The impacts of nanotechnology

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It is fairly easy to list the likely technical impacts of nanotechnology. The focus on applications to information processing, energy and health implies that these are the areas in which the greatest impact is foreseen. The most important impacts will, however, be on a broader plane, because nanotechnology epitomizes a deeper, more rational view of the universe, including all the practical aspects of our environment. Nevertheless, it is far from certain that humanity will take up the challenge of the new opportunities, the most potentially disruptive of which is the possibility for everyone to participate in shaping his or her own environment, as much a producer as a consumer. For this reason, those who hold this vision and see such a development as the only alternative offering a sustainable way forward for humanity (in other words for promoting its long-term survival) have a special responsibility to cultivate the vision and its realization.

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Nanotechnology Perceptions **7** (2011) 28–66
Received 31 March 2011

Part I: Introductory material

1. Introduction—measuring impact

Whenever one talks of impacts one should always have in mind how they will be measured. While in the laboratory, the impact or effect of a generalized force can be more or less readily quantified either by applying the force to the system under investigation and comparing the results to a system to which no force is applied or, if other conditions and states are sufficiently stable, to gather data about the system prior to the application of force, and compare that data to a fresh set gathered after the application.

This system of investigation also works outside the laboratory—albeit less straightforwardly and yielding results more open to divergences of interpretation. An interesting example is the fate of Germany during the 40 years following World War II. The country, which before unification less than eighty years earlier comprised many independent kingdoms and principalities, was split into two, the Federal Republic of Germany (FRG) in the West, but including West Berlin, and the German Democrat Republic (GDR) in the East. The former adopted Western, capitalist economic policies and the latter fell into the sphere of influence of the Soviet Union and adopted socialist economic policies. Undoubtedly the effects were very different. Of course one might argue that even though the two countries had a common official language and recent history, the characters of the "jolly Rhinelander" or the Bavarian in the West are very different from the characters of the austere, almost militaristic Prussian or the Saxon in the East. The different effects were, however, strongly observable when comparing East and West Berlin, the peoples of which were the same. The microcosm of Berlin and the larger scale case of the two Germanies is probably the most significant sociopolitical "experiment" that has been undertaken, at least during the past few centuries. In order to apply the same approach to understanding the impact of nanotechnology, one would have to introduce it in one country and strictly prohibit it in another, preferably neighbouring one with a very similar sociopolitical character at the beginning of the experiment. The alternative would be to observe development in one or more countries prior to the introduction of nanotechnology and then compare development with nanotechnology to an extrapolation of the previous history, but such an extrapolation is likely to be so uncertain the results of any such investigation must be rather speculative.

A quite different approach is to consider what we might expect or hope for as our society evolves, and then examine how nanotechnology can, could or might contribute to it. In particular, can nanotechnology help to solve the great and pressing problems of contemporary humanity? Although, if ranked, there might be some debate about the order, most people would include rapid climate change, environmental degradation, energy and other resource depletion, unfavourable demographic trends, insufficiency of food, and nuclear proliferation among the biggest challenges.[1] As well as these primarily "technical" problems (although it is increasingly recognized that they are, in fact, systems problems involving societal issues as well) there are some nontechnical challenges too, such as how to counter the seemingly inexorable trend for income inequality to increase (which is bad because it promotes social instability) and for

1 Cf. the "Millennium Development Goals" promulgated by the United Nations.

morals to be degraded (which is bad not only because it promotes social instability, but also because it undermines the fundamental principle of human solidarity).

Both these approaches require an appreciation of the impacts nanotechnology is having on some of our current core technologies—to represent which I have selected information technology, health and energy. According to the first approach (developed in Part II) we first need to estimate how things will develop without nanotechnology, and then consider how those trends might be affected by nanotechnology. For the second approach (developed in Part III), we shall take the grand challenges and examine how nanotechnology might contribute to solving them. Note that the fact that they have not yet been solved does not necessarily mean that we lack the necessary technology; it may be that we have it but face other obstacles, such as lack of money (it might be too expensive) and opposition from groups with a vested interest in the *status quo*.

Nanotechnology is being intensively developed by research institutes of various kinds, public, private and commercial, but whether the technology is actually adopted is another matter. We can develop a scenario of what is likely to happen if a certain technology is adopted, but in order to assess actual impact we must multiply by the probability of adoption. Hence we have, somewhat analogously to the risk of something being the product of the degree of hazard and the exposure,

$$\text{actual impact} = \text{theoretical impact} \times \text{probability of adoption} . \qquad (1)$$

Whenever it is possible to make a rational decision about adopting some innovation, one may do so on the basis of the “Judgment (J)-value”, initially developed by Thomas for assessing the worthwhileness of safety measures in the nuclear power industry,[2] but applicable to any sector.[3] The goal of any safety measure is, ultimately, to prolong life and increase its quality but having to pay the cost of the measure must decrease the quality of life, and the decrease should not exceed the increase. The J-value is essentially a tehnique for determining the quotient of the trade-off. In the case of nanotechnology, costs are incurred through developing specific applications, and it would be irrational to pursue development if those costs (expressed in terms of change of quality of life) were likely to exceed the benefits. It is difficult to reliably determine the development costs when technology is only at a very early stage, hence in this essay we shall not aim to calculate J-values.

“Innovation” itself needs some definition. If we start with the discovery of a phenomenon, such as electricity, it becomes progressively developed in the laboratory until a specific application is formulated (e.g., the electromagnetic motor, or the telephone), when engineering takes over to perfect it. A product must then be “brought to market”—this is commercialization, which includes raising capital for manufacturing, organizing supply chains and fulfilling any legislative requirements. “Innovation”, or sometimes “business innovation”, has lately been defined by the UK government as “the successful exploitation of new ideas”,[4] which would

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[2] P.J. Thomas et al., The extent of regulatory consensus on health and safety expenditure. Part 1: Development of the J-value technique and evaluation of regulators recommendations. *Trans. IChemE* B **84** (2006) 329–336.

[3] P.J. Thomas et al., The extent of regulatory consensus on health and safety expenditure. Part 2: Applying the J-value technique to case studies across industries. *Trans. IChemE* B **84** (2006) 337–343.

[4] For example, in the document *Concept to Commercialisation* published by the Technology Strategy Board in 2011.

include not only both engineering and commercialization but some of the laboratory science preceding it. Other authorities reserve use of the word "innovation" for commercialization. Presumably "successful" is defined in terms of the creation of a sustainable business, but sustainability may be short- or long-term, and there is no standard, agreed criterion or set of criteria for determining success. Furthermore, it seems inadequate to define it purely with respect to one company or a group of related companies. One also needs to consider the overall effects on society.

2. Definitions of nanotechnology

After having sketched out how we might be able to determine impact, we had better ensure that we have agreement on what is nanotechnology. It is defined as "the deliberate and controlled manipulation, precision placement, measurement, modelling and production of matter in the nanoscale in order to create materials, devices and systems with fundamentally new properties and functions".[5] Several organizations, especially in the USA, the EU and Japan (e.g., the U.S. National Nanotechnology Initiative, NNI) have promulgated their own definitions, but they are all basically the same as the one cited here. It follows that nanotechnology has three aspects:

1. A universal fabrication procedure;
2. A particular way of conceiving, designing and modelling materials, devices and systems, including their fabrication;
3. The creation of novelty.

The fabrication aspect has three subaspects:

1. "Top–down" (exemplified by ultraprecision machining and semiconductor processing);
2. "Bottom-to-bottom" (assemblers—essentially a downscaled version of additive manufacturing);
3. "Self-assembly" ("bottom–up", much of which is bio-inspired; its apotheosis is really biological growth, in which very complex and sophisticated structures, which have functional if not structural identity, can be reproducibly made).

Note that "novelty", considered to be an essential feature of nanotechnology, can be exemplified in several ways:

1. New physical (or physico-chemical) properties emerging in the nanoscale;[6]
2. Nano-objects with no bulk counterpart (e.g., carbon nanotubes);
3. Macro-objects acquiring new functionality because of ultrasmall components (the ultrasmallness may be of size or cost), yielding enhanced performance (this is sometimes called nano-enabled technology).

The definitions of nanotechnology rely heavily on definitions of the nanoscale. One approach to the latter is to equate the scale of the transition to novelty upon miniaturization as the upper level of the nanoscale,[6] which then becomes dependent upon the property under consideration, the material and the state variables (such as temperature) of its environment. Although the concept of the definition is simple, we then have a plethora of actual lengths determining the nanoscale. The alternative is to consensually fix a range for the nanoscale that

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5 E. Abad et al., *NanoDictionary*. Basel: Collegium Basilea (2005).
6 J.J. Ramsden and J. Freeman, The nanoscale. *Nanotechnol. Perceptions* **5** (2009) 3–25.

covers most cases; this has been done by the International Standards Organization (ISO), which defines the nanoscale as the range of 1–100 nanometres.

Nanoscience is defined as the science necessary for achieving nanotechnology, which has itself a purely practical aim.

We also have "soft" and "hard" nanotechnology, in the sense of unexceptionable and controversial, respectively. The former corresponds to the near term—in some cases what is already realized; the latter corresponds to the long term; that is, productive nanosystems, as embodied by the personal nanofactory. As with any long-term extrapolation of technology, there is a considerable element of speculation regarding the latter, especially concerning timescales.

Applications can be considered as both direct and indirect.[7] An example of the former is a nanoparticle that functions as a medicinal drug and can be injected as such directly into the bloodstream of a patient. An example of the latter is an information processor (computer) based on very large scale integrated chips with individual circuit components in the nanoscale (but the overall size of the device and that of many essential peripheral components is bigger than the nanoscale).

Nanotechnology implies scrutinizing the world from the viewpoint of the atom or molecule, while remaining cognizant of structure and process at higher levels. Practically speaking, this should have a huge impact on applied science, in which domain the most pressing problems facing humanity, such as food, energy and other resource security, fall. Nanotechnology will hopefully give humanity new impetus to solving these problems in a more rational way than attempted hitherto. The rational approach first ascertains whether the problem requires new fundamental knowledge for its solution, or whether it "merely" requires the application of existing fundamental knowledge. If the former, that new fundamental knowledge must be acquired through scientific research (i.e., research according to the scientific method). If the latter, engineering research is called for, including optimization.

3. The nano–bio–info–cogno (NBIC) quartet

Nanotechnology is undoubtedly an emerging technology, and is increasingly conflated with three other significant emerging technologies: biotechnology, information technology, and cognitive science.[8] We can now speak of "converging emergent technologies". Biotechnology, which, practically speaking, means the production of substances through the controlled activity of microorganisms and, conceivably, higher organisms as well, is poised to greatly benefit from convergence with nanotechnology, which will advance the DNA sequencing that nowadays underlies biotechnology and the sensors and actuators required to maintain fermenters (bioreactors) that are the main production units of the technology. Information technology relies on computer hardware with nanoscale features. The convergence of nanotechnology and cognitive science is taking place partly through hardware (e.g., ultrasmall electrodes for

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[7] J.J. Ramsden, What is nanotechnology? *Nanotechnol. Perceptions* **1** (2005) 3–17.

[8] The purist will argue that the last of these is not technology, which is absolutely correct, but the phrase "cognitive technology" does not convey a great deal of meaning. Our response is to say that it actually means the technology derived from advances in cognitive science, which includes such things as algorithmic pattern recognition and the workings of the human brain.

probing the nervous activity of the brain with the resolution of a single neuron) and partly through thinking about how quantum phenomena (which dominate sizes below the nanoscale) can have macroscopic expression.[9]

The full implications of nanotechnology can perhaps be better grasped by considering the implications of this quartet. For example, Roco envisages implications in the following areas:[10]

• Revolutionary tools, products and services (e.g., pharmaceutical genomics, regenerative medicine, biochips);

• Everyday human performance, such as work efficiency, learning and group performance;

• New organizations and business models, policies for reshaping infrastructure, setting priorities for research and development, facilitating the co-evolution of new technologies and human potential;

• Creation of a universal domain of information exchange encompassing ideas, models and cultures.

All too often, however, statements like these are made without real consideration of the steps needed to be taken to move from current capabilities to the long-term vision. One of the purposes of this essay is to suggest ways in which such steps can be constructed.

Part II: The main anticipated technical impacts

4. Impacts on science

Nanotechnology has already had a very important impact on investigations of structure and processes on the atomic scale, thanks to the wealth of nanometrology tools (such as the many different variants of scanning probe ultramicroscopy) that now exist. Nanoscale ultraprecision manufacturing capabilities have led to such things as reliable labs-on-chips, which have revolutionized chemical and biochemical analysis. A good example is the affordable "gene chip" (DNA array) invented by Fodor et al.[11] The availability of such chips (which can be used to identify bacteria[12] and quantify changes in gene expression in pathological states) does not change anything in principle, but if the technology is so costly one can only afford to carry out one measurement clearly the range of problems open to investigation is extremely limited. The comparison of healthy and diseased cells demands a great number of measurements, which would be prohibitively costly and cumbersome if the gene chip technology did not exist. A similar situation prevails in the use of evanescent wave technology for quantifying biomolecular binding (e.g., antibody–antigen) reactions: the most advanced technology is optical waveguide lightmode spectroscopy (OWLS), which works best if a grating coupler is used to register the lightmode spectrum (from the kinetics of change of which the binding coefficients are obtained). Until grating couplers could be produced on a large scale at low unit

[9] See J.J. Ramsden, Less is different. *Nanotechnol. Perceptions* **6** (2010) 57–60.

