Commentary on Royal Society Nanotechnology Workshop, Sept. 30, 2003

Prepared by Chris Phoenix, Director of Research
Center for Responsible Nanotechnology

We thank you for soliciting our comments on the workshop report. We are encouraged by many of the opinions expressed, especially the interest in issues of nanomaterial safety. However, we believe that the report pays insufficient attention to a significant expected application of nanotechnology.

Direct chemical manufacturing of complex nanosystems surely will be extremely difficult to develop. However, recent work has produced well-grounded and limited proposals that retain high value and utility. Sufficient effort might develop such systems in as little as a decade, and large incentives may motivate such early development. This possibility can be addressed within the current framework of your studies.

Section 3B of the report includes a discussion of the use of MEMS as a production technology. It reported consensus that if production could be scaled up, it could lead to "truly green manufacturing with no waste, no solvents and very efficient use of materials." Such a general-purpose manufacturing system is a major goal of nanotechnology, but was placed as far out as 2020.

Section 3E calls for a general road map for the development of nanotechnology, in terms of "aspects of technology push, consumer pull, control and regulation, and health and safety issues" in order to "help to put some of the prospective developments into a temporal context and show important potential technology linkages and potential markets." Both technology push and consumer pull can be estimated for MEMS-like manufacturing using mechanically guided chemistry and capable of producing MEMS-like products. This should be a component of your road map.

General-purpose Nanoscale Manufacturing

General-purpose nanoscale manufacturing may result from the convergence of several current technologies. These technologies include nanoscale fabrication, chemistry (especially positional chemistry), automated assembly, rapid prototyping, MEMS/NEMS, and carbon-based nanoscale structural materials. Certain features of nanoscale physics, including the inherently digital nature of covalent chemical operations, imply that manufacturing at that scale should be more precise and easier to automate than manufacturing at larger scales. These features may go a long way toward balancing the engineering awkwardness of other nanoscale phenomena such as surface forces.

We are not arguing for the "universal assembler" of early nanotechnology proposals. More recent work has focused on a limited molecular nanotechnology (LMNT) involving only stiff molecules, typically carbon lattice structure in three dimensions. Preliminary investigations show that this limitation probably preserves enough flexibility to build MEMS-like systems that should be capable of doing molecular fabrication operations (dry surface chemistry) with atomic precision.

A MEMS-like mechanochemical fabrication system would not be self-replicating, representing only the mechanical component of a von Neumann-type self-replicating system. But as far as theory can guide us, it appears that a suitably designed and controlled system based on carbon lattice chemistry could duplicate its structure. It should be noted that this is very similar to the MEMS manufacturing systems alluded to in your report. The question is how to design a chemical and structural system that can "close the loop"—a system that can build all of its component parts out of simple chemicals. Much theoretical work has already been done on such a system, and it appears that the diverse properties of carbon may facilitate such a project.

A manufacturing system based on this technology and chemistry would be able to fabricate a wide range of products. It would also be able to produce additional manufacturing systems as cheaply as any product. The benefits and low cost of creating and using local just-in-time manufacturing facilities could lead to a substantial surplus of manufacturing capacity and a sharp drop in the overall cost of manufacturing. The value of such a system might be extremely high, inspiring a concerted effort to develop it even at high cost and great difficulty.

Objections to the Proposal

A few limitations of nanoscale engineering are mentioned in the report, but these apply to different proposals than the current one. For example, Section 3D states that "if the technology to create self-replicating nanobots were to be physically possible, which many doubted, it would not be available until the distant future, perhaps 2080 at least." It is certainly true that a fully self-replicating "grey goo" nanobot would be quite difficult to design. However, general-purpose manufacturing in a limited domain based on carbon-lattice chemistry from special chemical feedstock may be significantly easier to achieve.

Section 4E asserts, "There is an enormous difference between controlling the physical properties of a single nanostructure in isolation and manufacturing a material whose properties are those of the individual nanostructures." This was stated in the context of optical structures. Mechanical properties are more closely tied to physical structure than optical or electronic properties are. It may prove quite feasible to design complex structures with desired mechanical properties and interactions, especially if physical structure can be specified by programmatic control and the results evaluated rapidly.

It has been asserted that the vacuum chemistry required of mechanochemistry is impossible. In the recent debate between Richard Smalley and Eric Drexler, Smalley took this position but failed to offer a convincing argument (see http://CRNano.org/Debate.htm). It has also been asserted that issues of control, power, or heat dissipation may prevent a manufacturing system from working. These are engineering issues, not fundamental limitations, and have been addressed in a recently published design for a tabletop-sized system (see http://www.jetpress.org/volume13/Nanofactory.htm). Friction is another issue sometimes cited as problematic, extrapolating from experience with MEMS. Although MEMS suffer from high friction, their surfaces are not smooth. Theory predicts that stiff smooth non-reactive surfaces, which cannot provide many modes of energy loss, may suffer significantly less from friction; it should be noted that graphite is a solid nanoscale lubricant.

It has recently been argued, especially by the U.S.-sponsored nanotechnology effort, that biochemistry should form the basis of nanotechnologic manufacturing. Such an approach requires solving problems including protein design and the integration of biological molecules with inorganic molecules and particles. This approach may work, but is likely to be quite difficult; the U.S. NNI expects it will take decades to develop. It is sometimes claimed that biological systems are far more efficient and competent than nanoscale mechanical systems can hope to achieve, but this claim has no foundation. Precise well-designed nanoscale mechanical systems, including energy transformation and transport systems, should approach 100% efficiency. Nanomachine-based systems are at least a strong competitor to biomimetic nanotechnology, and appear preferable on several counts.

