

The Ruse and the Reality of Nanotechnology

Robert A. Wolkow

Nanoscience involves inspection, understanding and tailoring materials at the finest possible level. It is widely expected, and very likely, that nanoscience will lead to extremely small functional entities. It is less well known that nanoscience will also lead to conventional looking materials and devices that will have attributes that derive from improved ordering of constituent atoms and molecules. For example, we might in the future have plastic water bottles that are as strong as bottles made today, but which have thinner walls and therefore require less material. This nano-structuring of large objects is perhaps less exciting than a vision focused on nano-entities, however it is equally important, not least because improved materials in general can lead to less waste of both the materials themselves as well as energy.

It appears clear that nanotechnologies will be broadly applied, from machinery to medicine. Due to the transforming potential of these technologies, there are substantial societal implications. Unlike most other technical advances, nanotechnology has captured public attention early on in its development. This is a good thing, in that it allows, and forces, scientists to explain their abilities and objectives to laypeople. Many accurate and informative articles have appeared, but unfortunately, some of the descriptions of nanotechnology found in newspapers and on television are highly inaccurate. The misconceptions being spread about nanotechnology go beyond those expected whenever a specialized issue is translated for public access. The confusion has been created by a group that has bypassed the rigour and review of normal scientific discourse to go directly to the public with a fanciful message, presented with enticing artist's conceptions and animations.¹ Though the predictions made by this group are akin to anti-gravity shoes – something we have no reason to expect will ever be developed – it

has convinced many, including some of our incoming students, of their views.

It is hoped that by offering a clear description of some of our capabilities today, of what will most likely be possible in the foreseeable future, and as well, what we do not ever expect to be able to do, that an informed discussion about nanotechnology will be enabled. My purpose is not to defend or unfetter nanotechnology. Indeed any technology so fundamentally based and broadly applicable can most certainly be applied for both good and ill, and therefore must be made accessible, be freely discussed, and where necessary, limited in application.

Since nanoscience is a converging of many ideas and fields, and in part an incremental refinement of known methods and materials, it is hard to know where to start an historical summary of the area. We might reasonably say that nanomaterials are as old as the earth, since during the earth's entire history, nanoparticles of diverse composition have been present. Even recently identified nanoparticles known as Fullerenes (also called nanotubes and Buckey balls) have been present on earth for hundreds of millions of years. This is clear because countless Fullerene particles are produced naturally whenever a sooty fire – including a forest fire - burns. This particular introduction to nanoscale materials highlights an often over looked point, that life on earth evolved in the presence of diverse nanoparticles. We do not know if evolving living organisms were helped, hindered or indifferent to these materials. Clearly some nanoparticles, such as those in automobile exhaust, have deleterious effects.

Another way to start a discussion about nanotechnology is with a description of the scanning tunneling microscope



(STM), invented by Binnig and Rohrer in the early 1980's.² More than any other single development the arrival of the STM, with its revolutionary power to see and even move individual atoms and molecules, has enabled nanoscience research. Perhaps surprisingly, given its great power, the STM is a very simple machine. It does not use lenses like optical or electron microscopes, rather a very fine probe, with just a few atoms at the apex, is scanned over a surface. The tip doesn't touch the surface under study, it hovers just short of contact, at a distance of less than one nanometre. An electrical "tunneling" current jumps from the tip to the sample. Tunnel current magnitude depends sensitively on tip-sample distance. Tip height can be automatically regulated to maintain a fixed tunneling current. The tip height is recorded at many points and an image is constructed, point-by-point and line-by-line.

