has become extremely important as we move towards engineering responsible technology. There are many good examples of ethical questions in industry but for the most part people are reluctant to share them or discuss them. This is where the ancient philosopher can guide the new engineer towards the use of technology responsibly. The engineer should be ready to understand the ethical context of their work. They should appreciate the social impact of engineering work and they should adopt the ancient vision of "involuntary" ethics where individuals lived and worked in symbiosis with their local community, not remote or detached from it. In short, ethics in engineering is about

1 https://epc.ac.uk/resources/toolkit/ethics-toolkit/

synthesis and analysis of the consequences of technology. It should not be left to philosophers and ethicists who might not grasp the technical details. The engineers who are responsible for the technology must have a central and active role in the debate.

Conclusions

It is clear that ethics is not a bolt-on extra, it is a way of life and an attitude that should lie behind everything that engineers do. Ethical issues are more common than we might think, in fact they are everywhere and so our mission should be to develop awareness of them. In other words ethics is not about conforming to the rules, ticking the boxes, but is about critically judging the rules and determining whether they are fit for purpose. We therefore have to shift from the conventional approach of reflecting on past mistakes and rather we must look ahead and anticipate the consequences in future of the work we are doing now.

Questions

Q: We had a fantastic lecture last month on batteries from Sir Peter Bruce. Several people raised the issue of lithium, implying that they were not happy with his casual attitude that we have lithium in many countries and it is widely available.

A: It is true to say that lithium can be recycled and recovered but this also requires energy and needs a support infrastructure. At the same time we can't simply switch off fossil fuels because many things around us, such as plastics for example, are derived from fossil fuels so in the absence of an alternative we would be switching off society.

Q: It seems that a lot of the things you describe are binary, with the answer being yes or no. for example should I licence the gold mine in exchange for funding for the hospital. In reality that's a very high level decision but there are many smaller decisions to be taken at many lower levels and the criteria may change as you go to a lower level. So when you use the word "harm" it depends on the circumstances and the context. Would it not be better to set an objective and then judge the decision on whether you have met the objective or not?

A: I think that you are making a semantic argument as well as a philosophical one. Really none of these issues are yes/no binary because they all depend on a human perspective.

Q: when you said that the students need to deal with uncertainty, would it not be better to say that life is full of problems that are non-absolute and therefore will have non-absolute solutions? It is not definitive but it still gives a solution.

A: Yes, but I still believe that when we talk about the future it is better to say that there are uncertainties. For example with AI: can you tell me what harm AI will do? I don't know whether it will do harm or will do good for us. How do you define harm in this case? For that matter, how do you define uncertainty?

Q: You mentioned a book from 1962 and said that it had a shocking conclusion in the back. But this was written a long time ago when Philip Morris were still advertising that smoking was good for your health and big companies were introducing DDT and thalidomide. Do you feel that now that we are 60 or 70 years further on that we are now better than we were back then? We now have the United Nations Sustainable Development Goals as you mentioned in the talk but we also have a political structure in the UK and also in the US that seems more driven by self-interest than ever before, and these two seem to be fundamentally incompatible. So are we better off than 1962?

A: I believe that you are right that we have not necessarily made progress, and this is why I am reluctant to say that we have established an ethical culture because there are all these levels. The only difference I would say is that today we are ashamed to say something like the statement in the book.

Q: You didn't touch on the way that society motivates people to do things, which I think is a huge part of ethics. For example we think that if someone is minded to be a nurse or a teacher, or even an engineer, that's a vocational choice and therefore you don't deserve to be paid as much as somebody who is pursuing a more self-centred approach to life. So are we improving or are we becoming more polarised?

A: I have two points to make. The first is that you are really addressing a societal issue whereas I was trying to put things in terms of technology but you never finish with ethics and I think the ethical culture is not there yet. Secondly I don't think that the vocational argument is clear-cut. You might say "I don't want to make so much money because I am an engineer" and I would say "I have studied for many years and my work is important to society so I should be paid above average."

Q: Without explicit enforceable standards on ethics for engineers how is an engineer to judge the respective choices and how is the engineer to avoid being judged in hindsight?

A: I think an individual has to choose themselves how to address this issue. We have a code of conduct for engineers, for example in the Institution of Chemical Engineers, and for some people having that framework and following the rules will be sufficient to satisfy them. I'm not happy with the code of conduct, because in some in some cases, the code of conduct says that you have to be loyal to the to the client and you have to be loyal to your boss, and sometimes this is a dichotomy. It's not possible to do that. So there is always an ethical issue to be resolved.

Q: It was suggested earlier that these decisions are entirely subjective. Is it really entirely up to the individual to decide?

