

Chapter 1

Introduction

Louis Laurent

Abstract During the twentieth century, progress in physics, chemistry, and biology brought a detailed understanding of the structure and properties of both living and inert matter on the nanometric scale, i.e., lengths of the order of one billionth of a metre. By the end of the 1950s, instruments were being developed to observe, manipulate, and assemble matter and devices on this same length scale. It was thus clear that the convergence of all this knowledge would open the way to spectacular applications, and yet it was not until the 1990s that nanotechnology truly came into its own. The most visible application was without doubt nanoelectronics, today present in an increasing number of products which are in the process of changing our lives. But nanotechnology is being put to work in many other sectors such as materials, sensors, energy, and medical applications. Thousands of products contain nanosized ingredients and, given the scope of these developments, concern has been expressed, particularly about the possible toxicity of nanoparticles and inadequate control of industrial applications. Since its inception, nanotechnology has been closely associated with the notion of economic growth, but its maturity will also depend on an understanding of the associated risks and its contribution to the crucial future questions of sustainable development.

1.1 There's Plenty of Room at the Bottom

Nanoscience and nanotechnology get their definition primarily from a scale of length, viz., the nanometer, which is a billionth of a meter. To see what this means, consider a hair. This will grow about a centimeter every month. Carrying out a simple calculation, we discover that this hair will grow at a rate of about four nm per second. But why does the nanometer play such an important role? To answer this, we must turn to the very constituents of matter.

The matter around us is made up either of atoms, which can be represented as tiny spheres with diameters of the order of a few tenths of a nanometer, or of molecules,

L. Laurent (✉)

ANSES, 14 Rue Pierre Et Marie Curie, 94701 Maisons-Alfort, France

e-mail: louis.laurent@anses.fr

which are strongly bound assemblies of atoms measuring a few nanometers across. In other words, the smallest amount of a substance we can speak about does indeed concern this length scale.¹ Atoms are so small that, in our everyday lives, we are unlikely ever to feel as though we are made up of such things. Even what we consider to be microscopic comprises a huge number of atoms. For example, a bacterium in the form of a rod 3000 nm long contains a hundred billion atoms, enough to build up the complex machinery that allows this bacterium to live. Simpler than the bacteria, viruses measure a hundred or so nanometers and still contain tens of millions of atoms. Likewise, sometimes highly complex microscopic systems can be made by industry, such as microprocessors, with features now measuring only a few tens of nanometers. This was the ‘nanoworld’ that Richard Feynman, Nobel Prize for Physics, was referring to in the title of a talk he gave on nanoscience back in 1959: *There’s plenty of room at the bottom*.

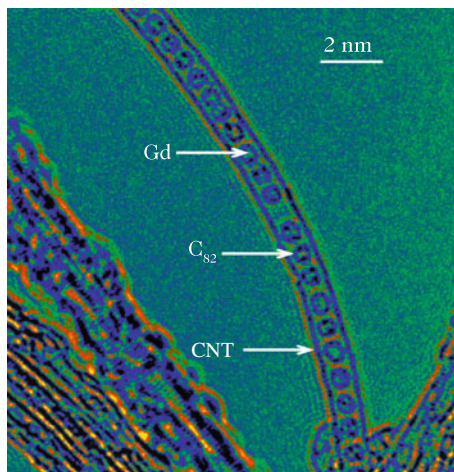
1.2 A Short History

The idea that the world is made of atoms is not a recent one. It is attributed to the Greek philosopher Leucippus and his disciple Democritus (circa 400 BC). However, it was not until the nineteenth century that progress in the sciences turned this into a serious hypothesis and then a reality, with implicit reference to the nanometric length scale. Between the end of the nineteenth century and the middle of the twentieth, techniques were developed for observing matter on this scale. For example, in 1931, two German engineers Ernst Ruska and Max Knoll invented the electron microscope. The underlying idea can be understood by comparison with the optical microscope, except that light is replaced by electrons which probe matter in much finer detail. After ten years or so, the electron microscope could already achieve a resolution of 10 nm, and further progress was made right through the twentieth century. A resolution of 0.1 nm, the size of a single atom, was reached in the 1990s. Figure 1.1 shows an example of such an image.

It was also in the 1980s that techniques were improved for laboratory manipulation of matter on the nanometric scale. A symbolic step was the invention of the scanning tunnelling microscope (STM) by two researchers at the IBM research center in Zurich, Heinrich Rohrer and Gerd Binnig. If the electron microscope is likened to a kind of ultra-powerful eye, the scanning tunnelling microscope could be described as a sort of finger that investigates matter by prodding it. A fine tip is displaced across the surface of the matter, so delicately that it can ‘feel’ the very atoms themselves on the surface. In the original version, invented in 1981, this sensing was carried out using electricity. As we shall see later on, each atom on the surface ‘attracts’ electricity. Then, from 1986, another version of the microscope appeared, measuring

¹However, it should not be thought that there is nothing smaller than an atom. The atom is itself a complex object, made up of elementary particles much smaller than the nanometer, but this matter is no longer of the kind we see around us.

