The nanotechnology industry

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Abstract

This article summarizes what the nanotechnology industry is and how it differs from other, chiefly manufacturing, industries. The emphasis is on brevity; the final section contains further reading for those wishing to go beyond the sources of information referenced in the main text.

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The nanotechnology industry is the (predominantly manufacturing) industry based on nanotechnology. Hence, in order to understand the nanotechnology industry, or nano industry for short, we must first of all understand what nanotechnology is (§1).

1. What is nanotechnology? I.

Technology is the systematic (i.e., scientific) study of the practical or industrial arts and, since around the mid-19th-century, the word has been used for a the "practical arts" collectively. Nanotechnology encompasses all those practical arts that *strive to control matter at the nanoscale*. In order to understand this, we must understand the nanoscale.

2. What is the nanoscale?

The nanoscale is named after the nanometre (nm), equal to 10^{-9} m or one millionth of a millimetre. In the Système Internationale the prefix "nano" denotes 10^{-9} (cf. "micro" denoting 10^{-6}, one millionth, and "milli" denoting 10^{-3}, one thousandth). The nanoscale is currently consensually taken to cover the range 1–100 nm [16]. Because consensus definitions of *nanotechnology* such as those of the International Standards Organization and the US National Nanotechnology Initiative (NNI) emphasize that the interest of nanotechnology is that size range "where the onset of size-dependent phenomena usually enables novel applications" (ISO) or with "materials and systems whose structures and components exhibit novel ... properties ... due to their nanoscale size" (NNI), it is more logical to make the range of the nanoscale dependent on properties and context [30]. As the characteristic size of materials and systems is reduced from the microscopic scale, some of them begin to exhibit novel properties at sizes well above 100 nm, whereas with others the onset might be at only a few nanometres. The disadvantage of this approach is that one needs to be fairly well acquainted with the physics and chemistry of the material or system under consideration in order to decide whether it is truly "nano", rather than simply determining its size. For now, the simpler approach (the range 1–100 nm for the characteristic size) prevails.

3. What is nanotechnology? II.

Having defined the nanoscale, we can return to the definition of nanotechnology. Let us start by looking at three published definitions: "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" [1]; "the understanding and control of matter and processes at the nanoscale, typically, but not exclusively, below 100 nm in one or more dimensions where the onset of size-dependent phenomena usually enables novel applications" [16]; and "the essence of nanotechnology is the ability to work at the molecular level, atom-by-atom, to create large structures with fundamentally new molecular organization" [24]. Essentially all three are the same, and can be expressed more succinctly as "atomically precise engineering", "atomically precise manufacturing" or, even more generally, "atomically precise technologies"; these phrases are useful as a mnemonic—for completeness, however, they would have to specify what is meant by "atomically precise". According to this definition it follows that nanotechnology has two main aspects: precisely structured objects, comprising materials and devices (the latter could be defined as information-processing materials); and a precise method of fabricating artefacts. It is a moot point whether objects manufactured conventionally and working conventionally (i.e., according to the same mechanisms as at the micro or macro scales), but which happen to have characteristic lengths less than 100 nm, belong to nanotechnology; on the basis of their degree of miniaturization enabling novel uses of the objects, it seems reasonable to assign them to nanotechnology. This is exactly the situation in which very large-scale integrated circuits for microprocessors now find themselves, one very prominent miniaturization-dependent use of them being practical mobile telephony.

4. The origins of the nanotechnology industry

4.1 Ultraprecision engineering

Figure 1 shows two classic views of the seemingly ineluctable drive to achieve greater manufacturing precision. On the left is Norio Taniguchi's sketch of the development of ultraprecision engineering. One could argue that any kind of engineering requires a certain degree of precision, otherwise it won't work. The most advanced and sophisticated artefacts always demanded a degree of precision beyond the norm, hence "ultraprecision". Taniguchi's first point was that, in absolute terms, the dimensional uncertainty that could be achieved has been shrinking. Secondly, progress has been exponential (in common with, apparently, all technological advances). Thirdly, once dimensional uncertainty approaches the size of atoms, that is, of the order of the nanometre, it will reach a limit. Taniguchi proposed calling this limit of ultraprecision engineering "nanotechnology"; he is the inventor of the term [34]. The exponential progress of miniaturization is very well captured by the data on the right of the figure, which illustrates the specific case of the semiconductor processing industry, and is called "Moore's Law" [23].

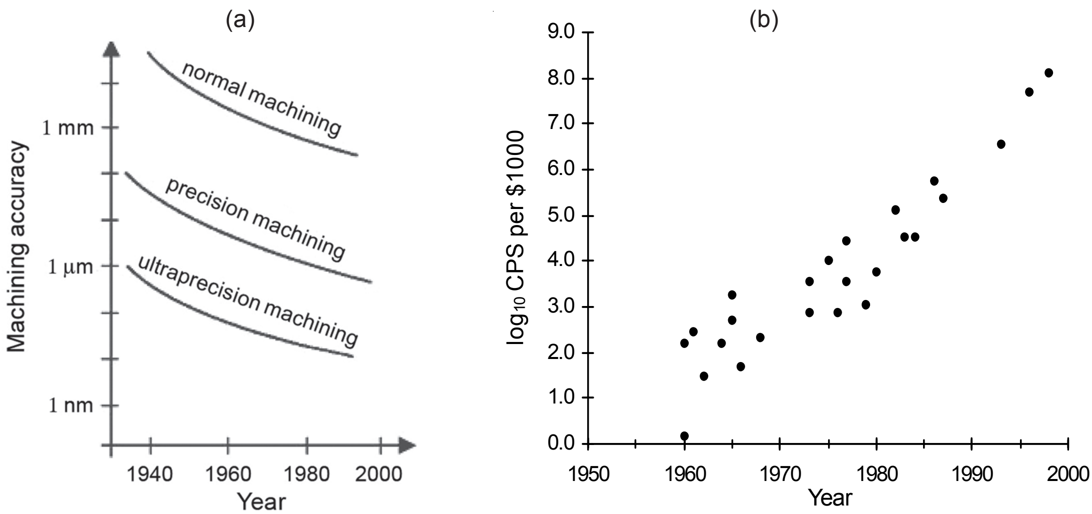

Figure 1. (a) On the left, the evolution of machining accuracy (after N. Taniguchi). (b) On the right, the evolution of the number of calculations per second (CPS) obtainable per $1000 of digital computer, starting with the IBM 1620 and ending with the Pentium II PC [20]. Note that the vertical scale is logarithmic in both cases. In its original form [23], Moore's Law asserted that the number of components per chip doubles each year.

