Book Section:

Jones, R.A.L. (2011) What has nanotechnology taught us about contemporary technoscience? In: Zülsdorf, T., Coenen, C., Ferrari, A. and Fiedeler, U., (eds.) Quantum Engagements: Social Reflections of Nanoscience and Emerging Technologies. IOS Press , Amsterdam . ISBN 978-1-6750-953-0

Pre-edited version of a chapter in *"Quantum Engagements: Social Reflections of Nanoscience and Emerging Technologies",* eds Zülsdorf, T., Coenen, C., Ferrari, A., Fiedeler, U., Milburn, C., Wienroth, M., IOS Press (Amsterdam), November 2011 (ISBN 978-1-6750-953-0)

What has nanotechnology taught us about contemporary technoscience?

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Abstract. Nanotechnology has emerged as one of the dominating themes of international science policy in the last decade. I argue that, rather than considering this as the emergence of a new scientific field, nanotechnology is best thought of as a socio-political project that has arisen as a result of influences both from within science, and from the wider political, economic and cultural climate.

Keywords. Nanotechnology, public engagement

Introduction

Nanotechnology was a dominant theme in science policy internationally for the first decade of the new millennium. Perhaps its star is fading now, and its longevity as a single project is questionable. From the point of view of a scientist, it is not clear that it has achieved full coherence as a discipline. But to think of the emergence of nanotechnology as the process of creation of a new scientific field perhaps risks asking the wrong kind of question. Instead we should consider it as a socio-political project, less created by the scientific community, than imposed on it by a combination of political and cultural forces.

This story prompts us to ask a number of questions. How and why did nanotechnology, considered as a socio-political project, arise at the time it did? Did the nanotechnology project change the way science is governed, funded and organised, and if so how? What general lessons can we learn, for example about other areas of emerging technology such as synthetic biology?

This article treats this issue from a personal point of view – I need to stress that these observations are not based on systematic study, and that my involvement in nanotechnology has not been that of a dispassionate observer. I have been a participant in the science, and have been an active protagonist of a particular point of view in a number of debates that have taken place around the subject (R A L Jones, 2004)(Richard A L Jones, 2008a). In addition, I have been directly involved in advising a national funding agency.

1. Where did nanotechnology come from?

What was the origin of nanotechnology? It's tempting to try and identify the single event or discovery that launched any field, and for nanotechnology we have a number of candidates. Was it the famous lecture by Richard Feynman "*There's plenty of room at the bottom*", given at Caltech in December 1959(Feynman, 1960)? Was it the coining of the term "nanotechnology" by Norio Taniguchi in 1974? Was it the publication of K. Eric Drexler's visionary and widely read popular science book "Engines of Creation" in 1986(Drexler, 1986)? Was it the invention of the scanning tunnelling microscope by Gerd Binnig and Heinrich Rohrer in 1981, or the use of a scanning tunnelling microscope by Don Eigler to pick out the letters "IBM" in individual atoms in 1989(Eigler & Schweizer, 1990)? Or was it the announcement in 2000 of a National Nanotechnology Initiative in the USA by President Clinton?

All of these events, along with a number of others, have played important roles in the emergence of the phenomenon of nanotechnology, but closer scrutiny tends to diminish the claimed unique significance of each of these milestones. Feynman's lecture, for example, has often been credited as the foundation of the field, but the careful historical work of Tuomey (Toumey, 2008) has highlighted the lack of immediate impact of the lecture and the retrospective nature of its claimed importance. What Taniguchi meant by nanotechnology was something rather specific – the very high precision machining of surfaces – which captures only a fraction of the interdisciplinary nature of what nanotechnology has become. Drexler's book made an impact on many with its originality, but it could equally be argued that it recycled a number of tropes that were already staples of science fiction(Milburn, 2008), without adding much in the way of specific details that could form the basis of real laboratory research programmes.

