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A Technical Commentary on Greenpeace's Nanotechnology Report

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I. Introduction

The purpose of this document is to augment a portion of the recent Greenpeace report on nanotechnology and artificial intelligence ("Future Technologies, Today's Choices") and to comment on a few specific statements in it. That report's treatment of molecular nanotechnology (MNT) was necessarily brief and did not cover several key areas. The present document supplements Greenpeace's work, explores further some of the misconceptions of MNT, and describes one area within MNT, limited molecular nanotechnology (LMNT), which is currently being pursued by most MNT researchers. LMNT can produce most of the desired medical devices, advanced materials, and product innovation goals sought after today and will be significantly easier to achieve. The Center for Responsible Nanotechnology (CRN) believes that recent advances in LMNT research should underscore to policy makers the urgent need for discussion of possible consequences, both positive and negative.

The Greenpeace report covered two very large topics, nanotechnology and artificial intelligence, so could devote only a few pages to MNT. Some important MNT research is currently in press, and much published work has not yet been synthesized into an accessible understanding of the recent developments in the field. Some commentators outside the field continue to assert obsolete arguments against MNT; this, as well as hype and misconceptions, further obscure the picture and make it unfortunately easy to ignore even decade-old work. CRN's focus on MNT provides a more accurate and detailed picture of the field's current state.

This document builds its case in several sections. Following this introduction, section II establishes a context for discussing MNT, including a description of LMNT. Section III covers the requirements for developing LMNT, concluding that the barriers to rapid development are mainly those of policy, not technology. There is no known scientific objection to LMNT, and the technical problems are rapidly being broken down into manageable sub-problems. Section IV discusses the probable capabilities and advantages of LMNT. The purpose of this is to demonstrate that LMNT, though much easier than full

MNT, may have nearly equivalent power, desirability, and impact. This implies that a targeted rapid development program may be launched for any of a variety of reasons in the near future.

Section V comments on specific MNT-related claims of the Greenpeace report in light of the earlier sections. In general, CRN agrees with them that MNT is possible, but does not agree that it poses only long-term risks. Although the power and relative simplicity of LMNT are not widely understood, the analysis is not difficult, and the knowledge has been available worldwide for years. A targeted LMNT development program may already be justifiable from an economic and/or military point of view. Such a program could lead to a sudden shift in sociopolitical conditions, leaving insufficient time to formulate policy.

Finally, section VI summarizes CRN's understanding of MNT and LMNT, and repeats the call for policy attention to LMNT.

II. MNT Background

Although the word 'nanotechnology' has come to be applied to a wide range of research and development activities, molecular nanotechnology (MNT) deserves special consideration for several reasons. Most nanoscale technologies seek to produce components that will be incorporated in larger products. By contrast, MNT is proposed as a flexible manufacturing technology, capable of building complete products. This would make it broadly applicable to a variety of industries and applications.

The key point of MNT is mechanochemistry: the ability to make chemical reactions happen under programmed control. In theory, this allows a few reactions, applied in many positions, to build a large range of shapes. With careful control, and assuming a suitable chemical toolbox can be developed, a mechanochemical manipulator should be able to build shapes physically as complex as itself. Molecular manufacturing should provide a variety of advantages, including less complex fabrication, extremely predictable results, and strong, efficient products, that would more than outweigh the difficulties of working in this unfamiliar realm.

As noted in the Greenpeace report, MNT has been associated with unusual amounts of hype. Early discussions asserted the ability to do almost anything that was theoretically possible with chemistry. The unfortunate phrase 'universal assembler' was coined, and rapidly attacked as being unworkable or at least too difficult. Descriptions of MNT-built products usually did not specify what sort of chemical assembly was to be used in making them, which lent an air of unreality to the whole topic. Public debate has largely stuck there, obscuring the fact that much research has been done since that time.

A body of work in the last decade has described a limited molecular nanotechnology (LMNT) that is far better specified than the popular picture of semi-magical nanobots. Starting with K. Eric Drexler's publication of *Nanosystems* in 1992, LMNT has developed a comprehensive overview of the requirements and functions of a limited molecular manufacturing capability based on the carbon lattice configurations—diamond, graphite, and fullerenes—known collectively as 'diamondoid'.

