THE ROYAL SOCIETY

Engineering and the physical sciences: the EPSRC takes an informal look into the future

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This special feature article contains interviews with a small group of leading UK scientists whose research is supported by the Engineering and Physical Sciences Research Council. In conversation with the first author, the scientists were invited to discuss their work and to make predictions for the future of science and technology, speculating on the developments that might be changing our lives in 20 years' time. These complement, in an interesting way, the articles by young scientists, which make up the bulk of the three Millennium Issues.

Keywords: engineering; physical sciences; Research Councils; Royal Society Research Fellowships; future of science and technology

Introduction

Most of the articles in these three Millennium Issues of the *Philosophical Transactions* (Series A) have been written by young scientists holding Royal Society University Research Fellowships. These fellowships are designed to provide extended support for young, top-quality research workers in all areas of science. They allow them to work in university departments, with the expectation that they will obtain permanent posts, in a UK University or industry, at the end of their fellowships. Candidates are under the age of 40, with 2–7 years' postdoctoral experience, and about 50 are elected each year. The length of tenure of a fellowship is 5 years in the first instance, with the possibly of extension, in two instalments, up to 10 years.

The Royal Society was, in fact, recently able to step up its programme of support to these outstanding young scientists thanks to a 14% increase in government funding. This arose when the Office of Science and Technology accepted in full the Society's bids to increase the number of University Research Fellowships and Dorothy Hodgkin Fellowships, and to strengthen the Society's science advice capabilities. The additional resources are enabling the Society to increase the number of University Research Fellows it supports, from about 278 at present to 310 in post by the end of 2001/2002. This number is divided between the physical sciences (represented by *Phil. Trans.* A) and the biological sciences (represented by *Phil. Trans.* B).

In contrast to these personal fellowships, the main source of government funding for university research in the UK is the Research Councils, of which the Engineering and Physical Sciences Research Council (the EPSRC) has a central responsibility for many of the areas covered by these three Millennium Issues. The main mission of the EPSRC is

> to promote and support high quality basic, strategic and applied research and related postgraduate training in engineering and the physical sciences, placing special emphasis on meeting the needs of the users of its research and training outputs, thereby enhancing the UK's competitiveness and quality of life.

It currently supports research and training through eight programme areas covering: chemistry; physics; mathematics; general engineering; engineering for manufacturing; engineering for infrastructure, the environment and healthcare; materials; and information technology and computer science. As part of its mission, the EPSRC also works to promote the public understanding of the research it supports, through a range of programmes, activities and publications, such as its quarterly magazine, Newsline.

As the new millennium approaches, Newsline has commissioned freelance science writer Nina Morgan to interview a small, broadly based and, hopefully, representative group of leading UK scientists to discuss their predictions for the future of science and technology and speculate on the developments that might be changing our lives in 20 years' time (Morgan 1999). The interviews below are reproduced from the September 1999 Newsline special issue on the public understanding of science. It is felt that these will complement, in a very useful way, the articles by young scientists that make up the bulk of these Millennium Issues.

2020 visions

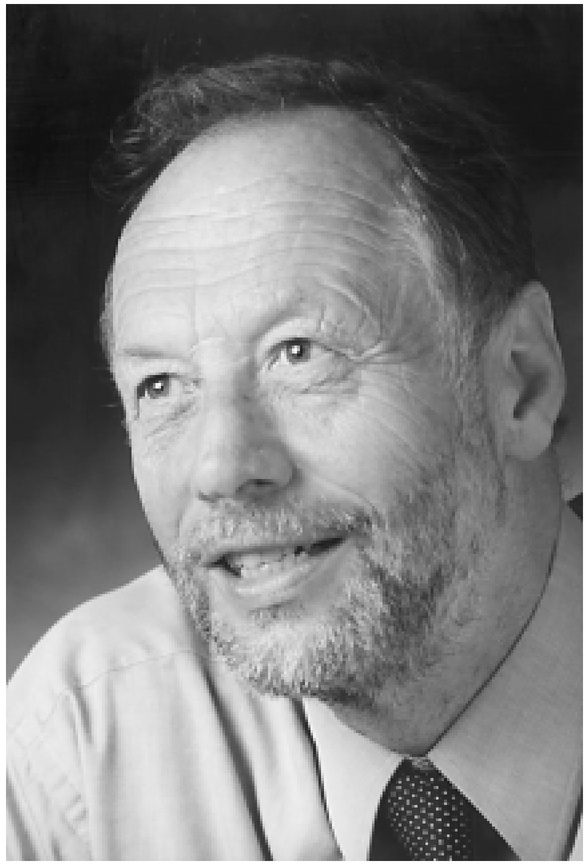
On the threshold of the new millennium, predictions abound about where science and technology may be leading us. So what developments in engineering and science can we expect in the next 20 years and what new technologies will be changing our lives? Nina Morgan asked ten leading British scientists, whose research is supported by the EPSRC, to explain their visions of the exciting and beneficial developments that may change our world in the year 2020.