Variants of the scanning process allow, in some cases, materials to be altered at the atomic level. Eigler inspired scientists and non-scientist alike when in 1989 he "typed" the letters "IBM" by controllably arranging several 10's of atoms, as shown in Figure 1.³ Just previously, Avouris and Wolowicz showed that STM could be used to provide an atom-resolved view of a chemical reaction.⁴ A clean silicon surface was imaged before and after ammonia molecules were allowed to react at the surface. As seen in Figure 2⁵, unreacted (white appearing) silicon atoms could be readily distinguished from reacted silicon atoms that appeared darkened. In addition to graphically demonstrating a new capacity to monitor structure, and transformations in structure at the atomic scale, the result showed that an STM picture of an atom contains more than 3-dimensional spatial information. It is seen that atoms and molecules have a property akin to colour. Depending on the energy levels probed – which can be selected by adjusting a voltage applied between the scanning tip and sample – atoms and molecules may be rendered visible or invisible. The observation that the reacted silicon atoms and the attached molecules appear invisible, tells us that the electronic energy levels at those particular sites are highly altered from those of the clean surface. These were exciting results – as they pointed to routes for tailoring material properties at the atom scale.

More recently, through a close coupling of experiment and advanced quantum mechanical computation methods, it has become possible to greatly extend our understanding of contrast mechanisms at work in STM images.⁶ This refinement of the technique has in turn allowed relatively complex surface-molecule structures to be determined. Today's state-of-the-art techniques allow hybrid silicon-molecular nanostructures with properties tunable at the level of the single molecule to be designed, created and studied.⁷ The absolute position of the nanostructure is pre-determined by a scanned

probe-directed movement of a single atom. The automatic, multi-molecular step-by-step assembly process can be monitored directly.⁸ An example of a "self-directed" growth process is shown in Figure 3a.⁹ The crystalline character of the chosen substrate imposes a desired order in the molecular assembly. In Figure 3b, a schematic diagram shows how each incoming molecule snatches a hydrogen atom from an adjacent site, preparing a reactive

silicon atom for attachment to the next in-coming molecule.¹⁰

We have understood the essential character of atoms, molecules and the bonds that hold them together - the building blocks of our world - for the better part of a century, but progress in tailoring materials properties has emerged rather slowly. One reason for our limited progress is complexity – nature offers up limitless variations of composition and preparative conditions, leading to endless variations in structure and properties. Milk can be churned into butter or aged to become cheese; common sand can be processed to create glass or to form a silicon microchip; any number of examples can be given. The outcome of a synthetic process often depends on rather subtle differences in processing conditions. A fuller understanding of reaction pathways would help greatly. Research in that area continues, but it is a difficult struggle. Another way forward can come from exquisitely detailed analysis of products. The description above of STM-based capabilities was an effort to show that we have today new "eyes and hands" for addressing matter at the level of individual atoms and molecules. STM, together with other powerful tools, gives us a chance to see subtle material variations resulting from adjustment of preparative conditions. It is this new access to the details of materials

The misconceptions being spread about nanotechnology go beyond those expected whenever a specialized issue is translated for public access.



properties that promises, at least for some subset of materials systems, new understanding and control over matter, and following from those, new technologies.

An example of a technology that will emerge in the relatively near-term derives from the hybrid silicon-organic nanostructure studies described above. By marrying organic materials with silicon, it is anticipated that silicon can be given a capacity to discriminately interact with its surroundings.¹¹ Highly sophisticated techniques that now exist for patterning silicon will be adapted to “address” attached molecules. Schemes are being explored for transducing molecule-molecule attachment or recognition events into electrical signals. The resulting molecular detectors are expected to be inexpensive and effective medical diagnostic tools.

In the more distant future, it is anticipated that techniques learned in creating hybrid silicon-organic detectors, will be merged with ideas for creating more complex molecular functions. Explorations of molecular digital memory and logic devices have already begun. Because computation will require many more “harnessed” molecules and much greater overall complexity, the emergence of molecular computers will take much longer than a five to ten year time frame. We can predict that higher-level molecular functional devices can be made – nature has proven this – but we do not know when such devices will appear.

