Prologue I

Great revolutions characterised the world of science in the 1900s. Among these, in the field of Physics, I will mention three. The first is **Quantum Mechanics**, which imposed a revision of the paradigm of Classical Physics when new phenomena were observed at the level of the structure of matter, such as the ultraviolet catastrophe, the photoelectric effect and the Compton effect. The second is Einstein's Theory of Relativity, through which it was necessary to reconsider the concepts of space and time, until then considered as distinct, and linked to a reference system and to well–defined sequences of "before" and "after". The third is Nanoscience, the search for the dimensions of a billionth of a metre, which took off definitively in the second half of the last century, starting in the 1950s, thanks to a succession of inventions, improvements in laboratory equipment, automation processes and even of luck, as sometimes happens. Nanoscience has proved to be one of the most fruitful areas of research in the Physics of Matter, and its results are still opening up new research horizons in many disciplines that are involved across the board, in turn offering opportunities for ever closer collaborations between researchers. The study of the History of Nanoscience and its applications in Nanotechnology allows us to retrace the fundamental steps that have been taken along this path. In this first chapter I will describe the fundamental concepts underlying this History. First, the reader will find the definitions of Nanoscience and Nanotechnology as they have been elaborated by authoritative organisations and research bodies. Then described the categories into which Nanomaterials can be divided. It was necessary to distinguish between Nanomaterials that appear in Nature and those that are engineered and industrially produced. Describe what techniques are used today to make devices at the nanoscale.

Starting from Soft Lithography, which uses elastomers to replicate structures, and which had great momentum between 1995 and 2005, describe then both the Physical and Chemical Deposition of Vapours, which allow extremely performing high quality materials to be obtained. After this, the reader will find the Etching technique, applied to make nanoengravings and Electron–Beam Lithography through which it is possible to perform the selective removal of parts of material in order to achieve the required part. Finally, the Focused Ion Beam as a technique of ablation of material and Photolithography is described.

The History of Science obviously includes a host of illustrious figures, and Nanoscience and Nanotechnology are no exception. In this first chapter of my research, I have considered three of the best known researchers whose contributions have been fundamental in the course of history, both from the point of view of their fields of research and of their written contributions, their books or articles. The first of these is Richard Feynman, who is often referred to as the founding father of nanotechnology, thanks to a speech he gave in December 1959 at the American Physical Society at Caltech, which was transcribed with the famous title There's Plenty of Room at the Bottom a few months later. The second name is that of Eric Drexler, the American engineer who is credited with having given a new voice to Feynman's work of more than twenty years earlier and with having allowed readers, even those not in the scientific field, to approach these topics through his text Engines of Creation. The Coming Era of Nanotechnology. The third person I have mentioned in this chapter, but he will certainly not be the last, is Norio Taniguchi, the Japanese researcher who is credited with the historical merit of having invented and given full definition to the term Nanotechnology for the first time in the history of science.

Further describe the history of Nanotechnology through its most significant years.

Nanoscience and Nanotechnology

The Nanoworld deals with objects whose scale is down to 10–9m. The modern Physics of the Nanoworld, the way we know it, began 70 years ago, shortly after the end of the Second World War. Generally speaking, if we observe the succession of events from a historical point of view, we can see how the Twentieth Century was characterized by three innovations, in the field of physics, which revolutionized the knowledge and direct experience of the world: Quantum Mechanics, the Theory of Relativity and Nanoscience. Quantum Mechanics was developed to overcome the inadequacy of the laws of Classical Mechanics applied to particular electron behaviours, for example. The Theory of Relativity modified the description of space and time known until the early Twentieth Century. Nanoscience has opened, not only virtually, the eyes of scientists on the universe of matter at a size close to atomic dimensions. On this scale, the properties of matter change to the point of giving rise to completely new phenomena, the study and development of which have lasted for decades and the results of which are, for the most part, already applied in everyday life.

Nanoscience is, in fact, a journey into the deep subsoil of matter, discovering what properties it demonstrates when it is investigated and made to interact at very small dimensions, of the order of one billionth of a metre. This journey has been undertaken by researchers in many fields, from Engineering to Medicine, from Physics to Biology, from Mathematics to Chemistry, and its end does not seem to be in sight at all: so many discoveries and opportunities follow one another, that it will not be easy to put an end to a search of this type. The results that are, almost daily, obtained are so many that a final event does not appear predictable in the medium or long term. Nevertheless, Nanoscience, and all its application fields that we shall shortly address as Nanotechnology, is already seventy years old and yet it seems to be at the dawn of its most radiant youth.

In the vast majority of historical writings dealing with this discipline, we read that doing Nanoscience already had a very specific purpose, even before starting in practice or possessing the appropriate tools to proceed: the investigation of the nanoworld was the solution, theoretically, through which an answer would be given to otherwise unsolvable problems. According to Richard Feynman, the inability to transcribe the entire Encyclopaedia Britannica on the head of a pin was linked to the absence, at his time, of the tools to do so. Why would such an operation be useful to people? Because it would mean the ability to condense entire libraries and make them transportable and usable practically anywhere, by anyone. In reality, doing Nanotechnology as a practical application of Nanoscience does not originate from a written mission statement. There is no document in which we can read: scientists set these goals and will go as far as this limit. The possibilities of this research seem limitless, its applications go beyond the imaginable. Nanotechnology is an open, boundless field in which we investigate for the pleasure of research and for economic achievement, for the improvement of the quality of life and for the acquisition of control over matter at any level. Yet, there is no apparently declared purpose for it, but perhaps only the underlying one of wanting to reshape the world, thanks to the properties of nanomaterials, in a different way than it is today, made with the same materials, at the bulk dimension.

However, a question must necessarily be asked and it is inevitable: is it really necessary to do this? The debate is open between the two main opposing factions: the supporters of Nanotechnology seen as a world of self–assembling machines and devices programmed by man for the most diverse purposes, and the detractors of this research, frightened by the fact that nanodevices can autonomously take control and supplant man in everyday life. To all intents and purposes, this seems to be a badly posed problem: it is not Nanoscience or Nanotechnology themselves that brings the connotations of positivity or danger towards man, but rather its use, and this is obviously left to the free will and conscience of those who apply it to the different fields.

In fact there is no scientific field that can be considered unaffected by the nanoworld. Composite materials, where nanoparticles are immersed in a polymeric matrix, with superior structural and robustness characteristics, transport systems for medicinal active ingredients, possessing the skill to precisely identify the release site, are just two of the fields in which it is expressed daily research in Nanotechnologies. To begin the discussion on History of Nanoscience and Nanotechnology (HNN), I will give the definition of both Nanoscience and Nanotechnology the way they are accepted today, through a description of how the definitions themselves changed over time, and then I will discuss a question that is often asked, at the beginning, in most of the works regarding the nanoworld: how old is “nano”? I will therefore talk about which nanomaterials are known today, giving the reader a general description of the two major areas, one about natural and the other about artificial nanomaterials, and how these last are manufactured.

Next, it is necessary to talk about those people who are considered the pioneers and founding fathers of this science, notably Richard Feynman, Eric Drexler, and Norio Taniguchi, through their most significant articles and books. Later, I will highlight, thanks to a paper by Christopher Toumey, how the transcript of the conference There’s Plenty of Room at the Bottom, by Richard Feynman, which is almost universally indicated as the founding document of Nanotechnology, is the subject of an interesting epistemological debate. I will bring to the attention of the reader both Toumey’s interpretations and the opinions of scientists – some of whom were awarded the Nobel Prize for their research in the field – from which it appears that this document does not always seem to have been fundamental for the discoveries. Indeed, in some notable cases, it was even unknown to researchers. I will then proceed to a description of the fields of study of Nanotechnology.

