Nanotechnology: radical new science or plus ça change?—the debate[1,*]

Faye Scott

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The focus of this debate is to explore the potential of nanotechnology, and more specifically to look at the degree to which it is a radically new departure from anything that has gone before, as opposed to being part of the continuous evolution of scientific knowledge. Regarding timescales: are we going to see nanofactories within just a few decades, or is it many many more years ahead? We shall be looking at engineering versus biology, at managing the effects of nanotechnology, and at the way that we can handle the risks associated with nanotechnology developments.

What biology does and doesn't prove about nanotechnology

Richard A.L. Jones

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The really central issue about nanotechnology is, what is the relationship between biology and nanotechnology?[2] There is an argument from biology, which in some ways is very persuasive, and which is perhaps the strongest argument that there will be something called nanotechnology that will be radical and will be a major departure. I want to argue that the way in which this may turn out is not the way most people with a radical vision about nanotechnology have argued so far. So I want to start with this very important argument. I'm talking about the radical end of nanotechnology, i.e. sophisticated nanoscale machines. The argument that we all must agree on, I think, is that it must be possible to make sophisticated nanoscale machines because biology is full of them. A typical example is the T4 bacteriophage (Figure 1). It is a sophisticated nanoscale machine. Another example is the famous enzyme ATP synthase. These examples—and there are many more—offer a tremendous existence proof of a radical vision of nanotechnology. So we know that we can make these machines.

This argument about radical nanotechnology was first made by Eric Drexler. Does it therefore prove that the Drexlerian radical vision is feasible? Just to expand on this, I

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[1] Held on 26 August 2005 at the University of Nottingham.

[2] Richard A.L. Jones. *"Soft Machines: Nanotechnology and Life"*. Oxford: University Press (2004).

Nanotechnology Perceptions **1** (2005) 119–146

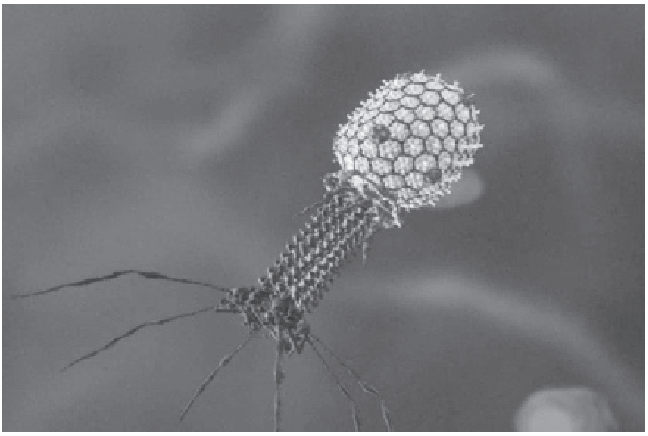

Figure 1. T4 bacteriophage (© Purdue University and Seyet LLC).

want to summarize something taken from Drexler's technical book *Nanosystems*:[3] my argument is that although biology is an existence proof for radical nanotechnology it is not necessarily an existence proof for Drexler's particular vision of nanotechnology as we shall now see. The reason is this: biological machines are not actually mechanical. What characterizes the sort of machines that we see in nature, like the motor protein kinesin, is that they are not made from the familiar hard materials of mechanical engineering, they are made from floppy materials and live in an environment that is dominated by Brownian motion and is highly dissipative. What do I think are the principles of mechanical engineering? I would say that in summary they are simply the application of Newton's laws, so in that sense there is nothing to distinguish advanced 16th century technology such as a pump (Figure 2) from the then active Derbyshire lead mines not too far from where we are holding this debate from Drexler's vision of nanotechnology, which is simply the application of Newton's laws at the nanoscale.

The central and important point I want to make is that the machines of biology are fundamentally different. What's going on in these biological machines is not a simple application of Newton's laws, it is actually an application of another set of laws, summarized by the Langevin equation. We have got a highly dissipative environment, so that instead of a simple force that equals mass times acceleration (Newton's famous $F = ma$) we have a more complex force that equals a friction coefficient times a velocity plus a random fluctuating force, so we have got a dynamics dominated by dissipation, inertia is almost negligible—that's a consequence of having very low Reynolds numbers—and we've got a Brownian environment so we have a random fluctuating force. Biological machines look beautiful and when viewing a simulation you could easily imagine that they work like a mechanical machine on the microscale,

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[3] K.E. Drexler. *"Nanosystems: Molecular Machinery, Manufacturing, and Computation"*. Chichester: Wiley Interscience (1992).

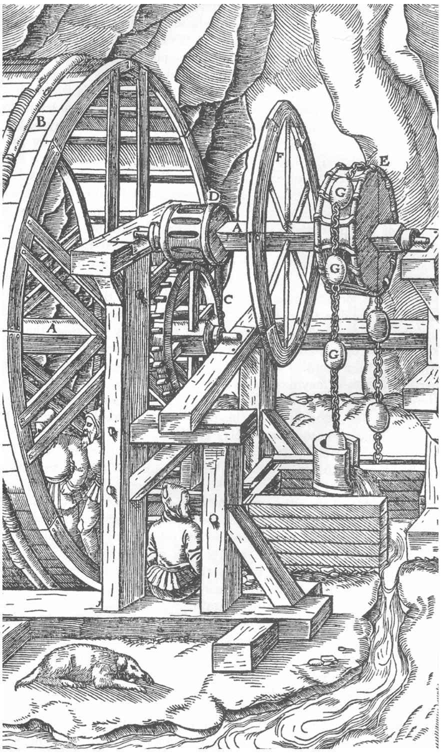

Figure 2. An illustration of a sixteenth century Derbyshire mine pump. Drexler and coworkers posit that this general type of engineering and technology can be scaled down to nanometre dimensions.

but fundamentally they work on a different principle. The question then is, why is the design philosophy so different? One answer is that physics looks different at the nanoscale, hence what is appropriate at the microscale is not necessarily appropriate at the nanoscale.

Let's imagine the iconic nanobot and ask, how would you design a nanoscale submarine? It's very different from designing a submarine at the microscale. You've got viscosity dominating, not inertia, so fluid dynamics works in a completely different way. The thing's buffeted by constant Brownian motion, it's going to be moving around and it's also going to be internally flexing, so you have to ask, how can you make anything rigid enough? You've got very strong surface forces, you know that one characteristic of the nanoscale is that when things come together they stick. Specifically in a medical context, the stickiest thing in the world is protein. So the practical problem that besets anything that gets placed in a biological environment is stopping proteins sticking to it. Those are the issues we have to cope with. We can add to that the big question of how do we make, not just one but the trillions that we shall need.

Let me put in a qualification. We are talking about an environment at 300 K and with water around. That's an important proviso. When I say that physics is different at the nanoscale, it is also different in a biological environment from an ultrahigh vacuum environment at 3 K, and there will be a correspondingly different set of design constraints. So this is not universal statement about the nanoscale, this is a statement about the nanoscale environment as you see it in nature. You've got these different design philosophies: one of which is the mechanical engineering approach. I'm not saying that Drexler is someone who doesn't know physics, of course he does. He talks about Brownian motion, he talks about surface forces. The philosophy of the mechanical engineering approach is to say, I know these things are there, they are problems, let's try to design around them, let's use really stiff materials to avoid the problem of Brownian motion. In contrast biology doesn't design around it, it actually exploits it. You can see this through the efficiency of biological machines. Consider ATP synthase. This is not a piece of jelly cobbled together that just about manages to work, it's astonishingly efficient as an energy converter, more than 95%, indeed its efficiency is so great it's difficult to measure its departure from unity. And why is it so efficient? Because it is exploiting its differences. It is not treating these various features of the nano world as problems, it is treating them as opportunities

Consider self-assembly: complex structures in nature made by self-assembly. Self-assembly is what you get when you take strong surface forces and you take Brownian motion, you put them together and you get this new principle that has no analogue in macroscopic physics, of programming stickiness into the materials, so that when you shake them all around they can try out all the combinations and find the ones that stick. Hence the sticky parts come together in the desired pattern.

How does muscle work? It's Brownian motion plus lack of stiffness. That gives you the idea of conformational transitions. Astonishingly, if you ask the mechanistic question, how does your muscle work? i.e. what actually makes the molecule change shape, the answer is its collisions with the water surrounding it, i.e. the Brownian motion. So Brownian motion is not a problem but something that needs to be exploited.

So my position is that there will be a radical nanotechnology that will be powerful and different from what's gone before, but it will need to learn nature's lessons. There are two ways of doing this: either steal bits of nature, biological nanocomponents, and incorporate them into synthetic structures—I call that biokleptic nanotechnology, or you can try using nature's design principles but with synthetic materials—I call that biomimetic nanotechnology.