The type of nanotechnology achievable through ultraprecision engineering is called "top–down". It is associated with great cost, whether through ultraprecision machine tools [22] or through the fabrication plants for integrated circuits (Intel's 2008 China facility is reputed to have cost $2.5 billion; just the mask for a chip made using 45 nm process technology costs about $1 million). Note that the products of this kind of engineering are often large; a complete processor chip is millimetre-sized, and the ultraprecisely finished surface of a space telescope mirror may be many square metres in extent.

4.2 Ultrafine powders

In contrast to ultraprecision engineering, which only very recently has been able to achieve precision approaching the nanometre, the technology of crushing, grinding and milling to produce small particles has been developed over millennia. The need for comminution and dispersion of coarse raw material is clear over a great range of technologies, ranging from bread making to the preparation of paint. For many of them, the optimum particle size is in the micrometre range, although the traditionally poor achievable control over the process usually resulted in a tail of finer particles down to the nanoscale. The traditional process is also very harsh: the material being milled may be significantly altered by the introduction of defects in the atomic arrangement and impurity atoms. In a few fortunate cases the alterations may enhance the properties of the final material; in most cases they prevent optimum performance from being achieved. The goal of development in this area is to achieve much better control of particle size and size distribution under much gentler conditions.

The other main approach to creating nanoscale powders is "bottom–up", starting from atoms, nucleating tiny clusters and growing them up. This can be done both in the gas phase to produce an aerosol or smoke or in the liquid phase to produce a suspension. Various ways of doing this were discovered in antiquity, such as lead sulfide nanoparticles used to colour hair black [37] and gold nanoparticles used both to colour glass red, for which the first ever patent in the modern sense was granted, in 1449 to John Utynam in England, and medicinally as potable gold by Paracelsus in the early sixteenth century [39]. The technology of fabricating nanoscale crystals was developed on a large scale by the photographic industry, starting in the early 19th century with Daguerre and others, in which photosensitive silver halide nanocrystals were prepared, with ever-increasing control, typically by the reaction in liquid between a soluble silver salt and a soluble halide salt (Daguerre actually exposed a silver plate to iodine vapour). In the middle of the 19th century there was widespread scientific interest in the properties of such nanomaterials (the paper [13] by Thomas Graham describes the preparation of many different ones) but little technology resulted (other than photographic emulsions); at the beginning of the 20th century the chemist Ostwald made an impassioned plea to pay more attention to the relatively neglected world of ultrasmall dimensions [25].

4.3 Bottom-to-bottom assembly

As biology gradually became more quantitative, it was apparent that prodigious mechanical feats were being performed by very small creatures such as ants. This seems to have inspired the physicist Richard Feynman to propose using (existing) machines to fabricate the parts for functionally identical but smaller machines, which would in turn be used to fabricate parts for even smaller ones, and so on down to the limit of atomic dimensions [8]. A concomitant advantage of controlling fabrication at the atomic scale (i.e., the nanoscale) is that unprecedented precision in the finished product is achievable as a matter of course. Feynman also perceived that many tasks, in particular the storage of information, had no intrinsic need of large size; in binary logic, the presence or absence of a single atom suffices.

This idea was subsequently developed by Eric Drexler in far more detail into an entire industrial system [6]. The key concept is the *eutactic* environment, with every atom in its place. In this scenario, ultrarigid nanoscale assemblers would fabricate the components of every conceivable artefact required by humans. Because of the vast discrepancy between the macroscopic size required by humans and the assemblers, vast numbers would be required and, hence, their first task would be to replicate themselves (whence concerns over "grey goo"). Drexler also developed the biological analogies in more detail [5]; by which time a great deal had been discovered about the submicroscopic world of molecular motors (such as muscles and the ubiquitous enzyme ATPase), offering a living proof-of-principle that machinery in the nanoscale was feasible.

Despite the attractions of the most universal manufacturing system conceivable and the extensive numerical simulations of assemblers demonstrating their capabilities, progress towards mechanosynthesis (a synonym for bottom-to-bottom assembly) has been slow and, indeed, its feasibility is hotly contested [33]. Today it is a somewhat marginal area of activity.

4.4 Self-assembly

Programmable self-assembly ("programmable" to distinguish the process from the trivial examples of crystallization and the formation of other infinite regular structures) has been mooted as a kind of compromise ("bottom–up") between "top–down" and "bottom-to-bottom", but originating independently within the cybernetic community in the 1960s [10] and independently from that found in key biological processes (e.g., [19]). The goal is to create fairly elaborate miniature objects (sometimes called nanoblocks) in such a way that, starting from a random configuration, they spontaneously join themselves together in a unique, finite arrangement, which could, in principle, be as elaborate as a logic circuit, although nothing as sophisticated as that has yet been accomplished [27].

