Where is nano taking us?

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Introduction

It would not necessarily have been obvious at the time of the emergence of Newcomen's cumbersome steam engine that this kind of motive power would, within less than a couple of centuries, reach its apotheosis in the crack railway expresses running at 150 km/h and mighty luxury liners traversing the Atlantic. A similar reflexion applies to the path from Orville and Wilbur Wright's first aeroplane to the Concorde supersonic airliner, or from spluttering "horseless carriages" barely able to overtake a pedestrian to urban canyons choked with motor cars, or huge "juggernauts" thundering along inter-state highways.

All these developments belonged to the Industrial Revolution, which also comprised large scale steelmaking and chemical manufacture and many others that sometimes individually and certainly collectively truly transformed our civilization, meaning not only the way we led our daily lives but also our attitudes and outlook more generally. For a technological development to qualify as a revolution it must have the power to effect a similarly far-reaching transformation of society through a web of pervasive and interdependent technologies. Thus the "Information Revolution" of the latter half of the 20th century, bringing huge computing power to a desktop and the intricacy of cellular telephone circuitry to a device small enough to be secreted in a pocket, to say nothing of the world wide web or internet, with which, for the first time in human history, all denizens of the planet are potentially connected to one another, also well-deserves its name. Notice, by the way, that whereas the Industrial Revolution unfolded over 200 years, the Information Revolution took barely 50. This is a reflexion of the exponential

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nature of technological progress.[1] Moore's "law", encapsulating the empirically observed growth of the number of components per chip and standing at the border between the Information and Nano Revolutions, is an extremely well-documented example of this exponential progress, and is too well known to require further elaboration here. Exponential progress implies that the past two and a half centuries are equivalent to only 25 to 30 years of progress at today's rates, and since human intuition seems to be biased towards linearity, our predictions about the future are likely to be too conservative and fundamentally limited by present experience. This in itself is potentially dangerous, since such a rapid advance in technology is unprecedented and it is extremely likely that even the most imaginative or open-minded approach will not be able to adequately anticipate the many social, economic and cultural issues that will surely result.

Our task in this article is to explore the "Nano Revolution". It is legitimate to ask whether there will be a Nano Revolution at all, hence after defining nanotechnology we shall explore whether it is truly revolutionary, before going on to envision future possible scenarios of our civilization, looking as much at lifestyles and attitudes as at the underpinning technology itself.

This paper is based on a Scenario Workshop organized as part of the European Union's 6th Framework Programme for Research (FP6) project: *DEEPEN: Deepening Ethical Engagement and Participation in Emerging Nanotechnologies* held on Friday 2 March 2007 at the Royal Geographical Society, London. The DEEPEN project is Europe's leading research partnership for integrated understanding of the ethical challenges posed by emerging nanotechnologies and their implications for civil society, for governance, and for scientific practice. By bringing together a range of experts from nanoscience, the workshop aimed to develop insights into the future of nanotechnology and nanoscience and current debates that characterize the field. Over the course of a full day's discussion the group constructed scenarios concerning possible advances in nanotechnology over the next 15–20 years, focusing particularly on nanosensors, nanoelectronics, bionanotechnology and nanomedicine. By thinking collectively the aim was not to define a definitive view of the future, but rather to assess the challenges posed by the development of nanotechnology for society in general.[2]

Defining nanotechnology

The usual definition[3] emphasizes the engineered construction of matter at the molecular scale. Expanding, one can distinguish direct, indirect and conceptual aspects of nanotechnology.[4] "Direct" would for example be nanomaterials such as nanocomposites (e.g. nanoparticles embedded in a polymer matrix to create novel materials with unique combinations of properties), or a single-electron transistor. "Indirect" would be the higher level applications such as very large scale integrated microprocessor circuits with feature sizes in the few tens of nm range, or indeed any object made with a nanocomposite. "Conceptual" nanotechnology refers to a way of looking at the world from a molecular viewpoint, e.g.