Finally, these are the areas I think that are going to drive nanotechnology, with big economic driving forces: sustainable energy, i.e. artificial photosynthesis for solar energy conversion (either biokleptic, e.g. use actual light harvesting complexes from plants and photosynthetic bacteria to generate hydrogen from solar energy, or biomimetic, e.g. dye-sensitized nano-titania solar cells (Grätzel cells), which are compatible with cheap, large area processing; information, organic based electronics; medicine, drug delivery, tissue regeneration etc. Nanobots have a bad reputation. But an interesting question is, if you were to make a nanobot, what would it look like? My answer is, something like a bacterium.

Nanotechnology

John Storrs-Hall

Chief Scientist, Nanorex, Inc., Michigan

Cats and dogs don’t have wheels. Fish and birds don’t have propellers. If we look at biological systems they don’t have many of the basic features that we see in mechanical engineering *except at the nanoscale*. A mechanical engineer would be very familiar with the parts of ATP synthase (Figure 3). Bacteria do in fact have propellers, and there are examples of electric motors, and shafts that carry torque. Evolution did not produce this kind of mechanism at any higher scale, but it did produce it at the nanoscale. So I assert that there is something very propitious about the application of the laws of physics at the nanoscale that is in fact favourable to doing mechanical engineering at that scale.

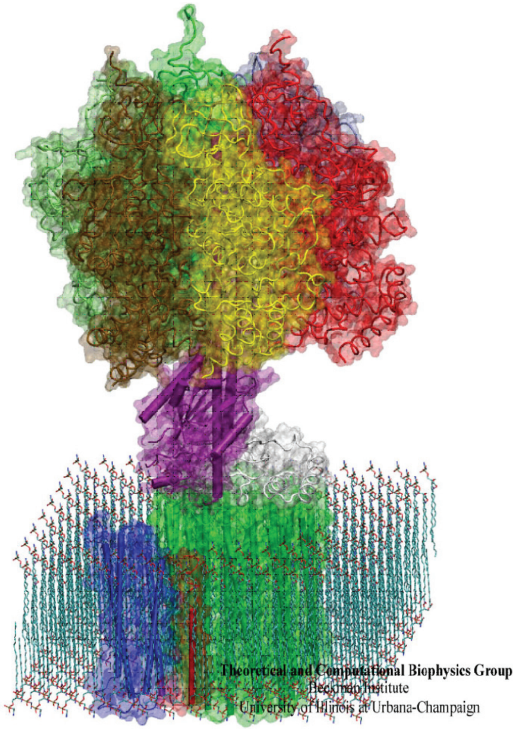

Figure 3. A model of the enzyme ATP synthase, constituted from a ‘molecular mill’ (top), in which an endoergic reaction (the synthesis of ATP from ADP and inorganic phosphate) is driven by mechanical force; Torque-carrying shaft (centre, in purple); electric motor (bottom), in which torque is generated by the passage of protons across the membrane in which it is embedded (© Theoretical and Computational Biophysics Group, University of Illinois at Urbana-Champaign).

The purpose of Figure 4 is to allow one to get a better feeling of the sort of mechanical motions that are taking place at the nanoscale. Note (Fig. 4b) the initial inertial régime during which the bearing is being accelerated to its designed speed, after which the applied torque is essentially zero. As for the planetary gear assembly, it turns out that it is a very efficient transmission gear. In the right operating range it can be over 90% efficient. However, there is elasticity in the shafts, the material is not stiff, which leads to the phenomenon familiar enough to electrical engineers: ringing. I suppose that if one has a mechanical system doing this, mechanically one has to do the same sort of things that an electrical engineer would do, i.e. terminating paths with appropriate impedances to damp the ringing. Engineers have the necessary mathematical tools to help solve this kind of problem at the macroscale, and it does not appear to be any harder at the nanoscale. Yet these nanoscale machines run a million to a billion times faster and have a million to a billion times higher power density.

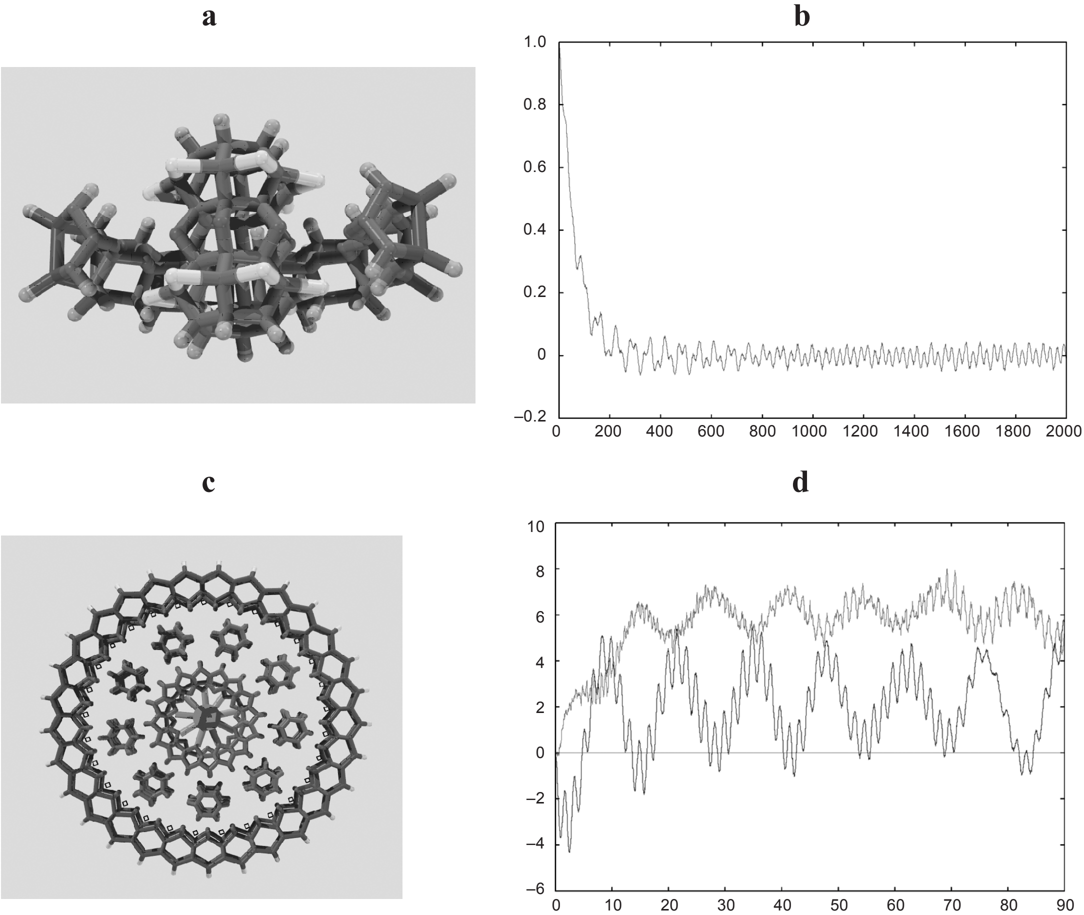

Figure 4. a, atomic model of a simple sleeve bearing; b, atomic simulation of the torque (full scale is 1.0 nN nm) driving the bearing vs time (full scale is about 70 ns), rotating at about 1 GHz (which is about two orders of magnitude higher than the thermal motion of the atoms constituting the bearing). This takes several hundred seconds to simulate; c, atomic model of a planetary gear; and d, atomic simulation of the planetary gear. Upper line, input shaft. Lower line, output shaft. Other details as in Fig. 4b.

We've also been doing some work on how we might actually construct such things as bearings, especially some theoretical work on tips, with which we hope that it will be possible to put together structures of this complexity. The absolute key is the atomic precision of the positioning of the parts. The molecular components may be floppy, but they are not sloppy. If you can build machines with every atom in place, you can come up with some remarkable properties, and if you can't then this sort of thing is really out of your reach, and the same is true of life.

There is of course some intellectual risk associated with tackling something that is this far-off in terms of actual physical realization, and such ventures are sometimes derided by people in the mainstream scientific community. Yet people have been taking risks of this order for a long time. Otto Lillienthal stated "I am far from supposing that my wings [approach] represents perfection of the art of flight. But my researches show that it is worthwhile to prosecute the investigations further". He did not claim that he was approaching perfection in his endeavours, but he did maintain that his results warranted further investigations. I close with the same sentiment as far as diamondoid mechanistic nanotechnology is concerned.