Fig. 1.1 Bright-field electron microscope image of Russian nanodolls showing tube-shaped structures made of carbon atoms, known as carbon nanotubes (CNT). Inside these nanotubes are small spheres called fullerenes, each made from 82 carbon atoms (C_{82}). Each fullerene itself encloses a gadolinium (Gd) atom. Courtesy of A. Gloter, Solid State Physics, Orsay, CNRS France–AIST Japan



the attraction exerted by each atom on the tip. This was the atomic force microscope (AFM). These much cheaper devices soon became commonplace in research establishments. Even more spectacularly, the tip of an atomic force microscope can actually displace a single atom. A symbolic event here was the feat achieved by Don Eigler who, in 1989, deposited 35 xenon atoms on a nickel surface to write the IBM logo. (Don Eigler worked for IBM.) This symbolic image is easily found on the Internet even today.

In parallel with these technical achievements came a growing understanding of the behaviour of matter on the microscopic scale. A good example is provided by the science of colloids. These are tiny pieces of matter with nanometric dimensions suspended in air or water. They are present throughout nature, e.g., milk is a colloid suspension. They were first identified in the nineteenth century, and were observed at the beginning of the twentieth century using the ultramicroscope invented by the chemist Richard Zsigmondy. However, it was only later in the twentieth century that colloid science came into its own, with industrial applications to materials, foods, cosmetics, and pharmaceuticals.

Another example is provided by molecular biology, which seeks to explain the way living organisms operate through the interactions between molecules taking place in cells. This science appeared in the 1930s, and over the next fifty years or so gave rise to a completely new outlook on cell dynamics and the advent of biotechnology.

A last example, but no doubt the most spectacular of all, is the development of microelectronics. The extraordinary expansion in this field at the end of the twentieth century brought the pursuit of ever smaller devices into the limelight. The first integrated circuit was invented in 1958 by Jack Kilby of Texas Instruments. This device integrates several components including transistors on a wafer of semiconducting materials and is ideally disposed to miniaturisation, provided that one has machines capable of making and positioning tiny components with sufficient accuracy.

As time went by, these different areas of understanding came together to form a field in its own right, the field of nanoscience (or nanotechnology when we speak of applications), taking up Richard Feynman's far-sighted challenge. The main lines of research were many and varied and the applications even more diverse. The unifying feature came above all from the length scale at which the different phenomena were taking place. The word 'nanotechnology' itself is attributed to professor Norio Taniguchi of Tokyo university who, in 1974, used this term to describe techniques for fabricating semiconductors. However, it was not until the end of the 1990s that the new field reached maturity. Various nanotechnological instruments, including the famous scanning tunnelling microscope, were by then available commercially and becoming standard equipment in research centers. At the same time, the microelectronics industry was well on the way down the road to miniaturisation and had already reached the scale of 200 nm, with the symbolic landmark of 100 nm in view. The prefix 'nano' was becoming common currency in the world of research and governments the world over were launching their first nanoscience and nanotechnology programmes, the former when concerned with improving understanding and the latter when they had applications in mind.

1.3 The Nanoworld

So what caused this sudden interest? The point is that, largely because it is being observed at these very small length scales, matter has very different properties, and while many of these properties can be deduced from laws of physics that have been around for over a century, it is only recently that observation and fabrication techniques have actually been able to demonstrate their existence, let alone build devices that put them to use.

1.3.1 Matter on the Scale of a Few Atoms

Researchers routinely manipulate small clusters of atoms, deposit ultrathin layers, and shape devices to an accuracy of 10 nm. The granular nature of matter on the atomic scale then becomes fully manifest. Solids and liquids look like more or less regular assemblies of atoms or molecules which hold onto one another via forces ensuring overall cohesion. The atoms will sit a few tenths of a nanometer apart. A cube of side 10 nm will contain roughly 25,000 atoms, although the exact number will depend on the material. Another important point is this: the smaller the objects, the greater the proportion of atoms that will lie close to the boundary of the nano-object. For example, 20 % of the atoms in the above 10 nm cube will be located at its surface. If we ourselves were microscopic and observed the world, two properties in particular would look strange.

The first of these is thermal agitation. On this scale, each atom, molecule, or cluster will be in permanent vibratory motion. When Scottish botanist Robert Brown observed this motion in pollen grains in 1827, it gave him the impression that the grains were alive. In a solid, an atom will often simply oscillate vigorously, otherwise held in place by its neighbour, although it may sometimes pass between them. In a liquid, it will move around and regularly change neighbours. But in a gas, it will hurtle headlong like a cannonball until it comes up against another atom or the wall of the container. And the hotter the matter, the more agitated the atoms become. At room temperature, this agitation corresponds to speeds of a few hundred meters a second. Sometimes we must cool an object under investigation in order to reduce this agitation.

Another disconcerting phenomenon is cohesion. Two small fragments of matter, whatever kind of matter it may be, will strongly attract one another like two magnets. These forces are basically of electrical origin. Atoms are made up of a positively charged nucleus surrounded by negatively charged electrons in such a way that the object as a whole is electrically neutral. However, these charges reorganise themselves all the time, and a (sophisticated) calculation reveals that the attraction between opposite charges wins through. This phenomenon is often exploited by researchers to build nano-objects. When separate components, molecules, or atoms are brought together, they will stick to one another, often forming very regular patterns. This force has a range of only a few nanometers and so would be quite imperceptible on the scale of our own world. But it is this force that ensures that solids maintain their cohesion or that water forms droplets, unless they are heated up so much that the atoms are agitated enough to escape completely.

