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Massive Manufacturing: The Promise and Peril of Nanotechnology

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Today, it takes a whole economy to produce the technology that goes into a factory. But this article describes a new technology that could produce a tabletop manufacturing system—compact, flexible, and fast enough to build a duplicate in an hour or so. That would be revolutionary—and dangerous.

For many purposes, nanotechnology is defined as anything small enough to be interesting and innovative. This can include large molecules, small minerals, modern semiconductors, and a wide variety of sub-microscopic structures with an equally wide variety of purposes. But nanotechnology has another meaning, one that's even more interesting: using programmable chemistry as the basis of a manufacturing system.

The first section of this article describes how this will work. The second section explains how powerful it could be. The third covers some possible positive and negative consequences, and the fourth explains why these consequences could happen within a decade. The conclusion includes a call to action.

Building By Atoms

Most manufacturing today is not precise. Pounding or pouring metal, squishing plastic into shape, cutting things out of bigger things—all are imprecise processes. But chemistry is perfectly precise. A chemical bond is either there, or it's not. The results of a chemical reaction are either right, or wrong. This means that the product of chemistry can be specified exactly. Chemistry is *digital*.

If you wanted to build a machine to paint a picture, you could plan a Rube Goldberg collection of levers and gears that would move the brush in just the right path. Or, you could attach a computer to a few motors. The mechanics would be very simple. What would be complex, in a computerized design, would be the software running on the computer—and that could be as complex as you liked. Systems that are *programmable* can make far more complex products than systems that are not.

The picture on a computer screen is built from a million tiny colored dots, controlled by a billion 1's and 0's in the computer's software. By bringing together all the little pieces, any desired image can be created. A *bottom-up* system that can assemble zillions of tiny pieces can make a product vastly more intricate and flexible than a top-down system.

A precise digital system is easy to automate. Your computer does trillions of calculations per day without a single error. It can do this because it's built around extremely reliable digital transistors. A manufacturing system built around digital chemistry could also be extremely reliable, producing thousands or millions of parts with exactly the same chemical arrangement. (Several aspects of nanoscale physics, including thermal noise and the squishiness of atoms, also make nanoscale robotics easier in some ways than human-scale industrial robotics.) As far as we can tell, it should be feasible to completely automate a nanoscale manufacturing system.

The idea of molecular manufacturing is to do chemistry, not by letting molecules float around and bump into each other randomly, but by binding and moving them where they should go. Biology does this to some extent—many proteins have recognizable machinelike functions—but biology is not completely digital and is only indirectly programmable. The difference between molecular manufacturing and biology is like the difference between a jet airplane and an eagle. The bird's design is more subtle and flexible, and probably more efficient, but the airplane is more powerful and can fly faster and higher.

The Power of Molecular Manufacturing

We don't yet know how powerful molecular manufacturing could be, but estimates have been made. Nano-built products should be very strong—somewhere between steel and diamond. Computers and sensors should be millions of times smaller and more efficient than today's models. Motors may be thousands or even millions of times more powerful, when they can be engineered at the level of atoms and electrons.

The most detailed description of molecular manufacturing was produced by Eric Drexler in 1992, in his book *Nanosystems*. He proposes developing the ability to make nano-parts out of diamond. Nanoscale robots could do chemistry to build the diamond shapes a few atoms at a time. *Nanosystems* calculated the chemical error rate (very low), size of computers and machines (very small), power density (very large), and strength (very high). *Nanosystems* and subsequent work also calculated how fast a chemistry robot could build stuff. It turns out that a plausible robot could build its own weight in an hour or so.

Today's top-down manufacturing requires hundreds of thousands of separate processes to build a complete range of products, or even a complete range of manufacturing equipment. A self-contained factory, one that included machinery to build all its machinery, would have to be huge. But building from the bottom up, adding a few atoms at a time in programmable positions, shifts the complexity from the hardware to the software. A relatively simple machine could easily make products as complex as itself. And since chemistry is digital, it could do so with a low error rate.

If you had a computer-controlled "nanofactory" that could produce its own weight of product in a few hours, what would you do with it? The obvious answer is: build another factory! It'll only take a few hours, and then you could produce twice as much stuff. As long as the factory costs more than its products, the economical thing to do is build more factories. Once these factories are a glut on the market, the cost of equipment won't contribute much to the cost of the product.

This implies that in addition to being strong, compact, and powerful, products of molecular manufacturing can be cheap — not much costlier than the raw materials. This includes nanofactories: a nanofactory will be able to rapidly produce its duplicate from nothing but cheap chemicals and software. Make a tiny fabricator build two fabricators fastened together, have them produce four, then eight, and so on—and within a few weeks, if all goes well, a microscopic fabricator has led to a tabletop manufacturing system. It turns out that a tabletop nanofactory could include 144 quadrillion chemical robots, about half the weight of the factory, all working in parallel to build their own weight in an hour or so. That means that bottom-up nano-scale chemical construction can be used to build human-scale products efficiently.

