The benefits of nanotechnology

First evolution, then revolution

Nano-pioneer Professor George M. Whitesides is one of the world's ten most frequently cited researchers in scientific journals.

George M. Whitesides, Professor of chemistry and chemical biology at Harvard University in Cambridge, Massachusetts, is considered worldwide a pioneer of nanoscience. He advanced the bottom-up principle, according to which atoms and molecules assemble themselves into nanocomponents. He described for *research* where the journey into the nanocosmos will lead over the next few years.

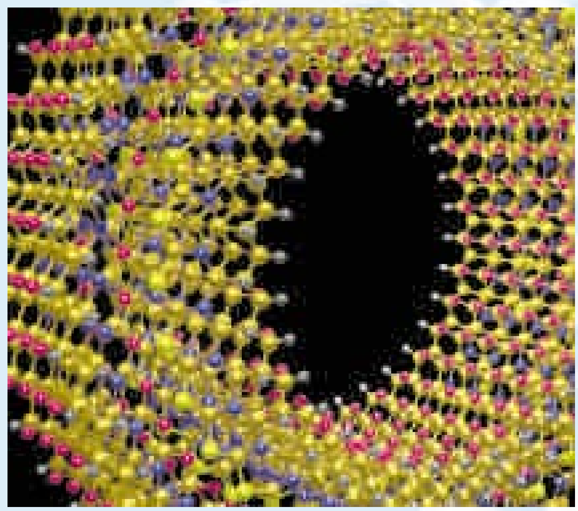
Nanoscience is the science of objects with diameters of a few nanometers to about 100 nanometers. In chemistry, this range of sizes has typically been associated with very large molecules, or aggregates of many molecules. These very small structures are intensely interesting, partly because many of their properties still mystify scientists. Very small particles, or very large collections of molecules and atoms, are simply not structures that science has been able to explore carefully. Furthermore, nanostructures are in a range of size in which quantum mechanics would be expected to be important. For example, quantum nanowires and dots prove to possess remarkable electronic properties. The field of biology has discovered a new area of research in the nanometer-size structures that make up cells, or biological "nanomachines". We have only just begun to understand their function. Nanostructures are also the basis of nanoelectronics: evolution in the semiconductor industry has brought the components of commercial semiconductor devices to sizes close to 100 nm, and miniaturization continues unabated.

Nanoscience has been around for a decade. But technologies growing from it are still few and far between, and the rate at which they have emerged has seemed slower than in areas like biotechnology. This circumstance poses some questions: Is there such a thing as nanotechnology? Will it ever exist? The answer is: Absolutely! And the right questions to ask are: How soon, and will there be one or two nanotechnologies?

There will certainly be an evolutionary nanotechnology, based on products that already exist and that have micro- and nanometer scale features, such as in microelectronics, material research and chemistry.

The real issue is whether there will additionally be a revolutionary nanotechnology, based on fundamentally new technologies, with products that we cannot presently imagine. These technologies will have entirely new capabilities, and they are emerging from new nanostructured materials, such as buckytubes (tubular structures comprised of carbon atoms), from the novel electronic properties of quantum dots, from fundamentally new types of architectures based on nanodevices, which in the future will handle computation and information storage and transmission, and from nanosystems that use or mimic biology. I suspect that revolutionary nanotechnology will develop, but I do not know for sure. And I suspect that it will – like most new technologies – emerge only gradually.

Revolutionary nanoscience is by no means Utopian. It already exists in the laboratories of universities. It is just not clear – at the moment – how much of this exciting science will migrate into new technology. Chemistry has emerged to play a leading role in the development of nanotechnology. In a sense, chemistry has always been the ultimate nanotechnology: chemists synthesize new substances by joining atoms and groups of atoms together with bonds. They carry out this sub-nanometer-scale activity on a megaton scale, and with remarkable economy and safety. Although initial expectations of nanotechnology in the media centered on nanoelectronics and nanomachines, the first new commercial technologies to emerge seem in fact to be in materials science: and materials are products of chemical processes.



Computer model of a molecular bearing for nanomachines of the future.

New opportunities for the chemical industry

Nanotechnology offers chemistry a range of opportunities. For example, buckytubes are beginning to find commercial uses, such as increasing the electrical conductivity of polymers. Quantum dots, which are small grains of semiconductor material that fluoresce, are suitable as probes in cell biology, and perhaps in displays for computers and cell phones. Phase-separated polymers can be used to optimize properties of polymeric materials. Finally, self-assembled monolayers make it possible to apply nanometer-thick films to surfaces, so as to provide corrosion protection, control friction or enhance biocompatibility.

What opportunities result for chemistry? The first of these – and one already well established – is materials and equipment for research, and increasingly for development. The scanning tunneling microscope invented by Binnig and Rohrer at the IBM laboratory in Zurich was the instrument that catalyzed the explosion of nanoscience. Instruments and materials for nanoscience are a growing market.