Forces

Let us take a closer look at the forces exerted between two objects in the nanoworld. On this scale, it is more convenient to use the nanonewton as unit of force. This is one billionth of a newton. This force is roughly equal to the weight of a sphere of radius 3 hundredths of a millimeter filled with water and containing 3.4 million billion water molecules.

Strong Bonds When two atoms join up in a chemical reaction by sharing their electrons, remaining firmly and permanently attached to one another at a separation of only a fraction of a nanometer, we say that they form a covalent bond. On the scale of the nanoworld, the force in a covalent bond is truly colossal. Indeed, to separate the two atoms forming a hydrogen molecule, one must exert a traction force of the order of a nanonewton, i.e., as we have seen, equal to the weight of a million billion hydrogen atoms. Such a force is hard to imagine on our own scale. If the two hydrogen atoms corresponded to two peas each weighing one gram, the force between them would be equal to the weight of 100 million Airbus 380 aircraft. This explains why hydrogen and many other molecules are so stable, making it very difficult to remove their atoms.

Weak Bonds When they are placed a distance of the order of a nanometer apart, i.e., several atomic diameters, atoms and molecules do not join together. When they come close enough, however, they attract under the influence of electric force, any gravitational attraction being completely negligible in comparison. These forces, known as van der Waals² forces, are of the order of a thousandth of a nanonewton, which is a hundred to thousand times weaker than covalent binding forces. They are nevertheless very strong. If the atoms were two peas placed a centimeter apart, they would attract with a force corresponding to 100,000 Airbus 380 aircraft. This is why, on the length scale of the nanoworld, everything is 'sticky'. However, there is another phenomenon that prevents matter from clumping together, and this is thermal agitation. When it gets hot enough, atoms that are stuck together begin to dissociate due to repeated impacts from neighbouring atoms. Room temperature often suffices for this dissociation. In other case, more heat must be supplied.

Sticky Nano-Objects Attractive forces play a major role in the dynamics of nano-objects. To begin with, they ensure cohesion, unless it gets too hot. However, they also cause nano-objects to stick easily to anything passing within their range. So when a cluster of carbon atoms of radius about 50 nm, which will contain around 60 million atoms, comes close to a container wall, each atom in the cluster will be attracted to that wall. It will thus stick to it, attracted by a force of several nanonewtons, i.e., 200 million times its own weight.

1.3.2 Electricity

When electrons move through matter, we observe an electric current on our scale. The 10 A that trigger a circuit breaker correspond to 60 billion billion electrons going by every second. Although each electron is not really a little grain of electricity carrying its charge, this is a convenient way on our scale to describe the current passing through a metal.

We have been making nanoscale electrical devices for several years now. The basic building blocks can be nanocavities a few nanometers across which store electrons, nanowires which carry a current, or films a few atoms in thickness. Some of these devices are found only in the laboratory, while others are mass-produced by the microelectronics industry. There is also the prospect of 'ultimate' electronic devices in which electrons are manipulated one by one. On the nanoscale, quantum mechanics becomes an essential tool for describing the behaviour of the electric current. In other words, while it may be satisfactory to treat the electron as a little grain of electricity when it is viewed from afar, the situation is quite different when we zoom in closer.

²Johannes Diderik van der Waals was awarded the Nobel Prize for Physics in 1910 for his work on the equation of state of gases and liquids. His research on the continuity of fluid states, and in particular gases and liquids, led him to discover short range cohesive forces.

An electron then looks fuzzy, spreading over several nanometers. Here we have to speak of its wave function, and it looks as though several possible electrons coexist, each being associated with its own position and speed. The phenomena observed have no equivalent in our own world.

The best known of these phenomena is the tunnel effect. In our macroscopic world, if we cut a copper wire carrying a current, this current will no longer pass through it. But this is not quite true on the nanometric scale. If the wire is discontinued over a very tiny distance of the order of a fraction of a nanometer, the electrons arriving at one side of the break already have one ‘foot’ on the other side. These electrons can then cross the insulating gap. A current passes as though by magic across the gap, although its strength falls off exponentially with the leap it must make. This phenomenon is exploited in scanning tunnelling microscopes (STM). A fine tip is displaced just above a conducting surface, at a distance of a few tenths of a nanometer. A current thus passes with a strength of a few billionths of an ampere, depending sensitively on the tip–surface separation. By displacing the tip and measuring the current at each of its positions, we can thus reconstruct an image of the conductor surface, and we can in a certain sense even ‘see’ the individual surface atoms. In other situations, the tunnel effect can be something of a nuisance, especially in the manufacture of nanodevices. Indeed, it becomes impossible to use insulators below a certain thickness, simply because a current can then cross them. This is why microscopic transistors in processors or memories are prone to leakage currents which increase the electricity consumption.