A: Some things are less subjective than others. If you steal from the person next to you that's generally held to be wrong. If you use data for a purpose beyond the permission that was given it is clear that that would also be wrong, but there are areas in ethics that are more grey than black and white; the previous case with the hospital funding for example. This is where the moral issue comes in. It depends on how we have been brought up, or which country we grew up in, or religious teachings or many other things. So we all have personal values – that's where our morals are and it is when our morals interact with society that they become ethics. A silly example would be when I first came to teach in the UK I was surprised that there was a discipline committee in the university for people who cheat in class. Why? It's because in Italy you are a bad person if you don't help your friends. That is how we were brought up. Who is right? Who is wrong? Now, in my present societal context I believe that it is wrong, but when I first arrived in the UK I had been brought up to see it as helping a friend in need.

Q: Does engineering education provide future engineers with sufficient understanding of the competing issues in the world in order to make ethical decisions?

A: Probably not yet but it is much better than 20 years ago. The fact that we are discussing it here didn't happen 20 years ago, so that's a positive aspect, isn't it?

Q: I liked your example of the hospital. Do you agree that whether it is a bribe or not depends on the degree of openness in the transaction? Secret commissions are a bribe but if it is announced in the papers, if there's oversight and if everyone knows where the money is coming from and going to then it is a lot less bribe-like than a brown envelope.

A: I agree – it is about transparency. If you know exactly what's going on in that hospital and how many lives have been saved that supports the process.

Q: In some instances mistakes are made and lessons need to be learned. In the case of the Millenium Bridge in London when it opened the number of people on the bridge was restricted and it functioned well. When the number increased the bridge began to dance and significant rework was required. The mistake was not deliberate; it wasn't an ethical mistake. You made the point about Apollo 13: there has never been another Apollo 13 style incident so someone somewhere along the line has done a redesign and has addressed the issues raised. That's what happens when engineers get a chance to make the decisions. Problems arise when the money men have an influence and that may be where good and bad ethics come in.

A: Yes, I agree that some decisions might be easier. For example with the bridge the error was identified and corrected so the mistake is not made in future. The problem comes when you can't identify anything as a mistake, not because it isn't there but rather because it can't be identified just because the situation is more complex. That's the reason that risk assessment is necessary. However I don't like that when we speak about ethics we always talk about disasters, whereas ethics is also about nice stories when good things happen because the right ethical decision was taken. The last thing that I want to say is that I am very happy that there has been good discussion here. We might have different ideas, but that was the point; to generate discussion and to share our different viewpoints.

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The Institution of Engineers in Scotland

Crossed Lines: Key Strategic Lessons from the Crossrail Project

Mark Wild

The Rankine Memorial Lecture presented to the Institution of Engineers in Scotland, 14th November 2023, chaired by IES President Dick Philbrick.

Mark Wild has more than 35 years of experience leading complex and critical infrastructure. An Engineer with Hons Bachelor's Degree in Electrical and Electronic Engineering and Masters in Business Administration. Mark started his career in the electricity sector, but the majority of his experience has been in transportation. He has had a long career in operating and building major transportation infrastructure. Mark is the former Managing Director of Westinghouse Signals and was the CEO of Public Transport Victoria. Mark is the former Managing Director of London Underground and the former CEO of Crossrail, Europe's largest infrastructure programme. Mark took up the role of CEO for SGN, one of the UK's largest gas distribution networks in August last year.

Introduction

The Crossrail project represents an engineering feat of unprecedented scale beneath London's streets. Initially conceived in the 1840s, Crossrail epitomizes the evolution in urban infrastructure planning and engineering innovation. Although fraught with challenges, the project's completion marks a significant milestone in civil and digital engineering integration. This article delves into the challenges, strategic insights, and engineering marvels associated with completing the project, now known as the Elizabeth Line, which stands as one of Europe's largest infrastructure undertakings. Over 75,000 people worked on the project over its ten year life. The lessons learned from this colossal enterprise provide valuable insights for future mega-projects.

Mark Wild

Historical Context and Project Genesis

The concept of an east-west railway beneath London dates back to the 1840s, proposed as a solution to alleviate urban congestion. The Liverpool-Manchester Railway, the first ticketed railway in the world, had been launched and the canal companies bringing their goods into the Regent's Canal in London had a blockage. They couldn't get the goods from north and west London to Tilbury Docks because the streets were overcrowded and there wasn't enough capacity on the canal that goes around north and northwest and east London. So the canal companies conceived a plan to build a railway underneath the city. This never materialised but the idea didn't go away and reappeared in the Abercrombie Report of 1949, This was probably the world's first integrated transport and land use planning exercise and it outlined the essential nature of such an east-west railway under London. Several further assessments were conducted in the 1970s and 1980s, leading to official planning commencement in 1999. The Elizabeth Line navigates some of the most complex geological and urban landscapes with 26 kilometers of twin tunnels up to 35 metres below ground level and a combination of surface and underground stations linking outer areas to central London. The clever thing about the Elizabeth Line is that instead of getting a big train to a London terminus and then getting on a little tube train to circulate around, this is a through running railway, a full size railway travelling at 100 kilometres an hour underneath London. This is not a novel concept – Parisians have had the RER since 1977 and the Germans introduced the S-Bahn in Munich in 1988. However, Crossrail is pretty much the first of the modern mega projects. It was planned to deliver a wider business benefit, with generation of up to £42 billion of additional economic activity.

