Molecular Manufacturing: Start Planning

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This paper was originally published in *Public Interest Report,* the
Journal of the Federation of American Scientists

Despite claims to the contrary, molecular manufacturing is coming soon. Because it will be so useful, there will be strong pressure to develop it as soon as possible, and past a certain point it could happen quite rapidly. Macro-scale integrated nanotechnology manufacturing systems will improve product functionality, product design time and manufacturing speed and cost by orders of magnitude. This advance may profoundly affect economics and geopolitics, creating enormous benefits and risks. It will be difficult to prepare adequately for such a powerful technology. For all these reasons, molecular manufacturing technologies should be a current topic in high-level policy and planning.

The word "nanotechnology" means several different things. Today's nanoscale technology research is mainly concerned with building small structures that have novel properties. Such research adds steadily to the technological toolbox, leading to improved products and occasionally to new industries. Broadly speaking, such nanoscale technologies create risks comparable to other material science work. The second kind of nanotechnology is the science-fictional kind, in which nanobots can go anywhere and do anything but generally do not conform to reality. The third kind of nanotechnology, which will lead to molecular manufacturing, is the focus of this article. Molecular manufacturing, which is sometimes called molecular nanotechnology (MNT), will combine chemistry and fabrication to produce precise machines and manufacturing systems at the nanometer scale. Much of the basic science work has already been done; what remains is the engineering to create a working device and then integrate many devices into a human-scale "nanofactory". Although most nanotechnology projects today focus on nanoscale technology, development of molecular manufacturing will surely become a priority within a few years. Full capability for this may not be developed for a decade or longer, but preparation for it should probably start now.

The economic value—and military significance—of a nanofactory will be immense. Even a primitive model will be able to convert CAD files to products in a few hours. Duplicate nanofactories will cost the same as any other nano-built product. The capital cost of manufacturing will be negligible by today's standards, and manufacturing capacity can be doubled in a matter of hours. Nanocomputers will quickly replace semiconductor technologies; whoever controls this technology will be able to produce more computers than the rest of the world combined. The ability to fit a supercomputer (or sophisticated robotics) into every piece of equipment, at no extra manufacturing cost, will enable new kinds of products and weapons. A nanotechnology-built surgical robot with a full sensor suite could be smaller than a hypodermic needle. Development and deployment of new weapons systems could be far faster and cheaper. Even the initial products of a nanofactory would be worth hundreds of billions of dollars, and the potential for extremely rapid advancement of nanotechnology fabrication capability means that no economic or political unit can afford to allow a competitor to control the technology.

Much evidence has accumulated to indicate that molecular manufacturing is possible. A decade ago, Nanosystems studied the required chemistry and engineering in detail; not a single significant error has been found so far. Cells, natural self-replicating machines, make a variety of minerals including magnetite and silica—and they do this under water, using chemical techniques four billion years old. Mechanically guided covalent chemistry has already been accomplished with a scanning probe microscope. The best arguments of intelligent critics regarding the feasibility of molecular manufacturing have been refuted in detail.[1] There is little doubt that a small self-duplicating system can be built. There is strong theoretical support for basing such a system on mechanochemistry. And given the variety of buckytubes, buckyballs, buckyhorns, and other graphitic and diamondoid shapes that have been manufactured or found in nature, it's likely that a self- duplicating nanoscale machine based on 3D covalent carbon mechanochemistry will be relatively straightforward to design.

A goal or milestone of molecular manufacturing is a "fabricator": a self-contained mechanical system capable of fabricating duplicates of itself from simple chemicals. Several researchers have investigated the requirements of a fabricator (sometimes referred to as an assembler), and Robert Freitas and Ralph Merkle are due to publish two books on the topic in 2003 and 2004. A single fabricator is not very useful, since it can only make very small products. However, if a nanofactory containing many fabricators can combine the tiny products (nanoblocks) into a single large product, the result would be extremely useful. It has been claimed that this will take years to achieve, blunting the utility of molecular manufacturing. However, work by the author demonstrates that a useful nanofactory can be pre-designed,[2] so that building and debugging the design might take only a few months. Once the first fabricator is built, a fully functional nanofactory—and the nanofactory's products—may follow in well under a year.

Although design at the atomic level will not be easy, a nanotechnology product designer will not need to worry about that—just as a software engineer does not think about the transistors in the computer. A small and pre-tested set of nanomachines, built into nanoblocks, can be combined in many ways to make a vast array of products. By designing with nanoblocks instead of atoms, a product designer loses little flexibility, and gains simplicity and reliability. Nanoblocks can be fastened together in a process called "convergent assembly." The joining process uses a single motion, requiring only simple robotics, and the joints retain most of the strength of the base material. A single nanoblock is big enough to contain a fabricator, computer, or motor, and small enough to be built by a single fabricator in a few hours. A nanofactory built of nanoblocks can build and assemble nanoblocks into a huge range of products-including duplicates of itself.

[1] "A Debate About Assemblers," http://www.imm.org/SciAmDebate2/index.html

[2] "Design of a Primitive Nanofactory," *Journal of Evolution and Technology,* http://www.jetpress.org/volume13/Nanofactory.htm

Such a powerful technology introduces many risks.[3] One obvious risk is an unstable arms race. Rapid development of new weapons technologies means less opportunity for surveillance and more uncertainty about the enemy's future capabilities. Weapons could be more powerful and far "smarter"—imagine the combined capability of a million unmanned aerial vehicles with on-board pattern matching and navigation capability. Many factors tempt a preemptive strike if a temporary advantage is gained in a molecular manufacturing arms race. The likely outcome of a policy of preemption would be either global domination requiring Draconian measures including denial of technology, or a series of increasingly destructive high-tech conflicts. Once weapons, or the systems that produce them, are dispersed, preventing guerrilla use of them would require inspection of literally every cubic millimeter, or continuous surveillance of entire populations.