Another relevant effect is quantisation. When an electron is trapped in a tiny region of space, it can only exist in a certain number of configurations. There is an analogy with organ pipes. Only sounds of a specific frequency can be emitted from a pipe of given height. This phenomenon, first observed for electrons in atoms, explains why each atom will only emit its own specific spectrum of light. However, the same phenomenon can now be reproduced by enclosing electrons in tiny boxes known as quantum dots. Like atoms, these have specific optical properties.

1.4 How Can We Make Such Tiny Objects?

A nanometer is a truly small length, much shorter than anything that could be perceived by our senses. So how could we possibly make objects on such a scale? Paradoxically, it is rather straightforward, since matter assembles itself spontaneously in nanometric form. For example, if we place a droplet of petrol of a few cubic millimeters on a bowl full of water, it will spread out to form a film a few hundred nm thick. The resulting iridescence is due to the play of light bouncing back and forth from one face to the other of this thin layer of petrol. The surface of a soap bubble may be of similar thickness and the same kind of iridescence is observed.

Even more surprising, in our everyday lives, we produce large amounts of nano-objects without ever appealing to nanotechnology. The main source of nanoparticles is the combustion of all kinds of materials, such as wood, cigarettes, petrol, and so on, all of which generate vast numbers of nanoparticles.

The Nanop Project

This project, which was financed by the *Agence française de sécurité sanitaire de l'environnement et du travail* (AFSSET), was led by researchers from different institutes.³ Experimental work was carried out in the *maison automatisée pour des recherches innovantes sur l'air* (MARIA), which is an experimental house run by the *Centre scientifique et technique du bâtiment* in Champs-sur-Marne (in the Seine-et-Marne, France). It contains all the standard household goods that a family would use on an everyday basis (see Fig. 1.2). Various devices measure the pollution generated by everyday activities and in each room of the house.

This experimental house was used to analyse nanoparticle emissions produced during daily life, including their concentration, chemical composition, persistence in the air, and propagation throughout the house. This project showed that many such activities do indeed produce these particles, including in particular petrol heating systems and cooking. Peaks of concentration can reach a million nanoparticles per cubic centimeter. These particles propagate extremely quickly from one room to another.



Fig. 1.2 Analysis of particles emitted in the living room. Courtesy of Corinne Mandin, *Centre scientifique et technique du bâtiment*

³These include the *Institut national de l'environnement industriel et des risques* (INERIS), the *Centre scientifique et technique du bâtiment* (CSTB), the *Institut de recherches sur la catalyse et l'environnement de Lyon* (IRCELYON), the *Laboratoire d'étude des particules inhalées de la ville de Paris* (LEPI), the *École des hautes études en santé publique* (EHESP), and the *université Paris-Est*.

In industry, many processes have been developed to produce nano-objects in a controlled way. These fall into three main groups: self-assembly, nanofabrication, and mimicking nature.

1.4.1 Self-Assembly

This first kind of process is useful for making nanoparticles and nanomaterials or treating surfaces. It exploits the tendency of atoms to stick together to form aggregates or even fibres. In scientific jargon, researchers call this the bottom-up approach, because we start out with atoms, at the bottom of the scale, and build structures up from there.

Sometimes when molecules are put in close proximity they assemble spontaneously into aggregates which may be nanometric. This tendency to self-assemble is exploited to fabricate nanoparticles in a great many industrial processes. One can simply heat the right kind of molecule or trigger a chemical reaction so that they break and the resulting pieces will tend to stick to one another. Nanoparticles or fibres produced in this way are then incorporated into a material whose properties one would like to modify, thereby producing a nanomaterial. Another process commonly used in industry is the production of thin films, with thicknesses measured in nanometers. Rather than have the atoms stick to one another, one arranges for them to stick to a surface.

Chemistry is also used to modify the surface of nano-objects such as nanoparticles or nanostructures machined on a surface. Molecules are grafted on to give them specific properties: therapeutic properties for a drug, properties of molecular recognition for diagnosis, and properties of chemical affinity for incorporation into a polymer matrix. The application of this kind of chemistry to nano-objects is referred to as nanochemistry.

Nanotrees in the Alps

These are in fact silicon nanostructures which grow on their own in the presence of a vapour containing silicon. The atoms arrange themselves spontaneously into structures with a trunk and ‘nanobranches’, giving the whole thing the appearance of a fir tree (see Fig. 1.3). These structures are particularly interesting for potential applications in the field of energy storage and energy conversion in photovoltaic cells.

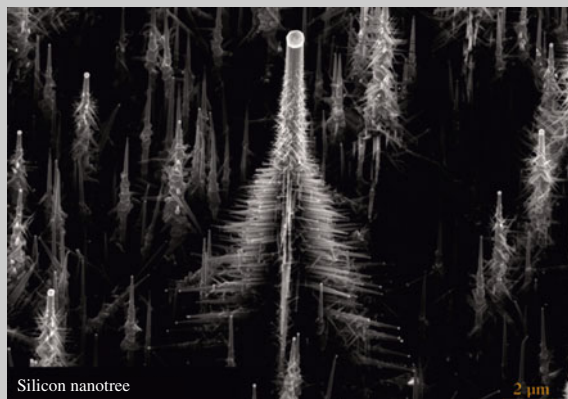


Fig. 1.3 Silicon nanotree. Image courtesy of Fabrice Oehler, CEA/INAC/SPMMM/ SiNAPS

1.4.2 Nanofabrication

This second kind of process encompasses a whole range of techniques for producing devices rather than materials. In this case, the elements are machined to an accuracy specified in nanometers, and above all they are positioned with similar accuracy. This is known as the top-down approach, because one starts out at the top length scale with the material to be machined and ends up with patterns and motifs of almost atomic precision.