1 Kurzweil, R. *The Singularity is Near*. New York: Viking (2005).
2 A report on the workshop will be published in April 2007 and directly contribute to subsequent public engagement research coordinated by the project.
3 E.g. Abad, E. et al. NanoDictionary. *Nanotechnology Perceptions*, 1 (2005) 147–160.
4 Ramsden, J.J. What is nanotechnology? *Nanotechnology Perceptions*, 1 (2005) 3–17.

nanomedicine in the sense of understanding disease by knowing what is happening to individual proteins and nucleic acids, or nanomachines that can result from the precise control of nanoscale components able to transform energy and therefore do useful work at the nanoscale. In many applications, all three aspects of nanotechnology are found. For example, indirect nanotechnology impinges on nanomedicine through new drugs made using nanofluidic-based reactors, and automated intelligent diagnosis using powerful computers whose circuits have nanoscale features, and direct nanotechnology would include nanosized sensors directly implanted in the body, and nanoparticles delivering drugs.

Some of the most commercially significant nanotechnologies are relatively mundane innovations that scarcely qualify as revolutionary by themselves, such as highly scratch-resistant paints incorporating nanoparticles, or electrically conducting paints, self-cleaning windows, super-hydrophobic textiles able to resist the deposition of dirt on them, bouncier tennis balls and so on. These innovations are not going to revolutionize our lives. We are therefore looking a few years ahead, to developments that are essentially still confined to the research laboratory at present, but where there has already been enough concrete progress to be able to envisage with reasonable confidence the shape of future applications. It is also worth noting that some nanotechnologies are extremely old; a good example is the pigments found in stained glass windows, which are actually based on quantum dots.

Another way of classifying nanotechnology (i.e. orthogonally from the "direct, indirect and conceptual" division outlined above) is into materials, devices and systems. This division will allow us to pinpoint where the revolution is likely to take place. Nanomaterials are likely to effect incremental rather than revolutionary changes. For example, nanocomposites may well allow us to build lighter, and hence safer and more fuel-efficient, aeroplanes, but will not call the whole paradigm of air travel into question. It is nanodevices that will have the potential to effect revolutionary change, and they almost inevitably imply nanosystems, since nanodevices are very small, and therefore there will have to be very many of them linked together.

During the workshop discussion three domains of nanotechnology research emerged as having the greatest transformative potential, including:

Nanoprocessors: it was felt that further exponential miniaturization of integrated circuitry (including optical computers enabling Moore's so-called law to continue beyond microprocessors) and the use of unconventional materials enabling printed and textile-based electronics would make powerful pattern recognition processing applied to medical diagnostics etc. ubiquitous: sensor clusters will become "smart", and simple processor-bearing artefacts such as our clothes and household objects will be able to communicate with each other and with themselves.[5]

It is also worth considering how understanding the nanoscale will allow a revolution in information processing that defines a whole new approach to computer architecture, not based upon von Neumann architectures. This would represent a paradigm shift of massive proportions since its effects would be felt in virtually every area of society already touched by technology.

Sensors and actuators: it was suggested that nanotechnology-based miniaturization with concomitant improvements in reliability and reduction of cost would enable 'total sensorization' of our world, impacting almost every facet of our lives, including medicine (implanted sensors to

[5] Note that this will not open a path to a "revolution of the saucepans" for example, since the artefacts will be unable to undertake any action beyond indicating their state.

continuously monitor our physiological state), food (portable personal sensors for freshness, pathogenic microbes etc., online potable water quality sensors), environment (noxious gases and vapours, and visual surveillance of human presence), etc. Many of these sensors will incorporate information processing capability and will work in tandem with actuators able to implement decisions made by the sensors, e.g. releasing a drug into the bloodstream.

Reactors: chemical reactions taking place in miniature reactors based on fluidics offer far better control (mainly due to far superior mixing), hence the elimination of by-products and faster reactions. The workshop group felt that the main current challenge is scale-up to large volume production.

These three fields are naturally linked: powerful information processors ("artificial brains") will ensure continuous data analysis and inference from the myriads of sensors everywhere; and successful fluidic reactors will have sensors embedded in them to continuously monitor the chemical state of the contents. Note that ubiquitous sensors and actuators will also require miniature power supplies, which will likely also depend on nanotechnology.

Nanotechnology and health

An area in which the workshop group anticipated major change was the health sector. The development of small and cheap nanosensors would enable their ubiquitous deployment on a large scale within our bodies, monitoring physiological state and even mood, and in the environment, giving us warning of toxic gases. The data from this flotilla of sensors will far surpass human capabilities of assimilation. This development would therefore also necessitate increased computer processing speeds and capacities, also based on nanotechnology developments in the production of intregrated circuitry

Another area of nanotechnology innovation in health care identified by the workshop was the development of increasingly individualized drugs synthesized by micro- or nanotechnologies in micro- or nanoreactors and used to remedy health deficiencies. The possible advent of bacterium-sized autonomous robots, "nanobots", able to circulate in the bloodstream and carry out nanosurgery would be a further development along these lines.