[10] M.C. Roco, The emergence and policy implications of converging new technologies. In: *Managing Nano-Bio-Info-Cogno Innovations* (W.S. Bainbridge and M. C. Roco, eds), pp. 9–22. Springer (2005).

[11] S.P.A. Fodor et al., Light-directed, spatially addressable parallel chemical synthesis. *Science* 251 (1991) 767–773.

[12] S. Chumakov et al., The theoretical basis of universal identification systems for bacteria and viruses. *J. Biol. Phys. Chem.* **3** (2003) 11–17.

cost,[13] individual gratings were prohibitively expensive, preventing any practical use being made of the technology.

After the development of scanning probe devices capable of nanoscale resolution, important new developments in optical microscopy have taken place,[14] to some extent offsetting the uniqueness of the capabilities of scanning probe technologies, the existence of which no doubt provided some of the impetus for further developing the more traditional rivals.

5. Impacts on engineering

Although nanotechnology tends to be defined in terms of physical processes (manipulation, measurement, production etc., see §2) the conceptual change of looking at the world with atomic precision in order to get to the bottom of mechanisms is just as much part of nanotechnology as creating materials and devices. The relationship of nanotechnology to engineering is thus similar to that of molecular biology to biotechnology and medicine. "Nanobiology" is thus a synonym for molecular biology, and "molecular medicine" is thus a subset of nanomedicine (the latter also including drug delivery agents, etc.; see §8). As an example, if we wish to apply nanotechnology to catalysts we need to understand how they work with atomic detail, and once we have that understanding we can then go on to make them. Nevertheless, that dream of quantum chemists to write down the Schrödinger equation for an entire organism is alien to the spirit of nanotechnology, which is essentially a mesoscale technology. For example, if the nanotechnologist wishes to design a protein, he will work with the amino acids as the basic building blocks, characterizing each of them with a small number of parameters, but not bothering about the hundreds of individual protons, neutrons and electrons from which they are composed. The trick of nanotechnology is to achieve the quality, specificity and individuality of a quantum object while working with something (a "nanoblock") that is large enough to manipulate in a convenient, practical fashion.

Vastification (i.e., a vast increase in the number of entities to be integrated in a system) is an easily achievable corollary of the miniaturization of the entities constituting the system. Indeed, as far as electronics is concerned, the progressive increase of processing power is due far more to the ability to produce circuits with more components than to the fact that those components are smaller and, hence, work faster. Moore's law is usually expressed in terms of the numbers of electronic components on a silicon chip, with the numbers increasing far more rapidly than the area of the chip, but the components are not simply adventitious neighbours as are grains of sand on the beach, but are *integrated* into a functional system. It is this necessity for integration that makes complexification a corollary of vastification. Although design (e.g., of electronic circuits) has been enormously facilitated by computers (the previous generation serving to facilitate the design of the next generation), the basic methodology is still that of a draftsman at the drawing board. Now, as integrated circuits contain of the order of 10^9 components per chip, we seem to have reached the "complexity ceiling" of that basic methodology. The existence of this ceiling is possibly rooted in what might be intrinsic limits of the human brain's working memory

[13] K. Tiefenthaler and W. Lukosz, Sensitivity of grating couplers as integrated-optical chemical sensors. *J. Opt. Soc. Am.* B **6** (1989) 209–220.
[14] E.g., S.W. Hell's stimulated emission depletion microscopy (STED).

for processing more than 7 ± 2 "psychological units" at any moment.[15] Therefore, nanotechnology must necessarily revolutionize engineering design. The complexity ceiling can be overcome by evolutionary design. This works as follows. The essential and possibly other features of the entity to be designed are encoded as a "genome", each feature corresponding to one "gene". The genome is just a numerical (e.g., binary) string. A vast population of genomes is generated, possibly with a large measure of randomness. The "fitness" of each genome is then evaluated—usually according to its ability to fulfil the functional goals of the design after decoding (it would, of course, be very cumbersome if each genome actually had to be "translated" into a real physical object that would then be subjected to various tests; hence the ability to simulate performance is very important part of evolutionary design). The best designs are then retained (possibly only very small proportion of the total population) and the rest are discarded. The population is then built up again by creating "offspring" of the retained designs via recombination and mutation, in analogy to the eponymous biological processes.[16] Fitnesses are again evaluated, unsatisfactory genomes eliminated and the population rebuilt repeatedly until the design goals have been achieved.

One characteristic of evolutionary design is that the human designer may not know how the finally selected entity actually works internally. Although this seems to be contrary to generally accepted engineering practice, even conventionally designed objects are nowadays very often so complex that it is not possible to test their performance under every possible combination of controlling parameters. Indeed, it has been suggested that unexpected behaviour is really inevitable under such circumstances.[17] A new paradigm of risk acceptance must therefore anyway be developed, and it seems that the products of evolutionary design could be well accommodated within that paradigm.

6. Impacts on information technologies

The current integrated circuit manufacturing paradigm (well expressed by the International Technology Roadmap for Semiconductors, ITRS) envisages Moore's law continuing for a few more years, driven essentially by further incremental improvements in semiconductor processing, and keeping the same basic mode of operation for the transistors making the logic gates making the circuits.

Beyond that, there are several alternatives to be considered. Single electron transistors and molecular electronics devices represent the innovation with the greatest degree of continuity. Circuits would still work in essentially the same way. The main difficulty is manufacturing them reliably (see §9). In all electronic circuits, as the volume density of components increases, heat dissipation becomes an increasing and possibly insuperable problem. It is therefore attractive to replace electronic charge as the carrier of information. If one nevertheless wishes to remain with the electron, electron spin is the obvious other electronic property worth

[15] G.A. Miller, The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychol. Rev.* **63** (1956) 81–97.
[16] E.g., J.J. Ramsden, *Bioinformatics*, 2nd edn, Ch. 10. London: Springer, 2009.
[17] E.g., C.B. Perrow, *Normal Accidents: Living with High Risk Technologies* (2nd edn). Princeton: University Press (1999).

considering as the carrier of information.[25] Spin electronics or spintronics can essentially work without generating heat. The quantum cellular automaton is another approach to currentless information processing. Information is represented by configurations of electrons on quantum dots, and the electrons tunnel within individual cells to change those configurations but do not move beyond the confines of those cells.

A more radical proposal is for all-optical computers. This depends on the availability of nonlinear optical materials that can be used to gate the passage of photons.[18] Photonics is more amenable to three-dimensional architecture (as opposed to the essentially two-dimensional architecture of present electronic circuits), which could achieve very significant increases of volumetric processor density.

More radical still is the development of quantum computers, with which we lose the link to logic gates. Information is represented as superpositions of quantum states, and the final result of a computation is extracted by carrying out a "measurement" on the system, forcing it to adopt its most probable state. A quantum computer might be realized optically,[19] but the concept is not closely linked to any particular kind of representation of information.

Whatever the outcome of the technology battles, the operation of Moore's law for almost 50 years is responsible for the present ubiquity of internet servers (and, hence, the World Wide Web) and cellular telephones. The impact of these information processors (i.e., the indirect impact of the nanotechnology within them) is above all due to their very high-speed operation, rather than any particular sophistication of the algorithms governing them. Most tasks, ranging from the diagnosis of disease to ubiquitous surveillance, involve pattern recognition, something that our brains can accomplish swiftly and seemingly effortlessly for a while, until fatigue sets in, but which requires huge numbers of logical steps when reduced to a form suitable for a digital processor. It has been proposed that despite the present clumsiness of this "automated reasoning", ultimately artificial thinking will surpass that of humans—this is Kurzweil's "singularity".[20] This singularity would be the ultimate revolution (see §16).

Data storage, as well as data processing, is also affected by miniaturization. Since there has been interest in and progress effecting such miniaturization (e.g., microfilm) for millennia this was perhaps the most readily imaginable impact of nanotechnology at the time of Feynman's lecture.[21] The physical embodiment of one bit of information could be in principle be the presence or absence of a single atom (the main challenge is reading the information thus embodied). At that time it was already known that genetic information was stored in deoxyribonucleic acid (DNA), each elementary unit of storage being a small molecule containing only a few atoms. As with processing power, we are talking about a prolonged period (that has so far lasted several decades) of exponential growth in digital data storage technology, which roughly follows Moore's law as well. In effect, the cost of storing one bit halves every 18 months or so. This has

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[18] E.g., E.K. Wolff and A. Dér, All-optical logic. *Nanotechnol. Perceptions* **6** (2010) 51–56.

[19] E.g., A. Politi and J.L. O'Brien, Quantum computation with photons. *Nanotechnol. Perceptions* **4** (2008) 289–294.

[20] R. Kurzweil, *The Singularity is Near*. New York: Viking Press (2005).

[21] R.P. Feynman, There's plenty of room at the bottom. *J. Microelectromechanical Systems* **1** (1992) 60–66 (transcript of a talk given by the author on 26 December 1959 at the annual meeting of the American Physical Society held at the California Institute of Technology).

gradually changed habits. Every piece of information, no matter how trivial, can be stored. The rapidity of bitwise searching means that it is not even necessary to index the information.

When vast processing power is combined with vast data storage capacity and the ubiquity of the World Wide Web, we have a potent mixture. The production of printed books and journals, and the maintenance of libraries, are all under threat. Nevertheless, it does not look as though they will be completely eliminated. The criterion is always one of convenience. It may still be quicker and more effective to retrieve a piece of essential information from a book or a reprint. Information cannot be retrieved from unstructured data if one does not know what search terms to use.

In summary, nanotechnology will help Moore's law to prolong its lifetime, but in the near- to medium-term its impact with respect to what is anyway expected to happen will be minor. Most of the developments in nanoscale components of logic gates can only live in the research laboratory because of the difficulty of reliable manufacture.

7. Impacts on the energy industry

Nanotechnology has the opportunity to contribute in several ways to the problem of energy. There are two important aspects: one of them is how to supply small quantities of energy to nanoscale devices (e.g., implanted therapeutic devices, see §8); the other is how to address the current global undersupply of usable energy (and the trend is for the gap to get worse). The first category is typically called "energy harvesting". Solving the problem would make a negligible difference to the energy gap, but will be enormously important in terms of convenience. The devices currently being envisaged are typically energy transducers rather than heat engines in the conventional sense (e.g., a steam turbine). Most of the devices to be supplied are supposed to be worn by human beings. Therefore the energy sources are considered to be heat, mechanical movement and chemical fuels. Heat harvesters would be based on pyroelectric materials positioned where significant heat gradients occur (e.g., in the skin). Mechanical movement is of course ubiquitous but the efficiency of any kind of inertial device scales unfavourably with nanification,[22] hence exploitation is likely to be based on zones where compression occurs (e.g., the soles of the feet). Energy-rich molecules such as glucose are sufficiently abundant in the blood for use as fuel, and fat reservoirs provide another potential source of chemical energy. Naturally, one will have to eat slightly more if energy is being tapped off for an artificial implant, but the difference is negligible. This would not apply if ambient radiant energy were harvested; the difficulty here is that the supply is typically irregular and hard to predict. The most exciting possibility is to exploit concentration gradients. This is of course how our cells provide high-quality energy, especially using the remarkable enzyme ATPase, which generates adenosine triphosphate (ATP) from transmembrane proton gradients.[23]

Most energy harvesting research is at present taking place at the microscale, and is indeed an important part of the field of microsystems technologies (MST). The most actively pursued

[22] C. Hierold, From micro- to nanosystems: mechanical sensors go nano. *J. Micromech. Microengng* **14** (2004) S1–S11.

[23] M. Yoshida, E. Muneyuki and T. Hisabori, ATP synthase—a marvellous rotary engine of the cell. *Nature Rev. Mol. Cell Biol.* **2** (2001) 669–677.

objectives are ways to power devices carried externally by human beings, such as cellphones and active clothing, for which the imperative to miniaturize down to the nanoscale is absent. Nevertheless, even a microscale energy harvester might usefully contain nanoscale components, hence nanotechnology will likely contribute to the field's development.

The second category, concerned with solving the world's energy shortage, can be considered from several viewpoints.

Solar energy. There is expected to be direct impact on photovoltaic cells converting radiant energy from the sun into electricity. The main primary obstacle to their widespread deployment is the high cost of conventional photovoltaic cells. Devices incorporating particles (e.g., Grätzel cells) offer potentially much lower fabrication costs, especially if inkjet printing technology can be adopted. The potential of incorporating further complexity through mimicry of natural photosynthesis, the original inspiration for the Grätzel cell, is not yet exhausted. The main challenge is to design and fabricate highly efficient and robust catalysts. This requires atomic resolution, however, and therefore must await the development of productive nanosystems (assembler-based fabrication). Robustness is a particularly difficult goal. Unlike natural systems, the components of which are constantly being renewed, the artificial system must remain functional preferably unattended for many years.