It is easy to be skeptical of theory applied in a new domain, but such skepticism should not give license to reject the theory or its implications without close study. Foundational work in the field, especially *Nanosystems* (Drexler, 1992), has laid out a detailed theoretical approach to nanoscale mechanochemical systems and other nanoscale machinery that has never been successfully criticized. If the theory is right, then the capability can be developed.

Section 7D of the report says, “The participants believed that initial progress in nanotechnology would likely be by small incremental steps in existing technology and products rather than by a series of dramatic breakthroughs. Similarly, the publics’ perception that nanotechnology is different from other technologies is incorrect.” Much of nanotechnology is indeed a series of continual or incremental improvements. However, the development of a self-contained general-purpose nanoscale manufacturing capability would certainly constitute a dramatic breakthrough, and is not a likely result of other technologies.

Basic Questions

The following questions, taken together, may serve as a basis for evaluating the significance of mechanical chemistry as a possible near-term general manufacturing technique.

Technical Issues

1. What range of reactions can be accomplished by mechanical chemistry? How many different reactions would be required to synthesize parts with precise nanoscale features in diamond or another stiff covalent material?
2. What kinds of nanoscale machinery can be made out of stiff covalent material? Which design issues between nanoscale and macro-scale machines are similar? Are there any issues that make nanoscale design especially difficult in comparison to macro-scale design? In particular, can some analogue of robotics be designed?

3. What issues might arise in integrating large numbers of nanoscale systems and machines? Given the use of stiff covalent construction material (with optional hinges, springs, and perhaps bearings), how much overhead will be required to isolate machines in order to allow independent design and operation?
4. How difficult would completely automated manufacturing be in a system with atomically precise parts and products?
5. To what extent can the productivity of mechanochemical systems be projected from scaling laws, or from comparisons with other systems such as bacteria?

Difficulty of Development

1. What would be the cost of cheap (e.g. semi-empirical quantum mechanical) simulation of a few thousand proposed mechanochemical reactions, and more detailed (ab initio quantum mechanical) simulation of the best contenders?
2. What would be the cost of developing a CAD program suitable for designing and controlling mechanochemically fabricated machinery?
3. What would be the cost of developing a "bootstrapping" technology capable of building a first mechanochemical system by self-assembly, scanning probe chemistry, 3D nanolithography, or other means?
4. How rapidly will such costs decrease? Will the costs ever sink significantly below the incentives for development?
5. What funding models could underwrite a very expensive project with high eventual payoff?

Incentives for Development

1. What range of products could be made with the contemplated system, using either small standalone fabricators or integrated fabricator arrays? At what time do other technology road maps contemplate making comparable products? What would be the value of such products if this technology could produce them substantially earlier?
2. What would be the cost of operation of a self-contained automated general-purpose mechanochemical manufacturing system? What are the economic implications of on-site, normally-idle, rapid-production manufacturing systems? What are the strategic implications of fast portable general-purpose manufacturing?
3. What are the economic implications of a manufacturing system in which rapid prototyping would cost no more than bulk production, and delivery of product could be accomplished by onsite on-demand automated manufacturing, requiring no retooling, retraining, or warehousing of unused product?
4. What are the societal consequences of extremely cheap high-tech manufacturing? (Note that applications may be as diverse as humanitarian relief, health care, rapid modernization, and surveillance.)
5. How could a general-purpose manufacturing technology be restricted?

Policy Implications

We believe that a set of plausible answers to the above questions predicts the targeted and rapid development of mechanochemical manufacturing—if not in the West, then in non-Western nations. Many of the development costs will fall rapidly, driven by factors including the rapid improvement of computers. If mechanochemistry works at all, it should be able to make products decades in advance of those made by competing technologies. As explored in our recent technical paper (http://www.jetpress.org/volume13/Nanofactory.htm), small products of individual mechanochemical fabricators could easily be joined together to make large and complex products. It also appears that autoproductive manufacturing systems may not be difficult to design in such a technology. This could drive down the cost of products enough to out-compete much of today's production and delivery infrastructure.

The rapidity with which this technology could be developed—an important question—is unknown at this point. However, the development of a limited-chemistry general-purpose manufacturing system appears to be largely a matter of engineering, not dependent on scientific breakthroughs. The rapidity of development will depend heavily on the available funding, and there may be extremely high incentives to develop this technology—particularly in nations such as China, where self-contained general-purpose manufacturing may be the only way to close an internal technology gap. Enabling technologies are being developed and published rapidly, and their progression toward nanometer-scale access can be charted. We believe that a well managed multi-billion-pound effort may be successful in less than a decade, even in nations that are currently coming up to speed technologically.

In short, mechanochemical manufacturing—with extreme implications—may be developed somewhere in the world within the time frame of governmental planning horizons. If Great Britain, Europe, and the world are to have any chance of formulating policy to deal with such a disruptive event, it is crucially important not to dismiss this possibility, but instead to explore the issue. The scientific theory can be examined immediately and in detail. If it cannot be disproved easily, the next step is to project the probable capabilities of the target manufacturing system and to study the incentives and abilities for large governments and corporations to develop it. This will provide a basis for a reasonable estimate of the development timeline, which can be used to guide policymaking efforts.

We urge the Royal Society, and all other groups investigating nanotechnology, to take the possibility of molecular manufacturing seriously and to act on it by commissioning scientific, technical, and economic studies as outlined above.

Please direct questions or comments to the author at cphoenix@CRNano.org.