Project Overview

The engineering ambitions of Crossrail were immense, featuring multiple signaling systems, unparalleled digital infrastructure, and intricate civil works at depths between 25 to 35 meters. At the time it was the largest civil engineering project in Europe and the fourth largest in the world and it was the first to really focus on the sustainability and net zero requirements that are now commonplace. Now, interestingly, it wouldn't get into the top three projects in Europe or the top ten in the world, however an interesting aspect of the project is that although it was originally projected to cost £15.9 billion the actual spend was £20 billion. This doesn't sound great – it is an overspend of 27% – but in fact very few mega projects are built on time and on budget so this performance is in the top three as well. The Elizabeth Line was successfully opened to the public on May 24, 2022 and the Royal opening Ceremony was the last public engagement of the late Queen Elizabeth II. Now the line is in full operation and is providing 250 million journeys a year, accounting for one sixth of all of Britain's railway travel.

Challenges and Strategic Oversights

After ten years of planning, which started in 1999 and included the tunnelling geometry, the track design and the signalling systems, construction started at Canary Wharf. A critical early misstep was setting a fixed project completion date of December 9, 2018, nearly a decade in advance. This date was announced early in 2010 and in 2014 David Cameron declared that the tunnelling was complete and the project was half finished. Such long-term forecasts introduced extensive pressure leading to underestimated workloads and an inflated sense of readiness as the project progressed. By 2017, it became clear that only roughly 60% to 70% of the project was complete despite earlier assessments estimating 95%. London is one of the most difficult cities in the world to build 42 kilometres of six metre wide tunnels. You can imagine why: the geometry east to west is very difficult in London. You've got to get under the river at some point. The geology changes quite dramatically from a type of clay in the west to silts and sands in the east. Also, you've got to get through a labyrinthine tube network which is very deep itself. There are also nowadays skyscrapers in the city of London with deep, deep foundations. Completion of the tunnelling drive in 2014, only about a few months late and a little bit over budget, was a remarkable achievement but declaring close to victory at that point was a mistake. I was in Australia at this time, so I can take no credit for the tunnelling or any downside for the decisions. Crossrail broke two major project rules that were given from the gods. Ever since George Stevenson, there have been two rules that I don't think can be broken. Firstly, projects aren't two halves – they're not civils and then electrical and mechanical engineering. They're three things. They are the civil engineering, the mechanical and electrical fit-out, and then the process of integration. So actually, this project started to go wrong in 2014 when it was stated that the project was half complete. It wasn't. It was a third complete. The big lesson is that the integration was pretty much underestimated. The second big rule that Crossrail broke, which will resonate with any young aspiring engineers or project managers is that the last 5% of the project will take 20% of the time. Now, Crossrail, over time, distorted these two kind of golden rules.

In 2016 when I was interviewed by Boris Johnson, who was at that time Mayor of London, for the job of Managing Director of London Underground, he was very confident that the project would be delivered on time, based on the public announcements that were being made. That meant that the project team were also really confident that they could do it, even though you would suspect at this point the project was in some trouble. By the early part of 2018 the Crossrail leadership team, who had done such a brilliant job up to this point, said that they needed a bit more time. There was nine months to go to the completion date set ten years previously and they said that they might need another six months and another £100 million. The reality was that there was still four years to go and £4 billion was needed. When we scrutinised the work schedules of all the subcontractors we found that there were 75,000 tasks listed in their programmes that were not in Crossrail's programme. These represented gaps in the overall work schedule, for example one contractor had pulled in a cable and another had terminated it but it couldn't be tested because a separate system hadn't yet been connected to it.

Lessons Learned

How could such a huge gap between expectation and reality have been created and not been noticed? We literally didn't know how to finish the project. How could a project have gone from really a stellar success of the amazing tunnelling job, renowned around the world as the project that was on time on budget? How could it have got a black hole of such magnitude? There were five key areas that shed some light on this problem.