The examples of current research and of future applications given above describe a research and development process based upon a step-by-step build-up of knowledge, of facing and overcoming challenges, while working toward a practical outcome. No claim is made that cannot be proven and all speculations are tested. This is the norm in the field. Unfortunately, the fantastic outcomes promised by some¹², are based on a most limited understanding of molecular science and no experimental or theoretical backing. Proposed entities, referred to as “nanoassemblers” or “mechanosynthesizers” call upon molecules to act as cogs in scaled-down machines. The proposals unravel for various reasons, most typically because the assumed properties of the molecular elements are not realistic; in some cases molecules are called upon to be impossibly stiff levers or structural ele-

ments, in other instances intermolecular interactions are ignored when in reality those would be dominant, in yet other cases interactions are assumed to be of a very particular strength and character, when no such interaction exists. While rigorously established principles allow a critical dissection and logical discarding of such proposals, such debate has failed to silence the proponents of nanoassemblers and the like.¹³

Does it matter that a fringe belief, after receiving lengthy consideration and a resounding dismissal¹⁴ is maintained by some? Ordinarily, one would think not. But an alarming number of people interested in nanoscience are being misled. For example, the Discovery channel recently ran an item on “Daily Planet”, a normally excellent science program, wherein the colourful, dynamic, and fictitious, assembler animations from the “Foresight Institute” were featured most prominently. It appears likely that it is only a matter of time before some policy makers also

become convinced of these popular notions. At that point, the fringe beliefs become harmful to society. This follows because misinformed discussion can lead to the misjudging of and a tolerance for poor quality or unsafe activities, while at the same time the inhibition of desirable research that could lead to beneficial new technologies.

For an informed discussion about nanotechnology to take place we have to distinguish the ruse from the reality. The widespread perception of nanotechnology today resembles the uninhibited enthusiasm for new technologies seen in the 1950’s and 60’s when promises of personal jet packs and tourist trips to outer space were widely thought to be just around the corner. Just as those claims were fanciful, forecasts of molecular machines, self-assemblers and nanobots are wildly unrealistic. The reality is, that a new and steadily improving grasp of the forces that control the bonds between atoms and within all matter will lead to wide spread change. Changes in materials and technologies will emerge incrementally and steadily for a very long time – beyond the lifetime of anyone living today. Early manifestations of nanotechnology will not be dramatic – perhaps improved plastic packages will emerge – allowing less material to be used while providing strength equal to today’s materials. Later, new sensors, for medical diagnostics and new devices

*For an informed discussion
about nanotechnology to take
place we have to distinguish the
ruse from the reality.*



for communication and information processing will likely emerge. In general there appears to be scope for materials and process improvements that will allow “greener” technologies to develop.

Because the knowledge revealed by nanoscience is fundamental to material properties, it is clear that virtually all areas of science and technology will be affected. There is no question that great good can come of nanoscience. It is also certain that the capacity for devious applications will exist. Society’s efforts to shepherd emerging technologies is hindered by misinformation and fantastic claims. This paper is a first effort to separate the reality of nanoscience and nanotechnology from the fantasy. A sustained effort in this direction will be required to ensure acceptable applications and sound policy development.

Figure 1 – Courtesy: IBM Research, Almaden Research Center. Also with permission from D.M. Eigler & E.K. Schweizer, Nature 344:525, 1990. Unauthorized use not permitted.