The main secondary obstacle to widespread deployment of photovoltaic cells is that except for a few specialized applications (such as powering air-conditioners in Arabia) the electricity thus generated needs to be stored, hence the interest in simultaneous conversion and storage in chemical form, mimicking much more closely natural energy harvesting. This can also be encompassed within the concept of the Grätzel cell. Undoubtedly natural photosynthesis is only possible through an extremely exact arrangement of atoms within the photosystems working within plant cells, and the more precisely artificial light harvesters can be assembled, the more successful they are likely to be. The problem of robustness is omnipresent.

In view of the intensive research into solar cells, the specific impacts of nanotechnology on progress might be quite difficult to discern. Reducing the thickness of some of the laminar elements in a photovoltaic cell will save on materials and may enhance efficiency. All applications using catalysts will benefit from rationally designed catalysts constructed atom-by-atom, but there is no practical fabrication technology for that at present.

Fuel cells. Although the scientific basis of this technology, whereby fuel is converted to electricity directly, was established over 150 years ago by Christian Schönbein, it has been very slow to become established. As with photovoltaic cells, the main primary obstacle is the high cost of fabrication. Nanotechnology is expected to contribute through miniaturization of all components (especially reducing the thickness of the various laminar elements), simultaneously reducing inefficiencies and costs, and through realizing better catalysts for oxygen reduction and fuel oxidation. A particular priority is developing fuel cells able to use feedstocks other than ultrapure hydrogen. The catalytic problem is particularly acute here, since there seems to be an inverse relationship between the efficiency of a catalyst and its sensitivity to inactivation by impurities in the fuel. Until we have routine atom-by-atom assembly, however, it seems that the impact of nanotechnology on catalyst fabrication will be minor since we shall not be able to much improve on existing technology.

Energy storage. The primary means of storing energy is as fuel, but unless photoelectrochemical cells generating fuel from sunlight receive renewed impetus, renewable sources will mainly produce electricity and except for some special cases (such as photovoltaic-driven air conditioning installations in Arabia as already mentioned) at least some of the electricity will have to be stored to enable supply to match demand. Supercapacitors based on carbon nanotubes have attracted especial interest for rapidly responsive energy storage, but the impact of nanotechnology is likely to be small since using ordinary carbon black has already enabled over 90% of the theoretical maximum charge storage capacity to be achieved, at much lower cost. In any case, the classic photoelectrochemical process generates hydrogen (from water), the storage of which is problematical. The same problem besets hydrogen-fed fuel cells—unless the storage problem is solved effectively and economically, the "hydrogen economy" will not be able to get established. Through the design and fabrication of rational storage matrix materials, nanotechnology should be able to contribute to effective storage, although whether this will tip the balance in favour of the hydrogen economy is still questionable. Conventional routes to materials synthesis had become highly developed without making use of nanotechnology, except in a secondary fashion by exploiting nanometrology tools during the discovery process (see §4).

Typically, energy storage devices such as batteries can be nanified by making internal layers thinner and more accurately, which not only reduces the costs of materials (provided they can be manufactured) but also improves their performance. The actual achievement, on an industrial scale, of nanoscale internal structure might well require a revolutionary change in manufacturing technology. Clearly achieving it through assemblers would be revolutionary. Otherwise, the most revolutionary contribution seems to be through the use of nanoparticles rather than thin films. This enables well established printing technologies to be used for fabricating devices.

Energy efficiency. Here we have a very heterogeneous collection of technical impacts. Traditionally there are two opposing influences, the "utilities", which are mainly commercial operations trying to sell as much of their product (gas, electricity etc.) as they sustainably can, and the consumer, who is trying to minimize costly energy consumption. Changes in generally held attitudes have resulted in most utilities helping consumers to minimize energy use. Since utilities are mostly local monopolies, they can offset reduced consumption by higher unit prices.

Nanostructured coatings with very low coefficients of friction and extremely good wear resistance will find application in all moving machinery, hence improving its efficiency and reducing the energy required to achieve a given result. Examples include electricity-generating wind turbines and electric motors. A similar example is the use of nanostructured surface coatings that can be painted on aircraft to reduce drag. The morphology of these coatings is typically biomimetic. Fuel savings of a few percent have been achieved in trials. The main difficulty is inadequate durability of the coatings. The materials themselves might not be particularly expensive, but the labour of applying them, especially if the aircraft has to be specially withdrawn from service for the operation, is costly.

For all applications where collateral heat production is not required, nanotechnology-enabled light-emitting diodes can replace incandescent filaments. Lighting based on light-emitting semiconductor diodes can achieve a similar luminous output for much less power than incandescent filament lamps. The heat produced by the latter may be of value in a domestic context (e.g., contributing to space heating in winter) but is simply wasted in the case of outdoor street lighting (although the aesthetic effect is agreeable).[24] In fact, the actual operational efficiency of a device in a given functional context typically represents only a fraction of the overall effectiveness in achieving the intended function. For example, if the intended function of street lighting is to reduce road accidents, there is probably an ergonomic limit to the number of lamps per unit length of street above which the reduction becomes insignificant. Although data is hard to come by, it seems that few amenities have been properly analysed in this manner. It may well be a 50% reduction in the number of lamps could be effected without diminution of their functional effect. Such a reduction would be equivalent to a really significant technological advance in the device technology that kept the same number of lamps.

Miniaturizing computer chips diminishes the heat dissipated per floating point operation (but, at present, not by as much as the increased number of floating point operations per unit area enabled by the miniaturization). Devices in which bits are represented as electron spins rather than as electron charges will dissipate practically no heat. If all digital information processors used single spin logic, which is most likely to be realized using nanotechnology,[25] given the growing ubiquity of such processors, the contribution to energy economy is likely to be very significant.

In summary, many of the energy efficiency impacts of nanotechnology are incremental, at least in concept.

Resource extraction. The current technologies based on pyrometallurgy used to extract metal from ores use vastly more energy than is theoretically required.[26] Nanotechnology can be brought to bear on this problem in many different ways. Biomimicry seems a very attractive route to explore especially since living organisms are extremely good at extracting very dilute raw materials from their environment, operating at room temperature and, seemingly, close to the thermodynamic limit.[27] Nano-engineered "artificial kidneys" can be used not only to extract desirable elements from very dilute sources, such as seawater, but also to extract toxic elements or compounds from natural water polluted with them, rendering it potable. Catalysts will in this field too doubtless play a very important role, especially if nanotechnologists succeed in creating durable artificial enzymes able to catalyse reactions at room temperature.

Localized manufacture. Possibly the greatest ultimate contribution of nanotechnology, once the stage of the personal nanofactory has been reached, to energy conservation will be

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[24] There has been much discussion about the psychological effects of different artificial light sources. The incandescent filament, which approximates to a black body and is therefore very natural, appears to correspond far better to a harmonious working environment than discharge lamps coated with fluorophores (i.e., what are commonly known as fluorescent tubes), the spectral emission profile of which is very different from that of a black body. Light-emitting diodes, which work according to the same principle (they are simply electroluminescent rather than photoluminescent) have a similar defect. Miniature nanoscale diodes could in theory be combined to create the same spectral output as the visible part of the black body radiation of an incandescent tungsten filament, but this does not seem to be a direction in which the technology is currently moving.

[25] E.g., S. Bandyopadhyay, Single spin devices—perpetuating Moore's law. *Nanotechnol. Perceptions* **3** (2007) 159–163.

[26] S.L. Gillett, Nanotechnology, resources, and pollution control. *Nanotechnology* **7** (1996) 177–182.

[27] The kidney is perhaps the most remarkable example of this nature (S.R. Thomas, Modelling and simulation of the kidney. *J. Biol. Phys. Chem.* **5** (2005) 70–83). Diatoms have the remarkable ability to concentrate silicon from the sea for use in constructing their rigid cell walls.

through the great diminution of the need to transport raw materials and finished products around the world. The amount of energy currently consumed by transport in one form or another is something between 30 and 70% of total world energy consumption. A reduction by an order of magnitude is perhaps achievable.

The above are realizable to a degree using already available nanotechnology—the main current issue is whether costs are low enough to make them economically viable.

8. Impacts on health (nanomedicine)

In medicine, scrutinizing the world from the viewpoint of the atom or molecule amounts to finding the molecular basis of disease, which has been under way ever since biochemistry became established, and which now encompasses all aspects of disease connected with the DNA molecule and its relatives. There can be little doubt about the tremendous advance of knowledge represented here. It, however, is part of the more general scientific revolution that began in the European universities founded from the 11th century onwards—and which is so gradual and ongoing that it never really constitutes a perceptible revolution. Furthermore, it is always necessary to counterbalance the reductionism implicit in the essentially analytical atomic (or nano) viewpoint by insisting on a synthetic systems approach at the same time. Nanotechnology carried through to productive nanosystems could achieve this, because the tiny artefacts produced by an individual assembler have somehow to be transformed into something macroscopic enough to be serviceable for mankind.

The application of nanotechnology to human health is usually called nanomedicine, and is thus a subset of nanobiotechnology.[28] To recall the dictionary definition, medicine is "the science and art concerned with the cure, alleviation and prevention of disease, and with the restoration and preservation of health, by means of remedial substances and the regulation of diet, habits, etc." Therefore, in order to arrive at a more detailed definition of nanomedicine, one needs to simply ask which parts of nanotechnology have a possible medical application.

Much of nanomedicine is concerned with materials. Quantum dots and other nano-objects, surface-functionalized in order to confer the capability of specific binding to selected biological targets, are used for diagnostic purposes in a variety of ways, including imaging and detection of pathogens. Certain nano-objects such as nanosized hollow spheres are used as drug delivery vehicles. Based on the premiss that many biological surfaces are structured in the nanoscale, and hence it might be effective to intervene at that scale, nanomaterials are being used in regenerative medicine both as scaffolds for constructing replacement tissues and directly as artificial prostheses. Nanomaterials are also under consideration as high-capacity absorbents for kidney replacement dialysis therapy. Other areas in which materials are important and which can be considered to be sufficiently health-related to be part of nanomedicine include the design and fabrication of bactericidal surfaces (e.g., hospital paints incorporating silver nanoparticles).

Diagnosis. Many diagnostic technologies could benefit from the contributions of nanotechnology. Superior contrast agents, which bind to selected tissues or cells, based on

[28] The order of concatenation of the prefixes is determined by the flow of information or utility. Thus nanobiotechnology is nanotechnology applied to biology, in contrast to bionanotechnology in which biology is applied to or incorporated in nanotechnology.

inorganic nanoparticles rather than organometallic molecules have already demonstrated enhancement of tissue imaging using X-rays or nuclear magnetic resonance (nmr). Nanoscale biochemical sensors for physiological parameters such as glucose offer potentially superior performance and less invasiveness than microscale ones, to the extent that implanted devices may be able to continuously sense useful parameters.

The advantages of miniaturized analytical devices for medicine ("labs-on-chips"), especially for low-cost point-of-care devices, is already apparent at the microscale. Further miniaturization would continue some of these advantageous trends, resulting *inter alia* in the need for even smaller sample volumes and even lower power consumption, although some of the problems associated with miniaturization, such as unwanted nonspecific binding to the internal surfaces of such devices, would be exacerbated. Whereas microscale point-of-care devices rely on the patient (or his physician) to take a sample and introduce it into the device, miniaturization down to the nanoscale would enable such devices to be implanted in the body and, hence, able to monitor a biomarker continuously. The apotheosis of this trend is represented by the nanobot, a more or less autonomous robotic device operating in large swarms of perhaps as many as 10^9 in the bloodstream.[31]

More powerful computers able to rapidly apply pattern recognition techniques to identify pathological conditions from a multiplicity of indicators provide an indirect diagnostic benefit. The ultimate aim is automated diagnosis. It is an inevitable corollary of the proliferation of diagnostic devices enabled by their miniaturization that the volume of data that needs to be integrated in order to produce a diagnosis becomes overwhelming for a human being. Interestingly, according to a University of Illinois study by Miller and McGuire,[29] about 85% of medical examination questions require only recall of isolated bits of factual information. This suggests that automated diagnosis to at least the level currently attainable by a human physician would be rather readily realizable. The program would presumably be able to determine when the diagnosis was too complicated for its capabilities and would still be able to refer the case to one or more human agents in that situation. Indeed, medicine has already become accustomed to depending on heavy computations in the various tomographies that are now routine in large hospitals. Diagnosis is essentially a problem of pattern recognition: an object (in this case, the disease) must be inferred from a collection of features. Although there have already been attempts to ease the work of the physician by encapsulating his or her knowledge in an expert system that makes use of the physician's regular observations, significant progress is anticipated when measurements from numerous implanted biosensors are input to the inference engine. This is an example of indirect nanotechnology: the practical feasibility depends on the availability of extremely powerful processors, based on chips having the very high degree of integration enabled by nanoscale components on the chips.