Definitions

It is important to distinguish at the very outset between Nanoscience, which is the study of phenomena at the very small scale, and Nanotechnology, which implies achieving a result that is in some way useful. According to this brief description, it is clear that Nanoscience and Nanotechnology are words that do not regard the same concept.

In 1994, the Royal Society/Royal Academy for Engineering Working Group on the subject adopted the following definitions:

Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at larger scale. Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometre scale (Whatmore 2006).

According to other more recent definitions, nanoscience is the study of structures and molecules on the scales of nanometers, ranging between 1nm and 100nm while the technology that uses nanoscience in practical applications such as electronic devices, medical applications and so on, is called Nanotechnology (Mansoori 2017).

Nanotechnology is indeed one of the most promising research fields of the 21st century. It is the skill to convert the nanoscience theories to useful applications through observations, measurements, assembling, controlling and manufacturing matter for dedicated purposes at the nanometric scale.

The National Nanotechnology Initiative, in the United States, defines Nanotechnology as a science, engineering and technology conducted at the nanoscale (1nm to 100nm) where unique phenomena enable novel applications in a wide range of fields, from chemistry, physics and biology, to medicine, engineering and electronics. In other words, Nanotechnology is the understanding and control of matter at the nanoscale […].

Encompassing nanoscale science, engineering, and technology, Nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale (National Nanotechnology Initiative 2020).

Both these definitions suggest that two conditions must be present when we are talking about Nanotechnology. The first is a matter of scale: Nanotechnology is concerned with matter whose structures possess a size at nanometric scale. The second issue has to do with novelty: Nanotechnology must deal with small things taking advantage of brand new properties because of the nanoscale; these properties do not appear in the bulk material. It is important to always make this distinction between Nanoscience and Nanotechnology. Nanoscience merges Physics, Material Science and Biology manipulating materials at molecular and atomic scales, while Nanotechnology is the ability to manipulate – whatever this word can mean, measure, assemble, manufacture, control – materials at a nanometric scale (Bayda et al. 2019).

How Old is Nano

It took a concatenation of events and a convergence of scientific discoveries to bring Nanotechnology into the public domain, from the invention of the Scanning Tunneling Microscope (STM), which saw the light in 1981, to the discovery of fullerenes in 1985 and graphene in 2004. Not only that, Nanotechnology received even more visibility thanks to the awarding of specific Nobel prizes, generally for Physics and Chemistry, to people whose names have remained milestones in the History of Science such as Heinrich Rohrer and Gerd Binnig, awarded in 1986 for the realization of the STM, Harold Kroto, Robert Curl and Richard Smalley in 1996 for the discovery of fullerene, ten years later, Andre Geim and Konstantin Novoselov in 2010 for their research on graphene.

The few events mentioned here were among those that brought to the fore the existence of a new science whose field of investigation belongs to Solid State Physics, where at leastone of the dimensions is of the order of 10–9m. From an historical point of view, it is legitimate to ask whether fullerene and graphene, for example, were the very first nanomaterials observed by researchers or, above all, the first materials produced on such a small scale. What we can say is that Man has always tried to mimic Nature, especially when he has come into possession of increasingly refined tools to investigate it. In this way, he was able to observe its structure, understand its mechanisms and try to artificially replicate what is present in the natural world in order to apply its secrets to as many outcomes as possible, adapting it in the laboratory, improving it for his own needs or even manipulating it, sometimes for his own purposes. Last but not least, Man has learnt a great deal from Nature, although some of the results Nature has achieved so far are still far from being replicated in a laboratory.

It becomes almost a need, therefore, to ask oneself if nanoparticles already exist in Nature and, if so, for how long have they done so. It is also easy to understand how extremely difficult it may be able to answer, at least the second question. The first question obviously has an easy affirmative answer. The presence of nanoparticles in Nature is quite predictable from the beginning, as practically every chemical compound – with the exception of liquid and gaseous compounds – has structures that can be made to fit into the nanometer size.

Starting from about the IV century AD, artisans have used materials in several circumstances which, thanks to their nanometric components, have led to improvements in metallurgy, glass art, ceramics and painting. The pigment known as Egyptian Blue (Fig. 1.1) has been used for thousands of years in Ancient Egypt. In nature, it can be extracted from a copper–calcium silicate, known as cuprorivaite, or copper–calcium tetrasilicate, whose chemical formula is $CaCuSi_4O_{10}$. Since this silicate is extremely rare in nature, it is not plausible that the Egyptians used it from natural sources, but rather that they were able to manufacture it through a complex and very precise process, which gives us reason to believe that their knowledge of chemistry was quite advanced; at the same time, the presence of this pigment in the artefacts identifies them as works of great value and prestige.

Egyptian blue powder. Source: Public Domain

Today we know that this pigment can be obtained by mixing sand with quartz content, a compound based on copper, calcium carbonate and alkaline substances according to the reaction:

$$Cu_2CO_3(OH)_2 + 8\ SiO_2 + 2\ CaCO_3 \rightarrow 2\ CaCuSi_4O_{10} + 3\ CO_2 + H_2O$$

which is performed at around 800°C or 1000°C.

The pigment has properties that make it possible to envisage applications today that go beyond the simple colouring of objects. When irradiated with visible light, Egyptian Blue emits intense near–infrared radiation, which makes it interesting, for example, for applications in microscopy and near–infrared spectroscopy. In medicine, imaging is a key tool for the analysis and prevention of dysfunctions. Typically, light–reactive substances called fluophores are used to mark the structures to be highlighted with a dye. By using reagents based on Aegyptian Blue, it is possible to investigate tissues in greater depth and obtain less distorted images. In 2020, a group of researchers at the University of Göttingen succeeded in obtaining nanosheets 100,000 times thinner than a human hair that give rise to near–infrared fluorescence, which is extremely stable and ideal for imaging (Selvaggio et al. 2020).

The brilliant turquoise–blue colour that has survived through the centuries in Central America is known as Maya–Blue, thanks to the pre–Columbian civilisation that created it, and has come down to us, unlike other pigments, because of its almost unique chemical characteristics. Technically, Maya–Blue is obtained when indigo is incorporated into palygorskite, a clay mineral. Indigo is extracted from the leaves of Indigofera suffruticosa and combined with a natural clay, palygorskite, a magnesium aluminium phyllosilicate with the formula (Mg,Al)2Si4O10(OH)×4(H2O), which is typical of clay soils but mysteriously only found in small deposits in southern Mexico and in areas where the Maya civilisation developed.

The chemical composition of Maya–Blue as we know it was determined in the 1950s through powder X–ray diffraction experiments, while a comprehensive study of the pigment has been made through techniques such as infrared spectroscopy, Raman spectroscopy, optical spectroscopy, voltammetry, nuclear magnetic resonance and computer simulation (Del Rio et al. 2011). This pigment results in a complex nanostructured organic–inorganic hybrid material of the components we have indicated, in which several positional isomers of indigoid molecules coexist with clay.

One of the most significant artifacts that must be recalled here is what is called the Lycurgus Cup. This is, technically, a diatretum cup, that is a glass container, from the Roman era and considered luxury item, which consists of an internal container and an external support cage, which detaches from the body of the cup, to which it remains attached through special supports. The depiction on the glass shows Lycurgus in the act of killing Ambrosia, a follower of Dionysus; however, the latter, transformed into a vine plans, wraps Lycurgus with its shoots, killing him before he achieves his purpose. The scene takes place under the teasing gaze of Dionysus and two of his followers.

One of the most famous artifacts in ancient history of science and art: the Lycurgus Cup. The cup displays its red aspect in transmitted light (left) and the green colour when under reflected light (right).