LMNT would implement only a tiny fraction of possible chemistry. Its chemical requirement is simply to build shapes, components, and sub-micron machines out of large, carefully fabricated, three-dimensional carbon molecules, with a few other atoms thrown in as necessary to extend the range of surfaces and shapes. However, it should be emphasized that this narrowing of technological focus still allows for a wide range of powerful products, and many of the claims made for the disruptive effects of MNT are still valid for LMNT.

One major change between traditional MNT and LMNT is the reduced emphasis on nanobots. Early descriptions of MNT envisioned manufacturing accomplished by the concerted action of legions of nanobot 'assemblers', floating around a growing product in a tank. Alternatively, the assemblers could make nanobot products that would do everything from cleaning your arteries to cleaning your house. LMNT does not require nanobots at all. Instead of free-floating assemblers, the mechanochemical fabricators would all be fastened down in a single nanofactory, with their sub-products conveyed along fixed paths to be joined into bigger components and finally large products. Some products of LMNT may be small robots, but product robots require no onboard manufacturing capability, and the appropriateness of using microscopic robots can be decided for each application individually.

A useful nanofactory would be able to build products familiar to today's engineers and users, without requiring the product designers to be experts in chemistry. This appears possible through the re-use of a few basic nanoscale components to build micro-scale systems. CRN has a peer-reviewed paper in press discussing nanofactory architecture, bootstrapping, and product design. Most product design would be carried out on the micro level, using 'libraries' of pre-designed 'nanoblocks'; computer software is already designed this way.

III. Development of Molecular Nanotechnology

If molecular nanotechnology is to be developed, even in limited form, several hurdles must be overcome. This section describes the physics, research, engineering, schedule, economic, and policy problems that LMNT may encounter.

As far as is known, the laws of physics do not in any way prevent LMNT from working as described in this document. Atoms are moved by thermal noise and quantum effects, but these effects are small at room temperature—if this were not the case, our bodies could not function. Like any other working system, LMNT manufacturing systems and products will produce heat, and require an energy source. However, these are engineering details, not fundamental hurdles. Likewise, the need to design and control vast numbers of sub-components is an engineering problem; as discussed later, it does not appear to be intractably difficult for certain classes of useful systems.

The chemical techniques required, though not yet fully investigated, do not appear to be a showstopper. Greenpeace correctly notes that Richard Smalley's "fat fingers" and "sticky fingers" theories are the most carefully thought out objections to MNT. However, it should be further noted that, in fact, not much thought went into these objections: published proposals for mechanochemistry do not involve "fingers" at all. The recent achievement of mechanochemistry on a silicon lattice demonstrates that if Smalley's objections are relevant at all, their scope must be limited—they certainly do not constitute a blanket disproof of the feasibility of MNT, much less LMNT.

The next question is how MNT could be achieved in practice. For LMNT, one possible course has three milestones. First, a set of mechanochemical reactions must be researched and developed, capable of making several forms of diamondoid from simple 'feedstock' chemicals. Second, a small fabricator must be designed and built, capable of carrying out the necessary manipulations to perform the mechanochemistry. Finally, large numbers of these fabricators must be combined with other equipment to make a nanofactory.

The first step, developing the necessary carbon-bonding reactions, will require much scientific research. The theoretical groundwork for this was laid in *Nanosystems*, with significant subsequent work by Ralph Merkle and Robert Freitas, including a book in progress on diamond surface chemistry. The second step, building a fabricator, will require mechanical and chemical engineering for the design, and a lot of lab work including the development of new techniques for the construction. It should be noted that the fabricator need not be autonomous in any sense; it would use only specialized chemicals, and would be inert without outside control and power. Once a fabricator is specified, a nanofactory can be designed. CRN's forthcoming paper discusses nanofactory design and bootstrapping. It appears likely that this final step will be the easiest.

