# Molecular nanotechnology

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(Redirected from Molecular manufacturing)

Part of the article series on
**Molecular Nanotechnology**

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Grey goo
K. Eric Drexler
*Engines of Creation*
*See also:* Nanotechnology

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**Molecular nanotechnology**
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**Molecular nanotechnology (MNT)** is the concept of engineering functional mechanical systems at the molecular scale.[1] An equivalent definition would be "machines at the molecular scale designed and built atom-by-atom". This is distinct from nanoscale materials. Based on Richard Feynman's vision of miniature factories using nanomachines to build complex products (including additional nanomachines), this advanced form of nanotechnology (or *molecular manufacturing*[2]) would make use of positionally-controlled mechanosynthesis guided by molecular machine systems. MNT would involve combining physical principles demonstrated by chemistry, other nanotechnologies, and the molecular machinery of life with the systems engineering principles found in modern macroscale factories. Its most well-known exposition is in the books of K. Eric Drexler particularly Engines of Creation. Detailed theoretical investigation, sections 4.3 and 4.4 below, have investigated the feasibility of molecular nanotechnology, but the topic remains controversial.

## Contents

# Introduction

While conventional chemistry uses inexact processes driven toward some balance to obtain inexact results, and biology exploits inexact processes to obtain definitive results, molecular nanotechnology would employ original definitive processes to obtain definitive results. The desire in molecular nanotechnology would be to balance molecular reactions in positionally-controlled locations and orientations to obtain desired chemical reactions, and then to build systems by further assembling the products of these reactions.

Formulating a roadmap for the development of MNT is now an objective of a broadly based technology roadmap project led by Battelle (the manager of several U.S. National Laboratories) and the Foresight Institute.[3] The roadmap was originally scheduled for completion by late 2006, then by early 2007, and most recently is set to be unveiled in October 2007.[4] The Nanofactory Collaboration[5]
is a more focused ongoing effort involving 23 researchers from 10 organizations and 4 countries that is developing a practical research agenda[6]
specifically aimed at positionally-controlled diamond mechanosynthesis and diamondoid nanofactory development. In August 2005, a task force consisting of 50+ international experts from various fields was organized by the Center for Responsible Nanotechnology to study the societal implications of molecular nanotechnology.[7] Ray Kurzweil predicts that full MNT will exist in 2025.

# Projected applications and capabilities

## Smart materials and nanosensors

One proposed application of MNT is the development of so-called smart materials. This term refers to any sort of material designed and engineered at the nanometer
scale to perform a specific task, and encompasses a wide variety of possible commercial applications. One example would be materials designed to respond differently to various molecules; such a capability could lead, for example, to artificial drugs which would recognize and render inert specific viruses. Another is the idea of self-healing structures, which would repair small tears in a surface naturally in the same way as self-sealing tires or human skin.

A nanosensor created by MNT would resemble a smart material, involving a small component within a larger machine that would react to its environment and change in some fundamental, intentional way. As a very simple example: a photosensor could passively measure the incident light and discharge its absorbed energy as electricity when the light passes above or below a specified threshold, sending a signal to a larger machine. Such a sensor would supposedly cost less and use less power than a conventional sensor, and yet function usefully in all the same applications — for example, turning on parking lot lights when it gets dark.

While smart materials and nanosensors both exemplify useful applications of MNT, they pale in comparison with the complexity of the technology most popularly associated with the term: the replicating nanorobot.

## Replicating nanorobots

MNT nanofacturing is popularly linked with the idea of swarms of coordinated nanoscale robots working together, a popularization of an early proposal by Drexler in his 1986 discussions of MNT, but superseded in 1992 (http://www.e-drexler.com/d/06/00/Nanosystems/toc.html)
. In this early proposal, sufficiently capable nanorobots would construct more nanorobots in an artificial environment containing special molecular building blocks.

