HAPPY AND GLORIOUS
Thanks to some Diamond Geezers

Queen Elizabeth II is not, of course, the first lady monarch to reach a Diamond Jubilee.

Sadly, this journal was not around in 1897 to review British scientific achievements during Victoria's reign. It is safe to say that the UK could have been just as smug at the end of the 19th century about our science, as the next ten pages show we are at the beginning of the 21st.

There were no Nobel prizes to win, and no citation rankings to dominate.

Nonetheless, her reign provided many heroes, whose names are still household words.

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Michael Faraday, reproduced by courtesy of the Royal Institution of Great Britain

James Clerk Maxwell© Peter Reid, FUSION: Focusing on University Science Interpretation and Outreach Needs, University of Edinburgh

Michael Faraday's development of electromagnetic induction gave us the electric motor.

Patients used to die of bacterial infection, rather than their original ailment until Joseph Lister gave us antisepsis.

It is now impossible to imagine operations conducted with brandy as the anaesthetic. The chloroform introduced by James Simpson is no longer used, but a whole new science opened up.

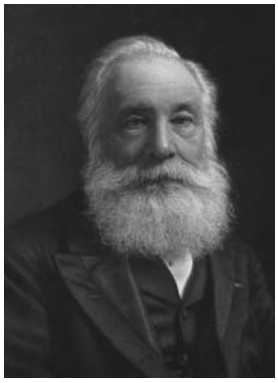
James Clerk Maxwell's analysis of waves in the ether allowed us to develop radio, television, radar, the internet and WiFi.

Brunel gave us tunnels, and bridges as well as trains and ships.

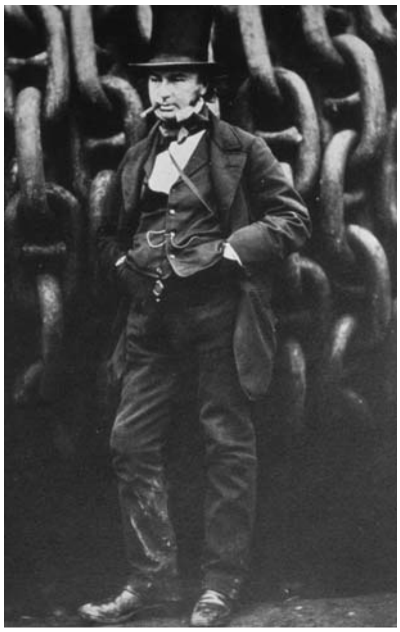
Perkin stumbled on synthetic dyes by accident, but spawned a major industry.

Darwin has been both feted and vilified for his theories.

The next few pages demonstrate clearly that Britain still has much to feel proud of when it comes to scientific innovation.



Sir William Henry Perkin© RSC library



Isambard Kingdom Brunel

BRITISH ACHIEVEMENT IN ENGINEERING OVER THE LAST 60 YEARS

Dr Natasha McCarthy
Head of Policy
The Royal Academy of Engineering

The Queen's Diamond Jubilee was a highlight of an Olympic year which has seen Britain celebrating and revelling in community spirit from a local to a national level. Like the Coronation, the Jubilee was a landmark in British social life, when the majority of the country was sharing a common celebration. However, there has been nothing less than a revolution in the ways that those events were experienced.

The broadcast of the Coronation was watched on black and white televisions with the whole family gathered around, often with neighbours who had no set of their own. But the coverage of the Diamond Jubilee events was enjoyed by millions on television, PCs and phones, anywhere and at any time. There was instant global reaction to what was broadcast – with a video of a hula-hooping Grace Jones at the Jubilee concert hitting YouTube within seconds of the performance, and with comments on it tweeted around the world.

The significance of these differences is that Queen Elizabeth's reign almost exactly matches the span of the digital revolution. This revolution in the way we live was enabled, inspired and shaped by engineering. British engineers have been at the heart of this revolution, and have played pivotal roles in each of its major stages. British engineers have also changed our world in many other ways over the last 60 years, by exploiting the opportunities presented by digital technologies.

Just four years before Elizabeth's coronation, 'Baby', widely acknowledged as the first modern computer, ran its initial programme at the University of Manchester where it was developed by British scientists and engineers. This ancestor of the computing devices now available bears little resemblance to the laptop or smartphone. However, from the point of Baby's invention, the development of computer science and software engineering accelerated, with developments in hardware and software occurring at pace.

A crucial aspect of the digital revolution is connectivity – communication between computers in local and global networks. In 1976, a year before the Queen's Silver Jubilee, and the year that The Royal Academy of Engineering was established, the Queen herself hit the 'send' button on an email utilising the first link between computer systems in the UK and US. The occasion was the formation of the Royal Signals and Radar Establishment, and the email utilised connectivity provided by ARPA in the US for the use of the defence community.

That initial connection was augmented by links between all continents, which have now developed into the internet, the global network of computers connected for the sharing of information. It requires no demonstration that the internet has become integral to individuals' and societies' lives and has changed many people's experience of the world. However, the reason that the networking of computers has been so impactful is due to the work of a British engineer, Sir Tim Berners-Lee FREng FRS. When working at CERN, Berners-Lee developed the basis of the world wide web. The now common concepts of Uniform Resource Locators (URLs), Hypertext Transfer Protocol (HTTP), Hyper Text Mark Up Language (HTML), were the work of Berners-Lee. These gave unique addresses for webpages so that they could be found by any user; a common means of computers to communicate information on webpages; and a common language to ensure that webpages were displayed faithfully on any machine. These devices allowed this global network of computers to share information in such a way that it can be viewed in a common format on any computer. It turned what was a system created and used by experts into a system usable by anyone with a PC, and ultimately into a movement which would change ordinary people's lives.

It was Berners-Lee's vision that ordinary people would be able to use the technology behind the world wide web, so that anyone could add information and content to the web themselves, sharing it with all users. This vision has been realised through the development and rapid adoption of social media. From Facebook to YouTube to Twitter, people are publicising their thoughts, reflections and creations to groups of friends and the world at large.