The glass the cup is made of is a dichroic glass showing different colours, depending on the light position with respect to the cup: if the light is frontal and is therefore reflected, the colour of the cup will be green while, if the light source is placed behind the cup and the light is transmitted through the cup, the glass will appear red (Fig. 1.2). This effect is a direct consequence of the presence of a small quantity of gold and silver nanoparticles, in colloidal form, in the glass paste; gold is responsible for the red colour while green produces the green colour. It is rather unlikely that this effect was deliberately obtained by master glassmakers, precisely because the size of the particles, around 70nm in diameter, and the quantities used are very small. It is more likely to think that the dichroic property of glass is a lucky result of a melting in a crucible in which other materials had been previously worked, and that they left residues in an exact but random quantity such as to produce the glass as we can admire it in the Lycurgus Cup. It must be remembered that the behaviour of glass, in the case of the Lycurgus Cup, depends on an absolutely precise concentration of colloids, on the oxidation state of some chemical elements present, on the diameter of the particles, on the proportions of the components, on the processing time, on the crucible temperature, from atmospheric conditions, probably, during processing. It would have been very difficult to obtain a second product with the same properties that have been described for the Lycurgus Cup. The glass technology that allowed the Romans to obtain these results did not, however, last very long.

A bladesmith from Damascus, Syria. Source: Studiolum.com, Public Domain, https://commons.wikimedia.org/w/index.php?curid=14837124

A blade so sharp as to be capable of cutting a piece of silk that inadvertently falls on it is the description made of those swords called Damascus Swords. These swords possess characteristics of very high mechanical resistance and such a flexibility that they are said to bend up to an angle of 90°. To understand the reason for the features of these swords, made of a metal that was believed to be legendary, a sample of the steel was dissolved in hydrochloric acid and then the remains were analysed under a high–resolution Transmission Electron Microscope and through Wide Angle X–ray Diffraction (WAXD). From the images, it was possible to highlight the presence of carbon nanotubes and cementite nanowires as residues from the forging process. The artisanal heating and forging process incorporates organic debris, in different steps, that allow the formation of nanostructures during the steel manufacturing process (Fig. 1.3).

Damascus steel was, in turn, forged from ingots of a steel originating in southern India, and which is known as Wootz steel. The carbon content in Wootz steel was granted by the preparation itself, that made use of Cassia auriculata wood and the leaves of the Calotropis gigantea shrub, two plant species characteristic of India and the island of Ceylon, together with minerals extracted in particular mines. Analyses have shown the presence of cementite also in weapons made with Wootz steel. During processing, the steel was repeatedly heated and hammered, in order to obtain a thin and shaped blade, a process that left very characteristic wavy patterns on the surface of the alloy (Fig. 1.4).

Close view of details of a 13th century Persian–forged Damascus steel sword. Source: image by Rahil Alipour Ata Abadi – Transferred from en.wikipedia to Commons., GFDL, https://commons.wikimedia.org/w/index.php?curid=50800188

Although they were extremely skilled, the blacksmiths of ancient India and Damascus could be defined as real “unaware nanotechnologists”, because they were certainly not aware of the fact that they were working on nanometre–sized materials. We might guess that they proceeded by trying and failing, trying again and finally reaching the result without knowing what was actually happening inside the material. The coloured glasses that adorn the stained glass windows and the rose windows of the cathedrals that arose, especially in Europe, during the Middle Ages are another example of how nanotechnologies can be applied for the realization or, as this is the case, the improvement of materials. The most superb examples of this glazing technique are in the windows of the Notre–Dame of Chartres cathedral (Fig. 1.5), whose construction began in 1194. Exactly as we said before regarding the roman glassmakers, it is logical to assume that the craftsmen were not aware of the physical principles capable of justifying the colouring, rather of the fact that by adding different metals to the melted paste they could obtain extremely particular shades of colour.

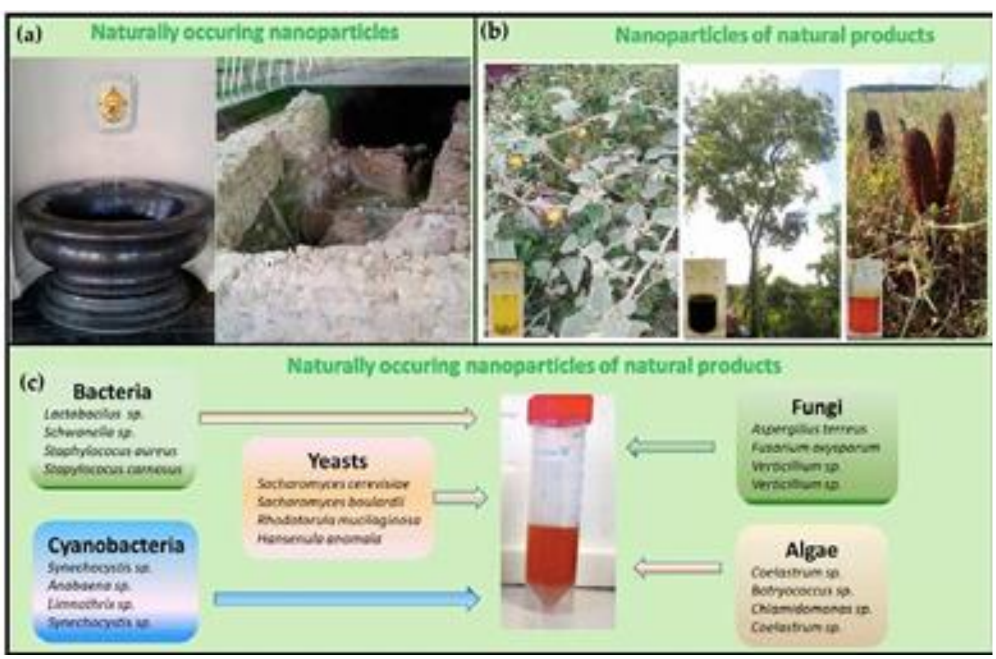
Detail of the Notre-Dame de la Belle-Verrière, or Blue Virgin (1180–1225), perhaps the most famous window at Chartres, Cathedral. Source: Vassil – Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6080958

What Nanomaterials do we know?

Nowadays nanotechnology, with its applications, is in fact omnipresent and is an integral part of the lifestyle we lead and the products we use, from silver nanoparticles in toothpastes, to particles that improve the release of the active ingredients of medicines, to nano additives that are used to reinforce plastics. Here describe the two main categories Nanomaterials can be divided into: Natural Nanomaterials and Industrial and Engineered Nanomaterials. Natural Nanomaterials appear as a consequence of natural or biological phaenomena, like volcanic eruptions, to give an example. Industrial Nanomaterials are designed and manufactured, instead, to answer to specific requests in different fields and must possess very precise characteristics.

Natural Nanomaterials

When it comes to nanoparticles, it is not always necessarily true that something artificial is being described. Through the research of scientists themselves, we have realised that Nature is an excellent nano–technologist. In fact, it is able to provide us with a wide range of particles, from inorganic ashes to soot, from sulphur nanoparticles to minerals found in wells or in the air, up to those produced by bacteria or yeasts, such as selenium nanoparticles. All these examples refer to nanoparticles which are completely natural and whose observation, not surprisingly, stimulates the interest of research in the development of natural products at the nanoscale, in new fields such as phyto–nanotechnology and phyconanotechnology (*Phyto–nanotechnology is a new emerging research filed of the nanoworld, where target–specific delivery of nanomaterials to agricultural crops and plants is studied, which may enhance or add plant functions, and achieve environmental monitoring and resistance to pollution as well. Phyco–nanotechnology can be defined as the study of algae–mediated biosynthesis of nanometals*.) The nanomaterials found in nature, together with those manufactured in laboratory, but which are still inspired by those that can be observed in the surrounding environment, have proved to be promising starting points for research in fields such as Medicine, Nutrition, Agriculture and Cosmetics. This is thanks to their unique chemical and physical properties, and their ability to be activated in biological structures (Griffin et al. 2018).