The notion of individualized drugs perhaps needs some explanation. It is known that most of the variety among the human population is not scattered randomly throughout the human genome, but concentrated in haplotype blocks, regions of about 10^4–10^5 nucleotides in which a few (< 10; the average number is 5.5) sequence variants account for nearly all the variation in the world human population.[6] Therefore the task of providing individualized drugs is not a task of providing thousands of millions of different drugs (which is not a wholly inconceivable one, using nanoreactors) to treat a given ailment, but of producing half a dozen to a dozen different ones. One important aspect of producing 'drugs-on-demand' *in situ* within a human being for instance is that potentially there would never be a high enough concentration of the material to establish long term toxicology or even establish patent rights over a formulation or given polymorph.

This relatively easy-to-construct scenario is firmly set in a human civilization looking much the same as the one we live in at present, which might be too conservative a view. Maybe

6 Ramsden, J.J. *Bioinformatics: an Introduction*. Dordrecht: Kluwer (2004).

it should be considered (for example) that nanosensors to monitor saloon air quality and to optimize combustion, hence minimizing air pollution from exhaust gases, in a motor car will be superfluous if we all live essentially permanently in individual cells, as imagined by E.M. Forster in his short story *The Machine Stops*.[7] Such a development might not depend directly on nanotechnology, but to house us all underground might be the only way to curb our seemingly insatiable desire for mobility.

The combination of sensors based on nanotechnology, the ability to extract meaningful data from them using powerful nanotechnology-enabled chips (processors), and nanoreactor-enabled individualized medicine, complemented by nanosurgery, offers a clear and attractive route to enhance and even revolutionize healthcare. At the same time it must not be forgotten that the nanorevolution will generate new health hazards, the most prominent of which is nanoparticles.[8] The most unambiguous conclusion of the recent Royal Society of London/ Royal Academy of Engineering report[9] was that the potential hazards of nanoparticles to human health and the biosphere more generally were largely unknown and needed to be urgently and properly investigated, in order to provide a sound basis for the regulation of their manufacture, use and disposal. At the very least, one should approach the topic with the wisdom acquired from asbestos and other particles known to be unpleasant.[10] However we must be careful to regulate our response to such anticipated threats. For instance nanoparticles are not new, the early Egyptians used colloidal gold and we are bombarded with aerial nanoparticles daily. We therefore have to take a measured response to such issues.

Missing from the discussion of nanomedicine so far is an appraisal of the possible consequences of a direct man-machine interface, symbolized by the vivid, but unlikely, image of acquiring a USB port connecting into our brains. Yet brain states can already be monitored, albeit very crudely, with external electrodes.[11] This takes us onto the next point.

Nanotechnology and human enhancement

It is but a small step beyond the repair of the consequences of accidents, the cure of ills, and the maintenance of good health to the enhancement of our corporeal, and possible even mental, lives.[12] Performance-enhancing drugs, effective at least in the short term, are already endemic in the world of sport. There, a decision about whether to use them can be made based on

[7] Forster, E.M. *The Machine Stops*. Oxford and Cambridge Review, November 1909.

[8] The combination of sensorization and automated diagnosis (inference engines) being doubtless less than infallible raises the interesting possibility of a greater prevalence of hypochodria. Possibly neuroses caused by misdiagnosis of illness might even lead to actual illness.

[9] *Nanoscience and Nanotechnologies: opportunities and uncertainties*. London: Royal Society and Royal Academy of Engineering (2004).

[10] van Oss, C.J., Naim, J.O., Costanzo, P.M., Giese, R.F., Wu, W and Sorling, A.F. Impact of different asbestos species and other mineral particles on pulmonary pathogenesis, *Clays Clay Minerals*, 47 (1999) 697–707.

[11] The limitations imposed by the 'Principle of Logical Indeterminacy' should however be borne in mind. See Ramsden, J.J. Computational aspects of consciousness. *Psyche: Problems, Perspectives*, 1 (2001) 93–100, for a discussion of this point.