The development of scanning probe microscopies such as STM certainly did generate new practical research programmes, but again, the novelty shouldn't be overestimated. Other forms of microscopy and scattering techniques had already achieved effectively atomic resolution; arguably STM and AFM had impact because of the immediacy of the outputs and (later) their relatively low cost. Eigler's demonstration of the potential of the STM for atomic manipulation was a marvellous technical feat and produced a much-reproduced image, but most applications of nanotechnology use quite different approaches to achieve atom-level control. Finally, while the National Nanotechnology Initiative was undoubtedly of great importance for US science policy, and was an important prompt in the discourse of national competitiveness which led to the growth of government nanotechnology funding programmes in Europe, Asia and other parts of the world, it was by no means the first government initiative in this area (in the UK, for example, the Department of Trade and Industry's Link Nanotechnology Program National Initiative on Nanotechnology began in 1988).

Instead of looking for a single foundational event, we should look to a much more varied combination of factors which came together to prompt the idea of nanotechnology. Some of these came from within the scientific community, and were associated were particular scientific and technical advances. But many came from outside science –from cultural influences and from political and economic changes. The story of the development of nanotechnology should comprehensively disprove, should such disproof still be needed, the notion that the scientific enterprise is an autonomous activity that takes place isolated from broader societal influences.

The very name of the field – nanotechnology – first came to wide prominence outside the scientific community. Although, as noted above, the word nanotechnology had an earlier origin, its widespread currency is undoubtedly due to the writings of K. Eric Drexler. Drexler has proved to be an enormously polarising figure, attracting attention amounting in some cases to adulation from a following of technology enthusiasts, but generating a growing degree of distrust from many mainstream, conventionally credentialed scientists working in nanotechnology. This divergence of opinions reflects some very interesting ambiguities in Drexler's status. On the one hand, he is technically trained and with impressive credentials, including a PhD from MIT, but on the other hand, he has not been socialised into any of the relevant scientific communities. He is a gifted and successful science writer, but the credibility of his popular work is built on some technically complex writings(Drexler, 1992) whose validity has largely been left unexamined in their details. His wide following has included many accomplished computer scientists and successful and prosperous IT entrepreneurs, but he has also been closely associated with the fringe movements of cryonics and transhumanism. This ambiguous status has led him to be effectively written out of some popular histories of nanotechnology; this seems to me to be a serious mistake.

The power of nanotechnology as an idea has been enormously boosted by its associations with a very characteristic and widespread visual iconography, which has been used to illustrate both factual descriptions of the subject and depictions in fiction, comics, video games and film. The most powerful of these images is, perhaps, the recurring theme of the nanosubmarine(Nerlich, 2008) – a medical nanodevice navigating through human blood-vessels. The notion of the robot surgeon was mentioned in Feynman's 1959 lecture, and attributed to his friend, the space scientist Al Hibbs. It's clear, though, that this idea was already current in science fiction at that date, before becoming even more culturally embedded through films such as Fantastic Voyage. Drexler's futuristic treatment nanotechnology in "Engines of Creation" has led to a new popularity of nanotechnology as a plot device in science fiction, through works such as Neal Stephenson's The Diamond Age.

Nanotechnology has been supported by the development of some compelling rhetorical tropes - a series of slogans were coined that captured key ideas in a pithy way. These are frequently recycled in popular literature, and on occasion, are satirised and subverted. These begin with Feynman's own lecture title "Plenty of room at the bottom", and Drexler's "Engines of creation" and have continued with slogans such as the title used by science writer Ivan Amato for the US National Nanotechnology's launch document - "Shaping the world atom by atom"(Amato, 1999).

Meanwhile, fertile ground for the development of a new techno-scientific project had been created by the major changes in the innovation systems of the USA and the UK following the political realignment of the 1980s. A major role in the promotion of the idea of nanotechnology was taken by businesses and government agencies who had an interest in promoting nanotechnology as a business and investment opportunity – a "*new new thing*" to follow earlier enthusiasms for biotechnology and internet related businesses. This played well to science and innovation policy discourses around the importance of new technology for national competiveness, inevitably framed as a race that developed countries were in danger of losing to a fast developing China.

Within science, there were many pre-existing fields whose own rhetoric could be adapted to the nanotechnology project. When political developments led to significant funding been attached to nanotechnology, this provided a clear incentive for these pre-existing fields to align themselves with the new project. But this relabeling went with the grain of a more subtle shift that was also taking place in the values of some branches of physical science, with less value being placed on testing and developing theories, and more to making functional devices, whose operation then became the object of study. The pages of high status journals, such as Science and Nature, increasingly featured articles whose content could be summed up as "*we made a nanowidget*".