Nanotech visions – broadening the debate

Jack Stilgoe

Demos, London SEI

My contribution to these introductory presentations is somewhat different from the others; I'm not a scientist. Demos is interested in building new forms of democracy: not just in the electoral sense, but in terms of involving people in the decisions that affect their everyday lives. Recently we've been working these ideas into the area of science, realizing that the government is not particularly good at dealing with issues of policy regarding science and society and that public trust in the way that governments deal with science has hit a bit of an all-time low. But we still have problems. Notably, in public thinking about bovine spongiform encelopathy (BSE), and genetically modified (GM) foods, we hear calls for a public debate about technologies, about areas of science that might be controversial. With GM there was a public debate, but everyone derided it immediately afterwards, they said it took place too late to actually make a difference. What we see with nanotechnology is government support for the idea of having an early debate. Unlike with GM foods, most of the applications are well into the future. The few applications already out there are very prosaic and unlikely to have controversial implications for the time being. What we saw in the recent Royal Society of London-Royal Academy of Engineering report[4] is that they not only said that this is the state-of-the-art in

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[4] " Nanoscience and nanotechnologies: opportunities and uncertainties". London: Royal Society and the Royal Academy of Engineering, 2004.

nanotechnology, but that these are likely to be some of the emerging social and ethical and health and environmental concerns, and the sooner we get a debate started the better.

As with all this kind of things, we may legitimately ask whether we are all talking about the same thing. Is there something that we can call nanotechnology, that we can talk about with a shared sense of purpose? Are we indeed talking the same language? If we talk to the public about nanotechnology, is there a way to establish some kind of mutual communication?[5]

So what's in a name and why is the government so interested? Recently I heard George Smith from Oxford University remark that the word 'nanotechnology' was derived from a Greek word meaning to attract research funding. Is that its common meaning? This is of interest both for social scientists such as myself who are looking at concerns over its future realization, and for those people who are making very interesting claims about what is possible in the area of nanotechnology. Some of these claims are about feasibility, such as we heard about in the previous talk. But there are also interesting claims about what society will be like in the future. I was recently rereading Drexler[3] and thinking, what an interesting book it is, not only because of the radical claims about the technology, but also because of the radical claims about what the society that accommodates that technology will look like, and what the public and what the government will have to be like to accept those things.

We can anticipate assertions about how the public will react to nanotechnology. It is easy to say they have a phobia about 'grey goo', although I suspect that very few people have really gone out there and actually asked them. Many of the public's ideas are much more sophisticated than grey goo. So we need to open up this debate about nanotechnology's future. We need to hear the voices of the public, as well as the voices of the scientists. Hence this debate today is very healthy. And let me emphasize: when we ask, what is the future likely to hold? we want not only to know what is possible or feasible, but also what is desirable, in other words what kind of future do we want to see? What are the uses to which nanotechnology should ideally be put?

I am interested that in the radical claims about the technologies, the people, the human element, are taken out. For example, whenever Moore's Law is discussed, the thing that is left out is that people—engineers, scientists and their administrative support staff—actually have to do the work to make the computers better. There's no law imposed by nature upon these people. So my plea is, let's talk about what is possible, but let's put the people back in.

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[5] James Wilsdon, Brian Wynne and Jack Stilgoe, 2005. The public value of science, or how to ensure that science really matters, Demos, http://www.demos.co.uk/catalogue/publicvalueofscience/.

Molecular manufacturing

David Forrest

President, Institute for Molecular Manufacturing (IMM), Foresight Institute, Palo Alto, California

Josh [Hall] has already talked about the gears and bearings of molecular manufacturing. One of the problems that we—the community working towards the realization of molecular manufacturing—are up against is that many people simply do not believe it's feasible. Now Richard [Jones] brought up the point that it works in biology, so of course it is feasible—to which the sceptics respond that there is something special about biology. But then there is already evidence from nonbiological systems. For example, in 1999—six years ago!—Ho and Lee at Cornell University took the tip of a scanning tunnelling microscope and by passing current picked up a single carbon monoxide (CO) molecule from a silver substrate and moved it over to a single iron atom that was sitting elsewhere on the silver substrate and passed current of the opposite sign to release the CO, whereupon it directly bound to the Fe (Figure 5). The operation could be repeated. This experiment spectacularly demonstrated the point that it is possible to do positional assembly by bringing a single atom to a single molecule or vice versa.

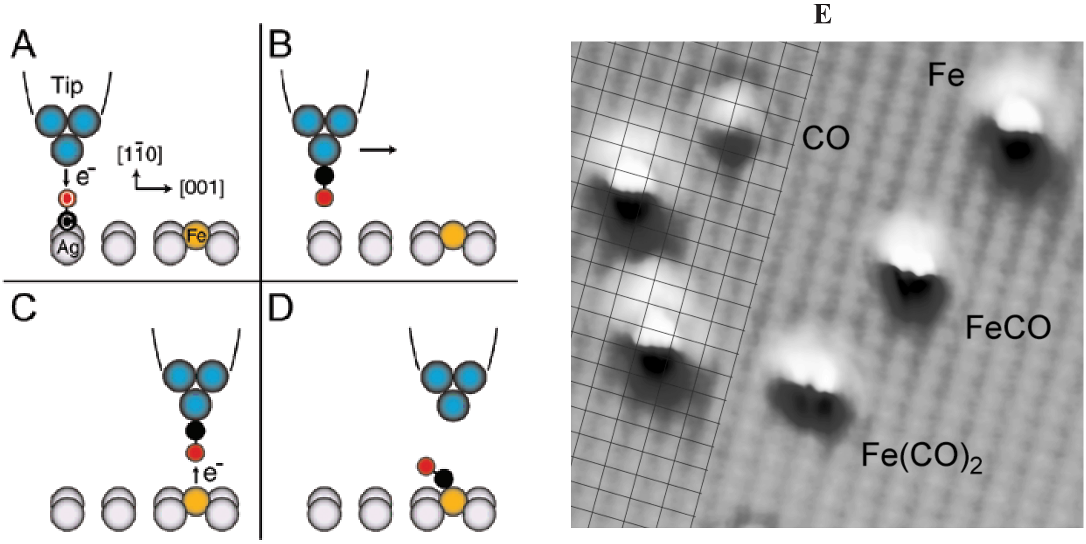

Figure 5. Pickup of a single CO molecule with the tip of a scanning tunneling microscope (A and B), and its deposition onto an iron atom (C and D). The experiment was carried out at 13 K. Part E, scanning probe micrograph of the mechanosynthesis (from H.J. Lee and W. Ho. *Science* **286** (1999) 1719).

There are a lot of possible designs for molecular manufacturing and molecular mechanical systems, and many of them appear in *Nanosystems*.[3] I am not going to repeat what Josh has already described, but I want to particularly address the concept of going from a chemical solution down to the ability to positionally control and manufacture objects with nanometre precision. Figure 6 illustrates a so-called *sorting rotor* that accomplishes this transition. On the left one has a reservoir of molecules bumping around with Brownian motion. The rotor has cavities for the molecule one wants to accommodate, and the cavity has selective stickiness for that molecule. Hence on the left one has the kind of molecules one wants coming in from an environment in which Brownian motion dominates and snapping into place, and on the right (B) they are being transferred to what is the equivalent of a conveyor belt, where the molecules are essentially fixed in orientation and one is controlling their trajectory. Furthermore, note that the mixture is being purified by excluding the molecules that don't fit into the cavity.

