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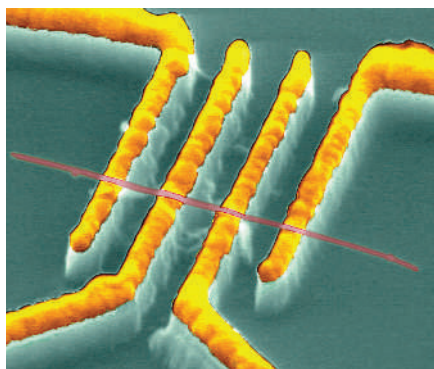
Governments invest billions in it and tens of thousands of papers are published on the subject every year, but what exactly is nanotechnology?

Most formal definitions of nanotechnology revolve around the study and control of phenomena and materials at length scales below 100 nm, whereas informal definitions almost always make a comparison with a human hair, which is about 80,000 nm wide. However, nanotechnology can mean different things to different people, which is why *Nature Nanotechnology* asked a range of researchers, industrialists and others what nanotechnology means to them. From enthusiastic to sceptical, the responses reflect a variety of perspectives.

For me, nanotechnology is all about building things. Judging by current rates of progress in fields as diverse as protein engineering and nanoelectronics, the emergence of atomic-precision manufacturing on an industrial scale is still some decades away. Nevertheless, it will happen — because physics and chemistry allow it, and because the economic incentives for continued progress are enormous. Information technology, worth roughly one trillion dollars per year in the global economy, already rests on over a century of progress in miniaturization. The ability to design and build complex things on ever-smaller scales is now transforming established fields such as medical diagnostics, energy conversion, and structural materials, and is sparking new fields such as quantum information processing and nanobiotechnology. Thus, the coming decades should be great ones for scientists as their discoveries both enable, and are enabled by, the burgeoning capability to engineer nanoscale structures.

Thomas Theis is director of physical sciences at the IBM Watson Research Center.

One way of defining nanotechnology is to talk about length scales. A different way is to see it as an upcoming economic, business and social phenomenon. Nano-advocates argue it will revolutionize the way we live, work and communicate. If it



A carbon nanotube freely supported on four gold electrodes.

will dramatically affect everyone, shouldn't everyone have a say in what developments take place — with what impacts, under whose control, and with who benefiting (and losing)? The promoters of genetically modified organisms failed to recognize that widespread adoption of a technology is a social, as well as a technical process. Nanotechnologies will have to go through a similar experience. Western democracies might deliberate on taxation, public services and foreign and military policy, but transformative new technology may have a bigger effect on people's lives. Innovation is going at a speed uncontrolled by national and international regulations, meaning that responsibility will pass to companies, scientists and developers, with all the uncomfortable scrutiny by civil society that this implies.

Doug Parr is chief scientist for Greenpeace in the UK.

There isn't just one nanotechnology; there are many nanotechnologies and these are primarily enabling technologies and not end products in themselves. It would not surprise me if the term nanotechnology disappeared from general use in the next decade, with the terms nanomaterials and nanobiotechnology assuming greater currency. There will be successive (and overlapping) waves of product development and introduction over the next 20–30

years. We are currently in the initial wave, in which most of the products on the market are nanomaterials in various forms, many arising from defence and security applications, or from sporting goods and consumer convenience items. Within 5–10 years, we can expect sophisticated electronic devices that use nanoscale circuitry and memory. After 10–15 years, the introduction of pharmaceutical products, drug delivery, and health-monitoring devices will begin. Beyond the edge of our conception, perhaps 25–30 years ahead, new forms of devices and processes may emerge.

Peter Binks is chief executive officer of Nanotechnology Victoria, a consortium of four research organizations focused on the commercialization of nanotechnologies in Australia.

Nanotechnology has only been developed systematically as an interdisciplinary field during the past decade. I see nanotechnology as a toolbox that provides nanometre-sized building blocks for the tailoring of new materials, devices and systems. The nanometre length scale (that is < 100 nm) offers unique size-dependent properties in physico-chemical phenomena. It also presents unique biomimetic features essential in the creation of complex structures for tissue scaffolds and artificial organs/implants. Over the past 10–15 years, nanotechnology has evolved by both bottom-up and top-down approaches. Tremendous advances have been made in bionanotechnology, supramolecular chemistry, nanostructured materials, self-assembly and nanofabrication. We now have a great toolbox that enables us to bridge between molecular sciences, nanoscience, functional materials, and micro-electromechanical systems.

Jackie Ying is the executive director of the Institute of Bioengineering and Nanotechnology in Singapore, and adjunct professor of chemical engineering at the Massachusetts Institute of Technology.

