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Moving the nanoscience and technology (NST) debate forwards: short-term impacts, long-term uncertainty and the social constitution

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Abstract

Nanoscience and technology (NST) are widely cited to be the defining technology for the 21st century. In recent years, the debate surrounding NST has become increasingly public, with much of this interest stemming from two radically opposing long-term visions of a NST-enabled future—'nano-optimism' and 'nano-pessimism'. This paper demonstrates that NST is a complex and wide-ranging discipline, the future of which is characterised by uncertainty. It argues that consideration of the present-day issues surrounding NST is essential if the public debate is to move forwards. In particular, the social constitution of an emerging technology is crucial if any meaningful discussion surrounding costs and benefits is to be realised. An exploration of the social constitution of NST raises a number of issues, of which unintended consequences and the interests of those who own and control new technologies are highlighted.

Keywords: Nanoscience and technology; Short-term impacts; Long-term uncertainty; Social constitution; Unintended consequences; Control

1. Introduction

Nanoscience and technology (NST) are widely cited to be the defining technology for the 21st century. The most common definition regards NST as "the ability to do things—measure, see, predict and make—on the scale of atoms and molecules and exploit

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the novel properties found at that scale" [1]. Traditionally, this scale is defined as being between 0.1 and 100 nm, 1 nm being one-thousandth of a micron (micrometre; μm), which is, in turn, one-thousandth of a millimetre (mm).

It is important to consider NST now because its emergence is anticipated to 'affect almost every aspect of our lives' during the coming decades [1]. This is because NST is said to be disruptive, enabling and interdisciplinary. Disruptive technologies are those that displace older technologies and enable radically new generations of existing products and processes to take over. As an enabling technology, NST, like electricity, the internal combustion engine, or the Internet [2], will have a broad and often unanticipated impact on society. Unlike these examples, however, NST is considered harder to 'pin down'—it is a general capability that impacts on many scientific disciplines [3]. This interdisciplinary feature of NST results in a driving force for innovation and discovery because it brings together scientists from traditionally separate academic groups.

Within recent years the debate surrounding NST has become increasingly public, involving civil society, non-governmental organisations and the media. Much of this interest stems from two competing long-term visions of a NST-enabled future. At one extreme, nano-optimists promise nothing less than complete control over the physical structure of matter—the same kind of control over the molecular and structural makeup of physical objects that a word processor provides over the form and content of text [4]. For example, macrostructures will simply be grown from their smallest constituent components: an 'anything box' will take a molecular seed containing instructions for building a product and use tiny nano-bots or molecular machines to build it atom by atom [5]. Inevitably, much excitement has followed these proclamations, largely because the associated possibilities seem virtually endless. Nano-optimists look forward to a society in which the costs of goods and services are massively reduced, computers operate at rates billions of times faster than today, and revolutions in medical technology have led to a virtual end to illness, aging and death, to name a few examples. In contrast, nano-pessimists see far more sinister implications. For some, NST will inevitably lead to severe exacerbation of present-day global inequalities and reinforcement of existing structures of societal control. Others foresee a world in which self-replicating 'nano-bots' have taken over the world; they consume its resources and render feebler carbon-based organisms such as ourselves obsolete or even extinct. Both nano-optimism and nano-pessimism have received much popular attention and are having considerable influence on present-day debate; present signs indicate that the public profiles of these opposing views are set to heighten within the coming years [11].

One consequence of these radical visions is that the NST industry has become plagued by both hype and cynicism. For example, many market analysts believe that it is too soon to produce reliable figures for the future NST global market share—it is simply too early to say where and when markets and applications will arrive [1]. And yet at the same time nano-optimists have been charged with hyping figures to 'reckless' and 'impossibly high expectations for…economic benefits' [6]. Most strikingly, the Nanoscale Science, Engineering and Technology (NSET) subcommittee of the US National Science and Technology Council (NSTC) predicted in 2001 that the total market for nanotech products and services would reach US$1 trillion by 2015, although the evidence base for this figure is unclear. These sentiments are echoed by Roy [7], a materials scientist, who describes the term ‘nano’ as a ‘halo regime’—a term that is sold to budget managers in order to increase funding. He concludes that “the [term] should be new, different, euphonious, and connected somehow, however, tenuously, to science”.

