NANOTECHNOLOGY: A KEY ADVANCE

by K. Eric Drexler, 1985

Foreseeable technological advances will enable us to build devices to complex, atomic specifications. This will make possible a nanotechnology that includes both nanomachines and nanoelectronics. As microtechnology involves micrometer-scale devices, so nanotechnology will involve nanometer-scale devices. These advances will change macroscopic technology as well, because all technology rests ultimately on our ability to arrange atoms to make hardware.

The prospect of nanotechnology forces a reevaluation of our expectations regarding the next several decades. New dangers make foresight vitally important. This paper outlines some basic facts regarding the nature and consequences of nanotechnology. It is condensed, containing more assertions than explanations--its goal is not to provide a thorough technical discussion, but merely to describe a set of facts and make them plausible to readers with broad technical literacy.

The Technology

Nanotechnology is synonymous with advanced molecular technology. It includes molecular electronics and the so-called biochip. It may be seen as the culmination of progress in many fields.

Microelectronic engineers construct ever-smaller devices, some only a thousand atoms wide. Chemists know a great deal about molecules, and they regularly design and build small molecular structures. Progress in both synthetic chemistry and microelectronics leads toward the construction of complex structures to atomic precision--that is, toward nanotechnology. Biologists study the molecular machinery of life; nanotechnology will provide them with greatly improved molecular tools and instruments. Through the molecular tools of pharmacology, physicians influence the molecular machinery of life. Nanotechnology will again provide tools of dramatically greater ability.

Researchers in these fields are laying the foundations for nanotechnology. Biochemists are learning to design ever-larger molecular systems, and groups in Japan, at the U.S. Naval Research Laboratory, and elsewhere are pursuing work in molecular electronics.

We can already see much of what this work will make possible, because physicists, chemists, and biochemists understand the laws that govern molecular systems. The behavior of these systems is often amenable to computer simulation, using ordinary mechanics to describe molecular motions and quantum mechanics to describe molecular bonding. The challenge of nanotechnology is one of developing better physical and computational tools, not of developing new fundamental science.

Nanomachines will be the key to nanotechnology. Because molecules are objects with size, shape, mass, and stiffness, they can serve as moving parts in nanomachines. Well-known biochemical systems--the rotary flagellar motor that propels bacteria, the actin-myosin system that powers muscle, and so forth--show that molecular machines exist and function. They prove (and calculations confirm) that thermal noise and quantum-mechanical effects do not prohibit machines with molecular-scale moving parts.

Molecular machines can build molecular machines. Enzymes direct the swift assembly and disassembly of molecular structures. Ribosomes act as numerically-controlled machine tools, assembling molecular devices (in this case, protein molecules) under programmed control. They demonstrate that nanomachines can build specific molecular structures by bringing reactive molecules together in the right orientations and surroundings. Genetic engineers use DNA to program bacterial ribosomes to build natural (but foreign) proteins. The design of novel proteins is an active area of research. Eventually, we will learn to build proteins that, like those in the cell, perform a wide range of chemical and mechanical functions. We will then be able to build ribosome-like protein machines which will in turn enable us to build non-protein machines. Protein engineering thus offers one path to nanotechnology. Physicist Richard Feynman outlined an alternative path as early as 1959.

By one path or another, we will eventually develop tools that enable us to assemble complex structures to atomic specifications. Such tools are called "molecular assemblers," or simply "assemblers." The development of assemblers will constitute a key breakthrough in technology.

Some Applications

Comparisons to known physical systems and straightforward design calculations indicate the feasibility of the following:

Replicators: Assemblers, if supplied with materials and energy, will be able to build almost anything--including more assemblers and more systems for providing them with materials and energy. Cells demonstrate that systems of molecular machinery can replicate themselves. Replicating assemblers will be as cheap as bacteria. Single cells proliferate and cooperate to build redwoods and blue whales; properly programmed replicators will likewise be able to build large systems.

Nanocomputers: If built with molecular components, the equivalent of a modern microprocessor will fit in roughly 1/1000 of a cubic micron. Megabytes of fast RAM and gigabytes of tape-like storage with sub-millisecond access times will fit within a cubic micron. The small size and low power dissipation of nanocomputers will make possible machines with massively parallel architectures.

Cell repair machines: Molecular machines in cells sense, make, rearrange, and destroy cellular structures. During cell division, they build whole new cells. Advanced nanomachines will be able to do likewise. Since typical human cells have a volume of roughly 1,000 cubic microns, they hold room enough for cell repair machines directed by on-site nanocomputers and wielding an extensive set of molecular-scale sensors and tools. Cell repair machines will bring surgical control to the molecular scale, enabling physicians to repair tissues that are unable to repair themselves, and to reverse the molecular disorders that cause aging. Replicators will make cell repair machines inexpensive.

