Of Chemistry, Nanobots, and Policy

The ability to build products by molecular manufacturing would create a radical improvement in the manufacture of technologically advanced products. Everything from computers to weapons to consumer goods, and even desktop factories, would become incredibly cheap and easy to build. If this is possible, the policy implications are enormous.

Richard Smalley, a prominent nanotechnologist, has tried for several years to debunk this possibility. Most recently, he participated in a published exchange with Eric Drexler, another prominent nanotechnologist, who has been the primary proponent and theorist of molecular manufacturing (also called molecular nanotechnology, or MNT).

This paper examines the arguments presented by each side and concludes that Smalley has failed to support his opinion that MNT cannot work as Drexler asserts. Much of Smalley's discussion is off-topic, and his assertions about the limitations of enzyme chemistry are factually incorrect—a fatal weakness in his argument. He therefore does not provide a useful criticism of MNT. Trying to bring the debate back on topic, Drexler spends most of his time restating his earlier positions. Despite these problems, the current exchange represents a significant advance in the debate, since Smalley's new focus on realistic chemistry (instead of the earlier “magic fingers”) permits detailed analysis of the technical merits of his claim.

The answer to the question of MNT’s capabilities will have a large effect on nanotechnology policy, and further research is urgently needed to find this answer. Smalley's factual inaccuracies and continued failure to criticize the actual chemical proposals of MNT strongly suggest that his denial of the possibility may be unfounded. In view of this, while we agree with Smalley that some scenarios of molecular manufacturing are worrisome, we reject his conclusion that the possibility of MNT should be denied in order to avoid scaring children.

This paper reviews the history of the MNT debate, analyzes the technical arguments on both sides, then briefly discusses the feasibility and desirability of further research and the potentially disastrous implications of continuing to ignore the possibility of molecular manufacturing.

History of the Debate

Molecular nanotechnology was first proposed by Richard Feynman in 1959. In a talk entitled “There's Plenty of Room At the Bottom,” Feynman asserted, “But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance.” In the 1980's, Eric Drexler elaborated on this vision and called it “nanotechnology,” projecting its consequences in the popular book Engines of Creation and working out a limited version of programmable chemistry in his MIT Ph.D. thesis.

In 1992, Drexler expanded his MIT thesis into the technical book Nanosystems, which outlined a proposal for building manufacturing systems based on programmable synthesis of nanoscale diamond components. This proposal may be labeled limited molecular nanotechnology (LMNT) to distinguish it from the broader vision of synthesizing “any chemical substance that the chemist writes down.” LMNT theory was developed in increasing detail in subsequent years. Meanwhile, commentators, including the media and science fiction authors, seized on the projected consequences of unlimited MNT—especially the so-called gray goo scenario in which a self-replicating nanobot eats the biosphere. Policy organizations, in particular the Foresight Institute (founded by Drexler), began to call for attention to the capabilities and problems implied by MNT.

In the mid to late 1990's, the U.S. and other governments, inspired by the promise of nanotechnology and the initial scientific research into the nanoscale, began to provide significant funding for such research. Many scientists discovered that they were doing forms of nanotechnology and joined the program. This caused a split between nanoscale technologies that were easy to fund, and molecular nanotechnology, which was not yet a mainstream field of research. The scientists working on nanoscale technologies and the administrators funding them had several incentives to try to discredit molecular nanotechnology, including justifying the current funding decisions and avoiding any association with gray goo and other doomsday scenarios.

In September of 2001, Richard Smalley published an article in Scientific American titled, "Of Chemistry, Love and Nanobots," and subtitled, "How soon will we see the nanometer-scale robots envisaged by K. Eric Drexler and other molecular nanotechologists? The simple answer is never." Smalley asserted that chemistry is not as simple as Drexler claims—that atoms cannot simply be pushed together to make them react as desired, but that their chemical environment must be controlled in great detail. Smalley contrived a system that might do the job, a multitude of "magic fingers" inserted into the working area and manipulating individual atoms. He then asserted that such fingers would be too fat to fit into the required volume, and would also be too sticky to release atoms in the desired location. He concluded that since his contrived method couldn't work, the task was impossible in a mechanical system.