5. Economic drivers for nanification

Although technologies sometimes emerge merely because they can be done, the sustained development exemplified by Moore's Law (Figure 1(b)) bespeaks of a technology yielding marked economic benefits, which generate the resources to further develop it. A similar process can be seen in the development, in an earlier era, of the steam engine (which, incidentally, was also crucially dependent on precision engineering to enable a piston to fit sufficiently tightly inside a cylinder). Although users of Moore's Law often focus on the relentless miniaturization of the smallest feature size of the electronic components on a chip, the Law was expressed by Moore in terms of the *number* of components on a chip [23]. One begets the other; thus "vastification is a corollary of nanification" [29]. A key feature of semiconductor processing technology is that all the components are created simultaneously on a chip in a multistep process and the cost of each processing step is essentially independent of the number of components; the cost per component therefore decreases inversely to the number per chip. Furthermore, by being smaller each component uses less material. Not only are chips with a given performance made cheaper, but also more advanced performance (including helping to design new chips) requiring more components can be achieved without increasing the cost.

In the case of information processing chips, nanification also makes them better—faster because the electrons that carry the information have shorter distances to travel. In other cases, too, machining precision is directly related to performance. Astronomical telescopes provide a good example: a large terrestrial telescope with mirrors finished to nanoscale precision can have significantly better resolving power than a space telescope, yet is much cheaper.

Nanification of information processing and storage devices is especially attractive because of the lack of any intrinsic lower limit of their extension (in the sense of size of their physical embodiment). One other area of industrial activity in which nanification offers untrammelled advantage is for any physical process that depends on a surface: if α is the degree of division of some characteristic length of material (e.g., mean particle diameter) then the proportion of atoms on the surface to the total number of atoms in the material increases directly with α, down to the tiniest nano-objects such as graphene, which have no bulk (interior) atoms at all. All the solid-phase catalysts used in the chemical industry act through heterogeneous reactions on their surfaces; the bulk is merely wasted and can be largely eliminated through nanification.

Generalizing the notion of surfaces to that of interfaces, most composite materials depend on enhancing the properties (e.g., mechanical strength) of a matrix material by admixing a second material, and the greater the degree of division of the second material, the greater the matrix–additive interfacial area.[1] When considering mechanical reinforcement of the matrix by admixing strong fibres, a further advantage of diminishing the fibre diameter is that the probability of any individual fibre having a structural defect diminishes, hence ultrathin fibres are extremely strong [12].

In all the above examples, nanification will only offer an economic advantage if the extra cost of achieving it is more than offset by the enhanced performance. Let us again consider the vision of atom-by-atom fabrication, the ultimate in precision assembly. With our present technologies we are able to make structures in the nanoscale with uniquely defined structural specifications, but at great cost. For example, a sophisticated pharmaceutical drug might require two dozen successive chemical reactions; in chemistry we do not have a eutactic environment; reagents approach each other diffusively in random orientations and many encounters between them are unproductive. It is, therefore, not surprising that some of these drugs are the most expensive man-made materials on Earth. Similarly with catalysts: maybe only a few percent of the grains in a catalyst powder have, fortuitously, the atoms crucial to the catalytic effect in the right mutual arrangement because they, too, are made by chemical means. Mechanosynthesis

[1] This notion can be further generalized to cover almost every industrial product. For example, the finer the lamellae of a platelet-shaped nano-additive added to packaging materials to prevent gases diffusing through it, the more effective the prevention per unit mass of additive; the smaller the particles of a highly thermally conductive substance added to enhance the heat transfer coefficient of a fluid, the higher the enhancement per unit added mass; and so forth.

by assemblers could achieve the desired drug molecules or catalytic particles with 100% yield from the starting materials, but we do not yet have that technology (and it is difficult to predict when we will have it). Instead, through better understanding of the processes leading to the end product, one can very significantly (by orders of magnitude in some cases) improve yields.[2]

Finally, we must not overlook one of the defining characteristics of nanotechnology, namely that it creates materials (and devices) with novel properties (§3). Even without the ability of precisely placing individual atoms at will to create a novel material, the ingenious adaptation of existing fabrication processes is creating novel materials with novel properties (the most iconic examples are probably the three "nano" forms of carbon— fullerenes, carbon nanotubes and graphene). Novelty is always difficult to quantify economically because there is no prior market for it but, even at the present stage of mastery of nanotechnology, novel materials whose unavailability prevents the economically viable realization of some other existing technology could be made and immediately find a market as part of that other technology. An example is the ability to make rather monodisperse fluorescent semiconductor particles with a radius smaller than the Bohr radius of the semiconductor charge carriers. Such particles have a band gap and, hence, an emission wavelength that depends on the particle radius, which can be easily controlled. The Bohr radius of most semiconductors is typically in the range of a few nanometres [30], hence instead of the laborious organic synthesis necessary to create a series of conventional dyestuffs emitting over a range of wavelengths, inorganic particle-based dyestuffs can be created at will.

Much discussion of nanotechnology focuses on the potential structural enhancements achievable through nanification. Apart from the collateral increase in processing speed when nanifying integrated circuits, many other applications of nanotechnology are attractive because of kinetic, rather than structural, effects. A familiar example is mayonnaise which, as a finely dispersed emulsion of oil in water can be considered to be a nanomaterial: apart from the influence of nanostructure on taste, the finer the dispersion the more stable it will be with respect to reversion (separation) back into the two phases from which it began. Numerous other examples will come to mind in which the rate of sedimentation of a substance in air or water can be greatly slowed down by nanification. Thinking back to surfaces, the combustion of solid fuel takes place at the surface of the fuel particles and, hence, the greater the ratio of surface to volume the faster the fuel will burn, whether in a power station or in a rocket. If, for whatever

[2] *Metrology* provides an exceedingly valuable input to achieving this understanding, and a very significant enabler of nanotechnology and the nano industry has been the development of metrology tools capable of measuring with atomic resolution. Some of these tools, such as the atomic force microscope (AFM) and related tip-based probes, have become iconic and are almost synonymous with nanotechnology (especially since they are the main experimental tools for exploring mechanosynthesis). Probably, however, high-resolution electron microscopy, which has a much longer history than AFM [15] is even more important for nanotechnology. As a result of the increasing demand for nanometrology, a flourishing niche industry of nano-instrument makers has grown up. As an example of its importance, it has recently been revealed that the blades of Damascus swords made hundreds of years ago and known to have extraordinarily advanced metallurgical features contain carbon nanotubes [31]. Their makers would have had no way of knowing this themselves, but the modern availability of the means for detecting these and many other nanoscale features should enable more precise feedback from performance in service back to manufacturing process and hence more rapid development of novel materials.

reason, the interval available for combustion is limited, the degree of completion of combustion will also be higher, the faster the burn rate.

