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TUTORIAL

'Mind the gap': science and ethics in nanotechnology

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Abstract
Nanotechnology (NT) is a rapidly progressing field. Advances will have a tremendous impact on fields such as materials, electronics, and medicine. A thorough review of the current literature, governmental funding, and policy documents was undertaken. Despite the potential impact of NT, and the abundance of funds, our research revealed that there is a paucity of serious, published research into the ethical, legal, and social implications of NT. As the science leaps ahead, the ethics lags behind. There is danger of derailing NT if the study of ethical, legal, and social implications does not catch up with the speed of scientific development.

(Some figures in this article are in colour only in the electronic version)

In August 2002, at the *World Summit on Sustainable Development* in Johannesburg, an organization called ETC held several workshops calling for a moratorium on the deployment of nanomaterials [1]. Meanwhile, over the past few years expenditure on research and development in nanotechnology (NT) has increased dramatically [2]. These two trends seem to be on a collision course towards a showdown of the type that we saw with GM crops (indeed, ETC, previously known as RAFI, coined the phrase 'terminator seed'). As the science of NT leaps ahead, the ethics lags behind. Activist groups have appropriately identified this gap, and begun to exploit it. We believe that there is danger of derailing NT if serious study of NT's ethical, environmental, economic, legal, and social implications (we call this NE^{3}LS research) does not reach the speed of progress in the science.

As the science leaps ahead . . .

NT is a rapidly expanding field, focused on the creation of functional materials, devices, and systems through the control of matter on the nanometre scale, and the exploitation of novel phenomena and properties at that length scale [3]. Several observations indicate that all of society, not just scientists, needs to take NT seriously. First, there have been major scientific and technological advances in microscopy, material science, molecular-level manipulation, and scientific understanding at the borderline between classical and quantum physics. A biomolecular motor, made of inorganic nickel propellers and powered by an ATPase enzyme, was created over two years ago [4]. In a major step toward downsizing electronic components, single-molecule transistors have been created [5]. Nanoparticle research has generated products including a nanoparticle carrier able to cross the blood–brain barrier to deliver a chemotherapeutic for the treatment of brain tumours [6] and gold nanoparticle probes that detect DNA from biological warfare agents such as anthrax [7].

Second, evaluation of the field by prominent scientists leaves little doubt that NT is going to lead to a major revolution that is going to have a significant impact on society. Dr Richard Smalley, Nobel laureate in chemistry, believes that 'the impact of NT on health, wealth, and the standard of living for people will be at least the equivalent of the combined influences of microelectronics, medical imaging,

Table 1. Global growth in NT R&D [2].

Country/region	1997	2002
USA	432	604
Western Europe	126	350–400
Japan	120	750
South Korea	0	100[a]
Taiwan	0	70
Australia	0	40
China	0	40
Rest of world	0	270

[a] Per year, for 10 years (in millions of dollars).

computer-aided engineering, and man-made polymers in this century' [8].

Third, major industrial countries are incorporating NT in their innovation systems: they see this as an engine for wealth creation in the near future. As a result they have begun to invest heavily in research and development (table 1).

Fourth, there are applications that are about to be introduced into the market. Nanomix, for example, intends to begin selling by the end of 2002 nanotube-based sensors for detecting gasoline vapours that will help protect refineries, chemical plants, and pipeline stations from leaks—these will be 10 times less expensive than current sensors, and can operate for a year on a watch battery [9].

. . . the ethics lags behind

What is worrying, though, is that the serious study of NE^{3}LS research lags far behind the science. Despite availability of research funds, NE^{3}LS research has not yet been taken seriously and pursued on a large enough scale.

Some commentators on NT have examined the implications of NT but have often focused on distant, controversial applications. For example, Bill Joy wrote an influential and widely discussed paper in Wired magazine [10], about 'gray goo'. Steven Block, Stanford biophysicist, suggests that much of this hype is an illogical extrapolation of current research. 'Nobody has a clue how to build a nanoassembler, much less get one to reproduce' [11].