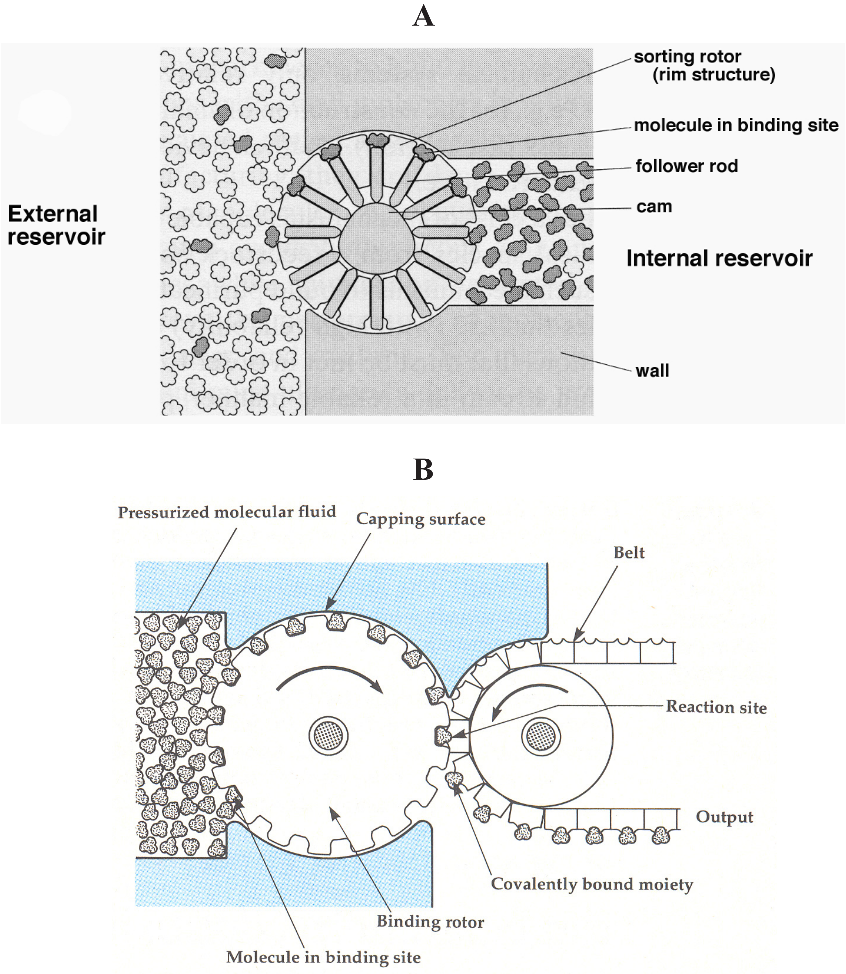

Figure 6. A, schematic diagram of a sorting rotor; B, the sorting rotor showing the transition from an environment with Brownian motion to a eutactic environment.

I want to emphasize that the essential concept of nanosystems is the passage into an environment in which all the molecules have their trajectories and their orientations controlled, i.e. what is called a eutactic environment. In other words one is moving from an environment where there is Brownian motion into an environment when all the motion is controlled. Of course there is still thermal vibration, and one does have to take account of that in terms of positional uncertainty, which is an example of the strong necessity of taking physics at the nanoscale into account.

A couple of points with which to finish up. First, people are building molecular machines now. Figure 7 shows a nanoscale electric motor built by Alex Zettl and his colleagues at Lawrence Livermore National Laboratory. It's based on nested carbon nanotubes with selective etching. Gold electrodes connect the outer ring of the carbon nanotubes and there is a gold rotor in the middle. By applying a voltage across the electrodes one can spin the rotor resting on the nested carbon nanotubes. This is a molecular motor built three years ago!

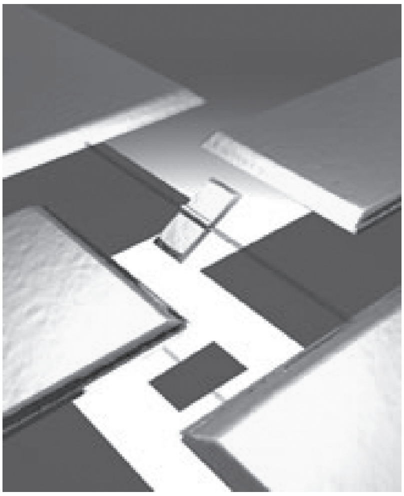

Figure 7. The Zettl nanomotor. A rotor (the plate at the centre of the image) is attached to a multiwalled carbon nanotube. Voltages are applied to the nanotube anchor pads (at the top left and bottom right corners of the image) and to stator electrodes (the other pads seen in the image) to drive rotation of the rotor. (A third stator electrode is below the nanotube/rotor). [From A.M. Fennimore et al. "Rotational actuators based on carbon nanotubes". *Nature* **424** (2003) 408].

My last point: we can argue whether the design of nanodevices ought to be biological in nature, whether they ought to be soft machines or hard machines, but this is not so important. The essential point is, do we or will we have the functionality that is being claimed for molecular manufacturing systems?

Finally, it is really important that as we develop molecular manufacturing systems, we do so in a safe and responsible manner. In that regard I should like to mention that Foresight (which has been around since 1986 exploring policy) and the IMM have proposed a set of guidelines (Tables 1–3) in order to ensure that we don't have anything like the grey goo catastrophe. We think that it is entirely avoidable if we have a reasonable set of consensus standards and we adhere to them. *Note added in proof*: David Forrest has posted some additional comments on the debate at http://davidrforrest.com/pub/forrest_debate_points.html. Richard Jones has, in turn, responded to these post-debate points at www.softmachines.org/wordpress/?p=172.

Table 1. Foresight guidelines for molecular manufacturing: Scorecard 1: Nanotechnology Professional Guidelines (Self-scoring: 0–5, 0 = no compliance, 5 = high compliance. Highest score in this section = 40).

1. Nanotechnology developers adopt and practice professional guidelines relevant to the responsible development of both near term and advanced nanotechnology.
2. Nanotechnologists attempt to consider proactively and systematically the environmental and health consequences of their specific technologies. They recognize that the scope and magnitude of potential problems are reduced to the extent that they consider the possibilities, and plan to minimize their effects.
3. Nanotechnology research and development is conducted with due regard to accepted principles and practices of environmental science and public health, with the understanding that significant changes in physical and physiological properties may occur when macroscale materials are developed and utilized on the nanoscale.
4. Nanotechnology products are conceived and developed using total product lifecycle analysis.
5. Molecular manufacturing system designs make no use of self-replicating machines.
6. When controversy exists concerning the theoretical feasibility or implementation timing of advanced molecular nanotechnologies, such as specialized molecular manufacturing components or assemblers, researchers address and clarify the issues rapidly, and attempt to resolve any controversy openly.
7. Any use of self-replicating systems is avoided except in approved and controlled circumstances.
8. Any developers who design or build self-replicating machines adopt systematic security measures to avoid unplanned distribution of their designs and technical capabilities. Both potential benefits and risks of alternative technologies are explored actively, in a balanced and rigorous manner.

Table 2. Foresight guidelines for molecular manufacturing: Scorecard 2: Nanotechnology Industry Guidelines (Self-scoring: 0–5, 0 = no compliance, 5 = high compliance. Highest score in this section = 4).

1. Industry self-regulation is practiced proactively, and tailored to the specific risk profile of the nanotechnology under development. For example, carbon nanotubes should be developed with specialized industrial hygiene controls for particle inhalation or absorption risk. Toxicology studies relating to nanomaterials should be advanced as rapidly as is feasible.
2. Self-replicating machines are distinguished from non-self-replicating manufacturing systems and end products.
3. When molecular manufacturing systems are designed or implemented, they use no self-replicating machines.
4. Any molecular manufacturing device designs specifically limit proliferation and provide traceability and audit trails.
5. Encrypted molecular manufacturing device instruction sets are utilized to discourage irresponsible proliferation and piracy.
6. Use of self-replicating systems is avoided except in approved and controlled circumstances.
7. Self-replicating machines (if any) have absolute requirements (e.g., for externally supplied information, interventions, environmental conditions, materials, components, or exotic energy sources) that are available only where deliberately provided to enable operation of the machine. Thus, self-replicating machines are designed to be incapable of replication in any natural environment.
8. Self-replicating machines (if any) are incapable of evolutionary change. For example, the information that specifies their construction is stored and copied in encoded form, and the encoding is such that any error in copying randomizes and thus destroys the decoded information.

Table 3. Foresight guidelines for molecular manufacturing: Scorecard 3: Government Policy Guidelines (Self-scoring: 0–5, 0 = no compliance, 5 = high compliance; Highest score in this section = 55).

1. Regulatory controls distinguish the wide variety of nanotechnologies, and recognize that their different risk profiles require different regulatory policies. Nanomaterials and non-self-replicating nanotechnologies and their end products are distinguished from potentially self-replicating technologies.
2. Regulations promulgated by researchers, industry, or government provide specific and clear guidelines, and encourage inherently safer designs for nanotechnology and molecular manufacturing.
3. Regulators have specific responsibilities and authorities, for providing efficient and fair methods for identifying different classes of hazards, providing approvals when necessary, and for carrying out inspection and enforcement. The goal is to provide the minimum effective regulatory environment to ensure the safe and secure development of various forms of nanotechnology.
4. Economic incentives are provided through discounts on insurance policies for molecular manufacturing and development organizations that certify Guidelines compliance. Willingness to provide self-regulation and open access for third party inspection that safeguards proprietary technology are a condition to utilize advanced forms of molecular nanotechnology.
5. Access to non-self-replicating special purpose molecular manufacturing systems and products is unrestricted unless the special purpose capabilities pose a specific risk.
6. The community of nations and non-governmental organizations practice an effective international means of restricting the deliberate misuse of molecular nanotechnology. Such means should not restrict the development of non-self-replicating nanoscale materials, molecular manufacturing systems, or defensive measures.
7. Accidental or willful misuse of nanotechnology is constrained by legal liability and, where appropriate, subject to criminal investigation and prosecution.
8. Eventual distribution of self-replicating molecular manufacturing development capability is restricted, whenever possible, to responsible actors that have agreed to practice these Guidelines. No such restriction need apply to special-purpose, non-self-replicating molecular machine systems, or to the end products of molecular manufacturing that satisfy the Guidelines.
9. Governments, companies, and individuals who fail to follow reasonable principles and guidelines for development and dissemination of MNT are placed at a substantial competitive disadvantage with respect to access to companies, collaborative organizations, R&D funding, plans, designs, software, hardware, and cooperative market relationships.
10. Industry and government developers collaborate on continuous improvement and use of best practices in nanotechnology and risk management, including the theory, mechanisms, and experimental designs for inherently safer molecular manufacturing, monitoring, and control systems.
11. Regulatory entities sponsor research on increasing the accuracy and fidelity of environmental models of nanotechnology and risk management, as well as the theory, mechanisms, and experimental designs for built-in safeguards and advanced nanodevice defensive or immune systems.