In April of 2003, Drexler wrote an open letter to Smalley, asserting that Smalley's fingers were no more than a straw-man attack since Drexler had never proposed any such thing, accusing Smalley of having "needlessly confused public discussion of genuine long-term security concerns," and calling for him to help set the record straight. In the absence of any response, Drexler followed up with a second open letter in July, noting that in 1999 and 2003, Smalley had stated the possibility of building things "one atom at a time," and asking for closure on the issue.

These letters prompted the debate published in the December 1 issue of Chemical and Engineering News. In the second part of this four-part exchange (the first part being the April letter), Smalley begins by praising Drexler for agreeing that fingers won't work. Smalley agrees that something like an enzyme or ribosome (components of cells) might be able to do precise chemistry—but, according to Smalley, only under water. He then suggests an even stranger alternative—that Drexler's nanofactory might contain complete biological systems—and spends most of the space describing the limitations of underwater chemistry. Finally, he asks, "Or do you really think it is possible to do enzyme-like chemistry of arbitrary complexity with only dry surfaces and a vacuum?"

Drexler replies that, as noted in his book *Nanosystems*, his proposal does assert that chemistry in dry surfaces and a vacuum ("machine-phase chemistry") can be quite flexible and efficient, since holding a molecule in one place can have a strong catalytic effect. He mentions chemical vapor deposition systems as an example of "dry" chemistry, and points out that, "Further, positional control naturally avoids most side reactions by preventing unwanted encounters between potential reactants"—in other words, it doesn't take a lot of subtlety to avoid making the wrong product.

Drexler also spends significant space in his reply talking about other design issues of molecular manufacturing systems, the need for an integrated and targeted research program, and the policy implications of failing to act: “The resulting abilities will be so powerful that, in a competitive world, failure to develop molecular manufacturing would be equivalent to unilateral disarmament. U.S. progress in molecular manufacturing has been impeded by the dangerous illusion that it is infeasible.”

Smalley's final answer is a direct attack on machine-phase chemistry. It is the most detailed technical criticism that Smalley has yet published. He claims that chemical reactions must be controlled through a many-dimensional hyperspace and that this cannot be achieved with simple robotics. Smalley repeats his claim that although enzymes can do precise and reliable chemistry, they can only work in water. (This claim is untrue; see below.) Smalley ends the debate with a two-paragraph appeal to others in the chemical community to join him in protecting children from being scared by stories of monstrous self-replicating nanobots from Drexler's dreams.

Technical Analysis of the Debate

If Smalley's goal is to demonstrate that machine-phase chemistry is fundamentally flawed, he has not been effective; he has not even demonstrated a problem with Drexler's proposals. Since 1992, Drexler has proposed that dry machine-phase chemical synthesis can be used to build intricate nanometer-scale objects. Smalley's strategy, both in the 2001 Scientific American article and in the current debate, has been to equate Drexler's proposals with something unworkable and then explain why the latter can't work. Thus Smalley's comments do not directly address Drexler's proposals, but attempt by example to show fundamental problems with his underlying theory. However, both of Smalley's attempts have failed, and the second failure is noteworthy for what it reveals about the weakness of Smalley's position.

Smalley's 2001 Scientific American article focused on the impossibility of using molecular “fingers” to manipulate each atom involved in the reaction. Drexler has never proposed separate manipulation of each atom; instead, he claims that much simpler control will suffice in a well-designed robotic system where chemicals can be kept apart until they are properly positioned. Besides, as Drexler pointed out in his open letter, enzymes and ribosomes do not need fingers. Thus challenged, Smalley responded by equating Drexler's proposal not just with enzymes, but with the entire apparatus of biological life. Smalley began by agreeing that an enzyme-based system could do precise chemistry, but then attempted to show that enzymes would not provide the capabilities that Drexler needed.

When Smalley substituted enzymes for his “Smalley fingers,” he lost the debate. According to Smalley, enzymes can only work in water, and underwater chemistry cannot build technologically interesting materials such as crystals of steel or silicon. If Drexler plans to avoid water, Smalley asks, “What liquid medium will you use? How are you going to replace the loss of the hydrophobic/hydrophilic, ion solvating, hydrogen-bonding genius of water in orchestrating precise 3 dimensional structures and membranes?” But Smalley is flatly wrong about the ability of enzymes to function without water.