Integration of Civil and Digital Systems

The underestimation of the integration complexity between civil constructions and digital systems was a major hurdle. This project was always two things. It was this epic tunnelling drive, but it was also the world's most advanced digital railway. The railway has undoubtedly the most advanced train in the

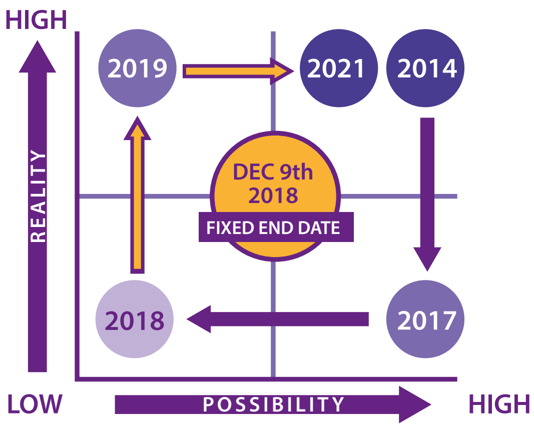

Figure 1 – Tension between possibility and reality

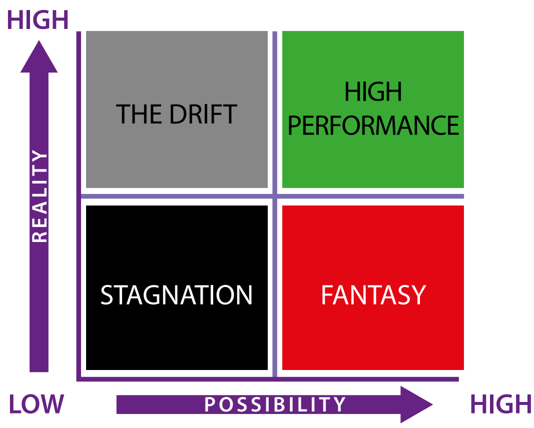

Figure 2 – Project Character

world. The train has three signalling systems attached to it. The drivers drive it in the Great Western, it's got to deal with the Heathrow tunnel and in the central section, it's an automatic railway where the computers drive the trains between the stations and the driver attends for an emergency, but isn't really active in the driving. This immensely complex railway was also off the charts in terms of its digital complexity with the building management systems for these immense stations being built. These stations in London are 10 story deep buildings sunk into the ground with the most advanced digital infrastructure and safety and security. Some of the civil works done in Crossrail are just absolutely extraordinary. There are some piles at Bond Street Station that are 65 metres deep. They get near the chalk aquifer. Three million tonnes of waste were taken out of the tunnels and an island was built off the coast of Essex, now a very beautiful bird sanctuary. They found thousands of bodies in the old Bedlam burial ground at Liverpool Street Station and archaeologists with teaspoons and brushes had to excavate a seven metre deep shaft, which they did over six months. This aspect of the project was a world of intervention. The problem is, on the other hand, there is an immensely complex digital railway. When people think of mega programs now, you really have to live in the spirit of intervention on the digital side as well. For example the rulebook for the drivers to drive the trains in the tunnels was not finalised until about two or three weeks before we launched the service in 2022. How

Figure 3 – Modular mock-up

Figure 4 – Reality in Farringdon

could this be? The reality was that they kept evolving the rulebook and the technology was following. What should have happened was the rulebook should have been fixed and then the technologists should have built around it. So two different projects with different mindsets was a real problem. Future projects must incorporate system thinking throughout their lifecycle, recognizing that civil engineering and digital innovations must be harmonized seamlessly.

There were five reasons for the black hole in cost and time opening up. The schedule was over-compressed, the system integration complexity was under-estimated and the opening date was fixed at a very early stage. The extent of work remaining was consistently underestimated and the actual work that had been done was regularly overstated. This is illustrated in Figure 1 which shows how the loss of realism was catalysed by naming the end date so early in the project.

The art of project management is neatly characterised by the green quadrant in Figure 2 – high ambition matched with high capability. You don't want to be in the red; full of ambition but totally unrealistic but you also don't want to be in the grey, very realistic but scared of your own shadow.

Modularity and Design Consistency

Crossrail started with an idea of modularity. We build things in factories and we bring them to site and build them together. Figure 3 shows, years and years ago, a mock-up of an East London factory where they had modular kits of parts. Unfortunately, by the time we built Crossrail, we ended up with the abomination in Figure 4, which is one of the entrances at Farringdon. And you might say, why isn't there a modular standard London Underground gate there? The reason is that the building development above the site was built before the station. It's a classic misalignment of design.

Modularity, building things in factories, bringing them to site, is a really smart thing to do. The story of Crossrail illustrates the necessity of strong design coherence and modularity, ensuring complex projects can be broken down into manageable components designed and tested off-site before construction.

Complexity

Modularity is an excellent way to break a large task into multiple repeatable sub-tasks, but even if you simplify Crossrail, you're left with a very, very complicated thing. Crossrail, end-to-end, has the digital complexity of two nuclear submarines, so it was always going to be complicated. Figure 5 shows another model where I think that Crossrail got it wrong. Crossrail lived for too long in