Drug sysnthesis. As well as analysis, synthesis (especially of high-value pharmaceuticals) is also an area where microtechnology is contributing through microscale mixers. This technology is very attractive to the pharmaceutical manufacturing industry. Enough evidence has accumulated for it to be generally recognized that many drugs are typically efficacious

[29] Quoted by W.E. Fabb, Conceptual leaps in family medicine: are there more to come? *Asia Pacific Family Med.* **1** (2002) 67–73.

against only part of the population. This may partly be due to genetic diversity, and partly to other factors, which have not yet been characterized in molecular detail. In the case of genetic diversity, it is possible that almost all the pharmaceutically relevant DNA sequence variants occur in haplotype blocks, regions of 10,000 to 100,000 nucleotides in which a few sequence variants account for nearly all the variation in the world human population (typically, five or six sequence variants account for nearly all the variation). If a drug that has been found to be efficacious against the majority haplotype variant can be made to be efficacious against the others by small chemical modifications, then the task of the drug developer would not be insuperable. At present, clinical trials do not generally take account of haplotype variation. Advances in sequencing, in which nanotechnology is helping both through the development of nanobiotechnological analytical devices (although it seems that microtechnological "labs-on-chips" may be adequate to fulfil needs) and through more powerful information processing, should make it possible in the fairly near future for haplotype determination to become routine. It is, however, not known (and perhaps rather improbable) whether small modifications to a drug would adapt its efficacity to other haplotype variants. At any rate, different drugs will certainly be needed to treat different groups of patients suffering from what is clinically considered to be the same disease. Micromixers represent a key step in making custom synthesis of drugs for groups of patients, or even for individual patients, economically viable.

The precise control of the hydrodynamic regimen that is attainable typically enables reactions that normally run to what are considered to be quite good yields of 90%, say, to proceed at the microscale without by-products; that is, to a yield of 100%. The advantages for the complicated multistep syntheses typically required for pharmaceuticals are inestimable. Added to that advantage is the ease of scaling up the volume of synthesis from a laboratory experiment to that of full-scale industrial production, simply by scaleout; that is, multiplication of output by the addition of identical parallel microreactors.

It is not, however, obvious that further miniaturization down to the nanoscale further enhances performance. Similar problems to those afflicting nanoscale analytical labs-on-chips would become significant, especially the unwanted adsorption of reagents to the walls of the mixers and their connecting channels.

Therapy. The most prominent development has been the creation of functionally rich nanostructured drug packaging, enabling more effective delivery of awkward molecules to their targets compared with unpackaged ones. Implants with controlled drug-eluting capability enabled by nanostructured coatings have also been demonstrated. Nanoscale implants with drug reservoirs could replace conventional methods of drug administration (via a tablet or an injection). Such implants not only diminish the systemic nature of the conventional methods, with which the drug is rapidly distributed over the entire organism, by localizing the drug's point of entry near to where it is required (the target), but also enable the variation of concentration with time to match optimum requirements. A drug administered conventionally inevitably arrives as a bolus, but this is actually required by only a few drugs; most would work far better if a steady concentration were maintained. A nanoscale implant would be programmed to continuously release a small amount of drug. A slightly more sophisticated implant could also measure the drug concentration (possibly using a probe situated at some distance from the point of release, around which the concentration will tend to be higher) and adjust its delivery program accordingly. A more sophisticated implant would measure the therapeutic effect of the released drug in order to provide information for optimal delivery; this combination of therapy and diagnosis is usually called "theranostics".

The largest part of any such implant is likely to be the drug reservoir, which might well exceed the nanoscale, especially for therapies designed to continue for several weeks. One way of miniaturizing the overall device is to make it the target for drug refills, which could be administered orally and then make their way to the implant, with which they would dock and deliver their charge for continuing the slow release therapy. The other way is to transform the implant into a miniature factory able to synthesize the drug using raw materials available from the ambient medium. Such a device can be considered to be an artificial gland.

Indirect therapeutic impacts include more powerful computers accelerating the numerical simulation stage of drug discovery. A related aspect is drug design. In many cases useful targets (enzymes, ion channels, promoter sites on DNA) for therapeutic action are already known through molecular biology work. The key tasks for the designer in current practice are (i) to generate a collection of molecules that bind to the target; and (ii) to select those that bind negligibly to structurally related but functionally unrelated or antagonistic targets. Task (i) may nowadays be largely accomplished automatically through molecular modelling (trial and error docking), and thus requires high-performance (possibly nano-enabled) computing. Task (ii) is a germane problem, the solution of which is mainly hampered through ignorance of the rival targets. However, the growing importance of scrutinizing biological processes not only from the viewpoint of what is now traditional molecular biology but also from that of the nano-engineer is yielding new insight (a particularly valuable example of such new insight is the characterization of the propensity of biomolecules to bind according to their dehydron density.[30]

Nano-enabled microreactors facilitating the affordable production of customized medicines, which depends at least in part of the availability of individual patient genomes, also count as a therapeutic benefit.

Overall, nanomedicine seems to be an area in which nanotechnology is making significant contributions. It is difficult to determine whether nanotechnology is actually accelerating progress in the ability to diagnose and treat disease, since the pharmaceutical industry is already probably the most research-intensive in the world. What seems to be happening is that the rate of discovery along the conventional paths is declining, but nanotechnology will keep up momentum in the area as much through the creation of novel, efficacious methods of delivering existing drugs as through the creation of new drugs.

Metallic particles that can to some extent be steered to their target using external magnetic fields and whose therapeutic action (which may merely be heating up to destroy the cell (e.g., a tumour cell) are already being investigated and could be thought of as very primitive medical nanobots.

Surgery. Miniaturized devices are making surgery less and less invasive. The basic surgical tools are unlikely to be miniaturized below the microscale, however, but their deployment may be enhanced by nanoscale features such as ultralow friction coatings and built-in sensors for *in situ* monitoring of physiological parameters. The autonomous robot ("nanobot") is still some

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[30] A. Fernández, *Transformative Concepts in Drug Design: Target Wrapping*. Springer (2010).

way in the future.[31] Superior nanostructured tissue scaffolds will enhance the ability to regenerate tissue for repair purposes.

Laparoscopic surgery using microscale tools is not only less invasive and more comfortable for the patient, but also more economical to deliver. This combination of attributes makes it very attractive for health delivery services. The benefits of further miniaturization down to the nanoscale are not especially obvious for tissue surgery, although they would be for interventions on individual cells.

Hence, the near-term effects of nanotechnology are likely to be rather minor. The availability of medical nanobots as routine agents for diagnosis and therapy would revolutionize the treatment of many pathological conditions, but it is still many years before we are likely to see the deployment of such devices.

Nutrition. Since diet is an important contribution to health, nanotechnology applied to foodstuffs can also be considered to be part of nanomedicine. This is of course a vast area, ranging from nanoscale sensors to discreetly probe food quality through nanoscale food additives (to create "neutriceuticals") to nanoscale field additives such as fertilizers, pesticides, and enhancers of agriculturally advantageous natural symbioses.

The required nanoscale sensors for food quality fall into two categories. One category is applied to foods harvested and sold as "fresh": they are chemical or biochemical sensors detecting the concentration of key freshness markers (e.g., oligoamines as indicators of the freshness of fish). The other category is applied to packaged foods. The sensor may actually be a dosimeter, recording whether storage temperature exceeded a preset value, or whether oxygen entered the package, for example. For this kind of sensor a sophisticated chemical undergoing a colour change might be sufficient; nanotechnology might not be specifically implicated. Other kinds of sensors could detect the presence of pathogenic bacteria or more sophisticated indicators of nutritional degradation. Nanotechnology might be useful in creating particular configurations of atoms useful for recognizing microbes and molecules.

Micronutrient (e.g., iron) deficiencies are quite common, and possibly increasing *pari passu* with the increase of processed food and high-yielding agricultural varieties that tend to be less efficient than normal varieties in taking trace elements up from the soil. Many of these micronutrients are metals, which taste unpleasant especially when administered as their soluble salts. One solution to this is to administer them in elemental form, but they are then poorly assimilated, unless formed into nanoparticles. This seems to be a convenient route to avoid both the unpleasant taste and the poor assimilation.

Should there be any residual issue with taste it can be solved by applying some suitable nanocoating (e.g., calcium carbonate) that swiftly dissolves as soon as the material arrives in the stomach.

The goal of fertilizer research is to deliver nutrients more effectively to plants. There is tremendous waste of the conventional fertilizers used at present, since a significant proportion of what is spread on the fields is simply washed away before it can be taken up by the roots. Furthermore, the presence of fertilizer in natural water creates many problems. At sufficiently

[31] T. Hogg, Evaluating microscopic robots for medical diagnosis and treatment. *Nanotechnol. Perceptions* **3** (2007) 63–73.

high concentrations the water may no longer be potable; thousands of French villages suffer from this problem (mainly due to nitrate). It also promotes the growth of algae, which scavenge dissolved oxygen, reducing the viability of aquatic animal life. "Nanofertilizers" are finely divided conventional fertilizers that offer more control over the rate of release of the active substance. But real progress in the area requires a much more detailed understanding of the soil and the soil/root interface

Especially since water is ingested by humans in greater quantity than any other substance, it might also be considered as "food", making nanotechnologies applied to water purification and potable water quality monitoring also part of nanomedicine. The use of irradiated nanoparticles made of materials such as titanium dioxide to mineralize recalcitrant organic pollutants has been extensively investigated in laboratories around the world, but it is not clear whether this can become a large-scale process for water purification. Electron–hole pairs created by the absorption of an ultraviolet photon react at the surface with any reducible and oxidizable compounds that have adsorbed there, breaking their bonds. Afterwards, the water needs to be purified from the particles. The economic viability of the process is unclear.

In summary, the impacts of nanotechnology in the area of nutrition are heavily dependent on further advances in knowledge of the biosphere at all scales.

Nanotoxicology. Considerations of health impact should also include the possibly adverse effects of nano-objects on human health. The topic has long been given consideration and extensive knowledge has been accumulated.[32] Nano-objects (usually nanoparticles and nanorods) penetrating into the human body may simply dissolve, and if the dissolution products (e.g., metal ions) are toxic then the nanoparticles must be deemed to be toxic. If they do not dissolve (e.g., blue asbestos fibres), depending on the surface chemistry they may trigger an inflammatory immune response, which may have secondary adverse effects. Past interest in nanoparticles (or ultrafine particles, as they were usually called) focused on aerial particles originating from combustion processes and quarrying, and particles generated *in situ* by friction (especially from prostheses implanted in the human body). The rise of nanomanufacturing creates new dangers: to workers in the factories making the particles or incorporating them into finished products; to users of finished products containing nanoparticles (e.g., antisun cream or toothpaste containing colloidal silver); to anyone in the vicinity of accidents or other incidents leading to the release of nanoparticles normally sealed or otherwise incorporated within massive structures; and to ecosystems acting as sinks for nanoparticles released from various sources (e.g., nanoparticles from impregnated textiles may be released in the laundry and end up in natural waters or the soil, with adverse effects upon the microbial community). The microbial community may also be adversely affected, in ways that are as yet far from fully characterized, let alone understood, by simple nanoparticles (e.g., iron spherules) added to soil to decontaminate it from, notably, chlorinated hydrocarbons. Presumably here there is an issue whether the nanoparticles have worse effects than the pollutants, the decomposition of which they are supposed to catalyse. If indeed they are acting as catalysts, they will persist long after the pollutant has gone, albeit probably in oxidized form and perhaps not very different from

[32] For a comprehensive review, see P.A. Revell, The biological effects of nanoparticles. *Nanotechnol. Perceptions* **2** (2006) 283–298.

mineral particles in naturally iron-rich soils. If they also react with the pollutant, attention must be given to whether the reaction products act more adversely with respect to the microbial community than the original pollution.

An even more recent development is dense inert metal explosive (DIME), made from heavy metal tungsten alloy (HMTA) fashioned into frangible projectiles designed to fragment into dust upon impact, releasing a highly lethal spray of superheated micro- and nanoshrapnel within a very small range (a few metres). Although DIME appears to be a "precision weapon" designed to destroy material targets, and specifically targeted individuals, the penetration of HMTA nanoparticles into any other human beings in the vicinity appears to inflict serious and complex injury,[33] falling into the category of "maux superflus" prohibited since 1900 by the Hague Convention. Now that some knowledge of these injuries is available, it may be that the use of DIME will be discontinued.

9. Industrial impacts

According to the proponents of "hard" nanotechnology, the basic industrial paradigm for manufacture must inevitably change with the advent of assembler-based nanofacture. Quite apart from that, however, current thinking about the future of manufacturing in developed economies envisages a continued shift from a resource base to a knowledge base, which is exactly what nanotechnology epitomizes. Assemblers can be rapidly reconfigured and represent the ultimate flexible manufacturing technology. Bottom-to-bottom manufacture based on assemblers is, in fact, merely a downscaled version of the additive manufacturing that is being rapidly developed at the micro- and milliscales as an ultraflexible manufacturing technology, one of the goals of which is "mass customization"—the ability to create a large number of functionally identical products that nevertheless differ from each other in some details according to the specific wishes of buyers.