Superstuff: The performance of systems depends on the pattern of atoms composing them. Assembler-built composites based on diamond fiber will have tens of times the strength-to-mass ratio of present structural metals, and excellent fracture toughness as well. Assembler-built screens, made from nearly-microscopic lens arrays, will display high-resolution, full-color, three-dimensional imagery. Assembler-built batteries with finely interleaved electrodes will have very low internal resistance and high power-to-mass ratios. This list could be extended almost indefinitely: assembler-built materials, components, and systems will advance virtually all fields of technology, making possible improved chairs, cars, spacecraft, and so forth.

Superweapons: Superior hardware will have superior military potential. Replicating assemblers will permit swift construction of such hardware. Programmable replicators will make possible a more controlled and practical (and hence more threatening) form of "germ" warfare. This list, too, could be extended.

Our Situation

These prospects raise certain questions about nanotechnology and its effect on our future:

Is nanotechnology good or bad? Nanotechnology raises obvious issues of life and death. Replicating assemblers will enable us to create material wealth of unprecedented quality and quantity; in much of the world, this is a life-and-death matter. More directly, cell repair machines will enable medicine to create and maintain health. Yet through the same capabilities that make these benefits possible, nanotechnology will also make possible new forms of warfare and oppression.

Could it be stopped? Advances in fields as diverse as medicine, weaponry, and chemistry will (intentionally or not) move us along the path to nanotechnology. Military motivations will be strong, and the verification of limits on research will be virtually impossible. In a world of competing technological states, local actions and local laws cannot stop such a technology. In the absence of means for verification, international treaties likewise offer little hope. Thus, regardless of the balance of its benefits and risks, nanotechnology seems virtually inevitable. We can only guide advances, not stop them.

When will it arrive? Present physical knowledge enables us to foresee some of what nanotechnology will (and will not) be able to accomplish, but estimates of when nanotechnology will arrive are far more speculative. Such estimates must reflect the possibility both of unanticipated shortcuts and of unanticipated delays. They must take account of obvious synergies, such as the application of expert-systems technology to computer-aided design, and the application of both to molecular engineering. Further, they must take account of research trends such as the commencement of "full-scale research efforts" on molecular electronics by NEC, Hitachi, Toshiba, Matsushita, Fujitsu, Sanyo-Denko, and Sharp. Finally, military interest in nanotechnology seems likely to eventually spawn an effort as urgent as the Manhattan Project. In light of these considerations, a plausible guess for the arrival date of molecular assemblers is twenty years, plus or minus ten. For some purposes (e.g., planning for medical care) it is safest to assume that nanotechnology will develop slowly. For other purposes (e.g., preparing for dangers) it is safest to assume that it will develop swiftly.

What is to be done? The prospect of nanotechnology raises a host of policy questions. Depending on the preparations we make, nanotechnology could bring either great benefits or a final disaster. Because nanotechnology will build on known principles of science and engineering, a measure of foresight seems possible. Because advances in nanotechnology seem easier to steer than to stop, a measure of foresight seems necessary.

The study of nanotechnology crosses disciplinary boundaries. To judge the possibilities requires engineering thought guided by knowledge in such fields as physics, chemistry, biology, and materials science. The basic technical facts in turn raise issues of social, political, and strategic importance. It seems that past expectations must be revised, perhaps drastically. We need to know more about nanotechnology and its implications, and we need to have that knowledge spread widely. The growth of knowledge is best served by critical discussion and by presentation of the results.

Further Reading:

Richard Feynman, "There's Plenty of Room at the Bottom." In Miniaturization, H. D. Gilbert, ed., Reinhold, New York, pp 282-296 (1961).

K. Eric Drexler, "Molecular Engineering: an approach to the development of general capabilities for molecular manipulation." Proceedings of the National Academy of Sciences (USA), 78:5275-5278 (September 1981).

Molecular Electronic Devices, Forrest L. Carter, ed. Marcel Dekker, New York (1982).

K. Eric Drexler, "When molecules will do the work." Smithsonian, pp 145-155 (November 1982).

Kevin Ulmer, "Protein Engineering." Science, 219:666-671 (11 February 1983).

Jonathan B. Tucker, "Biochips: can molecules compute?" High Technology, pp 36-47 (February 1984).

K. Eric Drexler, "Engines of Creation." Doubleday, New York (1986).