At present, there is a general understanding amongst industry that the level of hype surrounding NST has, to some extent, damaged investment potential. For example, Schulz [8] advocates the need for nanotech supporters to dampen unquestioning enthusiasm for NST. This is because, without discussion of the potential pitfalls, future research could be subjected to such extreme pressure that funding is jeopardised and research progress is slowed, perhaps halted altogether in some cases.

Cynicism is also considered damaging to the arguments of nano-pessimists. For example, self-replication is probably the best-known potential danger of NST. This centres upon the idea that self-replicating nano-robots capable of functioning autonomously in the natural environment could quickly convert that natural environment (i.e. ‘biomass’) into replicas of themselves (i.e. ‘nanomass’) on a global basis. Such a scenario is usually referred to as the ‘grey-goo’ problem but is perhaps more properly termed ‘global ecophagy’ [9]. However, not only do such concerns deflect attention from short and medium-term issues that demand more immediate attention, but they are also easy to dismiss as ‘fanciful’ [10]. Consider this rebuttal to grey-goo by Freitas [9]:

> “The replicators easiest to build will be inflexible machines, like automobiles or industrial robots…To build a runaway replicator that could operate in the wild would be like building a car that could go off-road and fuel itself from tree sap. With enough work, this should be possible, but it will hardly happen by accident. Without replication, accidents would be like those of industry today: locally harmful, but not catastrophic to the biosphere.”

This paper demonstrates that NST is a complex and wide-ranging discipline, the future of which is characterised by uncertainty. It argues that wide-ranging consideration of the present-day issues surrounding NST is essential if the public debate is to move forward. The rest of the paper proceeds as follows: Section 2 provides an overview of current developments in the NST industry; Section 3 looks at potential future developments from two contrasting positions—those of “cautious evolutionism” and “radical discontinuity” [11]—with reference to the informatics industry; Section 4 provides some suggestions as to how the NST debate might be moved forwards. The paper concludes that the social constitution of an emerging technology is crucial if any meaningful discussion surrounding costs and benefits of NST is to be realised. An exploration of the social constitution of NST raises a number of issues, of which unintended consequences and the interests of those who own and control new technologies are highlighted. These are crucial considerations if NST is to achieve its full potential in the long-term.

2. Present developments

One way to present the essential features of NST in a readily accessible manner is through illustration (Fig. 1).

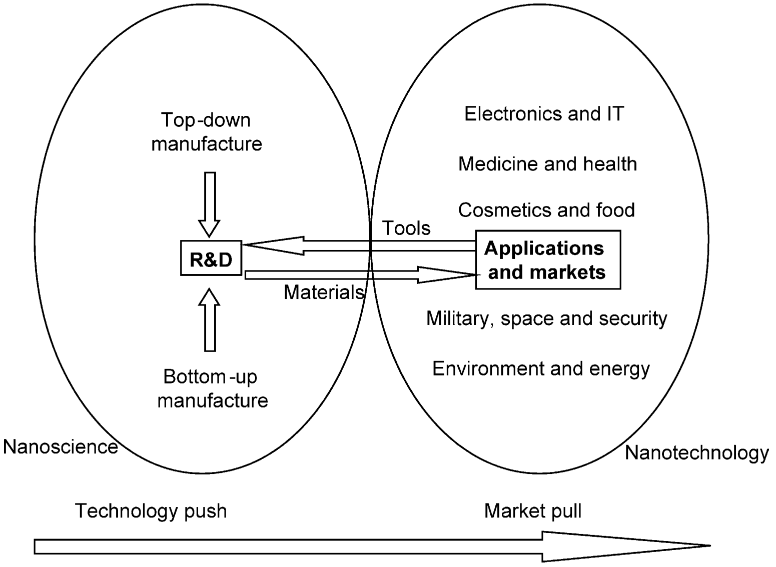

Fig. 1. Representation of the essential features of NST (nanoscience and technology).

Fig. 1 shows that the two central features of NST are nanoscience, which is here now and flourishing, and nanotechnology, which is still in its infancy. Woods et al. [11] define the former as “dealing with the manipulation and characterisation of matter on length scales between the molecular and micron size” and the latter as an “emerging engineering discipline that applies methods from nanoscience to create products.” Fig. 1 also shows how nanoscience and nanotechnology interact through a bi-directional flow of tools and materials. These flows are self-reinforcing: nanoscience produces materials which are then incorporated into products; nanotechnology leads to the production of tools and equipment which enable the advancement of R and D. Both disciplines are dealt with in turn below.

