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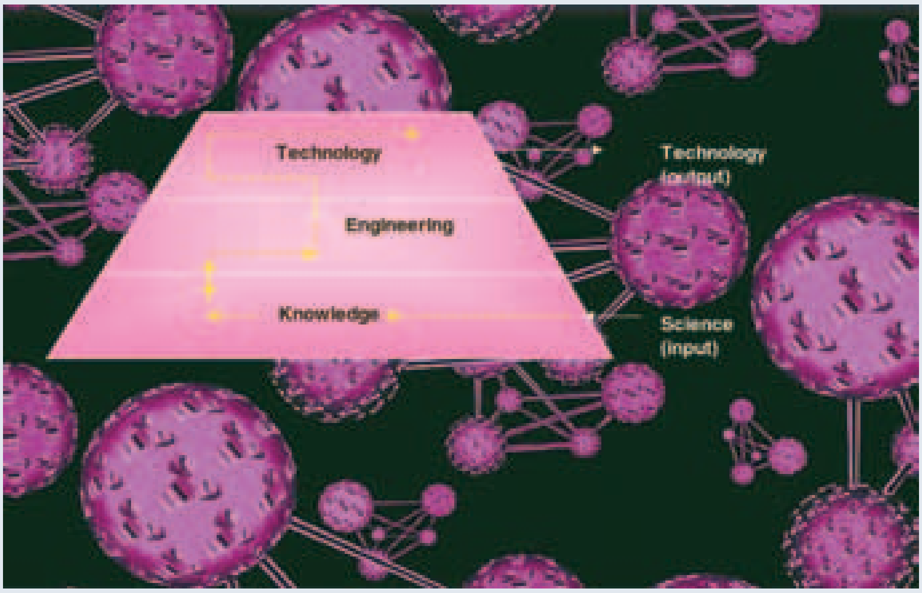


The journey: *from* science *via* engineering *to* technology

Science is the feedstock of engineering, but progress in scientific research itself now often depends on engineers stretching technology to its limits. This article looks at the interdependence of science, engineering and technology, and at how advances in science can force progress in engineering, resulting in, sometimes unpredictable, developments in technology.

Based on the Temple Chevallier Lecture, given at the University of Durham on the 7th November 2001. Astronomy has a long tradition at Durham, dating back to Thomas Wright (1711–1786) and Temple Chevallier (1793–1873), the first Professor of Mathematics and Astronomy.

Defining 'science', 'engineering' and 'technology'

Science can be defined as the quest for fundamental knowledge and understanding of all things, natural and man-made, their structure, properties and their behaviour. Pure science is concerned with extending our knowledge of matter and of nature's laws. Applied science takes pure science and uses it for specific purposes.

A short definition of engineering is:

> the knowledge required, and the processes applied, to conceive, design, make, build, operate and sustain something with significant technical content for a specified purpose. Technology is an enabling package of knowledge, devices and systems created for a specific purpose.

In London there is a library dedicated to Sir Charles Parsons with the words 'Scientist and Engineer'. Those words say it all. Without the discovery of the laws and principles of science, and the subsequent application of engineering, there would have been none of the devices or processes that are so necessary to the civilised world today.

These equations sum it up:

science + engineering = technology

technology + marketing = wealth creation

An engineer's life in the days of Parsons was somewhat simpler than it is today. Not easier, but simpler. If you were an engineer, you built roads, bridges, ships, trains and manufactured products. It was straightforward to define engineering and to identify those who deserved the privilege of being called an engineer.

Today the role played by engineering is more complex. Advances since the Industrial Revolution have meant that engineering now embraces a huge spectrum of activity and furthermore its horizons are constantly expanding.

The evolution of many different areas of activity, such as the chemical industry, aerospace, and electronics, the explosion in telecommunications and information technology, and the recent emergence of bio-medical engineering, have completely redefined the engineering landscape. It has changed so much that no one is certain any more where the horizons of engineering begin and end and who should be entitled to call themselves an engineer.