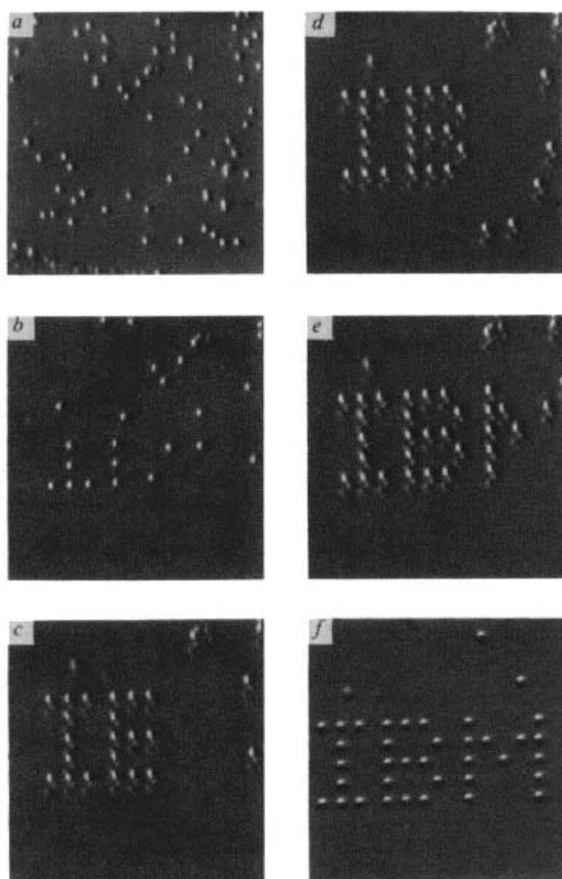
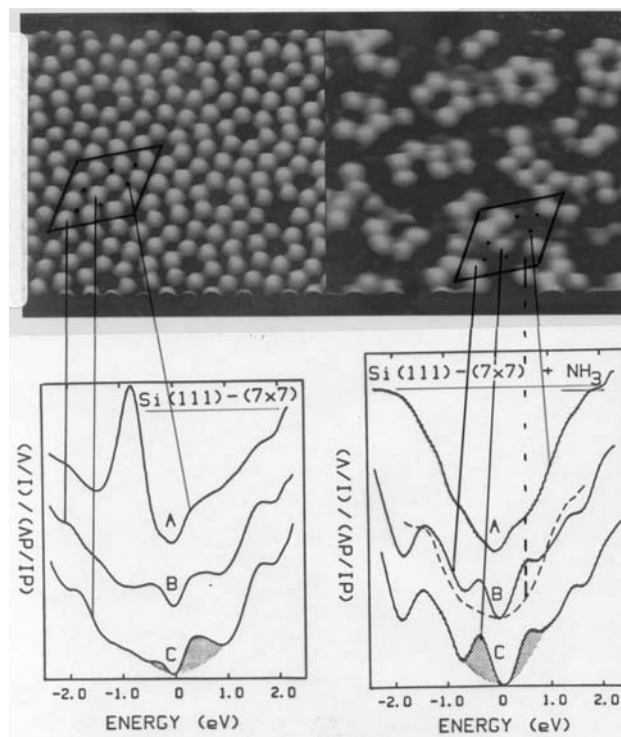


Figure 2 – Reprinted with permission from R.A. Wolkow & Ph. Avouris, Physical Review Letters, 60: 1049, 1988. © 1988 by the American Physical Society.



Figures 3a and 3b are reprinted with permission from Nano Letters, Forthcoming, 2004. Copyright (2004) American Chemical Society.

