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Nanoscience and nanotechnologies: hopes and concerns

Nanosciences: Evolution or revolution?

Les nanosciences : (R)évolution des savoirs et des technologies ?

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ABSTRACT

In miniaturized objects fabricated by modern technology the smallest linear size may be of a few nanometers. In the field of microelectronics, the advantages of such a miniaturization are huge (increased complexity and reliability, reduced costs). The technology is now approaching the limits where further size reduction will be impossible, except for very novel techniques such as molecular electronics. Miniaturization research has also led to the discovery of nanometric objects such as carbon nanotubes, which turn out to be particularly appropriate for inventing new materials. Miniaturization techniques have been progressively applied in other fields, with the hope of obtaining improvements similar to those encountered in microelectronics. Examples are biochips, which concentrate on a few cm^2 the recognition of ADN sequences, or 'lab-on-a-chip' devices, each of which constitutes a whole laboratory of chemical analysis, or MEMs (Micro Electro Mechanical Systems). New therapies will use miniaturized objects with multiple functions: For instance a nanoparticle can both recognize the target organ thanks to an appropriate protein, and deliver the therapeutic molecule to this target. These results have only been possible through new observation instruments, able to observe and manipulate nano objects. Is the observed evolution really a revolution of science and techniques? This is a point discussed in the conclusion, which also deals with risks associated to nanotechnologies, while the need for a social regulation is stressed.

RÉSUMÉ

La miniaturisation a conduit à la fabrication d'objets dont les plus petites dimensions sont de quelques nanomètres. Dans le domaine de la microélectronique ceci a apporté des avantages considérables (complexité accrue, fiabilité augmentée, coûts réduits). Cette technologie parvient maintenant au voisinage de limites qui lui interdiront très bientôt de poursuivre la réduction des dimensions sauf à s'engager dans des voies très nouvelles telles que celles de l'électronique moléculaire. La recherche en miniaturisation a aussi permis d'aboutir à la découverte d'objets nanométriques tels que les nanotubes de carbone qui se révèlent être des composants de choix pour synthétiser des matériaux nouveaux. Les techniques de miniaturisation ont été progressivement appliquées à d'autres domaines avec l'espoir d'en tirer des avantages similaires à ceux rencontrés dans la microélectronique : les biopuces qui concentrent sur quelques cm^2 des opérations de reconnaissance de séquences ADN, les laboratoires sur puce qui assemblent tout un laboratoire d'analyse biochimique, les MEMS ou microsystèmes électromécaniques miniaturisés. En médecine, la thérapeutique bénéficie de la maîtrise de la synthèse d'objets

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miniaturisés rassemblant plusieurs fonctionnalités : par exemple une nanoparticule peut transporter jusqu'à un organe cible à la fois une protéine de reconnaissance de l'organe et une molécule-médicament. Tout ceci n'a été possible que grâce à la mise au point de nouveaux instruments d'observation capables d'observer et de manipuler les nanoobjets. La conclusion soulève la question suivante « l'ensemble des évolutions observées est-il véritablement signe d'une révolution des sciences et des techniques » ? Enfin une dernière partie aborde le sujet des risques associés aux nanotechnologies et souligne le besoin de régulation sociale.

1. Introduction

Any person of some culture knows that inert or living matter consists of atoms. Nevertheless, in practice, this knowledge has no effect on everyday life. An atom is so small that it is beyond our perception. In spite of the discovery of radioactivity at the end of the 19th century, although the general progress of physical, chemical and biological sciences explicitly relies on the understanding of atomic nature of matter, real life could ignore the elementary bricks we are made of. However, at the end of the 20th century, with the breakthrough of nanotechnologies, we realized that the nanometric size, close to that of atoms, is no longer beyond our perception and our range of action. Nanos are now guests of our everyday life.

Let the history of nanosciences be briefly recalled. The discovery of the transistor in 1947 has deeply transformed electronics, as it was thus demonstrated that a small piece of germanium could do as well, if not better, as a complex and fragile vacuum tube. This piece of germanium, soon substituted by silicon, later became smaller and smaller, hence the name “puce” (flea) which designates a chip in French. Once the working mechanism of transistors has been well understood, it became possible to put several transistors on a single piece of semi conducting material and to connect them to obtain a complex electronic device, a microprocessor. As early as 1971, 2300 transistors could be assembled in the same processor. In the following years, the history of electronics became mainly a history of miniaturization, the problem to solve being: how to make the same circuits on smaller and smaller silicon pieces. Miniaturization had numerous advantages, the circuit becoming faster, cheaper and more reliable.