Much work will be required to accomplish the LMNT goal of making a diamondoid nanofactory. Some observers predict that the field will develop slowly, with much of the necessary research happening as an outgrowth of other projects. However, as discussed in the next section, the economic and/or military rewards of a successful LMNT project could be extreme. This indicates that at some point, perhaps soon, it will be worthwhile for someone to launch a targeted development project. If successful, the resulting nanofactory would find immediate use in a variety of applications, probably including the replacement of traditional fabrication technologies for many products.

The utility of LMNT depends largely on the capability of the nanofactory. In order to achieve a useful fabrication speed, the factory must contain myriad separately-controlled workstations making sub-micron parts a few atoms at a time, which would then have to be joined. This would require automated control and high reliability. Detailed calculations indicate that mechanochemical fabrication of stiff diamondoid parts could be sufficiently reliable at room temperature. CRN's nanofactory paper describes a mechanical joint that allows simple robotics to work with a high degree of reliability. A useful nanofactory would also have to be fast, easy to use, and cheap to operate; these requirements also appear to be achievable with fairly straightforward factory architecture.

At some point, the cost of an LMNT project will become comparable with the cost of developing a new military airplane—tens of billions of dollars—if it hasn't already. As discussed below, LMNT would facilitate the rapid development of a variety of powerful new weapon systems, as well as enhancements to existing ones and great improvements in military logistics. Economic incentives for commercial development are also immense; from computers to medical instruments, the range of products that could benefit from LMNT is broad enough to warrant a high level of investment.

It appears that the main barriers to development of LMNT are matters of policy. Uncertainty about its ultimate feasibility, though widespread in the United States and Europe, is unfounded. Uncertainty about the roadmap for technological development should at this point be addressable by theoretical studies, and in a crash project could be handled by concurrent exploration of multiple avenues as was done in the Manhattan Project. Although MNT has not yet come under regulation, this could present an additional hurdle to commercial development in some jurisdictions, though probably not to military development.

IV. Functionality of LMNT

This section discusses the consequences of the development of a limited molecular nanotechnology: a tabletop manufacturing system capable of making nanoscale carbon-lattice parts and integrating them into a human-scale product. In reading this section, it is important to keep two things in mind. First, although speculative, the capabilities described here are well grounded in current scientific theory and peer-reviewed publication. Second, although much work will be required to develop LMNT, much of this work can be started today and done in parallel; the development schedule depends largely on the incentive, not on any technological or scientific difficulty. As this section demonstrates, the incentive could be quite high.

Building at the molecular level, millions of parts could fit into the volume of a bacterium. Product designs would combine predefined and tested micron-scale machines—computers, sensors, and actuators, as well as inert structure—to make human-scale products with as little or as much complexity as desired. The extreme flexibility provided by nanomodular design would allow a wide range of products to be created by the same factory technology.

A variety of estimates indicate that the time required for a sub-micron mechanochemical fabricator to produce its own mass of product is probably well under a day—comparable to bacterial replication times. Thus a tabletop nanofactory could probably make a one-kilogram diamondoid product in an hour or so. It could also fabricate a duplicate of itself in under a day, at a cost comparable to the cost of any product. This implies that the manufacturing base could grow quite rapidly.

Being self-contained and automated, a nanofactory would be usable in a variety of environments, including areas with undeveloped infrastructure and near battlefields. It would also be suitable for manufacturing products near point and time of sale, and perhaps even for home use. Products built largely of simple carbon-based feedstock molecules would not need the metals or specialized materials used in today's technology. These factors could greatly decrease transportation, storage, labor, and inventory costs, and permit more rapid delivery of newly designed products.

A nanofactory could function as both a rapid prototyping machine and a production system. Just as a computer uses a few basic instructions to do many kinds of calculations, a nanofactory could use a few basic operations of mechanochemistry and assembly to build many kinds of products without retooling or prototype costs. This also implies that product manufacturing cost would be unrelated to product complexity. A new product design could be built straight from the blueprints in minutes or hours, tested and refined, and a new version built as soon as the new design was ready. The final version's blueprint could immediately be put into production at any location on any desired number of nanofactories. Development of new products could proceed far more quickly than today's practice allows.

Products built by a nanofactory would be limited by the underlying chemistry. However, mechanical devices depend on shape, not chemistry; most mechanical products would be achievable at all scales larger than one nanometer. Because some forms of carbon conduct electricity or are semiconductors, many electrical devices would also be achievable. There are also several ways in which a carbon lattice device could interact successfully with biochemical molecules.