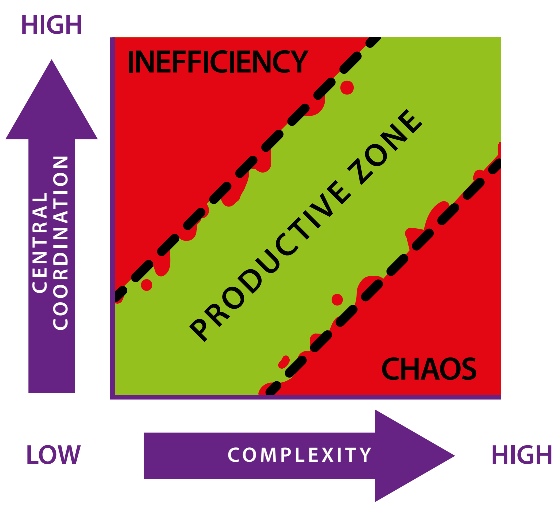

Figure 5 – Complexity vs Coordination Governance Structure

that bottom right-hand corner. There are two axes here. Complexity on the bottom axis, but on the vertical axis the amount of coordination required from the central guiding mind. This is a bit like coordinating an orchestra, or if you prefer, conducting an orchestra. Crossrail, in my opinion, lived too long in chaos. They were highly complex, but didn't really coordinate. Too much risk was transferred to the supply chain and the supply chain couldn't manage it in a suitably coordinated manner. As complexity increases, so does the need for the client to be highly coordinating and keep risk about what they can actually control.

The Crossrail project was set up with four levels of stakeholder governance, ranging from the programme oversight group through the executive group, the board of directors and, at the top, the sponsor board including the Secretary of State and the Mayor or London. These four levels were matched by four levels of quality assurance, assessing the performance and output of each level of governance. These were all highly qualified, highly motivated and highly paid people so how could they have missed 75,000 activities and a need for £4 billion. It seems that the governance team at all levels became quite arrogant about the progress of the project. This led to them become defensive when challenged on any point and gradually they lost their curiosity about what was actually going on. This meant that the assurance assessors, at all levels, spent their time trying catch the delivery team out, which reinforced the attitude of defensiveness.

The big lesson in this respect is that any mega-project requires an assembly of all the talents with a 360° view of the scheme so that they can ask "are you sure?" when something doesn't seem quite right or when two reports don't match up. This is what is meant by saying that more curiosity is needed.

Leadership

There are two things that are essential in leadership in major project programmes. Firstly, transparency. Transparency is essential because in mega complexity, you can't see the whole picture and these projects are now beyond the ken of individual human beings. They are even beyond the reach of individual groups of people. There is a lot of talk about AI but one of the concerns about AI is the loss of transparency. Things become obscured. The second thing is collaboration. The job of crossrail delivery was to put a man or woman in the front of the train and bring it to the highest possible reliability. I used to think of crossrail like a baton race, you know, from delivery team to the operator. Both running at the same time, stretching to achieve a smooth transfer. However, I now know that crossrail was really a massive obstacle course, like these tough mudders where everybody's got to cross the line together. If I was asked to look at a mega-programme in future I would be looking for how transparent they are and how much does the whole coalition own the whole project, including the train drivers, the operators? Far too often you see the opposite. Projects that are opaque and projects that are splintered and fractured, which is what happened to Crossrail.

Conclusion

The Elizabeth Line is a triumph not only in engineering but also in collaborative human effort, transforming transit possibilities for millions of Londoners. It is probably the greatest engineering infrastructure achievement in the UK of the past 60 or 70 years. When it opened it had a straight run of seven days of 100% performance thanks to the work that had gone into the preparation for that point. There are five points of advice for future leaders. Firstly it is important to have a singular higher purpose. The Crossrail team didn't consider that they were building a railway, but rather that they were building a railway for 250 million people a year, creating 2,000 high level jobs and contributing £43 billion to the economy. Secondly it is better to live in the house of intervention than the house of risk. In other words it is better to intervene today rather than hand a blank cheque to someone in five years time. The third point is that it is necessary for a mega-project to have a kind and inclusive environment where people feel that they can speak truth to power. Some people think that diversity and inclusion is tokenistic but in fact for a project like Crossrail it is essential to have all the talents seeing things from different perspectives and being willing to speak out. To do that, the fourth point is that it is essential to remove the fear of failure otherwise people start telling you what they think you want to hear, which is what happened in the middle stages of Crossrail. Finally it essential to remove ego from the leadership. The leader needs to be seen as part of the whole team because they need the engagement and commitment of the whole team to deliver a successful project.

The strategic missteps in the Crossrail story provide an extensive case study for future infrastructure projects, ensuring improved foresight and management in upcoming mega-projects.

Questions

Q: You mentioned a workforce of 75,000 people. How did you get them to "own the whole"?

A: The answer is that it is about purpose. This was an incredibly purposeful project. It basically halves the size of London. The project did an incredibly good job in the planning phase and did an amazing job in the tunnelling but then lost its way from 2014 to 2018 when it got into the fit out. The hype was all about a world class project on time and on budget when in fact it wasn't – these were the wrong words to use. It would have been better to talk about "a railway for all of us that will be worth the wait". This seems to be the problem with HS2. Nobody seems to have engaged with the purpose of the project, which was never anything to do with speed, it was about capacity relief.

