CURRENT SCIENCE

Volume 85 Number 4 **25 August 2003**

EDITORIAL

Nanotechnology

The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big.

Ultimately, we can do chemical synthesis. A chemist comes to us and says, 'Look, I want a molecule that has the atoms arranged thus and so.' ... The chemist does a mysterious thing when he wants to make a molecule. He sees that it has got that ring, so he mixes this and that, and he shakes it, and he fiddles around. And, at the end of a difficult process, he usually does succeed in synthesizing what he wants. By the time I get my devices working, so that we can do it by physics, he will have figured out how to synthesize absolutely anything, so that this will really be useless.

But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the order and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing and to do things on an atomic level, is ultimately developed – a development which I think cannot be avoided.

— Richard P. Feynman
There's Plenty of Room at the Bottom
Engineering and Science, February 1960

Development of the ability to design protein molecules will open the path to the fabrication of devices to complex atomic specifications, thus sidestepping obstacles facing conventional microtechnology. This path will involve construction of molecular machinery able to position reactive groups to atomic precision. It could lead to great advances in computational devices and in the ability to manipulate biological materials.

— K. Eric Drexler
Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation
Proc. Natl. Acad. Sci. USA, 1981, **78**, 5275

They reconfigured the nanoparticles to add solar power and memory. They rewrote the particle program to include a genetic algorithm. And they released the particles to reproduce and evolve, and see if the swarm could learn to survive on its own.
And they succeeded.
It was so dumb, it was breathtaking.

— Michael Crichton
Prey, Harper Collins, 2002

Nanotechnology's beginnings may be traced to Eric Drexler's 1981 paper in the *Proceedings of the National Academy of Sciences USA*. Drexler's focus then was on proteins; his paper contained a single table in which the common devices of everyday technology were related to a biological counterpart, invariably a protein molecule. Drexler compared cables and collagen, drive shafts and bacterial flagella, containers and vesicles, pipes and tubular structures and likened glue to intermolecular forces. He even made a comparison of 'sigma bonds', an everyday connection in molecules to rotary bearings. Drexler's paper, remarkable for its free-ranging speculation appears to have successfully bridged the gap between the terms that engineers readily comprehend and the sometimes impenetrable language of biochemistry. Drexler, of course, was inspired by an even earlier masterpiece of loud thinking; Richard Feynman's famous lecture on miniaturization, delivered at Caltech on 29 December 1959. Over four decades later we are still a long way from assembling molecules by putting 'the atoms down where the chemist says'. But the ability to manipulate atoms and molecules has advanced enormously since Feynman's days. Nanomachines, nanorobots and nanotechnology have become popular in fiction; Michael Crichton's bizarre vision of swarms of intelligent nanoparticles hunting down humans in the Nevada desert appears to have risen from a confluence of information technology, biotechnology and nanotechnology.

Nanotechnology seems to be on everyone's lips these days. A clear sign of a new and booming field of science is the number of conferences that are advertised, many in attractive and exotic locations. Government agencies also begin to target funding into the new boom areas. The US Congress is reported to have earmarked '$2.36 billion over three years for nanotech R&D' (Perkel, J. M., *The Scientist*, 28 July 2003, p. 20). In India, the Department of Science and Technology has already adopted nanotechnology for a special thrust and undoubtedly other agencies will follow suit. The Department of Biotechnology has advertised for projects in the area of 'nano-biotechnology', a fusion of the two most glamourous prefixes in science today.

Most importantly, in projecting the prospects for a new 'nano era', it is 'technology' that is emphasized. There are two possible reasons for this. It is possible that 'nanoscience' is already a well-established discipline. Or, it might be that we could conceivably reap the benefits of a new technology without necessarily investing a great deal of time and money understanding the underpinning science. Drexler's 1981 paper offers some insights into his views at that time: 'Engineers (in contrast to scientists) need not seek to understand all proteins but only enough to produce useful systems in a reasonable number of attempts … . Thus, the difficulties encountered in predicting the conformations of natural proteins do not seem insurmountable obstacles to protein engineering.'