No matter what the definition of its scope, engineering is the nation's wealth creator. It determines how competitive the UK is going to be on the world stage. It isn't the work of the City, or tourism, or the service industries that makes us competitive. It is engineering. And its feedstock is science, without which engineering could not produce technology.

Astronomy and particle physics

Let me describe some examples where our knowledge of the physics of the Universe has enabled us, through engineering, to develop new areas of advanced technology. These are areas that I have come to know much better in the last few years as Chairman of the Particle Physics & Astronomy Research Council.

At the beginning, in a time span of less than a microsecond, the universe was the realm of high energy particle physics. Now, some ten thousand million years later, the mission of particle physics is to pursue fundamental questions of particle physics, such as:

- What is the universe made of?
- What is out there?
- Are we alone in the universe?
- How did it all start?
- How will it end?

The answers to these questions depend totally on scientific and engineering skills being pushed to the limits.

It is significant that, in the past, such activities have given rise to whole new branches of engineering, such as electronics, and more recently, the World Wide Web.

It may seem a paradox, but it could be a law of physics, that we need bigger and bigger machines to study the smaller and smaller, such as in particle physics, and the ever more distant and faint signals from outer space, in astronomy. Scientific progress demands that each new machine is more powerful than the last. Successive generations of equipment to exploit these areas of scientific investigations stretch engineering and technology skills to the limit. That is a very important ingredient in our recipe for future commercial success.

Figure 1 CERN

Particle accelerators at CERN

The largest single piece of engineering for physics research is the 27 km circumference particle accelerator at the European Particle Physics Laboratory, CERN, near Geneva (Figure 1). The current machine, the Large Electron Positron Collider will soon be replaced by the even more powerful Large Hadron Collider, which, with American, Japanese and Russian contributions, will be the first truly global particle physics project.

In a tunnel some 100 metres below ground, the new collider will accelerate charged particles to unprecedented high energies of 14 TeV (Figure 2). Even to build the tunnel itself required the development of new civil engineering surveying techniques. Some of these found immediate applications in the building of the Eurotunnel.

For those who used to dream that the world would be advanced through the science of superconductivity it is significant that this will be the world's largest superconducting installation. The beam line will require the use of some 1300 superconducting dipole magnets, producing fields of 8.36 Telsa, and kept cooled to within 2° of absolute zero with 700 000 litres of liquid helium. Twelve million litres of liquid nitrogen will be vaporised, just for the initial cooling down of the 31 000 tonnes of material. The beam line will have to be pumped out to a near perfect vacuum, with techniques, pioneered by CERN, reaching 10^{-10} torr. Just to put this achievement into context, an electron will travel some three billion kilometres before it meets a stray molecule of gas! There is yet another spin off here because the use of vacuum technology is vital in the production of microchips and in the development of nanotechnology.

Tim Berners-Lee's work at CERN's when developing the World Wide Web is an outstanding demonstration of the extraordinary and unpredictable

Figure 2 Large Electron Positron Collider tunnel

consequences of applying the latest in engineering to the greatest challenges of science. The development of the key software for the World Wide Web, at CERN, in order to share and analyse data, is affecting society and business in ways none of us would have thought possible a few years ago.

In the new accelerator, the detectors, as large as a medium sized office block, will track the results of some 800 million proton collisions per second, handling as much information as the entire European telecommunications network. Some of the events being looked for will show up as just one out of every 100 million million collisions. To cope with this avalanche of information engineers at CERN are developing new solutions in ultra-fast electronics and computing.

The next generation of the Web, the so called computational Grid, will bring about a new revolution that will inevitably result in major new industrial applications, for example in the rapidly growing field of global communications.

Observing space

At the other end of the scale, over a year ago the European Space Agency launched its largest scientific spacecraft.

The X-ray Multi-Mirror XMM mission has a major UK involvement. It has now been renamed The Isaac Newton Observatory, a tribute to the UK's long pioneering tradition in X-ray astronomy (Figure 3). It will study some of the hottest and most violent events in the universe, such as black holes and supernovae. It is a prime example of forward thinking.