Critics have doubted both the feasibility of self-replicating nanorobots and the feasibility of control if self-replicating

nanorobots could be achieved: they cite the possibility of mutations removing any control and favoring reproduction of mutant pathogenic variations. Advocates address the first doubt by pointing out that the first macroscale autonomous machine replicator, made of Lego blocks, was built and operated experimentally in 2002.[8] While there are sensory advantages present at the macroscale compared to the limited sensorium available at the nanoscale, proposals for positionally controlled nanoscale mechanosynthetic fabrication systems employ dead reckoning of tooltips combined with reliable reaction sequence design to ensure reliable results, hence a limited sensorium is no handicap; similar considerations apply to the positional assembly of small nanoparts. Advocates address the second doubt by arguing that bacteria are (of necessity) evolved to evolve, while nanorobot mutation could be actively prevented by common error-correcting techniques. Similar ideas are advocated in the Foresight Guidelines on Molecular Nanotechnology,[9] and a map of the 137-dimensional replicator design space[10]
recently published by Freitas and Merkle provides numerous proposed methods by which replicators could, in principle, be safely controlled by good design.

However, the concept of suppressing mutation raises the question: How can design evolution occur at the nanoscale without a process of random mutation and deterministic selection? Critics argue that MNT advocates have not provided a substitute for such a process of evolution in this nanoscale arena where conventional sensory-based selection processes are lacking. The limits of the sensorium available at the nanoscale could make it difficult or impossible to winnow successes from failures. Advocates argue that design evolution should occur deterministically and strictly under human control, using the conventional engineering paradigm of modeling, design, prototyping, testing, analysis, and redesign. The limited sensorium is no handicap because, for example, prototype nanoparts could be fabricated via dead reckoning using positionally controlled chemically active tooltips, then characterized by chemically inactive scanning probe tooltips or other technical means, with errors corrected or design changes implemented in the next prototyping iteration.

In any event, since 1992 technical proposals for MNT (http://www.e-drexler.com/d/06/00/Nanosystems/toc.html) do not include self-replicating nanorobots, and recent ethical guidelines put forth by MNT advocates prohibit unconstrained self-replication. [11] [12]

## Medical nanorobots

One of the most important applications of MNT would be medical nanorobotics or nanomedicine, an area pioneered by Robert Freitas in numerous books[13] and papers.[14]
The ability to design, build, and deploy large numbers of medical nanorobots would, at an optimum, make possible the rapid elimination of disease and the reliable and relatively painless recovery from physical trauma. Medical nanorobots might also make possible the convenient correction of genetic defects, and help to ensure a greatly expanded healthspan. More controversially, medical nanorobots might be used to augment natural human capabilities. However, mechanical medical nanodevices would not be allowed (or designed) to self-replicate inside the human body, nor would medical nanorobots have any need for self-replication themselves[15]
since they would be manufactured exclusively in carefully regulated nanofactories.

## Utility fog

Another proposed application of molecular nanotechnology is "utility fog"[16] — in which a cloud of networked microscopic robots (simpler than assemblers) would change its shape

Diagram of a 100 micrometer foglet

and properties to form macroscopic objects and tools in accordance with software commands. Rather than modify the current practices of consuming material goods in different forms, utility fog would simply replace many physical objects.

### Phased-array optics

Yet another proposed application of MNT would be phased-array optics (PAO).[17] However, this appears to be a problem addressable by ordinary nanoscale technology. PAO would used the principle of phased-array millimeter technology but at optical wavelengths. This would permit the duplication of any sort of optical effect but virtually. Users could request holograms, sunrises and sunsets, or floating lasers as the mood strikes. PAO systems were described in BC Crandall's *Nanotechnology: Molecular Speculations on Global Abundance* in the Brian Wowk article "Phased-Array Optics."[18]

# Potential social impacts

Despite the current early developmental status of nanotechnology and molecular nanotechnology, much concern surrounds MNT's anticipated impact on economics[19] and on law. Some conjecture that MNT would elicit a strong public-opinion backlash, as has occurred recently around genetically modified plants and the prospect of human cloning. Whatever the exact effects, MNT, if achieved, would tend to upset existing economic structures by reducing the scarcity of manufactured goods and making many more goods (such as food and health aids) manufacturable.