Nanoscience and nanotechnology can be regarded as areas defined by a chosen boundary, but I find it more fruitful to see them as directions united by shared objectives. Central among these is the atomistic understanding and control of an increasing range of physical systems and phenomena. Of special importance are combinations of understanding and control that enable the systematic development of classes of diverse, complex nanosystems. A strategic direction for this work will be to develop nanomachines that are analogous to ribosomes but able to assemble a broader range of structures with broader capabilities. I see this as furthering the age-old process of using tools to construct better tools, advancing along paths that have led us from iron hammers to the borders of nanotechnology. In areas where theory can describe what cannot yet be made, computational modelling points to paths that can lead far indeed, increasing capabilities and applications at each step.

K. Eric Drexler wrote *Nanosystems and Engines of Creation* and is chief technical advisor to *Nanorex*.

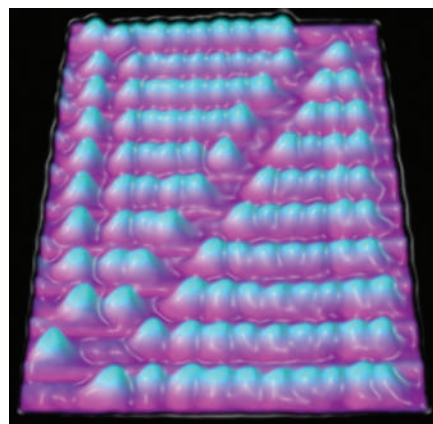
Nanoscience is a very handy word for rather small things with a rather big impact. Why should we care about such small things? We may find properties that are useful for everyday life. For example, nanostructured surfaces that mimic lotus leaves are already used in cars, windows and so on, which means that they can be cleaned by the next shower of rain. Currently, anything on the nanoscale is called “nano” — be it chemical, medical, physical, biological or any other “cal”. I don’t expect the nano hype to last very long. It means too much and expectations are very high. More information and public discussion would sharpen the view on the opportunities and threats of this technology, and would facilitate a conscious decision about what research field and what nano products are appreciated by society.

Elisabeth Schepers is in the department of museums education at the *Deutsches Museum in Munich*, where she has recently been working for the *EU Nanodialogue project*.

Everyone has probably heard about Richard Feynman’s 1959 comments at the American Physical Society meeting at Caltech, often referred to as inspiring the beginnings of nanotechnology. The transcript of his talk published soon after, entitled *There’s Plenty of Room at the Bottom*, is an amazing

document. In every paragraph there is something outlandish or at least a little edgy for that time, but nothing that is out of the ordinary now. It is a testament to the brilliance of Feynman and, for someone who was fifteen years old at the time, shocking just how long ago 1959 was. But even Feynman in 1959 did not seem to see the scanning probe microscopies coming. For that we have Gerd Binnig and Heinrich Rohrer to thank, and that invention is truly the watershed between nanotechnology and everything really small, like molecules, which came before but were, in the main, only accessible collectively.

Kary Mullis shared the Nobel Prize for Chemistry in 1993 for his work on the polymerase chain reaction technique. He is currently working on chemical methods to control and direct immune responses.



The ‘beads’ in the world’s smallest abacus are single C_{60} molecules.

The converging interests of nanotechnology foresee the precise control of individual atoms or molecules, leading to an unprecedented ability to design material and device capabilities. One distinctive aspect of nanoscience is its preferential search for the systematic behaviour of individual atoms or molecules, rather than their ensemble averages. The significance of the dimension depends on the field, varying from a few nanometres to observe electronic or quantum effects to a few tens of nanometres for delivery properties of nanoparticles in biological systems. The parallel pursuit of technological advances has already generated a range of promising examples, such as conceptually new quantum devices, drug-delivery agents and novel materials. One should be aware that the viability of nanotechnology depends on its industrialization and commercialization. There is no doubt that the scientific

and technological advances will bring significant benefits to multiple scientific disciplines and innovation to manufacturers.

Chunli Bai is executive vice president of the *Chinese Academy of Sciences*, director of the *China National Center for Nanoscience and Technology*, and chief scientist of the *China National Steering Committee for Nanoscience and Nanotechnology*.

In some sense we are labelling what we were already doing, except that now we can actually visualize the outcome of these actions and develop predictive rules that can be rigorously tested. An even more striking development is the ability to direct the assembly of atoms and molecules into new materials that were hitherto kinetically inaccessible, and to test their properties. But for me, the most fascinating aspects of nanoscience and nanotechnology are that properties on this length scale are exquisitely sensitive to the surrounding environment. Indeed, one could reasonably argue that it is meaningless to refer to the innate properties of nanoscale systems without due reference to the influence of environmental factors such as surface termination, substrate interactions and electrical and mechanical contacts. Although this sensitivity is a challenge for nanoscale materials processing, it brings with it the potential for unprecedented levels of control of material and device properties.

