

Dr. K. Eric Drexler
Chairman, Foresight Institute
24 October 2003

Dr. Andrew Dunn
Manager, Study on Nanotechnology
Royal Society/Royal Academy of Engineering

Dear Dr. Dunn,

In preparation for my 29 October oral evidence session with the Royal Society's Working Group, I've prepared this written response on the six topics you listed.

My technical work has focused on understanding what current scientific knowledge can tell us about the limits to future technological capabilities. This effort combines applied physics with generalizations from observed phenomena to support design and analysis in the domain of systems engineering. Results in this field form a small but substantial technical literature. This work indicates that progress in atomically precise nanotechnologies will eventually support the emergence of powerful manufacturing abilities based on molecular machine systems, fulfilling a vision first articulated by American physicist Richard Feynman in 1959.

The far-reaching positive and negative consequences of such future abilities have engendered both hype and rejection. The controversy surrounding the "grey goo" fears that helped stimulate the present study has been a facet of this.

My concern with communicating crucial issues to a broader audience has thrust me into a role as spokesperson and advocate on matters that have generated excessive heat and enormous confusion. Accordingly, my remarks will focus on what science can tell us about technologies not yet developed, and will discuss both communications and policy issues. In particular, I hope to show how we can move beyond the myths generated by hype and rejection to enable a somewhat more rational discussion of genuine prospects and concerns.

The Royal Society study could become the first open, scientific assessment of these issues. Thus far, communication has been largely polarized and dominated by simplistic and often incorrect accounts in the press. I hope that the present study will move beyond the myths, discarding both the exaggerated fears and the groundless dismissals of legitimate future concerns that have become so common in public discussions on this topic.

Regarding the study topics:

- 1) define what is meant by nanoscience and nanotechnology
- 2) summarise the current state of scientific knowledge about nanotechnology
- 3) identify the specific applications of the new technologies, in particular where nanotechnology is already in use
- 4) carry out a forward look to see how the technology might be used in future, where possible estimating the likely time scales in which the most far-reaching applications of the technology might become reality
- 5) identify what environmental, health and safety, ethical or societal implications or uncertainties may arise from the use of the technology, both current and future
- 6) identify areas where regulation needs to be considered.

1) What is meant by “nanotechnology”

Confusion around divergent uses of this term have spawned much of the confusion around the subject. The term was used by an author in Japan in the early 1970s to describe, among other things, precision glass polishing. It came into wide use and gained an aura of excitement after 1986, when I used it to label the Feynman vision of nanomachines building products with atomic precision. Over the next decade and a half, it has increasingly been used to re-label a diverse and often little-related collection of research efforts involving small parts or particles, embracing microlithography, fine particles, chemistry, thin fibers, and so forth.

It was the Feynman vision and its consequences that gave “nanotechnology” its reputation as a revolutionary technology with enormous promise and dangers, but it is current research that gives a different sort of “nanotechnology” a reputation as something happening right now. Confusion between these meanings – and the natural urge of numerous researchers to dissociate their current work from promises and dangers that they neither understand nor plan to deliver – has generated much heat. Since some current research is, in fact (largely unintentionally) developing the capabilities needed for implementing the Feynman vision, the two meanings of “nanotechnology” do have some relationship. Further, although the research community has settled on the inclusive, current-technology meaning for the term, the chief fears and concerns articulated by the public stem from the previously established meaning of “nanotechnology” as a label for molecular manufacturing and its products.

Moving from history and analysis to prescription, how should “nanotechnology” be used? The natural course would be to follow general usage, which applies the term to any technology with significant nanoscale features. This has the advantage that recent computer chips, for example, are now “nanotechnology”, making broad, simplistic fears absurd.

This leaves the problem of how to describe and distinguish the Feynman vision from this diffuse field. I have since the early 1990s used the term “molecular manufacturing” to describe the core enabling technology of the Feynman vision (large-scale mechanosynthesis based on positional control of chemically reactive molecules). Since the emphasis is on large-scale atomic precision, it is natural to seek a name that refers not to the nanometer scale of the parts, but to the number of distinct, designed parts in a macroscopic product, typically on the rough order of a sextillion (10^{21}). Since the prefix “zetta-“ denotes this number, the term “zettatechnology” naturally describes molecular manufacturing and its products (for comparison, the total world output of transistors has not yet reached one sextillion). One can thus speak of advanced nanotechnologies as eventually enabling zettatechnology, through further development of basic techniques followed by a major systems engineering effort. This clearly separates the concepts by providing distinct, contrasting labels.

Regardless of the choice of terms, it is crucial to recognize the confusion described above, including its effects on both press accounts and the response of lab scientists to the longer-term vision. Allaying false fears (and false denials of fears) begins with drawing the correct distinctions.