Consequences of Molecular Manufacturing

Suppose you have a nanofactory that can make almost anything you want, in almost any quantity, at very low cost. Do you live happily ever after? Or do you worry about what your neighbors are doing with their nanofactories?

Unfortunately, we probably have to worry. One nasty neighbor could ruin everyone's day. A country that designed and built lots of cutting-edge weapons potentially could take over the world. That possibility could easily lead to an arms race—one a lot less stable than the nuclear arms race, because weapons development would be much cheaper, faster, and easier to hide. Criminals could send smart bugs to spy on you or make your life miserable unless you paid protection money. Wastrels could easily build enough nano-litter to destroy the environment. Cheap personal manufacturing could disrupt economics and trade, destabilizing the world's current political systems.

Nano-manufacturing, if once released to the public, would be very hard to control. A miniature self-contained nanofactory could be the size of a grain of salt: impossible to detect in a search, but easily doubled and redoubled to create a large manufacturing system. This argues that strict control should be maintained over any nanofactory that's developed.

The trouble with a regime of strict control is that everyone will want easy access to nanofactory manufacturing—and most people should have it. Molecular manufacturing has the potential to solve many of the world's most urgent problems. Cheap, clean, local, self-contained manufacturing could rapidly wipe out poverty while simultaneously reducing our environmental footprint. Medical devices as well as weapons could be built cheaply. Large-scale engineering projects could be far less costly and more inventive, allowing the rapid development and installation of new systems for energy and agriculture. Some people think that *only* molecular manufacturing can solve the current environmental crisis.

The technology should not be prevented. Indeed, it cannot be—it will rapidly become easier to develop. But it also cannot be allowed to spread unchecked. So much power in the hands of millions of people and organizations would lead to instability, and then disaster. But controlling this situation would require incredible concentration of power. Massive distributed power would lead to massive distributed disasters. Massive concentrated power could easily lead to totalitarianism. We must find a solution to this—and soon.

Urgency

How long till molecular manufacturing is developed? It could be less than a decade. Already, we can build relatively large bottom-up nanosystems with chemistry—hundreds of atoms wide. Top-down fabrication processes can build things smaller than that. A hybrid technology, though awkward, could be used to “bootstrap” a fully bottom-up technology. With heavy funding, this might be done in the next few years, and it will rapidly get easier.

The cost of developing molecular manufacturing depends on the cost of computers, which is dropping by half every two years. The cost also depends on how many lab techniques need to be invented. Already, we can make machines (top-down) small enough to physically grab individual molecules (bottom-up), and the pace of progress continually surprises me.

Ten years ago, a rapid development program would have had to try many false paths, multiplying the cost. Today, it would be much easier to decide which development pathways to focus on. Experimental work on many nanoscale technologies is quickly showing what each technology is capable of. Theoretical work continues to refine the molecular manufacturing concept, showing what is needed. Considering all these factors, I predict that the cost of developing molecular manufacturing will fall by half every two years or so.

In my opinion, a well-managed, well-funded program on the level of the Manhattan Project could almost certainly develop molecular manufacturing in less than ten years—perhaps as few as five. If such a program has already started somewhere in secret, it might finish in the next few years. Five years from now, even if no government has funded a Manhattan Project, the lower cost and greater certainty will probably make a five-year development plan attractive to a number of large corporations.

Conclusion

Molecular manufacturing is based on a few simple, powerful ideas: programmable control, bottom-up chemical fabrication, automation, and the ability of a small factory based on these principles to rapidly make one twice as big. Biology comes close to achieving this, but engineering should easily be able to improve on biology, at least for simple tasks. (Remember, biology never developed the wheel.)

We should plan for the possibility of molecular manufacturing being developed in less than a decade. To ignore this possibility would be imprudent, to say the least. Molecular manufacturing has the power to correct environmental and humanitarian disasters, but will also create new and potentially disastrous problems.

The power of molecular manufacturing is too great to be released randomly. However, good administration of the technology will not be easy to design. The Center for Responsible Nanotechnology believes that this is one of the most urgent issues facing the world today. We need better studies of the development schedule and the range of possible consequences. We need to develop systems of administration that can handle the unprecedented power of the technology. Public awareness will be crucial; we can't prepare for what we don't know about.

Think about how molecular manufacturing would change your life. Ask yourself and your co-workers what impact it would have on the plans you make. Learn more about it: Foresight.org and CRNano.org are good places to start. Begin questioning ten-year projections that do not take the possibility into account. If we do not prepare ourselves for molecular manufacturing, it will take us by surprise—and a surprise of this magnitude will almost certainly be unpleasant.

This essay is original and was specifically prepared for publication at Future Brief. A brief biography of Chris Phoenix can be found at our main Commentary page. Recent essays written by Mr. Phoenix can be found at his Center for Responsible Nanotechnology. Some earlier essays are archived at Nanotechnology Now. He receives e-mail at cphoenix@crnano.org.