It is convenient to consider materials and devices separately. At present only nanomaterials made in a statistical fashion (with a corresponding statistical distribution of properties) are commercially viable. Such materials are adequate for use in paints and other coatings with special features (e.g., electrical conductivity or abrasion resistance). They are not adequate for applications requiring a high degree of particle size monodispersity, such as quantum dot lasers. Silver halide nanocrystal-based photography also benefits from monodispersity.

Apart from the very sophisticated technical problems posed by the simultaneous fabrication of the order of 10^9 components on a chip (an example of the vastification that is an almost inevitable corollary of miniaturization, cf. §5) there is the fundamental problem posed by the intrinsic variability of miniature multi-atom objects. If a collection of n entities is assembled through n independent events, the uncertainty of n is $\sqrt{n}$. This is the famous "$\sqrt{n}$ law" used by Schrödinger to deduce that the fundamental unit of information storage in living beings must be a small molecule,[34] almost a decade before the structure of DNA was discovered. The statistics

[33] E.g., A.C. Miller et al., Neoplastic transformation of human osteoblast cells to the tumorigenic phenotype by heavy metal tungsten alloy particles: induction of genotoxic effects. *Carcinogenesis* **22** (2001) 115–.

[34] E. Schrödinger, *What is Life?* Lectures delivered at Trinity College, Dublin in February, 1943.

of photons falling on a small area (such as a silver halide grain in a photographic emulsion) obeys the same, Poisson, distribution.

When structures become really small, containing of the order of 100 atoms, the "$\sqrt{n}$ law" dictates that the intrinsic variability will be of the order of 10%. As Kelly has pointed out,[35] the real difficulty comes from the implications of this variability on the electrical, magnetic, optical etc. properties of such structures. For example, if the structure in question is a nanopillar, the quantum confinement energy for electrons has a contribution inversely proportional to the cross-sectional area, and if this contains of the order of 100 atoms, the confinement energy uncertainty will be of the order of 10%, that is, 20 meV for a typical confinement energy of 200 meV and even worse for smaller quantum dots, which is too great for optical applications.

The only way to overcome this problem is to use a manufacturing technique that does not depend on a statistical process like physical vapour deposition. Software-controlled tip-based atom-by-atom assembly is one possibility (although still far from being a high-volume manufacturing technique): in principle structures could be assembled with an exact and reproducible number of atoms. The most powerful demonstration of the ultimate feasibility of this approach comes through biology. Proteins are the essential building blocks of living organisms, and a typical protein contains between 5000 and 10,000 atoms, grouped into ~ 100 amino acids. Since they are the actual blocks used in protein construction, the "$\sqrt{n}$" uncertainty would be of the order of 10 amino acids. Even if we took the atomic uncertainty, this would still correspond to a variation in the protein sequence of one or two amino acids. Yet, proteins have a quality, specificity and individuality resembling that of quantum objects. Their identity is achieved through what amounts to software control—the DNA sequence that governs protein assembly. Self-limiting self-assembly is another way to overcome the problem.[36]

The problem of scaling up production to useful volumes is omnipresent in industrial nanotechnology. The essential nano paradigm is to use "scaleout" rather than scaleup—in other words to arrange for many nanomanufacturing units to work in parallel. In K.E. Drexler's vision, the nanofacturing units are assemblers.[37] Scaleout is achieved by having the assemblers first work on making copies of themselves. Assembler-based nanofacture is still likely to be many years away.

Two of the topics already briefly addressed under Energy (§7) will have significant industrial impact: resource extraction and localized manufacture. The aim of future resource extraction is to run processes close to their theoretical maximum efficiencies using ingenious constructions. Living and growing organisms use such processes extensively, and the careful study of how they accomplish them in principle is doubtless the best way to start creating artificial equivalents. A particular challenge is to achieve the high efficiency (minimal entropy production) of reversible processes and the high throughput of irreversible ones. The growing scarcity of enriched natural deposits of metal ores as well as growing public concern over environmental preservation will provide valuable support to the development of biomimetic extraction technologies able to use seawater, for example, as feedstock.

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[35] M.J. Kelly, Intrinsic top-down unmanufacturability. *Nanotechnology* **22** (2011) 245303.
[36] E.g., L.F. Knapp, The solubility of small particles and the stability of colloids. *Trans. Faraday Soc.* **17** (1922) 457–465.
[37] K.E. Drexler, *Nanosystems: Molecular Machinery, Manufacturing, and Computation.* Wiley-Interscience (1992).

Localized manufacture, which depends upon the availability of assembler-based nanofacture, is somewhat further away but would spell the end of all vestige of the "dark satanic mills", as William Blake called them. Coupled with the distribution of design ability throughout the population (see §18), the social consequences will be immense.

We conclude from the above that the industrial impact of nanotechnology (i.e., the likelihood that the availability of nanotechnology will significantly change a significant number of existing industrial processes or introduce new ones) is likely to be small in the near-term, but large in the long-term if assembler-based fabrication is developed.

10. Commercial impacts

The three aspects of commercial impacts that we shall look at in this section are: supply through commoditization, technology push versus market pull, and the use of the notion of readiness or availability levels to enable companies to manage technological developments.

Supply. Although the nanotechnology research community is very healthy, judging by the tremendous amount of publishing activity (one might even say overhealthy, because there is insufficient coordination, leading to duplicated effort and the neglect of gaps), the same cannot be said of the nanotechnology industry. There are numerous companies offering nanomaterials (overwhelmingly nanoparticles), mostly in the USA and China, but these materials are in no sense standardized and buyers are likely to have to pay a premium price because of the difficulty of comparison (absence of real competition). A highly significant milestone has been the launching, at the end of 2010, of the Integrated Nano Science and Commodity Exchange (INSCX),[38] which offers trading services in nanomaterials and nanodevices akin to the well established exchanges for commodities such as metals and grains. This exchange is expected to transform the way nanomaterials are sourced. Among other effects, it is likely that the price of many nanomaterials (e.g., nanoparticles for enhancing a rocket fuel, for example) will fall to a level at which their use can be contemplated (whereas at present, although there may be clear technical advantages, they are simply too expensive).

Table 1 elaborates the four current business models comprising the nanomaterials supply chain, covering NAL 4–8 (see Table 3). By dividing the chain up in this way, the amount of investment needed to take a new material that emerges from a research laboratory (NAL 2–3) to a finished good in the market (NAL 8) is also divided into more attainable parts, especially by a small start-up company. Most nanotechnology start-ups use model A or B, sometimes C: they must rely on finding other companies able to act as customers or partners in order to deliver goods to the marketplace (e.g., Nucryst has partnered with Smith & Nephew). Models C and especially D require large quantities of (venture) capital.

It remains an open question whether the nanotechnology industry will follow the consolidation that has occurred in microtechnology—in 1997 there were around 360 organizations worldwide offering to supply technology or prototypes,[39] contracting to around 60 by 2001 and 10 or less (counting profitable suppliers only) by 2006.

[38] C. McGovern, Commoditization of nanomaterials. *Nanotechnol. Perceptions* **6** (2010) 155–178.

[39] J.M. Wilkinson, Nanotechnology: new technology but old business models? *Nanotechnol. Perceptions* **2** (2006) 277–281.

Table 1. The nanomaterials supply chain.[39]

Business model	Description	Examples of products	Examples of companies
A	Nanostructured materials supplier	Nanoparticles, CNT, quantum dots, dendrimers	Thomas Swan, Qinetiq Nanomaterials
B	Formulations and additives	Dispersions, pastes, powders in dispensers	Zyvex (CNT formulations), Oxonica (diesel fuel additives)
C	Enhanced materials	Ready to use polymer composites, coated fabrics, laminates	Nucryst (wound dressings)
D	Finished goods incorporating nanotechnology	Car body panels, clothes, tennis balls, pharmaceuticals	Uniqema (paint)

It is often stated that the driver behind Moore's law is purely economic. This is not, however, self-evident. It presumably means that growth is dominated by "market pull" rather than "technology push", but this raises a number of questions. It is doubtful whether there are intrinsic markets, and even if there were why should the technology advance exponentially? How could the actual doubling time be predicted? Does it depend on the number of people working on the technology? If they are mostly employed by large corporations (such as semiconductor chip manufacturers) the ability of those corporations to pay the salaries of the technologists indeed depends on economic factors, but this would not hold in the case of open source development, whether of software or hardware. Similar questions apply to all technical innovations, which generally grow exponentially. Technology push seems to require fewer assumptions as an explanation than market pull. However, it may be erroneous to say that the dynamics must reflect either technology push or market pull. Both may be in operation; in analogy to the venerable principle of supply and demand, push and pull may also (possibly under certain circumstances, the special nature of which needs further inquiry) "equilibrate".

Technology availability. The notion of Technology Readiness Level (TRL) originated in the NASA Advanced Concepts Office,[40] specifically designed to characterize the progress of technologies used in space missions. Despite this association with a very closed and controlled uncommercial environment, it has since then been widely adopted to characterize general industrial technologies; Hodgkinson et al. proposed modifications to render the scheme more suitable for general use,[41] which might be called Commercial Readiness Levels (CRL), and summarized in Table 2.

Further modifications would be useful to represent the progression of nanotechnology, because of unique features, not least its extremely rapid progression and the intermingling of academic and industrial research. Hence, the concept of *Nanotechnology Availability Level* (NAL) might be useful to more accurately describe the state of a given part of nanotechnology with respect to the desired application (Table 3). Note that the levels are not ordered in a strict sequential hierarchy throughout: NAL 4 may well accompany NAL 3; availability at NAL 5 may only be of research grade material. Levels 0 to 6a would typically be reached in the

[40] J.C. Mankins, *Technology Readiness Levels*. NASA Advanced Concepts Office, 6 April 1995.
[41] J. Hodgkinson et al. Gas sensors 2. The markets and challenges. *Nanotechnol. Perceptions* **5** (2009) 83–107.

Table 2. Commercial Readiness Levels.

CRL	Description
1	Basic principles observed
2	Proof of concept
3	Technology application formulated
4	Component validation in the laboratory environment
5	Component validation in the real environment
6	Prototype system demonstration in the real environment
7	Commercial introduction
8	Commercial success

research environment; levels 0–3 might well be carried out in an academic environment; institutes of technology might continue work through levels 4 and 5, possibly transferring operations to a spin-off company at that stage in order to progress the technology further. NAL 6a corresponds to the interest of the supplier and ultimate manufacturer; NAL 6b and 7b to the interest of the ultimate end-user, which is likely to have to shoulder the burden of the research work labelled R3. 6a and 6b are likely to take place in parallel; likewise for 7a and 7b. Ongoing R4 is generally required for sustainable deployment.

Table 3. Nanotechnology Availability Levels (NAL), giving next step requirements (NSR).

NAL	Description	NSR[a]
0	Idea	R1
1	Basic principles observed	R1,V
2	Proof of concept	I
3	Technology application(s) formulated	IP
4	Demonstration for some specific application	P
5	Available in some form	St
6a	COTS availability	R3, SC
6b	Validated for a desired application	R3, SC
7a	Complete supply chain established	R4
7b	Incorporated into the product	U, R4
8	History of success	R4

[a] Key to next step requirements:

NSR	Description
R1	Exploratory laboratory work
V	Verification
I	Inspirational thinking
IP	Patent application
P	Development of a feasible production route
R2	Research to establish whether the technology can be used for the desired application and whether it is superior to existing technology
St	Standardization
R3	Testing in the desired application
U	Use
SC	Establishing the supply chain
R4	Optimization

Level 7a can be further divided into the following maturity levels (taken from the ITRS):

1. Manufacturable solutions are not known
2. Interim solutions are known
3. Manufacturable solutions are known
4. Manufacturable solutions exist and are being optimized.

Level 7b could already begin to be accessed once Level 7a.2 or 7a.3 is reached (as we can respectively label items 2 and 3 from the above list of manufacturing maturity levels).

In conclusion, there is presently a lively debate about many aspects of the commercialization of nanotechnology. The main barriers to commercialization appear to be in place due to an attitude prevalent among researchers developing novel nanomaterials and nanodevices: there seems to be considerable reluctance to acknowledge that manufacturing according to agreed standards and transparent pricing are prerequisites for the acceptance of nanomaterials and nanodevices as components of larger systems, and for the sustained growth of a real nanotechnology industry.

11. Economic and political impacts

The economic and political impacts of "soft" nanotechnological innovations are likely to be relatively minor. There will be many such innovations but these will in turn breed new demands and one cannot therefore expect a dramatic change in work–life balance. At least, this has been the experience of the developed world for the last century or so and there is no reason to expect radical change from what are essentially incremental improvements. In other areas, "laws of compensation" seem to work to prevent rapid change. For example, many of the new nanostructured drug delivery vehicles will lead to therapeutic enhancement, but once the old ailments are cured, new ones are likely to be found requiring further new drugs. In contrast, the "hard" implementation—the personal nanofactory—will lead to very dramatic changes in terms of personal empowerment. The entire system of the joint stock company concentrating resources into large, central, capital-intensive factories will become obsolete.