1. Getting better all the time

Tiny particles will lead to big breakthroughs

'At the moment I feel as if I were standing on the edge of a great boom in technology', says Professor Brian Johnson, of the Department of Chemistry at Cambridge University. 'Throughout my life we just seem to have gone from one exciting topic to another and I'm sure this will continue. Now, for example, nanoparticles—multiple atom systems that fall within the 1 to 100 nanometre size range—are bringing about a revolution in the electronics world.

'Using these very small conducting, semi-conducting and non-conducting particles in electronic devices means that you can drastically cut both the amount of power they use and their size. And if you lay nanoparticles down in polymeric supports,



Brian Johnson

you can produce materials with a whole range of unusual electronic properties. The implications for developing new electronic devices are fantastic.

'People are already beginning to use them in all sorts of fabricated equipment. These include things such as wires, "electron jump" devices, which modulate the flow of current one electron at a time, and capacitors—devices used to store energy. It's easy to imagine using them to help build computers and sensors so small and inconspicuous that doctors could strap them onto people to monitor their body functions. Or they might be used to make tiny devices to put down oil wells to monitor sulphur concentration, for instance. The possibilities are endless.

'Nanoparticles also have important applications in other new materials. There is already a lot of successful work going on now using nanoparticles embraced within silicate materials to develop clean catalysts for a whole variety of chemical processes such as petrochemical production.

'As a scientist, I think life will get much better as we gain the ability to sense and monitor things carefully. We can decrease the amount of pollution that occurs, for example, or improve the way we detect bodily malfunctions.

'Having made the materials we are now finding all sorts of uses. And I've no doubt further applications will be found. But, of course, by the nature of things, I can't predict exactly what they will be!'

Colin Humphreys

2. Purpose built

Dreams will become reality

'The really exciting thing in materials is that we now understand enough about the physics and chemistry so that we can now do "genetic engineering" with materials', says Professor Colin Humphreys, of the Department of Materials Science at Cambridge University.

'We can design materials, change them, engineer them at an atomic level and then fabricate bulk articles afterwards. This opens up an incredible range of possibilities for the future.

'Biomaterials—for example, implants used in people's bodies—will get better and better. They'll last longer, too. Today's artificial hip joints last 10 to 15 years. In the future, we'll be able to make artificial joints that, once implanted, will last a lifetime. But that's not all. Biologists and materials scientists will work together on tissue engineering. By starting with a person's own tissue and combining it with a framework made of a biodegradable polymer to get the right shape, they'll be able to grow completely new body parts. These are really exciting developments that will change our concept of healthcare.

'Materials scientists will also develop new materials for semiconductors, so we can look forward to much faster computers. When optical computers—which use packets

Wendy Hall

of light, called photons, instead of electronic circuits—become a reality, we'll be designing the materials that emit and detect the light.

'New materials will also be developed for use in fuel cells and turbine blades. Then we can look forward to non-polluting cars and super-efficient power stations.