This miniaturization was made possible by breakthroughs achieved in several technical domains, including photographic masks, more and more controlled chemical etching, strongly directed ionic etching, the use of shorter and shorter wavelength radiation for the pattern transfer, masks directly written with an electron beam... Size reduction proceeded steadily. The smallest elementary size achieved in a commercial circuit was 0.35 μm in 1995, 0.13 μm in 2001, 0.065 μm in 2007, and 0.028 μm in 2010. An advantage of reduced size was the increased number of transistors per chip. From 2300 in 1971 as already said, it doubled every two years since that time and reaches more than 2 billion in 2010.

The size reached at the end of the twentieth century is clearly in the nanometer range ($1\ \text{nm} = 10^{-9}$ meter or 0.001 micrometer). A 22 nm wide motif, which is presently available represents a silicon ribbon of only about 60 atoms. Microelectronics is thus becoming nanoelectronics. In other fields of sciences and technology a similar nano-revolution took place, either spontaneously or stimulated by the progress of electronics, computer science, fabrication techniques (masks, etching,...) and observation methods (microscopes). These different fields will now be reviewed.

2. From microelectronics to nanoelectronics [1]

The rapidly decreasing size of electronic devices had several consequences, including a considerable increase of the computing power and data processing capability, reduction of cost of devices, and an increased reliability. As a result, microelectronics became important in many fields where this was not necessarily expected, as can be seen from our everyday experience. Moreover, completely new fields have been created as by-products of these powerful and cheap electronics, for instance electronic games, high speed telecommunications, mobile telephones and Internet, to quote only the largest markets. These newcomers have been profoundly transforming social life, including communication, access to culture, social links, ... Thus, nanoelectronics triggered a revolution which is developing, and whose latest achievements are not yet known.

What are the limits for size reduction? It has been clear for a long time that there were limits. Indeed, below 10 nm, the operation of electronic devices will be appreciably modified. Matter discreteness can be no longer ignored since the atomic size is about 0.3 nm. The number of electrons acting in a nanoelectronic device is not necessarily very large. The usual statistical laws which rule diffusive transport of electrons are not always applicable since certain electrons undergo a collisionless (or ‘ballistic’) transfer between two electrodes while others are not transferred at all (in fact, single electron transistors have been devised and are already fabricated). Facing problems resulting from matter discreteness as well as those resulting from increasingly difficult fabrication with decreasing size, nanoelectronics will soon meet a limit which will be difficult to overcome. Should one conclude that within 3 or 4 years the progression of microelectronics will be frozen and that there will not be any further progress in complexity, reliability and cost reduction? Of course not! The ultimate size of devices is not the only way for improvement. Even with a fixed pattern size, the architecture of processors can be improved (for instance multicore processors). Memories (especially magnetic ones) can still be improved and internal communication within the processor can be made faster.

Moreover, while the compactness of electronic circuits has been increasing, these are still confined in a single plane, the silicon crystal surface. Using three-dimensional stacking techniques one might put more circuits in the same package. Finally, by reducing energy consumption in processors, it will be possible to increase compactness without increasing heating, and improve the autonomy of mobile electronics.

Anyway, silicon based microelectronics will certainly reach an optimum, when any new improvement will imply both major technical difficulties and an excessive fabrication cost increase. Presumably, future progress will rely on molecular electronics. The active element, namely the transistor, would then be replaced by a single molecule connected by molecular wires. This idea was put forward a long time ago; however, its concretization proceeds slowly. Organic electronic devices are already existing, namely Organic Light Emitting Diodes (OLEDs). Also, memory prototypes have also been fabricated in which the active element is a single molecule at the crossing point of two conductors. The density of memory points is then increased by several orders of magnitude. Another prospective direction is the replacement of the silicon transistor by a single molecule connected to three electrodes, which may be conventional wires or made of conducting molecular chains. The future realization of such molecular devices will be a huge step for miniaturization. There are still beautiful days ahead for powerful and inexpensive microelectronics.