2.1. Nanoscience

A major difficulty of characterising nanoscience is that the field does not stem from one established academic discipline. Rather, we can say nanoscience is a R and D-centred activity that operates at the boundaries between physics, chemistry, materials science and biology. Two features of this R and D are important here.

First, NST is primarily about making ‘nanomaterials’—novel materials whose molecular structure has been engineered at the nanometre scale [1]. Many of the materials produced involve either bulk production of conventional compounds that are much smaller (and hence exhibit different properties) or new materials, such as fullerenes and nanotubes. Two techniques lead to the fabrication of nanomaterials: ‘top-down’ and ‘bottom-up’. Top down refers to the creation of “nanoscale structures by machining and etching techniques” [12]. This means more than just miniaturisation: at the nanoscale level properties of traditional materials change as the behaviours of surfaces start to dominate the behaviour of bulk materials. Bottom-up technology—often referred to as molecular nanotechnology (MNT)—applies to the creation of organic and inorganic structures, atom by atom, or molecule by molecule [12]. It is this area of NST that is the most futuristic and has created the most public interest.

Second, nanoscience is generally 'technology pushed': urged on by the potential market impacts of nanotechnology, the R and D community is achieving rapid advances in basic science and technology. This level of scientific interest is gauged by Compano and Hullman [13] who examine the world-wide number of publications in NST in the Science Citation Index (SCI) database. They conclude that for the period between 1989 and 1998 the average annual growth rate in the number of publications is an 'impressive' 27%.

2.2. Nanotechnology

As nanotechnology utilises the methods derived from nanoscience to create products, the applications of nanotechnology are also extremely diverse. Holister [3] estimated that there were 455 public and private companies, 95 investors, and 271 academic institutions and government entities involved in the near-term applications of NST world-wide in 2002. The ability of such institutions to transfer research results into industrial applications can be indicated by the number of filed patents. Compano and Hullman [13] provided an analysis of this, using the number of nanopatents filed at the European Patent Office (EPO) in Munich. Over the 1981–1998 period, the number of nanopatents rises from 28 to180 patents, with an average growth rate in the 1990s amounting to 7%.

One important characteristic of nanotechnology is that much of the work in near-term applications is 'market-pulled': in each case, a particular and potentially profitable use within industry and/or the consumer market has been identified. In some instances, major markets are fairly well defined. For example, in the food industry 'smart' wrappings (that indicate freshness or otherwise) are close to the market [12]. By 2006, beer packaging is anticipated by industry to use the highest weight of nano-strengthened material, at 3 million lbs., followed by meats and carbonated soft drinks. By 2011, the total figure might reach almost 100 million lbs [14]. In other cases, important applications are identified but the eventual market impacts are more difficult to predict. For instance, if potential applications in catalysts are realised then their impacts will be dramatic. This is because catalysts—as arguably one of the most important technologies in modern society—enable the production of a wide range of materials and fuels [12].

2.3. Progress to date

It is clear at present that the bottom-up NST 'dream' is far from being realised. As Saxl [12] notes: "Top-down and bottom-up can be a measure of the level of advancement of NST, and NST, as applied today, is still mainly in the top-down stage." This state of relative infancy is often compared in the literature to the Information Technology (IT) sector in the 1960s, or biotechnology in the 1980s. Moreover, Compano and Hullman [13] state that one-quarter of all NST-related patents filed are focused on instrumentation or tools, an observation which supports the idea that NST is at an early stage of development and is co-evolving with a number of enabling technologies and techniques. These tools provide the instrumentation needed to examine and characterize devices and effects during the R and D phase, the manufacturing techniques that will allow the large-scale economic production of nanotechnology products, and the necessary support for quality control [1]. Thus it is seems reasonable to assume that during the next two to three years most activity in NST will still be in the area of basic R and D, rather than completed products. It is probable that nanotechnology will initially be limited to a few specific products and services in this time frame, where consumers are willing (or able) to pay a premium for new or improved performance.

Global R and D spending is currently around US$4 billion [15], with public investment increasing rapidly (503% between 1997 and 2002 across the 'lead' countries). Table 1 summarises these rises.