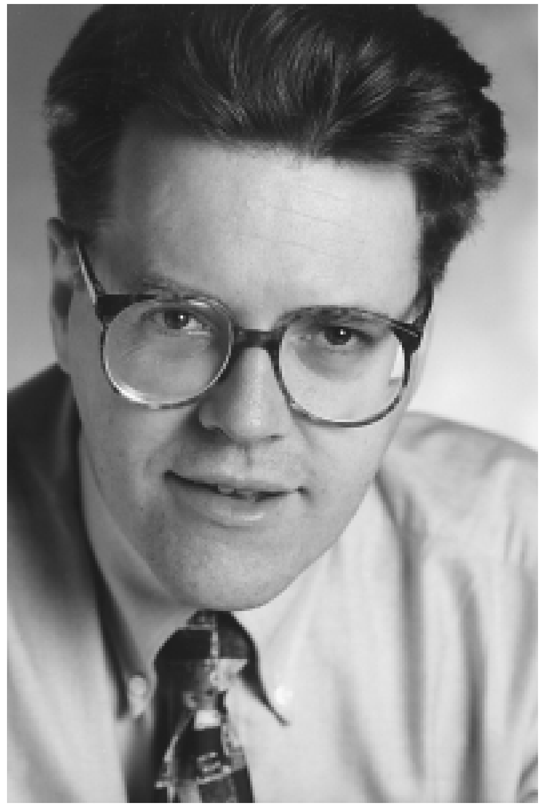
'With increasing knowledge, new developments will only be limited by our imagination. We'll imagine what kind of materials we need and we'll have the knowledge to make them. In the past, these sorts of "designer" materials have been the stuff of dreams. But I think that, in the future, science will make our dreams become reality.'

3. All in one

Looking forward to communication integration

Wendy Hall, Professor of Computer Science in the Department of Electronics and Computer Science at Southampton University, is a woman with a mission. 'Increasingly, technology gives us more and more access to information, so life gets more and more chaotic. My overall quest is to try to make some sense out of the information chaos', she explains. 'In my group, we are working with various types of agents—effectively autonomous computer processes—to help people find the information that they want, when they want it.

'Agents already exist on the World Wide Web. Some shopping sites, for example, are beginning to incorporate agent technology behind the scenes. The idea is that



Keith Burnett

the agent looks at sites all over the Web to find you the best deal. But it is very early days for commercial systems to have real agents in them, let alone any agents that learn. In 20 years' time it will all be very different.

'For a start, the personal computer will effectively be dead. Of course, specialist-knowledge workers will still need quite powerful computing devices that can deal with information processing. But, instead of buying a computer, most people will buy devices with computers in them. And those devices will talk to each other. This is not rocket science. The technology exists today, but the infrastructure doesn't. Who, or what, is your fridge going to talk to at the moment?

'The big breakthrough will come when all communication technologies become integrated. Then you'll have an all-in-one device that communicates. It will be a computer, a phone, a television or whatever you want it to be. Twenty years from now we won't talk in terms of a phone call. Instead, there will be an integrated global information network—so you can communicate with people and other devices instantly to get all the information you might want.'

4. Try it and apply it

Today's science fiction will be tomorrow's routine technology

Professor Keith Burnett, at Oxford University's Department of Physics, likes to keep an open mind about future developments. 'Most of the technology we have

Janet Thornton

today has developed serendipitously or by adventure, rather than by planning', he says.

'Once you make the technology feasible and routine, people will just try it out and apply it. Remember how lasers were viewed in the beginning? Then, no-one could imagine what they would be used for. Now they are used everywhere.

'In my own current fields of research—cold atoms and intense laser fields—the possibilities are weird, wonderful and exciting. Clouds of ultra-cold atoms are beautifully smooth, extremely fragile and influenced by the weakest of forces. Like the canaries miners used to carry underground to warn them of changing conditions, cold atoms can be used as sensitive indicators of tiny changes in their environment.

'The compact, very powerful laser fields we now have in the lab can rapidly rip electrons off an atom and make it emit coherent X-rays. They could be used to make coherent tabletop X-ray lasers for various applications in chemistry or physics. For example, crystallographers need powerful X-ray sources to 'photograph' and work out the structure of molecules. These lasers could provide X-ray sources useful for studying the structure of objects on the scale of cells, but the X-rays produced would not be suitable for studying biological molecules such as proteins. Or intense, short laser pulses could be used to create very hot clusters of atoms that act as tabletop sources of neutrons for use, say, in research in particle physics. These days the neutrons are produced using big particle accelerators and synchrotron sources.