As far back as 1983, an article in *Science* described enzymes working not only in other liquids, but in vapor phase without any solvent at all. One of the authors of that article, Prof. Klibanov, wrote in

1994, "...using an enzyme in organic solvents eliminates several obstacles that limit its usefulness in water. For example, most compounds that interest organic chemists and chemical engineers are insoluble in water, and water often promotes unwanted side reactions. .... Consequently, once it was established that enzymes can work in organic solvents with little or no water, R&D in the area surged." In other words, enzymes often work better without water. Smalley's objection collapses.

In his closing statement, Smalley finally confronts machine-phase chemistry directly rather than by example. He argues that chemistry requires great subtlety of control in order to prevent undesired reactions: "You need to guide the reactants down a particular reaction coordinate, and this coordinate treads through a many-dimensional hyperspace. I agree you will get a reaction when a robot arm pushes the molecules together, but most of the time it won't be the reaction you want." Smalley is asserting that any chemical reaction can proceed in a wide variety of ways, depending on each motion of each nearby atom, and that without the ability to control each atom separately the result of the reaction cannot be controlled. This may be true for underwater chemistry, especially protein folding. But in vacuum chemistry without water on stiff surfaces, it is possible to exclude all or nearly all undesired reactions by controlling the collective positions of the reactants so that the molecules can only touch at the location of the desired reaction. Atoms will not magically jump out of position to spoil the reaction. As Smalley himself stated (in Scientific American), atoms "move in a defined and circumscribed way."

In his final statement, Smalley asserts, "I have never seen a convincing argument that [Drexler's] list of conditions and synthetic targets that will actually work reliably with mechanosynthesis can be anything but a very, very short list." But the evidence shows that Smalley has not carefully studied Drexler's work. The dry enzyme result was cited in a 1994 paper of Drexler's. In addition, Smalley's apparent uncertainty (in his first statement) about whether Drexler was proposing wet or dry chemistry, and his repeated distortion of Drexler's proposals, appear to demonstrate a substantial lack of familiarity with Drexler's work. Smalley's failure to see a convincing argument can be attributed to this lack of attention, and does not indicate any identifiable problem with Drexler's proposals.

In the absence of a cogent objection to respond to, Drexler could only restate his earlier work. His description appears to be consistent with the description in *Nanosystems*, which has not been scientifically criticized in the decade since its publication. The validity of his position can be inferred from repeated failures to debunk it. At this point, scientific investigation rather than debate will be needed to test Drexler's theories; there appears to be no simple argument that can disprove his conclusions.

Discussion

The question of whether machine-phase chemistry can be used to construct machines is vitally important. As both Smalley and Drexler recognize, such a capability would enable radically powerful and compact manufacturing systems with potentially extreme consequences. We might expect that both participants in this debate would have put their strongest arguments forward.

Smalley's task was to demonstrate that Drexler's proposals for machine-phase chemistry cannot lead to a workable nanoscale manufacturing system. Smalley began by inventing molecular "fingers" and describing why they don't work. Then, he invented a nanofactory based on wet chemistry, and described why it cannot produce many useful products. Not until the end did he address Drexler's actual proposals, and his argument at that point depended heavily on a clearly incorrect understanding of enzymes. In addition to being largely off-topic, and apparently contradicting his own statements of 1999 and 2003 that were referenced in Drexler's open letter, Smalley's argument is sprinkled with factual errors about chemistry, as noted above.

Smalley's final technical criticism of machine-phase chemistry is not convincing. It appears to be based on the idea that machine-phase chemistry taking place in vacuum with positional control will have as many unwanted reaction pathways as wet chemistry, but will have less ability to avoid them. However, most of the unwanted reaction pathways in wet chemistry are a result of the presence of water itself, or result from the lack of positional control experienced by floppy floating biomolecules. It appears that the lack of degrees of freedom in machine-phase chemistry may eliminate undesired reactions even as it simplifies the possible pathways of the reactants. In theoretical terms, then, machine-phase chemistry may be at least as flexible and reliable as wet chemistry; Smalley's arguments do not seriously challenge this possibility. In addition, the reduction in degrees of freedom may make it quite a bit easier to design desired machine-phase reactions than protein-based reactions, since protein is notoriously complex.