Other situations involve both structure and kinetics. A paradigmatical example could be the beneficiation of ore in order to separate it into mineral and gangue. If it can be crushed sufficiently finely such that each particle is either exclusively mineral or exclusively gangue, it is very easy to separate them using froth flotation with a quick single pass through the process rather than the lengthy iteration needed with coarse grains.

6. Opportunities in nanotechnology

The "big three" areas where nanotechnology is expected to make an impact are often stated to be energy, health and information technologies (IT). This, however, ignores the vast but heterogeneous array of applications in aerospace, architecture, catalysis, food, lubricants, mineral (including oil and gas) extraction, paper, textiles etc., all of which involve *materials*. Moreover, the energy applications all involve materials. As for IT, this is a rather closed opportunity in the sense that the industry is dominated by the small number of very large, established manufacturers whose future is already well mapped out in their *International Technology Roadmap for Semiconductors* (ITRS). Therefore, in this section we shall focus on materials and health only.

6.1 Nanomaterials

6.1.1 *Definitions*

Let us first briefly recapitulate the agreed (according to the International Standards Organization) terminology [17]: a nanomaterial is a material with any external dimension in the nanoscale or having internal or surface structure in the nanoscale. There are two kinds of nanomaterials: nano-objects, which are materials with one, two or three external dimensions in the nanoscale; and nanostructured materials, which are materials having internal or surface structure in the nanoscale. Nano-objects are in turn divided into three categories according to the number of dimensions in the nanoscale: nanoplates, which have one external dimension in the nanoscale and two non-nano dimensions (a nanoplatelet, not defined by ISO, is a nanoplate having small non-nano dimensions, typically in the microscale); nanofibres, which have two similar external dimensions in the nanoscale (nanofibres are in turn subdivided into nanorods, which are mechanically rigid; nanotubes, which are hollow; and nanowires, which conduct electricity); and nanoparticles, which have all three external dimensions in the nanoscale. A highly elongated nanoparticle might be better described as a nanofibre.

The European Union, doubtless with an eye on consumer legislation rather than specifications to assist industry, has promulgated a someone different definition of "nanomaterial"—"a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm." In turn, "particle" is defined as "a minute piece of matter with defined physical boundaries" [7].

6.1.2 *The long-term, radical vision*

Certain projects, of which the most prominent, because of its undoubted economic utility, is the space elevator, can only be realized using ultrastrong nanomaterials. The space elevator would be a colossal, but apparently feasible, engineering project [26]. The main technical barrier to constructing it is the difficulty of procuring the necessary materials—the supply chain simply does not exist at anything like the scale that would be required.

Another vision, which has been analysed in some detail, is the transformation of the world economy on the basis of almost everything, even food, being produced by mechanosynthesis (assemblers) organized into "productive nanosystems" [11]. Given the very rudimentary state of this technology at present, its realization, even from a purely technical viewpoint, does not seem possible until after several more decades, although once it does exist it is likely to advance extremely rapidly.

A somewhat different kind of project concerns the replacement of pyrometallurgy by artificial kidneys capable of concentrating valuable elements from seawater. Given that eventually conventional minerals will be exhausted, there is certainly a long-term economic necessity for developing replacement sources. The connexion with nanotechnology is that only the kind of low-cost precision engineering that it is in principle able to achieve would appear to provide a chance to mimic the amazingly sophisticated, intricate mechanism of the biological kidney [35]. Very little, if any, progress appears to be being made on this at present.

6.1.3 *Nano-object–matrix composites*

This constitutes a vast and diverse collection of applications. A landmark was the demonstration of significant enhancement of mechanical and other properties of a nylon-6 matrix by incorporating a nanoscale additive into it by Usuki et al. at the Toyota Central Research and Development Laboratories [36]. Nevertheless, despite the importance of this finding and the exemplary way in which the research was carried out, it does not seem (yet) to have had the worldwide impact that one might have expected (in the sense that the apparently favourable cost/benefit ratio suggests that almost every use of polymers should incorporate nano-objects). Possibly other, smaller interested companies and academic laboratories lacked the resources to investigate the phenomenon as thoroughly as Toyota but, without such thoroughness leading to deeper understanding of the mechanism of enhancement, every attempt to apply the principle to a new system would need its own extensive series of empirical testing of what are, in fact, rather complicated systems comprising not only the matrix and the nano-additive but also, typically, a third material added to ensure good interfacial interaction between matrix and additive as well as perfecting the process for incorporating the nanoadditive into the matrix. These so-called "nanocomposites" are not precisely engineered in the sense that, although the nano-additive may be a true nano-object, it is dispersed in a largely random, statistical way in the matrix, whereas true nanotechnology requires each nano-object to be in a precisely determined position in a precisely determined orientation (unless it is perfectly symmetrical). Therefore, the details of the incorporation process may strongly influence the properties of the final composite.[3]

[3] In order to minimize variability arising through inadvertent variations in the mixing details, it is attractive to incorporate with all due attention to detail the nanoadditives into the matrix at a higher concentration than in the final product to form a masterbatch, which can then be subsequently blended into more matrix material with a much lower risk of introducing variability into the final material.

The recently reported work by Hao et al. on a significantly novel metal nanocomposite, to which 23 scientists contributed, is illustrative of the effort involved [14].