'Stranger still, these laser-like sources might make "wave matter" holograms a

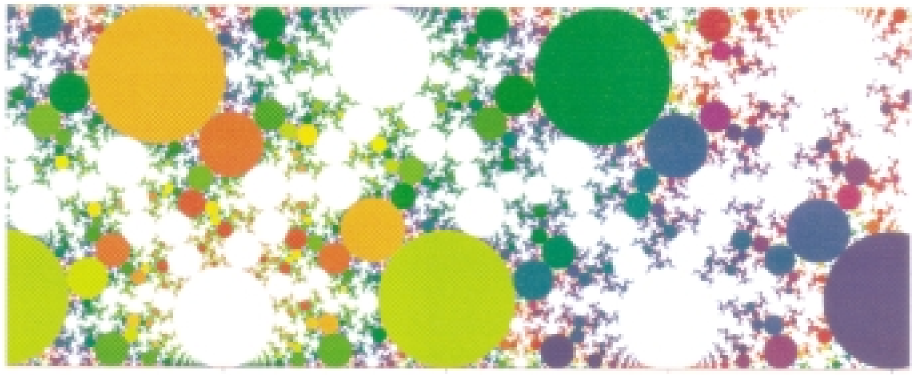


Figure 1. Fractal image.

reality. In holograms, laser light is used to create a three-dimensional image of a wave matter object—a physical object to you and me. With wave matter holograms, the process would be reversed, so a virtual object would be turned into a physical object as matter waves pass through it and are altered by a laser beam. For me now, it's just curiosity, but I have strong feelings that it really will develop. With luck, in the future we'll be looking at lasers making objects for us out of what seems to be thin air.'

5. Sequence, structure and function

The changing face of biology

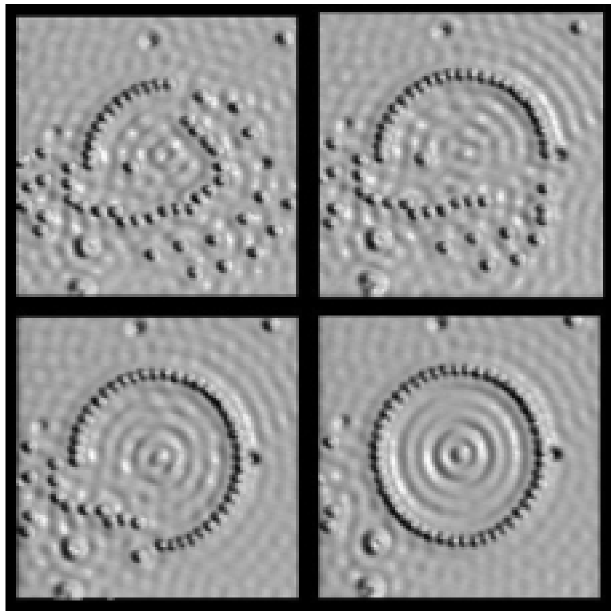
'The genome projects are changing the whole face of biology', says Professor Janet Thornton. She is Head of Research at the School of Biomolecular Sciences, a joint Birkbeck College and University College London venture that includes structural biologists, biochemists and molecular biologists.

'Complete sequences for several bacteria, yeast and a small worm have just been determined and in the next year we will probably have the complete sequence for the human genome. Now the challenge is to make the leap from sequence, through structure, to understand about the function. The structures reveal how biology works at the molecular level. For the first time we can see how the complexity of life is achieved.

'These scientific breakthroughs are changing the face of biology itself. In the future, multidisciplinarity will flourish. Everyone has different things to offer—and I think that the biology is just so exciting that chemists, physicists and computer scientists are all going to want to be involved. This mix of expertise has enormous potential for making new discoveries.

'Several major challenges are looming during the next 20 years. Interpreting the chemical information from the human genome project in terms of biological function will certainly be one of the main challenges.