It is generally considered that future citizens of a molecular-nanotechnological society would still need money, in the form of unforgeable digital cash or physical specie[20]
(in special circumstances). They might use such money to buy goods and services that are unique, or limited within the solar system. These might include: matter, energy, information, real estate, design services, entertainment services, legal services, fame, political power, or the attention of other people to your political/religious/philosophical message. Furthermore, futurists must consider war, even between prosperous states, and non-economic goals.

If MNT were realized, some resources would remain limited, because unique physical objects are limited (a plot of land in the real Jerusalem, mining rights to the larger near-earth asteroids) or because they depend on the goodwill of a particular person (the love of a famous person, a painting from a famous artist). Demand will always exceed supply for some things, and a political economy
may continue to exist in any case. Whether the interest in these limited resources would diminish with the advent of virtual reality, where they could be easily substituted, is yet unclear; one reason why it might not is a hypothetical preference for "the real thing".

Molecular nanotechnology also raises the feasibility of repairing cells that have been vitrified through cryonic preservation as well as abolishing the diseases which are not curable by today's means when an individual is reborn from cryonic stasis - creating conditions whereby individuals could be held accountable for their actions after death.

#### Risks

Molecular nanotechnology is one of the technologies that some analysts believe could lead to a Technological Singularity. Some feel that molecular nanotechnology would have daunting risks.[21] It conceivably could enable cheaper and more destructive conventional weapons. Also, molecular nanotechnology might permit weapons of mass destruction that could self-replicate, as viruses and cancer
cells do when attacking the human body. Commentators generally agree that, in the event molecular nanotechnology were developed, mankind should permit self-replication only under very controlled or "inherently safe" conditions.

A fear exists that nanomechanical robots, if achieved, and if designed to self-replicate using naturally occurring materials (a difficult task), could consume the entire planet in their hunger for raw materials,[22] or simply crowd out natural life, out-competing it for energy (as happened historically when blue-green algae appeared and outcompeted earlier life forms). Some commentators have referred to this situation as the "grey goo" or "ecophagy" scenario. K. Eric Drexler considers an accidental "grey goo" scenario extremely unlikely and says so in later editions of *Engines of Creation*. The "grey goo" scenario begs the Tree Sap Answer: what chances exist that one's car could spontaneously mutate into a wild car, run off-road and live in the forest off tree sap?

In light of this perception of potential danger, the Foresight Institute (founded by K. Eric Drexler to prepare for the arrival of

future technologies) has drafted a set of guidelines[23]
for the ethical development of nanotechnology. These include the banning of free-foraging self-replicating pseudo-organisms on the Earth's surface, at least, and possibly in other places.

# Technical issues and criticism

## Universal assemblers versus diamondoid nanofactories

A section heading in Drexler's *Engines of Creation* reads[24] "Universal Assemblers", and the following text speaks of molecular assemblers
which could hypothetically "build almost anything that the laws of nature allow to exist." Drexler's colleague Ralph Merkle has noted that, contrary to widespread legend,[25]
Drexler never claimed that assembler systems could build absolutely any molecular structure. The endnotes in Drexler's book explain the qualification "almost": "For example, a delicate structure might be designed that, like a stone arch, would self-destruct unless all its pieces were already in place. If there were no room in the design for the placement and removal of a scaffolding, then the structure might be impossible to build. Few structures of practical interest seem likely to exhibit such a problem, however."

In 1992, Drexler published *Nanosystems: Molecular Machinery, Manufacturing, and Computation*,[26] a detailed proposal for synthesizing stiff, diamond-based structures using a table-top factory. Although such a nanofactory would be far less powerful than a protean universal assembler, it would still be enormously capable. Diamondoid structures and other stiff covalent structures, if achieved, would have a wide range of possible applications, going far beyond current MEMS technology. No specific proposal was put forward in 1992 for building a table-top factory in the absence of a near-universal assembler, but other researchers have begun advancing tentative proposals [27] for this in the years since Nanosystems was published.