Others have tended to hype the potential applications of NT. Gary Stix, who edited a special issue of *Scientific American* on NT [12], has observed that 'there has emerged a cult now of futurists who foresee NT as a pathway to a technological utopia: unparalleled prosperity, pollution-free industry, even something resembling eternal life' [13].

The first guidelines on molecular NT [14] have been produced by the Foresight Institute, led by K Eric Drexler, an early thinker on NT and the person largely responsible for first introducing NT to the public in his book *Engines of Creation*. While the guidelines focus on the prevention of uncontrolled self-replication, they also touch on broader issues of global wealth distribution, environmental protection, and regulation to prevent the misuse of NT. Authors of the guidelines suggest that further research into the implications and regulation of NT by the global community of nations and NGOs is required.

There have been two important conferences recently convened to discuss ethical, legal, and social implications of NT [15, 16]. At both of these conferences the discourse,

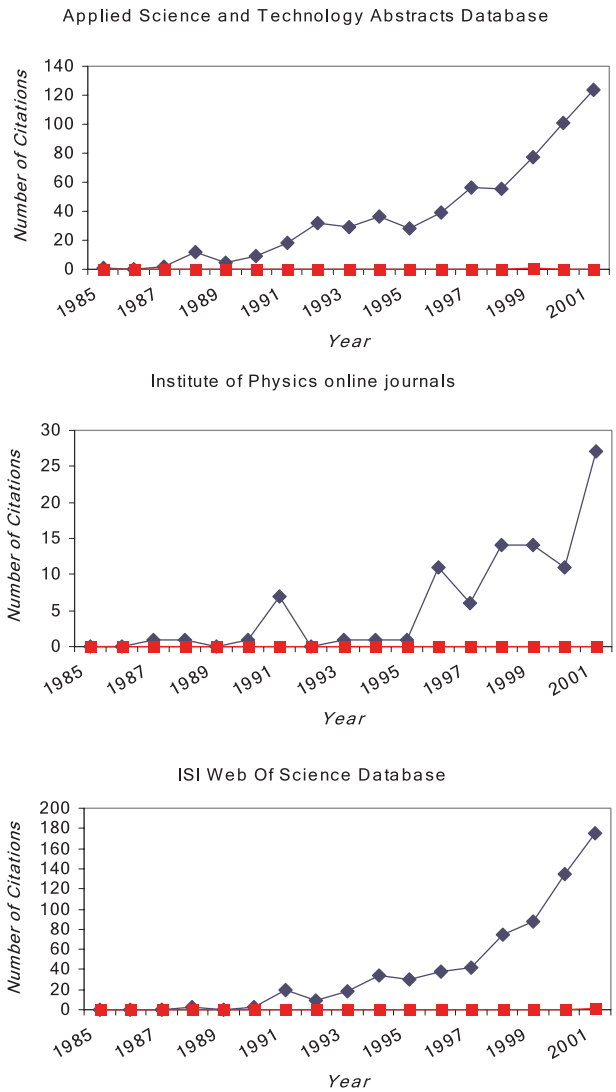

Figure 1. Citations in scientific databases on NT and on ethics or social implications of NT. ♦: NT; ■: ethics or social implications of NT.

as can be expected at this stage, has been at the level of generalizations and motherhood statements. There are calls to study the ethical implications, pointing out that NT is a powerful and revolutionary development that is likely to have a significant impact on society; comparisons to past technological revolutions and the impact that those have had on society; important taxonomic distinctions—for example, between nanomaterials (nanates) and nanomachines (nanites) [17]; eulogies to unforeseen consequences; calls for scientists to help the public understand ethical issues; and exploration of different methods of public engagement [18].