The current global market size of polymer-based nanocomposites is estimated to be around 150,000 t per annum, valued at around $1 billion. This compares with the global polymer market size of around 200 million t per annum. Some form of clay is used in about 50% of the composites and carbon nanotubes in about 20%. The persistently tiny size of the polymer nanocomposites market is partly due to the R&D problems mentioned in the preceding paragraph, and partly due to the fragmented supplier base, which makes it very difficult to ensure the reliable supply of crucial nanomaterial additives. It is to be hoped that the introduction of an exchange system for trading nanomaterials made to common specifications will largely alleviate this problem [21].

The gap between the total polymer and the polymer-based nanocomposites markets represents a striking opportunity: there is certainly enormous scope for developing the market. Nanifying the additive typically enables achievement of the desired property improvement with a significantly lower mass or volume loading, which in turn facilitates the addition of multiple materials enabling multiple property improvements, a direction that has been scarcely exploited hitherto. And, as the cost of “smart” (with sensing and actuating, i.e. information processing, capabilities) nano-objects decreases, we can also expect to find them being incorporated into polymers, resulting in even more exciting properties.

Nano-inks, for which the classic prototype is Indian or Chinese ink, consisting of a suspension of fine particles (usually carbon) in a dilute, usually aqueous, solution of a film-forming polymer, also rank as nanocomposites. The pigment size has to be reduced to the nanoscale for ease of flow through the nozzles of computer-driven printing devices. Since true nano-objects scatter very little light, they are encouraged to agglomerate as the ink dries in order to enhance their visibility. With the growth of printing-on-demand, the market for such inks is rapidly increasing.

6.1.4 *Ultrathin films*

Although, strictly speaking, thin films incorporating nano-objects and used to coat bulk objects are actually nanocomposites and could have been discussed in §6.1.3, they tend to have a rather different market which is, incidentally, of comparable size (around $1 billion per annum). The two converge on food packaging, which are often laminates of different materials: it may be more economical (for the same performance) to coat a thick film that mechanically encloses the contents with a special thin film having ultralow gas permeability (for example).

Paint constitutes a very large and important class of additive-containing films, albeit not generally ultrathin ones. The optimum pigment particle size (at which the greatest amount of light scattering occurs) is, however, larger than the nanoscale. Nanoparticles may nevertheless be added to enhance attributes other than colour and opacity, such as abrasion resistance.

Many ultrathin films, such as photocatalytic coatings for keeping surfaces sterile, consist of just the nano-objects, which bond directly to the substrate; that is, there is no film-forming matrix and, hence, these films are not composites.

6.1.5 *Additive manufacturing*

Originally conceived as a quicker and lower-cost way of prototyping artefacts compared with making them in the workshop, additive manufacturing, also known as three-dimensional (3D) printing, is now entering the mainstream because of its rapidly falling cost base (cf. printing books on demand). It is especially attractive for *mass customization* of artefacts. Although the powders from which objects are currently built up are in the microscale, the concept is identical to assembler-based bottom-to-bottom nanofacture (§4.3). In fact, assembling objects somewhat larger than atoms, called nanoblocks, would be a somewhat easier engineering challenge [4] and may be achieved by the same path of incremental improvements that led from ultraprecision engineering to nanotechnology being applied to 3D printing (cf. Figure 1). This would create a completely new market for nanoblocks.

An ingenious and highly effective system of additive manufacturing in the nanoscale was developed over 20 years ago in order to create "gene chips" [9]. These are very large arrays of DNAs; for example the Affymetrix "genome-wide human SNP array 6.0" contains about one million single nucleotide polymorphisms (SNPs).

6.2 Health

Applications of nanotechnology to health problems are usually labelled "nanomedicine", which is a branch of nanobiotechnology, in contradistinction to bionanotechnology, which is the exploitation of biological objects in nanotechnology [18]. These applications can be classified as either direct or indirect. Direct applications involve nano-objects—usually nanoparticles—to assist diagnosis and therapy.

The purpose of the nanification is above all to facilitate penetration of the nano-objects throughout the body, firstly via the bloodstream, including the smallest capillaries, and, in some cases, into individual cells, possibly through channels traversing the outer cell membrane and designed for the passage of large molecules.

The diagnostic agents are essentially materials to enhance the contrast of clinically relevant features where they are designed to be concentrated (cf. the barium sulfate slurry taken orally to render the gastrointestinal tract visible in an X-ray photograph). They are usually surface-modified to confer on them a specific affinity for the target cells or tissue, for example by coating them with an antibody specific for a molecule that is expressed only on the surface of a target cell.

The simplest kind of therapeutic particle is simply made of a ferromagnetic material (i.e., with a very high magnetic susceptibility) but small enough to be superparamagnetic (i.e., having no remanence), which means in the nanoscale. Once gathered at the site of action, an oscillating external electromagnetic field is applied to cause it to heat up and kill the offending cells by hyperthermia. More sophisticated particles carry a reservoir of drugs that are released when the particle reaches its site of action. A simple example is a hollow particle made from calcium carbonate filled with a drug to combat some stomach ailment. Given orally it will pass unchanged through the mouth but the chalk shell will dissolve in the highly acidic environment of the stomach, releasing its contents. More sophisticated particles are surface-modified like the diagnostic ones, to give them a specific affinity for target cells or tissue. Once they reach it, the binding of the receptor on the particle to a ligand characteristic of the target must trigger release of the therapeutic drug, which poses quite a nano-engineering challenge.

Preventing opsonization. The major challenge faced by nano-objects intended to be introduced into the living body of a human being (or into animals of veterinarary interest), whether for diagnosis or therapy, is to prevent them from being identified and destroyed or otherwise eliminated from the body by its highly sophisticated defence mechanisms, above all the immune system [2]. Although some progress has been made with this and, indeed, some nanomedicines are currently undergoing clinical trials [3], the difficulties are considerable. If opsonization can be successfully prevented, the problem of how to eliminate the nano-objects after they have done their work arises. At present, the outlook does not look too promising for nanomedicine, despite its enormously attractive potential for eliminating the systemic action that so bedevils conventional pharmacotherapeutic medicine. The generally fragmented and limited knowledge about the risks of introducing nanomaterials into human beings imposes restraint in contemplating clinical trials of nanomedicines [32].