Figure 3a

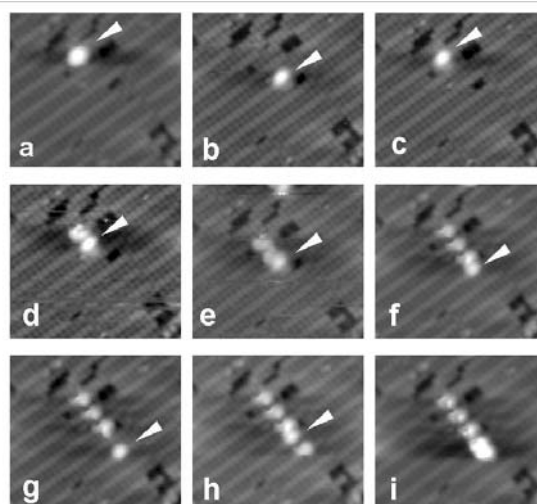
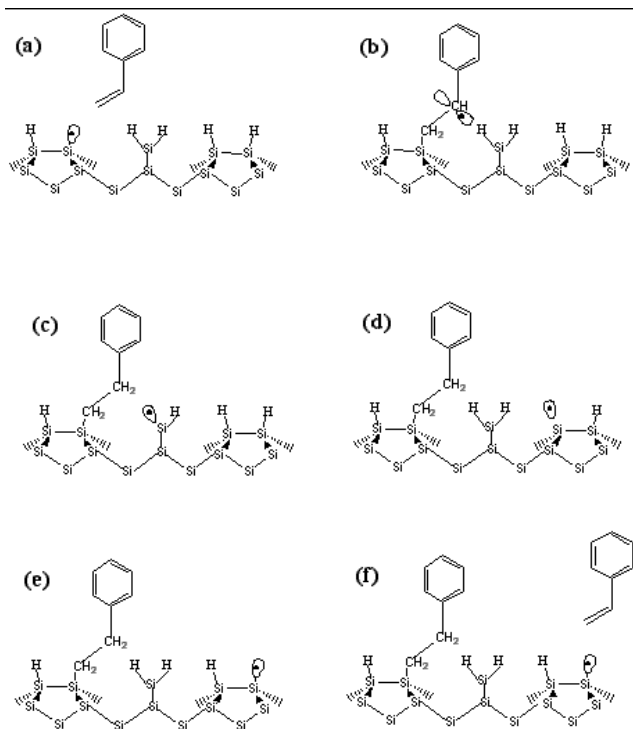


Figure 3b



Robert A. Wolkow, Professor, Department of Physics, University of Alberta and National Institute for Nanotechnology Edmonton, Alberta.

- 1 K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (New York: Anchor Books, 1986), online: Foresight Institute <<http://www.foresight.org/>>.
- 2 G. Binnig *et al.*, "Surface Studies by Scanning Tunneling Microscopy" (1982) 49 *Physical Review Letters* 57.
- 3 D.M. Eigler & E.K. Schweizer, "Positioning Single Atoms with a Scanning Tunnelling Microscope" (1990) 344 *Nature* 524.
- 4 R.A. Wolkow & Ph. Avouris, "Atom-resolved surface chemistry using scanning tunneling microscopy" (1988) 60 *Physical Review Letters* 1049.
- 5 *Ibid.*
- 6 R.A. Wolkow, G.P. Lopinski & D.J. Moffatt, "Resolving Organic Molecule-Silicon Scanning Tunneling Microscopy Features with Molecular Orbital Methods" (1998) 416 *Surface Science* L1107; W.A. Hofer *et al.*, "Adsorption of Benzene on

Si(100)-(2x1): Adsorption energies and STM image analysis by *ab initio* methods" (2001) 62 *Physical Review B* 085314.

- 7 G.P. Lopinski, D.D.M. Wayner & R.A. Wolkow, "Self Directed Growth of Molecular Nano Structures on Silicon" (2000) 406 *Nature* 48.
- 8 Xiao Tong, Gino DiLabio & Robert A. Wolkow, "A self-directed growth process for creating covalently bonded molecular assemblies on the H-Si(100)-3x1 surface" *Nano Letters* [forthcoming in 2004].
- 9 *Ibid.*
- 10 *Ibid.*
- 11 R.A. Wolkow, "Controlled Molecular Adsorption on Si: Laying a Foundation for Molecular Devices" (1999) 50 *Annual Review of Physical Chemistry* 413.
- 12 *Supra* note 1.
- 13 An "open debate" was featured in *Chemical and Engineering News* ((2003) 82:48, 37). Nobel Laureate Richard Smalley, among others, had been openly critical of the views and scenarios offered by Eric Drexler and his organization known as the Foresight Institute. Drexler posted an open letter on his web page, attempting to rebut comments made by Smalley. C&E News published Drexler's open letter and a written exchange between the two. Drexler was unable to understand, or in any case failed to respond, to the limitations brought to his attention.
- 14 Among the author's hundreds of acquaintances in the field of nanoscience, not one gives credence to the nanoassembler schemes.