[12] Miller, P. and Wilsdon, J. (eds). Better Humans? The politics of human enhancement and life extension. London: Demos (2006).

straightforward premisses. But what of drugs influencing our mental state? Again, it can be argued that there is nothing essentially new here. Stimulants such as caffeine and theine have been known for centuries, alcohol and other mood-enhancers such as the so-called ‘recreational drugs’ have an even longer history, and there are also examples of people using drugs in an attempt to enhance creativity.[13] However throughout the workshop discussion it was felt that mood enhancement becomes both possible and potentially more powerful in a world where nanotechnology is pervasive. For example, minute sensors embedded within our bodies (including out brains), and discreetly observing us in our environment, whose output is processed by the incredibly powerful nanotechnology-enabled computers, might be able to administer far more powerful drugs (or electrical stimuli) far more effectively, so that we can be, for example, in a perpetually good mood.

Speculations about such possibilities usually end around there. However, the workshop discussion highlighted some of the social challenges posed by such developments. For example, is a perpetually positive mood necessarily desirable? If it is acknowleged that most creativity springs from an ever-evolving variety of sensations and moods, an extremely subtle blend of self and environment, to which the occasional use of a stimulant merely contributes, would such developments reduce human creativity and spontaneity?

Furthermore, the processing of the data, including the decision about what to inject and when, would take place under the control of human-written software (unless we move to evolving software, discussed below). Who would write the programs? We might write them ourselves—given that high level computer languages are highly restricted subsets of natural languages, it is not inconceivable that this could become a universally accessible task. But even we would be confronted with the Principle of Logical Indeterminacy,[12] quite apart from the incredible tedium of attempting to capture in advance all possible moods of ours, when in fact they can only be accessed by explicit simulation of every step, including that of our environment. A hopeless task, but the alternative, that we allow ourselves to be subject to a program written by others, is a scenario even more sinister than that of George Orwell’s *1984*. It is perhaps superfluous to develop the idea further.

Nevertheless, there remains one possibly beneficial use of mood enhancement. Presumably a similar approach could be used to detect, and pre-empt, criminal intent. Burglars, murderers and so forth would be effectively neutralized. It is at least superficially a straightforward way of rendering our environment more secure. But *quis custodiet ipsos custodies*? Who would write the programs that would control the pre-emption of criminal intent? We cannot argue from the premiss that criminals have lesser rights than others, for these people have been convicted of no crime, nor have they carried one out, physically. This knotty problem is perhaps even more pressing than the one of the legal rights of intelligent robots.

Bionic man, meaning the gradual replacement of body and brain parts with artificial ones, can scarcely be called revolutionary, since it has been practised by humanity ever since the first

[13] The most celebrated example is perhaps Thomas de Quincy’s *Confessions of an English Opium Eater* (London: J. Moyes for Taylor and Hessey, 1822). Most people who read this book, which is considered a classic because of the oddity of its subject matter rather than any literary merit, seem to find it a very tedious work. Hence it appears that published accounts of the effects of such drugs on creative output should be sufficient to discourage their use, and indeed there seems to be no example of any significant scientific or mathematical work having been produced under the influence of opium or the like.

wooden leg was substituted for an amputated one. Perhaps if sufficient replacement is carried out, what is merely a quantitative difference will become a qualitative one. In particular, science fiction authors have already extensively speculated on the notion of downloading our identity (defined as "the unique progression of personal acts and decisions made throughout life"[14]) onto a synthetic data storage medium.

In attempting to grasp the implications of these developments, an interesting discussion emerged throughout the workshop, concerning the effect on personalization that the ubiquity of computing devices would create. There are useful analogies here from the use of data stored on the laptop computer or smaller device that accompanies us everywhere; and many of us have placed extensive parts of our life story on personal web pages, freely accessible by everyone else in the world. If one compares this development with the rather staid and dull earliest "web pages" maintained by public or private organizations and containing minimal information that was all available in printed form as brochures, one might well remark that the web has become more personal and individual, when even a six year old child can present his or her daily musings to the world. On the other hand, compared with the keeping of handwritten and strictly private diaries, this sudden opening up of personal content to everyone inevitably emphasizes the collective and impersonal aspects of civilization—evidently, posting pages on the world wide web only has sense if the contents are understandable, at least at some superficial level, to all, hence they must be composed in a common language, most typically a kind of simplified English that has yet to be given an official name. This stands in sharp contrast to well-known Renaissance diarists such as Samuel Pepys, the contents of whose diaries were so secret that they were written in cipher, incomprehensible to others, presumably to guard against the eventuality of them being read by anyone other than their writer. In short, the internet has actually brought us (or is bringing) us back to the rather impersonal viewpoint characteristic of the Middle Ages, in which individual thoughts and feelings were definitely subordinate to the collective spirit of the age.