Indirect applications are less controversial. For example, powerful nano-enabled microprocessors may enable the exploitation of sophisticated pattern-recognition algorithms for diagnosing diseases from a plethora of symptoms. More specific to nanomedicine is the possibility opened up by sufficiently powerful computers to direct the machining of a customized prosthesis using tomography data acquired while the patient is already on the operating table. A noncomputational application is the possibility of using microreactors, possibly enhanced with some nano features, to economically synthesize customized variants of otherwise conventional drugs. Finally, nanotechnology will doubtless provide more biocompatible materials for implants, precision-engineered with guidance from our ever-deepening knowledge of the molecular nature of the biological environment, and for the increasingly miniaturized forms of surgery that are proving to be so effective, including swallowable, quasi-autonomous devices that can, at least in the gastrointestinal tract, carry out some surgical functions.

7. Environmental aspects of nanotechnology

In their 2003 report *The Social and Economic Challenges of Nanotechnology*, Wood et al. asserted that through nanotechnology “the environment will have been repaired to a pristine state” [38], without, however, indicating how that repair would take place. Perhaps they were imagining, along the lines of Freitas [11], that nanotechnology would make everything so abundant anything, including cleaning up the countryside, would be feasible. Putting these vague assertions to one side, however, it is obvious that responsible nanotechnology is beneficial to the environment. The primary principle is that if less material is used to accomplish a given task, hence less energy is needed to process it and less energy to transport it. The same applies to lightweighting automotive components: less fuel is needed to power the vehicle, hence fewer fuel deliveries and so forth. This kind of effect should apply wherever nanomaterials substitute conventional materials. It is, of course, preferable that the energy and other resource consumption of the nanomanufacturing (nanofacturing) process is lower than that of the classical manufacturing process it replaces.

Many other nanoproducts contribute to reducing energy consumption, such as catalytic nanoparticles added to diesel fuel to enhance combustion and nanoparticles added to base oil to reduce friction. Other nano-enabled technologies, such as printing books on demand, reduce resource consumption generally (no more piles of unwanted books to be disposed of!). It would be hard to conceive of a nanoproduct (defined as a product whose essential attributes are in some way enhanced by nanotechnology) that did not reduce the overall burden on the environment.

Ultimately, the question of preserving the environment is one of sustainability [28]. Since the essence of applying nanotechnology is to do more with less, by exploiting the possibilities of precision to its ultimate capabilities, the promotion of nanotechnology should generally contribute to achieving sustainability (always with, of course, due regard to the entire life cycle of any product under consideration).

8. How the nano-industry differs from other industries

This section focuses on just the nanomaterials part of the industry (i.e., leaving IT and nanometrology aside). Unlike other industries supplying materials, which generally strive to supply standardized products with highly uniform and repeatable attributes, together with the possibility of customizing them should demand be sufficient, the nanomaterials industry, in so far as it exists, seems to prefer to make everything on demand. While this is superficially impressive and attractive, the proud assertion that "we can make any kind of nanoparticle you want" is unlikely to be helpful to the buyer seeking to substitute a nanomaterial for conventional materials in an existing product. Such a buyer would already like to know precisely which nanomaterial will provide a satisfactory substitution. Given the immense amount of publicly funded research that has been done in nanotechnology during the last decade or so, with a correspondingly immense output of published papers in the scientific literature, one might suppose that the information needed to be able to precisely specify the required nanomaterial is already available. Unfortunately the information is highly fragmented and there has been a notable lack of effort to systematize it in such way as to make it of practical use to the prospective buyer. One valid reason for this lack of effort is the rapidly advancing nature of the field. There is no point in systematically analysing data that will soon be superseded. Nevertheless, in some areas understanding would appear to be more or less complete and such a systematic analysis will be worthwhile.

Another possibly valid reason is that nanomaterials are usually far from simple. When one purchases a chemical, the molecule is typically well defined and the only issues are impurities and (if it is crystalline) polymorphism, which can usually themselves be well defined in turn. On the other hand, suppose we have a nanomaterial of chemical formula MX—for the sake of this illustration let us suppose that it is in the form of nanoparticles with a nominal diameter of 10 nm. Current manufacturing technologies would typically produce a distribution of sizes and, possibly more subtle distributions of atomic arrangements. Apart from impurities, foreign molecules may be deliberately added in order to prevent agglomeration or aggregation if the particles are to be used in a liquid. Since these molecules should coat the nanoparticle surfaces they could be present in a quantity comparable to that of the molecules constituting the nanoparticles themselves. Hence even the "simple" product is far from just MX.

Furthermore, the end use is likely to be esoteric and specific to the individual buyer and it is unlikely to be feasible for the nanofacturer to be able to assure the quality of the nanoparticles by end-use testing. Even if it is found to work satisfactorily, meanwhile the plant will probably have been used for other materials and the general experience of industry so far has been that it is extraordinarily difficult to produce a later batch with identical attributes. The closest established industry to the new nanomaterials activity is the photographic industry making silver halide emulsions, and it took many decades of intensive research and engineering to achieve the extremely high standard of modern photographic film. Importantly, this industry has always been highly integrated. In one part of the factory the nanoparticles were synthesized; in another part they underwent post-synthesis treatment (sensitization); then they were coated as a thin film onto a substrate, and finally they were tested sensitometrically under conditions essentially identical to those of the end-user, enabling feedback to be swiftly delivered to every point along the manufacturing chain. Such integration cannot be found in present manufacturers of nanomaterials.