## The Smalley-Drexler debate

Several researchers, including Nobel Prize winner Dr. Richard Smalley (1943-2005),[28] attacked the notion of universal assemblers, leading to a rebuttal from Drexler and colleagues,[29] and eventually to an exchange of letters.[30] Smalley argued that chemistry is extremely complicated, reactions are hard to control, and that a universal assembler is science fiction. Drexler and colleagues, however, noted that Drexler never proposed universal assemblers able to make absolutely anything, but instead proposed more limited assemblers able to make a very wide variety of things. They challenged the relevance of Smalley's arguments to the more specific proposals advanced in *Nanosystems*.

## The feasibility of the proposals in *Nanosystems*

The feasibility of Drexler's proposals largely depends, therefore, on whether designs like those in *Nanosystems* could be built in the absence of a universal assembler to build them and would work as described. Supporters of molecular nanotechnology frequently claim that no significant errors have been discovered in *Nanosystems* since 1992. Even some critics concede[31] that "Drexler has carefully considered a number of physical principles underlying the 'high level' aspects of the nanosystems he proposes and, indeed, has thought in some detail" about some issues.

Other critics claim, however, that *Nanosystems*
omits important chemical details about the low-level 'machine language' of molecular nanotechnology.[32][33][34][35] They also claim that much of the other low-level chemistry in *Nanosystems* requires extensive further work, and that Drexler's higher-level designs therefore rest on speculative foundations. Recent such further work by Freitas and Merkle [36] is aimed at strengthening these foundations by filling the existing gaps in the low-level chemistry.

Drexler argues[37] that we may need to wait until our conventional nanotechnology improves before solving these issues: "Molecular manufacturing
will result from a series of advances in molecular machine systems, much as the first Moon landing resulted from a series of

advances in liquid-fuel rocket systems. We are now in a position like that of the British Interplanetary Society of the 1930s which described how multistage liquid-fueled rockets could reach the Moon and pointed to early rockets as illustrations of the basic principle." However, Freitas and Merkle argue [38]
that a focused effort to achieve diamond mechanosynthesis (DMS) can begin now, using existing technology, and might achieve success in less than a decade if their "direct-to-DMS approach is pursued rather than a more circuitous development approach that seeks to implement less efficacious nondiamondoid molecular manufacturing technologies before progressing to diamondoid".

To summarize the arguments against feasibility: First, critics complain that a primary barrier to achieving molecular nanotechnology is the lack of an efficient way to create machines on a molecular/atomic scale, especially in the absence of a well-defined path toward a self-replicating assembler or diamondoid nanofactory. Advocates respond that a preliminary research path leading to a diamondoid nanofactory is being developed. [39]

A second difficulty in reaching molecular nanotechnology is design. Hand design of a gear or bearing at the level of atoms is a grueling task. While Drexler, Merkle and others have created a few designs of simple parts, no comprehensive design effort for anything approaching the complexity of a Model T Ford has been attempted. Advocates respond that it is difficult to undertake a comprehensive design effort in the absence of significant funding for such efforts, and that despite this handicap much useful design-ahead has nevertheless been accomplished with new software tools that have been developed, e.g., at Nanorex. [40]

A third difficulty in achieving molecular technology is separating successful trials from failures, and elucidating the failure mechanisms of the failures. Unlike biological evolution, which proceeds by random variations in ensembles of organisms combined with deterministic reproduction/extinction as a selection process to achieve great complexity after billions of years (a set of mechanisms which Richard Dawkins
has referred to as a "blind watchmaker"), deliberate design and building of nanoscale mechanisms requires a means other than reproduction/extinction to winnow successes from failures in proceeding from simplicity to complexity. Such means are difficult to provide (and presently non-existent) for anything other than small assemblages of atoms viewable by an AFM or STM. Advocates agree this is a valid constraint using current technology, but they insist that this is not a fundamental constraint imposed by the laws of physics. They assert that, once mechanosynthetic tooltips and similar future positionally-controlled molecular tools are fabricated, the same technology could permit prototyping, testing, and rework of failed designs. However, both critics and advocates agree that this expectation remains to be proven and further research will be required to resolve the issue.