3. Nanomaterials and nanochemistry [2]

While the small transistor is traditionally the remnant left after etching of a silicon crystal, another method appeared based on the relatively classical methods of chemical synthesis. Indeed, nanometric objects are naturally produced by chemistry, namely, more or less complex molecules. The trick is to orient the synthesis either toward the production of molecules suited for certain complex functions, or towards the fabrication of “objects” which consist of thousands, or more, of properly assembled molecules which are dedicated to particular functions. This technique is called ‘bottom-up’ while the traditional etching approach is called ‘top-down’.

A few examples will be given, which demonstrate that sometimes matter shows some good will for the creation of nanometric objects with remarkable properties.

Carbon nanotubes have been discovered accidentally in 1991 by the Japanese scientist Sumio Iijima as he observed with an electron microscope the soot generated by an electric arc. Carbon nanotubes are tubes made of a rolled graphene sheet. Graphene is a graphite layer of atomic thickness, in which all electrons of the external shell of the carbon atom are paired. A carbon nanotube has the periodic structure of a crystal. Its diameter is a few nanometers while its length can reach hundreds or thousands of nanometers. Nanotubes can be either conductors or insulators. They exhibit remarkable mechanical properties since they can be bent drastically without breaking and their mass is small since carbon is a light atom. They can now be synthesized at an industrial scale. They already have many applications: improvement of mechanical resistance (tennis rackets), an additive to resins to render them conducting, electron emitting cathodes, high efficiency gas absorption…

How are nanotubes synthesized? They are generated from the surface of a nanometric metal droplet in presence of carbon vapor. Metal absorbs carbon from the surrounding vapor, and the supersaturating carbon is eliminated as a ring at the surface of the drop. This process has some analogy with certain knitting techniques used to produce woolen tubes. Using similar principles, many other nanotubes or nanowires can be prepared, especially from semiconductors, e.g. silicon, ZnSe, ZnO, MgO. Semiconductor nanowires can be doped during their growth, and the doping can be modulated along the tube so that a nanowire can be grown directly with the properties of an electronic diode. These new elements are appropriate for light emission or absorption, since nanowires, due to their shape, are not subject to some limitations encountered in planar components for incident or outgoing light. High efficiency solar cells are being developed, as well as blue or UV LEDs (Light Emitting Diodes).

The remarkable properties of carbon nanotubes, made of a rolled graphene sheet, have encouraged scientists to explore the properties of graphene itself. This material can be obtained directly by exfoliation of a graphite sample, or by crystal growth on silicon carbide (SiC) as a substrate. Graphene has exceptional properties, such as a very high electronic mobility which can be modulated by a transverse electric field. Very high frequency FET (field effect transistors) prototypes have already been fabricated, as well as an element of logic circuit. The Nobel Prize in Physics was awarded in 2010 to Andre Geim and Konstantin Novoselov for their works on graphene. This material may be a good candidate for future microelectronics.

Nanoparticles. Using recent synthesis techniques, nanoparticles can be obtained from various materials, e.g. gold, silver, titanium oxide TiO_2, carbon (fullerenes) and many types of semiconductors. Of particular interest are semiconductors, such as cadmium selenide which, in the bulk state, emit infrared light when irradiated by ultraviolet light. As nanoparticles, they turn out to emit visible light, of which color depends on particle size. These new fluorescent markers are efficient and stable. They are frequently used in biology.

Nanoparticles can also receive complementary functions by grafting active molecules or specific coatings (drug, contrast agent, radiation absorber, etc.). This point will be addressed in more detail later when dealing with nanobiotechnologies.

Nanochemistry. The fabrication of the above described objects requires the contribution of various fields of chemistry which are now regarded as forming a single one, namely nanochemistry. Chemistry has always been used for synthesizing molecules of nanometric or even subnanometric dimensions, but the term ‘nanochemistry’ designates a branch of chemistry which aims at object synthesis by assembling elementary molecules. The overall size of such objects is in the nanometric range, so that they display specific properties. Among the many goals of nanochemistry, the following may be mentioned in addition to those cited above:

- Bulk materials with a nanometric structure obtained by self-organization;
- Self-assembly of several molecules using supramolecular chemistry;
- Nanostructuration by molecular printing which makes possible the synthesis of organic or inorganic materials incorporating cavities designed for specific molecular recognition.