In summary:

There is a clear vision of molecular manufacturing.
Its theoretical basis has been established through engineering analysis.
Positional molecular assembly is experimentally proven.

Molecular machines based on carbon nanotubes have been made—"hard machines" are a reality.

The technology is coming—but there is much to do still.

Both new and old, safe and unsafe, that's nano!

Saul Tendler

School of Pharmacy, University of Nottingham

Let's look at nanotechnology and ask a few simple questions.

First, what is nanotechnology? My point here is that it's not one science, it's a collection of sciences. In that way (as well as many others!) it is different from genetically modified organisms (GMO). That is essentially a single technology, whereas the scope of nanotechnology is much broader. Hence it's much safer to talk about nanotechnologies.

Second, is it old or is it new? I would say that it is both. Large parts of nanotechnology are not new. For example, nanoparticles mostly belong to that part of chemistry called colloid science, which was already well established at the beginning of the twentieth century. Now it's rebranded as nanotechnology, and operates in a different context, so it's important to look at the context, one aspect of which is that the size and scale of the phenomenon under consideration needs to be taken into account.

Context is very important when it comes to assessing risk. Again take nanoparticles. Nanoscale particles are around us all the time. If you simply walk outside you will inhale millions and millions of nanoparticles. And how many of you imagine that you have an instrument at home that can produce nanoparticles at a great rate, mostly in the morning? Most of us have instruments called toasters. I, and most of us, are quite happy to be exposed and let others be exposed to such tasty nanoparticles.

Opportunities and risks are important and we need to understand them. What is important in nanotechnology is that certain materials below a certain size exhibit new properties. Materials that we thought about as being unreactive become reactive, and this is where we should start to become concerned. There is a need to regulate. Nanoparticles are out there on the High Street and they are used daily. Sunscreens obtainable in any retail shop contain nanoparticles, usually zinc oxide or titanium dioxide, and no one has shown conclusively that the nanoscale sunscreen particles are safe. Is it safe to rub them into the skin? We do not know at present, especially if one has eczema or sunburnt skin.

At present, we normally have no idea whether a particular product available on the retail market contains nanoparticles. This cannot be right. There is a further dilemma; is it better not to use a sunscreen and risk being sunburnt or even getting a melanoma, or risk unknown toxic effects from the nanoparticles? This is a risk-based dilemma, and it is a dilemma we need to understand.

A couple of closing observations. There are many outrageous claims made about nanotechnology and we need to be cautious about this. Even government organizations make outrageous claims. Look at the National Science Foundation in the USA. They claim that by 2015 cancer will be eradicated because of nanotechnology. Not curing it, *eradicating* it so that it will simply not exist, like smallpox. This sounds like good news but also sounds unlikely. It reminds one of the alchemists who claimed that they could turn lead into gold.

Biology has been doing complex nanotechnology for years. One needs to have a clear distinction between biotechnology and nanotechnology—they are not at all the same thing. If you wanted to make for example foot and mouth disease virus particles, would you use molecular machine and make it bit by bit by bit? Probably not—you would grow it in a pig or a jar. Biotechnology is the way to mass produce biology, and it is already doing it.

There are undoubtedly areas of growth falling under the 'nano' umbrellas: materials and electronics and nanomedicine. These are interesting experimental sciences. Examples are quantum dots as probes, and DNA motors. These things are exciting, and they may turn into products. But all of these products will have to conform to the rules of nature and the laws or physics.

Floor debate (questions to the panel)

Robustness and reliability

Q: James Hayton. (a) Referring to the nanoscale factory with the conveyor belts and so forth, how does friction come into that? and (b) in surface science experiments, we know that it is very difficult to keep them free from defects. It's a long way from moving one molecule or atom from one place to another to scaling that up and keeping the system free from defects. How do you propose to get around that?

A1: Hall. Basically when you're designing a system like that the phenomena that dissipate energy are not really the same as friction at the macroscale. On the other hand you do have phenomena that you have to worry about. A number of them get analysed and discussed by Drexler in *Nanosystems*.[3] Nowadays, you can do a much better job simply by doing a molecular dynamics simulation of a specific system, and it's looking feasible to design systems where the modes of motion that you're interested in for a mechanical device (e.g. a bearing) are only very weakly coupled to modes that would dissipate energy. It's also easy to design systems where that's not true and one makes a device that wastes energy like crazy and the device will overheat in milliseconds, but it does appear to be possible to design systems where there's enough lack of coupling between the modes of interest and the dissipative modes that you can get well over 99% efficiency, much better efficiency in fact than in typical macroscale system.

A2: Forrest. Measurements have been done on nested carbon nanotubes, and it has been found out that there is extremely low friction between those surfaces. But as to your question about the eutactic environment, i.e. how do you get that, in the devices I showed you we assumed that you already have the ability to assemble things to atomic precision, which we don't have right now, so I agree that with today's technology it is very difficult to keep contamination out of the system. Given that you have a system that will build things atom by atom to atomic precision it will be possible to keep contamination out. Some things to worry about are: hydrogen has finite diffusion rates in diamondoid materials, so you will have to find a way of grabbing the hydrogen and transporting it back out, and you can't keep out cosmic rays, so there will be the occasional cosmic ray coming in and knocking out a conveyor belt, so there is an issue of reliability (some of which are addressed by Drexler in *Nanosystems*).

A3: Jones. I think this is a crucial point and it will be a very difficult practical barrier getting in the way of the implementation of some of those designs. Regarding the friction issue there is a lot more known about friction at the nanoscale than there was say 10 years ago, and there is some understanding of what these wearless friction mechanisms are. Simulations indicate that some of the estimates may be underestimates. The question of contamination is more serious. What really gives you friction is when you get tribochemistry, essentially uncontrolled chemistry. It's interesting that the Drexler vision is all about mechanochemistry. Now mechanochemistry can do bad things as well as good things. If a contaminating molecule gets into two things that are moving apart there may be free radicals generated: all the simulations are generally carried out with perfectly terminated surfaces, but if this condition is relaxed then all bets are off. At the moment I can imagine that this technology would work in ultrahigh vacuum at three degrees Kelvin but by necessity the systems are going to have to communicate with the outside world and come into contact with essentially uncontrolled environments, e.g. in biomedical applications, for which the engineering difficulties of keeping the environment out of the inner workings of a nanosystem are going to be a very major challenge.

Simulation veracity

Q: Peter Feibelman. What's your opinion on how faithfully a force field needs to represent nature before you can trust the output of a simulation to mean anything other than a way of making Hollywood style pictures? My experience of force fields is that typically they are terrible and that if there is no validation then there is no way of telling whether the force field means anything or not.

A: Hall. That's pretty true. The force field we are in the process of developing for simulations is a new one that we're developing specifically for simulations of this kind, because all of the ones that are available that are developed with solution chemistry in mind do in fact give you very poor results in many of the situations we are interested in modelling. Finding a good force field is a serious endeavour that I am spending quite a lot of time on developing a new one, and I'm not going to trust my life to it until we get some experimental verification. Let's put it this way: these are issues that we are aware of and concerned about, and are addressing.

A: Jones. A simple question to ask about any simulation is, is it able to reproduce things like surface reconstruction behaviour? These are hard things to simulate.

Q: Trevor Rayment. On the basis that one man's contamination is another man's chemistry: is there a known chemistry that would allow one to build something atom by atom? I'm thinking especially of the difficulty of taking something from one chemical environment and putting it in another.

A: Hall. The best we've got so far is the paper on carbon transfer by Allis and Drexler,[6] where they are essentially just monitoring the energetics of the deposition. It's fairly preliminary stuff and there's a lot more work to be done. Once there is reasonable agreement on the theory then there will be a lot of work to design the machines that put together the parts we've been talking about here. There's quite a long hard road ahead, but each step seems to be feasible, and we have not run into anything like a showstopper. The main problem is that we just don't have enough people working on it to make progress faster than we are doing at present.