The rise in interest in NST is not confined to a small number of central repositories [16]. Instead, research is spread across more than 30 countries that have developed NST activities and plans [3]. Compano and Hullman [13] examine the distribution of this interest using numbers of academic publications as an indicator. Based upon their findings, the most active is the US, with roughly one-quarter of publications, followed by Japan, China, France, the UK and Russia. These countries alone account for 70% of the world's scientific papers on NST. In particular for China and Russia, the shares are outstanding in comparison with their general presence in the SCI database and show the significance of nanoscience in their research systems.

As the range of associated tool and fabrication techniques begin to mature, NST is set to become increasingly commonplace in the coming decades. In fact, current industry jargon would probably describe NST as "coming on stream"—although the underlying technologies and their applications are still at an early stage of development, there are applications emerging into the market that are likely to make a significant impact on the industrial scene by 2006 [17]. Ideas vary as to which markets will emerge first but generally centre on two or three applications. Mihail Roco, the senior advisor for nanotechnology to the NSF, believes that "early payoffs will come in electronics and IT,

Table 1
World-wide government funding for nanotechnology research and development (US$million)

Area	1997	1998	1999	2000	2001	2002	2003
US[a]	116	190	255	270	422	604	710
Western Europe	126	151	179	200	225	~400	N/A
Japan	120	135	157	245	465	~650	N/A
Others[b]	70	83	96	110	380	~520	N/A
Total	432	559	687	825	1502	2174	N/A
(% of 1997)	100	129	159	191	348	503	N/A

Source: [1]; N/A: not available.

[a] Excluding non-federal spending, e.g. California.

[b] 'Others' includes Australia, Canada, China, Eastern Europe, the Former Soviet Union, Singapore, Taiwan and other countries with nanotechnology R and D. For example, in Mexico there are 20 research groups working independently on nanotechnology. Korea, already a world player in electronics, has an ambitious 10-year programme to attain a world-class position in nanotechnology [1].

and medicine and health" (quoted in [18]), whereas Holister [3] points out that pharmaceuticals is a huge market, thereby implying that revenue for NST in this area could be substantial. Roco and Bainbridge [19] believe that, due to the high initial costs involved, "nanotechnology-based goods and services will probably be introduced earlier in those markets where performance characteristics are especially important and price is a secondary consideration". Examples of these are medical applications and space exploration. The experience gained will then reduce technical and production uncertainties and prepare these technologies for deployment into the market place. Ultimately, the longer-term structural impact of nanotechnology on a whole range of sectors—in manufacturing, transport, services and domestic practice—could be substantial in 30–50 years.

3. Future developments

Contemporary discussions surrounding NST are almost invariably focused on the future. In such dialogues one question tends to feature widely: what kinds of products might we expect and when? This is not a straightforward question as the answer depends upon what Woods et al. [11] have described as "your stance in a range of conceptions of what this emerging technology encompasses, and judgements of what it might mean for society." Two of these positions developed by [11] are considered here which represent the extremes of the continuum: 'cautious evolutionism' and 'radical discontinuity'. According to the former, the nature of NST is very much rooted in present realities and the technology is likely to develop in an incremental way. The adoption of this position consequently makes future developments relatively simple to predict. In contrast, the second position is much more focused on theoretical potential and views NST as a fundamental advancement. Future developments are harder to foresee if this stance is assumed because the inevitable surprises and breakthroughs commonly associated with emerging technologies are emphasised.

This section demonstrates cautious evolutionism and radical discontinuity by way of reference to the informatics industry. It concludes that, while the cautious evolutionary position seems to hold into the near to medium-term, the emergence of radical discontinuity in the more distant future is likely. Thus the future of the informatics industry is highly uncertain beyond 2015.

3.1. The informatics industry

Informatics, or information science, can be thought of as consisting of three interrelated areas: electronics, magnetics and optics. This section primarily concentrates on electronics, acknowledged by Compano [20] as one of the major drivers of the worldwide economy. In fact, the current market for miniaturised systems is estimated at US$40 billion and the market for IT peripherals to be more than US$20 billion. The field is dominated by the US and Japan; apart from a few niche markets where Western European companies are able to compete, recent technological breakthroughs have been largely due to major manufacturers in these countries [17].