Q: Do you think "infrastructure" is too general a word to communicate to people successfully?

A: I'm an engineer, proud to be a Chartered Engineer, but I think that the engineering fraternity don't talk enough about the outcome. When we look at great engineers of the past like Charles Parsons, Isambard Brunel or George Stephenson, and no doubt William Rankine, they were all about the outcome. They were doing something purposeful.

Q: Regarding the contract, why was NEC3 selected and how many non-standard modifications were made to it?

A: NEC3 (the New Engineering Contract) is a risk sharing contract. It gives a target cost and then the client and the contractor work together. It was definitely the right contract for this project but with a couple of caveats. Firstly, it was very vanilla – there were very few amendments. That is good but the problem was that with the artificially forced end date of 9th December 2018 the management team lost control of the design process. This meant that many, many supplemental agreements were required at greatly increased cost. There should have been float in the end date and we should have spent more time on the client design. Inevitably some contractors installed what they thought was the right thing and then the client changed their mind. It would have been better, say in 2014, to take time to get the design correct and approved. This might have taken a year at a time when the commitment was still to 2018, but it would have saved time and money further down the line. So it keeps coming back to the problem of the committed final date.

Q: You mentioned in your last point about leading by commitment, not by ego. Did you mean politicians' ego or engineers' ego?

A: It doesn't take much to spruce up a politician's ego so you have to be very careful what you offer them. However I think the problems started with the engineers and the project managers. They have to stand firm and not promise something that they know the politicians want but can't be delivered. As soon as the politicians were offered a singular end date eight years in advance the gun was loaded for a very, very difficult ride. It's hard to give bad news, but better to give it early. When the Crossrail programme went late compared to the unrealistic date promised back in 2010 the politicians were quite ruthless and brutal.

Q: You mentioned a climate of fear – at what level was this fear evident?

A: The real issue seemed to be in the senior middle management who felt that they didn't have any opportunity to raise their concerns. It was like the slow bicycle race in the Olympics where everyone is hanging back waiting for someone else to make the first move. When I took over I interviewed 100 of the senior engineers, project managers and project directors. All 100 said that they knew that ball was bust but they couldn't speak. The project had become too big to fail. However this type of fear isn't a really nasty thing, it is more of a state of mind, a cultural thing. That's what needs to be removed and it is both a skill and an art.

Q: Any idea what the final cost-benefit ratio was?

A: There are two perspectives on this. Firstly the benefits have probably been delayed by Covid, perhaps by as much as two or three years. The cost overrun is also delaying the final outcome. The £4 billion is being paid by an 1 pence levy on London business taxes for the next 20 years, so there is a downside. However the traffic figures are where they are intended to be so I think we will get our £42 billion of agglomerated benefit. The BCR will be 2:1 – that's two pounds back for every pound that was put in.

Q: You mentioned the dichotomy between the delivery team and the assurance team. It has been suggested that the project reports were progressively watered down as they travelled upwards. Was that your experience?

A: Well I was there and I can tell you that there was no conspiracy to hide the facts, although looking back I can see that I was guilty of not receiving good news well. What I think happened was that there was a general environment where bad news isn't welcome so the project representative who was embedded in the project would produce reports but they were written in a sort of code to make them more palatable to the senior representatives and politicians. It might say for example "There are a few challenges" or "This might be difficult" but the real issues were not flagged in a way that drew attention to them. Things that should have been tagged as red were not red – the colour red was not welcome. One of the things I did when I took over was to get rid of the colour amber so that instead of flagging things as red, amber or green it was just red or green. That's a really good trick to draw attention, and if you are not entirely sure of the status, make it red rather than green. So we then became curious about all these red status items and started to take action. When red status is seen as "bad news" and project managers are under pressure to deliver a positive story they might choose amber, or even worse use red/amber because they haven't quite got the confidence to tell it like it is. The creation of an environment where people can be curious about things starts at the very top.

Q: Were the reasons that Crossrail went over time and over budget the same as for other major projects like the Edinburgh trams or the Scottish Parliament building, or was Crossrail special?

A: A recent book called How Big Things Get Done, by Bent Flyvbjerg[1], addresses this question. He gives a good example of the Sydney Opera House. They started building it because the then premier of New South Wales had terminal cancer and they wanted to start to give him a good send off. They ended up 1,500% over budget and 10 years late with an unbuildable design, but nobody regrets building the Opera House now. In comparison with the two projects you mentioned, particularly the trams, the thing that Crossrail did better was that they got the fundamentals right. The design was right, the stability was right and the sponsored requirements were absolutely brilliant. The thing that Crossrail got wrong was that in execution it didn't deal with uncertainty. So, it was better than the parliament and especially the trams where they had the wrong specification, the wrong integration, the wrong value model, didn't have a proper systems approach and bought all the trams before the diversions. Crossrail wasn't like that – it's problem was not dealing with complexity in execution and I think that

1 https://sites.prh.com/how-big-things-get-done-book

it could have been finished in 2020 if a realistic approach had been taken back in 2014 when it was said to be two years behind programme. Nobody could accept that position and that's what went wrong.

