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OPINION

Safe exponential manufacturing

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Abstract
In 1959, Richard Feynman pointed out that nanometre-scale machines could be built and operated, and that the precision inherent in molecular construction would make it easy to build multiple identical copies. This raised the possibility of exponential manufacturing, in which production systems could rapidly and cheaply increase their productive capacity, which in turn suggested the possibility of destructive runaway self-replication. Early proposals for artificial nanomachinery focused on small self-replicating machines, discussing their potential productivity and their potential destructiveness if abused. In the light of controversy regarding scenarios based on runaway replication (so-called 'grey goo'), a review of current thinking regarding nanotechnology-based manufacturing is in order. Nanotechnology-based fabrication can be thoroughly non-biological and inherently safe: such systems need have no ability to move about, use natural resources, or undergo incremental mutation. Moreover, self-replication is unnecessary: the development and use of highly productive systems of nanomachinery (nanofactories) need not involve the construction of autonomous self-replicating nanomachines.

Accordingly, the construction of anything resembling a dangerous self-replicating nanomachine can and should be prohibited. Although advanced nanotechnologies could (with great difficulty and little incentive) be used to build such devices, other concerns present greater problems. Since weapon systems will be both easier to build and more likely to draw investment, the potential for dangerous systems is best considered in the context of military competition and arms control.

1. Introduction

Manufacturing systems that cannot be turned off were the stuff of legend and nightmare long before the Industrial Revolution, as in the stories of the Sorcerer's Apprentice and the magic quern that made the sea salty. Molecular manufacturing added two additional reasons for fear: the manufacturing system would be too small to see, and would be able to make more of itself. Early descriptions of molecular manufacturing systems proposed devices with capabilities uncomfortably close to self-replication. In hindsight, it is no surprise that the idea of runaway replication became intimately associated with the broader idea of nanomanufacturing.

This paper examines more recent proposals for molecular manufacturing, showing that the easiest and most efficient systems will not have the capabilities required for autonomous runaway manufacturing. Despite widespread impressions, apparently derived from a scenario sketched by one of the authors (Drexler 1986, chapter 11), the development and use of molecular manufacturing need not at any step involve systems that could run amok as the result of accident or faulty engineering.

There is a deeper message in the legends: that deliberate human use of powerful systems can lead to serious trouble. Although runaway replication cannot happen by accident, no law of nature prevents its deliberate development. Far more serious, however, is the possibility that a powerful and convenient manufacturing capacity could be used to make powerful non-replicating weapons in unprecedented quantity, leading to an arms race, war, terrorism, or oppression.

Products that cannot self-replicate will be more efficient—and in the case of weapons, more dangerous—than products that can. Policy investigation into the effects of molecular nanotechnology should consider deliberate abuse as a primary concern, and runaway replication as a secondary or more distant issue.

2. Molecular nanotechnology and exponential manufacturing

In 1959, Richard Feynman gave a talk (published in 1960) in which he detailed some of the advantages of doing engineering at the scale of atoms and molecules. Biology, of course, has been producing complex nanoscale structures and machines for billions of years, but biological systems are evolved, not designed, and work in a specialized environment with limited chemistry. Feynman suggested that familiar types of machines could be built at that scale, and that such systems could produce familiar types of products. In the last decade, this proposal has been developed into a body of design and analysis that shows how such machines could work and why they would be very much worth building.

In a journal article (1981), Drexler described an approach to developing systems for the nanoscale fabrication of complex structures by means of nanoscale chemical machinery (mechanochemistry). In 1986, Drexler's book *Engines of Creation* used 'nanotechnology' to describe this capability, giving the term its initial widely accepted meaning. Since then, the meaning of the term has broadened to include any interesting nanoscale structure created by any possible mechanism. In an attempt to reduce confusion, Drexler proposed 'molecular nanotechnology' (MNT) and 'molecular manufacturing' as more specific terms describing the use of nanoscale mechanochemical fabrication methods.