It is generally difficult to predict commercially successful technologies in the world of electronics [3]. However, if one considers that nanoscience has constituted a major driving force in microelectronics for the last decade, then it follows that nanotechnology will play an important role in the future of this industry [21]. There are few nanotechnology products in the market place at present but future growth is expected to be strong, with a predicted composite annual growth rate of 30–40% and emerging markets of around 70% [1]. A number of recent forecasts, although varying greatly, reflect this market confidence. For example, Miles and Jarvis [17] put the market for nanotechnology-based IT and electronics devices at around US$70 billion by 2010. A second estimate states that nanotechnology will yield an annual production of about US$300 billion for the semiconductor industry and about the same amount again for global integrated circuits sales within 10–15 years [22]. Similarly, for micro and nanotechnology systems in the telecommunications sector, the market is presently estimated as being in the order of US$35 billion with an anticipated compound annual growth rate of around 70%.

3.2. Moore's law

The forecasts given above largely rely upon continuing refinements to the microelectronic industry's basic complementary metal oxide semiconductor (CMOS) process. CMOS technology has been developed for over 20 years, driving the 'line width'—the width of the smallest feature in an integrated circuit (IC)—down from 10 μm to 0.25 μm [22]. This is the force behind Moore's law, which predicts that the processing power of ICs will double every 18 months [21]. Based on Moore's law, industry predictions until 2014 are summarised in Table 2.

But Moore's law cannot continue indefinitely. In the years following 2015, additional difficulties are likely to be encountered, some of which may pose serious challenges to the traditional CMOS process. Most immediately, limits to the degree that interconnections or

Table 2
Anticipated technological computing developments for 2001–2014

Feature	Year					
	2001	2003	2005	2008	2011	2014
Memory						
Minimum feature size DRAM[a] (1/2 pitch in nm)	150	120	100	70	50	35
Gbits/chip	2	4	8	24	68	194
Density (Gbits/cm^2)	0.49	0.89	1.63	4.03	9.94	24.50
Logic (processing power)						
Minimum feature size (gate length in nm)	100	80	65	45	30–32	20–22
Density (million transistors per cm^2)	13	24	44	109	269	664
Logic clock (GHz)	1.7	2.5	3.5	6.0	10.0	13.5

Adapted from [20].

[a] DRAM: dynamic random access memory, a type of memory used in most personal computers.

wires between transistors may be scaled could in turn limit the effective computation speed of devices because of the properties and compatibility of particular materials [23]. Thermal dissipation in chips with extremely high device-densities will also pose a serious challenge. This issue is not so much a fundamental limitation as it is an economic consideration, in that heat dissipation mechanisms and cooling technology may be required that add to the total system cost, thereby adversely affecting the marginal cost per computational function for these devices. Eventually, however, CMOS technology may hit a more crucial barrier, the quantum world, where the laws of physics operate in a very different paradigm to that experienced in everyday life. For example, futuristic circuits operating on a quantum scale would have to take Heisenberg's Uncertainty Principle into account. Overcoming this barrier is a different matter altogether, where the problems are no longer merely technological [21].

3.3. Beyond Moore's law

Industry has already begun to investigate the Moore's law problem in a number of ways. Two of the most commonly cited approaches—molecular nanoelectronics and quantum information processing (QIP)—are expanded upon here.

Organic molecules have been shown to have the necessary properties to be used as molecular nanoelectronics. Devices made of molecular components would be much smaller than those made by existing silicon technologies and ultimately offer the smallest electronics theoretically possible without moving into the realm of subatomic particles [3]. Molecular electronic devices could operate as logic switches through chemical means, using synthesised organic compounds. These machines can be assembled chemically in large numbers and organised to form a computer. The main advantage of this approach is significantly lower power consumption by individual devices. Several approaches for such mechanisms have been devised. For example, in 'DNA computing', the similarities between mathematical operations and biological reactions are used to perform calculations.

A number of primary obstacles stand in the way of molecular nanoelectronics. One issue is that molecular memories must be able to maintain their state, just as in a digital electronic computer. Also, given that the manufacturing and assembly process for these devices will lead to device defects, a defect-tolerant computer architecture needs to be developed. Fabricating reliable interconnections between devices is an additional challenge. A significant amount of work is ongoing in each of these areas. Even though experimental progress to date in this area has been substantial, it seems unlikely that molecular computers could be developed within the next 15 years that would be relatively attractive (from a price and performance standpoint) compared with conventional electronic computers [23].