For a cause of this shift, one might look to the increasing importance attached to intellectual property in universities, driven in the USA by the Bayh-Dole Act, but with counterparts in other countries. If spin-out companies were beginning to make some university academics rich, one could understand that physical scientists might begin to feel some envy for their colleagues in biotechnology who were leading the way in commercialising their own research. And if spin-out companies need the protectable intellectual property to form their founding assets, then scientists need to focus more on patentable products and devices rather than the less readily commercialised currencies of theory and understanding.

2. "Between promise and application"

Support for the nanotechnology project – whether this is financial support from funding agencies or within private corporations, or rhetorical support from representations in the media and popular culture – comes in return for a series of promises. Claims that areas such as manufacturing, medicine, energy, information technology will in due course be transformed by the applications of nanotechnology have been ubiquitous. The nature of the promise varies on the interests of the groups promoting the technology. For business groups and science policy makers, it is the promise of economic transformation that has been most compelling – the idea of a new "*trillion dollar industry*". For visionaries like Ray Kurzweil, nanotechnology provides is an essential enabling technology for the event at which humanity transcends its earthly limitations, its mortality and limited power, in a technological singularity(Kurzweil, 2005).

On the obverse of these promises are a series of threats. For science policy, there has been the very widespread discourse of national competition – the idea that the USA or Europe will be overtaken by countries who more enthusiastically seize the opportunities that the new technology offers. Even those groups who oppose the technology do this from a position that implicitly accepts the claims that it will deliver sweeping societal and economic impacts. Nanotechnology, then has been a central part of the "*Economics of technoscientific promises*" (Felt & Wynne, 2007).

In this way of thinking, we are invited to think of nanotechnology as a "thing" which is making progress, which can be faster or slower according to the priority we give it and the receptiveness of our society to innovation. Progress is signalled by a series of scientific advances, described in the press releases that accompany high profile scientific publications as breakthroughs, whose significance is in giving further credence to the imagined futures they invoke. Meanwhile commercial applications of nanotechnology are heralded as outriders of the economic boom that is imminent. In this economy of promises, then, scientific advances and early applications are to be thought of as down-payments on the promise of things to come.

Nanotechnology, in this view, is conceptualised as a single enterprise that finds itself poised between promise and application. What's at fault with this is that it ascribes too much unity to the many different elements that make up nanotechnology; in fact there is a more interesting dynamic at work.

Because nanotechnology is forged from many different fields, these different fields can contribute differently to this economy of promises. For some of the fields that went into nanotechnology, it was promises that they were most rich in. But other fields already had applications, and nanotechnology benefited from a symbiosis of the two. For fields that were rich in promises, the association with fields that had already produced bankable results lent credibility to those promises. The fields that already had applications, in return, were able to acquire some of the glamour of the fields with more extravagant promises.

3. The many roots of nanotechnology

One popular narrative about the history of nanotechnology presents this as a simple contention between the visionaries, led by Drexler, and incremental scientists who appropriated the term and the excitement associated with its expansive visions to increase funding for their own much more mundane endeavours, which have resulted in products such as stain resistant trousers1. To subscribe to this view is to ascribe a much too monolithic character to the many different branches of science that came together as part of the nanotechnology project. While part of the story of the development of nanotechnology involves the interaction between the scientific enterprise and political, economic and cultural forces outside science, another part involves a process of contention and negotiation between different fields of science, which is very far from being monolithic, for ownership, or for the terms for sharing the ownership, of the nanotechnology project.

It is very important to realise that nanotechnology did not arise afresh; instead the scientific fields from which nanotechnology was forged were well developed before the idea of nanotechnology became a significant part of science policy, and even with the ascendency of nanotechnology these fields retain much of their original identities. Each field has its own symbolic victories, its own leaders and heroes, its own shared narrative, but each has contributed ideas, promises made and realised, scientific figureheads and images to the composite picture from which nanotechnology emerged.