Quantum effects

Q: Chris Binns. The possible missing ingredient in this discussion about forces are mesoscopic scale new forces that appear at the sizes we're talking about, such as the Casimir force. This seems as if it might provide a bit of a link between the biology and the engineering side of things, because although to biological systems that have evolved with them they are as natural (at the nanoscale) as gravity is to us.

So I just wonder if you would comment on that, and in particular on the effect that leaving out a force like this could have on nanosystems.

A: Hall. As far I understand it, that force is reflected in the non-binding interactions using Buckingham potentials taking into account atoms that are nearby. The Casimir force is accounted for in that particular interaction, and it is actually part of the simulation.

Q: (cont'd). Binns. It will change magnitude, possibly even with changes in the shape of a cavity. That kind of thing is really important for biological systems and the sort of things that produce self-organization. The force might even change sign with a change of shape of a cavity.

A: (cont'd). Hall. The sign changes really fast, you put atoms close and you get repulsion and you put them far apart and you have attraction, so the sign changes all the time.

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[6] D.G. Allis and K.E. Drexler. *Journal of Computational and Theoretical Nanoscience* **2** (2005) 45–55.

A: (cont'd). Jones. Firstly, that's absolutely right. Clearly, those kinds of forces are dominant at those scales and of huge importance in self-assembly. Secondly, it depends what you mean by Casimir force, the classical Casimir force arises through electromagnetic field fluctuations, and it has been dealt with in the kind of simulations that we've been talking about, but only at the level of pairwise interactions, which is not a particularly good approximation, and it is in fact very hard to ensure that these dispersive forces are right. Thirdly, there is the idea of a generalized Casimir force that comes from any kind of fluctuations, particularly the Brownian fluctuations, and interestingly it's increasingly starting to look as though the interactions in proteins are actually mediated by fluctuations, rather than by classical physical forces. The classical example is the Helfrich force that acts between membranes, membranes have a repulsive force between them simply because they fluctuate due to Brownian motion. The number of configurations is therefore reduced as they come close, which produces a net repulsion. This has a formal similarity to the Casimir force, but it is a classical fluctuation of structure, rather than a fluctuation of electromagnetic field. So it is an interesting point in modern biological physics as to how important those forces are, and the answer is more than people suspected, maybe not surprisingly given that they were mostly discovered only 10 or 15 years ago.

Nanomachine production

Q: Clive Roberts. Is self-replication of nanomachines possible? Is there a vision of how it could actually be done?

A: Hall. We're fairly certain that biological machines can replicate! I've spent a fair amount of time investigating self-replicating manufacturing architectures. If you have the basic mechanical components, it's not really all that difficult to build a self-replicating machine. It's actually reasonably straightforward to build one at the macroscale, assuming that you have a supply of parts. The hard part is to get the macroscale machine to take raw materials and process them and make usable products, and one of the reasons for wanting to get down to the nanoscale is that there appears to be very good control over atoms, and therefore it's easy to make parts that are exactly the same from instance to instance, which is probably why you see biology operating at that scale. You can get the phenomenon of self-replication from evolution at the molecular scale, and all the stepped-up applications that occur in biology above the molecular scale are simply based on the molecular scale replication itself. It appears to be a 'sweet spot' in the range of possible machine configurations and sizes to do this at the nanoscale. Replication in the manufacturing base is of the utmost importance. The basic productivity of manufacture depends critically on the amount of time it takes a given unit of capital to create another unit of capital of the same size. Essentially what happened in the Industrial Revolution is that the time was reduced and you could replicate in a much briefer period of time the capital of industry using the productivity of the capital of industry. Where the nanotechnology of our kind would really make the most difference is in what we predict the amount of time would be to replicate a relatively large quantity of productive capital, and that is essentially the key point that leads to many of the fantastic-sounding claims, they just follow from that. Once you have a factory that can build a copy of itself in less than a day then a whole bunch of assumptions in economics simply become invalid.

A: (cont'd). Forrest. What we're talking about here is building large objects, macroscopic objects, to atomic precision with virtually no defects and doing this in some finite amount of time, and in order to do that you need massive parallelization, not just billions or even trillions but numbers that tend towards 10^{23}, all working together. In order to get those kinds of numbers you've got to have machines that can make many many copies of themselves and which can be reprogrammed to make parts you want to make in order to make the desktop or larger molecular manufacturing system. One of the criticisms we've had for a long time is that nobody knows anything about self-replicating machines, but actually there is a fair body of knowledge about this, e.g. Freitas.[7]

A: (cont'd). Moriarty. (a) Just to clarify, that work [referring to Ref. 6] and quite a lot of Freitas et al.'s work is actually density functional theory (DFT)-based, so we are moving away from molecular mechanics. (b) The example you (Forrest) showed (the carbon monoxide and iron to build up FeCO) explicitly involves tunnelling reactions, and is done at 13 K. To date there has not been a single mechanosynthesis experiment, in that the most basic step in terms of abstracting a hydrogen atom from a diamond surface has not been done.That has to be proved in order to demonstrate the viability of the machine approach. I've never been able to square that with the statement that there are no showstoppers—not one experiment has been done, correct? Some of the calculations are based on very rudimentary force fields. Even the higher level DFT work uses a cluster as its object, but that cluster has to be supported, and the structure that is supporting it—the tip—is not taken into consideration. So to say that there are no showstoppers when we haven't seen a single experiment seems to be an exaggeration. People have abstracted silicon [atoms] from silicon in the atomic force microscope,[8] but what is needed is to do that on a hydrogen-terminated silicon surface, or a hydrogen-terminated carbon surface. Those are really good choices because they don't reconstruct, and that's the key thing (especially regarding contamination), as so many surfaces do reconstruct.

A: (cont'd). Hall. I would define a showstopper as a piece of knowledge that proved that something couldn't be done as opposed to a lack of a piece of knowledge that proved it could be done.

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[7] R.C. Merkel and R.A. Freitas Jr. *Kinematic Self-Replicating Machines*. Georgetown, Texas: Landes Bioscience (2004).

[8] N. Oyabu et al. *Physical Review Letters* **90** (2003) 176102.

A: (cont'd). Feibelman. The problem is that there are no showstarters.

A: (cont'd). Tendler. I think that the same is true of the self-replicating systems. To take an earlier observation, what we're dealing with is chemistry, you have to show the chemistry that would be involved to produce a self replicating system. Waving our hands and saying that this is feasible, everything is possible, is unacceptable.

A: (cont'd). Forrest. I certainly agree with you, Philip [Moriarty], that experiments need to be done and that the lab work is not there yet, but they have been a number of theoretical analyses of the hydrogen abstraction reaction, first by Charles Musgrave and then by Donald Brenner, e.g. showing a diamond anvil coming down onto a diamondoid surface, and what his molecular dynamics simulations (at room temperature) have shown is that the hydrogen abstraction reaction does in fact work. You're right in that we still need to do the lab work, but the analyses that have been done so far show that it will work.

A: (cont'd). Moriarty. It's a question of duplicating sites. If it's an AFM tip with a radical centre at its end, which you do need for a lot of the proposed chemistry, you've got to find the site, and you've got something that is very reactive moving about to find an individual site. Recall the point that James Hayton raised earlier about contamination. Anyone who works with UHV knows that there are quite a few adsorbates you do not want, and getting rid of that kind of contamination is incredibly difficult. That's not to say that it is not a very interesting problem (thinking about how you might be able to functionalize a tip), but it is simply an incredibly difficult problem and the molecular manufacturing community need to realize that and not just baldly say that there are no showstoppers.

A: (cont'd). Forrest. I agree with you. I cringe when I hear people just brushing things off, and there are many of us who realize that these are hard problems to solve and that they have to be solved. The analysis that has been done so far simply shows that we have a theoretical basis for believing that we can do this.

A: (cont'd). Hall. It may be worthwhile to point out that Drexler's preferred pathway is through biology.

A: (cont'd). Moriarty. That seems to be an even less likely route [to diamondoid molecular manufacturing]. I take note of the fact that no one in the vast worldwide scanning probe microscopy (SPM) community is working on Drexler's polymer-based strategy [i.e. Stage 1 in Chapter 16 of *Nanosystems*]. On the other hand, Freitas and Merkel have made a very good choice by pursuing the UHV atomic manipulation approach, because that is being very actively investigated by the SPM community.