The most exciting economic implications of nanotechnology will come through the development of assembler-based manufacture, the ultimate embodiment of which is the personal nanofactory. Freitas has subjected this to a thorough and careful analysis,[42] which, in view of the uncertainties regarding the advent of the personal nanofactory, is only considered by the author to be a first look at the problem. There seems to be a general view held by analysts of the impact of the personal nanofactory (or productive nanosystems) that material goods will become abundant. Given that our current economic system (which is inextricably intertwined with our political system) is based on scarcity, the emergence of abundance would appear to have profound implications for social organization. But there is no need to suppose that society organized on the basis of abundance would look dramatically different from our present society. Consider, for example, a country like Hong Kong, which, because of the abundance of state revenues from its entrepôt activity has no need to impose taxation on its citizens, neither direct nor indirect. Its social organization is not conspicuously different from that of European

[42] R.A. Freitas, Jr. Economic impact of the personal nanofactory. *Nanotechnol. Perceptions* **2** (2006) 111–126.

countries, which typically have draconian taxation régimes. This is of course a vast topic, to which we cannot possibly do justice in this essay, but the only point to make here is that the advent of "hard" nanotechnology does not necessarily imply social disruption from economic considerations.

An oft-debated issue is whether developing economies (the "Third World") can disproportionately benefit from adopting nanotechnology in order to shortcut the laborious path of technical development that has been followed by the "old" economies. A key idea is that for many products much less capital investment is required to set up nanomanufacturing than to set up conventional production. Computer hardware need not be included in the manufacturing portfolio because high-performance chips are anyway available practically as commodities nowadays. One of the attractive features of promoting "nanotechnology in the jungle", and we might call it, is its potential to benefit the overall economy through the promotion of disequilibrium as advocated by Hirschmann:[43] the technological demands of having any success at all in an advanced system of production necessarily force the rest of the economy (parts of which must inevitably supply the ultrahigh technology part) to develop in its train.

In summary, the short-term economic impacts are likely to be small, but possibly disproportionately large in developing countries. In the long-term, impacts are likely to be truly revolutionary.

12. Environmental impacts

One often hears it stated that nanotechnology will enable the environment to be returned to a pristine state,[44] without an accompanying explanation of the process by which this rather vague assertion might be realized. It seems that there are going to be two principal impacts of nanotechnology on the environment. The first is immediate and direct, the second long-term and indirect. The immediate, direct impact is concerned with the use of nanoparticles for environmental remediation. In particular, iron-containing nanoparticles are being promulgated as superior alternatives to existing remediation procedures for soil contaminated with chlorinated hydrocarbons using a more or less comminuted scrap iron.[45]

The long-term and indirect effects follow from the obvious corollary of atomically precise technologies—they essentially eliminate waste during fabrication. This applies not only to the actual fabrication of artefacts for human use, but also to the extraction of chemical elements from the geosphere (should those elements still be necessary). If the manufacture of almost everything becomes localized, the transport of goods (a major contributor to energy consumption and environmental degradation) should dwindle to practically nothing; the localized fabrication implied by the widespread deployment of productive nanosystems and personal nanofactories should eliminate almost all of the currently vast land, sea and air traffic involved in wholesale and retail distribution; this elimination (and a commensurate

[43] A.O. Hirschmann, *The Strategy of Economic Development*. Yale: University Press (1958).
[44] E.g., S. Wood, R. Jones and A. Geldart, *The Social and Economic Challenges of Nanotechnology*. Swindon: ESRC (2003).
[45] This proposed technology raises the number of questions—to start with there does not seem to be any conclusive evidence that it is actually efficacious, and furthermore there is the still open question of the effect of dispersing a significant concentration of nanoparticles (and it has to be significant, otherwise there would be no significant remediation) on the ecosystem, especially microbial life.

downscaling of transport infrastructure) will doubtless bring about by far the greatest benefit to the environment of any aspect of nanotechnology. Furthermore, atom-by-atom assembly of artefacts implies that discarded ones can be disassembled according to a similar principle, hence the problem of waste (and concomitant environmental pollution) associated with discarded obsolete objects vanishes.

In the intervening period, the general effect of nanotechnology in promoting energy efficiency (§7) will of course be beneficial to the environment—less transport of fossil fuels, less pollution from combustion and so forth.

Concerns have, however, been expressed that some of the nanoparticles being promoted for use in a variety of products, especially those with some kind of antibiotic activity, among which silver nanoparticles are the most widespread, are harmful if released into the environment. The environment contains innumerable bacteria and other microbes, and nanoparticles designed for their antibacterial activity are evidently going to continue that activity wherever they are. Release is almost inevitable. Many textiles are already sold conjugated with silver nanoparticles; some of them will be released when the textiles are laundered. Once nanoparticles, not just silver ones, and other objects become routinely produced industrially, it is inevitable that they will find their way into watercourses and soils. Food chains will ensure that they are disseminated throughout the ecosystem. Being ultrasmall, nanoparticles are highly mobile and it will be extraordinarily difficult to contain them even during the manufacture of finished products incorporating them. Furthermore, there can be little control over their fate once the artefact containing them is discarded.

This is why there are already widespread calls for stricter regulation of the deployment of nanotechnology, particularly nano-objects in consumer products. These calls are driven by a growing awareness of the potential dangers of nano-objects penetrating into the human body, and by the realization that understanding of this process is still rather imperfect, and prediction of the likely effects of a new kind of nano-object is still rather unreliable. Furthermore, there have been a sufficient number of cases, albeit individually on a relatively small-scale, of apparently unscrupulous entrepreneurs promoting nano-object-containing products that have turned out to be quite harmful.

These calls, while seemingly reasonable, raise a number of difficulties. One is purely practical: once nano-objects are incorporated into a product they are extraordinarily difficult to trace. Traceability is only feasible up to the point of manufacture, and even then only if the manufacturer has sourced materials through a regulated or self-regulated commercial channel such as a commodity exchange. Establishing the provenance of nanoparticles that might turn up in a waste dump, for example, poses a very difficult forensic challenge.

Furthermore, regulation will become essentially meaningless if productive nanosystems become established: every individual would be producing his or her own artefacts according to his or her own designs and it is hard to see how this could be regulated.

Hence, we conclude that although on the whole nanotechnology must have a favourable impact on the environment, there are also some problematical aspects, which might be partly alleviated by regulation.[46]

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[46] See also the paragraphs on nanotoxicology in §8.

13. Societal impacts

Further aspects connected with "push" and "pull" (cf. §10) are the degree to which technology changes society, and the degree to which society is ready for change. The internet—first e-mail and now social networking sites—has enormously changed the way people communicate with one another as individuals. It cannot be said that there was a market for these innovations, or for mobile telephony; the market was somehow created. Cellphones in particular epitomize many aspects of a sustainable commercial activity; most users are eager to keep up with the latest technological innovations, which themselves imply a high degree of personal enthusiasm among the technology developers. Although these technologies are already nano-enabled (through their ultraminiature information processors) the economic model behind them is basically that of the Industrial Revolution. The new communications media are heavily infiltrated by commercial advertising. Internet search engines and social networking sites are not actually floating somewhere in cyberspace but are firmly anchored to strong financial interests and user preferences can easily be linked to advertising via the cellular phone. All this activity has taken on a strong cultural dimension, since for it to be widely acceptable culture has somehow had to become dominated by its commercial and popular side, virtually squeezing out anything else. Although this general trend appears to be fully in the spirit of Adam Smith's "invisible hand"—every member of society acting in his or her best interest and thereby contributing to the general good—there seems to be a growing asymmetry between "producers" (production itself is anyway becoming more and more automated) and "consumers". Whereas previous visions extrapolating the trend of ever more efficient production, which implies ever increasing leisure time, have thought of this leisure time being used for personal cultural enrichment and "working out one's own salvation", presumably because of the preponderance of information technology today, personal leisure is also nowadays characterized by "producers" and "consumers"—even though the technology actually enables anyone to be an author, film-maker, journalist or singer, we have not arrived at increasing micro-production of culture, with works produced for small audiences, maybe of just a few dozen, with everyone more or less on an equal footing; these potentially very enriching aspects have been, at least until now, largely thrown away.

Possibly thanks to that rather influential book by E.F. Schumacher, " Small Is Beautiful" (1973), nanotechnology has started with a generally benevolent gaze cast upon it. The contrast is especially striking in comparison with biotechnology, one of the recent products of which, genetically modified crops, has excited a great deal of controversy that is far from being settled (and probably cannot be without more extensive knowledge of the matter, particularly at the level of ecosystems). Wherever bulk is unnecessary, miniaturization must necessarily be good, and what else is nanotechnology if not the apotheosis, in any practical sense, of miniaturization? The formation of a favourable public opinion must, however, be tempered by the knowledge that only a few percent of the population actually have an intelligible notion of what nanotechnology is. One might expect that the more solid the tradition of scientific journalism, the higher the percentage—the Swiss are rather well informed—but in France, with such a tradition almost as good as in Switzerland, the percentage of the general public that knows something about nanotechnology seems to be no greater than in the UK. The English language press of the world does not, indeed, seem to have set itself a very high standard for nanotechnology reporting.[47] Interest in the topic enjoyed a brief surge after the publication of Michael Crichton's novel "Prey" (2000), but has not persisted. There has been considerable effort, some of it sponsored by the state, to disseminate knowledge about nanotechnology among schoolchildren, with the result that they are probably the best-informed section of the population.

Just as electricity led to the telephone, which profoundly changed the way that individuals socially interact with each other, this being also a consequence of the mass-produced motor-car, we need to ask how nanotechnology, having the technical, environmental, commercial and so forth impacts that we have already briefly looked at in the preceding sections, will change society. It seems obvious that incremental changes, such as more scratch-resistant paint (incorporating ultrahard nanoparticles) for motor cars, or stronger, lighter tennis racquets (made from carbon nanotube composites) will have little societal impact. Even self-cleaning glass, which has revived the popularity of buildings with their outer façades made predominantly from glass, cannot be said to be effecting a revolutionary change.

Information technologies have already enabled the "personal nanofactory" of culture to be realized (but little use has been made of this possibility by the vast majority). If and when the real personal nanofactory capable of fabricating virtually any artefact becomes established, will things be different? Open source software demonstrably works and its products seem on the whole to be superior to those produced in closed, "professional" companies. Attempts are already being made to mimic this model as open source hardware. Nanotechnology implies that everyone can be a designer, or at least contribute to design in the case of a complex technology. Among other things, this implies the complete obsolescence of patents and intellectual property laws. At present, nanotechnology is at best seen as an enabler of "mass customization", taking a little further existing technologies that allow the purchaser of house paint, and possibly of a T-shirt or a motor-car, to specify a unique, individual colour. Ultimately, though, everyone would be as much a producer as a consumer, of hardware as well as software, which would render not only the present commercial model obsolete, but also transform society.

Nanotechnology should certainly change the way we look at population. The ancient injunction "be fruitful and multiply", highly appropriate for an r-limited ecosystem,[16] has been viewed critically at least since the publication of the T.R. Malthus's *Essay on the Principle of Population* in 1798. Nevertheless, military exigency ensured that the ideal of a large and growing population continued to hold sway, especially in France, starting in the Napoleonic era, and China starting in the era of Mao Tse-tung). During the last century the difficulties of expanding agriculture to feed a growing world population competed with the capitalists' need for expanding markets for the products of their factories. The latter ensured that the r-limited paradigm remained at least as in part in force. But, the new commercial model based on the economics of abundance ushered in by ubiquitous personal nanofactories[42] has no need for vast numbers of consumers. As a result, the paradigm of the K-limited ecosystem,[16] which has long been appropriate, should finally become established, and humanity can focus on acquiring knowledge. A nanoscopic view of the genetics of a small (which humans are, even with 10 milliard individuals, compared with, say, arthropoda, let alone bacteria) population of a complex species

[47] See, e.g., H. Matthews, A plea for intelligent nanotechnology journalism. *Nanotechnol. Perceptions* **5** (2009) 233–235.

reveals the great danger to the stability of the proteins (and, *a fortiori*, the protein networks on which a properly functioning organism depends) from the genetic drift inevitable in a small population.[48] Although one way to diminish this danger would be to vastly increase the human population, the magnitude of the increase required does not seem to be even remotely attainable, hence we had better use our capacity for acquiring scientific knowledge to find ways of neutralizing the threat. The criterion of optimizing our capacity to acquire knowledge could provide a new basis for setting a desirable population size, starting with infancy. Our present crowded, frenetic, consumerist lifestyle makes it very difficult for parents, who under practically any social regimen are almost solely responsible for the development of their children during the crucial first three years, to devote sufficient care and attention to their upbringing. Similar deficiencies seem to attend every stage of education, making it far less effective than it could, should and will have to be in the future.