Before Drexler, there was nanotechnology as a development of precision engineering. As mentioned above, the first use of the term nanotechnology came from the engineer Taniguchi in 1974, to refer to engineering processes that resulted in a surface precision finish of less than a nanometer. This sense of the term had some currency in the 1980's and 1990's, when the microfabrication techniques being used to produce miniaturised electronic circuits underwent very rapid development. Remarkable developments in production techniques – such as phase shift photolithography – and experimental techniques like e-beam lithography and focused ion bean etching – have meant that nanotechnology in Taniguchi's sense is now a fully realised technology. Paradoxically, the aspect of nanotechnology that really did lead to the revolution we have seen in information and communication technologies didn't really take a full part in nanotechnology's economy of promises, because that promise had already been redeemed before the rhetoric surrounding nanotechnology's possibilities had reached its highest pitch.

[1] For a very clear exposition of this view, see Adam Keiper, *Feynman and the Futurists*, Wall Street Journal, Jan 8 2010.
http://online.wsj.com/article/SB10001424052748703580904574638160601840456.html (accessed 5 July 2011)

While industry used micro-fabrication to make the integrated circuits that have revolutionised computing and consumer electronics, physicists were using it to look at the interesting new physics that arises when electrons are confined on the nano-scale. This is the concern of some very fruitful branches of physics - meso-scale2 physics and the physics of low-dimensional semiconductors. In tandem with new technologies for making semiconductors with very precisely controlled nanostructures, these efforts yielded both new physics[3] and new technologies. In particular, the idea of "band-gap engineering" led to a number of new optoelectronic devices, such as white light emitting diodes and a number of different types of solid state laser, which underpin much of our modern optical information infrastructure.

Progress in miniaturisation of electronics formed the conceptual driving force for another field that has played a major role in shaping the development of nanotechnology in the academic arena – this is the area of molecular electronics, which seeks to create electronic circuits in which the components are individual molecules. This field pre-exists the idea of nanotechnology – a recent article (Choi & Mody, 2009) summarises key events in its history. It is, I think, fair to say the field has had a long history of overpromising, with a series of waves of excitement and disillusionment. As long ago as 1992, the physicist John Hopfield was moved to write that "*the field suffers from an excess of imagination and a deficiency of accomplishment*". It is impossible to discuss the role of molecular electronics in the history of nanotechnology without discussing the strange case of Jan-Hendrick Schön. Schön was a young physicist working at Bell Labs who produced a dazzling series of papers in the highest profile journals, Science and Nature, often with eminent physicists as co-authors. These finally seemed to realise the promise of molecular electronics, until they were revealed to be the result of fraud and data fabrication.

Despite this set-back, a more workaday cousin of molecular electronics, plastic electronics, was beginning to produce marketable products. This field stemmed from the discovery of polymers that conduct electricity[4]; work by physicists such as Richard Friend demonstrated that these materials could be made into devices such as light emitting diodes and field effect transistors, not in the form of individual molecules, but as thin, often nanostructured, films. But it has not been universally accepted that plastic electronics should be considered part of nanotechnology.

No such doubts have been expressed about the centrality of cluster chemistry to nanotechnology, at least in the case of its most high profile discovery, the fullerenes - new forms of carbon discovered by Smalley, Curl and Kroto in 1985, for which they won the 1996 Nobel Prize for Chemistry. Depictions of the (association) football like structure of C60 Buckminster fullerene have become one of the most widely used emblems of nanotechnology. Chemistry's claim to be central to nanotechnology is reinforced by the related fields of colloid science and powder technology. From academic colloid chemistry came quantum dots, nanosized particles of semiconductors whose optical properties – notably the colours with which they fluoresce – depend strongly on their size, because of quantum confinement effects. Meanwhile incremental developments in industrial power technology led to better size control of such powder materials as titanium dioxide, a widely used white pigment, and innovations in their surface coatings which opened up new applications in areas such as sun-screens and other cosmetics, developments that have been heralded as early commercial applications of nanotechnology.