This wide range of materials leads to a variety of applications, a few of which are mentioned hereafter:

- TiO_2 nanoparticles for solar protection (although the bulk material is white, nanoparticles become transparent to visible light but still absorb efficiently UV light);
- TiO_2 nanoparticles which catalyze destruction of organic pollutants. For instance their incorporation in concrete prevents its blackening;
- Self-cleaning glasses get dirt eliminated by rainwater. They are coated by a super-hydrophobic film. Its properties are obtained by surface nanostructuration similar to that observed on lotus leaf;
- Silver nanoparticles have a bactericide power and may be incorporated into textiles;
- Tyres can be reinforced by incorporation of silica particles to improve their mechanical properties, etc.

Thus, nanochemistry is an essential field of nanotechnologies. It creates the building bricks necessary for assembly of more complex structures. It will also play an essential part in the transfer of the discoveries of nanotechnologies to widely used products or materials where they were not necessarily expected (concrete, tyres, paints, ...).

4. Nanobiotechnologies [3]

At the end of the last century, biology too has been affected by remarkable transformations. The genetic code was identified, deciphered, and it became clear that life itself was also a matter of atoms and molecules. Of course, living matter is mainly made of macromolecules but its complexity is huge. Many contacts between biology and nanotechnology have progressively been established and this led to define the field of nanobiotechnology. The main applications which follow on from these contacts will now be described.

4.1. Biochips

A biochip is, as suggested by the terminology, something like a chip for biological use. In fact, they are not so small, but the word is commonly used.

A first class of chips is constituted by DNA-chips. The aim of these components is to simultaneously determine a large number of DNA sequences in a genome to be analyzed. Synthetic DNA probes, complementary of the researched sequences, are attached to a glass or a silicon slab. Each kind of sequence is deposited on a specific area of the chip. The slab is then brought into contact with a solution which contains the DNA to be analyzed, which has first been marked by fluorescent molecules. When there is complementarity between a sequence attached to the slab and one in the solution, the latter sticks to the slab, and can be detected by fluorescence. In addition it is identified through its location.

Biochips are obtained by miniaturization techniques derived from microelectronics. A chip can contain tens of thousands of probes, so that a whole genome can be investigated with a single experiment.

The identification of the whole DNA sequence in a cell is not identical with that of the subset which is active at a particular time in that cell. To obtain the latter information, protein-chips have been devised. Their principle is similar to that of DNA chips. A set of receivers is prepared, each one with a strong affinity for a given protein that one wishes to identify and to quantify. The difficult point is to find for each investigated protein a peptide or another molecular component with a strong affinity and specificity. The receivers are attached to the chip which is then brought into contact with the solution to be analyzed, the proteins of which have been provided with a fluorescent or radioactive marker or whatever.

Another variation of biochips is the cell-chip. In that case living cells are fixed on the chip. Each cell can be stimulated by an electrode or subjected to a specific treatment, e.g. the introduction of a foreign gene (transfection). It is thus possible to simultaneously analyze a large number of identical cells subjected to different parameters. Although their dimensions are not really nanometric, these microsystems are considered to belong to the field of nanobiotechnology in an extended sense.

4.2. Lab-on-a-chip

Many medical actions imply the detection of biological or chemical molecules in the human body. This detection must be reliable and, if possible, fast and quantitative. The same requirement applies to sanitary controls in the food industry or environmental monitoring. The classical way is to extract a sample, then separate the elements to be analyzed, which are finally purified and dosed. To achieve those operations, laboratories are equipped with specific instruments. A satisfactory result can only be obtained from a sufficient volume of samples and reagents, and a minimum time is needed. All these conditions can be expensive and time-consuming, and require conveying the samples to the laboratory.