Microelectronics began to develop in the 1960s and with it, so did lithography. The material to be machined, usually silicon, is coated with a light-sensitive resist. The image of some very fine motif that one would like to engrave is then projected onto this resin, thereby transferring the motif to the resin. The silicon is subsequently etched at the places where it is no longer protected by the resist, in the case where the latter is qualified as ‘positive’. However, it is also possible, depending on the resist, to modify the silicon at places that are not protected, depositing metals or implanting atoms and hence changing its electrical properties. The cycle of operations is then repeated above the first film to develop, complete, or modify the pattern. A microprocessor is thus built up gradually, layer by layer.

In fifty years or so, we have reached an astonishing level of control in these processes, engraving surfaces with lines measuring a few tens of nanometers. While these processes were inspired by technology that largely predates the nano era, the machines designed to achieve such technical feats have become considerably more sophisticated. They require ultra clean conditions since the tiniest grain of dust would look like a huge rock in comparison. They ensure remarkable positioning accuracy in such a way that successive layers are precisely superposed one above the other. They

exploit new developments in optics, using ultraviolet light with ingenious expedients for getting beyond the classical limits of optical resolution. As a result, factories can now cost billions of euros to set up and run.

1.4.3 *Mimicking Nature*

From the standpoint of a biologist, living beings are highly complex machines in which most of the components operate on the nanoscale. They make admirable use of the properties of the nanoworld, and in particular the binding forces between molecules and thermal agitation. These components, which are often proteins housed in cells, carry out a range of tasks from the production of the molecules necessary to life to the destruction of waste products, transport of nutrients, information handling, energy transfer, communications, and so on.

Will we be able to do things as well as this one day? In his book *Engines of Creation: The Coming Era of Nanotechnology*, which appeared in 1986, Eric Drexler predicted that mankind would build ‘assemblers’, nanorobots that would assemble matter atom by atom.⁴ So humans could eventually do as well as nature herself, or even better. These ideas remain in the domain of science fiction. We are still a long way from being able to compete with nature when it comes to nanofabrication. However, research has since taken a different road. Our understanding of living beings is being refined all the time, and the tools for reading and writing the genetic code are now available to an increasing number of scientists. Even in the 1970s, we were able to insert extra genes into cells to produce drugs, for example. The term used here is ‘synthetic biology’. This research aims to use the same methods as nature to fabricate macromolecules such as drugs or biofuels, but also nano-assemblies such as the components of a vaccine.

1.5 What’s It All For?

A key difference between nanoscience and other fields of research is that it is cross-disciplinary, underlying extremely varied applications, as the reader will soon realise in the following chapters. Nanotechnology has already taken its place in our everyday lives. This is the topic investigated by the Woodrow Wilson Institute in its project on emergent nanotechnologies. The institute regularly publishes inventories of products appearing on the Internet which involve some mention of nanotechnology.⁵ They note a steady increase in the number of such products: 54 in 2005, then 1317 in 2010, and probably 2000 in 2013.

⁴K.E. Drexler: *Engines of Creation: The Coming Era of Nanotechnology*, Doubleday, New York (1986).

⁵<http://www.nanotechproject.org/inventories/>.

However, nanotechnology should not be considered as an industrial sector like the automobile industry, for example. This is hardly surprising, because the word ‘nanotechnology’ derives from a length scale, not a type of product. So there are nanoscale ingredients in almost every area of application, either through the presence of microelectronic devices or, more often, through the incorporation of nano-objects in existing products. These ingredients are sometimes mere details, representing only a few percent of the value of the product. Without claiming to be exhaustive, nanotechnological applications can be divided into three main categories: nanomaterials, nanoelectronics, and nanobiology (including nanodrugs).

1.5.1 Nanomaterials

This was the oldest field of applications if we take into account certain materials going back several centuries, whose properties derive from inclusions or motifs of nanometric dimensions. Consider for example steels, or glasses coloured by metal precipitates, but also materials made from living materials like wood, bone, leather, or paper. Having said this, it should be remembered that these were in a certain sense unintended nanotechnologies. The difference today is that industry knowingly appeals to nanometric ingredients, incorporating them into materials or depositing them on their surface. These nanomaterials, some of which have utterly novel properties, can be used in an extremely wide range of applications. It would be difficult to make a complete list, so disparate would it appear, but one can nevertheless cite some examples. An important one is the improvement of material properties such as strength, permeability, and hardness, e.g., strengthening of plastics or concretes by incorporating nanoparticles or nanofibres. Another example is the development of materials with large surface area for absorbents or filters, antipollution surfaces, and anti-bacterial surfaces. The latter application in particular has seen considerable development over the past few years. The idea is to fix silver nanoparticles to a given surface to kill bacteria. More generally, the most commonly used nanoparticles are silver, carbon, silica (nanosands), and titanium dioxide, which absorbs ultraviolet sunlight and destroys atmospheric pollutants.