Quantum information processing (QIP) crosses the disciplines of quantum physics, computer science, information theory and engineering with the aim of harnessing the fundamental laws of quantum physics to "dramatically improve the acquisition, transmission and processing of information" [17]. Two aspects of QIP are considered especially attractive: first, QIP represents computing at the smallest possible scale, in which one atom is equivalent to one bit of information. Second, QIP is capable of massive parallelism in computation (i.e. the ability to perform simultaneous calculations) [3].

These concepts are qualitatively different from those employed in traditional computers and will hence require new computer architectures. A preliminary survey of work in this area by Antón et al. [23] indicates that quantum switches are unlikely to overcome major technical obstacles, such as 'error correction, de-coherence and signal input/output', within the next 15 years. If this proves to be the case, QIP-based computing, as with molecular nanoelectronics, does not appear to be competitive with traditional digital electronic computers for some time.

3.4. Conceptions of technological development

The two positions previously outlined—cautious evolutionary and radical discontinuity—can be related to anticipated developments in the informatics industry. For cautious evolutionists, NST is rooted in present realities and is likely to progress in an incremental fashion. This is evident in Table 2, in which the starting point for future developments is present-day technology and miniaturisation is occurring steadily between the years 2003 and 2014. Consequently, progression in the informatics sector can be predicted with a high degree of accuracy over this time period. For example, the range of confidence expressed for the minimum feature size in Table 2 is fairly small—between 20 and 22 nm by 2014. In contrast, those advocated radical discontinuity are much more focused on theoretical potential and view NST as a fundamental advancement. Thus most attention tends to be given to the more sophisticated technological advances—molecular nanoelectronics and quantum information processing (QIP) in this case. Clearly these developments rely upon paradigmatic breakthroughs and are therefore much more difficult to timetable. These ideas are illustrated in Table 3 which summarises anticipated developments within the informatics industry. It shows that pre-2015 the cautious evolutionary position prevails, whereas post-2015 the radical discontinuity view is likely to dominate. Thus it is extremely difficult to foresee many outcomes that developments in this field will bring beyond 2015, let alone assess their likelihood.

A review of other nanotechnology sectors (see Fig. 1) in terms of cautious evolutionism and radical discontinuity is beyond the scope of this paper. However, it is possible that in some cases significant developments will arise in the absence of radical discontinuity, i.e. from 'straightforward concepts founded in solid science' [3]. To illustrate, a disruptive effect in the energy sector might occur as a result of solar cell manufacture becoming much less expensive, or in the drug delivery industry as a consequence of improvements in spatial or temporal resolutions to existing arrays. But even in these examples additional sources of uncertainty are likely to remain. First, while many of the technologies highlighted in the NST literature often appear advanced, it is worth emphasising that most contemporary experimental capabilities are still in their infancy. Therefore future nanotechnology research could move in a number of different directions depending, in part, upon the institutional and political factors outlined above. Second, longer-term impacts can be difficult to estimate because of potentially new and unanticipated applications. For example, if simply reducing the microstructure in existing materials can make a big market impact, then this may, in turn, lead to a whole new set of applications.