Microelectronics development at the end of the 20th century made possible the design of lab-on-a-chip. A slab of a few tens of cm^2, made of silicon, glass or plastic, hosts a 'laboratory' fabricated using all the resources of micro technologies: etching of channels, reservoirs, filters, insertion of circulation pumps, deposition of heating resistances or fast cooling systems, actuators, localized injection of reagents, insertion of electric or magnetic sensors, etc. A lab-on-a-chip is thus aimed at the complete or partial realization of an analysis.

An important requirement in a lab-on-a-chip is the transport of fluids in the channels. It is ruled by the laws of microfluidics. Essential features of this regime are laminar flows and diffusion induced admixtures. The fluid can be moved by applying an electric field along channels (electro-osmosis). To purify a sample and get rid of the largest particles one use the difference in diffusion coefficients of various species. Another possibility is to make a traditional filter by etching pores in a membrane. A system of affinity chromatography, which holds analytes of interest on the surface of a solid, can be implanted: the fluid is forced to move within a forest of pillars whose surfaces have been functionalized to detain the analyte. The pillars can be made by etching the substrate or by enclosing microspheres in a reaction chamber dug into it.

A variety of functions have thus been achieved within microlabs, for instance, nucleic acid amplification of a DNA sample by the reaction known as PCR (Polymerase Chain Reaction) which requires successive heating and cooling.

A lab-on-a-chip finally contains a detection system, generally based on electrical or optical methods, which provides the result of the analysis itself.

Labs on chips are a very active area of research. Particular functions have already been implemented successfully. The full integration of a comprehensive analysis is still in progress. The complete development of such microdevices will offer many new applications, either to carry out environmental testing, or to specify a medical diagnosis at the bedside of a patient, or even to make on site food inspections.

4.3. Nanoparticular vectors

The development of new therapeutic approaches is often based on determining the best way for the administration of an active molecule, the path that will be used to reach the diseased organ without undergoing degradation or elimination. The drug vector should allow both to increase its efficiency and to reduce its toxicity. From this point of view nanoparticles can be an interesting approach because many strategies can be imagined to avoid them to be recognized as intruders, to allow them to recognize the target and to penetrate into the organ. The size is a determining factor according to the target organ.

Nanoparticular vectors are organized assemblies of molecules. One distinguishes:

- lipid nanoparticles, solid spheres that can incorporate the active molecule;
- micelles consisting in molecules presenting a hydrophilic and a hydrophobic termination. In aqueous media they organize into a spherical monolayer enclosing a reservoir containing the hydrophobic ends while in an organic medium, reverse micelles are formed which enclose a hydrophilic reservoir;
- phospholipid liposomes are organized into unilamellar bilayers enclosing an aqueous reservoir. Liposomes are models of cell membranes.

Nanoparticle size should be below 90 nm to enable them to circulate in the capillaries and to penetrate, especially in the liver, through the windows of communication between it and the vessels.

To reach its target, a nanoparticular vector must be stealthy, i.e. be covered by a modified surface to prevent it from being recognized as extraneous by macrophages, as this would lead to its elimination. Particles are thus coated with proteins which are not recognized by macrophages, such as those present on the surface of red blood cells or bacteria. This allows one to increase drastically the residence time of modified particles in the blood. To improve the vector effectiveness, targeting of the diseased organ is necessary. For instance, the vector surface can be grafted with a protein presenting a high affinity for a surface protein of targeted cells. However, the specificity of this targeting should be checked, so as to avoid simultaneous processing of healthy organs. The development of this type of technology is obviously complex.

Physical targeting methods are also available. Encapsulation of magnetic elements inside nanoparticles is used to concentrate them in a region of the body where an external magnetic field is applied. Similarly, heat-sensitive or pH-sensitive liposomes have also been synthesized. Tumors presenting hyperthermia or an acidic pH would thus naturally destroy these liposomes so that the active ingredient would be released locally. Various products are on the market, which use nanoparticle vectors, mainly in the field of oncology and ophthalmology. Many clinical trials are ongoing.