Instruments for the mission were built by scientists and engineers in British universities. This initiative led to the involvement of many UK companies, with the consequential effect of job creation in high technology areas.

Described as a masterpiece of precision engineering, at its heart are three sets of 58 high precision mirrors in concentric conical shells (Figure 4), with a total collecting area of 120 m^2. Made of gold-plated thin nickel sheets, the mirrors have to be very accurately aligned to focus on the detectors at the end of a 7½ metre tube.

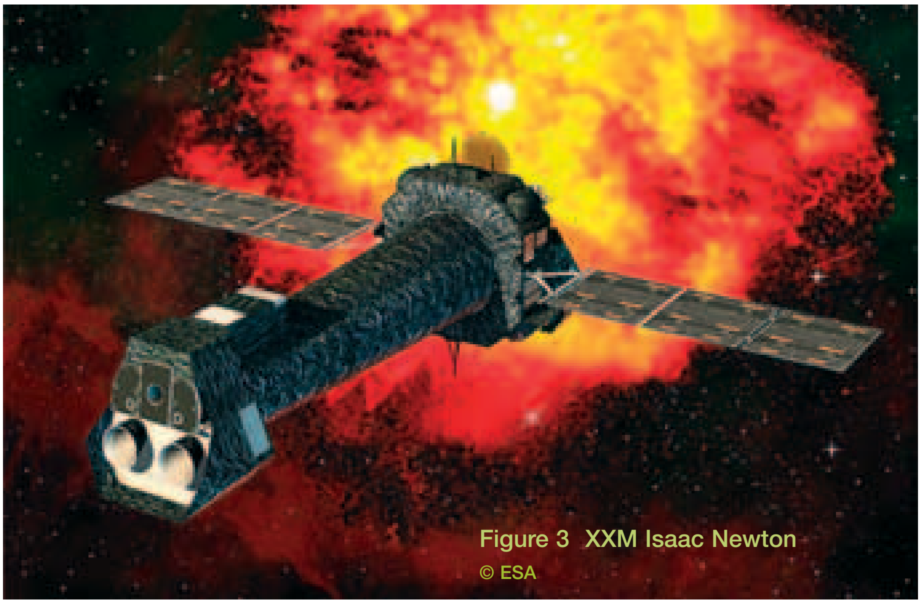


Figure 3 XXM Isaac Newton

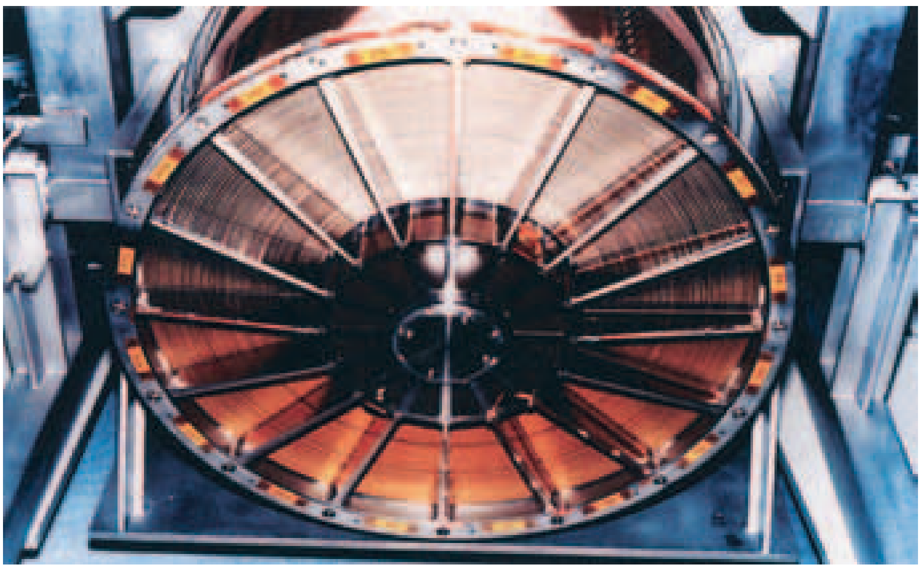
Other instruments include three camera modules and two similar spectrometers, which will tease the X-rays into their component wavelengths. The spectrometers include an array of 200 reflection gratings, made up of grooved gold plates, which gave the Issac Newton Observatory a great leap in sensitivity and resolution over all previous similar missions. The cameras have a resolution equivalent to reading a stop sign at 2 kilometres.