Table 3
Summary of application areas for informatics

Material/technique	Applications	Time-scale (to market launch)
Pre 2015 (cautious evolutionary)		
Quantum well structures—ultra-thin layers of semi-conductor material (the well) grown between barrier material by modern crystal growth technologies [12].	Telecommunications/optics industry. Potentially important applications in laser development for the data communications sector, e.g. fibre optic communications in building and computers. Quantum well/dot structures can potentially overcome obstacles of cost and high-temperature operating conditions.	Quantum well lasers already utilised in CD players. Not yet optimised for the communications market (i.e. fibre optics): 4–5 years.
Quantum dot structures—fluorescent nanoparticles that are invisible until 'lit up' (source as above).		Still in research stage: 7–8 years.
Photonic crystal technologies—photonic integrated circuits can be nearly a million times denser than electronic ones [17].	Many potential market opportunities for very low power devices, e.g. optical communication sector, such fibre optics.	Still in basic R&D, but very strong commercial interest emerging.
Carbon nanotubes—graphitic carbon tubes typically with an internal diameter of 5 nm and external diameter of 10 nm.	Nanotubes hold promise as basic components for nanoelectronics as they can act as conductors, semiconductors and insulators. Specific applications include memory and storage; RAM; display technologies and E-paper [3].	Commercial prototype nanotube-based RAM predicted in 1–2 years. Consumer flat screen by the end of 2003. Limited commercialisation of E-paper in 1–2 years.
Spintronics—the utilisation of electron spin for significantly enhanced or fundamentally new device functionality [20].	Ultra-high capacity disk drives and computer memories.	Near commercial: a read-head has been demonstrated that can deal with storage densities of a terabit per square inch.
Polymers—organic-based materials that emit light when an electric current is applied and vice versa [20].	Display technologies. This sector is driven by the electronics consumer market.	Some commercialisation, e.g. Cambridge Display Technologies has been formed in the UK.
Post 2015 (radical discontinuity)		
Molecular nanoelectronics (including DNA computing) [20].	Circuits based on single molecule and single electron transistors will appear, initially in special applications.	Single atom transistor demonstrated recently. Still immature, but huge potential [17].
Quantum information processing (QIP) [20].	Computationally intensive tasks too time-consuming for existing digital computers, e.g. factoring large numbers (essential for cryptographic applications) and searching large databases [23].	Still in pure research phase, although some US defence money has been made available [3].

4. Moving the debate forward

Sections 2 and 3 above have demonstrated that the NST industry is in a state of relative infancy and that many of its long-term impacts are highly uncertain. This is in the context of continuing controversy surrounding the long-term future of NST and a debate that has the potential to become polarised between radically opposing positions, neither of which fully reflect current understanding. There is a need, then, to move beyond current rhetoric: instead of debating the speculative, long-term technical possibilities and ramifications of NST, it is necessary to broaden the discussion by focussing on present-day developments and asking “what are the real issues at stake here?” And “what do these imply for the long-term future of NST?” This means more than simply extrapolating current trends. Rather, the contemporary political and social processes surrounding the introduction of technologies must be taken as central to their development pathway. Only then can a serious discussion of the future costs and benefits of NST begin to emerge.

The ‘social constitution’ of an emerging technology [24] is crucial. This social constitution is constructed from the answers to questions such as:

- Who is in control?
- Where can I get information that I trust?
- On what terms is the technology being introduced?
- What risks apply, with what certainty, and to whom?
- Where do the benefits fall?
- Do the risks and benefits fall to the same people? (e.g. mobile phones are popular while mobile phone masts are not)
- Who takes responsibility for resulting problems?

At this stage it is not possible to answer these questions with clarity for NST; indeed, the answers may be different for the different sectors in which NST will impact. However, it is possible to point to towards two of the issues that an exploration of the social constitution of NST raises. These concerns relate to, first, unintended consequences and second, and more subtly, to the interests of those who own and control new technologies.

4.1. Unintended consequences

The difficulties associated with predicting future impacts of emerging technologies due to radical discontinuity have already been highlighted above. However, a second, more immediate consideration remains. This has to do with the fact that, once the technical and commercial feasibility of an innovation is demonstrated, subsequent developments may be as much in the hands of users as in those of the innovators [19]. As a result, new technologies can affect society in ways that were not intended by those who initiated them. Sometimes these unintended, or ‘second-order’, consequences are beneficial, such as spin-offs with valuable applications in fields remote from the original innovation. A good example of this is the Internet, a technology that was originally developed by the US Defence Advanced Research Projects Agency (DARPA) in the 1970s and 1980s for communication and logistics on the battlefield, but was later adapted to create the World Wide Web [25]. Other times, unintended consequences are detrimental. No one intended, for example, that pesticide use in the 1970s and 1980s would have the impact on British wildlife that it did. Becoming aware of, and ultimately preventing, the downside of technological development is clearly relevant to the long-term future of NST.