John J. Boland is professor of chemistry and director of the *Centre for Research on Adaptive Nanostructures and Nanodevices* at *Trinity College, Dublin, Ireland*.

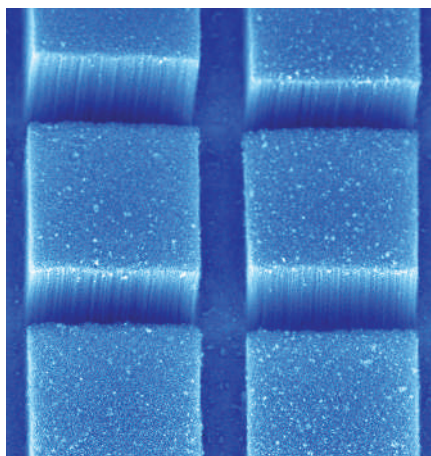
Nanotechnology is concerned with work at the atomic, molecular and supramolecular levels in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure. I expect there will be many areas that nanotechnology will have an impact on in the next decade and beyond. We are examining the possibility that nanotechnology may lead to new drug-delivery systems, as well as new imaging and diagnostic systems. Particularly in drug delivery, the ability to create nanoparticles that can encapsulate drug molecules is very important, as their small size enables them to travel through the bloodstream and be taken up by specific cells where they can controllably release their cargo.

Certainly, I hope that nanoparticles will be useful in targeting drugs for cancer treatment and many other diseases in the years to come.

Robert Langer is one of 13 Institute Professors at the Massachusetts Institute of Technology, the recipient of the 2002 Draper Prize and a member of the National Academies of Sciences and Engineering and the Institute of Medicine.

Actually, nanotechnology has been around for over a hundred years. Irving Langmuir was one of the first to truly develop the technology in the General Electric labs in the 1920s and 1930s. Nanoscience is a label given now to the new work emerging from the technology we have developed to manipulate, visualize and make atomic and molecular structures. It would have been called surface science in the 1960s and 1970s. In the immediate future, we will see incremental changes in materials for energy generation and storage, improved and safer cosmetics and other domestic products, and new methodologies for healthcare, water treatment and pollution control. The field has been evolving steadily, and the explosion of interest might lead to radically new applications in areas of molecular electronics and drug design and delivery in the next two decades.

Peter Dobson of Oxford University has recently started two companies that use nanotechnology: Oxonica and Oxford Biosensors.



Carbon nanotube 'towers' grown on a silicon substrate for applications in solar cells.

Nanotechnology has created excitement amongst the young and a greater interest in science itself. This alone makes the subject important. Nanotechnology has created a kind of revolution in the physical sciences and engineering, somewhat comparable to what happened when high-temperature superconductivity was discovered in 1986. The difference is that this new area encompasses not only physics, chemistry, materials science and engineering, but also biology and medicine. A well-orchestrated plan in various laboratories and nations is likely to result in a worthwhile future. Coming to India, this subject has aroused great interest in the government and amongst the public, at a time when science had become somewhat unattractive. I want to be sure that the benefits of nanoscience reach all mankind. Although the research is being carried out in only a few countries

and laboratories, I do hope that the poorest of the poor will benefit from the results of research in nanoscience and nanotechnology.

C. N. R. Rao is a national research professor and the honorary president of the Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India.

At the nanoscale there is no difference between chemistry and physics, engineering, mathematics, biology or any subset thereof. An operational definition of nanotechnology involves three ingredients: (1) nanoscale sizes in the device or its crucial components; (2) the man-made nature; and (3) having properties that only arise because of the nanoscopic dimensions. In addition, I typically think that "it ain't nano if you ain't got the math to back it up" — we must be able to model or explain it. The great promise of nanotechnology may be the necessary focus on solving problems, rather than on academic distinctions and the setting of disciplinary fences to benefit ivory-tower dwellers. One of my interests — cancer nanotechnology — revolves around solving real cancer problems with really small tools. My bottom line, however, is that the field should worry less about self-serving definitions (including my own!), and more about how to be of true benefit to humankind.

Mauro Ferrari is professor of molecular medicine at the University of Texas Health Science Center, of experimental therapeutics at the M. D. Anderson Cancer Center, and of bioengineering at Rice University.