A very precise attitude and control system will keep the satellite on course for its 10 year mission and enable very accurate 'jitter' free directional pointing for long periods. As if that is not enough, all these highly sensitive instruments have to be capable of surviving the tremendous shaking from the launch of an Ariane 5 rocket and then the vacuum and extreme temperatures of space. With no chance of a repair mission, unlike the Hubble spacecraft, they must be 100% reliable.

There are not many other devices that need to cope with such extreme conditions, but they came through with flying colours and the mission is already a great triumph.

Figure 5 is a picture taken by the XXM. It shows M81's spirals around a huge black hole.

Figure 4 Mirror for Isaac Newton



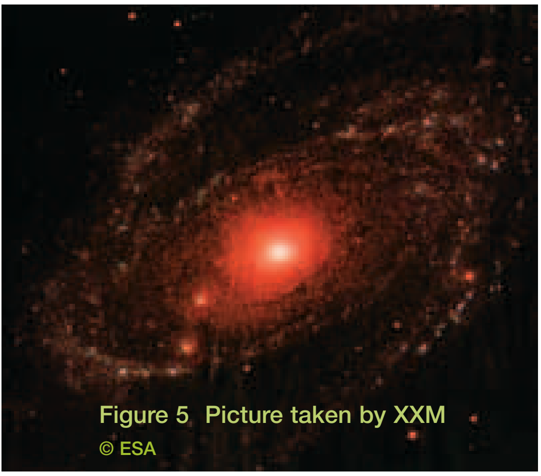


Figure 5 Picture taken by XXM
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The Gemini telescopes

Another example of science and engineering brilliance is the 'Gemini' telescope project (Figure 6), with one telescope on Hawaii and one in Chile. As with much big science today the development of these telescopes is an international venture, in which the UK has a quarter share.

Gemini North, on Hawaii, was officially dedicated in 1999. Gemini involves many engineering feats. The telescopes, over 340 tonnes, must move with very high accuracy and no shudder and withstand heating and cooling effects and high winds. They are so finely balanced that they can be moved by a gentle push and so precisely controlled that the starlight from the primary mirror is focused to a point only 0.06 millimetres across (Figure 7).

The telescopes' positions are maintained to 0.01 millimetres while they track astronomical objects across the sky. That's Swiss watch precision on a massive scale and it has been described as Arnold Schwarzenegger moving with the grace of Nureyev!

The mirrors themselves, the heart of each machine, are formed of 55 blocks of low expansion glass, fused together to make the blank, over 8.1 metres in diameter, weighing 32 tonnes but only 27 cm thick (Figure 8). Their shape is maintained by a computer-controlled support system. The mirrors are then polished to an accuracy of 30 nanometres. This accuracy, over a diameter of over 8 metres, is equivalent to about 2 cm over the width of the Atlantic Ocean, or put another way, if the mirrors were enlarged to the size of the United States, no undulation would be larger than a speed restriction bump.

Finally, one of the smartest features: the telescopes use adaptive optics to overcome the problems of atmospheric distortion. By detecting the distortion of the incoming beams of starlight, the shape of the secondary mirror is adjusted up to 100 times a second, to compensate for the ripples and provide a much sharper image, approaching that of Hubble at infra-red wavelengths. These are engineering triumphs of the highest order.