Products built of diamond lattice would also have several advantages. Most obvious is strength: carbon lattice may be 100 times as strong as steel. Nanofactory-built products could require far less material than today's versions. The ability to design at nanometer scale allows many products, including computers and motors, to be far more compact; a supercomputer could fit inside a grain of sand and use a fraction of a watt. The precision of molecular design should allow bearings to be nearly frictionless, in contrast with today's MEMS devices. Most human-scale products would be mostly empty space, giving mechanical engineers unprecedented freedom to design function rather than structure and further simplifying the design process.

Weapons are one obvious application of such a manufacturing technology. Aerospace hardware, especially the avionics, could be far lighter and stronger. New kinds of weapons could be developed, smaller (or larger), more powerful, and more complex than today's systems. If prototypes could be produced rapidly at low cost, designers could get much more inventive. With manufacturing cost unrelated to complexity or miniaturization, even the smallest weapons could have a full onboard computer/sensor/actuator suite, and be produced in sufficient quantity to compensate for their size. As with all nanofactory products, deployment would be almost immediate and require little effort. CRN is particularly concerned about the possibility of an unstable arms race fueled by ultra-rapid development of weapons of unprecedented power and functionality.

The same factors that could make even limited MNT a powerful military force multiplier may also make it a powerful economic asset. It's said that in order to be accepted, an innovation has to be ten times better than what it replaces. According to calculations, depending on the criterion, LMNT products could be between one hundred and one million times better. Reduced costs, easier product development, and easier manufacturing could make LMNT products even more attractive. The flexibility of the manufacturing process means that a wide range of products could be produced. LMNT could provide a substantial economic boost to undeveloped areas, since a nanofactory would require very little infrastructure. Whoever controls LMNT could end up dominating a wide range of industries, and disrupting many others.

V. Discussion of Greenpeace Report

Here we will comment on a few specific points raised in the report published by Greenpeace.

In section 2.4.2, and again in 2.6, the report predicted that MNT would be developed about 35 years in the future. This appears to be based on two assumptions: first, that full MNT is necessary for full effects, and second, that development will not be accelerated by a crash project. Both of these assumptions are questionable. Limited MNT, as outlined here, would produce most of the benefits and risks of full MNT. However, it could be developed quite a bit sooner and with less uncertainty. This in turn increases the military and commercial incentives for early development, even to the extent of justifying targeted multi-billion dollar projects.

In section 2.4.2.2, the report mentions nanobots and nanomedical devices as an area of exceptional hype. This has been an area of great confusion, especially since traditional MNT discussion frequently has failed to distinguish between nanobot fabricators and nanobot products. LMNT fabrication does not rely on nanobots at all. However, it could easily build a variety of nanobot-type products incorporating nanometer-scale diamondoid components. With a limited chemistry toolbox, LMNT products may not be able to interact fully with biochemistry. However, simple tools such as microsurgical robots and high-capacity implantable sensor arrays could cause rapid improvement in some areas of medical practice.

Section 2.4.3 is titled "Fundamental barriers to these visions," and states that some "major technical obstacles ... might be virtually insurmountable." As discussed above, Richard Smalley's "fat fingers" and "sticky fingers" criticisms have little or no relevance to LMNT. The report correctly notes that "Diamond assemblies might be relatively easy to assemble; other structures, such as biological configurations, are infinitely more complicated." As the present document demonstrates, diamond assemblies—LMNT—could accomplish much of what has been claimed for MNT. Finally, the "major problems concerning energy sources and dissipation" and similar practicalities have been addressed in detail in CRN's forthcoming exploration of nanofactory architecture. No fundamental barriers to LMNT are known or even suspected at this time.

Section 2.5.1 defines as "long-term" any hazard that "due to challenges associated with technological development, is unlikely to manifest itself within a 10-15 year time frame." CRN believes that in the case of LMNT, hazards that may occur ten years from now need attention today. An LMNT development program could proceed with surprising speed, especially in the final stages, which according to our research will probably require mainly traditional engineering. The time to start making policy is before such a program is launched; given the incentives described here, and the recent progress in defining the tasks required by LMNT, such a program could be initiated at any time.