These are some examples of natural and biological materials containing nanoparticles. We can find naturally occurring nanoparticles of elemental sulphur in hydrogen sulphide–rich mineral wells (a) such as at the Elisenbrunnen in Aachen, Germany. Mechanically produced nanomaterials (b) have been evaluated for medical and agricultural applications. Also naturally produced nanomaterials from natural and biological products exist (c) such as nanoparticles of elemental selenium, coated with microbial proteins formed by bio–reductive, or oxidative, metabolism in bacteria and fungi.

When we talk about "natural" nanomaterials, it is important also to make a distinction between those nanomaterials that are "natural" because they are already present in nature without any human intervention, and those ones that are, at the same time, "natural" and also "bio", i.e. they exist in nature as a result of biological activities, primarily referring to biological substances or materials. This is not just a semantic distinction, though. In the following picture (Fig. 1.7) this division is illustrated, providing some interesting examples of natural nanoparticles of particular interest, and nanoparticles from natural products.

Mother Nature really is a very skilled nano manufacturer. To understand completely where natural nanostructures may have appeared from, we must first refer to the hypothesis proposed by Aleksandr Ivanovič Oparin in 1927, stating that the first step of evolution on Earth involved the chemistry of simple organic substances, within the warm primordial oceans formed after the cooling of the Earth, in its younger stages. Oparin believes this level was inevitable even at a former era, regarding carbon compounds: However, the Earth was gradually cooling down and the time must have come when combinations of free elements began, the elements mixed together. (Oparin, 1977).

Further on, the author goes into the discussion of the nitrogen and carbon compounds that are recognized as the basis of life. Eventually, the time came when the temperature of the surface layers of the Earth dropped to 100°C.

[...] The first organic substances that had hitherto remained in the atmosphere were now dissolved in the water and fell to the ground with it. What were these substances? […] They were substances with a large reserve of chemical energy and possessing a great chemical potential. Since they were in the Earth's atmosphere, they had begun to combine with each other, giving rise to very complex compounds. They also combined with oxygen and ammonia to give hydroxy–derivatives and aminoderivatives of hydrocarbons (i.e. compounds of hydrocarbons with oxygen and nitrogen, respectively). When these substances fell from the atmosphere into the primitive ocean, they did not cease to interact one with each other. Specific organic substances brought by the waters met and combined. Thus, even larger and more complex molecules were formed. We can easily get a fairly accurate picture of this process of aggregation (polymerization) of organic substances on Earth, by studying it in our chemical laboratories. In fact, the conditions, under which organic substances existed at the stage of development of the Earth we are dealing with, can be realized quite easily in our laboratories. If we subject substances such as hydrocarbon radicals to the conditions described above, and leave them to themselves, we must find that the entire chain of reactions described above takes place. The hydrocarbon radicals will be oxidized at the expense of oxygen in the water and air to give the largest variety of derivatives (alcohols, aldehydes, acids, etc ...). This process takes place particularly quickly at high temperatures, and in the presence of iron and other metals (ibidem). In a later paragraph, we can read also that: In this mixture, we can even find, among other things, compounds of the nature of carbohydrates and proteins. Both of these types of compounds play an important role in the structure of living material.

We find them in animals and plants without exception. In combination with other and even more complex substances, they are, so to speak, the basis of life (ibidem). This is the first stage of the chemical evolution.

At a second stage, the structures Oparin predicted combined to form amino acids and other complex structures such as peptides, proteins and so on. The dehydration process allowed the polymerization of small units, so the process could happen, at this level, abiotically.

A third stage involves the interaction of these polymers with each other to give rise to aggregates known as protobionts. These primary aggregates do not possess all the features of a living being, since they cannot reproduce, but at a further stage they acquired the possibility of reproduction and passing of information from one generation to the next. This kind of genesis of living beings on Earth was no longer possible after the appearance of photosynthetic organisms that filled the atmosphere with oxygen. The presence, in the upper atmosphere, the O3 allotropic and resonant form of oxygen, and its interaction with the UV frequencies rendered abiogenesis impossible. A new form of evolution was then necessary under a completely new form of atmosphere that transformed in composition and temperature to be the one that nowadays surrounds the planet.

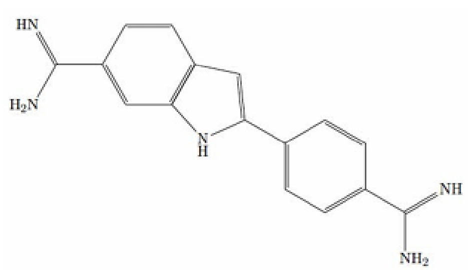
In this changing environment, the organisms that evolved were nanometric in size, or could contain nanometer–sized organelles needed to perform their fundamental functions and ensure survival, and were able to organize themselves into more complex structures of different shapes and sizes. Not only that, they were able to interact with the surrounding environment, with light, water, temperature, the conditions of acidity or basicity around or with other molecules and organisms. Therefore, we must think that nanoparticles were already existing when the evolution of life on Earth began; for example, single particles of nanometric size, and not connected to each other or connected to something else, were found in different fluids of natural origin. Viruses, organelles of living cells, diatom shells incorporated in grains of sand suspended in water or on the seabed of the oceans are no exception. Because of the global conditions described by Oparin, the first organisms to evolve on Earth had to be thermophilic, able to survive in warm environments, and they developed a chemotropic metabolism in order to extract energy from inorganic substances such as sulphur or carbon to ensure their survival.

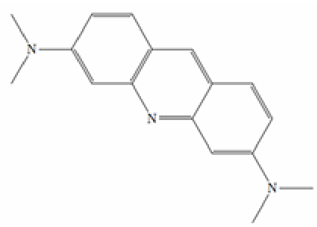
About 2.5 billion years ago, at the end of the Archean era, the temperature on Earth dropped to 72 degrees Celsius, which has been recognized as the maximum limit for triggering the phenomenon of photosynthesis, and allowing the production of free oxygen in the atmosphere. The cyanobacteria then present improved the photosynthetic process, causing a radical change in the composition of the Earth's atmosphere, and the disappearance of those organisms whose survival depended on an environment rich in carbon dioxide and methane. Life then evolves to more complex forms, characterized by the presence of nanoparticles such as biopolymers like DNA and RNA, certain types of proteins, cellular organelles such as mitochondria for respiration, ribosomes for protein synthesis, chloroplasts for the completion of the photosynthesis process, the nucleus seat of genetic information and so on.

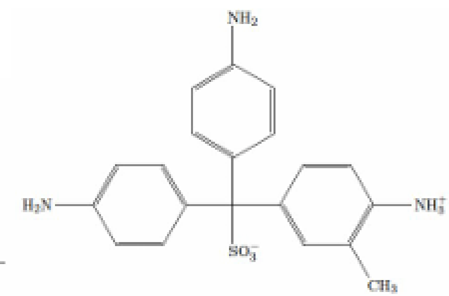
The earliest life forms that appeared on Earth were necessarily very small in size, as higher size structures and higher complexity evidently entailed unmet evolutionary stages. Some of the nano–organisms that then appeared can be grouped into three main categories: nanobi, viruses, and bacteria.

Nanobi are filamentous structures, comparable to actinomycetes, which were dated in the Triassic, between 251 and 199.6 million years ago, and in the Jurassic, between 199.6 and 145.5 million years ago, in sedimentary rock structures and sandstone. We recall that the temporal interval between these two periods was marked by the great mass extinction of the great reptiles. Due to their size, the smallest can measure between 1nm and 20nm in diameter, so it can be assumed that it is the smallest form of life, being up to ten times smaller than the smallest bacteria known so far. Since they were found in rocky sediments, the first interpretation that has been attributed to these living beings is that they simply are crystalline formations, however the presence of DNA, found in nanobi specimens, would prove the opposite. Indeed, nanobi are non–crystalline and show the presence of an outer membrane, which encloses two regions that have been observed.