Developing the Web

As mentioned earlier, the most significant product that has arisen from the needs of physicists to carry out advanced research, is the World Wide Web which was developed at CERN to help particle physicists share and to handle experimental data. This has led to the unprecedented explosion in e-knowledge and e-business. Staggering as it was, with such profound global effects, more is now needed.

At CERN the large Hadron Collider comes on line in 2005. This will collide groups of protons with energies of 7 TeV every 25 nanoseconds. As soon as these collisions occur data will pour out at a rate of 'a 1 kilometre high pile of CD ROMs every second'. Particle physicists and engineers are currently building the fast electronics that will filter information from the most interesting collisions, reducing the data by a factor of 10^{10} in less than a micro second, but this will still leave a vast amount of data that will need to be analysed by thousands of physicists around the world. So physicists and engineers are now developing 'the Grid', which will link large numbers of computers in separate locations to handle the resultant complex calculations. But, of more significance, the Grid will enable the processing of the huge volume of data that arises not only from experiments in particle physics but also in astronomy, geophysics and genomics.

So in the near future science will enter a whole new era of discovery with the ability to handle vast amounts of information of high quality at separate dispersed locations.

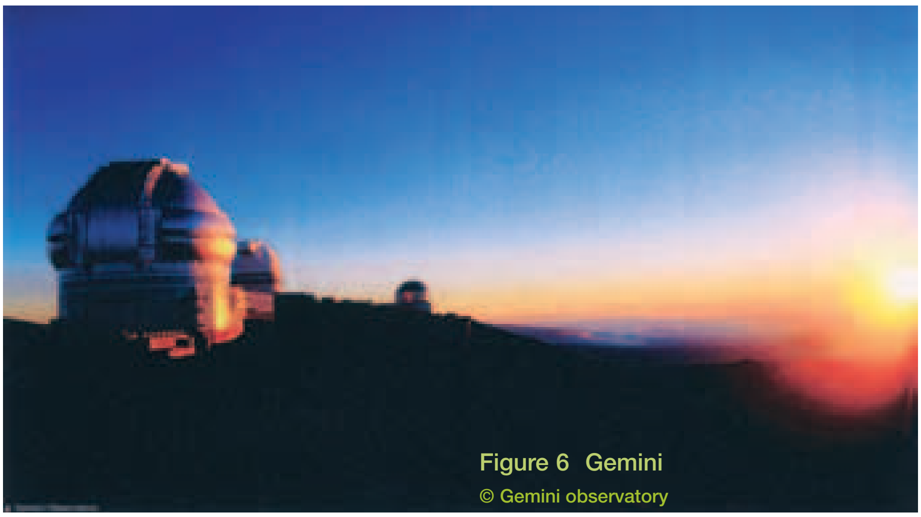

Figure 6 Gemini
© Gemini observatory

Figure 7 Gemini Construction
© Gemini observatory

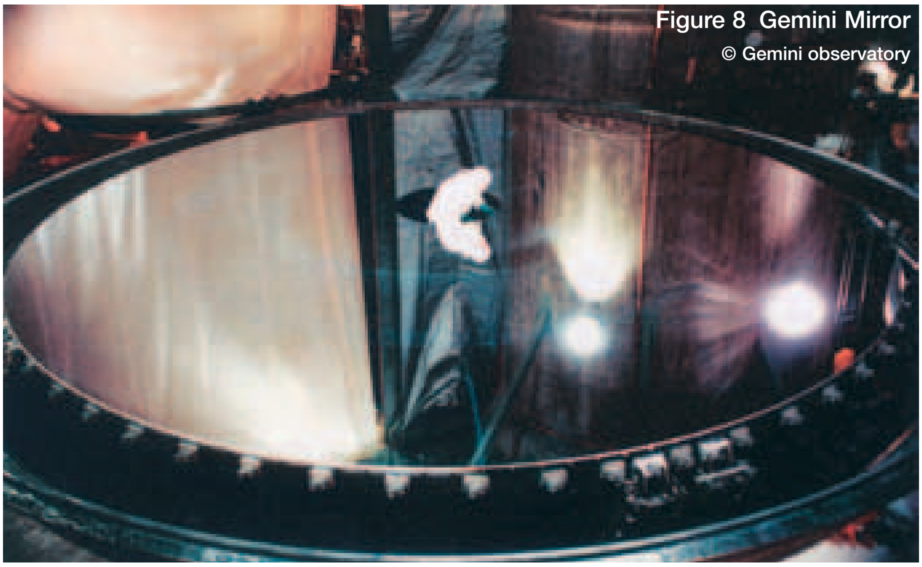

Figure 8 Gemini Mirror
© Gemini observatory

Physics into products

On the more day-to-day front, photodetectors, used for detecting radiation from the far side of the Universe, are also everywhere in commercial use.

Photodetectors detect movement and then open doors. They are the heart of the remote control systems used to switch on and off televisions and they have numerous other applications.

Another example arises from the work of scientists at Cambridge who studied radio emission from distant galaxies. The spin-off is software installed in mobile phones that can enable the user to determine exactly where they are: this is useful if you are in a car that breaks down or if you need to find out how close you are to a given location, say, a cash dispenser.

Scientists at Southampton, Bath and Heriot-Watt have used materials that control the propagation of light to develop optical fibres, waveguides and beam splitters for telecommunications systems.

In 2000, three scientists were awarded the Nobel Prize for Chemistry for the discovery and development of conductive polymers which will find widespread use in electronic display systems. For smaller applications, Napier University researchers have produced fluorescent dye doped polymers that absorb ambient light and emit a range of colours without the need for electrical power.