Drexler's task in this debate was to defend his assertions about the feasibility of molecular manufacturing, in particular his 1992 book Nanosystems, against Smalley's attack. Unfortunately, Smalley's repeated straying from the topic did not provide Drexler the chance to respond to meaningful criticism. However, Drexler's statements are consistent with his own earlier assertions, do not contradict any known physical law, and address several practical engineering details of machine-phase chemistry and how to use it in a manufacturing system. Drexler ends his statements by calling for further research, beginning with an independent scientific review of molecular manufacturing concepts. This call clearly is justified by the evidence to date.

Smalley's last word is an appeal to other scientists to close ranks and oppose further discussion of molecular manufacturing, in order to prevent “our children” from being scared by the possible consequences. This is, to put it mildly, unwarranted and premature. Despite access to two forums and three chances to express convincing arguments against Drexler's theories, Smalley has been unable to do so. This does not prove Drexler right; however, it raises the distinct possibility that Smalley is wrong. For Smalley to urge that debate be terminated at this point is unscientific and irresponsible.

Policy implications

Current nanotechnology policy in the U.S. and several other countries is based on the belief that molecular manufacturing as described by Drexler is impossible. Smalley, with his reputation as a Nobel Prize winning chemist and nanotechnologist, has been a major exponent of that belief. But he has demonstrated that he is unable to make a cogent case against Drexler's theories. It is time for independent scientific investigation of mechanical chemistry, not merely continued authoritative but unsupported scientific statements of impossibility.

If molecular manufacturing will work as Drexler describes, preparation for its consequences must begin well in advance. Vehement opposition from credentialed nanotechnologists has prevented any significant efforts to prepare for the possible development of this technology, or even to assess whether and when it might be developed. As nanoscale sensing, manipulation, and chemistry are developed further, the situation may become rapidly more dangerous. Recent technical work by CRN has raised the possibility that the final stages of development may be extremely rapid. Given the poor quality of MNT criticism thus far, it would be foolish to bet our future on the hope that no new policy will be necessary, without a much more detailed examination of the theory behind MNT.

Failure to anticipate the development of molecular manufacturing could have serious consequences. Simple physics theories, conservatively applied, predict that the technology will be dangerously powerful. A working molecular nanotechnology will likely require the design and enforcement of policies to control the use of compact advanced manufacturing systems and their products. But panicked last-minute policy will be bad policy—simultaneously oppressive and ineffective. The military implications are even more perilous. Molecular manufacturing systems are expected to be able to produce weapons as powerful as nuclear bombs, but much more selective, easier to manufacture, and easier to use. If a powerful nation suddenly realizes that molecular manufacturing is possible, and discovers that rival nations are already making material progress, they may react violently, or may enter into an arms race that will probably be unstable and thus may result in war with weapons of unprecedented power.

On the positive side, molecular manufacturing may be able to mitigate many of the world's humanitarian and environmental crises. Advancing its development by even a year or two could alleviate untold suffering, raising standards of living worldwide while sharply reducing our environmental footprint. However, rapid and effective humanitarian use may also depend on sound policy developed well in advance.

During the past decade, increasingly detailed proposals have been developed for the architecture and technology of molecular manufacturing systems. Such proposals cannot be developed fully in the absence of laboratory work and targeted research, but we now know enough to initiate action based on existing work. Machine-phase chemistry—the proposal that Smalley has failed to criticize—can and should be investigated in detailed chemical simulations. The theories about nanoscale physics in Nanosystems should also be investigated; such studies may be expected to produce results relevant to other nanoscale technologies. We can, and should, begin to quantify the expected capabilities of LMNT-type systems: What substances and devices can they build? How rapidly can they work? How easy will it be to design products for LMNT-type manufacturing systems? How much will it cost to create the first system, and how quickly will that cost decrease over time?

If no flaw can be found in the proposals of limited molecular nanotechnology, it must be assumed that LMNT may work as described. In the past decade, no flaw has been found. The proposals are sufficiently detailed to support a much more thoughtful critical study than has yet been done, and such a study would result in further refinement of the proposals. The responsible course of action is not to hide from imaginary monsters, but to direct increasing energy toward examining both the theory and its implications.

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