The first region is densely occupied by electrons, and is usually interpreted as a kind of cytoplasm, the second, centrally located, is less dense and is referred to as the nucleus, as it has shown reactivity to three organic dyes. The first of these dyes is DAPI (Fig. 1.8), or 4’,6–diamidine–2–phenylindole, a dye that is highly reactive to regions rich in adeninethymine blocks, and which can be used for both the analysis of live cells and fixed cells, thanks to its ability to penetrate the cell membrane. In the following figure the molecule of DAPI is represented.







The structure of DAPI molecule.   The acridine orange structure. The leucofuchsin molecule structure

The second technique involves acridine orange (Fig. 1.9), an aromatic heterocyclic compound that can, in turn, cross cell membranes to interact with DNA or RNA, in the first case by intercalation, in the second case by electrostatic attraction.

Finally, it is possible to highlight the nucleus of these nanostructures through the procedure that takes the name of Colouring of Feulgen, from the name of the German physiologist Robert Feulgen (1884–1955), who first perfected it in 1914. With this technique, which involves the use of decolorized hydrochloric acid and fuchsine (the so–called Schiff reagent, see Fig. 1.10), it is possible to colour the DNA, not highlighting, at the same time, also the RNA, thus differentiating the two nucleic acids. Nanobi, which are carbon, nitrogen and oxygen compounds, grow aerobically at room temperature.

Viruses are not considered as living beings, since they are not able to sustain all the vital functions characteristic of what is defined as autonomous life, such as they cannot reproduce without a host, they cannot metabolize autonomously, they do not possess a cellular structure. To be able to exactly date the appearance of viruses on Earth is not so simple, as there are no fossils that testify their presence in ancient times. One of the most likely hypotheses is that they were subject to some form of evolution, from complex protein molecules and nucleic acid, before the appearance of life on Earth. Other hypotheses, based on the analysis of different virus genes, suggest that they originated from cellular DNA fragments and only later became independent. A third possibility is that these viruses appeared very early in the evolution scale, and part of their DNA remained bound to the genome of some cells. The fact that some viruses are able to infect humans as well as animals, suggests that they may have had a common origin that could be dated to several billion years ago. They are entities of nanometric dimensions. The Parvoviridae family includes the smallest known viruses, measuring between 18nm and 28nm. These viruses are linear, not segmented and consist of a single strand of DNA, the average size of their genome is about 5000 nucleotides and their viral capsule consists of 2 to 4 proteins.

Alongside these, Pandoraviruses (1000nm) and Phitoviruses (1500nm) are, among the isolated viruses, those with the largest size. Bacteria are the oldest known organisms. Their evolution is approximately between 3.5 billion years ago and 2.7 billion years ago. The almost total absence of competition with eukaryotic organisms and their simplicity of organization have allowed their enormous development in virtually every environment. Pathogenic bacteria, usually referred to as microbes, develop nanoparticles in the environment, through biomineralization processes that allow them to produce inorganic substances such as iron and silicon nanominerals, carbonate and calcium phosphate. Nanobacteria, or nano–size bacteria, are the smallest bacteria in the cell wall, and include ultramicrobacteria as a possible dormant form of larger cells (200nm) and mycoplasms (300nm) as the smallest known form of bacteria. Organisms belonging to precise subdivisions of the classification system, namely bacteria, fungi, algae and plant cells, have all attempted the biosynthetic production of nanometals and it is no secret that unicellular and pluricellular organisms can synthesize inorganic nanomaterials through intracellular processes, but also through extracellular processes. Bacteria belonging to the genus Leptothrix and the genus Gallionella are able to oxidize iron to produce the energy necessary for their survival, producing metal nanoparticles of ferrihydrite and iron(III) oxide–hydroxide.

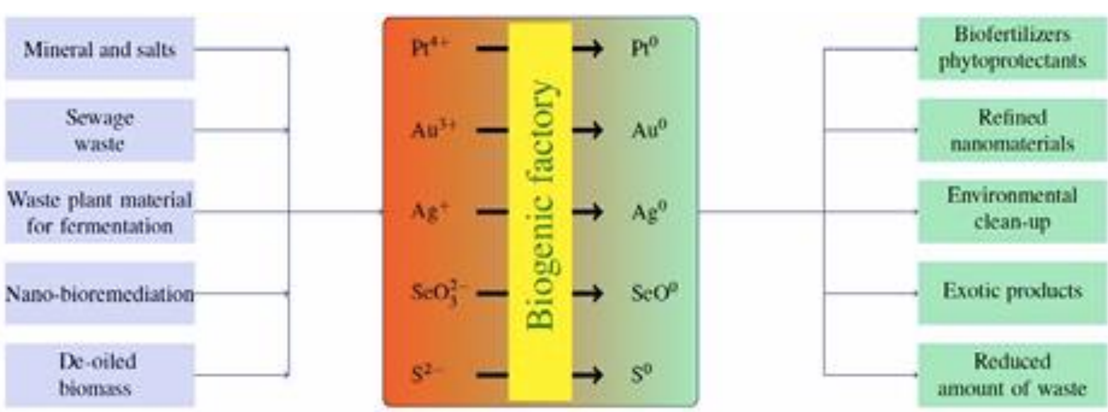
The search for nanoparticles in our environment is also characterised by a number of natural particles that do not belong to the realm of the living such as, for example, ash and soot particles, products of volcanic activities, in whose clouds one can observe microscopic and nanometric particles containing silicates and ferrous compounds, or fires, i.e. different types of combustion.

These particles are found in nature, but cannot be traced back to biological processes. Their size, varying between 100nm and 200nm, means that they have a significant impact on health once inhaled, as they can penetrate deep into the respiratory tract, trachea, bronchi and lung alveoli. In the case of combustion of organic substances, such as the wood of particular tree species, it has been possible to measure nanoparticles of a smaller size, whose structure is typical of multi–walled carbon nanotubes, between 15nm and 70nm.

The processes of precipitation, oxidation and reduction, albeit to a minimal extent in the latter case, are responsible for the formation of nanoparticles, transformed from higher structures already present in nature. Water, examined under the microscope, provides the medium for the suspension of calcium carbonates and sulphates coordinated with iron oxides. The suggested mechanisms for their formation range from slow precipitation to abrasion, which must lead us to think that the nanometer–sized particles that are present in our environment are not as rare as we might think. The nanometric materials generated in nature, through simple chemical processes that are more or less random, are characterised by a rather coarse morphology, far removed from the structures that can be precisely obtained in a laboratory, where conditions are controlled. If, for example, we consider natural sulphur–based nanoparticles, they may have originated from a simple sulphide (HS–), inorganic polysulphides (HS–x) or elemental sulphur (S). These three classes of compounds are highly reactive and can be easily converted into each other in the presence of oxidising agents, mainly air, or chemical reductions. In the laboratory, however, sulphur nanoparticles of appreciable quality, almost uniform size and virtually spherical shape, with a diameter of around 150nm, can be obtained under controlled conditions and reactions similar to those performed by nature. Typically, sulphide and sulphite (SO2–3) are proportioned through redox.