'If these challenges are met, I think we can expect many new practical applications that will have a wide impact on almost every part of life, especially medicine and agriculture. A battery of new diagnostic tools will lead the way to better treatments designed for individual patients using better drugs. Where better to learn how to



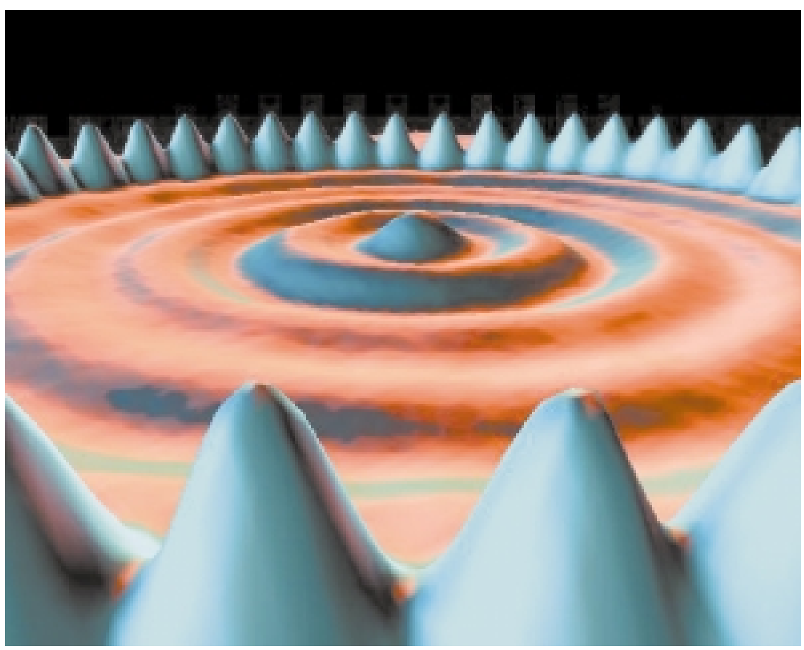
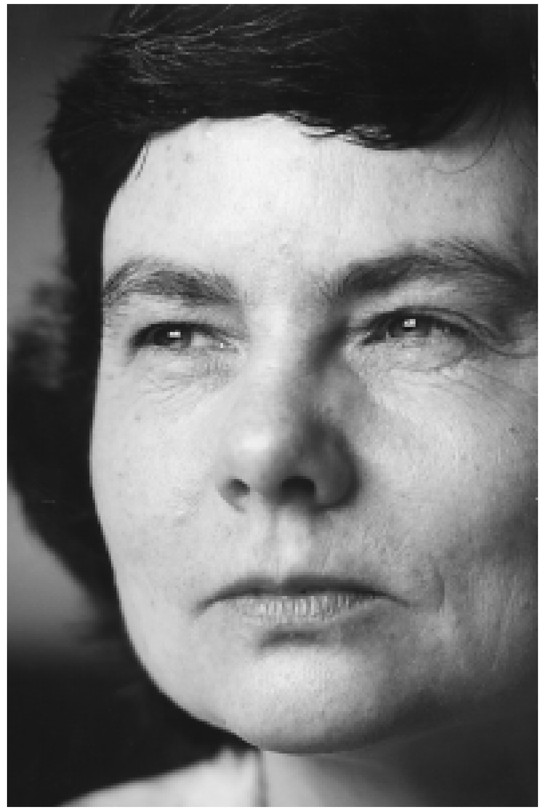


Figure 2. Researchers can manipulate individual atoms by using tools such as a scanning tunnelling microscope (STM). In the lower image STM has been used to place 48 iron atoms in a ring to 'corral' electrons, forcing them into 'quantum states'. Top: various stages in the construction of the corral. Images: Crommie, Lutz, Eigler, from the IBM Almaden Research Centre home page http://www.almaden.ibm.com/vis/vis_lab.html.



Caroline Series

respect our environment than from biology itself? Also, new varieties of plants will reduce the need for pesticides and improve yields.

'This new information will undoubtably help us to find cures for diseases too. But I'd be amazed if we could conquer every disease—biology is too cunning. Nevertheless, I think life expectancy will certainly increase with enormous implications that need much thought and consideration.'

6. Evolving models

When life gets complicated, more people will turn to mathematicians

When Professor Caroline Series, of the Department of Mathematics at Warwick University, looks into her crystal ball, she sees new ideas in geometry playing an ever increasing role in helping to solve problems.