The development that has been most responsible for the proliferation of images of nanoscale was the invention of scanning probe microscopes – particularly the scanning tunnelling microscope and the atomic force microscope[5]. These are now widely used in many different branches of nanoscience, but their origin is in the field of surface science. Scanning probe microscopy has an important role in the development of nanotechnology, not because it provided the first way of visualising individual atoms and molecules, but, in

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[2] To many physicists, the nanoscale is *larger* than the length-scales they are used to thinking about, not smaller – hence the largely overlapping, alternative pre-existing nomenclature the *"meso-scale"*.
[3] An early example being the discovery of the quantum Hall effect, for which Klaus von Klitzing won the 1985 Nobel Prize for Physics.
[4] For which discovery Alan Heeger, Alan MacDiarmid and Hideki Shirikawa won the 2000 Nobel Prize for Chemistry.
[5] For which Gerd Binnig and Heinrich Rohrer won the 1986 Nobel Prize for Physics.

part, because these instruments soon became cheaper and easier to use than the relatively well-established techniques of electron microscopy, which remain largely restricted to specialists. The other contribution of scanning probe microscopy – important because of its symbolism rather than any practical use, which remain negligible, is in the idea of manipulating matter atom by atom. Eigler's image of the letters "IBM" picked out in individual atoms carries enormous symbolic power(Eigler & Schweizer, 1990), as it apparently vindicates some of Drexler's central claims, that it will be possible to build new materials atom-by-atom. It has, however, proved to be rather technically difficult to build on this initial achievement.

If manipulation of individual atoms with a scanning tunnelling microscope epitomised the promise of nanotechnology, it is the field of materials science that has supplied many of the early applications. Materials science, however, is rather an old discipline. The key ideas on which the area of nanomaterials is founded have a long history, dating back at least to the experiments of A.A. Griffith in 1920, which first demonstrated that thinner glass fibres were stronger than thick ones[6]. By the late 1950's, Arthur von Hippel was promoting the idea of molecular engineering, which exactly prefigures much of the rhetoric surrounding nanomaterials. The discovery of carbon nanotubes in 1991[7], however, gave a new nano-object on which older ideas (embodied in the existing technology of carbon fibre) could be attached.

The idea of making synthetic molecular machines, has, in the scientific community, become most closely associated with the field of supramolecular chemistry - a branch of synthetic chemistry, which exploits relatively weak chemical interactions to assemble quite complex molecular constructs which can have moving parts[8]. This area is also closely associated with molecular electronics. Self-assembly is also an important theme of the fields of soft matter physics and chemistry[9]. Here the idea that designed molecules can self-assemble into complex nanostructures is not only familiar and well-understood theoretically, but also has large scale commercial application in the form of block copolymers, which are used both in bulk applications and as surface treatments (including the notorious stain resistant trousers).

Perhaps some of the most interesting interactions arise between nanotechnology and various branches of the life sciences, rather unsurprisingly, since the fundamental operations of cell biology take place at the nanoscale. These interactions take place in two directions. The field of single molecule biophysics uses the tools of nanotechnology – notably scanning probe microscopy and the method of "optical tweezers"[10] – to study the operation of biological molecular machines. In areas such as tissue engineering and drug delivery an understanding of the nano-scale workings of the cell is combined with soft matter physics and chemistry with the aim of creating devices for effective medical interventions. Biomimetic nanotechnology attempts to mimic the operating principles of biology to create synthetic nano-scale structures and devices. Some very elegant examples of this approach (though currently without any imminent applications) can be found in the area of DNA nanotechnology.

By now it might seem that I am labouring the point that very many and diverse areas of academic and industrial science and technology have become associated with the nanotechnology project. What is very important to stress that there is no evidence that these different fields have merged, or are likely to merge, into a new field of nanotechnology. Nor should we expect any one of these fields to prevail, in the sense of being widely recognised as the truest embodiment of nanotechnology. But understanding these many roots

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[6] This story is beautifully told in the 1968 popular science book "The New Science of Strong Materials", by J.E. Gordon (Gordon 1968)

[7] This discovery is credited to S. Iijima, although there is some evidence for earlier observations of nanotubes. As a colleague working in this field said to me, "*Iijima didn't discover them first, but he discovered them best".*

[8] See for example Balzani et al, 2004

[9] The phrase "soft matter" ("la matière molle" in the original) was popularized by the physicist de Gennes (Nobel prize for physics, 1991) to describe systems in which interaction energies are comparable to thermal energies, in which phenomena such as self-assembly and molecular shape change are prominent. Examples of such systems are polymer solutions and melts, colloids and liquid crystals.