British engineering has been central to enabling this democratisation of the web, making it the accessible and constantly changing system it is now. The British-based company ARM has developed processors that power many smartphones and other mobile devices which have enabled this further stage of the digital revolution. These processors have brought computing power not just into every home, but into every pocket. Mobile computing enables connectivity everywhere,

ARM technology powers mobile devices such as smartphones - image courtesy ARM and it has led to the development of manifold applications including those that allow just the kind of real time sharing of information and data that has enabled the uptake of social media, and which has played a crucial role in making the Jubilee and Olympic events of 2012 truly social experiences – this being the first truly 'digital' Olympics, broadcast on the web as well as television. It has created an industry of creative design of 'apps' in which the UK plays a major part.

The digital revolution highlights just how closely and intimately engineering affects people's lives at an individual and societal level. However, all aspects of engineering have significant impact on everyday

The ethos of the internet was presented by Sir Tim Berners-Lee at the Olympic opening ceremony - image copyright Press Association

Digital technology is powering a revolution in healthcare - image courtesy ARM

life, be that in the delivery of utilities such as power and water to homes and businesses, transport infrastructure, or the technologies that support modern medicine. The digital revolution has transformed, and will continue to transform, the ways in which these services are delivered and managed.

Infrastructure will become increasingly 'smart' through the use of computing power. Smartness consists in collecting data about the status of a system and using that data to manage better the system, either automatically, via a human operative, or communicating it to users of the system to influence their behaviour. Transport systems are increasingly intelligent, and the separate systems which govern land, air, rail and sea can become a single system. This will be valuable to travellers to allow them to manage better journeys and will enable the better use of new transport technologies, such as electric and even driverless cars. Data can be collected about quietest routes and related directly to vehicles, to manage better the system and improve individual journeys. Analogously, a smart electricity grid is one which uses data about demands in real time to manage the way that power is distributed and used. Depending on demand at a given time, devices can be charged, switched off, or even add power to the grid. For example, electric cars could be charged when the grid is experiencing low demand, or batteries in some devices could be used as distributed storage with that stored power downloaded into the grid. This creates a more efficient system, better able to use low carbon energy, reducing carbon emissions.

The biomedical engineering sector is also utilising digital technologies to revolutionise the way that healthcare is delivered and managed. 'Telehealth' or 'e-health' exploits mobile computing to allow healthcare to be better tailored to an individual, and to allow a patient to be treated in their own home without need for frequent lengthy trips to hospitals. A patient's heart rate or blood pressure can be regularly monitored by a device on their body which relays readings to a service that tracks the patient's wellbeing, only making contact when a problem arises. Such systems are being developed by Professor Lionel Tarassenko FREng at the University of Oxford, with the aim of delivering healthcare which better serves the patient and allows them greater freedom and autonomy during their treatment.

In these ways, engineers have not only been the instigators of the digital revolution over the last six decades, but have grasped the opportunities it creates across all areas of engineering. Engineers have both initiated and stimulated the rapid development of computing technologies.

The last 60 years have without doubt seen many leaps forward by British engineers. I have not sought here to enumerate or list individual achievements but have illustrated how British engineers have had a key role in a movement that has transformed both everyday life and engineering itself. However, there is value in noting individual engineering achievements and celebrating them. For this reason, Her Majesty has lent her name to the Queen Elizabeth Prize for Engineering, which will be awarded for the first time next year. The Prize will identify and celebrate the kinds of truly life-changing technologies that have had a global benefit to humanity and will no doubt continue to change the way we live over the next 60 years and beyond. Whether it is awarded to a British or international engineering achievement, the development of the Prize shows that Britain is proud of the achievements of engineering and their capacity to change our world.

SIXTY YEARS OF SUCCESS IN UK LIFE SCIENCES

Professor Dame Nancy Rothwell
President and Vice-Chancellor, University of Manchester;
President, Society of Biology.

Since the early 1950s, the period marked by the Jubilee celebrations, Life Sciences in the UK – by which I mean all areas of biology, biomedical and medical science – has experienced a remarkable revolution. We have seen major discoveries in fundamental science, transformations in medicine and health, major impacts on food supplies with significant economic, social and health benefits. The UK is, by many measures, amongst the world leaders in this area. On one recognised measure, citations of our published work, we are second only to the USA. When this and other measures are adjusted for population or for national research spend, the UK comes top worldwide. The UK also has an impressive array of Nobel Prizes in Life Sciences – most in Physiology or Medicine, but many biological discoveries have also won the Prize in Chemistry.

The Queen's coronation coincided with what is widely recognised as the biggest breakthrough in Life Sciences of the last century.

DNA AND THE GENE "REVOLUTION"

In 1953, James Watson, Francis Crick, Maurice Wilkins – and not to forget the key role of Rosalind Franklin – published the structure of DNA. Aside from revealing the true beauty of the structure, this changed our understanding of life with the realisation that DNA is the fundamental building block of all life and is the code that determines all our proteins.

This was followed by a flood of discoveries and innovations, many in the UK. Fred Sanger discovered how to do fast and accurate sequencing of DNA, wholly new disciplines of molecular biology and genomics were born and the Sanger Centre was established in 1993. In the 1990s the genomes of important organisms such as worms and yeast were solved. Then as the new millennium dawned, the first draft of the human genome was published, jointly by researchers in the UK and the US.

A second explosion of discoveries followed, with faster and cheaper genome sequencing resulting in a better understanding of how small changes in the genome can have massive implications for disease, and opening the potential for new treatments and "personalised" medicine. Alec Jeffreys brought us DNA fingerprinting. We learnt that just one gene separates human males from females and started to discover specific mutations that cause disease. In 2000 it cost about $1 billion to sequence a genome, today it's about $10 thousand; by 2015 it will probably cost less than $1 thousand and may be a standard diagnostic in doctors' surgeries.