Q: HS2 was calculated on the basis of saving time for business people. What was the case for Crossrail?

A: Crossrail's interesting in that it was the first business case in the Western world that took in wider agglomeration. The reason that it's so purposeful is not only the dramatic journey time saving – Heathrow to Canary Wharf seamlessly in 38 minutes, which generates a lot of the business travel. It also has a stellar property case. The plan was to build 25,000 houses. It's ended up being 90,000 houses on Crossrail. Now, a lot of that capture, of course, is in property values along the routes that have been lost. So Crossrail's business case is in two parts. Journey time saving, bringing 1.5 million people into the activity zone and a great boost in housing and commercial property. And the question is, of course, post-COVID, will London as a central activity zone make sense? HS2 has just got the wrong business case. The business case for HS2 is relief of the West Coast between Birmingham and Manchester. The biggest problem that HS2 is trying to resolve is the congestion south of Manchester, but it got conflated in a bit of ego, I think, into this high-speed thing. Also, the specs are crazy – it's too fast. They've built something that's got an insane level of speed, which means, as you all know, the geometry is very, very difficult. So I hope HS2 gets itself sorted out. It's a really important project for capacity.

Q: What was the most difficult part of the project? Is it the design and build or is it the integration of multiple items?

A: I'm an electrical engineer who spent most of my career in system integration. So I would say, well, the system integration is very difficult, but I've been amazed by the civil engineering. I mean, it's absolutely astonishing how on earth it was done. How they built 10-story buildings underneath London and how they refurbished the Connaught Tunnel. So I would say it takes all the talents across the whole thing. I'm no American football fan, but I've seen the movies where they have different squads come out for different play. I think that's the big lesson from Crossrail. You need your civil engineers. Then you need your fit-out people. Then you need the squad of integration and through this all, you need the golden thread of what you might term systems thinking which I think is the most important skill of all. Not system engineering. Systems thinking would be the key, I think.

Q: To avoid a recurrence, do you believe that we could benefit from implementing more robust value and risk management concepts in projects?

A: That is so important. We talked in the presentation about the house of intervention as a mindset and the house of risk. That is the art of major project management. When can you defer a risk? When do you need to intervene? I've generally become more inclined as I got older to intervene more early than write the risk for the future. I'll leave you on one thought. Crossrail has pretty much come in at the same cost as the estimate that was given in 2005. There was an estimate that said this is how much it's going to cost. Then they took out nine intermediate shafts to cut costs as part of a value engineering exercise. These were shafts every 500 meters along the route that were used for ventilation and for intervention by firefighters. This saved about £800 million in value engineering. What a disaster because it completely altered the risk profile for the fire brigade. The tunnel ventilation system became incredibly complex. Dealing with this cost many, many more hundreds of millions than taking those shafts out. Anybody doing value engineering at the beginning shouldn't take physical things out. They should take the risk out. What should have happened in Crossrail is that they should have reduced the signaling systems from three to two. They should never have taken the intermediate shafts out. So all the engineers out there, don't get trapped in somebody twisting your arm to take proper assets out as value engineering. Take the risk out.

Robert Harley

26th May 1954 – 7th October 2024

The recent death of Robert Harley has been a great blow to all who knew him. Robert joined the Institution in October 1996 and he was a member of Council for over 20 years off and on. He was a key member of the James Watt Dinner group and the Membership Group. Robert was integral to our events and activities and supported all that we do. Members of Council have remembered a kind, enthusiastic, friendly man who helped each new member of Council with a kind, quiet good humour, always willing to help – a great person to have on the team. IES Members expressed sorrow as a fine man 'gone too soon'.

The text below has been extracted from Robert's family's obituary:

Robert Harley passed away peacefully at home on Monday the 7th of October 2024 surrounded by his immediate family. Robert was a proud dad to Julie and Alec, a loving partner to Pamela and an adoring grandpa to Emily, Dylan and Erin. He was a beloved father-in law, son, brother and husband to late wife Janice. He was much loved and will be sadly missed by all that knew him.

There is a famous Glasgow saying that perfectly describes Robert "he was Clyde Built". Born in Partick, Glasgow, shipbuilding was in his DNA, it was in his blood, and it was in his soul. He was Yarrow Shipbuilders/Bae SYSTEMS man and boy, joining the company in 1970 at the age of 16 and finally retiring in 2022 at the age of 68, a career in shipbuilding that spanned some 52 years. His achievements are too numerous to mention in this post and he was an inspiration to many.

Robert was a naval architect and proud to be part of the engineering teams that built some of the finest ships in the world. He was educated at the University of Strathclyde obtaining a BSc in Naval Architecture and went on to study at the University of Glasgow obtaining a Master of Business Administration (MBA). He actively sought continuous learning and development during his long career.