While the number of publications on NT *per se* has increased dramatically in recent years, there is very little concomitant increase in publications on the subject of ethical and social implications to be found in the science, technology, and social science literature. A survey of several databases (figure 1) from 1985 to 2001 reveals a paucity of citations on the ethics or social implications of NT.

While there are significant research funds available, at least in the US, these funds are not being used. In 2001, the US

National Nanotechnology Initiative allocated $16–28 million to societal implications, but spent less than half that amount. The NSF, responsible for spending $8 million, did not fund a single social science project focused on societal implications of NT. One of the main reasons for the lack of awards was the lack of meritorious research grant proposals [19]. The European Community [20], Canada [21], and Australia [22] have all recognized the importance of ethical discussion but so far have done little to foster it.

The lack of dialogue between research institutes, granting bodies, and the public on the implications and directions of NT may have devastating consequences, including public fear and rejection of NT without adequate study of its ethical and social implications.

Why worry?

Is there anything special about NT that requires a specific discussion now, and perhaps specific regulatory mechanisms in the future? The ethical issues fall into the areas of equity, privacy, security, environment, and metaphysical questions concerning human–machine interactions.

Equity. Who will benefit from advances in NT? Today we talk of the digital divide as something that is harmful and that we should attempt to correct. We have also talked about the emerging 'genomics divide' in a similar fashion [23]. This is because we have come to understand that technology and development are intricately linked [24], and that what at first appears to be very 'high-tech' and costly and therefore perhaps irrelevant for developing countries, in the end might come to be of most value for those same developing countries [25]. Thus NT, were it to develop in the way it ought, might ultimately be of most value for the poor and sick in the developing world. At the Johannesburg summit, the main issues for developing countries were poverty reduction, energy, water, health, and biodiversity. NT has the potential to make a positive impact on all of these if its risks either do not materialize or are appropriately managed. The poor could benefit from NT, for example, through safer drug delivery, lower needs for energy, cleaner energy production, and environmental remediation. It is also possible that health could be improved by better prevention, diagnosis, and treatment. One of the biggest health problems in developing countries is trauma, especially from road traffic accidents, and absence of rehabilitation facilities [26]: better nanomaterials for making safer tyres, or NT-based scaffolds to grow bone [27] may be extremely important, especially if the promise of mass production at very low cost materializes. Furthermore, if developing countries were to see the potential of NT and became early players in the field (see China's increased expenditure on NT R&D; table 1), NT might have an impact on their economic development and obviate the need quite soon for these countries to become net importers of NT. This is similar to what is happening in biotechnology, a field in which countries such as India, China, Brazil, and Cuba have already begun to invest in [28].

Privacy and security. NT is capable of dramatically improving surveillance devices, and producing new weapons. How would individual privacy be protected if near-invisible microphones, cameras, and tracking devices become widely available? Will these new technologies increase security or add to the arsenal of bio- and techno- or even nano-terrorism? Who will regulate the direction of research in defensive and offensive military NT? How much transparency will be necessary in government and private NT initiatives to avoid misuses? There are also very interesting legal questions [29] involving monitoring, ownership, and control of invisible objects [17].

The next asbestos? Environmental issues. NT has already generated novel types of matter such as fullerenes and carbon nanotubes. Where do these and other nanomaterials go when they enter the environment and what are their effects? This year, the US environmental protection agency (EPA) has added the funding of research projects that explore potential environmental dangers of NT to its list of priorities. 'There are always possibilities for environmental or health harms', said Barbara Karn, EPA official [30].

Human or machine? Some avenues of research in NT include the incorporation of artificial materials or machines into human systems, as is beginning to happen with implanted computer chips [31]. The modification of living systems is met with great scepticism by much of society. How acceptable will technologies such as implantable cells and sensors be for the general population? What are its implications and what are our limits?