At Massachusetts Institute of Technology, scientists have developed electronic ink that responds to an electrical field. Tiny microcapsules, containing a suspension of white particles in a dark dye, are suspended in a liquid. When an electrical field is applied, the white particles move to one end of each microcapsule, making them visible. Reversing the field makes them invisible. This can be done remotely through the Internet. The scope for their use in displays in consumer electronic devices or even electronic books is said to be large.

There are many other examples of commercial products that have resulted from blue-sky cutting-edge research:

- Electron beam accelerators, developed at CERN, are in use to sterilise medical instruments, pasteurise food and treat plastics.
- Positron emission tomography (PET) has been used for many years in medical scanners.
- In the late 1980s, scientists in Germany and France, working separately, discovered large resistance changes occurred in materials that were made up by alternating very thin layers of metallic elements, when these were at low temperatures and in very high magnetic fields. This phenomenon, called the 'giant magnetoresistive effect', has revolutionised disk drives for small portable handheld computers.
- The laser was invented in the early 1950s and now has countless uses, ranging from reading bar codes to cutting metal, and of course for reading and writing to CDs and DVDs. As the technology has developed it has become possible to store more and more data on a single disk. In fact if you uncurl a single track from a DVD it will stretch over 11 km!
- In the medical world, lasers are used to stop damaging changes in retinal blood vessels in the eye, a common cause of blindness, or for the repair of small tears in the retina, or even to sculpt the surface of the retina to correct near sightedness.

The new products developed in telecommunications utilising fibre optics that have arisen from laboratories around the world, are too numerous to mention.

The third millennium

Emerging new technologies will be of profound importance. We have seen the dramatic effect of the Internet, the foundations for which lay in scientific discoveries made two decades ago. Advances in biotechnology, pharmaceuticals, nanotechnology, new materials, alternative clean methods of energy production, genomics, and the need to ensure a sustainable global future, will be even more significant over the next two decades.

So, as we embark on the third millennium, what are the opportunities, or challenges, that are presenting themselves to put science to work through the process of engineering and so create new advanced industries, employment and wealth?

Biomedical engineering will become an increasingly important area and, as has been the case for the past 50 years, the breakthroughs will come, not from doctors, but from scientists and engineers. Implants, using silicon that can deliver automatic drug delivery systems within the body, will move from the realms of science fiction into the world of engineering fact.