A: (cont'd). Jones. Regarding the route through wet systems, we have these examples by Ned Seeman on DNA.[9] But this is a completely different design philosophy, and the two are not really compatible. Hydrogen-terminated diamond may be a good choice for all kinds of reasons, but we have to remember when considering projections

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[9] W.B. Sherman and N.C. Seeman. *Nano Lett.* **4** (2004) 1203.

for using it for nanosystems that diamond is not enough. The systems have got to have other things apart from diamond. Consider the example of the electrostatic motor. When we read about the huge power densities that we will get with nanotechnology, remember that this relies on two different metals and an insulator whirling round with a gap that controls the tunnelling current.

A: (cont'd). Moriarty. Metals are a problem, because metals diffuse a lot at room temperature. The problem that comes up time and time again in discussions with the molecular manufacturing community is that although in principle the parameter space in which one can make choices is very large, in practice only a very small number of materials might actually work.

Public perceptions

Q: Michael Smith. Given the public perception about grey goo and things like that, and considering that the technologies that we have just been talking about seem to be a long way off from making nanobots and that sort of thing, is it (1) reasonable to talk about nanotechnology as one science encompassing things that we have got now, like nanoparticles in sunscreens, and another dealing with things that are years and years away? and (2) do you think that we ought to be trying to engage the public more about where the state of nanotechnology is now, because a lot of people have the idea that we are only a few months away from making self-replicating autonomous nanobots and so on, and realizing a scenario like that described by Michael Creighton in his novel *Prey*.

A: Jack Stilgoe. Firstly I'm not sure that all that many people are really do have that idea. One of the problems that we have in public engagement issues is that quite a lot of people read the Daily Mail! Another problem we have is that scientists and policy makers quite often look at the Daily Mail and think that it represents public opinion, which it in no way does. (There's plenty of social science work to suggest that when people pick up a tabloid newspaper they consider that the content is mostly rubbish.) A really interesting thing about nanotechnology is that actually public concern and public worries are very much up in the air. There are, I agree, some specific emerging concerns about the toxicology of nanoparticles that need to be addressed, and that's partly a task for public engagement and partly a task for regulatory science. Quite a lot of the time when we talk about nanotechnology and society it emerges that grey goo as a focus for public concern has largely been debunked, but it serves a useful social purpose, not so much regarding the mechanics of how it might occur, or the likelihood of it occurring, but regarding what concerns expressed in terms of grey goo can tell us about the way that people relate to technology. With GM it was pretty much game over for the food technology companies when the term "Frankenstein foods" appeared in the tabloids, because that seemed to tap into a way that people related to GM technologies, such as their lack of controllability, the uncertainties around them, and the fact that the

GM companies appeared to be scarcely accountable for their actions. The important thing that we can do is listen when people talk about things like grey goo (which I don't believe they are doing on the whole) and ask what lies behind it. That tells us something socially useful about how people relate to their technologies and makes us think that maybe we should let people have more say in their technological futures.

A: (cont'd). Tendler. Would you be happy if people took a nanomedicine? Pragmatically, if a sick child then got better people would be very happy with nanotechnology. There are dangers and risks, and it's very important that people do not pretend that nanotechnology doesn't exist, because it clearly does: this is about people understanding science, and it follows that it's important that people are given appropriate and accurate information. So for example I'm a fan of certain materials containing nanoscale products being labelled accordingly so that people can see that it contains nanoparticles and make a choice. One of the difficulties is that there are an awful lot of materials that contain nanoparticles, but that doesn't mean that they could release nanoparticles. There are many materials that do not contain nanoparticles but which can release some under certain conditions. An example is a wooden bench: if it caught fire it would release nanoparticles abundantly, but it seems absurd to label it with a statement that if it caught fire it would release nanoparticles. The tyres on our cars contain nanoscale carbon black particles, but they're not going to release the carbon black under normal circumstances. The issue is about people understanding science and technology better, probably more than anything else understanding risk, and within the UK at least there is a real lack of understanding about risk and science and their interrelationship.

A: (cont'd). Stilgoe. Can I just add that it's also about scientists understanding people. Scientists quite often feel as though it is somehow more objective to think about their work in isolation from society than in a societal context, so they remove themselves from thinking about some of these broader questions. It's important for them to actually themselves ask people what they think about their work, and ensure they get out into the world and speak to people about it.

System problems with complex structures

Q: Michel Rossi. Molecular biology is a very descriptive science—consider the biochemical pathways and so on and so forth. When I see your animations of molecular motions I ask myself the question, what is the driving force of all of this? As long as we don't know what the forces are we're like a blind man trying to control a machine that we don't know where it's going. This question of driving force has to do with the conformation of proteins, entropy, free energy etc., and we don't even know in such a complex system what the system actually is. Consider for instance the cell interior, what do you take as the system? It is very crowded, and if you change the conformation of a protein at one spot, hundreds of nanometres away you can affect the chemical environment of other proteins. The movies of the type that are commonly displayed in presentations about nanotechnology give a completely wrong impression; one might imagine for example that one can make a macromolecule rotate and not influence molecules around it. At the moment the whole thing looks like a house of cards.

A: Hall. You have one very good point, and that is that there is another input into the process of designing and building machines, which is the ability of human engineers to actually design them, and in fact the stuff that goes on inside the cell is outrageously complicated, and we humans are not smart enough to actually design something like that. On the other hand we are smart enough to design simple machines with bearings and gears, even though it may be harder to build. In effect we are going to be giving up quite a bit of efficiency, simply because were not really all that smart, but when one considers the simplistic mechanical machines, one of the points in their favour is that we are actually smart enough to design machines like that, and we're not smart enough to design what goes on inside a cell.

Q: (cont'd). Rossi. But will they do what they are designed to do? For example you are citing molecular dynamics. Molecular dynamics is by no means a predictive tool. It predicts motion on a timescale of hundreds of thousands of picoseconds—hundreds of nanoseconds at most, so where are the motions that we are talking about that are taking place on the millisecond or fraction of the second timescales?

A: (cont'd). Hall. In the cell they are indeed taking place on those timescales. That's why it's difficult to design biomimetic stuff. But in a diamondoid nanomachine we're talking about gigahertz frequencies. You can actually simulate an entire machine cycle with modern clusters of computers, which puts the nanomachine within the reach of modern analytical tools in a way that is not true of the systems inside living cells.

Q: (cont'd). Rossi. This puts us into the realm of belief. *Credo quia absurdum*. There is no validation, you have not shown us any validation. A model is a model is a model for simulation. I've heard about the force field, the Buckingham potential and so on—they are notoriously bad for complex systems. They're very good for H_2! How can you convince us that what you're doing actually has any sense of being close to reality?

A: (cont'd). Hall. In the long run, that will only happen when it works. In the short run, I take what I can get.

A: (cont'd). Jones. That is an absolutely valid point. This issue of control is at the heart of it. Trying to control things. Maybe we have to say we can't control it, we have to understand that complex web of interactions that goes on in the cell to make it work. We are now seeing systems biology starting to become some kind of discipline. It is looking into the fantastic interactions that allow *E. coli* to swim towards its food, for example. There is a magnificent cascade of conformational change here, chemicals diffusing out there, etc. I don't think we will unlock the true power of the nanoscale unless we can deal with that, and we cannot deal with it at the moment, and I don't think we'll ever be able to deal with it in an engineering sense of being able to control every step along the path. We'll have to understand how we can use that kind of complexity to produce the results we want.

Q: (cont'd). Rossi. I am also as optimistic as you are, but perhaps in a different sense, from first principles.

Implementation and resources

Q: Michael George. For people to accept this paradigm shift you have to deliver a system. You touched on the problems of physics, but there are certainly huge step changes in chemistry needed to be able to effect this. My first question is, do you think that there are enough resources in the West in this area to be able to effect it? If the answer is no, does the panel think that such a paradigm shift could come out of emerging scientific powers such as China, and if that were the case how would that affect the social science issues that we're so concerned about in the West?

A: Hall. The Chinese are putting quite a lot of effort into this. If you go to a Chinese city that you haven't seen for five years, you will not recognize it. They have come out of their century-long funk and are moving fast, and we in the West are in a real danger of falling behind.

A: (cont'd). Tendler. That's an intriguing question, what you are asking is whether there is enough money in the West to overcome the threat of Chinese science. In other words, does China have more money, or more brains? There might be difficulties about developing such an argument. Do you need a huge amount of money to resist this new scientific activity in the developing world, or would it be rather a question of natural flair? I suspect that if one looks at real step changes in science, they're not driven by money, they are driven by intellect. If you look at what's come out of the huge science programmes, e.g. in the US, one may legitimately ask, have they given value for money? One has to be careful in moving towards a position in which one is stating that it is improper for science to flourish in the developing world.