2) The current state of scientific knowledge

Scientific knowledge in 1959 was sufficient to give Richard Feynman considerable confidence in the feasibility of what has since been termed molecular manufacturing. Subsequent work has drawn on both laboratory demonstrations of chemical processes and computational studies based on standard physical theory. It confirms that suitable molecular machine systems can, once constructed, be used to build more molecular machine systems and a wide range of atomically precise products. This work also indicates that such processes can be clean, reliable, efficient, and orders of magnitude more productive than conventional manufacturing processes. These properties stem from fundamental scaling laws that enable small devices to operate at high frequencies, and from physical principles that enable them to join molecular building blocks with digital precision.

Early descriptions of molecular manufacturing spoke of self-replicating machines as an industrial tool, and of very different self-replicating machines (engineered to use natural sources of energy and raw materials) as a potential threat (“grey goo”). These concepts become confused, and some scientists sought to distance their work from perceived dangers by denying the physical possibility of both sorts of machines. I believe that an examination of their arguments shows them to be without a scientific basis, addressing straw men rather than actual proposals. The actual core concepts of molecular manufacturing have withstood scientific scrutiny for more than a decade.

Efforts to calm public fears of “grey goo” through false denials of the feasibility of self-replicating nanomachines will inevitably fail, damaging the credibility of the deniers. The self-replicating nature of life and the biomimetic aspirations of nanotechnologists

guarantee this. A better policy is to point out that such issues are both distant and manageable.

3) Specific and current applications of nanotechnologies

Current and near-term applications of nanotechnologies are far narrower than those that will be enabled by molecular manufacturing. Better materials, smaller and faster electronics, and so forth, are part of the ongoing, gradual revolution of modern technological development. In contrast, the transition to zettatechnology (which will enable atomically precise products with sextillions of parts) has structural features (stemming from the nature of its tools) that will enable a far more abrupt revolution in technological development, with broad applications to physical technology as a whole.

4) The most far-reaching applications and their likely time scales

A broad set of far-reaching applications will be enabled by the development of molecular manufacturing. This includes computational systems of a scale and efficiency that will enable a billion GHz processors to fit in an air-cooled desktop package, inexpensive materials with 100 times the strength to weight ratio of structural steel, efficient photovoltaic cells in the form of tough, flexible sheets, sub-cellular scale medical sensors and tools, and much more.

The very breadth of this range of applications has stimulated a reflexive rejection of the possibility of the enabling technology. This is, however, like rejecting data on the neutron-induced fission cross-section of the U-235 nucleus in 1940 because one disbelieves the possibility of a million-fold increase in the energy density of explosive devices. The magnitude of the expected consequences gives reason for careful evaluation of feasibility, not for emotional dismissals. Thus far, the dismissals have effectively inhibited the feasibility studies.

Estimates of the time scale for developing early molecular manufacturing systems, made by researchers who have examined the technical questions in a problem-solving frame of mind, range from years to a few decades at most. The key enabling technologies (mechanical manipulation of molecules, self-assembling molecular building blocks, computational modeling of nanosystems) are part of the current research agenda in the U.S., Europe, and Asia. Better estimates of development times await further research, centered on the comparison and evaluation of alternative systems engineering proposals. This, in turn awaits the emergence of a more rational and scientific discussion of the established concepts.

5) Environmental, health and safety, ethical or societal implications

Today's incremental nanotechnologies raise incremental questions regarding public policy issues. Many of these are extensions of familiar questions raised by progress in chemistry, sensing, and information technology. Nanotechnologies for implementing molecular manufacturing and future zettatechnology raise different concerns. Their

development will enable a wholesale revolution in productive technology that demands precautionary attention. Its consequences are, however, too broad and novel to fall within the scope of a study focused on current laboratory nanotechnologies.

6) Areas where regulation needs to be considered

Current nanotechnologies seem to raise no fundamentally novel questions of public policy. When nanoscale structures with novel beneficial properties are released into the environment or the human body, they must be regarded as potentially having novel harmful properties as well. There seems little reason to think that they pose greater risks than do novel chemical substances.

Molecular manufacturing and future zettatechnology, in contrast, will be deeply transformative. Their military implications require attention to issues of arms control, cooperative development, and strategic stability. Strict regulation against abuse of the most powerful of these technologies and limitation of the capabilities of widely deployed systems seem essential to most analysts. In light of this, on-going dialogue regarding the societal and economic consequences of these technologies is essential.

I would be glad to elaborate on these topics and to provide documentation regarding them after our conversation later this week.

Best wishes,

Dr. K. Eric Drexler
Chairman, Foresight Institute