4.4. Activable nanoparticles

These are not active in the absence of an effective stimulation. They have a therapeutic core which can be activated by an external energy source. This concept is developed and implemented by the company Nanobiotix and has different versions which differ in the type of radiation used:

- magnetic activation by a radio frequency field as used in Magnetic Resonance Imaging. The field induces a rapid spin particle rotation, thus producing local tissue destruction;
- activation by laser radiation. Cell destruction results from the creation of free radicals at the nanoparticles surface by a laser beam;
- activation by X-rays. The core of the particle releases a large amount of oxygen based free radicals. For a given therapeutic efficacy, this procedure can reduce by a factor three the X-ray dose required to treat a tumor;
- activation by ultrasounds.

In all cases the active substance present in the particle core is coated with a layer of silica which makes it biocompatible. To ease its attachment the particle is coated by a protein which is recognized by target cells. The use of localized radiation further increases the specificity of the treatment, since particles are inactive in the absence of radiation.

The concept of synthetic nanoparticles comprising a combination of several functions perfectly illustrates the potentials of nanotechnology in the biomedical field.

5. Micro- and nano-mechanical systems

5.1. MEMS (Micro Electro Mechanical Systems)

Since the beginning of microelectronics, in the 1970s, technologies were used for fabricating elements of microelectromechanical systems. Indeed the layout techniques developed for silicon allow one to make much smaller and much cheaper objects than using traditional techniques of micromechanics. This trend has not abated. Device fabrication, actuator integration, and electronic control elements lead to multiple object fabrication for a very low cost. The most common application of microsystems is presently airbag triggers. The sensitive part is a small silicon mass suspended by fine silicon wires. Under the effect of a shock, the silicon block moves, and this induces a change in capacitance which is electronically detected. If the displacement exceeds a preset threshold, the order of balloon inflation is given. Everything must happen in a very short time.

Another example of widespread microsystems are drop generators in inkjet printers. They are combining electronic and fluidic microchips which can produce a string of drops on demand.

The on-chip microlabs mentioned above are other examples of microsystems applied to fluidics.

5.2. NEMS (Nano Electro Mechanical Systems)

The progress of miniaturization now makes it possible to fabricate microsystems of smaller and smaller size which incorporate nanometric elements, hence their name NEMS. This research area is still in the stage of demonstrating the validity of the concept. According to the few teams working on this topic, the interest of such devices would be to allow working at the single molecule level, for example to detect or to analyze proteins one by one.

Furthermore one can design sensors working at a scale where quantum phenomena are predominant and thus take benefit of some useful properties (quantization of photons, phonons or electronic transport). Moreover, the very fact of having tiny components allows manufacturing millions of them simultaneously. This may lead to the realization of systems with a high level of parallelism.

A first example of significant achievement is the mass spectrometer dedicated to detection of a single molecule, realized by the team of Michael Roukes at Caltech. The sensitive element is a suspended silicon carbide wire only 100 nm wide for a length of 2 µm. It is incorporated in an electronic circuit controlled by the resonant vibration of the wire at very high frequency (450 MHz). The vibration frequency depends on the mechanical properties of the wire and on its mass. The sensor is associated with the first stage of a conventional mass spectrometer that generates ions in a vapor to be analyzed. When the wire captures a molecule, its mass changes and the vibration frequency drifts abruptly. The frequency shift is used to identify the mass of incident molecules. The very small sensor size allows parallel connection of many of them, and thus thousands or even millions of simultaneous measurements can be recorded.

In another application, the nanowire can be treated to selectively adsorb a chemical species. The resonance frequency of the circuit associated with this sensor will be modified whenever a molecule of the targeted species will be captured. By selectively combining a number of dedicated sensors to different molecules it is possible to determine the proportion of these molecules. This device called “electronic nose” is thus able to determine the profile of molecular species in a given sample. One objective of this project is the early detection of certain cancers by analyzing the exhalation of a patient (recall the current attempt to train dogs to perform this detection by their smell). One can also think of multiple applications in the food industry to control taste and fragrance products.

Finally, the research on molecular motors can be mentioned. Such tiny motors are present in living systems as proteins responsible for transporting protons across the cell membrane (ATP synthase) or for dragging the muscle fibers along one another (myosin) or for intracellular transport (kinesin). Some of these motors can be isolated, fixed or adsorbed on a support and their motion can then be detected. They could certainly provide new elements for an exciting “nano-meccano”. But now we are still at the stage of speculation.