The potential of nanotechnology is surely positive, because it offers the opportunity for all to fully participate in society. The answer to the question how one can move more resolutely in that direction would surely be that under the impetus of gradually increasing technical literacy in an era of leisure, in which people are as much producers as consumers, there will be a gradually increasing level of civilization, including a more profound understanding of nature. The latter in particular must inevitably lead to revulsion against actions that destroy nature, and that surely is how the environment will come to be preserved. In fact, the mission of the Field Studies Council (FSC), which was born in the UK around the time of the 1944 Education Act, namely "Environmental Understanding for All", is a worthy exemplar for the nano-era, which could have as its mission "Technical Understanding for All". And just as the FSC promoted nature conservancy,[49] it is appropriate for nanotechnology, with its very broad reach into all aspects of civilization, to have a wider mission, namely "Elevation of Society." This, by the way, implies other concomitant advances, such as in the early (preschool) education of infants, which has nothing to do *per se* with nanotechnology, but which will doubtless be of crucial importance in determining whether humanity survives.

In summary, revolutionary societal changes must await that crucial moment when quantitative change is large enough to become qualitative. The key events will be the development of productive nanosystems,[50] and Kurzweil's singularity.[20]

14. Military impacts

Military budgets are everywhere coming under pressure to deliver the same or increased security while spending less. At the same time potential enemies are not stagnating but continuously increasing their own technical capabilities, compelling constant drive to remain in the vanguard of technical development. As far as hardware is concerned, the essential goal is for the range (in the widest sense) of one's weaponry to exceed that of the enemy. This might be

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[48] A. Fernández and M. Lynch, Non-adaptive origins of interactome complexity. *Nature* **474** (2011) 502–505.
[49] R.J. Berry, Ethics, attitudes and environmental understanding for all. *Field Studies* **8** (1993) 245–255.
[50] See, e.g., T.T. Toth-Fejel, When China develops productive nanofactories. *Nanotechnol. Perceptions* **5** (2009) 37–59.

achieved using higher energy density explosives, possibly by incorporating energetic nanostructured materials into them; using smaller and lighter structural components of missiles (typically achieved using composites), and miniaturizing and lightening the loads carried by the private soldier.[51] "Precision weaponry" has already been referred to (in the paragraphs on nanotoxicology in §8).

One very significant way in which cost savings have been achieved, especially for electronics, is to use commercial off-the-shelf components and systems (COTS). Already happening for the electronics within weapons, this is likely to be the model for incorporating nanotechnology into military hardware.

It is a striking fact that the mechanization of war has resulted in a reversion of society's involvement in fighting to an early epoch when every member of a tribe was essentially a warrior. During the last 3000 years, the trend in civilized countries was for fighting to become a highly specialized activity practised by a small minority. This changed dramatically in the First World War. Not only was the actual number of fighters a significant proportion of the active working population, but virtually the entire rest of the nation was actively working for the war effort, supporting the fighters. The nature of the warfare also changed. Military activity was beginning to become highly mechanized in the First World War, but it still saw battlefields of the kind epitomized by the Battle of Waterloo; that is, places where pitched battles between the professionals took place, in a manner analogous to a game played on a sports field, but in the Second World War the tendency was rather to speak of battle theatres, and that war was marked by wholesale bombing of great civilian centres, made relatively easy by advances in the design and production of aircraft. More recently, this trend to involve the entire civilian population has continued through urban resistance movements turning civilian cities into battlegrounds. Against this background, it is highly pertinent to inquire how nanotechnology will affect the social organization implicated in warfare. Clearly, many of the technical advances brought about by nanotechnology are useful for military purposes. At present, though, even though the entire population might be involved in a war, it is still only the professionals who are armed; the civilian population might at best have handguns; they are essentially defenceless. Advances in nanotechnology that are put to belligerent use would appear to mainly serve the professional military services; the performance of munitions can be enhanced or made cheaper. But in the era of the personal nanofactory (productive nanosystems), any individual could design and fabricate offensive weapons, such as small pilotless flying objects. Thus, the ultimate impact of military nanotechnology is in principle much greater for the civilian population, who will in principle be able to defend themselves rather effectively against aggression from any source. However, the universal plenty ("economics of abundance", §11) that the Nano Revolution is supposed to usher in should largely remove the raison d'être for warfare in the first place.

15. Impacts on individual psychology

The ultimate purpose of any science is to enable man to gain deeper insight into his relationship with the rest of the universe. In the past, it has been the appearance of innovative new ideas through science (rather than through engineering) that have contributed to this insight.

[51] J. Altmann, *Military Nanotechnology*. London: Routledge (2006).

Nevertheless, some of the achievements of technology in creating gigantic objects (such as the pyramids of Gizeh or the Forth railway bridge) certainly inspire mankind to have greater confidence in his powers. Nanotechnology also has a role to play in this regard, through striving for unparalleled accuracy in the description of the world.

Much of what has already been written in the preceding sections impacts psychology in a more mundane fashion, both positively and negatively. Although, as noted above, nanotechnology generally seems to be perceived in a benign light (excluding the vociferous pronouncements of a small minority of activists, who have a vested interest in promoting anxiety); there are nevertheless some identifiable negative aspects. People worry about information overload, which might be quite as harmful psychologically as overloading the biosphere with nano-objects is environmentally. It would be sad indeed if the environmental benefits of nanotechnology, resulting from far more efficient resource extraction and general energy utilization, were countered by the inadvertent release of nanoparticles into rivers, for example. On the other hand, the steady march of nano-enabled processor power must provide the ultimate remedy to information overload: the automated processing of vast quantities of raw data. "Theranostics", therapy combined with diagnostics, as exemplified by ingested nanoparticles that can both diagnose an internal ailment and release a drug to treat it, is seen as disempowerment of the patient (whereas if he or she is prescribed a drug to take as a tablet, it is after all possible to refuse to take it).

As well as with the growth of processing power, information overload is associated with a vast increase in memory capacity. Ever since the invention of writing, man has been storing information but the traditional technologies, whether clay tablets or books, are voluminous, and hence capacity is limited, whereas the miniaturization of storage that has already been envisaged creates what is essentially unlimited capacity. One manifestation of this huge capacity is the possibility for all of us to have our own individual "life log"—a quasicontinuous record of events and physiological variables throughout our lives. Insofar as our personalities and indeed very identities are defined by the unique progression of personal acts and decisions made throughout life,[52] we would thereby appear to be confiding our very personalities to a passive storage medium. Presumably, though, to be complete the life log would have to also include our thoughts, which poses certain technical problems.

In summary, nanotechnology will impact us all individually and personally through enhancing our understanding and appreciation (through that understanding) of the world around us, the natural no less than the artificial, which should inevitably promote our survival.

Part III: Can nanotechnology contribute to tackling the grand challenges?

Near the beginning of this essay rapid climate change, environmental degradation, energy and other resource depletion, unfavourable demographic trends, insufficiency of food and nuclear proliferation were mentioned as being the biggest challenges facing humanity. In this Part we briefly sketch out a "reactive" view of the potential impacts of nanotechnology, taking each one in turn and looking at how nanotechnology can contribute to solving the problem. To make the assessment definite, we shall first run through the eight Millennium Development Goals of the

[52] J.J. Ramsden, Computational aspects of consciousness. *Psyche: Problems, Perspectives* **1** (2001) 93–100.

United Nations. The goals themselves are expressed fairly precisely (for example the first one ("eradicate extreme poverty and hunger") aims to halve, between 1990 and 2015, the proportion of people whose income is less than $1 a day), but usually without specifying any boundary conditions (such as population level or carbon dioxide emissions). Furthermore, many of the goals are linked, sometimes positively (for example, Goal 2 ("achieve universal primary education") should impact positively on eradicating poverty). The goals can be grouped into three broad categories, socio-economic (concerning poverty, education and gender equality); health (concerning child mortality, maternal health and infectious diseases); and environmental–commercial (Goal 7, "ensure environmental sustainability", also includes a target to improve access to safe drinking water, which really belongs to health, as does one of the targets within Goal 8, "develop a global partnership for development", which calls for providing access to affordable essential drugs).

Productive nanosystems, the economics of abundance and a much lower world population would themselves largely achieve the goal of eradicating extreme poverty and hunger. Other improvements could come through understanding in nanoscopic detail critical agricultural processes such as biological nitrogen fixation and how it can be enhanced through nanotechnology. Integrative approaches to very complex problems such as desertification will be assisted by the availability of powerful information processors. Meanwhile universal primary education may well be achieved by through the disequilibrium resulting from the presence of very high technology (i.e., nanotechnology) implanted in the midst of ignorance. Education—raising the level of knowledge of the population—is in fact the key to improving the situation regarding poverty, health and water.

As well as being interdependent, the millennium goals and targets are also subjected to external constraints, which have to be appraised essentially arbitrarily. In other words, they boil down to ethical and religious beliefs and values. One of the most important of these constraints is population. For some people, world population should be "as large as possible" (which is not in itself very precise, of course, but it seems to mean that no special measures to restrain it should be undertaken). A more pragmatic view would be to say that the target population should be that necessary to enable the millennium goals to be achieved. A more rationalist view is to strive to reach a population that enables individual human development to be maximized; to determine what that population might be probably requires an additional specification of the distribution of individual human development: if that specification is merely the average, one would be able to choose between a situation in which everyone would have roughly the same degree of development and a very different situation with a few outstandingly developed individuals and a mass of underdeveloped ones. Then there is also the question whether global consensus on this matter should be reached—insofar as the decision will have global effects on, for example, global warming, global consensus is probably required.

Population and standards of living (as measured by the level of goods and services per capita) are really the key issues, because everything else in the challenges listed at the beginning of this section or in the millennium goals depends on them. It seems to be clear that these issues cannot be resolved endogenously; we have no supreme authority that could impose nanotechnology on us (even if that were sufficient to meet the challenges). The hope embodied in nanotechnology is that by it becoming disseminated among the entire population, everyone will take a direct and personal interest in the future of the planet and will, out of a sense of conviction and through acts of individual volition, contribute to ensuring the future survival of our kind. This mechanism is really that of Adam Smith's "invisible hand": everyone acting (and allowed to act) in their own best interest contributes to the common good. As Adam Smith realized, the successful functioning of this mechanism presupposes agreement, at least at the level of consensus, over what constitutes "best", which in turn implies a shared set of values (i.e., ethics or religion).

Ad interim nanotechnology can only help in a piecemeal fashion. Microenabled nanoreactors may be able to purify contaminants in water and make it fit to drink, but if the reactors are simply distributed among an ignorant population their use will scarcely be sustainable.

Part IV: Towards a conclusion

16. Nanotechnology as revolution

The potentially revolutionary consequences of nanotechnology on our entire economic and social organization prompt careful analysis, above all since we are now in a position to carry it out. It is doubtful whether the first flint knappers speculated about the implications of their discovery on society—such as it then existed—as a whole. Even the Industrial Revolution "just happened" by many entrepreneurs acting essentially individually, albeit guided in some fashion by the general spirit of the age. As John Donne sagely remarked, "No man is an island". Thus Birmingham almost imperceptibly became, for a time, the greatest industrial centre in the world, without any plan, but merely through the industrious activity of a host of individual entrepreneurs, working independently but with much interdependence. The whole process illustrates remarkably well Adam Smith's idea of the invisible hand—each person allowed unhampered to work for his or her own best interest contributes to the general wellbeing. Only *post hoc* were these events subjected to intense scrutiny. Buckle's "History of Civilization in England" was perhaps the pioneering work in this regard. Since then numerous historians have addressed the subject; that is, of trying to understand why there are such differences between nations. What we are trying to do now is assess the likelihood that nanotechnology will lead to a qualitative transformation in society, at a time when not very much nanotechnology exists, taken as a fraction of overall commercial activity, but ideas abound about what nanotechnology can do.

The future is of course always untouchable but in a certain sense is no more unreal than the past, which is also untouchable in any objective sense. Attempting to predict the future has become almost indissociable from civilization. Governments regularly organize censuses of their entire populations with the justification that they need the data to "build the future". Apart from invocations to soothsaying, which are perhaps difficult to analyse rationally, the most primitive approach to predicting the future is by extrapolation. Since any system with three or more degrees of freedom can behave chaotically,[53] this can only possibly work either for very short intervals into the future or for very special cases. Nevertheless, its use is widespread; given that knowledge of the limitations of extrapolation is growing, it is surprising that reliance on extrapolation is, if anything, growing as well.[54]

[53] J.C. Robinson, All possible chaotic dynamics can be approximated in three dimensions. *Nonlinearity* **11** (1998) 529–545.

[54] Perhaps this is merely an indication that the movement of people onto the most primitive rungs of scientific understanding and achievement is faster than their ascent to higher levels.

Despite these difficulties, it would perhaps be unreasonable to expect humanity to renounce attempting to predict the future. But more sobriety would be in order: "we should do better to seek out good cooks and look forward, at the very least, to sound, plain food."[55]

What constitutes a technical revolution? The anatomically modern human being, *Homo sapiens*, emerged some 200,000 years ago. Over 100,000 years apparently elapsed before his superior mental capacities began to be exploited, as evidenced by figurative arts, bodily embellishment (jewellery, etc.), musical instruments and sophisticated hunting tools, which have been found in Africa dating from 90,000 years before the Christian era (BCE), although the initial bursts seem to have later died out; about 45,000 years ago one finds similar evidence in Europe and western Asia (the so-called upper Palaeolithic explosion). The first writing (cuneiform script) dates from as recently as around 3000 BCE, and comprehensive written records of the past (i.e., the beginning of history) only emerged around 600 (China)–500 BCE (Greece).