[10] In this technique, an individual molecule can be manipulated by being attached to a colloidal particle which is held in the focus of a laser beam. It was developed by the physicist Steven Chu (Nobel Prize for physics, 1997).

helps us to understand why nanotechnology is understood in different ways in different parts of the world, and why tensions appear between the visions of nanotechnology proposed by different high status academic champions, and disparities are apparent between these visions and the nature of actual products which are claimed to use nanotechnology.

If there are doubts about the longevity of nanotechnology as a socio-political project, that does not mean that the future of the fields from which it has been forged are in question, though their fortunes will undoubtedly ebb and flow. These fields are tough, self-confident and transnational. Being resistant to socio-political projects, they will probably outlive nanotechnology, but they will be (and indeed, already have been) changed by it.

4. Changing innovation systems, particularly in USA and UK

Academic science in the post-war West thrived under the protection and sponsorship of an innovation system associated with a particular type of corporate, oligarchical capitalism. This dramatically altered in the USA and the UK as a result of the political changes of the 1980's; in my view the emergence of nanotechnology needs to be considered as part of a response – a response that has still not fully been worked out – to these changes.

A substantial proportion of the research spending in the UK and the USA in the post-war period took place in the corporate laboratories of large conglomerates. In the UK, ICI and GEC covered chemical research and electronics respectively, while in the USA the laboratories of IBM, du Pont, GE and Bell, to give a non-exhaustive list, exerted a dominant hold on the national innovation system. These laboratories made major contributions, not just in product development and applied R&D, but in quite speculative branches of science. Bell Laboratories, in particular, was as famous for its Nobel prize winners as for its practical discoveries. These corporate laboratories were well placed to function as intermediary organisations, linking the world of academic science to the more product centred research and development carried out by the different business units of these conglomerates.

However, the resources and freedoms enjoyed by scientists working in these corporate laboratories were arguably the product of the oligopoly or near-monopoly status of these businesses. Following the election of governments in the UK and the USA strongly favouring free markets, a process of deregulation and a drive to "unlock shareholder value" eroded the positions of these corporations and led to the disappearance of the monopoly rents that had sustained their corporate laboratories. For Bell Labs, the governmental mandated break-up of the telephone monopoly of its parent company AT&T in 1984 began a slow process of shrinkage leading to the spin-off of the laboratory in much reduced form in 1996 to a new company, Lucent. In the UK, the chemicals conglomerate ICI was subject to a hostile takeover bid by Hanson plc in 1991. The bid, which would have led to the breakup of the company, ultimately failed, but nonetheless set in train a series of demergers and corporate reorganisations that soon led to the end of the ICI Corporate laboratories.

The innovation system that has emerged in the UK and the USA places much more emphasis on direct translation of research from Universities into direct spin-out companies supported by venture capital. Of course, small, highly innovative companies have always been important, particularly for bringing disruptive innovations to market, but a new emphasis on intellectual property, particularly in universities in the USA as a result of the 1980 Bayh-Dole act, gave the University spin-out particular prominence.

A new conception of a high technology company arose from the reification of intellectual property, and the development of a strongly transactional approach to different company functions, culminating in the notion that most of these functions could be outsourced. Some nanotechnology companies embodied this conception in quite an extreme form. The major inputs to the company were a portfolio of protectable intellectual property from a university, on the basis of which a venture capital investment was made. Almost all aspects of the commercialisation of this IP could be outsourced, including the identification of market need, manufacturing, the incorporation of the manufactured nanomaterials into a finished product, and the marketing of that product. This left few activities for the company to do itself – largely a repository for IP, it might do some further R&D to develop its IP portfolio further, often doing this in partnership with universities or using the facilities of the state-sponsored nanotechnology centres that many countries have built.