6. New observational instruments

The success of nanoscience and nanotechnology was made possible by the use of new, innovative instruments, which were powerful and relatively inexpensive, thus allowing their wide dissemination in laboratories and industrial plants.

6.1. The scanning tunneling microscope

This was a real breakthrough in imaging techniques. While all microscopes operated according to the same principle as the eye (radiation illuminates an object, the eye picks up the radiation and produces an image) the innovation was to make an instrument operating on the principle of the finger (as a blind reads a character in Braille by feeling the protrusions of the paper with his finger). The idea of Gerd Binnig and Heinrich Rohrer was exactly that. Approaching a metal tip close to a conducting surface, one measures the gap by measuring the electric current flowing between tip and surface when a voltage is applied. This current is non-zero only if the tip is close enough, so that it flows thanks to tunnel effect. This current is about 1 nanoampere for a gap of 0.5 nm. By moving the tip parallel to the surface while monitoring its distance to keep this current constant, it follows the roughness of the surface and allows one to reconstruct its topography. One can therefore reconstruct an “image” without ever having seen it. To obtain a good image resolution, the first condition to fulfill is to make a thin enough tip, so that its extremity consists of a single atom. Although very difficult, this problem is now commonly solved by experimentalists. A second condition is that the tip location must be very precisely tuned and measured in all directions of the space. This problem is solved by piezoelectric actuators. The tip sharpness and position accuracy is sufficient to reconstruct images of surfaces with a resolution of 0.01 nm. For this invention Binnig and Rohrer received the Nobel Prize in 1986.

Other types of microscopes have been invented according to analogous principles. The difference is usually the type of interaction between tip and surface: Van der Waals force, electrostatic force, magnetic force. These new microscopes produce multiple and complementary images of surfaces, highlighting various physical properties such as electron density, density of empty states, localization of magnetic moments and electric charges, and so on.

6.2. Near-field optical microscope

The use of light has not been abandoned, however. One tries to overcome the diffraction limit according to which, in conventional microscopy, it is not possible to see details whose size is below the half wavelength of the radiation used (i.e. 250 nm when using green light). This limit may be lowered if ultraviolet radiation is used, but this raises other problems (especially for biological samples, that are degraded by UV light). In this way the possibility of progress was limited. New instruments have now emerged, which overcome the limitation by other means.

Instead of detecting light in the far field, subject to the diffraction limit, one considers the evanescent wave observable in the near field. Illumination and/or collection of light is made through a thinned and metalized optical fiber, which is located in the immediate vicinity of the diffracting object (a few nm). The fiber displacement is obtained with techniques similar to those used in the scanning tunneling microscope. It is possible to reconstruct an image of the surface with a resolution of up to 25 nm, i.e. 1/20 of the wavelength of the illuminating light.

All these new tools, called local probe microscopes, have greatly contributed to the development and dissemination of nanotechnologies in many laboratories.

7. Conclusions

The above description of nanoscience and nanotechnology may look like a list of little correlated domains and multiple applications. Where is the unity of the field? What is the nature of the evolution (or revolution) proposed in the title? The domain is indeed very composite, it involves many fields of science and technology and the objects of interest have dimensions which range from nanometer to micrometer. There are however a few unifying concepts:

- The genesis of all these innovations shows that one mover was the technology of microelectronics, which during 40 years has continuously provided new techniques to miniaturize circuits and reduce their cost. One result has been the considerable development of information technology and its dissemination in all fields.
- Another result was the introduction of miniaturization and new ways of computing in other technical areas: biology and biotechnology, mechanics. Nanochemistry and nanomaterials have also progressed, but with less obvious connections. In all these areas a number of innovations have been identified, but future projects are even more numerous.
- Another remarkable feature of this recent development is the combination of disciplines and different fields of knowledge. At the nanoscale, physics, chemistry, biology and mechanics are linked. The collaboration of the knowledge and skills of different disciplines is mandatory.
- Basic science and technology are also inseparably linked. The manufacture of objects and the understanding of their properties have to move simultaneously.

The term “nano revolution” has been used more than once. Clearly, what we are witnessing is not really a revolution but rather a quite continuous progression of knowledge and techniques with sometimes remarkable qualitative leaps. However, the development of information technology, born in the last third of the twentieth century with the undeniable support of micro and nanotechnology, has been a true revolution in many fields.