A programmable mechanochemical fabricator would be a general-purpose (though not 'universal') manufacturing system, able to build a wide variety of structures and products within the limits of its chemistry. A fabricator that is itself constructed entirely of molecular parts that it is capable of building, and that includes mechanisms for putting the parts together, should be able to be directed to build a copy of itself. In other words, a properly designed molecular manufacturing system could be directed to build a second manufacturing system as cheaply and easily as it could create any other product of similar mass and composition. Since a single molecular fabricator has a low mass throughput (at a million cycles per second, product accumulates at about a nanogram per year), many fabricators must work together to build a macroscopic quantity of product. Thus, the ability of a fabricator to build many duplicates seems to be a practical necessity if MNT is to be a useful macroscale technology.

When MNT was first proposed in 1986, manufacturing systems were described as large numbers of cooperating self-contained production units, or 'assemblers,' each with mechanochemical fabricators, control computers, and communication and navigation systems on-board. More recent work, starting with the publication of *Nanosystems* in 1992 (Drexler 1992), has focused on a far more efficient manufacturing system in which the fabricators are fastened down in a factory framework: a 'nanofactory.'

3. Reproduction, self-replication, and autoproduction

Biological life is noted for its ability to reproduce: to autonomously make near-perfect copies of itself in a wide range of environments. A single bacterium can reproduce and spread rapidly. Invasive non-native species can cause severe disruption to entire ecosystems.

Engineered systems that can duplicate themselves exactly in limited environments have been called self-replicators. The Morris 'worm' computer program is an example of a self-replicator. Copying itself from one computer to another, it shut down the Internet for several days in 1988. One kind of assembler-based system, as described in *Engines of Creation*, would be a self-replicator, able to operate in a vat providing special fuel and raw material molecules, and autonomously producing a duplicate assembler. The book elsewhere raised concerns about self-replicators engineered to gather resources from natural environments, which could—if constructed but not controlled—convert biomass on a large scale into a 'grey goo' of identical self-replicators. Drexler wrote: 'The gray goo threat makes one thing perfectly clear: We cannot afford certain kinds of accidents with replicating assemblers'. Science fiction authors and journalists focused on this scenario, and runaway replicators became closely associated with MNT.

A set of blacksmith's tools can be used by a blacksmith to make a duplicate set. By themselves, the tools are inert, but with a careful input of skill and muscle they can be used to produce duplicates of themselves. Such a system, which can be replicated but only with substantial outside help, can be called 'autoproductive' to distinguish it from a self-replicating or self-reproducing system. A sufficient condition for the safe use of exponential manufacturing is to use only systems that are autoproductive, but are missing functionality that could make them self-replicating.

4. Manufacturing versus free-range self-replication

A manufacturing system must convert simple input materials into functional parts and join those parts into products. A self-replicating system must meet additional constraints (making a product as large and complex as itself), and a free-range self-replicating system—one that can propagate in an unstructured environment—must meet constraints more difficult still. Although the earliest proposals for MNT manufacturing systems included self-replicating components and contemplated the potential for free-range self-replicating systems, recent work has focused on designs that are very different. In light of the continuing confusion in this regard (Smalley 2001), it is worth reviewing why engineering considerations for autoproductive manufacturing systems make devices resembling free-range self-replicators not only undesirable, but also inefficient and unnecessary.

Fictional pictures of MNT commonly assume that pulling molecules apart would be as easy as putting them together—that assemblers could swarm over a pile of grass clippings and convert it directly into a personal spaceship. This is not the case. The chemistry proposed for machine-phase systems requires that every atom of every molecule be in a known position (indeed, so-called 'disassemblers' were proposed not as bulk material processors, but as scientific instruments; Drexler (1986)). A high-entropy mix of polysaccharides, proteins, lipids, and water, such as a biological material, does not meet this constraint, and hence would not be a suitable input. An MNT mechanochemical system would instead require as inputs simple chemical feedstocks, such as acetylene or acetone, in which every molecule is identical and impurities are easy to recognize by their shape and size. To produce its input materials an MNT mechanochemical system will require something like an ordinary chemical plant.

