Nanotechnology: radical new science or plus ça change?

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Is a radical nanotechnology involving the construction of *macroscopic* products via software-directed manipulation of single molecules possible? Are we only a few decades away from a technological utopia where virtually any product may be constructed via molecular manufacturing?[1] These and other similarly provocative questions formed the backdrop for a well-attended debate on nanotechnology held in the University of Nottingham last year (26 August 2005). To the best of the author's knowledge, the Nottingham event represented the first time that key proponents of the molecular manufacturing concept (originally put forward by Drexler in 1981[2]) debated with leading British scientists in a public forum in the UK. A transcript of the entire debate features in this issue of *Nanotechnology Perceptions*, and the reader will find that a variety of thought-provoking technical and societal issues were raised during the two hour session. While, for reasons of space, I am restricted here to providing a short introduction to the debate, a forthcoming issue of this journal will feature an article comprising both a commentary on some of the key issues arising from the Nottingham event and a synopsis of my stance on the feasibility of the "matter compilation" technology at the core of Drexler's (and others'[3–5]) proposals for molecular nanotechnology (MNT). (The article will place recent web-based discussion[6] on a rather more formal footing).

I should perhaps start, however, with an explanation of the title of the debate. The "Radical new science or plus ça change?" question was chosen so as to highlight the

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1 K. Eric Drexler. *"Nanosystems: Molecular Machinery, Manufacturing, and Computation"*. Chichester: Wiley Interscience (1992).
2 K. Eric Drexler. *Proc. Nat. Acad. Sci.* **78** (1981) 5275 .
3 Ralph C. Merkle. *Nanotechnology* **8** (1997) 149.
4 Ralph C. Merkle and Robert A. Freitas Jr. *J. Nanosci. Nanotechnol.* **3** (2003) 319.
5 J.S. Hall. *Nanotechnology* **10** (1999) 323.
6 http://www.softmachines.org/wordpress/index.php?p=70

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gulf that can exist between various groups' understanding of the term *nanotechnology*. There has been a dramatic international rebranding of very many areas of condensed matter research so that any type of activity involving structures with sub-micron (or sometimes even "super-micron") dimensions is currently largely classified as nanotech. In a number of cases, what is now labelled as nanoscience or nanotechnology[7] is simply a rather mature research area given a funding-friendly new 'spin'. Thus, spontaneous arrangements of atoms at surfaces are now usually described, if at all possible, as nanowires, nanorods, nanodots or an appropriate nano-prefixed alternative. Twenty years ago many of these nanostructures were collectively described within the surface science community as surface reconstructions. Similar arguments can be made regarding the rebranding of key aspects of, for example, colloid science, materials processing, and thin film growth. Pushing the 'rebranding' argument to its limits, some have proposed[8] that nanoscience is largely advanced chemistry. Hence, one school of thought is that much of nanotechnology is simply "The Emperor's New Clothes" writ small, or, from the rebranding perspective, *plus ça change, plus c'est la même chose.*

The mechanosynthesis and molecular manufacturing concepts originally put forward by Drexler in his Massachusetts Institute of Technology PhD thesis (published as *Nanosystems* in 1992) represent a dramatically different type of nanotechnology, which, rather than stemming from what some might call incremental modifications to conventional surface or synthetic chemistry, *is* radical and revolutionary. Indeed, Drexler and proponents of his work lay claim to the *nanotechnology* term, claiming that it has been usurped by the wider scientific community to describe both top-down and bottom-up developments in the processing and study of materials at the nanometre scale. To distinguish the Drexler-inspired version of nanotech from other, arguably more incremental/conventional variants, I will adopt the *molecular nanotechnology/ molecular manufacturing* labels commonly used to describe the nanoscience laid out in *Nanosystems*. As defined in *Nanosystems* (and as explained clearly by Jones, Hall, and Forrest in their introductory pieces for the Nottingham debate), molecular manufacturing is best described as the principles of mechanical engineering applied to chemistry. This succinct and helpful definition does not, however, quite communicate the controversial concepts at the core of Drexler et al.'s designs of nanomachinery, *viz.*: (i) it will be possible to scale down the engineering principles that govern the operation of macroscopic gears, motors, bearings, and mills (for example) to the atomic/molecular level; (ii) the construction of nanomachines and nanomaterials will be computer-controlled, potentially entirely autonomous, and will progress with atomic/molecular precision, and (iii) (perhaps most controversially of all) that the preceding conditions naturally lead to the emergence of a nanofactory/matter compilation technology

[7] I will return to a discussion of whether it is important to draw a distinction between nano*science* and nano*technology* in the commentary to be published in a forthcoming issue.
[8] http://www.nanotec.org.uk/evidence/oralKrotoFRSProfHarry.htm

whereby *macroscopic* products (of virtually any design/type) can be constructed via a hierarchy of molecular machines.