On the social front, there will be many more centenarians. A substantial proportion of the labour force in advanced countries will be working taking care of the elderly. Replacement body parts and the control of ageing through drugs and medication will become major industries.

Ceramics is another area that will take on a more central role in improving the quality of life. Whether scaling up for engineering megaworks, or scaling down for tiny electronic components, that disappear inside integrated systems, ceramics will play a vital role in the key technologies of the next century. Just one major application for a new generation of ceramics will be in the desalination and filtration of water, an application that clearly has most far-reaching potential for millions of people in Third World and developing countries.

Other areas where there will be major leaps forward are in the development of clean sustainable technologies, transport and, of course, information technology and telecommunications.

Nanotechnology

However, the most revolutionary technological development we are likely to witness in the foreseeable future is the rise of nanotechnology. The role of nanotechnology, as a major driver of technologic change, and its consequent importance in the shaping of world economies in the futures, is undisputed.

'Nanotechnology' can best be described as a 'catch-all' description of activities at an almost vanishingly small scale that have applications in the real world. A nanometre, a billionth of a metre, is about 1/80,000th the diameter of a human hair or just 10 times the diameter of a hydrogen atom.

Tremendous opportunities will arise in integrating electronics and semiconductor technologies into systems or components in high-added-value niche market products, notably for biomedical and related applications. There will also be important opportunities in the manufacture of the machine tools that industry will require in order to make products with nanoscale components or dimensions.

It is essential, therefore, that we identify those technologies that may offer the most economic benefits to society. Imagine building micro-electromechanical systems, motors, sensors and tools by manipulating atoms or molecules, or producing advanced catalysts using microparticles with nanocoatings.

A strategy for nanotechnology must be developed as a key component of a healthy UK economy in the future.

The advent of the nano-industrial revolution means that scientific and engineering disciplines can no longer allow themselves to be 'pigeon-holed' and this applies equally to university departments, research councils and the engineering institutions. Cross-fertilisation is crucial.

Engineering provides the skills on which physics depends. But advances in physics provide new challenges and test beds for those skills, which can, and often are, applied elsewhere. For example, modern materials research, and, increasingly, modern biology research, depend on intense X-ray radiation, originally a tiresome byproduct of particle accelerators. Magnetic resonance imagers in medicine depend on superconducting cable originally made for particle physics. X-ray detectors, originally designed for X-ray astronomy, are finding applications in dentistry. These few examples show the dependence of science on engineering, and engineering on science.

Conclusion

In the very early days there were no divisions between these kingdoms of science, engineering and technology. For example, as Lord May recently pointed out in *Ingenia*, on Holborn Viaduct in London there are four statues representing Victorian society – Agriculture, Commerce, Art and Science, and the figure of science holds a symbolic Watts Governor, a device that regulated the power produced by early steam engines.

After the Victorian era the kingdoms drifted apart and boundaries and barriers appeared between them. But today's breathtaking progress means that the boundaries now so overlap that we now see no frontier posts or passport controls as we move smoothly from pure science through applied science and engineering to technology. They truly are all part of one exciting ever-changing world. ■

Dr Robert Hawley was Chief Executive of British Energy plc until 1997 and until 1995 he was Chief Executive of Nuclear Electric plc. He is Chairman of Taylor Woodrow plc and RockTron Ltd and a Non-Executive Director of Colt Telecom Group plc and Rutland Trust plc. He is an Advisor to HSBC Investment Bank plc and is registered with the Securities & Futures Authority. He is an acknowledged international expert on power generation energy and the environment and the author of several books and many papers on aspects of power generation and dielectrics. Dr Hawley is a Past President of the Energy Industries Club and of the Institution of Electrical Engineers. He is a Fellow of The Royal Academy of Engineering, the Royal Society of Edinburgh, a Member of the National Academy of Engineering of Korea and an Honorary Fellow of the Institution of Nuclear Engineers. He has served on a number of Government engineering and scientific committees.