'The principles we are discovering will make it possible to handle very complicated systems', she predicts. 'Mathematical modelling is becoming ever more sophisticated. In the future we're going to be able to extract much more order and sense out of apparent randomness than you would think.

'Just one example, fractals, will change the face of many mathematical models (figures 1 and 3). There are already a lot of stunning pictures of fractals—shapes that present the same complicated crinkled patterns no matter how much you magnify them—but recently, mathematicians have begun to study them using much more

Roland Clift

sophisticated techniques. Because the obvious shape of many natural phenomena is a fractal, I think fractals will be used more and more to describe all kinds of real life things such as modelling how light falls on the surface of the sea, or understanding the flow of traffic on the internet using fractal statistics.

'Our ability to make mathematical models or to do simulations of complicated situations is getting better and better because we also now have fantastic computing power. Mathematicians can save you a lot of time by pointing to likely starting points and to which features are worth most attention. Computing is changing the way mathematicians think about mathematics, too. Where they once asked "could it ever be done at all?", they are now asking "is it realistic and how long will it actually take?"

'But no matter how much mathematics develops, we'll never solve all the problems or run out of powerful ideas. I can confidently predict that we'll always have new challenges and that computers are not going to put us out of work.'

7. The great challenge

A sustainable future

'In 20 years' time I very much hope I'll be living next door to a chemical plant', says Professor Roland Clift, Director of the Centre for Environmental Strategy at

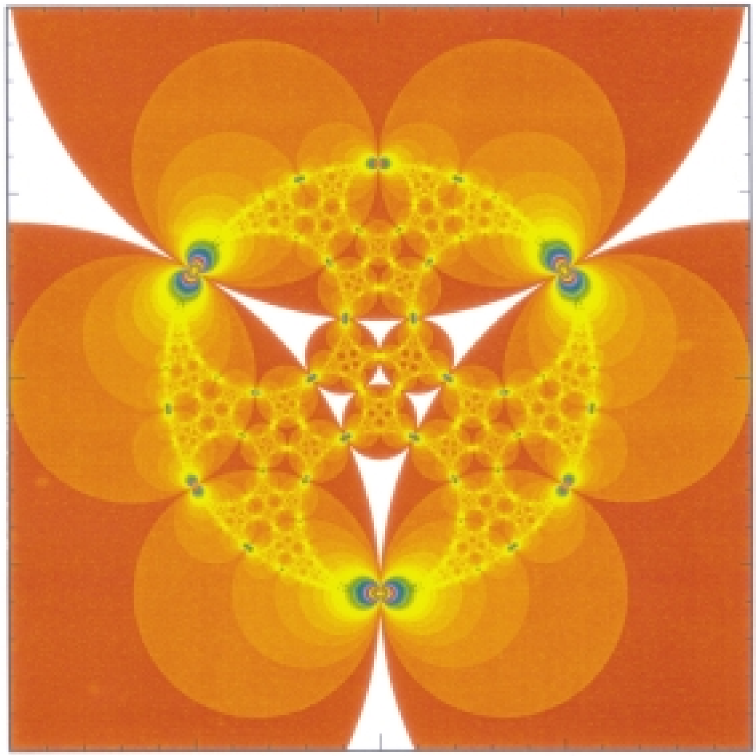


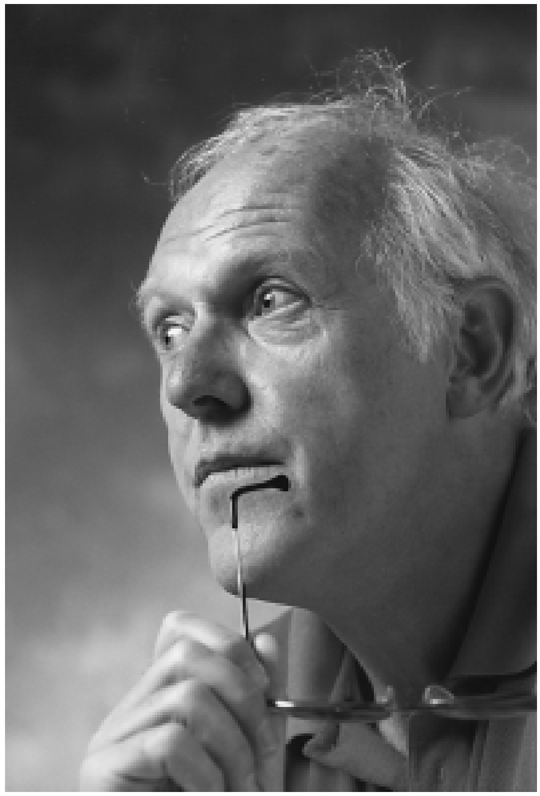
Figure 3. Fractal image.