1.5.2 Nanoelectronics

Since the 1960s, the electronics industry has been following its road map with steady miniaturisation of circuits and components. In the last 50 years, engineers have achieved extraordinary technical feats. The smallest detail on circuits mass-produced in 1960 was of the order of 55,000 nm, but it went down to 1,000 nm in 1990, then 32 nm by 2010. Smaller transistors are faster and more of them can be placed per unit area. This has led to a considerable increase in computational power per euro of components bought. Regarding products for the general public, computational

powers are now measured in billions of operations per second. There have been a great many applications, such as image and video processing, automatic translation, voice recognition, and others. Today one finds calculators in many everyday products, from domestic appliances to cars, not forgetting smartphones. Another striking example of what miniaturisation can achieve is provided by data storage on computer hard disks. In the 1990s, the capacity of the hard disk on a PC was of the order of 100 megabytes. In just 20 years, this capacity has been increased by a factor of 10,000, so that today each point memorised is written on a spot measuring about 15 nm across, i.e., the area occupied by a few thousand atoms. In other words, a week's worth of video can be stored on one square centimeter.

1.5.3 Biology, Nanomedicine, and Health

This area has seen less development than the last two, but the prospects are very promising. Technology inspired by microelectronics is already commonly implemented in analytical methods involving just a few molecules. Another field with much promise is the development of nanodrugs. Ideally, drugs are molecules that affect the way a living thing works, but if possible, acting only on the part that requires treatment. For example, an ideal antibiotic should in principle block some process that is crucial to a bacterium, but without interacting with the cells of the patient. Likewise, for a product used in chemotherapy, the idea is that it should be toxic for cancer cells, but not for healthy ones. Unfortunately, in reality, treatments are often more invasive than one would like.

Nanotechnology opens up new prospects here. The drug molecule is replaced by a more complex system, a drug nanovector, which will carry the molecule precisely to the sick tissue. The molecule is encapsulated to protect it during transport to the target region, and it is provided with antennas to fix it exclusively onto the sick part. At the same time, this makes it possible to use more aggressive molecules. Clinical trials, especially for the treatment of certain tumours, are already under way.

1.6 The Debate

Nanoscience and nanotechnology comprise a ragbag of subjects whose unifying feature is the nanometer. Such a situation is not unique in the history of science. One may think of the science of complex systems which deals with phenomena as diverse as ecosystems, the brain, the economy, or the climate, the common denominator being complexity. However, nanotechnology is particular in the sense that it leads to applications in almost every field of life.

Another key factor is that nanoscience reached maturity at the same time as the so-called knowledge economy, at the beginning of the 2000s. This new development was part of what has been called the Lisbon strategy. The idea is that nations should build

upon innovation to reconcile growth, sustainable development, and social cohesion. Among all the areas of science able to contribute to such goals, nanotechnology and information technology stand out. These two areas have seen considerable development in Europe, the United States, and above all in Asia. One of the symbolic events that has contributed to making nanotechnology a flagship activity was President Clinton's launch in 2001 of a national initiative, a wide-ranging programme that would soon exceed the billion dollar mark, followed closely by many similar undertakings on every continent.

The rapid growth of nanotechnology at the beginning of the 2000s was accompanied by often exaggerated claims from the various stakeholders. It was frequently described as a new revolution that would raise thousands of billions of dollars and profoundly change the structure of society. In the United States in particular, there were claims that nanotechnology could play a role in cyber-humanity, immortality, and artificial life forms, while various science fiction writers described futuristic scenarios in which nanotechnology would become a commonplace feature of our lives, or else would cause major disasters. In the latter category, one of the best known novels is *Prey*, published in 2002 by Michael Crichton. Combined with the extensive and extensively publicised research programmes being set up just about everywhere, such excessive claims soon led to a raging controversy over the nanotechnologies. For each extravagant promise of benefits, there was a matching fear of risk: new synthetic life forms would suddenly appear and start taking over, there would be changes to human nature, populations would be controlled by implanted chips, and new weapons would be developed. Since then, over the past ten years, such wild claims have faded into the background and the debate over risks has refocused on more concrete issues, which are not in fact specific to nanotechnology, even though it sometimes has to be taken into account in particular ways.

Toxicity

Millions of tons of nanoparticles of all different kinds are already produced industrially and new species are periodically introduced onto the market. For the main part, nanoparticles are integrated into nanomaterials, but they can nevertheless escape when the material gets worn through use or ages in a waste disposal site. These nanoparticles are also present in factories where nanomaterials are made and may affect the personnel and the environment. One must therefore inquire as to their toxicity. Indeed, there is no particular reason to assume that new kinds of particles recently introduced onto the market would present no risk to humans, or more generally, to ecosystems. The case of asbestos fibres⁶ is there to remind us that this is not just a theoretical matter. So what are the risks with nanofibres?

⁶These generally have diameters of the order of a 1000nm, but some are 10 times thinner.