Section 2.5.2.2 discusses self-replication and biosphere destruction, saying that "...while the danger seems slight, even a slight risk of such a catastrophe is best avoided." It should be emphasized that the development and use of LMNT manufacturing does not involve self-replication. A nanofactory would be able to duplicate its physical structure, if the right set of blueprints were downloaded. However, it would include no manipulators to gather biomaterial, no legs or wheels to travel, no chemical plant to process biomaterial into pure feedstock chemicals, and no power supply. The chance of such a thing running amok is not merely slight—it is zero. There is, unfortunately, a slight risk of some malicious or irresponsible person deliberately integrating all the necessary components to create a self-replicating machine, but such a project would be quite difficult, and this risk is overshadowed by the more powerful non-replicating weapons that could be designed and built with much less effort.

Section 2.5.3.2 points out the dangers of a "nano-divide" in which only the rich would have access to the new technology. CRN shares this concern, especially since denial of the technology to any population would fuel demand for illicit and uncontrolled versions. A more optimistic scenario is one in which nanofactories are made widely available, and noncommercial designs could be manufactured at cost. The Open Source software movement has demonstrated its ability to produce high-quality, free, complex digital products; its methods and practices would be highly applicable here. Unfortunately, this scenario could be sabotaged by current trends in intellectual property that will take time to reverse—another reason why MNT policymaking should begin now.

Section 2.5.3.3 discusses destructive uses of MNT. CRN emphatically shares this concern. An international organization may be necessary to monitor military uses of MNT or development of unmonitored fabrication capability. LMNT could be developed with surprising speed, and could proliferate with even greater speed once the first nanofactory is functional; additionally, with just a little reverse engineering or information sharing, subsequent development projects could progress much faster than the initial project. The initial stages of such a project, involving distributed lab work and computational experiments, would be relatively easy to conceal, and the final stages could proceed quite quickly. If a cooperative international response will be necessary, planning must start long before the problem appears urgent.

A few minor inaccuracies in the report are worth pointing out. Section 2.5.3.3 states that fourth-generation nuclear devices incorporate nanotechnology. In fact, they would use MEMS and precise machining—much more prosaic technologies. Section 2.4.2.2 describes the NanoWalker as an "autonomous miniature robot." It should be noted that "autonomous" here merely means that NanoWalkers are controlled by infrared signals rather than by wires, and that they can move around a workspace; they are not capable of performing tasks on their own. Section 2.5.4 describes the Foresight Institute as following a strategy of "launch[ing] pre-emptive strikes against any problems with public acceptance of nanotechnology." In fact, Foresight was founded in order to call attention to the risks of molecular nanotechnology and other advanced technologies.

VI. Conclusion

The Greenpeace report correctly notes that molecular nanotechnology appears to be possible, and could have significant negative impacts. However, their analysis is based on an early understanding of MNT, and does not take into account the limited MNT that has been proposed more recently and developed in more detail. LMNT would be much simpler and cheaper to develop, and powerful enough to be extremely attractive to a variety of interests. If there is not already a targeted LMNT development program somewhere in the world, there probably will be soon.

Although some of the consequences of traditional MNT, such as self-replicating nanobots, become less significant with LMNT, other potential consequences remain areas of considerable concern. The sudden discovery of an LMNT project nearing completion would not allow time for formulating and implementing good policy. It should be emphasized that the final stages of LMNT development are likely to be the easiest and most rapidly accomplished. Hurried or panicked policy would likely be both oppressive and inadequate to prevent the negative consequences, including geopolitical instability, economic disruption, and a variety of unfortunate products and capabilities being widely accessible.

However, cautionary discussions should not ignore the fact that MNT, including LMNT, could be a strong positive asset. If administered well, the existence of cheap, clean, local, easy-to-use manufacturing capability (even limited to diamondoid products) could go a long way toward reducing poverty and underdevelopment, as well as alleviating current environmental impacts. Whether suitable administration can be developed depends largely on how soon the policy process begins.

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