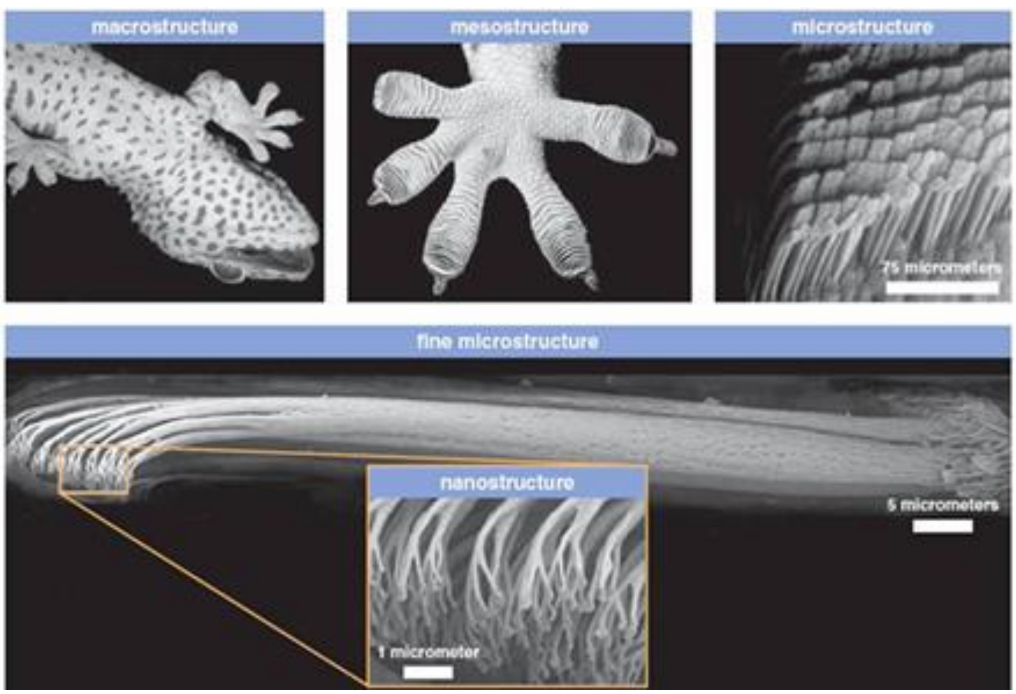
It is not only processes linked to volcanism or mineral springs that give rise to natural nanoparticles. Living cells can use a variety of reactions to produce such compounds. It is precisely because of their size that cells have to deal with nanotechnology: a DNA strand has a diameter of around 2.5nm for instance, a virus is about 100nm wide, while a typical bacterium is about ten times larger, at around 1µm–3µm. It should therefore come as no surprise that cells are engaged in nanotechnology. It should be noted, however, that cells do not work in the solid state because any type of deposit, precisely because of the size involved, could lead to the death of the cell itself and must be effectively expelled from it. The expulsion of deposits, which these organic nanolabels achieve in the form of almost spherical particles, is the end of a real mechanism for producing nanoparticles that has been mimicked. These processes can be exploited to produce particles of good quality and yield, even in food products, or for bioremediation or decontamination of soils that have been enriched/polluted with toxic metals or semi–metals. Removing environmental contaminants (heavy metals, pollutants, organic or inorganic) from contaminated sites by means of nanoparticles or nanomaterials derived from plants, fungi or bacteria, what is called nanobioremediation (NBR) is an environmentally friendly and cost–effective alternative to traditional chemical methods. The three main strategies of this modern bioremediation, which aims primarily at removing contaminants, include the use of plants, microbes or isolated enzymes such as laccase or nitrate reductase. The nanoparticles that are generated by these organisms are no longer seen as pollutants but as valuable alternatives of natural origin. One of the most interesting compounds for the development of selenium nanoparticles, whose medical/therapeutic applications are being investigated, is selenite anion, a selenium oxyanion whose formula is SeO2–3, which can be processed by microorganisms such as Saccharomyces cerevisiae and Staphylococcus carnosus. Through these microbes, it is possible to obtain rather homogeneous silicon nanoparticles, the diameters of which can be measured between 60nm and 80nm. After being cleaved by the cell, these particles can be recovered for application as food supplement or antimicrobial agents, thanks to the properties they have been shown to possess. Not only that, possibilities have also opened up for their use in agriculture where, at the same time, they can strengthen foodstuffs, provide plants with elements for their natural defences and eradicate pathogens from plants.

Other bacteria, such as Pseudomonas aeruginosa, Thiobacillus Serratia and Stenotrophomonas employ a reductive or oxidative detoxification pathway that eventually leads to the formation of elementary particles of sulphur, selenium, silver and gold (Fig.).



A schematic description of a biogenic factory, i.e. bacteria that can detoxify wastes or dangerous ions into useful compounds and elemental metals.

It must be emphasised that nanoparticles of natural origin are not comparable to materials that are made in the laboratory, as they cannot be chemically pure and contain a natural coating of proteins, a reflection of the organic environment in which they were produced. Eventually, we can imagine a process in which bacteria are grown on contaminated soil and, as they reclaim that soil, produce well–defined nanoparticles that can be harvested and used in medicine, agriculture or other applications. The benefits that could result from such an approach can be substantial and are not far–fetched either, since major contaminants such as heavy metals often also form the basis for the production of particularly interesting nanoparticles. Nature is a source of inspiration for researchers, who observe the nanometric biological structures that are already present, in order to translate them into synthetic materials of common use, or into technological structures for the most advanced uses. One of the most remarkable examples is the so–called Gecko–Tape, a synthetic tape that aims to reproduce the structures under the legs of the reptile known as the gecko. The legs of the gecko have attracted attention because they allow this lizard to adhere to a wide variety of surfaces without having to secrete adhesive substances, but rather because of their structure, which allows Van der Waals forces to be exploited. The underside of the legs is covered with microscopic hairs, called setae (from the Latin seta), consisting of fibrous structural proteins that protrude from the dermis, thinner, on average, than a human hair. On each of these setae are thousands of even smaller structures called spatulae. The large number of spatulae serves to maximise the area of contact between the animal and the surface (Fig.).



The hierarchical structures on a gecko's foot. https://en.wikipedia.org/wiki/Gecko_feet

Since these structures are the ones in contact with the surface, they are the ones that are studied most carefully in terms of friction and adhesion capacity, considering the forces acting on them.

Kendall's model (Kendall 1975) makes it possible to study how a tape behaves when it is detached from a surface through the interaction of three terms, elastic, potential and surface. The equation, quadratic in F/b, which groups them is as follows.

$$\left(\frac{F}{b}\right)^2 \cdot \frac{1}{2hE} + \frac{F}{b} \cdot (1 - \cos\vartheta) - G = 0 \quad (1.1)$$

Here F=F(J) is the force needed to detach the tape – the gecko's leg –, b the width of the tape – the spatula pads –, h the thickness, E the elastic modulus, J the angle of detachment, and G the breaking energy, which is needed to break a unit area of surface at a detachment angle of 90°. A difference we have to note is that Kendall's model does not include any term referring to friction, which for gecko must be considered. The two terminal levels in the hierarchy of gecko structures, those dedicated to adhesion on surfaces, are the setae and the spatulae. Let us see how the study of adhesion and friction mechanisms between a single spatula and the substrate is treated in literature.

$$E_x = E_0 \sin(2\pi x / x_0) \quad (1.2)$$

so that the friction force is:

$$F_f = -\frac{dE_x}{dx} = -\frac{2\pi E_0}{x_0} \cdot \cos\left(\frac{2\pi E_0}{x_0}\right) \quad (1.3)$$

where x0 is a spacing that refers to the atomic lattice, or the size of the asperities on the surface of the spatula and the substrate. When Ex = 0, then FL = Fmax f and the maximum static frictional force, in the absence of external load, between the two contacting surfaces is obtained. If a force greater than this is applied, the surfaces begin to slip and then slide. If, on the other hand, FL ≤ Fmax f, the friction force becomes FL = Ff, and the surfaces remain in contact, although some extremely slow microslip cannot be excluded. The Lennard–Jones model, which includes an attraction energy EA and a repulsion energy ER, allows us to calculate the normal potential EZ and the force FVdW between the two surfaces along the z direction.