It remains to be seen how viable this model is for bringing the products of nanotechnology to market. It's certainly possible to make a case that it systematically underestimates the value of tacit knowledge and know-how in manufacturing processes, and overestimates the importance of protectable IP. In practical terms, the requirements of venture capitalists to make a return on capital imposes requirements for unrealistically fast timescales to bring the products of a complex material technology to market, especially compared to the entirely digitally based businesses that offer alternative opportunities for investors.

5. The end of the endless frontier?

The emergence of nanotechnology has also coincided with changes in the way public funding for scientific research is conceptualised and justified. Large-scale public funding for science dates from the immediate post-war period in the USA, when the National Science Foundation was set up following an enormously influential report by Vannevar Bush – "Science – the endless frontier"(Bush, 1945).

This report, in arguing that the state should support basic science, even though basic scientists do not (and indeed should not) consider the potential applications of their research, insisted that applications would indeed follow from this basic research. Furthermore, it argued that those nations that did support basic science will gain economic rewards.

One can ask whether science ever did operate like this, or indeed whether it should. Nonetheless, this view has exerted a powerful hold, not just over science policy makers, but over the whole scientific community.

In recent years, however, we are seeing a new context for the public funding of research. There is pressure from governments for publicly funded science to deliver clearer economic and societal benefits, but this arises at a time marked, as just discussed, at a time when the innovation system that in the post-war years had delivered these benefits has evaporated. Another manifestation of change is an increasing emphasis on goal-oriented, intrinsically interdisciplinary science, with agenda set by a societal and economic context rather than by an academic discipline. In the phrase of Gibbons et al, we are seeing a shift to "*Mode II Knowledge Production*" (Gibbons et al., 1994). Many national and transnational funding agencies are shifting (or considering shifting) more support into research into directions defined by societal challenges, such as the need to move to a sustainable energy economy, to adapt to climate change, or manage an ageing population.

While in my view there are many positive aspects to this development, it does raise some problems. The most pressing of these is the issue of who defines the societal need – what are the processes by which these choices acquire democratic legitimacy? Other problems arise in systems where detailed technical decisions about science funding are left to scientific experts. While such experts are clearly in a very good position to make informed judgements in their own disciplinary areas, in strongly interdisciplinary projects it may well be difficult to find the expertise to define the technically possible in strongly multidisciplinary projects. Furthermore, to the extent that judgements about what research should be prioritised involve judgements about the social as well as the technical, one needs to ask who subjects the social theories of scientists to critical scrutiny?

From the point of view of the nanotechnology project, this shift is two-edged. On the one hand, nanotechnology offers a paradigmatic example of a goal-oriented, intrinsically multidisciplinary approach to science that should fit well into this new contextualisation of science. On the other hand, once the principle is established of creating a large-scale multi-disciplinary team to address a societal problem, one might ask what is gained by calling this a nanotechnology project, rather than, say, a multidisciplinary project in sustainable energy. Perhaps we should see nanotechnology as, in part, a transitional stage in moving from disciplinary based research to interdisciplinary research in pursuit of societal challenges.

6. Moving public engagement upstream

Nanotechnology entered public consciousness at a very interesting time in terms of the development of thinking about public understanding of and engagement with science, especially in the UK(R A L Jones, 2011)[11]. The 1980's and 1990's had seen a series of science policy setbacks, such as an acrimonious debate about agricultural biotechnology and criticism of the government's handling of an outbreak of bovine spongiform encephalopathy, which led some to worry about a breakdown in trust between science and the public. The initial response from the scientific establishment had been to call for greater scientific literacy amongst the public, in the belief that greater knowledge would lead to greater understanding of and trust in science. This view came under sustained criticism, in particular from Brian Wynne and colleagues, who characterised it as being based on a "deficit model" of the public understanding of science (Wynne 2001).

It was in response to the perceived shortcomings of the established "deficit model" that a movement to recast interactions between scientists and the public into a more two-way process, in which scientists would learn as much from the public as the public learnt from the scientists, and in which technologies would be discussed at an "upstream" stage, before the course of development of the technology was irrevocably set, and applications of the technology were entrenched in the market-place (Willis 2004).