In addition to copying its structure, an autonomous self-replicator must contain and copy the information necessary to direct its own duplication. Small autoproductive systems would be much more efficient without this complexity. A system that is incapable of storing its complete program—one that requires a stream of input instructions in order to build anything—will be simpler to build. Such a system would be inert in the absence of deliberate and continuous control.

In order to be dangerous, an autonomous self-replicator would have to be mobile. A sufficiently small replicator could be blown by the wind, but a larger replicator would require a propulsion system. It would be difficult in practice (more complex, less efficient) to use a microscopic nanofactory, or even a collection of them, for macroscopic manufacturing. The problems of moving and coordinating many small devices while providing each with information, power, and raw materials are daunting, and the protective casing of a small replicator would be a large fraction of its total mass. A macroscopic nanofactory will be only fractionally harder to design and build than a small one (Phoenix 2003), and the fixed relationship among its manufacturing elements makes the flow of information, power, and materials far easier to engineer. Thus, the natural scale for MNT manufacturing systems is macroscopic, and they will be no more mobile than a desktop printer.

5. Safe autoproductive nanotechnology

The above considerations indicate that a molecular manufacturing system, even if autoproductive, would have little resemblance to a machine capable of runaway replication. The earliest MNT fabrication systems will be microscopic, but simplicity and efficiency will favour devices that use specialized feedstocks and are directed by a stream of instructions supplied by an external computer. These systems will not even be self-replicators, because they will lack self-descriptions. As manufacturing systems are scaled up, these same engineering considerations will favour immobile, macroscopic systems of fabricators that again use specialized feedstocks.

An autoproductive manufacturing system would not have to gather or process random chemicals. A device capable of runaway replication would have to contain far more functionality in a very small package. Although the possibility of building such a device does not appear to contradict any physical law, a nanofactory simply would not have the functionality required.

Thus, there appears to be no technological or economic motive for producing a self-contained manufacturing system with mobility, or a built-in self-description, or the chemical processing system that would be required to convert naturally occurring materials into feedstocks suitable for molecular manufacturing systems. In developing and using molecular manufacturing, avoiding runaway replication will not be a matter of avoiding accidents or mutations, but of avoiding the deliberate construction of something dangerous. Suggestions in fiction (Crichton 2002) and the popular science press (Smalley 2001) that autoproductive nanosystems would necessarily be microscopic, uncontrollable things are contradicted by this analysis. And a machine like a desktop printer is, to say the least, unlikely to go wild, replicate, self-organize into intelligent systems, and eat people.

6. Risks of exponential manufacturing

The authors do not mean to imply that advanced mechanochemical manufacturing will create no risks. On the contrary, the technology introduces several problems more severe than runaway replicators. One of the most serious risks comes from non-replicating weapons.

The general rule that a product without a self-replicative capability will be more efficient than a product with such a capability applies also to weapons. A non-replicating weapon could be more rapidly destructive and harder to find, and such a thing might well be created and released deliberately. Unfortunately, there are no simple technical solutions to this problem, which involves questions of military power and political control.

More broadly, general-purpose exponential manufacturing has the potential to profoundly disrupt economies and international relations. A nation making full use of this capability could see its GDP grow by thousands of per cent per year or more, with reduced dependence on foreign trade. Policymakers will have to deal with rapid and radical shifts in the ability to produce wealth and resources.

Increased production capabilities could have large effects on the environment. Although mechanochemical manufacturing is expected to be clean and efficient as a result of controlling every molecule, it could be used to produce vast quantities of products—some of which could be environmentally destructive. On the other hand, wise use of the technology could substantially reduce our ecological footprint. These issues will require careful attention and policy.

7. Conclusion

Early proposals for manufacturing systems based on molecular nanotechnology included devices that had some similarity to runaway self-replicating machines, in that they were, at least, self-replicating. It has since become clear that all risk of accidental runaway replication can be avoided, since efficient manufacturing systems can be designed, built, and used without ever making a device with the complex additional capabilities that a hypothetical 'grey goo robot' would require. However, this does not mean that molecular nanotechnology is without risks. Problems including weapon systems, radical shifts of economic and political power, and aggregate environmental risks from novel products and large-scale production will require close attention and careful policy-making.

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