Table 4
Examples of intended and potential unintended impacts of future NST development

Issue/domain	Examples of intended impacts	Examples of potential unintended impacts
Environmental. The potential impact of nanostructured particles and devices on the environment is perhaps the most high profile of contemporary concerns.	*Sustainable energy sources*. Projections indicate that such nanotechnology-based advances have the potential to reduce world-wide consumption of energy by more than 10%.	*Pollution*. Quantum dots, nanoparticles, and other throwaway nanodevices may constitute whole new classes of non-biodegradable pollutants.
Equity and justice. If scientists are successful in developing nanofabrication techniques for manufacturing nanoelectronic devices in huge volumes at very low cost, then the impact on society will certainly be enormous.	*Access to information*. Advances in nano-informatics may provide previously disempowered peoples across the world new opportunities to access cheap and abundant information.	*Nano-divide*. The transition from a pre-nano to post-nano world could be very traumatic and could exacerbate the problem of haves vs. have-nots.
Medical. Nanotechnology, combined with biotechnology, are the underpinning technologies pushing the rapid advances in genomics, combinatorial chemistry, high throughput robotic screening, drug discovery, gene sequencing and bioinformatics and their applications.	*Better medicine*. Rapid advances in nano-based medicines may lead to reductions in unwanted side effects, improved patient compliance, lower doses and other new possibilities.	*Ethical considerations*. Concerns over nanotech applications for enhancing the performance of the human body might arise. A major question is whether such enhancements can be forced upon people.
Military. New technologies, notably IT, are playing an increasingly important part in modern warfare.	*Collateral damage*. Might be more targeted than existing technologies, reducing civilian casualties.	*Terrorism*. Once the basic technology is available, it would not be difficult to adapt it as an instrument of war or terror.

Table 4 provides examples by comparing some of the intended and potential unintended consequences that future NST development may result in.

4.2. Control of new technologies

The emergence of the ‘precautionary position’ as an important part of international law (such as Biosafety Protocol on genetically modified crops, for example) is, to a certain extent, intended to deal with the possibility of unintended consequence. But there is also increasing interest in the wider concept of precaution, which is now recognised to include the need for greater participation in the control and direction of technological innovation. This kind of process produces not only a better evidence base, but also more informed decisions. Unintended consequences of a particular new technology cannot always be foreseen; however, if these consequences become a collective problem, it is unreasonable to expect collective responsibility if the decision to proceed with the technology was made by an influential few.

At present investment in NST has attracted a wide range of interest, both from public and private sources. The main reason for government interest is strategic: to achieve an advantageous position so that when nanotech applications begin to have a significant impact in the world economy, countries are able to exploit these new opportunities to the full. Harper [26], who describes the current situation as a "global arms race", puts these ideas into perspective: "You only have to look at how IT made a huge difference to both the US economy and US military strength to see how crucial technology is. Nanotechnology is an even more fundamental technology than IT. Not only has it the ability to shift the balance of military power but also affect the global balance of power in the energy markets."

There are an estimated 470 nanotech companies distributed across North America, Europe and Asia [15]. Of these, about 230 are based in the US, about 130 in Europe, and about 75 in the Asia-Pacific. The difficulties involved in drawing upon accurate corporate data from within the public domain are far more substantial than those encountered with regard to public investment. However, it is important to recognise that, urged on by the growing interest (and hype) currently surrounding nanotechnology, spending by big firms in 2002 is anticipated to match or even exceed government spending [3]. Furthermore, this private investment is very often at the forefront of application development in the marketplace.

At present, civil society critiques of the immense R&D and commercial efforts taking place in nanotechnology are quite sparse, but already there are signs that this is changing. In the wake of the furore in the UK over genetic modification, the idea of a 'public debate' about new technologies is in vogue, but this has to be meaningful or it will simply promote cynicism. If public dialogue on science is to mean anything, the approach of nanotechnology is a huge opportunity. Instead of waiting for potential adverse reactions, the scientific community could be proactive. For example, it could hold a series of citizens' juries to determine scientific priorities on nanotechnology. From each of the agricultural, defense, energy, pharmaceutical, and IT sectors (and the numerous cross-overs), working groups could examine current research and its potential. It could suggest which areas need to be highest priority. It would look at the potential short- and long-term applications and the 'blue skies' element necessary for any research programme. British Research Councils such as the Biotechnology and Biological Sciences Research Council (BBSRC) and the Engineering and Physical Sciences Research Council (EPSRC) could commit to considering results and utilizing the insights from the findings of such juries. If dialogue between science and society is to be more than just a sophisticated means of engineering user-acceptance, Research Councils must adopt this kind of participatory initiative to allow ordinary people to have a say in the types and trajectories of technological innovation. This will be crucial if NST is to achieve its full potential in the long-term.

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