Q: (cont'd). George. My question was not about that at all. What I was trying to say is, there is a huge science base in China, nanotechnology developing there is something very new, and what are the social science implications of that for their society?

A: (cont'd). Stilgoe. The question is important. We call it the new geography of science. India and China are mentioned every time Tony Blair and Gordon Brown talk about science. Putting that into a political context, they tend to refer to it in what we call a "wild East" way—the Orient are racing ahead doing certain things that we don't understand, they are competing with us. That argument is often put forward by people who want less regulation, less public engagement in Britain: they would much rather that scientists be left to get on with things, which I don't think is good for anybody. Moreover it suggests that science is all about economics whereas I hope that we think that it is about something more than that. It also assumes that science is purely competitive, whereas we actually see quite a lot of collaboration between nations, it's not just about Asian countries racing ahead and filling in the gaps left by the overregulated laggards in the West. The whole picture is much more complex than is suggested by a lot of the political rhetoric that one hears nowadays.

A: (cont'd). Jones. We should be really pleased to see all the science going on in China and India. I agree of course that science is a good thing, and I think that it will help develop prosperity in those countries and in the rest of the world, i.e. it is part of the aim of getting the world to a state of general sustainable prosperity for the whole world's population, and as such is an immensely good development. There are interesting social science issues—different cultural backgrounds do go into science being carried out elsewhere, and I'm sure that the picture of the "wild East" is not correct at all, doubtless they have all their own constraints, which may just happen to be somewhat different from ours. It is fascinating to see science evolving in different cultures.

The nanomotor

Q: Laurence Eaves. I'm fairly optimistic about applications of nanoscience and technology. Recently in my own field I've been very impressed by the experiments with carbon nanotubes, making transistors and light-emitting diodes. They are very impressive achievements, but based on well-established science and technology. You put electrons and holes in for example and you get photons out in a fairly controlled way. On the other hand I was fascinated by the movies that we have seen of rotors turning, and positioning atoms to build up molecular structures. What is not so clear in these processes is, where is the energy coming from? What is the driver—is it a chemical process, are they are electrically driven?—what is actually turning the wheels, and providing the source of molecules?

A: Forrest. The nanomotors are electrostatic.

A: (cont'd). Hall. They are electric motors. It's not rocket science.

Q: (cont'd). Eaves. Yes, but what is the driving force? Can you draw me a circuit? These are not electromagnetic motors. Are they charge-driven or something like that? One-electron?

Q: (cont'd). Janine Swarbrick. If it's that easy, why hasn't it been done yet? We don't even know how to make the cogs. I'm sure they wouldn't look like they do in the animations. How would you turn them? As far as I can tell all the different elements of the machines you propose cannot yet be made. It seems to be misleading to say, oh it's just an electrostatic motor. If it's that simple, why can't you make it?

Q: (cont'd). Eaves. If you're dealing with one electron there's quite a lot of charging energy involved—do things get clogged up? Have you thought about things like Coulomb charging, whether you can release your charges quickly enough, and things like that?

A: (cont'd). Forrest. Some of it is dealt with in *Nanosystems*. I'd like to make a general comment about the animations. I really want to defend them, because the people who went about making them—and incidentally I'm not one—really took great care to put as much analysis into them as possible. Some of that analysis came out of *Nanosystems*, and a lot of it has been done subsequently. The dimer reaction for the mechanosynthesis part came out of the quantum mechanical analysis, and there have been a lot of molecular mechanics calculations. The errors might be quite large, say 15%, but it's the best we can do at this point. To emphasize: we have really taken great pains to present something that is as realistic as we can do right now.

Q: (cont'd). Eaves. But my question is simple: how are you going to turn the cogs? Have you got a well-defined circuit or scheme for turning the cogs? Please show us on the blackboard!

A: (cont'd) Hall. My personal preference for an electric motor is different from what has been shown. The idea is that you have a rotor, and that you have electrostatic charge in the rotor, and you have electrodes connected to two wires, which could even be macroscopic, and you change the voltage on those wires and it produces a rotating electric field, and that causes the motor to turn round.

Q: (cont'd). Moriarty. Are the wires metallic?

A: (cont'd). Hall. I think you would do better to make them out of some kind of arrangement of carbon, such as conducting nanotubes. The details are part of an ongoing discussion between myself and Drexler.

The future

Q: Rayment. We have spent most of our time discussing the Drexler version of nanotechnology. I would value the panel's comments on the following suggestion: that in a decade's time, that will have been seen to have been a valuable digression, and in the meantime the rest of the world will have moved on, very profitably, into new areas of nanoscience, but it will be an entirely different subject.

A: Hall. I think that's a very good description of the past decade, but at the moment there seems to be some movement in the other direction.

A: (cont'd). Forrest. The Drexler vision is not science, it's a manufacturing technology. They certainly are areas of nanoscale science that are quite divergent from that view, but there is an economic driving force towards making high-quality objects at low cost, that have much higher performance than today's objects; ultimately the economic driving forces will put us towards some form of productive nanosystems. Professor Jones has a different approach, and if that works better than what has been proposed in *Nanosystems*, then fine—it's the end result we're looking for: high-quality atomic precision macroscale products at low cost, however we get there.

A: (cont'd). Jones. I agree entirely with your premise. Drexler's contribution, and it is important, has been to point out the general potential of doing neat things on the nanoscale. Putting up an Aunt Sally is a brave thing to do, it's fun to tear it apart and see what's wrong with it, but ultimately when we look back on this we will have productive nanosystems that will not look anything at all like that. I disagree about the economic drivers though, there are big economic drivers for nanotechnology but they are not in manufacturing. If you want to get an everyday artefact that is not too bad at essentially no cost it's no problem—just go to IKEA! The major driving force now is energy, clean sustainable energy; it's medicine, working medicine, regenerative medicine, therapies for things like cancers; it's information, ever more powerful processing of information. Even if I thought that the Drexler approach was more practical than I think it is, I'm not convinced that it would be the one we would choose just on the basis of economic driving forces. If you want to make cheap large area solar cells, it's conventional nanoscience that's doing it. It might be directly biologically inspired in terms of artificial photosynthesis, it might be less directly inspired as in Grätzel cells, or organic photovoltaics, it could be III-V technologies—all of these are conventional nanoscience. If you look at medicine, nanomedicine by definition has to work at 300 K and in the presence of water: it has to be biomimetic, it's got to fit in the environment of the body. Information: I don't know how it will turn out, it would be nice to give molecular electronics a try; it may be quantum computing, I'm not sure about that either. You can see all these possibilities, but I'm not sure that the Drexler approach is a front runner. Even if you thought it would work I don't think you would put all your money on it. So I agree with the questioner's proposition: it was a great demonstration to show us that we ought to think of what we can do at the nanoscale, but what will come out in the end will be all kinds of things that are probably going to surprise all of us.

A: (cont'd). Tendler. I'd agree almost entirely with that. To a certain extent one could argue that the interests were driven by economic factors, and the rush to develop a large science funding vote in the US. One could argue that there was a degree of patronage that was useful, and then became less useful. There may be parallels with US foreign policy regarding whom they funded, and then chose not to fund. I think in a few years time it will go away. There are many other exciting areas of science that are founded on sound physical laws and sound physical concepts that will win out. Part of the difficulty is being able to say no, you can never do that. Scientists find that really difficult. You can always find a simulation that may suggest you can do the impossible, but the issue is relating the simulations to the real world, to real chemistry, real physics and real biology.

A: (cont'd). Stilgoe. The Drexler vision has value in that it opens up possibilities, it asks certain questions, it opens social possibilities, and leads people to ask social questions. It will be very interesting to see whether in 10 years time people will still be using the term nanotechnology. There is a sense in which people doing public engagement with nanotechnology are already fighting the last battle. Maybe there are new challenges around, related to convergence, that are going to become more important in the public mind in a decade's time, and I think we should be aware of that and start following the fracturing of nanotechnology into whatever subfields it ends up as.

A: (cont'd). Moriarty. For me, there is a really good idea at the core of *Nanosystems* in that we should do atom-by-atom chemistry: SPM groups around the world are [now] doing that. We can extend that, we can try and do, for example, computer-controlled epitaxy. You could think about trying to extend the kind of experiments that Eigler et al. have done in two dimensions and build it up into three dimensions to form artificial crystals to probe novel states of matter. My problem is extrapolating that to nanofactories and self-replicating assemblers, and to say we will have that kind of technology in 10 years time is just overstepping the mark.

Conclusion

Faye Scott. With that we now conclude, and allow me to add just one little comment. From my viewpoint, it has been most gratifying to hear scientists asking questions about public engagement, showing how wrong it is to assume (as some of those in my area of work tend to do) that scientists don't think about these things.