It may of course be that this is an inevitable cyclical development: our very eagerness to communicate with others implies a certain subordination of individuality—at the very least we must all agree on a common language, and hence are ultimately all entrained into a common pattern of thought. But the stable and uniform society that this implies might favour the growth of the pockets of individuality that presumably are constantly created by chance fluctuations (and many of them are promptly annihilated)—and that is what the Renaissance effectively was: a "collective outburst of individuality". The creativity that that implies inevitably leads to scientific advance, i.e. the growth of knowledge and technology, and the allure of that technology may eventually become so great as to collectivize humanity again. Perhaps now the great open question concerns the English-speaking world, which includes Europe, North America and India, versus China (and all the overseas Chinese). That is a world rich and diverse enough to be able to exist without English at all. On the other hand the Chinese are publishing more and more (nanotechnology research results) in English-language periodicals.[15]

[14] See Ramsden, J.J. Computational aspects of consciousness. *Psyche: Problems, Perspectives*, 1 (2001) 93–100, for a discussion of this point.

[15] Kostoff, R.N., Koytcheff, R.G. and Lau, C.G.Y. The growth of nanotechnology literature. *Nanotechnology Perceptions*, 2 (2006) 229–247.

Nanotechnology and the environment

Without such a radical reconfiguring of our familiar urban environment as in Forster's image[7] (and which is perhaps not so radically different from the town-sized communities living in a single skyscraper in many booming Chinese cities, for example), the trio of nano-enabled developments (processors, sensors and reactors) may well largely operate in the background and lead to incremental rather than revolutionary change. Undoubtedly our environment will become safer if we sensorize it, but note some difficulties, e.g. that a choice of what to sense among the myriads of pollutants will have to be made, since even nano-sensors will consume finite (i.e. not infinitesimal) resources. Furthermore, other concomitant changes may counter the impact of environmental sensors. In particular, dramatic changes in modes of production (e.g. the introduction of sensorized nanoreactors) and communication (information processing power and communication channel bandwidth may allow videoconferencing to become so realistic, including haptic and olfactory information for example, so as to eliminate the need for many personal meetings) may render any elaborate apparatus designed to detect and counter pollution irrelevant, since the main sources of pollution, such as transport, may disappear.

A straightforward extension of sensorization of our environment is sensorization of our person, in the sense of being perpetually trackable, much in the fashion that supermarket merchandise is now routinely tagged and tracked using RFID devices. As with the universal mood-effectors discussed above, this raises the question of *quis custodiet ipsos custodies*? Even if we do not fall into the state of certain socialist countries such as Roumania or Yugoslavia, when half or more of the population was essentially engaged in surveying the other half, and the surveillance is carried out automatically, who would write and authorize the programs? One might respond that our so-called Western democracies provide sufficient safeguards, i.e. the people elect representatives, who appoint custodians to write and administer the surveillance programs and programmes. But this might be an illusion. One should bear in mind that the only real democracy in the West is Switzerland, i.e. where the people really do have the last say through a well-established system of regular popular referenda, and the government, i.e. what is called the cabinet in the UK, is subordinate to them and Parliament in turn, and has merely executive powers. Of course it always tries to step beyond its constitutional bounds, but in most other countries, the record of the government abusing its position is dismal indeed.

What could a familiar experience, e.g. going to a restaurant, be like ten years hence? The waiter, possibly a humanoid robot, has just brought a bottle of wine, selected, like the rest of the menu, before our arrival according to our various moods detected before leaving home, and combinatorially optimized to ensure that none of our guests are confronted by foods they dislike. The waiter pours out a little wine to taste, and the smart glass has instantly activated its battery of sensors, an electronic nose and tongue, to measure a dozen oeno-markers before pronouncing, in its inimitably humanoid voice, "ok". What a relief not to be oenologically challenged, when nanowine does not even require grapes for its manufacture.