A second class of commercially important nanostructures will be new materials: structural and electrically, magnetically or optically functional polymers and composites for a range of applications, from spray-painted automobile bumpers to printed organic electronics for smart shipping labels. In these applications, chemistry and chemical process technology will be the key to their exploitation.

High-performance nanomaterials will, however, pose a dilemma for the chemical industry in that, at least initially, the volumes required may be relatively low. Our world no longer needs new, billion-dollar chemical plants. It requires agility to succeed in an era of rapid technical innovation. The industry will thus be faced with the choice of trying to manage businesses that make small amounts of special materials, or trying to move downstream, meaning into competition with traditional customers, in order to capture some of the value of the systems in which the materials are used.

The third set of opportunities will be created by new materials for nanoelectronics. The development of photoresists, and processes for chip structures in the sub-50 nanometer range will present major challenges for both materials science and chemistry. A fourth opportunity is specialized nanoparticles for a wide range of applications, from drugs with improved bioavailability to electrodes and phosphores for new graphic displays. The

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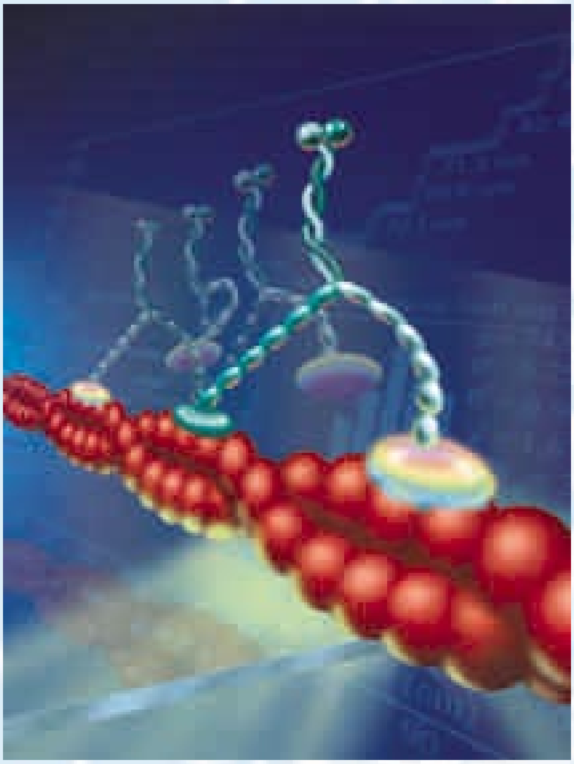

Biological nanomotors are involved when muscle movement in the human body causes the protein myosin to migrate step for step along a strand of actin.

final and most exciting class of opportunities for nanotechnology comprises revolutionary ideas, from nano-CDs (data storage media like compact disks) that are read by an array of parallel atomic force microscope tips known as a "centipede", to quantum computers or nanomachines based in presently unimaginable ways on functional structures occurring in the cell.

Nanotechnology is new, and it is not surprising that the public is wary of its potential for harm. One concern is that nanotechnology will get out of control, that small machines will replicate themselves, escape from the laboratory and eat the earth. I see no way that such devices can ever exist. In contrast, public concern has some basis when it comes to nanoparticles. We do not, in fact, understand the interaction of small particles with cells and tissues. Most nanomaterials are undoubtedly safe, if only because they are embedded in other materials for use. Moreover, they are already common in the environment.

In my opinion, the most serious risk of nanotechnology comes from the use of evolutionary nanotechnology in electronics and telecommunications. The rapid progress in data storage and processing speeds will make it possible to collect enormous quantities of data about people. These data can be used to identify and characterize individuals, and the ease with which that occurs poses a direct threat to historical norms of personal privacy. The way information technology has changed our world is more pervasive and deep-seated than anything that will come from "revolutionary" nanotechnology in the foreseeable future.

Nanoscience today is an important, central topic in fundamental research, and it will soon become an important part of technology. But in our enthusiasm for "nano", we must not forget "micro". For many applications, microtechnology is more important than nanotechnology. Researchers must focus on the development of technologies at the right size. "Nano" is not always the best or only answer.

Nanoscience is now a thread woven into many fields of science. Chemistry will play a role; whether this role is supporting or leading will depend in part on how the field develops and what opportunities emerge. But it will also depend on how imaginative and aggressive chemists and chemical engineers are in creating their parts.

Taking full advantage of the opportunities of nanotechnology will require the chemical industry to behave in new ways. Maintaining agility when confronted with new opportunities is always a difficult trick to perform; and particularly difficult for an industry that, for some decades, has not been rewarded for embracing new ideas or accomplishing new tricks. The chemical industry faces a number of interesting challenges.

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http://gmwgroup.harvard.edu/domino/html/webpage/homepage2.nsf
Information on the research activities of Professor Whitesides and his team.