An instructive simulation of a nanofactory, which featured a number of times in the Nottingham debate, may be found at http://www.nanotech-now.com/Art_Gallery/John-Burch.htm, and it is well worth viewing this movie to gain a better understanding of the molecular manufacturing/mechanosynthesis concepts advocated by Drexler et al. The qualitative similarities between the molecular machinery seen in this simulation (and indeed in *Nanosystems,* on whose principles the movie is based) and conventional macroscale machines are striking. Jones, however, argues both during the debate and elsewhere[9] that future advanced and potentially radical nanotechnology/molecular machinery is unlikely to be based upon this type of 'scaled down' macroscopic engineering. Rather, it will most likely involve nature's design principles, which have been optimized via evolutionary tuning over many millennia. If one were to identify *the* core theme of the debate, it would be this question of deterministic 'hard' inorganic molecular manufacturing (espoused by Hall and Forrest) vs. evolutionary bionanotechnology (espoused by Jones and Tendler).

A wide variety of technical issues related to the viability of molecular manufacturing were explored in the debate. (It is worth highlighting that the debate took place during a UK Surface Science Summer School in Nottingham, funded by the Engineering and Physical Sciences Research Council (EPSRC) and involving 30 prestigious surface- and nano-scientists from the UK, Europe, and the US. Many of those scientists were in the audience.) In addition to the discussion of the relative merits of biologically-inspired nanotech and inorganic (e.g. diamondoid) molecular manufacturing —sometimes referred to as the 'soft and wet' vs. 'hard and dry' approaches—members of the audience raised questions related to, for example, the rôle of friction and contamination in molecular machines, the accuracy of the theoretical force fields underlying some of the simulations carried out by the molecular manufacturing community, and the physical mechanisms underlying the operation of the molecular motors used in the Drexler-Burch simulation cited above. The debate, however, did not solely focus on technical and scientific questions: there was also discussion of the societal impact of nanotechnology/molecular manufacturing (including an interesting interlude concerning the rôles of China and India in the future development of nanotechnology).

The transcript on the following pages is the first time that a public (and lengthy) debate on the feasibility of nanomachines and molecular manufacturing, involving a significant number of world-leading surface- and nano-scientists, has been published in its entirety in the scientific literature. It is, of course, not the first time that Drexler et al.'s molecular nanotechnology concept has been debated. Perhaps the highest profile treatment was *Scientific American*'s publication of two nanotechnology-themed issues[10]

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[9] Richard A.L. Jones. *"Soft Machines: Nanotechnology and Life"*. Oxford: University Press (2004).
[10] *Scientific American* April 1996 and September 2001.

in the past decade, which were both extremely critical of the molecular manufacturing concept (and, in some cases, of the molecular nanotechnology community). Following publication of the *Scientific American* articles, the Foresight Institute issued detailed rebuttals on their website. More recently, correspondence between Drexler and Richard Smalley that stemmed from an article Smalley had written for the Sept. 2001 issue of *Scientific American* entitled *Of Chemistry, Love, and Nanobots* was published in *Chemical and Engineering News*.[11] Since then there has been considerable weblog (blog)-based debate at a number of key sites including Richard Jones' *Soft Machines* blog,[6,12] the Center for Responsible Nanotechnology blog,[13] and the Foresight Institute's *Nanodot* site.[14]

In my commentary in a forthcoming issue of *Nanotechnology Perceptions* I will return to a number of technical questions arising from both the Nottingham debate and the blog discussions cited above. For now, I close by echoing a comment I made towards the end of the debate. Drexler's molecular manufacturing scheme has at its core an inspiring yet demonstrably valid concept: computer-controlled single atom/molecule chemistry (although the most basic mechanosynthetic reaction described in *Nanosystems* —mechanical single hydrogen atom abstraction—remains to be implemented[15]). What is missing from *Nanosystems* is a description of the low-level machine language—i.e. the detailed, material-specific (mechano)chemistry—required to implement the assembly routines that form the core of molecular manufacturing.

An experimental research programme that has as its focus the development of basic mechanosynthesis protocols would be a laudable and exciting goal of state-of-the-art nanotechnology. At present, such an experimental programme does not exist. Development of mechanosynthesis protocols can, however, only be possible for a judicious choice, and thus narrow subset, of materials systems (*Nanosystems* focuses heavily on H-passivated diamond surfaces for precisely this reason). Claims that a nanoassembler (or set of nanoassemblers) will—when 'embedded' in the appropriate molecular manufacturing architecture—be capable of manufacturing *virtually anything* are, to my mind, fundamentally flawed. It has been suggested that, with appropriate high levels of funding, a prototype nanofactory based on nanoassembler technology could be developed on a very short time scale (some claim that such a "Nanhatten project" could yield a molecular manufacturing system in less than a decade). It is interesting to consider this claim in the light of the Nottingham audience's reaction (see the following transcript) to the nanofactory simulation movie that was shown during the debate.

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[11] *Chem. Engng. News* **81** (2003) 37.
[12] http://www.softmachines.org/wordpress/?p=130; http://www.softmachines.org/wordpress/index.php?p=80
[13] http://crnano.typepad.com/crnblog/
[14] http://www.foresight.org/nanodot/?p=2029
[15] This in itself is an exciting experimental challenge.