Nanomaterials are fundamentally superior to conventional materials because they are rigorously engineered with atomic precision. If the same rigour and precision could be applied to all other aspects of the industry apart from just the basic manufacturing process, immense progress would be made.

9. Summary and conclusions

Nanotechnology is atomically precise engineering; that is, engineering at the nano- or atomic scale; and the "nano industry" is the industry built on that premiss. Nanotechnology refers to both the means of production and the products. Thus, a "nano-industrial company" could be either, or both, a company using nanotechnology to produce materials or devices with nanoscale precision or a company using nanomaterials or nanodevices in other products.

The consensus definition of nanotechnology is everything between the size of an atom (of course different atoms have different sizes and for convenience the lower limit is often taken to be simply 1 nanometre) and 100 nanometres. This means that the feature sizes of the current generation of very large scale integrated circuits (microprocessor chips) are comfortably in the nanoscale and, therefore, almost the entire computing industry, with a global market value of several (US) trillion dollars and dominated by a few extremely large companies, is nominally part of the nano industry. Computer chips aside, the rest of the industry is dominated by nanomaterials.[4]

Although "pick-and-place", "atom-by-atom" assembly is the apotheosis of nanofacture (defined as manufacturing in the nanoscale), it is still far from becoming a viable industrial technology. Hence, all current nanofacture is an approximation to true atomic precision. Nevertheless, a great deal can still be done. The fundamental premiss underlying its desirability is that with such precision, directed by deep knowledge, things work much better, with materials having enhanced and, often, quite novel characteristics.

The novelty in particular attracted humans to nanotechnology even in antiquity—most of the applications concerned some form of colouring, whether of glass, hair, or of jewellery and ornamental utensils. In modern times, attention has focused on enhancing a vast range of other attributes, such as mechanical strength, abrasion resistance, electrical and thermal conductivity and, increasingly, information processing ability.[5]

In many cases the enhancement is achieved through composite materials—matrices incorporating nanoscale additives (nano-objects), and less of them than if they were not nano. Nanotechnology is very much about "doing more with less". Almost every performance

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[4] Instruments for nanometrology, albeit essential and themselves the basis of a highly successful industry, are a mere niche in comparison.

[5] A "smart" or sensorial material, possibly also having the power to actuate something, of course acquires information processing ability and, hence, becomes a device. There is, therefore, no actual discontinuity between materials and devices.

enhancement that relies on the interface between two phases becomes better if the additive becomes more finely divided—down to the nanoscale. Thus, less material is required, in turn requiring less energy to produce and be transported, and its products are also lighter and interact with less friction, requiring less energy to power them. In this way nanotechnology is beneficial to the environment and makes the manufacturing economy more sustainable. Once the Nano Revolution is complete, nothing will be larger than the size it theoretically needs to be.

A general consequence of small size is accessibility, and the size of nano-objects is commensurate with many biological structures, to which they can gain access more readily than conventional medical drugs and devices. Great effort is now being expended on developing materials for health applications but, like pharmaceuticals, these materials are generally produced in very small quantities and are extremely expensive. Actually, applications are still mostly at the research stage, although even full commercialization would not require vast quantities, hence the issue of scaling up to produce megatons does not arise.

Curiously, few if any of the producers of genuine nanomaterials (thinking now of discrete nano-objects such as nanoparticles, nanotubes or nanoplatelets) seem to have seriously attempted to establish high-volume production. Moreover, it would be impossible for a potential end-user (such as a polymer composite manufacturer) to source a large volume of nano-objects from multiple producers because all of them make a unique material. This appears to be partly due to the deliberate desire to differentiate one product from another, and partly due to the technical limitations of the currently employed nanofacturing processes. Furthermore, many producers pride themselves on making exclusively bespoke materials. Every batch is different, either intentionally or unintentionally. One of the most urgent needs, therefore, is to promulgate standard specifications for nanomaterials for use in the most attractive applications.

Nanotechnology provides a universal manufacturing paradigm. Just as (binary) digitization allows any kind of knowledge to be represented, (atom-by-atom) nanofacture allows (almost) any kind of material (or device made from material) to be constructed. And, just as the consequences of digitization are enormous, the consequences of this material "digitization" are also enormous. To take just one example, print-on-demand, the inks, the precision nozzles through which they are applied and the computer hardware driving the printers are all nanoproducts. The outputs of such printers are not merely books but also three dimensional objects and even, latterly, electronic circuits. Furthermore, they are not simply substituting for conventionally mass produced equivalents, but ushering in the new age of customization; books are only printed when required, without waste, and the same applies to all the other artefacts that it is possible to make in this way. At the same time as we have this customization, the system enabling it is a whole requires to be permeated with agreed standards—just as the benefits of digitization would be negligible without the now ubiquitous standard protocols that allow information to be smoothly exchanged between any two arbitrarily chosen devices.

Despite over a decade of lavishly state-funded research in the world's leading economies, the commercial opportunities in nanotechnology remained largely untapped. In the public eye, nanotechnology is more about marvels than about building a solid, sustainable industry and this view is undoubtedly reinforced by the news media, which assume that the more outrageous the claim, the more enticing the story, and most researchers seem to have got into the habit of pandering to this distortion of reality. The still fledgling nano industry needs to ignore all that and concentrate on the sound commercial principles that underpinned the original Industrial Revolution. The sometimes fatiguing consensus building that agreeing standard specifications requires will not make the headlines, but an industry will not be made without it.

10. Further reading

Ramsden, J.J. *Applied Nanotechnology*. Amsterdam: Elsevier (2009).
Ramsden, J.J. The impacts of nanotechnology. *Nanotechnol. Perceptions* **7** (2011) 28–66.
Ramsden, J.J. *Nanotechnology: An Introduction*. Amsterdam: Elsevier (2011).