$$E_z = -E_A \left(\frac{z}{z_0}\right)^{-n} + E_R \left(\frac{z}{z_0}\right)^{-m} \quad (m > n)$$

and:

$$F_{Vdw} = -\frac{dE_z}{dz} = -nE_A \left(\frac{z}{z_0}\right)^{-(n+1)} + mE_R \left(\frac{z}{z_0}\right)^{-(m+1)} \quad (1.5)$$

when Ez has the minimum value, FVdW = 0 with a gap between the surfaces D0. When the two surfaces are compressed against each other, D < D0 and the force FVdW is repulsive,

when Ez has the minimum value, FVdW = 0 with a gap between the surfaces D0. When the two surfaces are compressed against each other, D < D0 and the force FVdW is repulsive, while if it is D > D0 the force is attractive and reaches a maximum value ***Fn = Fmax VdW,*** when the surfaces separate spontaneously. The maximum attractive force calculated per unit area, if D < D0, can be approximated with the relation:

$$P_{VdW}^{max} \approx \frac{A}{6\pi D_0^3}$$

where A is the so–called Hamaker constant (1905–1993), a parameter that relates the Van der Waals energy to the distance separating two molecules. If, on the other hand, D > D0 the relation must be corrected in the following:

$$P_{VdW} = \frac{A}{6\pi D^3}$$

At steady state there are three forces acting in three precise zones. The first is the contact region, where the Van der Waals force is balanced by the steric repulsive surface forces: here, obviously, the overall force acting on the blade has zero resultant. The second zone is the detachment zone, where the force FVdW of the blade is balanced by the force F(J) along the axis of the blade itself. The third is where the Van der Waals force is negligible and where the tensile force is F(J) along the axis. We can write:

$$F(\vartheta) = F_n \sin\vartheta + F_L \cos\vartheta \tag{1.8}$$

The bending force Fb(J - 90°) can be neglected because the bending inertia of the individual spatula is also negligible. The individual components of (1.8) are:

$$F_n = F_{VdW} = F(\vartheta)\sin\vartheta \tag{1.9}$$

$$F_L = F_f = F(\vartheta)\cos\vartheta \tag{1.10}$$

The following integral allows the calculation of the attractive force in the detaching area.

$$F_{VdW} = \int_0^{\vartheta} \frac{A}{6\pi D^3} \cdot bR\, d\phi = \int_0^{\vartheta} \left\{\frac{A}{6\pi[D_0 + R(1-\cos\phi)]^3}\right\} \cdot bR\, d\phi \tag{1.11}$$

where the denominator expression has been expanded taking into account that the radius R of the spatula is related to the critical separation distance from the relationship:

$$R = \frac{D_c}{1-\cos\vartheta} \tag{1.12}$$

and D0 represents the distance between the surfaces. It is possible to evaluate the Van der Waals force from the expression of the force between a plane surface and a cylinder whose radius is half of R:

$$F_{VdW} = \frac{Ab\sqrt{R}}{16\sqrt{2}\, D^{5/2}} \tag{1.13}$$

Equation (1.6) can be used to give an estimate of the attractive component Fc,VdW in the contact region which allows the contribution of the adhesion force to the friction Ft to be calculated. If the values A = 0.4´10–19J and D0 = 0.3nm are considered as the separation distance of two surfaces, the equation leads to the following value Pc,VdW = 80MPa. In the contact region, the net attractive force is:

$$F_{c,VdW} = L_c \cdot b \cdot P_{c,VdW} \tag{1.14}$$

where Lc·b is the contact area between the spatula and the substrate. The maximum friction force, using the result shown in (Urbakh, Klafter, Gourdon and Israelachvili 2004) for the friction coefficient:

$$F_t^{max} = \mu F_{c,VdW} \tag{1.15}$$

where µ is the coefficient of friction. Since this coefficient, for a polymer that is rubbed against a chemically inert surface, or Van der Waals surface, varies on average between 0.2 and 1.0, one can estimate Fmax t to be around 900nN–4500nN. It has not been possible to directly measure the friction force of a single spatula yet. Instead, a friction test for a single silk was done years ago (Autumn et al. 2000) and showed that the maximum friction force of a single silk is around ≈200µN. If we estimate, for a single silk, a number of spatulae varying between 100–1000, then the value of Fmax t is around 200nN–2000nN, in agreement with the theoretical prediction. As is well known, one cannot have a high adhesion normal force Fn for small pull angles, if the lateral friction force is high. The total normal force can be written as:

$$\begin{aligned} F_n(\vartheta) = & \quad F(\vartheta)\sin\vartheta \\ = & \quad \left(F_f\cos\vartheta + F_{VdW}\sin\vartheta\right)\cdot\sin\vartheta \\ = & \quad 0.5F_f\sin 2\vartheta + F_{VdW}\sin^2\vartheta \end{aligned} \tag{1.16}$$

If the value FVdW(10°) = 70nN is applied, it is possible to observe that for high angular values, i.e. for J > 60°, the term FVdW gives the greatest contribution to the value of Fn(J), while for small angles, i.e. J < 30°, it is Ft that provides the most significant contribution to the total normal force. The highest adhesion force is obtained for small angles J and this is fundamental to understand how these reptiles manage to exert such a large adhesion force that they can run on ceilings. The contributions to the total lateral force are:

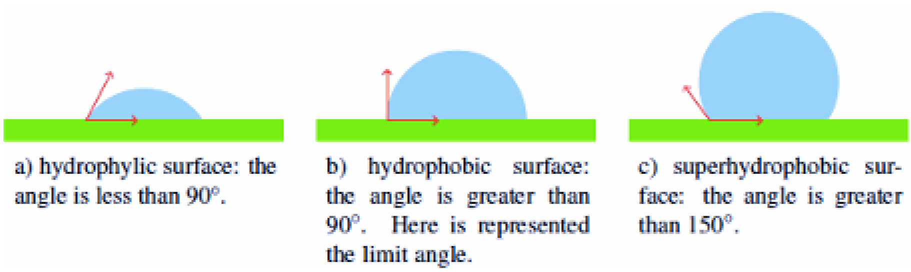
$$\begin{aligned} F_L(\vartheta) = & \quad F(\vartheta)\cos\vartheta \\ = & \quad \left(F_f\cos\vartheta + F_{VdW}\sin\vartheta\right)\cdot\cos\vartheta \\ = & \quad 0.5F_{VdW}\sin 2\vartheta + F_f\cos^2\vartheta \end{aligned} \tag{1.17}$$

When the angle J becomes small, the friction reaches very high values and justifies why the gecko can hang from the ceilings. When the spatulae are placed on the surface, they form an angle of about 30° with the silk and are practically orthogonal to their support structure so, when they adhere to the substrate, the angle between the spatula support and the latter will be close to 90°, with a low adhesion force, which has been measured at about 8µN. When the gecko, however, takes hold on the surface, the angle that can be measured between the silk backing and the surface is reduced in a range between 0° and 30°, which is in the range for which the adhesion force has been shown to be maximum. For an angle around 10°, the calculation resulted in a value of 200µN. This may be the scientific explanation for the behaviour of the gecko's legs and thus their ability to remain firmly attached to surfaces and run on ceilings. Finally, in order to evaluate the detachment force applied to a silk, if N is the average number of spatulae present on a silk that detach instantaneously, B the length of the total support of the spatulae, v the detachment speed and T = B/v the detachment time of a single silk, we have:

$$F_{n-seta} = \quad \frac{1}{T}\int_{t=0}^{t=T} NF_{VdW}\cdot\frac{(B-vt)}{L}\,dt \quad = \quad NF_{VdW}\cdot\frac{B}{2L} \tag{1.18}$$