In the latest report *A Matter of Size: Triennial Review of the National Nanotechnology Initiative*[41] put out by the National Academies Press in December 2006 (roughly twenty years after Engines of Creation was published), no clear way forward toward molecular nanotechnology could yet be seen, as per the conclusion on page 108 of that report: "Although theoretical calculations can be made today, the eventually attainable range of chemical reaction cycles, error rates, speed of operation, and thermodynamic efficiencies of such bottom-up manufacturing systems cannot be reliably predicted at this time. Thus, the eventually attainable perfection and complexity of manufactured products, while they can be calculated in theory, cannot be predicted with confidence. Finally, the optimum research paths that might lead to systems which greatly exceed the thermodynamic efficiencies and other capabilities of biological systems cannot be reliably predicted at this time. Research funding that is based on the ability of investigators to produce experimental demonstrations that link to abstract models and guide long-term vision is most appropriate to achieve this goal." This call for research leading to demonstrations is welcomed by groups such as the Nanofactory Collaboration who are specifically seeking experimental successes in diamond mechanosynthesis. [42] Perhaps the eventual "Technology Roadmap for Productive Nanosystems"[43] will offer additional constructive insights.

It is perhaps interesting to ask whether or not most structures consistent with physical law can in fact be manufactured. Such a question is a great deal more difficult to answer than, for example, the four-color map theorem which was proposed in 1852 and proven in 1976, and it is conceptually impossible to prove the negative of this question since no proof by counter-example can be provided. Advocates assert that to achieve most of the vision of molecular manufacturing it is not necessary to be able to build "any structure that is compatible with natural law." Rather, it is necessary to be able to build only a sufficient (possibly modest) subset of such structures -- as is true, in fact, of any practical manufacturing process used in the world today, and is true even in biology. In any event, as Richard Feynman once said, "It is scientific only to say what's more likely or less likely, and not to be proving all the time what's possible or impossible."[44]

### Existing work on diamond mechanosynthesis

There is a growing body of peer-reviewed theoretical work on synthesizing diamond by mechanically removing/adding hydrogen atoms [45] and depositing carbon atoms [46] [47] [48] [49] [50] [51] (a process known as mechanosynthesis). This work is slowly permeating the broader nanoscience community and is being critiqued. For instance, Peng et al. (2006)[52] (in the continuing research effort by Freitas, Merkle and their collaborators) reports that the most-studied mechanosynthesis tooltip motif (DCB6Ge) successfully places a $C_2$ carbon dimer on a C(110) diamond surface at both 300K (room temperature) and 80K (liquid nitrogen
temperature), and that the silicon variant (DCB6Si) also works at 80K but not at 300K. Over 100,000 CPU hours were invested in this latest study. The DCB6 tooltip motif, initially described by Merkle and Freitas at a Foresight Conference in 2002, was the first complete tooltip ever proposed for diamond mechanosynthesis and remains the only tooltip motif that has been successfully simulated for its intended function on a full 200-atom diamond surface.