Haptic sensors in our cutlery detect unusual trembling of our hands and actuators linked to them are ready to release subtly volatile tranquillizers onto our food from the reservoir in the handle should stress be diagnosed. Embedded brain enhancers are poised to suggest a new auto-generated joke whenever the conversation flags, ensuring that the backgrounds and tastes (at least those parts of them that are publicly available) of the company around the table are taken into account. Alcohol content in the blood of each diner is constantly monitored, and should it rise above the pre-set limits, alas not yet personalized, imposed by the government, channels accessing alcohol-sequestering resins in the stems of the glasses will discreetly open, rendering the beverage harmless.

Much discussion about environmental sensors centres on sensors for chemicals, but noise sensors will also be important, especially when combined with active noise reduction, again a nano-enabled or -enhanced technology. Hence a future nano-world may be a much quieter one (although if, as suggested below, the need for travel is anyway greatly reduced, perhaps the greatest present contribution to environmental sound will be largely eliminated).

Nanotechnology and government

The abundance of sensors and small powerful processors analysing their outputs implies widespread distributed computing, in effect a vast extension of the SETI (Search for Extra-Terrestrial Intelligence) project in which volunteers put their personal computers at the disposal of researchers collecting vast amounts of raw data in which patterns may be hidden. This is in stark contrast to some current trends, in which for example efforts are being made to put the entire medical, tax or police records of a nation on a single central computer, whereas formerly they would be held in different regional offices. Nevertheless, there is an apparent inability to implement such mammoth combinations (the recent failed attempt to create a central record for the UK National Health Service is a good example). Moreover the organization of significant parts of the world into large blocs (e.g. the European Union) lacking internal borders makes this measure ineffective unless it is continued to the level of combining all national records into a central bloc record, which is even less feasible on past records of success (and note that the failures appear to have human, rather than technological reasons). Hence it might be more realistic to conclude that the miniaturization of computers will lead to the domination of distributed information processing. Who will be the custodians of it? Custodianship will, in fact, become equally distributed. This neatly solves the otherwise unanswerable question *quis custodiet ipsos custodies*? In effect the state really will wither away. It is likely that, similarly to P2P file distribution, which runs in a semi-autonomous manner to optimize the transfer process, distributed computing will follow a similar route establishing *quid pro quo*s on a local basis. And if we enter an age of material superabundance (see 'Molecular manufacturing' below) problems of income redistribution (the essential purpose of taxation, one of the main features of government control) will become irrelevant anyway.

The complexity of nanosystems and how to control them

The basic elements of any nanotechnology are by definition very small, hence they must ultimately be very numerous in order to be effectual at the macro-, i.e. human scale. This means that nanosystems will inevitably be very complex—because of their size, variety and interconnexions. In fact, the latest very large scale integrated circuitry is already bumping up against the "complexity ceiling": it is scarcely possible nowadays to explicitly take every component into account in designing a processor. It was felt that Moore's "law" will not have to advance very much further to render the present approach to design, already making heavy use of semi-automated aids, unworkable. A similar argument applies to the software designed to run on such chips, which may have many hundreds of thousands of lines.

Throughout the workshop a choice emerged, of either maintaining contemporary notions of total control, and abandoning further progress in increasing the power and sophistication of hardware and software, or moving towards more distributed models of technical control, allowing for self-assembly in the spirit of computational evolution (CE).[16] For such a model all that is needed is to specify the high-level function of the device or program rather than its detailed internal workings. In a sense the human body is a working model of this design paradigm. We do not need to explicitly articulate all the details of the muscular movement involved in moving a finger, and in the case of response to microbial infection, usually even the actuation is automatic, subordinated to a very high level command such as "keep my body healthy". It is also possible that the complexity ceiling will mean that control has to be relinquished to some degree to allow functionality. This behaviour is common in complex interconnected systems where the interacting nodes can be modelled as agents, and emergent processes are allowed to develop.

Molecular manufacturing (MM)

MM, also known as desktop manufacture, nanoassembly, mechanosynthesis or fabbing, and the actual devices carrying it out as fabbers, 3D printers or personal nanofactories, would be a truly revolutionary development. It involves 'pick and place' assembly of objects, i.e. feedstock atoms or molecules (acetylene is a popular and convenient choice) are conveyed to and released at the exact position where they are required to build up any conceivable artefact. Diamond thus becomes the universal construction material. The main question relevant to the present discussion is the likelihood of its implementation within the time frame we are considering.