WIDER IMPACT OF GENOMICS

Genetically modified (GM) crops and animals is a sensitive issue, where we must inform and debate much better, not least because this is a means by which we can change global food supplies and have environmental impact. For example, genetically modified "purple tomatoes" have anti-inflammatory and anti-oxidant properties which could lead to reductions in cancer, cardiovascular disease, diabetes and other major disorders. Many such manipulations of our normal foods could have similar health benefits.

Animal health influences our farm stocks, wild animals and our pets. We have made great advances in understanding and treating diseases of animals. For example: hundreds of millions of chickens had to be killed as a result of avian flu. Genetically modified chickens developed in the UK should limit the spread of bird flu and safeguard future flocks and eggs.

Figure 1: Purple tomatoes, genetically modified to include anti-oxidant genes. Thanks to Dr Cathie Martin, John Innes Centre.

Genetically modified crops can greatly improve yields and much needed foods for desperately struggling populations and have huge societal benefits. GM crops need much less agrochemicals (pesticides and fertilizers) with massive environmental benefits.

FUNDAMENTAL DISCOVERIES WITH MAJOR IMPACT

This section could occupy literally hundreds of pages. I have chosen just three illustrative examples.

Peter Mitchell's "chemiosmotic hypothesis" showed how organisms use oxygen and energy from food to convert this in the cell compartment known as mitochondria into a "currency" of energy that can be used by all cells – stored in a molecule called ATP. Mitchell, often described as a "typical British eccentric", was the founder of this important field which led to other major UK discoveries in energetics and mitochondria and several Nobel Prizes.

As a very different example, Kathleen Drew, a "cryptogamic botanist" of my own University, devoted her life to seaweeds. She discovered a previously unrecognised stage in the life-cycle of the seaweed known in Japan as Nori. Her discovery enabled Nori to be cultivated rather than then simply collected, and the world production of this seaweed had risen from 21,000 tonnes in the

1950s to over 500,000 tonnes today. This is just one of numerous examples of the unexpected impacts of "curiosity driven" research on society.

My last example of fundamental science discoveries is "model organisms". This means using lower species, like worms and flies, to understand the biology and diseases of higher organisms, like humans. This has been a hugely successful area and none more so than the first sequencing of the genome of a worm – for which our scientists shared yet another Nobel Prize. This is close to my own area of research (on brain disease) and I often tell schoolchildren and students the story of "a small worm" where genes were first discovered that determine if cells will live or die. This is now a fundamental basis of degenerative diseases – where too many cells die, and cancer – where aberrant cells don't die.

UNDERSTANDING DISEASE AND NEW MEDICINES

It is only possible in a short space to highlight the major leads from the UK. These include modern antibiotics, histamine blockers to treat stomach ulcers, beta blockers to lower blood pressure and alleviate heart disease, therapeutic antibodies – then later personalised antibodies to target diseases. Some drugs were developed through "serendipity" which always needs the observant and prepared mind, as is illustrated by the case of Viagra!

The UK has often led on "evidence based medicine", most notably in Richard Doll's careful studies providing the clear links between smoking and cancer. We also developed randomised controlled clinical trials, and developed Cochrane collaborations that bring together the results of numerous trials to give an overall assessment of efficacy of any intervention.

The UK has also provided leadership in governance and regulatory issues, including research ethics and integrity, animal experimentation, GM organisms, the Human Fertilisation and Embryology Authority, NHS guidelines, our assessments of medical costs vs benefits (through NIHCE), and the advocacy for open access publishing.

INTERDISCIPLINARY APPROACHES

I was delighted to speak alongside leaders in physics and chemistry in highlighting UK achievements. But the reality is that it is increasingly difficult to distinguish between scientific disciplines – perhaps more so in the UK than in many countries. Interdisciplinarity is a great UK strength.

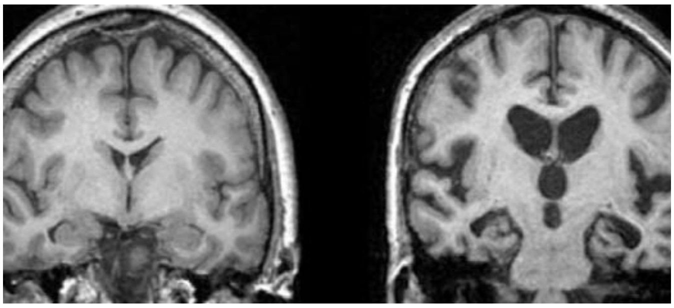


Figure 2: Magnetic Resonance Imaging developed by Sir Peter Mansfield. Reproduced with permission of the Medical Research Council.

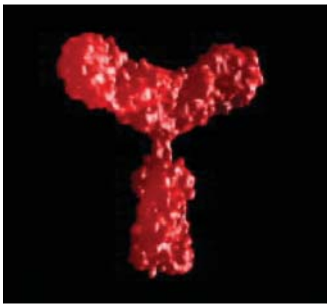


Figure 3: Therapeutic antibodies. Monoclonal antibodies were first isolated by Drs. César Milstein and Georges Köhler. Reproduced with permission of the Medical Research Council.

Again the list of our successes is long. Advances in understanding biological structures (which is fundamental to understanding functions), fast genome sequencing, CAT and ultrasound scanning, magnetic resonance imaging, medical devices such as hip replacements, cochlear implants, artificial lenses, cardiac stents and prosthetics – all depend on our strengths in engineering, physics, chemistry, maths – as well as biology. Here I can't pass on the great opportunity and UK lead on graphene! This is the thinnest, strongest, most conductive (and so many more superlatives) material ever known. There are huge possibilities for Life Sciences. As a UK discovery and one of many UK Nobel Prizes, this gives us a great opportunity for future innovation.

There is always a temptation, especially in times of limited funding, to focus funding and effort on one or two areas such as life sciences or physics. This would be a grave mistake. Much of the UK's success has depended on interactions between the very best scientists across disciplines.

WHY IS THE UK SO SUCCESSFUL?