The tooltips modeled in this work are intended to be used only in carefully controlled environments (e.g., vacuum). Maximum acceptable limits for tooltip translational and rotational misplacement errors are reported in Peng et al. (2006) -- tooltips must be positioned with great accuracy to avoid bonding the dimer incorrectly. A skeptical observer might initially look at the positional uncertainty of carbon atom placement in Figure 9 of that work and conclude that it is achieved only via a simple cheat as per the text of the article: “Simulations were performed by tethering all 50 carbon atoms in the topmost plane of the tool handle to their energy-minimized positions using a large force restraint equal to the MM2 force field C–C bond stiffness of 440 N/m, or 633 kcal/mol-Å, with different initial atomic positions and randomized initial velocities for each independent simulation....” Such a critic might complain that this unrealistically ignores the need for some type of larger frame to position the tool handle with respect to the workpiece, the larger frame of necessity having its own non-infinite stiffness and finite vibrational modes leading to additional positional uncertainty. However, Peng et al. (2006) reports that increasing the handle thickness from 4 support planes of C atoms above the tooltip to 5 planes decreases the resonance frequency of the entire structure from 2.0 THz to 1.8 THz. More importantly, the vibrational footprints of a DCB6Ge tooltip mounted on a 384-atom handle and of the same tooltip mounted on a similarly constrained but much larger 636-atom "crossbar" handle are virtually identical in the non-crossbar directions. Additional computational studies modeling still bigger handle structures are welcome, but the ability to precisely position SPM tips to the requisite atomic accuracy has been repeatedly demonstrated experimentally at low temperature, [53] [54] constituting a basic existence proof for this capability.

Further research[55] to consider additional tooltips will require time-consuming computational chemistry and difficult laboratory work.

A working nanofactory
would require a variety of well-designed tips for different reactions, and detailed analyses of placing atoms on more complicated surfaces. Although this appears a challenging problem given current resources, many tools will be available to help future researchers: Moore's Law predicts further increases in computer power, semiconductor fabrication techniques continue to approach the nanoscale, and researchers grow ever more skilled at using proteins, ribosomes and DNA to perform novel chemistry.

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# Reference works

- Drexler and others extended the ideas of molecular nanotechnology with two more books, *Unbounding the Future: the Nanotechnology Revolution* [2] (http://www.foresight.org/UTF/Unbound_LBW/) and *Nanosystems: Molecular Machinery, Manufacturing, and Computation* [3] (http://www.e-drexler.com/d/06/00/Nanosystems/toc.html) . *Unbounding the Future*, an easy-to-read book, introduces the ideas of molecular nanotechnology in a not-too-technical way; and *Nanosystems* provides an in-depth, physics-based analysis of hypothetical nanomachines and molecular manufacturing, with extensive analyses arguing in favor of their feasibility and performance. Other notable works in the same vein are *Nanomedicine* Vol. I (http://www.nanomedicine.com/NMI.htm) and Vol. IIA (http://www.nanomedicine.com/NMIIA.htm) by Robert Freitas and *Kinematic Self-Replicating Machines* [4] (http://www.MolecularAssembler.com/KSRM.htm) by Robert Freitas and Ralph Merkle.
- *Nanotechnology: Molecular Speculations on Global Abundance* Edited by BC Crandall (ISBN 0-262-53137-2) offers interesting ideas for MNT applications.

# Works of Fiction

- In The Diamond Age by Neal Stephenson diamond can be constructed by simply building it out of carbon atoms. Also all sorts of devices from dust size detection devices to giant diamond zeppelins are constructed atom by atom using only carbon, oxygen, nitrogen and chlorine atoms.

# External links

- Foresight Institute (http://www.foresight.org)
- Main Page - Wise-Nano (http://wise-nano.org/w/Main_Page) A wiki for MNT
- Dr. Freitas's bibliography on mechanosynthesis (http://foresight.org/stage2/mechsynthbib.html) updated here (http://www.MolecularAssembler.com/Nanofactory/AnnBibDMS.htm) (also includes related techniques based on scanning probe microscopy)
- The Molecular Assembler website of Robert A. Freitas Jr. (http://www.MoleculArassembler.com/)
- Nanotechnology Now (http://www.nanotech-now.com/) Nanotechnology basics, news, and general information
- Eric Drexler's personal website and digital archive (http://www.e-drexler.com/)
- National Nanotechnology Initiative (http://www.nano.gov)
- Institute for Molecular Manufacturing (http://www.imm.org/)
- Accelerating Future's MNT articles (http://www.acceleratingfuture.com/michael/blog/?cat=6)



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