The development of man is marked by technological breakthroughs, especially those concerning materials processing. So important are they that the technologies give their names to the successive epochs of prehistory: the Stone Age (predating the emergence of *Homo sapiens*), so-called because of simple stone implements, for example axes, made by knapping flint; pottery first seems to have been made around 20,000 BCE (but it took another 15,000 years before the potter's wheel was invented); the Bronze Age (starting about 3000 BCE); the Iron Age (starting about 1000 BCE, coincidentally with the emergence of glassmaking); rather than modes of life such as hunting, agriculture (starting about 12,000 BCE), pastoralism (around 5000 BCE), urbanization etc.

The most significant change in our way of life during the last two or three millennia was probably that brought about by the Industrial Revolution, which began in Britain around the middle of the 18th century and marked the beginning of the Industrial Age; by the middle of the 19th century it was in full swing in Britain and, at first patchily but later rapidly, elsewhere in Europe and North America. Note that this revolution, unlike its predecessors, was very much production-oriented (in other words, manufacturability was as much a consideration for what was produced as usefulness). This in turn was replaced in the latter half of the 20th century by the still ongoing Information Revolution, which ushered in the Information Age, marked by the development of unprecedented capabilities in the gathering, storage, retrieval and analysis of information, and heavily dependent upon the high-speed electronic digital computer. The next revolution already appears to be on the horizon, and it is thought that it will be the Nano Revolution.

Within a revolution capabilities grow exponentially—one could even say that the duration of the interval of such exponential growth temporally defines the revolution. Such growth is sometimes quite difficult to perceive, because an exponential function is linear if examined over a sufficiently small interval, and if the technology (or technological revolution) unfolds over several generations, individual perceptions tend to be strongly biased towards linearity. Nevertheless, empirical examination of available data shows that exponential development is the rule (Ray Kurzweil has collected many examples, and in our present epoch the best demonstration is probably Moore's law), although it does not continue indefinitely, but eventually levels off.

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[55] A.B. Pippard, *Response and Stability*, p. 38. Cambridge: University Press (1985).

Very often a preceding technological breakthrough provides the key to a successive one. For example, increasing skill and knowledge in working iron was crucial to the success of steam power and steel, which were the hallmarks of the Industrial Revolution, which ultimately developed the capability for mass production of the very large-scale integrated electronic circuits needed for realizing the subsequent Information Revolution.

Why do people think that the next technological revolution will be that of nanotechnology? Because once the technology has been mastered, the advantages of making things "at the bottom", as Feynman proposed,[21] will be so overwhelming it will rapidly dominate all existing ways of doing things.[56] Once iron-making and -working had been mastered, no one would have considered making large, strong objects out of bronze; mechanical excavators now reign supreme on building sites; no one uses a slide rule now that electronic calculators are available, and even domestic appliances such as washing machines are controlled by a microprocessor.

Is it to be expected that information technology will be crucial for the realization of nanotechnology? Very probably yes. The design of nano materials and systems will be heavily dependent upon computation. Furthermore, nanofacture is scarcely conceivable without computer-enabled automation of (bottom-to-bottom) assembly.

The Nano Revolution will consummate the trend of science infiltrating industry that began with the Industrial Revolution. This infiltration can be roughly described in four stages of increasing complexity (Table 4).[57] Note that Stage 4 also encompasses the cases of purely scientific discoveries (e.g., electricity) being turned to industrial use. Clearly nanotechnology belongs to Stage 4, at least in its aspirations; indeed nanotechnology is the consummation of Stage 4; a corollary is that nanotechnology should enable science to be applied at the level of Stage 4 to even those very complicated industries that are associated with the most basic needs of mankind, namely food and health. Traditional or conventional technologies (as we can label everything that is not nanotechnology) also have Stage 4 as their goal but in most cases are still quite far from realizing it.

Table 4. The infiltration of science into industry (after Bernal).[57]

Stage	Description	Characteristic feature(s)
1	Increasing the scale of traditional industries	Measurement and standardization
2	Some scientific understanding of the processes (mainly acquired through systematic experimentation in accord with the scientific method)	Enables improvements to be made
3	Formulation of an adequate theory (implying full understanding of the processes)	Possibility of completely controlling the processes
4	Complete integration of science and industry, extensive knowledge of the fundamental nature of the processes	Entirely new processes can be devised to achieve desired ends

Consideration of the anticipated impacts of nanotechnology on society needs to be set in the general context of technology impacts. Bernal[57] has pointed out the difficulties that arise from the discrepancy between the primitive needs of man, which are actually extraordinarily complex from the scientific viewpoint (e.g., the biochemistry of food preparation, and the

[56] T.T. Toth-Fejel, A few lesser implications of nanofactories. *Nanotechnol. Perceptions* **5** (2009) 37–59.
[57] J.D. Bernal, *The Social Function of Science*. London: Routledge & Kegan Paul (1939).

animal psychology involved in hunting and domestication), and the need for understanding to proceed from the simple to the complex: what can be understood rationally must necessarily be simple, at least to begin with. Unfortunately the simplest sciences, astronomy and mechanics, appeared (around 3000 and 400 BCE, respectively) only after the main techniques of human life had already been fixed. As a result, these techniques—encompassing such things as agriculture, cookery, husbandry, metalwork, pottery and textiles —remained almost unchanged for many centuries at least until the early 18th century, largely untouched by the scientific method. Subsequent attempts to improve them "scientifically" have actually led to a mixture of benefits and disbenefits, and rational expectations of the impacts of nanotechnology must be tempered by this past history. The Industrial Revolution led to a focus on machine production rather than direct human needs such as food and health. A fundamental difference between the Nanotechnology Revolution and the Industrial Revolution is that the former is consumer-oriented, unlike the production orientation of the latter. The ultimate stage of nanotechnology, productive nanosystems, in essence abolishes the difference between consumer- and production-orientation. Nanotechnology has the potential of refocusing the way society satisfies its needs on the more human aspects, which is itself a revolutionary enough departure from what has been going on during the last 300 years to warrant the label Nanotechnology Revolution. Furthermore, the Nanotechnology Revolution is supposed to usher in what Good has referred to as the "intelligence explosion",[58] when human intelligence is first surpassed by machine intelligence, which then rapidly spreads throughout the entire universe. This is what Kurzweil calls the singularity—the ultimate revolution.[20]

17. Impacts on ethics

If we follow the Baconian progression of the idea leading to the science (i.e., the testing and verification of the idea) leading to the technology, which then requires engineering to transform it into a useful product, which is then finally used, ethics emerges as the ultimate stage of application (considered to be everything from technology onwards in this scheme): the use made of the technology should be "ethical". What do we mean by that? The word in itself is just short for "in accordance with my ethical principles". These principles could also be yours but ultimately they are a matter of individual responsibility. It is no sanction for a wrong action (i.e., an action contrary to one's own ethical principles) that the majority (which must necessarily be a local majority, since that is all we apprehend: telecommunications mean that locality is not merely spacial) approve of it.

Perhaps there is an underlying current of thought that the new era of rationality that might be ushered in by nanotechnology and its way of looking at the universe would lead to an indefeasible and unique set of "natural" ethical principles. Certainly the technology encourages a more consequential attitude: if one knows a structure with atomic precision then its properties should be more predictable than those of conventional or statistically assembled materials; likewise the "atoms" of ethical convictions have certain consequences for human survival, and if they lead to the destruction of humanity those convictions should be discarded. At the same time the use of evolutionary design principles (§5) means that we shall become surrounded by

[58] I.J. Good, Speculations concerning the ultraintelligent machine. *Adv. Computing* **6** (1965) 31–88.

devices, the mechanisms of whose inner workings may not be known. This will perhaps focus attention on the real features of reality, notably its microdiversity, open-endedness and continuous evolution, which the preponderance of engineering based on fixed, uniform systems and science based on linearity and isolation have tended to eclipse.

It should not be forgotten that morals are essentially stationary, and dependent on the state of intellectual knowledge for their interpretation. Therefore, if there is some agreement on a common set of ethical principles, nanotechnology as part of intellectual knowledge could at least contribute to, and hopefully enhance, their interpretation and effectiveness.

18. Concluding remarks

Francis Bacon was firmly convinced that science discovery should be driven not just by the quest for intellectual enlightenment, but also for the relief of man's estate. A great deal has already been written, in this journal and elsewhere, about the marvellous technology and potential technology that falls under the banner of nanotechnology. Much less has been written about whether nanotechnology has the potential for positively benefiting civilization by contributing to the elevation of society. Society being made up of individuals, its elevation boils down to the individual development that we have mentioned before, and see the previous section, §17.

The real benefits of nanotechnology, which by changing the way we understand technology and science will also impact on the way we understand our relationship with the rest of the universe, can only be realized if there is a significant—at least tenfold—increase in the technical literacy of the general population. Technical literacy means the ability to understand an intelligible account of the technology (that is, an account in plain language not requiring any prior specialized knowledge). It would be tragic if the technology remains—like so many technologies today—a mysterious, impenetrable black box. Basic education today, both in the developed world and presumably what is intended by Millennium Goal 2 (see Part III), seems to have little ambition beyond essential literacy and numeracy. There are doubtless implications of the new vision that accompanies nanotechnology at all levels, starting with the newborn infant and continuing throughout life. The commercial and political reorganization implied by the growth of nanotechnology provides an opportunity to thoroughly rethink the whole structure of education, especially the formal years of schooling from the ages of six to eighteen. The content of what is currently taught seems very far from what would be required for future designers of nanoartefacts.

For a world of designers is, very succinctly, what the world with nanotechnology will ultimately look like. Science and technology will be essentially indistinguishable and everyone will be able to participate—everyone will be designer, maker and consumer, sculpting what they need from the atoms all around us. If we step back for a moment and look at our present situation, we have reached it through following a trend aiming at just the opposite. The explorer Wilfred Thesiger describes in *Arabian Sands* how in the desert he and his Bedouin travelling companions made coffee: the beans were first roasted over the campfire, then ground in a mortar with a pestle, before cooking with water. Even my parents, in a domestic setting (we lived in Buckinghamshire, England) did essentially the same thing when I was a small boy (except they used the oven for roasting and we ground the beans in a coffee-mill) but, relentlessly, more and more was done before the coffee arrived in the house: first the beans were already roasted, then they were already ground, then prepacked, and now the apotheosis is the "Nespresso" system of ground coffee predispensed in capsules and all one has to do in order to make a cup of coffee is press a button on a machine. The coffee is somehow less "authentic" as a result but seemingly uniformly excellent in quality of taste. Nanotechnology implies essentially reversing this trend and "reverting" (although we are not turning the clock back, because the new order is firmly built on profound knowledge of universal mechanisms) to an era in which we are again mostly personally responsible for the artefacts and processes around us.

Does that mean that the rate of discovery, of acquiring new knowledge, will slow down and even stop, because we will all be so busy fashioning the artefacts essential for life from atoms? That would be a very undesirable and even dangerous (for a future survival) outcome, but one that is unlikely to come about, because fashioning artefacts is so strongly knowledge-based—in this sense nanotechnology represents the apotheosis of the knowledge economy. In any case, much of this activity would rapidly become largely automatic.[59] Broadly speaking, maintaining the growth of knowledge as the first priority for humanity is the best guarantor of sustainability. Not everyone will directly participate in knowledge growth (although the proportion could be significantly greater than now), but everyone should take an interest; in Bernal's words,[57] "There is nothing for science like the concentrated and trained appreciation with which football matches or horse races are followed; and this is not to be explained only by the lack of a financial interest in science fancying or by the intrinsic difficulties of the subject. There are finer points in cricket or billiards than are often to be found in biological and physiological arguments; while if people were really interested in science it would very soon be discovered what excellent sport could be had in backing Professor B's theory against Professor A's at 10 to one ... science has become detached from popular consciousness and the result is very bad for both." This is also a facet of technical literacy and the knowledge economy. There seem to have been periods in the past (e.g., the late 17th and early 18th centuries) when there was intense public interest in science (think of Mme du Châtelet translating Newton's *Principia*, for example); now the tapestry of knowledge is much richer, yet general interest has diminished or become bowdlerized. Needless to say, if such interest can be recaptured, the whole (and nowadays quite intensive) debate about science communication (i.e., downstream "public understanding" and upstream "public engagement", etc.) will become largely irrelevant—the problem will have solved itself.

What of aesthetics? Undoubtedly assemblers are machines—does this mean that we face a future in which, in the words of Imre Madách, "... all is fashioned by machinery, in forms of service and simplicity"? Insofar as nanotechnology really began with artistry—think of the Japanese *suminagashi* practised over a thousand years ago, and probably earlier still in China—this seems unlikely. In any case, as long as we all remain in charge of what we make for ourselves—and perhaps it is only natural to also wish to make things for others as well—it would require conscious and concerted volition to abandon artistic considerations. The fact that many artists are already showing vigorous interest in nanotechnology suggests that we can look forward to a rich interplay between art and nanotechnology, to the mutual benefit of both.

[59] Indeed, a possible development would be for individuals to again outsource the provision of their basic needs.