In the UK, a public debate about the potential societal impacts of nanotechnology had been initiated by a high-profile public intervention by the heir to the throne, Prince Charles. In response, the UK government commissioned the Royal Society and Royal Academy of Engineering to make a study of nanotechnology. This report (Royal Society 2004) was notable for being the product of a working group that included, not just high status scientists, but also social scientists, philosophers and representatives of NGOs. It accepted entirely the move to upstream engagement, asking that "*a constructive and proactive debate about the future of nanotechnologies should be undertaken now – at a stage when it can inform key decisions about their development and before deeply entrenched or polarised positions appear*."

But despite an apparent consensus on the need for public engagement around nanotechnology, there are substantial differences on this question: what problem were people were asking public engagement to solve?

For many, the call for public engagement arose from fear of what one might term an "anticipatory backlash" against the technology. But, even here, there were a number of factors driving this. The first of these, particularly important in Europe, was the fear or hope that nanotechnology would provide a replay of the debate about agricultural biotechnology. The opposition to nanotechnology was led by NGOs who had previously been centrally involved in arguments genetic modification of foods, and their rhetoric explicitly linked the two enterprises[12].

Meanwhile, the expansive visions of Drexler and his followers for nanotechnology as a truly revolutionary technology, had, of course, equally dramatic potential downsides. The most notorious of these was the idea that nanotechnology would permit the creation self-replicating devices that would consume all the resources of the biosphere, leading to the extinction of humans and all other pre-existing life. Drexler himself gave this notion life by coining the memorable phrase "*grey goo*" for it, while Bill Joy gave it widespread currency in an influential article (Joy 2000). Curiously, it was many of the most enthusiastic proponents of the radical visions of nanotechnology who were most active in promoting the discussion of the its most extreme deleterious putative consequences. This is a good example of a general phenomenon identified by Nordmann(Nordmann, 2007), in which a speculative ethics of potential futures is used to give credence to more extreme projections of technological progress.

These fears, arising from the more radical visions of nanotechnology, provided a strong stimulus for mainstream nano-scientists to argue in public that Drexler's vision of nanotechology was impossible. However, the incremental nanotechnology of nanoparticles and carbon nanotubes raised their own fears – the suggestion that such small particles had a different toxicity profile to their macroscopic counterparts,

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[11] For a fuller treatment of the interaction between debates about nanotechnology and public engagement in the UK, see 1Jones (2011).

12 The small Canada based organization ETC played a particularly prominent role, particularly through their report "The Big Down" (ETC 2003).

and that the use of nanomaterials could cause immediate and/or long-term harm to people and the environment.

But there was substantial institutional and rhetorical support in the UK for public engagement around nanotechnology as part of a process of "upstream dialogue", as called for by the Royal Society report, and in at least one case, for nanomedicine, there was a direct connection between a public engagement exercise and a decision about the direction of science funding(Richard A L Jones, 2008b). In this more positive framing of public engagement, it can be considered part of a process of "responsible innovation" – helping to make sounder decisions about highly interdisciplinary science in the context of societal needs.

Of course, there remain serious obstacles standing in the way of the wider adoption of public engagement as part of the process of deciding science and technology funding priorities. The practical difficulties of cost and time are large, but in addition to this there are some who will make more fundamental objections. For example, some scientists will oppose any infringement of the sovereignty of the "independent republic of science". Politicians may regard the use of direct public engagement as an infringement of the principles of representative democracy. Finally, there will be opposition from free market purists, who will insist that the market provides the route by which informal, non-scientific knowledge is incorporated in decisions about how technology is developed. On the other hand, there may be those who will welcome a turn to public engagement in science policy as a way of keeping hold of the public value of science in the face of growing marketization of higher education and state sponsored research.

7. Looking forward

Nanotechnology has provided a fascinating lens on a number of current issues for students of science and technology studies and of innovation studies. It is still too early to draw definitive conclusions, though I believe there are already some valuable lessons to be learnt, which may well be relevant for the development of other emerging technologies[13]. In particular, the development of the field of "*synthetic biology*" offers many interesting parallels, and perhaps some contrasts.

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[13]Indeed, calling into question the very notion of an "emerging technology" may well be one of these lessons.

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