We are still a long way from understanding all the mechanisms involved in the toxicity of chemical products where this question is already relevant, but the situation is even more worrying for nanoparticles, if only because we have so much less experience with them. It has been clearly demonstrated that nanoparticles can easily enter the body, for example by inhalation, move around inside us, and sometimes damage cells via various mechanisms. Appropriate toxicity tests still need to be developed, and for each species of nanoparticle we will need to specify a level of exposure below which there is judged to be no risk.

One thing that causes concern among the general public is the large scale arrival of commercial products containing nanoparticles, without specific regulation, or even any obligation to inform the consumer of their presence. In France, an important step was taken toward traceability of nanotechnological products in the law of 12 July 2010 known as Grenelle 2. This requires all persons fabricating, importing, or distributing substances liable to release nanoparticles to declare them to the relevant authority. On 30 June 2013, 3400 such declarations were made by more than 930 declarants. At the same time, studies of the risks involved in nanoparticles are making some progress, but it will probably take some time before we are able to build up a firm understanding of these risks.

Nanoparticle Surface Areas

One property that is often cited when discussing the risks relating to nanoparticles is the high ratio of surface area to volume. Since all interactions occur via the surface, this vastly increases their capacity to interact with the environment and the cells in our bodies. To illustrate this, consider a cube of matter of side one centimeter (see Fig. 1.4). This has a surface area of 6 cm^2 . If we now cut this cube up into smaller cubes of side one mm, we obtain 1,000 such cubes, and taken together, these have a surface area of 60 cm^2 . If we go on to cut these up into cubes of side 10 nm, we end up with a billion billion cubes and a total surface area of 600 m^2 . And all this from one cubic centimeter of matter, a volume easily held on a spoon. Quite generally, this is known as the specific surface area of a nanopowder, a quantity measured in square meters per gram. It is not unusual to find commercial powders with specific surface areas of a few hundred square meters per gram.

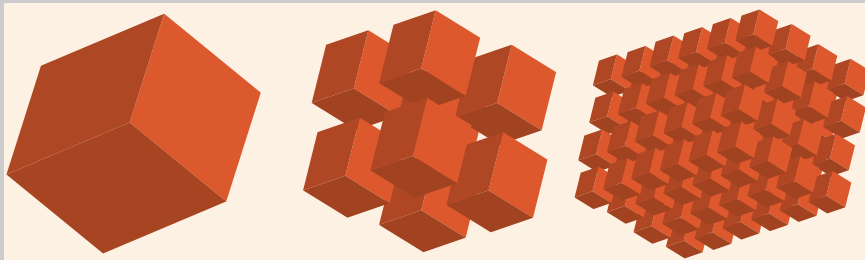


Fig. 1.4 Increase in the ratio of surface area to volume in the transition from a homogeneous solid to a set of nanoparticles

The main characteristic of a material reduced to a highly divided powder is thus its enormous surface area compared with its volume or its weight. And it is often precisely this enormous surface area that motivates potential users of nanoparticles. For example, when we wish to eliminate a pollutant from a certain environment by introducing particles to neutralise it, we expect the process to increase in efficiency as the particle size is reduced, since this will increase the surface area for exchange to take place.

Who decides?

Scientists push forward our knowledge and understanding, and at some point a new idea for an application can spring up. A long process is then set in motion to make this application possible, starting with technical trials, then industrialisation, and finally the arrival of new products on the market. This raises the following question: To what extent did citizen or consumer decide to realise this application? The question becomes more pressing still if the negative aspects of these new products, such as suggested or proven risks, effects on the environment, the establishment of monopolies, and so on, tend to outweigh apparent benefits like efficiency, reduced cost of a service, sustainable development, and so on. In some cases, the only possibility for any kind of influence left to the consumer, viz., the decision not to purchase, is effectively eliminated because nothing on the label indicates the presence of the ingredient that causes concern. Nanotechnological products fall perfectly into this category, with the explosion of new products over the past five years, despite the urgent need to address the question of risk. And the benefits are not always there. So while nanomedicine brings much hope and new products resulting from the miniaturisation of transistors and memories have led to a boom, other nanoproducts are clearly futile, with no obvious benefits.

Protection of Privacy

The development of information technology means that more and more details of our various activities are stored in memory, whether this be commercial or administrative data or just personal information to be found on the social networks, including now in the form of video. As early as the 1960s, there was already concern over the abusive exploitation of such data by an Orwellian state, or indeed by private individuals. But at that time there was no question of nanotechnology, whereas today, this innovation looks as though it can only complicate the situation, since more data can be intercepted, processed, and stored, thereby considerably aggravating the problem.

1.7 Prospects

Recall the title of this book: *Nanoscience and Nanotechnology: Evolution or Revolution?* What is the current situation? What has been happening over the last ten or fifteen years? Perceptions vary:

- For most scientists, nanoscience and nanotechnology are just the continuation of a long series of discoveries made through the twentieth century, along with the development of measurement and manipulation techniques on the atomic scale which allow us to observe and identify the novel properties of matter on this scale.
- For some of those who administrate science, but also for a whole range of commentators, the appreciation has been rather different, referring to an industrial revolution in which it was essential to invest in order to remain competitive.
- For those in industry, the exploitation of nanotechnologies generated by research has led to the creation of new products or improved existing products in some way, depending on the sector.
- For the citizen or the consumer, the advent of these technologies, mainly at the beginning of the 2000s, was rather sudden, without due consideration of their added value or risks. Within a few years, nanotechnology has thus become a subject of social dialogue and sometimes controversy.