References

1. Abad, E. et al., NanoDictionary. Basel: Collegium Basilea (2005).
2. Arshady, R. and Kono, K. (eds), *Smart Nanoparticles in Nanomedicine*. London: Kentus Books (2006).
3. Bourzac, K. Nanotechnology: Carrying drugs. *Nature* **491** (2012) S58–S60.
4. Craver, T. Safer molecular manufacturing through nanoblocks. In: N. Bostrom et al., *Nanotechnology Implications: More Essays*, pp. 155–160. Basel: Collegium Basilea (2006).
5. Drexler, K.E. Molecular engineering: an approach to the development of general capabilities for molecular manipulation. *Proc. Natl Acad. Sci. USA* **78** (1981) 5275–5278.
6. Drexler, K.E. *Nanosystems: Molecular Machinery, Manufacturing, and Computation*. Wiley-Interscience (1992).
7. Commission Recommendation of 18 October 2011 on the Definition of Nanomaterial. *Official J. Eur. Union* 20 October 2011 L 275/38–40.
8. Feynman, R.P. There's plenty of room at the bottom. In: H.D. Gilbert (ed.), *Miniaturization*, pp. 282–296. New York: Reinhold (1961).
9. Fodor, S.P.A. et al. Light-directed, spatially addressable parallel chemical synthesis. *Science* **251** (1991) 767–773.
10. von Foerster, H. On self-organizing systems and their environments. In: *Self-Organizing Systems* (eds M.C. Yorvitz and S. Cameron), pp. 31–50. Oxford: Pergamon Press (1960).
11. Freitas, R.A., Jr. Economic impact of the personal nanofactory. In: N. Bostrom et al., *Nanotechnology Implications: More Essays*, pp. 111–126. Basel: Collegium Basilea (2006).
12. Gordon, J.E. *The New Science of Strong Materials*. Harmondsworth: Penguin (1968).
13. Graham, T. On liquid diffusion applied to analysis. *J. Chem. Soc.* **15** (1862) 216–255.
14. Hao, S. et al. A transforming metal nanocomposite with large elastic strain, low modulus, and high strength. *Science* **339** (2013) 1191–1194.
15. Hawkes, P.W. From a fluorescent patch to picoscopy, one strand in the history of the electron. *Nanotechnol. Perceptions* **7** (2011) 3–20.
16. ISO/TS 80004-1:2010(en). *Nanotechnologies—Vocabulary—Part 1: Core terms*. Geneva: International Standards Organization (2010).
17. ISO/TS 80004-4:2010(en). *Nanotechnologies—Vocabulary—Part 4: Nanostructured materials*. Geneva: International Standards Organization (2010).
18. ISO/TS 80004-5:2010(en). *Nanotechnologies—Vocabulary—Part 5: Nano/bio interface*. Geneva: International Standards Organization (2010).
19. Kellenberger, E. Assembly in biological systems. In: *Polymerization in Biological Systems*, CIBA Foundation Symposium 7 (new series). Amsterdam: Elsevier (1972).
20. Kurzweil, R. http://www.singularity.com/charts/page67.html

21. McGovern, C. Commoditization of nanomaterials. *Nanotechnol. Perceptions* **6** (2010) 155–178.
22. McKeown, P.A. et al. Ultraprecision machine tools—design principles and developments. *Nanotechnol. Perceptions* **4** (2008) 5–14.
23. Moore, G.E. Cramming more components onto integrated circuits. *Electronics* **38** (19 April 1965) 114–117.
24. National Nanotechnology Initiative: *The Initiative and its Implementation Plan*, pp. 19–20. Washington, D.C.: National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology (2000).
25. Ostwald, Wo. *Die Welt der vernachlässigten Dimensionen*, 7th & 8th edns. Dresden & Leipzig: Th. Steinkopff (1922).
26. Pearson, J. The orbital tower: a spacecraft launcher using the Earth's rotational energy. *Acta Astronautica* **2** (1975) 785–799.
27. Ramsden, J.J. Concepts in self-assembly. In: *Advanced Nanomaterials* (eds K.E. Geckeler and H. Nishide), vol. 2 pp. 767–790. Weinheim: Wiley-VCH (2010).
28. Ramsden, J.J. What is sustainability? *Nanotechnol. Perceptions* **6** (2010) 179–195.
29. Ramsden, J.J. *Nanotechnology: An Introduction*. Amsterdam: Elsevier (2011).
30. Ramsden, J.J. and Freeman, J. The nanoscale. *Nanotechnol. Perceptions* **5** (2009) 3–25.
31. M. Reibold et al. Carbon nanotubes in an ancient Damascus sabre. *Nature* **444** (2006) 286.
32. Resnik, D.B. and Tinkle, S.S. Ethical issues in clinical trials involving nanomedicine. *Contemporary Clinical Trials* **28** (2007) 433–441.
33. Scott, F. et al. NanoDebate. *Nanotechnol. Perceptions* **1** (2005) 119–146.
34. Taniguchi, N. On the basic concept of nanotechnology. *Proc. Intl Conf. Prod. Engng Tokyo, Part II* (Jap. Soc. Precision Engng), pp. 18–23 (1974).
35. Thomas, S.R. Modelling and simulation of the kidney. *J. Biol. Phys. Chem.* **5** (2005) 70–83.
36. Usuki, A. et al. Interaction of nylon-6–clay surface and mechanical properties of nylon-6–clay hybrid. *J. Appl. Polym. Sci.* **55** (1995) 119–123.
37. Walter, Ph. et al. Early use of PbS nanotechnology for an ancient hair dying formula. *Nano Lett.* **6** (2006) 2215–2219.
38. Wood, S., Jones, R. and Geldart, A. *The Social and Economic Challenges of Nanotechnology*. Swindon: ESRC (2003).
39. Zsigmondy, R. and Thiessen, P.A. *Das kolloide Gold*. Leipzig: Akademische Verlagsgesellschaft (1925).