Availability of unregulated molecular manufacturing could create several serious problems. Criminal and terrorist activity would benefit from smaller, more capable products. Small, widely available, cheap surveillance devices would allow an unprecedented invasion of privacy by governments, criminals and neighbors. Cheap microscopic products can lead to widespread microscopic litter, with possible environmental or health consequences. Small self-contained foraging self-replicating systems ("gray goo") appear to be theoretically possible, and might be released by terrorists, saboteurs or even irresponsible hobbyists. Though probably less dangerous than all-out war with nanotechnology-built weapons, such devices could be significantly more destructive than invasive biological species because they would have no natural enemies. Many of these problems can best be addressed by widespread environmental monitoring, but the required systems may not be deployed quickly or universally.

Molecular manufacturing may cause substantial economic disruption. Several of today's sectors, including manufacturing, shipping and raw materials, would be disrupted or outmoded. Fully automated self-duplicating factories would reduce the value of both capital and labor, and drive down the cost of goods. Large disparity between cost and value would provide strong incentive for protectionism and anticompetitive policy, resulting in widespread black markets. The entertainment industry is already experiencing similar problems; molecular manufacturing may extend them to most manufactured products.

Simplistic attempts to regulate molecular manufacturing could create more problems than they solve. Attempts to restrict proliferation may generate oppressive or even abusive regulation. Today, billions of people live in sickness or poverty for lack of a few basic products like water filters, mosquito netting and computers. All of this would be easy to produce with nanotechnology-based manufacturing, but US attempts to block a WTO effort to provide affordable pharmaceuticals to poor nations indicate that the same could happen with MNT. A population denied access to lifesaving benefits of cheap molecular manufacturing due to protectionist economic policy or paranoid security policy (or even just blatantly overcharged) would have a strong incentive to steal, duplicate or "crack" the technology. Multiple independent programs to develop molecular manufacturing would multiply many of the risks, including the risk of necessary regulations and technical

[3] For more extensive discussion of risks, benefits, and administration options, see "An Overview of CRN's Current Findings," http://www.crnano.org/overview.htm

restrictions being bypassed. Since nanofactories will be self-contained, incredibly valuable and easily concealed, a black market in nanofactories would be difficult to prevent. Ultimately, control of the technology could be lost, and regions with excessive regulation may be sidelined.

In developing molecular manufacturing, it may be that the safest course is a single, international development effort, leading to a technology that can be widely distributed and carefully administered—with tight technological controls in place to limit its use. This would provide an infrastructure for rapid humanitarian relief with basic products, profit making with other products, and perhaps even arms control—if nations could be restrained from developing independent, unmonitored molecular manufacturing capability. If this is in fact the best approach, the need for action is even more urgent. A nation with an entrenched development program may be less likely to join or support an international development effort. It will not be easy to convince military and political leaders, captains of industry, and environmental and social watchdogs that the best course of action involves giving up some control in order to retain some control.

Development of molecular manufacturing[4] appears inevitable for two reasons. The first is its immense value. Even if public pressure prevented it from being used in consumer goods, various militaries would not hesitate to develop it as a tremendous aid to military capability. In conventional conflicts, the improvements in logistics, miniaturization, development and cost would give an overwhelming advantage to the possessor of such technology, both in preparation and in actual combat. The second reason is the increasing ease of development. Enabling technologies are improving each year. New families of structural chemicals are being discovered. New fabrication technologies, new nanoscale imaging technologies, and increased computer power for mechanochemical simulation will rapidly decrease the difficulty of building a fabricator—and thus a nanofactory. Today, a successful program might require billions of dollars and several years. A decade from now it might be possible for only $100 million, within the reach of many corporations and nations. At that point, if molecular manufacturing is not already widely available, it will be developed in multiple labs around the world—and will be almost impossible to control.

By encompassing all phases of production from chemical processing to final assembly, molecular manufacturing can be far more flexible than any other single technology, with the possible exception of programmable computers. A few other technologies may be equally dangerous, but are easier to control. Nuclear technology can only be used for a few things—bombs, power generation, cancer treatment—so it has been possible for a fairly small international effort to keep control of various aspects of this technology. Biotechnology is flexible in its domain, but biotech products have been difficult to engineer. Conventional rapid prototyping systems will improve gradually; it will be a while before they can make complete products, and even longer before they can cheaply duplicate themselves.

A single technology with the programmability and speed of digital computers, the chemical flexibility of biotechnology, the military potential of nuclear technology or

[4] "Developing Molecular Manufacturing," http://www.crnano.org/Developing.htm

airplanes and the utility of very advanced rapid prototyping will bring many changes. The variety of potential problems, in economic, military, political, humanitarian and environmental spheres, indicates that no simple solution can work. A balance must be struck between national defense and arms control, between capitalist practice and social needs, and between unrestricted private use and oppressive restriction. These issues will not be easy to solve.

The final stages of development will occur too quickly for solutions to evolve.[5] If a well-designed plan is not in place before this happens, one or more serious risks will very likely lead to military destruction, social or economic disruption, or unnecessary human suffering on a large scale. Each major risk should be studied in detail. Public education and discussion should take place. Policy makers need to be informed. There is very little doubt that molecular manufacturing will be developed in the next three decades, and it may be within ten years. It seems likely that some sort of international administration will be necessary. Any large administrative body, especially one requiring complex international cooperation, will take time to design, fund and create. All this may require more than a decade. A large international development effort may also be necessary, and would have to begin even sooner. These factors indicate that preparation for molecular manufacturing technology should become a current topic in high-level policy and planning.

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[5] "Sudden Development of Molecular Manufacturing," http://www.crnano.org/essays05.htm#6,June