Surrey University. 'Because if I am, it will be proof that industry, driven both by legislation and a real change in environmental awareness, has got the message and made big changes in the way it operates.

'Massive chemical plants will be replaced by a number of small, extremely environmentally friendly chemical plants spread around the country. When you look at the role of transport in our environmental footprint the small plant, supplied by bulk ingredients and manufacturing close to the point of use, makes a lot of sense. Life-cycle assessment—the idea of following a product's entire supply chain—is already established as the way to improve environmental performance. But we've gone beyond that now and are starting to look at two new areas: industrial ecology and sustainable development.

'Industrial ecology carries on from life-cycle assessment to consider what happens to a product after use. What can be done with used products and materials? Take the case of plastics, where additives or colours may be included at some stage just because it is the easiest and most cost-effective way of providing a particular set of properties. But those additives may impede the subsequent reprocessing or recycling. Can we modify the "upstream" supply chain to reduce its environmental impact and eliminate materials that get in the way of recycling or re-use?

'For a commercial company, sustainable development means assessing its economic and environmental performance and also deciding whether it provides a sufficient social benefit to allow it to continue operating. In the coming decades the successful



Mike Brady

industries will be those that take the idea of sustainable development seriously and actually achieve significant reductions in their material and energy throughputs.

'There will be some technological challenges to overcome, of course, but I don't think solving these will present the main difficulties. The greatest developments will come through getting engineers, scientists, social scientists and ethical philosophers to talk to each other.'

8. Minimalist surgery

Advances in imaging technology will ensure patients get maximum benefits with the minimum of surgical intervention

'Keyhole surgery on knees means patients are up and about in hours', notes Mike Brady, the BP Professor of Information Engineering at Oxford University. 'One day soon, we'll have keyhole brain and breast surgery, too.

'It's a big step. Knees are relatively simple—with keyhole surgery you can rely on an optical fibre to provide all the information you need about the inside of a knee. But brains and breasts are immensely more complex, so you need much more detailed information. To do keyhole surgery on these parts of the body you first have to use imaging tools to "map" the patient in three-dimensions and then you have to continually update the map as things change during the operation.

Julian Jones

'Developments in image analysis mean that three-dimensional structures can now be viewed changing over time and in real time. Improvements in imaging techniques are making it possible to "see" inside the body more easily and more clearly than ever. High-resolution magnetic resonance imaging, for example, is already capable of resolving things smaller than an individual cell. And even X-ray techniques are becoming more advanced, with full-field digital mammography set to transform the quality and precision of breast screening and diagnosis.

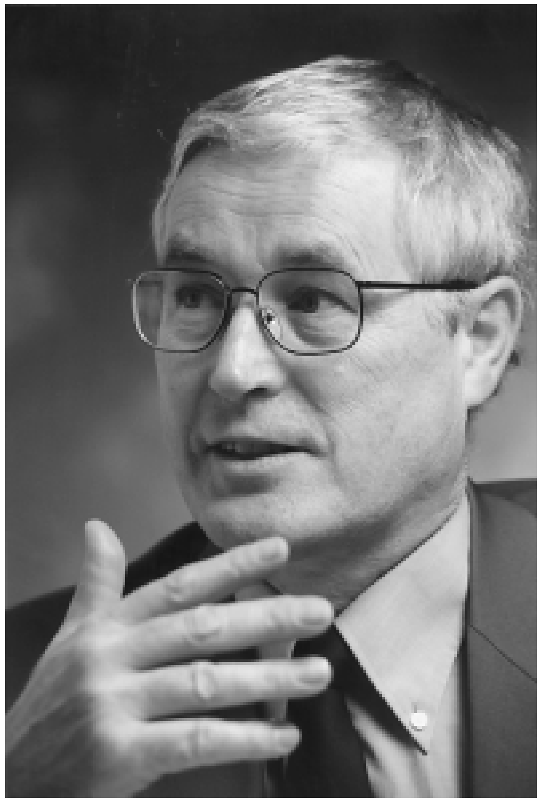
'But, best of all, I think we've barely scratched the surface of what is possible! Scientifically, I think the most exciting possibilities for the next decade or two lie at the interface between image generation and analysis, and molecular medicine. Linking molecular-level explanations of cellular processes with functional images of the morphological shape of those cellular processes taking place could revolutionize our understanding. But, however advanced imaging and analysis techniques become, I can never foresee the time when clinicians won't be needed.'