Robert was a champion for young engineers and actively supported work colleagues at all levels in the shipbuilding industry. I am sure many of you will have your own memories and stories. This included a long involvement, some 24 years at committee level, with the Scottish Branch of the Royal Institute of Naval Architects. This has been recognized as the longest serving member of this committee. He also had a long association with the Institution of Engineers and Shipbuilders in Scotland, and he was the organiser for the past 15 years of the Shipbuilders Supports Club Table at the James Watt Dinner.

Ian Broadley

We regretfully have to notify members that Past President, Ian Broadley, passed away on 4th Dec 2024.

Ian served as President from 1991-1993 and continued to support the institution over the years until his health stopped him being as active. In January 2010 he delivered a paper to the Institution (which was referenced by current President Graeme Fletcher in his recent Presidential Address) "Building QE2 – and other Tales of the Riverbank". Ian was formerly a Director of John Brown Engineering, Engineering Resource Manager for Britoil and as a consultant for the DTI. We hope to include a full obituary in our next volume.

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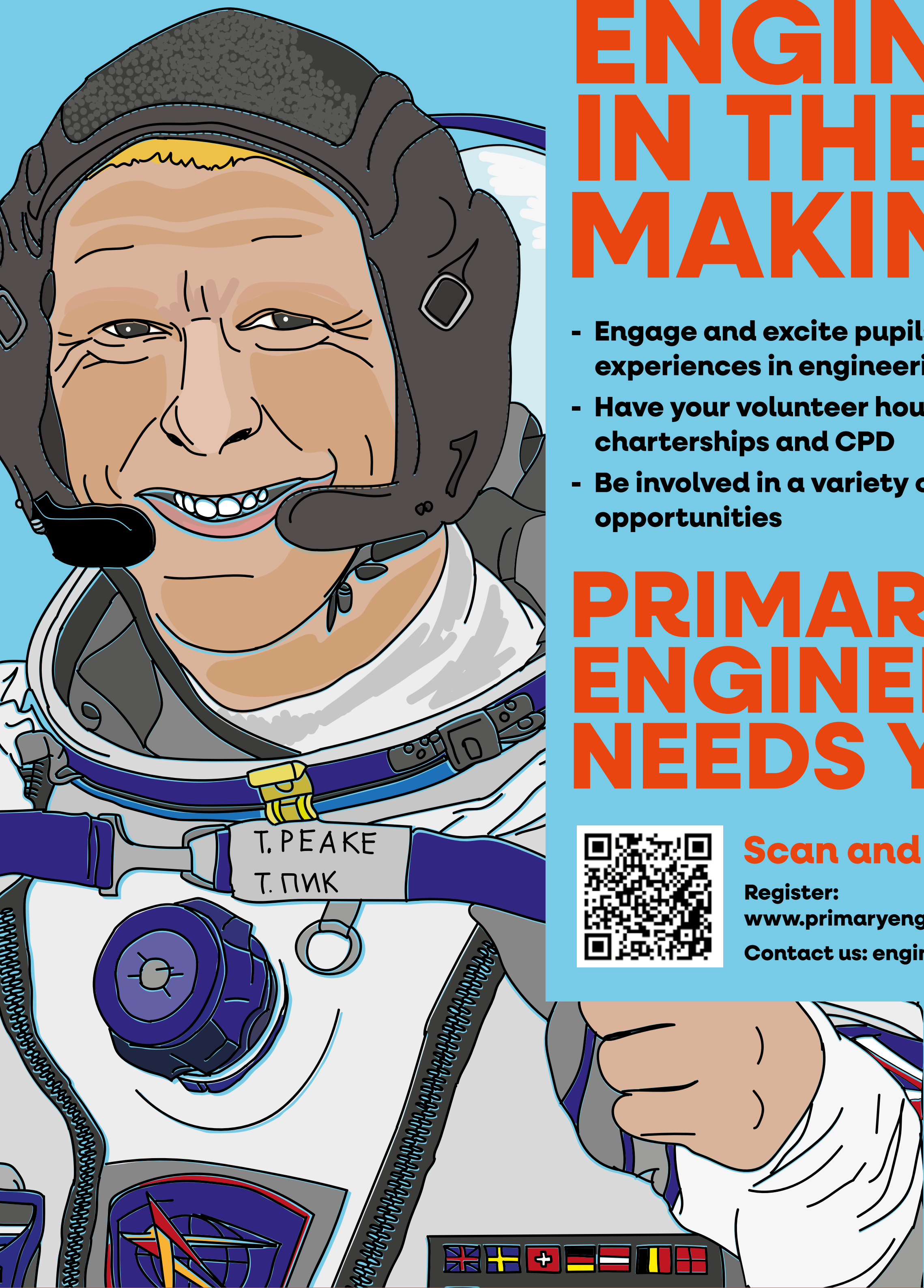

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