Closing the gap between science and ethics. NT can learn from earlier efforts to address social implications of genomics and biotechnology. Here are some of these lessons:

- *Appropriate funding of* NE^{3}LS*research.* In the *Human Genome Project*, James Watson recommended that 3–5% of the budget be devoted for study of ethical, legal, and social implications. This massive infusion of research funds energized the ethics community. The US seems headed down this path for NT, although it has not yet made a percentage commitment. Other countries do not seem to have allocated portions of their NT budgets for ethical and social implications.
- *Large-scale interdisciplinary research platforms.* We should try to avoid from the beginning the navel-gazing type of ethical, legal, and social implications studies that were done in the early days of the *Human Genome Project* and which have been heavily criticized in recent evaluations [32, 33]. An example of a large-scale interdisciplinary research platform is shown in figure 2 [23].
- *Capacity strengthening.* The lack of meritorious proposals in response to funding announcements mirrors the early experience with the ELSI programme of the *Human Genome Project*. The appropriate response is to focus on strengthening capacity in NE^{3}LS research at all levels from undergraduate summer students, through graduate students, post-doctoral fellows, junior faculty, and senior investigators. This can be done through career awards, training grants, and also emphasizing the development of highly qualified personnel in large-scale

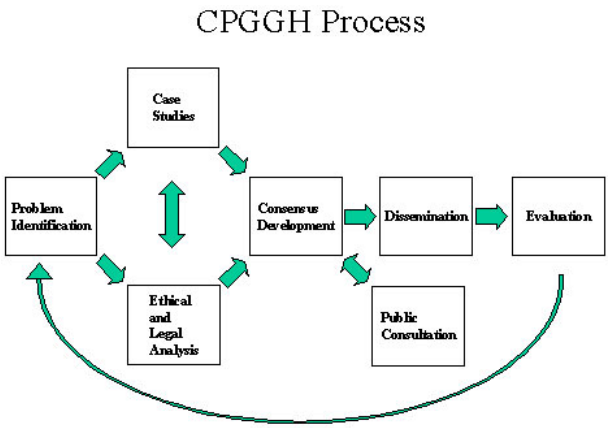

Figure 2. An example of a large-scale interdisciplinary method: the Canadian Program on Genomics and Global Health (CPGGH). The large-scale interdisciplinary platform has been designed specifically to address the deficiencies of current approaches to the study of the ethical, environmental, legal, and social implications of scientific and technological advances [23].

NE^{3}LS grant applications. Capacity strengthening should also include different sectors and developing countries.

- *Intersectoral approach.* One of the problems with previous ELSI work is that it is conducted in isolation from major players. Those studying ethical and social implications of NT should have regular opportunities to interact with, and represent, scientists, NGOs/activist groups/pressure groups, government, and industry.
- *Involvement of developing countries.* The great tragedy of ELSI research on genomics is how it ignored, until recently, the role of genomics and biotechnology in developing countries. Voices on NT from developing countries must be included now. This could be done through the formation of a global geomics initiative similar to the one proposed for genomics [34, 35] or other forms of global issues networking [36]. We should develop, using Internet-based tools for collaborative networking, a global opinion-leaders network for ethical and social implications of NT.
- *Public engagement.* As the UK *White Paper on Science* [37] noted, the most pressing issue in science is public involvement. Journalists need to be involved in the early stages of NT since they have an important influence on public perceptions. Innovative mechanisms such as plays, used for example by the Wellcome Trust and others to engage the public in genomics, need to be fostered. Science museums should consider how they might include exhibits on the ethical and social implications of NT. Modules examining ELSI implications of NT should be developed for secondary-school students, so citizens can be engaged early in balanced discussion of issues. All these approaches [38, 39] are now beginning to be used in genomics, and should be rapidly adapted to NT.

The call by ETC for a moratorium on deployment of nanomaterials should be a wake-up call for NT. The only way to avoid such a moratorium is to immediately close the gap between the science and ethics of NT. The lessons of genomics and biotechnology make this feasible. Either the ethics of NT will catch up, or the science will slow down.

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