Unless we can answer this important question, we can't ensure success in the future. There are no definitive answers, but I suggest below some likely reasons for UK success, in each case followed by possible threats that we need to be aware of:

- **Outstanding training.** But we need to consider how the new University student fee regime may influence student choices and entry into postgraduate training.
- **Open challenge.** We need urgent reform of our libel laws to protect valid and valuable scientific critique.
- **Supporting "mavericks".** Many discoveries and breakthroughs challenged dogma and were made by those who "broke the rules". A worry is that we are under ever increasing "red tape" and legislation.
- **Creativity.** Fundamental discovery in science is a creative endeavour which we must continue to fund. Some feel that a push towards application and impact could have a stifling effect.
- **Interdisciplinary research.** Big breakthroughs often depend on scientists with different skills coming together. We must break "silo mentalities" and ensure funding for cross disciplinary activities.
- **The NHS and patient data.** This is a huge resource so we must ensure it is not damaged by changes in and funding of the NHS.

THE JUBILEE

Over the 60 years of the Queen's reign, life span in the UK has increased dramatically – by an average of 5 hours a day. There are a number of reasons for this, but discoveries in Life Sciences are a major contributor to the health, wealth and quality of life in the UK and more widely.

Acknowledgements

Thank you to my colleagues at The University of Manchester, the Society of Biology, MRC, BBSRC and the Wellcome Trust for giving me so many great examples of UK advances in Life Sciences. Sorry I could only include a small fraction.

Meeting of the Parliamentary and Scientific Committee on Tuesday 10th July

BRITISH ACHIEVEMENT IN CHEMISTRY OVER THE LAST 60 YEARS

Professor Lesley Yellowlees MBE
President, The Royal Society of Chemistry
Professor of Inorganic Electrochemistry, University of Edinburgh

In celebrating our Queen's Diamond Jubilee it is appropriate that we reflect on the period as one of phenomenal scientific advance. From the discovery of the structure of DNA in the coronation year to the discovery of the Higgs Boson this year, all the sciences have made bold steps forward in explaining our world and improving it.

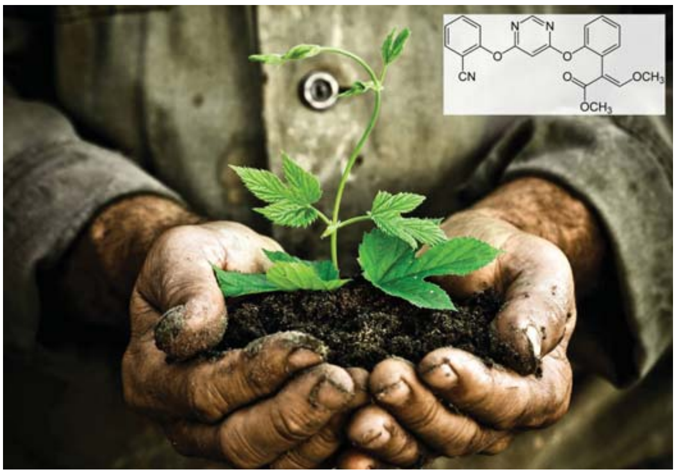
Far beyond our size, we are a nation of Nobel Laureates. For chemistry, the Queen's reign began in style with the award of the Nobel Prize, in 1952, to Archer Martin and Richard Synge for the invention of partition chromatography. They had discovered a method for the separation of substances from complicated mixtures, a new powerful tool. Thanks to their work, once hopelessly complicated problems across all the sciences were now solvable. A new era was dawning.

Since Martin and Synge, chemists have gone on to show that understanding the building blocks of the world around us is the way to build that second Elizabethan era. Chemistry is behind state-of-the-art technologies including screens and batteries in our smartphones and laptops. John Goodenough's identification and development of Lithium Cobalt Dioxide (Li_xCoO_2) as the cathode material of choice for the Li-ion rechargeable battery means I can carry my phone in my pocket everywhere and work on my laptop until too late at night. And I'm able to see all this information through a liquid crystal display, which is based on the cyanobiphenyl materials invented by Professor George Gray and colleagues at the University of Hull.

Chemistry is developing sustainable alternatives to fossil fuels and lowering carbon emissions, increasing energy efficiency in areas ranging from domestic electronic products to nuclear power stations. We need those answers – a recent report by the Committee on Climate Change showed the pace of UK emissions reductions needs to increase fourfold – and it is only technological advance that can make that happen.

Fuels. Energy. Materials. All are chemistry. And they come together in the planes that move us round the globe in a way few could have imagined. Airbus' next-generation A350 XWB aircraft will be lighter and more efficient because more than half of it will be built from lightweight composite materials that chemists constructed; a far cry from the small and slow plane that brought the new Queen back from Kenya after her father's death.

Not just a more efficient world, but also a safer world. Chemistry is working for people's security, building faster, smaller and more sensitive devices able to detect microscopic levels of explosives. And chemistry is also working for a larger, safer and better distributed food supply. Take, for example, Azoxystrobin the agricultural fungicide, developed by UK-based chemists in the last thirty years that has increased yields of more than 120 types of crop in over 100 countries.



Azoxystrobin, the leading agricultural fungicide, was developed by UK-based chemists.

And a healthier world. Blockbuster therapies which serve the needs of a wide patient population have transformed healthcare in recent decades and most are made in Britain. At least ten of the top-selling drugs worldwide have UK-trained PhD organic chemists as named inventors. Amlodipine is one of those drugs underpinned by UK chemistry patents: 2.2 million Britons take it to ease angina and this drug has reduced the number of days a patient visits hospital, cutting costs to both patient and the NHS. Or, for example, Tamoxifen, which has revolutionised breast cancer treatment. In 1957 a woman who developed breast cancer had a less than 70% chance of surviving more than 5 years, while today she now has a 90% chance of survival. An amazing turnaround.

British chemistry discoveries are everywhere transforming our world and they are central to our economy – and to economic recovery. In 2007 Chemistry-related industries supported 6 million jobs and contributed £258 billion to the UK economy – 21 per cent of GDP. Workers in the UK's chemicals industry produce £83,500 per employee, double the UK average labour productivity.