9. Talking points

New technologies will mean new ways of working

'Any predictions about the future tend to tell you more about the present', warns Professor Julian Jones, of the Department of Physics at Heriot-Watt University, in Edinburgh. 'But at the risk of sounding like an old science fiction film in a few years' time, I'm willing to predict that in 20 years from now instead of thinking of an individual machine that does a specific job, we'll be thinking in terms of a society of machines, all interconnected and working together.

'It will no longer make sense to differentiate between computers, communication systems and devices such as television cameras, or even between industrial processes. In the future, different physical technologies will interact so closely that they will be like one technology. It will become pointless to distinguish, for example, between an electrical and an optical machine.



Tony Hey

'The implications are profound. For a start, multidisciplinary research teams will become the norm. But rather than becoming more impersonal, progress in science and technology will increasingly require more people to talk to each other and to work together. Already there is now almost no item of significant technology that an individual could design alone because no one person could possibly understand everything that goes on in it. So communicating and sharing ideas and expertise will become more important than ever.

'There is a big lesson in this in terms of how you plan for the growth of technology. It means, for example, that people will have to develop a fluid way of working. We'll have to find mechanisms that will bring together the right teams to do a particular job and to form new teams when the job is done.

'I can't predict the future, but I am sure of one thing: tomorrow's technology is only as good as tomorrow's technologists. It's the quality of the people that counts.'

10. The start of something small

Big breakthroughs in very small things

'We are now on the verge of doing extremely exciting things, manipulating things atom by atom, fabricating single electron gates, detecting single photons (figure 2). With these we can build a whole new technology', says Tony Hey, Professor of Computation in the Department of Electronics and Computer Science at Southampton University.

'We will be able to tailor the properties of devices like light emitters and single electron transistors to our demand and put them all together on silicon. We might also be able to develop new, coherent quantum electronic devices, or even build a quantum computer.

'As well as the two spin states of a single electron, quantum theory also allows the possibility of storing a superposition—a mixture of two states at once—of a 1 and a 0, known as a qubit. Qubits can be manipulated using quantum versions of reversible logic gates. Up to now, people have only succeeded in building a single quantum gate acting on two qubits, but I'm sure that within the next few years we'll be able to build some small quantum computing devices. Large-scale quantum computers are another story, though. To build one that can really do something useful will require many qubits and thousands of gates—and that, I believe, is a long way off.

'Instead, I think we'll exploit the technology that we've developed in handling silicon to integrate quantum components into conventional computers. This may lead to faster computers, but more likely the result will be devices with different capabilities and sensitivities. For example, we'll be able to detect single photons and electrons, and produce photons with special properties for telecommunications and other uses. In fact, EPSRC is already funding this kind of research all around the UK.

'But exactly what we can do with such quantum technology itself? I'm not totally sure! Who knows what the so-called "killer application" will turn out to be?'

This feature article is a special contribution to the Millennium Issues, and as such is in contrast to the peer-reviewed papers that are normally published in the *Philosophical Transactions*. The opinions expressed by the interviewed scientists are entirely their own, and in no way represent the views of the Royal Society. The interviews conducted by Dr Nina Morgan are reproduced with the kind permission of the editor of Newsline, Julian Richards (EPSRC, Polaris House, North Star Avenue, Swindon SN2 1ET (j.richards@epsrc.ac.uk)), from whom copies of EPSRC's Newsline can be requested.

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