Towards molecular manufacturing

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Manufactured products are made from atoms, and this is starting to matter. What a product is, what it does, depends on how its atoms are arranged. Better control on a microscopic scale has brought better computer chips; better control on a molecular scale has already brought better materials. Future manufacturing processes will use molecular machines to get the details right—ultimately, molecular precision.

With early results appearing in journals, with theoretical studies showing where progress can lead, and with research programmes starting to speed up, molecular manufacturing is ready to attract major investment in 1992. Advances toward molecular manufacturing carry diverse adjectives and nouns: chemical, molecular, atomic, angstrom, biotechnology, nanotechnology. All these advances deliver precise control of molecular structure.

Progress will accelerate on several fronts: biotechnology is rapidly moving beyond the slavish copying of natural molecules to engineering new molecular objects with new capabilities. Chemists too have raised their sights, making ever-more complex sets of self-assembling molecules. At MIT, Julius Rebek recently made a new self-replicating molecule. Computer simulations of molecules have become easier as the computers have improved dramatically. IBM physicists led by Donald Eigler have written their corporate logo using a scanning-tunnelling microscope (STM) with 35 xenon atoms; and they have built an electrical switch that works by the motion of a single atom. The STM and the related atomic-force microscope can see direct images of molecules on surfaces. This will let future experimenters see what they are doing.

Journals and research efforts are coalescing. Two journals, Molecular Engineering and Nanotechnology, have appeared. In Silicon Valley, Ralph Merkle has started a Computational Nanotechnology Project at the Xerox Palo Alto Research Center; the Institute for Molecular Manufacturing has been established nearby. Japanese research initiatives have included the Kunitake Molecular Architecture Project (studying self-assembling molecular systems), the Hotani Molecular Dynamic Assembly Project (reverse-engineering molecular motors from bacteria), and the Aono Atomcraft Project (building structures atom-by-atom using STMs).

What will be the next major milestone? For 100 years and more, chemists have built molecular structures without being able to grasp molecular fragments and put them in place. Now physicists are learning to manoeuvre molecules directly, poking at them under microscopes. 1992 should see moves to join these separate strands of research together to form a new and powerful technology. By attaching molecular grippers to atomic-force microscopes, scientists will, in effect, have the tool kit of chemical organic synthesis. This may take several years to achieve, but it should be worth the wait.

This ability to put molecules where they are wanted will enable the construction of molecules 1,000 times more complex than those chemists can make today (containing about 100,000 parts, rather than about 100). The catch is that these molecules will make molecules one by one, whereas chemists consider a billion molecules to be a tiny number.

Speed, tiny speed

Yet even a single molecule can be valuable if it gives new information about chemical reactions or about proteins and other biomolecules. This technology will permit the building of molecular-scale DNA readers able to sequence a human genome. It could build devices that can build more devices, riding a doubling curve up into the realm of industrial quantities. Progress toward such complex products should be swift: the machines will resemble computer workstations in size and cost. They will let researchers make and correct mistakes with the speed of computer programmers.

At Xerox, computational models of molecules are being used to design molecular machines. Molecules are objects, and conventional engineering concepts can be applied with remarkably few adjustments. Molecular machines can do the things that large machines do, but at much higher frequencies. Molecular mechanical computers (not unlike Babbage's Analytical Engine) will execute 1 billion instructions a second while consuming one ten-millionth of a watt of power and occupying a space no bigger than that of a bacterium.

A molecular manufacturing system will assemble molecular parts at a rate of a million a second, churning out products equaling its own mass in a fraction of an hour. Starting with industrial-chemical feedstocks, the products can include computers, superstrong materials, more manufacturing systems, and other things made of atoms, the value added can be large. These systems will get the details right, all the way down. The demise of microtechnologies such as integrated circuits will be only the beginning.

John Armstrong, IBM vice-president for science and technology, writes that "nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early 1970s." Nature magazine reports that nanotechnology "seems destined to become Japan's next priority target for industrial research." Is it any wonder?