Two decades later the obstacles, to 'protein engineering' in the production of technologically useful devices, are still formidable and largely unsurmounted. A quick search of the Internet with *Google* yielded 536,000 hits for nanotechnology and only 58,000 hits for nanoscience; clearly a sign that nanotechnology must be a popular term. Remarkable definitions abound on the World Wide Web. Consider this: 'Manufactured products are made from atoms. The properties of those products depend on how those atoms are arranged. If we rearrange the atoms in coal we can make diamond. If we rearrange the atoms in sand (and add a few other trace elements) we can make computer chips. If we rearrange the atoms in dirt, water and air we can make potatoes.'

The exploding interest in nanotechnology almost two decades after Drexler's paper does not seem to be based on any one major scientific advance. The atomic force microscope and the optical tweezer still appear to be research devices and not the routine machines of technology. How then did nanotechnology suddenly move to centre stage? In searching for answers I found it difficult to find definitions of the field but did come across some interesting statements: 'Unlike such fields as immunology and electronics, nanoscience deals not with a specific area of research, so much as a length scale: 0.1 to 100 nanometers' (Perkel, J. M., *The Scientist*, 28 July 2003, p. 20). This report goes on to quote the US National Nanotechnology Initiative: 'Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomena, and processes due to their nanoscale size'. The Internet provided a more pithy definition of 'nanotechnology', 'molecular nanotechnology' or 'molecular manufacturing': 'Whatever we call it it should let us (i) Get essentially every atom in the right place (ii) Make almost any structure consistent with the laws of physics that we can specify in molecular detail (iii) Have manufacturing costs not greatly exceeding the cost of the required raw materials and energy.' To me, all of this sounds very much like chemistry and chemical technology.

Is nanotechnology really chemistry in disguise? Is it a new discipline that is springing up on the borders of biology, chemistry, physics and engineering, which will eventually have a unique identity of its own? Or is it an attempt to project a new range of potential applications based on conventional science? Moving atoms and molecules as Feynman envisaged in 1959 still seems to lie at the heart of the aspirations of nanotechnology. This has always been the realm of chemistry, with particle sizes alone constituting the parameter for distinguishing chemistry from nanoscience. 'Biology inspired physics' is another new term that is making the rounds; an area which should at some stage seamlessly integrate into nanotechnology. There are many terms which have become commonplace in the literature of chemistry, particularly at its borders with physics and biology, which appear to describe old phenomena in new language; investing conventional topics with a novelty that journal editors and referees find beguiling. Molecules nowadays do not 'crystallize', as they did in my youth; instead they 'self assemble', conjuring up a Drexlerian vision of a new technology in the making. The electron microscope has reached a level of sophistication that 'seeing' the nanoworld has become possible; Feynman would have been immensely gratified. As a result, nanoscientists (technologists?) describe with an infectious exuberance their observations of 'nanotubes'. The fullerene (carbon) nanotubes are the current favourite, little hollow carbon pipes which have for the past several years attracted great attention (Yakobsen, B. I. and Smalley, R. E., *American Scientist*, 1997, **85**, 324). The literature is now full of reports of 'nanotubes' observed in unique situations. My favourite is a paper, coauthored by the late Max Perutz, which carries an emphatically assertive title: 'Amyloid fibrils are water filled nanotubes' (Perutz, M. F. *et al.*, *Proc. Natl. Acad. Sci. USA*, 2002, **99**, 5591–5595). Biologists are undoubtedly drawing inspiration from the lexicon of nanotechnology. There is a sudden resurgence of interest in old areas. The physicists have discovered colloids and the chemists have rediscovered the hydrogen bond. Condensed matter physicists, materials scientists and many 'born again' chemists have converted to the new religion of nanotechnology. Very soon an army of biologists will move in, promising the fruits of fusion – nanobiotechnology. With a little luck and of course, plenty of work new technologies and even new science may undoubtedly emerge.

Even as the number of private nanotechnology ventures increases in the West in a manner reminiscent of the growth of the information and biotechnology industries, the backlash from environmental activists has already begun. Michael Crichton's novel *Prey*, which is based on an implausible scenario, may serve as a rallying point for activists against a new 'nano threat' (*Physics World*, July 2003, p. 13; *Nature*, 2003, **424**, 237). The often wild claims made on behalf of nanotechnology by its proponents will fuel the backlash. Interesting times lie ahead; neither the nanotechnologists nor the activists are capable of reigning in their imaginations. Raucous debate, enlivening but rarely informing, will undoubtedly continue for some time to come.

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