Fundamental chemistry research remains indispensable to the search for solutions to some of the most important technological and societal challenges facing us.

To tackle the big issues of the next sixty years we need to use all our talents. The Queen, our second longest-reigning monarch, is beaten only by Queen Victoria. A lesson to us all, perhaps, about the steeliness and determination of women to stick it out! I have the honour to be the first female president of the RSC in its 171-year history. But I know it won't be another 171 years because I am determined to help diversify the people who make up the science establishment. Not to squeeze out those already there, but to widen, deepen and strengthen the great British talent I see coming through my university month after month.

Of 103 Nobel laureates in Chemistry, only four are women. Of those four, only one is British: Dorothy C Hodgkin. She was awarded the rare honour of an unshared Nobel Prize in 1964 "for her determinations by X-ray techniques of the structures of important biochemical substances." Knowledge of a compound's structure is essential in order to interpret its properties and reactions, and to decide how it might be synthesised from simpler compounds. Hodgkin's contribution to the field was enormous: she carried out a large number of structure determinations primarily of substances of biochemical and medical importance. She was the first one to describe the structures of the antibiotic penicillin and of vitamin B12. The determination of structure is the crowning triumph of X-ray crystallographic analysis in respect of both the chemical and biological importance of the results. With her colleagues she unravelled the structure of insulin so that millions could manage their diabetes.

She was a great scientist first and foremost. But she was an inspirational woman too. Dorothy Hodgkin was a rare talent, but British chemistry simply cannot afford to look back sixty years from now and see her as unique for her gender as well as her talent.

To use all our talents we need policy makers and scientists working together and listening to each other. We are both the kind of people who want to change the world. And we've shown that we can do that together in the past.

Sixty years ago London was engulfed in the Big Smog. Not the first or last of the era of the peasouper. But the point at which people said something must be done. Deaths and ill health were not a price worth paying.

London itself still bears the scars to this day. The cleanup has taken sixty years. But the legislation to clean the air was quick because we already understood the chemistry to clean the air. The Clean Air Act of 1956 banned emissions of black smoke and made homes and industry move to smokeless fuels. Many thousands of lives have been saved through good science and good legislation.

We've done it before and we can do it again. With good science contributing to good legislation and a wide, diverse science base we really can make the world a better place.

It is these inspiring stories and global challenges that will bring in the next generation of Dorothy Hodgkins and Nobel laureates. At the RSC we work to inspire young people to study chemistry, and to raise the public's awareness of the importance of chemistry. We are the largest non-governmental supporter of chemistry education in the UK. In the last decade we have spent more than a quarter of a billion pounds advancing the chemical sciences. We pursue excellence in our work, with our scientific journals, our educational and public engagement activities and our work with policy makers.

To borrow a biologist's analogy, everyday we plant seeds, with fruits of success to be harvested whether that is in the next month, next year, or ten years down the line.

In order to continue to have great British scientific achievements we need proper funding of the sciences. On-going fundamental research is essential to ensure a continuing flow of scientific and technological breakthroughs. Fundamental research, like the work of Dorothy Hodgkin, is essential also to ensure that the UK maintains a highly skilled and innovative workforce. To be well placed to adopt, and advance, new ideas, to exploit successfully new technologies, and to develop new and better products and services we need the profound discoveries that come from fundamental research. As it has been done in the past decades, these will fuel our economy. They are a necessary condition for attracting inward investment to the UK – and contributing to the 21% of GDP that is in the chemical-related industries. Fundamental chemistry research remains indispensible to the search for solutions to some of the most important technological and societal challenges facing us.

The Queen's reign has been one full of great British scientific achievements. We must be proud but we must hold tight to the spirit of enquiry, challenge and thirst for new knowledge that has taken us so far. That is how science and the chemical sciences will thrive for the next sixty years.

Lithium batteries and liquid crystals are ubiquitous in today's portable electronic devices. They are both British achievements of the last 60 years.

PHYSICS – FORCES OF NATURE

This article is a transcript of the talk given by Professor Brian Cox to the Parliamentary and Scientific Committee on 10th July, prepared by Christopher White of the Institute of Physics.

Back in July we made what is one of the biggest scientific discoveries if not in the Queen's reign then of all time – the discovery of the Higgs particle.

That might seem hyperbolic – it's just another subatomic particle – but to step back and look at the story in which that particle plays a part is instructive.

The universe began in a big bang 13.75±0.11bn years ago, which in itself is a remarkable measurement – a measurement that not only was not known with that degree of precision when the Queen took the throne, but the idea that the universe had a beginning was not known to be the correct description of the universe at that time. What we now know is

> . . . The universe began in a big bang . . .

that around a billionth of a second after the universe began, as it was expanding and cooling, something happened that caused a condensate to condense out of empty space. This is the Higgs particle. So the picture today is that every cubic centimetre of space is rammed full of Higgs particles that condensed out of the vacuum less than a billionth of a second after the universe began.

> . . . This is the Higgs particle . . .

The LHC, where the Higgs was discovered, is a proton collider. It bangs protons together, and that's how it gets energy into small regions of space, so that we can investigate the universe as it was around a billionth of a second after the big bang. That technology is

> . . . That technology is British technology . . .

British technology. One of the first two proton colliders was built in Birmingham in 1953 – the year of the coronation. That machine was looking at nuclear structure – the structure of nuclei was not well known. It also wanted to find some clues as to the nature of the force that holds the nucleus together. We didn't know about one of the four fundamental forces of the universe – the strong nuclear force.

Fast forward 60 years and we have the Large Hadron Collider. It's the same technology – it's a proton synchrotron. It accelerates beams of protons, now not slowly around something the size of a garage, but to around 99.999999% the speed of light. It collides protons together up to 600 million times every second; the proton beams themselves are less than the diameter of a human hair, but carry the energy of an aircraft carrier travelling at 30 miles an hour. Yet we can take pictures of those collisions; we can make high-precision measurements, and in July we discovered the Higgs particle.