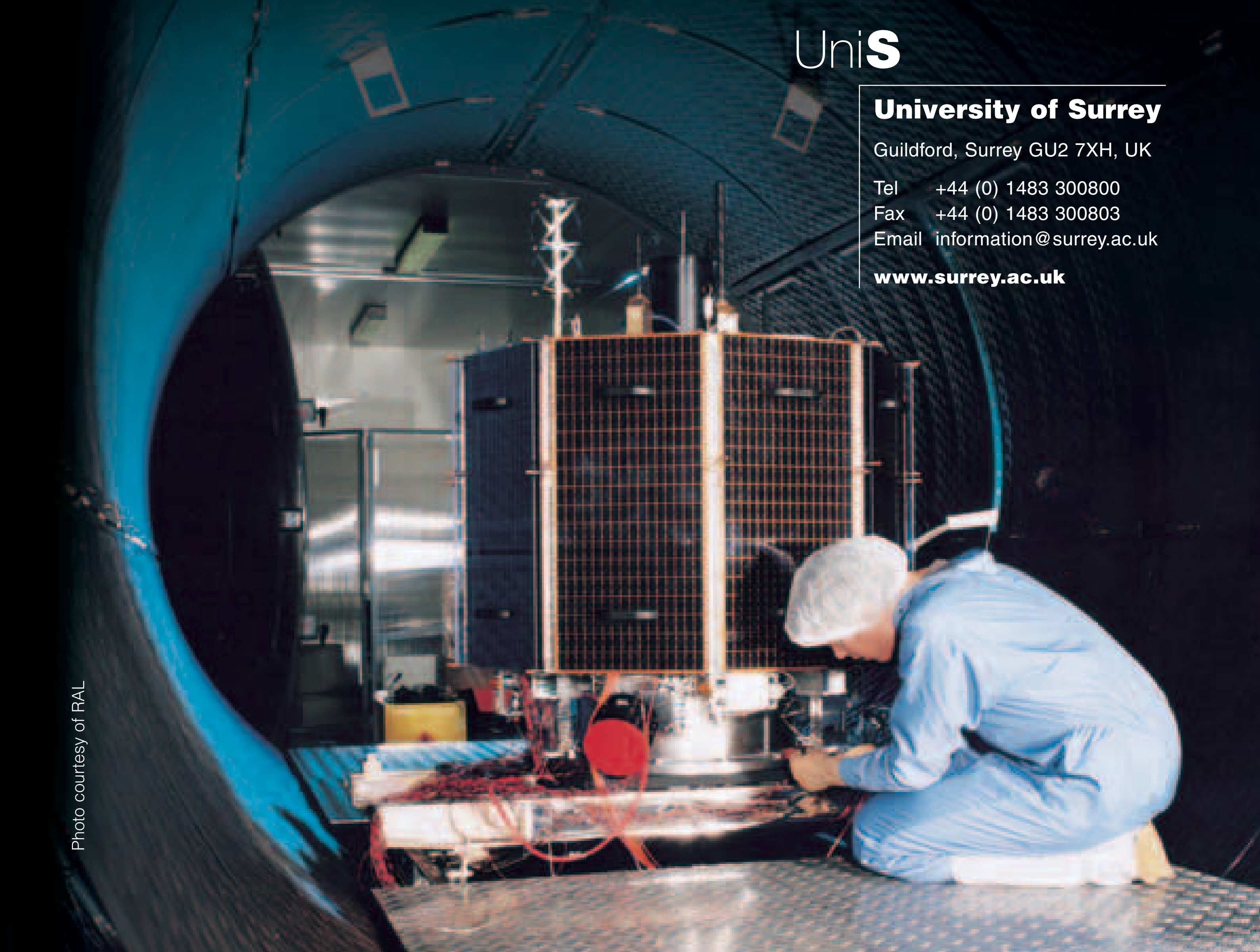

Photo courtesy of RAL

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