So is this more like an evolution than a revolution? The actual situation is undoubtedly more complex. This would be to forget that, generally speaking, there is no direct route from a scientific discovery to a breakthrough product capable of transforming society, since this kind of product usually incorporates the results of many such discoveries. Nanoscience and nanotechnology are no different in this respect. Having said this, however, taking stock of the way things are going these days, it must be agreed that, through the miniaturisation of components they make possible, nanoscience and nanotechnology, associated with progress in other domains, have already made a major contribution to the revolution in information technology and communications. The cross-disciplinary dynamics of nanoscientific research will be illustrated in many other ways throughout the book, associated with new scientific horizons in the fields of energy, the environment, health, and medicine.

We may thus attempt to extrapolate the prospects from current research, and reflect upon what use can be made of them. Many such prospects will be further discussed in the following chapters. To this end, we shall consider three important examples.

Information Processing

The miniaturisation of components can already be exploited to make devices capable of processing and storing very large amounts of information. For the moment, this is without doubt the most tangible manifestation of the impact of nanotechnology on our everyday lives. Recent developments such as Internet, smartphones, social networks, and geopositioning, have had a profound impact on society and will probably continue to do so in the future. The literature is full of forthcoming innovations involving devices made possible by miniaturisation which may soon escape the confines of science fiction. As an example, we could before long find ourselves with smartphones that record videos of our every waking hour, enabling us to retrieve scenes on demand, or we could interact with machines simulating our conscience, and omnipresent sensors making our lives entirely ‘transparent’ and accessible on the social networks. Unless of course the world evolves in some other direction and we prefer to anticipate the increasing scarcity of energy and raw materials, realising sustainable information technologies and ensuring that personal data acquired in this way should remain private.

Novel Properties of Nanomaterials for Energy, the Environment, and Therapeutics

Nanomaterials are called upon whenever there is a need to improve materials or bestow them with new mechanical, optical, or electrical properties. However, over the past two decades, society’s outlook has changed considerably. It has become increasingly important to save energy and raw materials. Another growing concern is risk. In the past, various promising substances used in materials have turned out to be dangerous, to the point where some have even been forbidden. The classic example is asbestos, but there have been others. We have become wary of mass-produced molecules and nanoparticles which are incorporated in materials and later turn up in the environment, the air in our houses, and our bodies.

On the other hand, nanomaterials are also a source of hope, because they may provide ways of avoiding certain molecules that have become undesirable, saving energy by improving insulation and reducing the weight of transported goods, and improving the efficiency of systems such as batteries or solar cells. The future of nanomaterials will clearly depend on the benefits they can procure and progress in understanding the toxicity and environmental properties of nanoparticles. For this reason some institutes have opted for a new orientation by setting up what they call

green nanotechnologies. These aim to produce less toxic materials, or ones that make more efficient use of energy.

Moreover, one should not focus only on materials. Active molecules could be replaced by nano-objects incorporating not only these molecules but also other components, such as a capsule or a securement system. This idea, already used to make nanodrugs, could be adapted to many other substances as a way of improving efficiency or reducing toxicity.

Active Systems: Biomedical Applications

In the overlap of the two previous topics, there may be progress with active materials. We now know how to produce very small sensors and calculators, as well as actuators (a kind of motor) almost on the molecular scale. There is nothing to prevent us from integrating these into a material capable of exchanging with its environment, or even acting on its environment. These are likely to be relatively expensive materials, but could be adapted to highly specific applications.

One can get a better grasp of this idea by drawing a parallel with computer technology. From the centralised computers of the 1960s, we made the transition to personal computers in the 1980s, then to embedded systems, i.e., very small computers integrated into other devices in the 2000s, and the trend toward increasing integration of computer systems into materials themselves will doubtless continue in the mid-term. In the same way, factories were equipped with a centralised machine at the beginning of the twentieth century, but individual motors were widespread by the 1950s with the development of the automobile, and are now commonly integrated into dozens of everyday consumer products. In the end, we can easily imagine a more far-reaching integration of motor functions in materials, just as in biological tissues. In short, just what would be needed to make the sorting hat in the Harry Potter series.

In the biomedical field, an application of choice must certainly be tissue regeneration. Intelligent systems could be made to control the growth of new healthy cells by providing the molecular scaffolding and at the same time delivering the chemical signals needed for the growth of the tissues themselves. Naturally, very different applications can be envisaged here.

What we have just summarised so briefly represents only a tiny cross-section of the possibilities. The aim is to put nanoscience and nanotechnology in perspective, but as always, predictions are hazardous in such a field and it is important to keep an open mind.

Nanosciences and Nanotechnology

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Lourtioz, J.-M.; Lahmani, M.; Dupas-Haeberlin, C.; Hesto,
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