The LHC has four giant detectors, all of which have important contributions from UK universities. The ATLAS detector is 44 metres wide, 22 metres in diameter, and at its heart there are silicon detectors, which are like CCDs in a digital camera, but in an extremely high-radiation environment. UK universities manufactured and built those silicon detectors. It is a tremendous engineering achievement. With it we can see Higgs-candidate events. We detect other particles produced by the decay of the Higgs, and if you measure the energy and momentum of those with precision, and trace them back, you find out that they came from a new particle weighing around 126 times the mass of the proton. Go back to 1953 in Birmingham, and the accelerator had the energy to make one extra proton. The Higgs particle weighs 126 times the mass of the proton, and that's why we

. . . four fundamental forces of the universe . . .

need something as big as the LHC to make it.

There has been a long road to the discovery of the Higgs. The two famous papers by Peter Higgs were published in 1964. There were also papers published by Tom Kibble, another British theoretical physicist. Two of the five theorists who contributed most to this theory are British. How was it that they were able to make this prediction? What a bizarre thing to suggest – that

. . . 126 times the mass of the proton . . .

empty space is stuffed full of Higgs particles, and we get mass by bouncing off those Higgs particles. The answer to that is the standard model of particle physics – in itself one of the greatest achievements of the 20th century. Its equations describe three of the four fundamental forces of nature – everything that we know of, other than gravity, is described by this simple equation. And it predicts the Higgs field.

It is interesting to note that the prediction was entirely mathematical. It's the best example of what the great physicist Eugene Wigner called "the unreasonable effectiveness of mathematics in the physical sciences". Higgs, Kibble and others noticed that our description of three of the four forces of nature didn't work – it was logically inconsistent; it failed mathematically – without the introduction of the Higgs field. So back in the 1960s this idea was postulated.

The standard model of particle physics is itself based on quantum mechanics, and the pivotal moment in the development of quantum mechanics was the publication of the Schrödinger equation, which showed how particles behaved as waves. That was in 1926, the year of the Queen's birth. Without doubt the best example of the use of quantum theory is the invention of the transistor, ubiquitous today. In one year there are more transistors manufactured than grains of rice have been consumed on Planet Earth since the Queen came to the throne. Transistors work because atoms talk to other atoms in a very strange way. They work because single particles won't go into the same energy level around different atoms, and when you put that in a crystal of silicon you get what's called a 'band gap' and you can use this as a switch. Without quantum theory – this most abstract of theories – the transistor could not have been invented.

. . . empty space is stuffed full of Higgs particles . . .

Where do we go next? What is the next discovery? Could there be a replacement for the transistor? The answer is yes, and it's yet another British success story. The 2010 Nobel Prize was given to University of Manchester physicists Andre Geim and Konstantin Novoselov for their discovery of graphene. One of its most exciting applications is in answer to the question of what replaces the transistor. Graphene transistors have already been manufactured: IBM manufactured one in April last year that was ten times faster than anything manufactured in silicon. In February this year, the Manchester group demonstrated the technology that allows these to be packed together – one of the big problems had been how to build graphene chips. Now we know – we did that in Manchester.

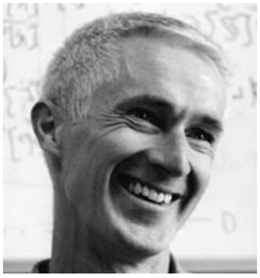
. . . the prediction was entirely mathematical . . .

This is an interesting example of a discovery that's based on esoteric physics but has immediate commercial applications. It's a 21st-century discovery in every way. And it's interesting to read Andre's observations in his Nobel Prize speech. He was talking about his history, of why he came to Manchester. He pointed out that by 2003 he'd already established a lab, as a result of seedcorn funding set up by Lord Sainsbury. But he goes on to say why he thinks the Nobel Prize was brought to Manchester and to the UK. He thanked the Engineering and Physical Sciences Research Council. This funding system – in responsive mode, he emphasises – "is democratic and non-xenophobic; your position in an academic hierarchy or an old-boys network counts for little. Also visionary ideas and grand promises to address social, cultural and economic needs play little role when it comes to peer-review. In truth, the responsive mode distributes its money on the basis of a recent track record, whatever that means in different subjects, and the funding usually goes to researchers who work both efficiently and hard. No system is perfect, and one can always hope for a better one. However, paraphrasing Winston Churchill, the UK has the worst funding research system – except for all the others that I'm aware of."

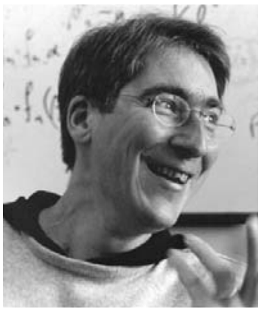
. . . showed how particles behaved as waves . . .

That's powerful and important when we decide to try and fix our research-funding system. Because Andre Geim, who used it to great effect, thinks it's the best in the world.

MATHEMATICS IN THE NEW ELIZABETHAN AGE (60 Years of British Mathematics)