It was felt that the present state of the field is:

1. Detailed calculations of the assembly process, and simulations of some of the assembled devices, have been carried out;[17]

2. Primitive pick and place has been demonstrated;[18]

3. Fairly detailed analysis of the economic impact has been carried out.[19]

A sober assessment of the situation is that while plausible, there is still a big question mark associated with the feasibility of MM. Critics point to the absence of experiment,[20] while advocates point to exponential technological progress, which of course is very slow at the beginning. Because

[16] Banzhaf, W., Beslon, G., Christensen, S., Foster, J.A., Kepes, F., Lefort, V., Miller, J.F., Radman, M and Ramsden, J.J. From artificial evolution to computational evolution: a research agenda. *Nature Reviews Genetics*, 7 (2006) 729–735.

[17] e.g. Allis, D.G. and Drexler, K.E. Design and analysis of a molecular tool for carbon transfer in mechanosysnthesis. *J. Computational Theor. Nanosci.*, 2 (2005) 45–55.

[18] Schweizer E.K. and Eigler D.M. Positioning single atoms with a scanning tunnelling microscope. *Nature* (Lond.), 344 (1990) 524–526; Oyabu, N., Custance, O., Yi, I., Sugawara, Y. and Morita, S. Mechanical vertical manipulation of selected single atoms by soft nanoindentation using near-contact atomic force microscopy. *Phys. Rev. Lett.*, 90 (2003) 176102.

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

[20] Scott, F.S. et al. Nanotechnology: radical new science or plus ça change? *Nanotechnology Perceptions*, 1 (2005) 119–146.

MM would appear to imply a superabundance of every conceivable material artefact,[19, 21] its advent must necessarily overturn the present economic order, which is at root based on scarcity. Hence MM probably deserves to be considered the most revolutionary aspect of nanotechnology. Because of the uncertainty over its ultimate feasibility, serious scenario planning needs to consider both ‘MM’ and ‘no MM’ scenarios. Our discussions, on which this article is based, did not venture very far into that territory however, except for the issue of choice, see below, hence we have to leave that topic for another occasion.

Choice

The material superabundance ushered in by MM implies a superabundance of choice of material artefacts.[19, 21] This might be as trivial as lipstick available in the 16 million colours with which an image can be printed on a modern laser printer, and includes personalized drugs that, in order to offer comprehensive medical care, might have to have as much variety as that of the proteins in our bodies, i.e. of the order of 10^5.

On the other hand, it might equally well mean being surrounded by far fewer material objects. Those that remain would be multifunctional and reconfigurable, able to respond to the need of the moment, rather like (only far more sophisticated than) currently available combined fax-printer-copiers. This would be very important for solving the global waste disposal problem. Note that universal molecular manufacturing is not a prerequisite for such a development; it should anyway be enabled by better understanding and control of matter and its assembly.

Choice also arises through the general enhancement of human capabilities, both at the individual level—bionic enhancement of muscular function apart, this includes superior thinking powers with the aid of “digital assistants” interfacing with our brains—and at the collective level: the totality of human experience and expertise will become available to us through the internet (here we are barely extrapolating from the present situation), and thus anyone will be able to make a film, for example. This will be neatly commensurate with the personalization of everything, not only drugs, but also entertainment: millions will be making films, and each one will typically only be seen by a few dozen people. Indeed, with material production largely taken care of, the main human activity will be the exchange of ideas (cf. footnote 7). It remains to be discovered how important involvement with practical tasks is for inspiring new ideas.

Conclusions

Interesting and lively discussion suggested that within the next 10–20 years, nanoprocessors will vastly improve computing power, nanosensors will monitor us and our environment both internally and externally, and nanoreactors will enable high-value drugs to be custom-made for targeting individual ailments.

Corollaries are likely to be a shift towards distributed computing, a less individual and more impersonal and collective world outlook, and a shift towards an individual rather than a statistical approach to medicine, nutrition etc. These in turn might to lead to a diminished importance of central nation-states, and a significantly lower world population.

[21] Burgess, S. The (needed) new economics of abundance. *Nanotechnology Perceptions*, 2 (2006) 107–109.

A major imponderable is whether molecular manufacturing (MM) will become a reality, with personal nanofactories becoming ubiquitous. However, none of the above conclusions relies on MM, although they might be facilitated by it.

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