7.1. Should we be afraid of nano's?

This presentation of nanoscience and nanotechnology cannot be closed without evoking the hopes and fears and even demonization which have affected this field of science and technology.

As said above, the last decades have witnessed the rapid development of microelectronics and telecommunications. Computers and the Internet profoundly impacted modes of communication, modified economy and accelerated globalization. All these social transformations, that generate anxiety, decommissioning or unemployment, have been associated with innovation. Up to the end of the 20th century, the idea of progress was associated with the car, the washing machine or the television set. Technical innovation and progress seemed almost automatically linked. Recently this link has been put in question and even a part of population puts now the emphasis on negative aspects of technical development. Among these unilateral criticisms, the following ones may be quoted:

- Miniaturization favors the development of surveillance cameras;
- RFID chips may be used for tagging individuals;
- Mobile phones may be used by police to watch citizens;
- Geolocation allows one to locate any vehicle and, in the future, any phone if they are equipped with GPS;
- Antibacterial socks are useless and even harmful (what happens to nanoparticles of silver when the sock wears out or ends up in the trash?);
- Carbon nanotubes are toxic (they have been found in the brains of exposed mice…).

All this is true … but … incomplete. Of course, all these claims should be offset by a mention of the expected utility of those innovations. The only statement of a drawback is not sufficient to disqualify an invention. Cars are not only a source of accidents and pollution.

The few statements noted above, among many others, evidence the concerns generated by novelty. Every innovation, every new product brings both advantages and drawbacks, usefulness and real possibility of abuse. But it is equally unreasonable to assert that all innovations are good and useful than to discard anything that appears from nanotechnology.

However, as new goods and new uses are bursting in, it is difficult to sort out the good, the worse and the downright bad. Our practice does not have time to adapt to new techniques. This has become even more difficult since new objects are proposed or even imposed by the means of marketing. Who decides which products survive? The market. Customer demand (stimulated by all the resources of the suggestion and communication) will rule.

This excessive criticism certainly responds to the excessive enthusiasm of researchers. It is a reaction against the excessive extrapolations of the prophets of a new world and a new man. Indeed, according to some, all limitations and burdens that we know would soon be swept away by technology: human beings would enjoy endless life, magnified physical and intellectual powers, a world without pollution, costless energy, etc. Such a transhumanist visions make easy the criticism of an entire segment of the contemporary technological research.[2]

How can the useful be distinguished from the useless? How can a sensible acceptance of innovations be balanced with refusal of products which are harmful to health or autonomy of the individual? It is clear that it is not easy to keep a balance between many conflicting currents. As it is not possible to rely on the supposed wisdom of the "inventors", it is not permissible to trust market forces alone. The need for social regulation is therefore absolutely essential. Its mission should be to avoid the production and release of hazardous materials, protect privacy and personal autonomy, promote socially useful innovation.

Although our societies are not lacking resources to monitor the safety of products on the market, as well as the drifts in file-creating or breach of privacy, the importance of vigilance of citizens and functioning of democratic institutions must be stressed. All these topics are also addressed in other articles of the present dossier.

Nanoscience and nanotechnology promise a lot. Hopefully they will actually help address a number of challenges that society faces: pollution, need of clean energy in sufficient quantity, health and aging… It is up to them to show they can do that without inducing any new risks or make further pollution, or endanger the legitimate rights of individuals.

Supplementary material

The French version of this article is supplied as Supplementary Material with the electronic version of this article.
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[2] Remarkable examples will be found in the report of a symposium organized at the initiative of the National Nanotechnology Initiative in the U.S. in 2001 on "Societal implications of nanoscience and nanotechnology". This report is available at the following address: http://www.wtec.org/loyola/nano/NSET.Societal.Implications/nanosi.pdf.

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[2] Catherine Brechignac, Philippe Houdy, Marcel Lahmani (Eds.), Nanomaterials and Nanochemistry, Springer, 2007.
[3] Patrick Boisseau, Philippe Houdy, Marcel Lahmani (Eds.), Nanoscience, Nanobiotechnology and Nanobiology, Springer, 2007.