Ken Brown
University of Glasgow

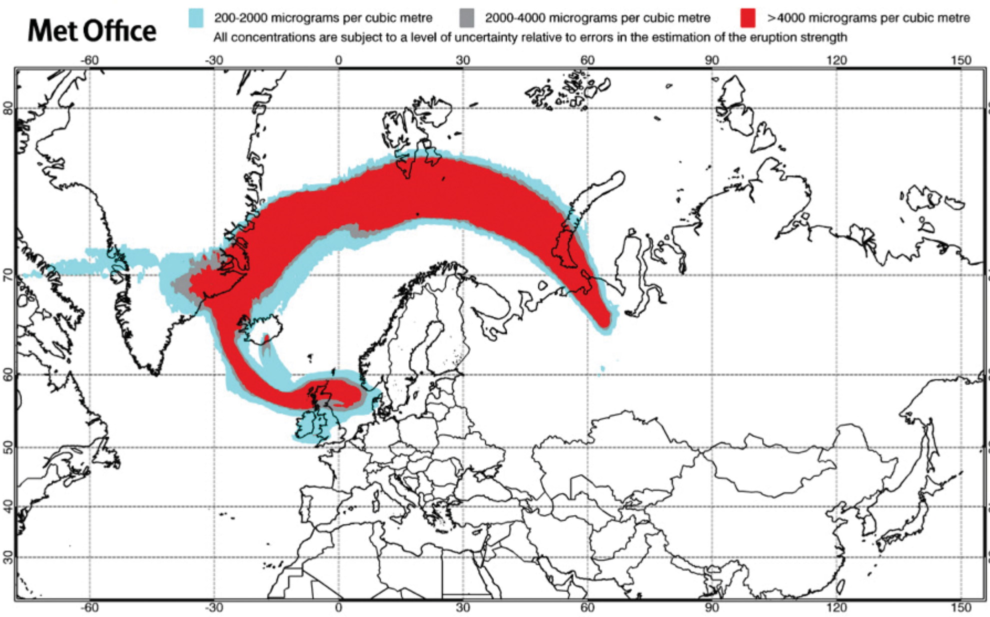


Paul Glendinning
University of Manchester

In June 1993 Andrew Wiles gave a series of seminars at the newly-created Isaac Newton Institute for Mathematical Sciences in Cambridge. In the final minutes of the last seminar he claimed to have solved a 250 year old mathematical problem: Fermat's Last Theorem. This became headline news across the world because of the romance in the story (lone British mathematician solves ancient mystery), and also because the problem itself is relatively easy to state. The interest generated by this achievement is rare for mathematics, though many other developments in mathematical science over the last 60 years are on a par with it. This is partly because mathematics is often seen as too abstruse or specialised for 'ordinary people'; and partly because major advances in applied mathematics and statistics are often sub-plots of bigger stories in biology, physics, economics or engineering.

In this article we want to redress this invisibility and stress the key international role played by British mathematics. Mathematics has changed enormously over the new Elizabethan age, and this has been a global effort. However, the UK has played an important role in most of these changes – a far greater role than its relative size would suggest. Thus, for the period 1998–2008, Scotland and England were respectively second and fourth in the world for citations per paper published in the mathematical sciences[1]. Although we concentrate on research in the rest of this article, it is worth remembering that most researchers are also teachers, and we rely on them to pass on the intellectual thrill of the discipline and to create the skilled workforce needed in the banking, computing, engineering and pharmaceutical industries.

The rise of computers and the ubiquity of smart technology form one of the greatest changes to our lives since 1952. The early prototypes of this technology were developed by Alan Turing and others at Bletchley Park (to decode the German ENIGMA machine) and then at the National Physical Laboratory (NPL) and the University of Manchester. Turing committed suicide in 1954, so he only just makes it into the new Elizabethan age, but his achievements in computing, logic and mathematical biology have had an immense influence. As computers began to be used to solve complex engineering problems in industries such as aeronautics, the UK contribution was key to creating a new mathematical discipline, numerical analysis, which emerged to ensure that these



A computer generated prediction by the Met Office of the position of a volcanic ash cloud.

large computations – computations that can now be done on a laptop! – were reliable. Here we mention two examples. James Wilkinson worked with Turing on the early computers at the NPL in Middlesex, where he discovered ways of analysing floating point arithmetic that enable the accuracy of computer calculations to be understood. His methods remain as valid as ever for today's largest supercomputers[2] and he went on to develop other now standard tools in algebraic manipulation. In many industrial and scientific problems some quantity needs to be optimised. In the 1970s such concerns prompted the UK mathematicians Roger Fletcher and Mike Powell to develop methods for solving optimisation problems numerically that are still the basis for many of today's techniques. UK mathematics underpins computer simulations all over the world!

. . . lone British mathematician solves ancient mystery . . .

The speed and memory size of computers grew rapidly and it became much easier to collect data. But while data can now be gathered on a massive scale, it is much harder to work out what to do with it. Many of the fundamental ideas behind the mathematical treatment of data sets, statistics, were formulated in the 1920s at Rothamsted by Fisher. This tradition of excellence in statistics within the UK has continued during the new Elizabethan age, making it possible to analyse the effect of new drugs, or the meaning of the human genome, much more efficiently, and also to analyse models of systems with uncertainty (financial markets, spread of epidemics, life expectancy of smokers ….). Perhaps the most influential statistical contribution of the jubilee years has been Sir David Cox's 1972 paper[3] allowing mathematical models to be built on actuarial life tables, so permitting causal inferences based on sparse data. This work has been fundamental to countless medical and actuarial studies. In a related later development, the former Director General, Knowledge and Innovation, at BIS, Sir Adrian Smith, showed how useful information could be obtained from probabilistic models[4]. This technique, called Markov Chain Monte-Carlo inference (or MCMC for short), is now ubiquitous throughout the sciences.

The internet and world wide web brought computers into our daily lives, with new possibilities and problems. The method used to process secure financial transactions on-line is based on number theory, specifically the difficulty of finding the prime factors of large numbers. The RSA algorithm at the heart of this method was first developed by Clifford Cocks, a number theorist working at GCHQ. Unfortunately no one at GCHQ appreciated its potential (it was filed as 'secret') and the algorithm is now known by the initials of the US-Israeli team that patented the method in 1978!

Not all new mathematics is immediately applicable, and a fundamental development of the new Elizabethan age has been the renaissance of geometry. Geometry and physics have been intertwined through most of their history, but drifted apart in the 60 years leading up to 1980. However, starting from discussions between Sir Michael Atiyah and the American physicist Ed Witten, the picture has changed greatly over the last 35 years, and now the connecting road is a motorway. Atiyah is one of the six UK Fields medallists (the mathematical equivalent of the Nobel Prize) – only France and the US have more – and has been a central figure in world mathematics during the new Elizabethan age. The maths-physics motorway is not just one-way: in the striking example of mirror symmetry from string theory, Philip Candelas, now at Oxford, and his collaborators were able to use the amazing intuition of the physicists to predict the solution of a century-old problem in classical geometry ("counting the number of rational curves in the quintic").

Mathematical physics itself (quantum theories and relativity) has also changed dramatically. Stephen Hawking and Roger Penrose, both working in mathematics departments, described the mathematical structure of black holes, stars so massive that even light cannot escape their gravitational pull. Hawking went on to show that there is a sense in which black holes actually do emit radiation! The existence of the Higgs particle that may have been observed recently and which is responsible for mass in quantum theory was predicted by Peter Higgs at the University of Edinburgh, with others including Tom Kibble at Imperial College, using mathematical arguments.

. . . ways of analysing floating point arithmetic . . .

Sir Michael Atiyah ©Marc Atkins

With advances in both methods and computing power, the scope of what mathematicians can model has expanded. This has led to changes in the way that weather forecasting is reported (using ideas from chaos theory) and the increasing use of mathematics in modelling financial markets. The sophistication of computer models is such that a model of the human heart at Oxford can be used to make predictions about heart treatments without using a living subject. Often, in such applications to the life sciences, mathematicians now work in teams with other scientists as equal partners. Mathematical modelling is also used to inform policy decisions: strategies for the foot and mouth outbreak of 2001, the distribution of vaccines, and the safety of air flights through volcanic ash clouds in 2010, were all assessed using mathematics.

So what lessons can we learn from the success of UK mathematical science in the jubilee years? Here are some observations from the chalk-face.

- Structures must be flexible enough to allow many flowers to bloom: nobody can predict what the next breakthrough will be, far less from where it will appear.
- The time between formulation of a seminal mathematical idea and its application may be brief (as in Cox's 1972 work on regression analysis) or very long (as in Turing's 1936 discussion[5] of thinking machines, now at the heart of Artificial Intelligence). It is misguided to aim to reward only a fast pay-off. Worse, even with the best intentions this

. . . mathematical models to be built on actuarial life tables . . .

policy tends to lead to incremental research rather than real innovation, which is inherently unpredictable.

- The openness and non-hierarchical structure of British culture allows new ideas to gain a foothold, new talent to find a ready audience.
- Diversity (of scale of organisation, of mode of research – solo/team, interdisciplinary/narrow, applications-focused/blue skies) is key.

All the above features of UK mathematical science have been massively aided by the dual support system for funding research, allowing new ideas to start with small first steps, new talent to develop from a wide base (it is worth remarking that the Cambridge mathematician and Fields Medallist Sir Tim Gowers has never held a research council grant).

The key message from the last 60 years is that most progress has been through glorious surprises. No one except a few crazy science fiction writers could have predicted the way computers would come to pervade our lives, nor the way that new mathematics would be needed to facilitate this. Modern statistical methods allow information to be extracted from data in previously unimagined ways. The deep interconnections between different areas of mathematics, and between mathematics and the sciences, that have emerged are similarly mysterious and could not have been foreseen in 1952.This does not mean that all future developments are unpredictable – it is clear that the mathematisation of the biological sciences will continue apace and holds some exciting prospects, and understanding climate change provides a challenge – but it does make it likely that the next real innovations will, by definition, be surprises.

The UK has been at the forefront of change over the past 60 years, and we need to ensure it remains at the cutting edge of progress for the next 60 years. Not just for the intellectual excitement of discovery, but also for its societal impact. How will the next 60 years go? All we can say is: watch this space!

Acknowledgements: We are grateful to Penny Davies, Patrick Dorey, Jerome Gauntlett, Nick Higham, Oliver Jensen, Stephen Senn, Richard Thomas and Mike Titterington for helpful guidance, some of which we ignored due to lack of space.

Footnotes

1 Figures from Thomson Reuters at http://www.timeshighereducation.co.uk/story.asp?sectioncode=26&storycode=406463 Denmark were first, the USA third.

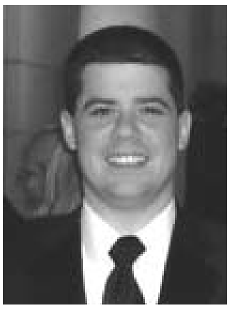
2 J. H. Wilkinson, *Rounding Errors in Algebraic Processes*. Englewood Cliffs, New Jersey: Prentice Hall, 1963.

3 D.R. Cox, Regression models and life tables, *J Royal Statistical Society B* 34 (1972), 187-220.

4 A.E. Gelfand and A.F.M. Smith, Sampling-based approaches to calculating marginal densities, *J. American Statistical Association* 85 (1990),398-409.

5 A. Turing, On computable numbers, with an application to the Entscheidungsproblem, *Proc. London Math. Soc.*

AN UNSCIENTIFIC CAMPAIGN



Bradley Keelor
Science and Innovation Team
British Embassy Washington

Science has not traditionally taken centre field in US political campaigns and it is unlikely that this campaign will be an exception. Issues around the economy, jobs, healthcare and taxation are likely to be the battle grounds of the next few weeks.

When science does enter the campaign, it will most likely be as a supporting player in the blue touch paper issues such as climate change, other environmental policy, or stem cells. For example, early in the campaign one of Governor Romney's most frequently broadcast advertisements highlighted his promise to restart construction on the Keystone XL Pipeline – the extension to the Keystone Pipeline which currently brings crude from the Athabascan fields in Alberta to Illinois. Keystone XL would add capacity and extend the pipeline to Texan Gulf Coast refineries. Whilst President Obama approved the Cushing, Oklahoma to the Gulf Coast portion of the Keystone XL, he has delayed, pending further environmental review, the section which would cross the Ogallala Aquifer in Nebraska, one of the largest reserves of fresh water in the world.

At writing, Governor Romney's team of advisors on science is structured in much the same way John McCain's was in 2008; that is, there is no central science advisor, but small teams focusing on issues such as space, energy, and health. These teams are often populated by names familiar from President Bush's Administration. Former NASA Administrator Mike Griffin advises on space; former Missouri Congressman Jim Talent serves on the energy team; and former Environmental Protection Agency Administrator and Health Human Services Secretary Mike Leavitt is advising

. . . no central science advisor . . .