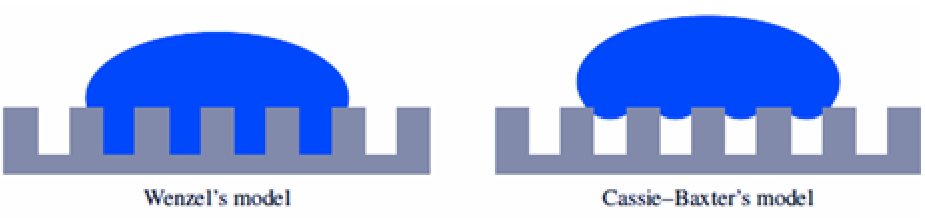
where L is the projection of the silk support on the surface (Tian et al. 2006). Another of the best–known examples of the presence of nanostructures in Nature is that of the surface of lotus leaves (nelumbo nucifera). In the course of evolution, this plant has perfected itself, developing exceptional water–repellent properties, properties that are now being studied in the laboratory and applied to advanced materials, although it is not yet possible to reproduce Nature's perfection exactly in this case. The leaf of the lotus, or rather the upper page of the leaf, is the most super–hydrophobic of those that can be found in the plant kingdom, because it is able to develop a contact angle with water of up to 170° and a sliding angle of 5°, a characteristic that allows the leaf to remain clean even in muddy environments, i.e. to quickly remove the raindrops that fall on it during rainy seasons, thus removing, thanks to the watery spheres, any dirt and debris that may be present. This is because the adhesion between water and dust is greater than the adhesion between dust and leaf.

This characteristic of the leaf is known as the "lotus effect". In 1997, Wilhelm Barthlott and Christoph Neinhuis observed the unique structure of this plant under a scanning electron microscope. The leaf structure is organised in a cuticle and an epicuticular wax coating. This makes it possible for the plant to trap air under the water droplets and give rise to superhydrophobic behaviour. The way in which a drop of water interacts with a surface allows it to be classified as hydrophilic, hydrophobic and superhydrophobic (Fig. 1.13). This classification is usually related to the angle the droplet forms with the surface; when this angle is less than 90°, the surface is hydrophilic, when the angle is greater than 90° the surface is hydrophobic, and when the angle is greater than 150° the surface is superhydrophobic.



A schematic description of the behaviour of a surface where a waterdrop lies.

In order to understand how the wettability of a surface and its roughness are related, the Wentzel and Cassie–Baxter models have been proposed (Fig. 1.14). They illustrate how a drop of water can occupy the interstices of a rough surface (Wentzel 1936) or rest on the asperities, avoiding interstitial locations (Cassie and Baxter 1945).



A schematic description of the models proposed when a water droplet (blue) lies on a rough surface (in gray).

In the latter case, the asperities allow the air to wedge below the water droplet, which results in the after having a high contact angle with the surface. Let's see how these models differ, from a mathematical point of view.

According to the Wentzel model, as we have seen, the liquid wets both the roughness and the interstices of surfaces that are chemically inhomogeneous. The apparent contact angle, denoted with Jv, of a droplet on a rough surface is calculated with the equation:

$$\cos\vartheta = r \cos\vartheta \quad (1.19)$$

where rv is the roughness factor, which is defined as the ratio between the effective area of the rough surface and the geometric projection of the area considered. This factor, as defined, is always greater than unity. In the equation, JE is the angle of equilibrium of the liquid droplet on a flat surface. When, on the other hand, we are dealing with a heterogeneous surface, the contact angle predicted by the Cassie–Baxter model, where the droplet is supported by the roughness of the surface, is defined by the Cassie–Baxter equation:

$$\cos\vartheta = f\cos\vartheta + f - 1 \quad (1.20)$$

where f is the fraction of the surface area of the solid area that is wetted by the liquid (Jia, Lei, Yang and Wang 2016).

INDUSTRIAL AND ENGINEERED NANOMATERIALS

Before talking about industrial and engineered nanomaterials, it is worth talking about one of the most well–known scientists in the History of Physics that, absolutely by chance, found himself with a nanoparticle solution unintentionally obtained, something that is not uncommon in a laboratory. Among those who gave an impetus to the study of nanomaterials in colloidal suspensions, and among these materials gold, in particular, we should certainly mention Michael Faraday (1791–1867) who, in the mid–1800s, quite by chance realised that he had created a ruby red solution while preparing slides for microscopic observation of thin gold leaves. Faraday's interest in studying the properties of light as well as matter led him to publish his Bakerian Lecture (Faraday 1857) in 1857, in which he detailed his study of the experimental relationships between light, gold and other metals, having prepared the first sample of what he called activated gold in the same year. By using phosphorus to reduce a solution of gold chloride, Faraday achieved one of the earliest known examples of colloidal gold, a solution that is still optically active today. Faraday was able to attribute the ruby red colour of the preparation to the very small size of the gold particles in suspension; the light scattering phenomenon observed by Faraday is now known as the Faraday–Tyndall effect. Faraday knew that gold foils could be shrunk to 1/282000th of an inch, approximately 10 8m, and were able to transmit green light, reflect yellow light and absorb a portion of light incident upon it. Faraday actually used foils made of an alloy in the proportion of 12 silver, 6 copper and 462 gold; according to the scientist himself, 2000 such foils weighed about 384 grains, just under 25 grams. One of the 2,000 leaves Faraday is also said to have used, weighing a total of 408 grains, an average of two–tenths of a grain per leaf, gave a yellow orange reflection of light and a warm green transmitted light. By chemically attacking the leaves with chlorine or potassium cyanide, their thickness could be reduced to the point where virtually white light could pass through. Part of the process of preparing the leaves for observation involved rinsing the gold to produce a pale red solution. Faraday stored samples in bottles and used them for transmitted light experiments. Faraday is a scientist known not only for his results, but also for the meticulousness of his laboratory notes which he kept for about thirty years, starting in 1832, numbering each paragraph for quick reference. Faraday had also thought to use phosphorus to reduce gold "*in an excessively subdivided condition*". He observed that: If the solution be weak and the phosphorus clean, part of the gold is reduced in exceedingly fine particles, which becoming diffused, produce a beautiful ruby fluid. This can be considered the first historical realisation of metallic gold colloids, based on nanoparticles randomly obtained from the gold processing.

The 1970s and 1980s saw the convergence of scientific discoveries in terms of research apparatuses such as STM and AFM microscopes, definitions – such as the very definition of Nanotechnology – and the first results, for example the manipulation of xenon atoms, which proved the effective possibility of directly operating at the nanometric and atomic scales. The invention of the STM microscope, by Gerd Binnig and Heinrich Rohrer, of the IBM Research Laboratory in Zurich, opened up the possibility of intervening on matter at dimensions that had previously been inaccessible. It was in that period, as a matter of fact, that the manipulation of matter began in practice, and exactly according to the definition of Nanotechnology: man was able to intervene on the deepest basis of matter to radically modify it, according to his own purposes. Only a few years later, in 1986, the introduction of the AFM microscope would have removed the operational limitations that had characterized and, in some ways limited, the use of the STM microscope. Not only that, but this instrument would prove to be of fundamental importance in supporting Scanning Electron Microscopy, whose results are excellent in terms of visualization for particles above 5nm, allowing the analysis of a very wide range of samples, from the non–conductive ones, to organic molecules. It is important to understand that, when the creation of ever more sophisticated materials is pursued, being able to observe the structure on such a small scale becomes of fundamental importance. Electron microscopy not only allows to physically see the structure of matter, but also to intervene on it, and this feature led to lab–engineered nanomaterials. Artificial nanomaterials are those materials designed and made by man, in which more than 50% of the particles that constitute them have, according to the definition, a variable size between 1nm - 100nm. One of the reasons why these materials are made is, for example, that the properties that are observed at the nanometer size are completely new, or virtually undetectable in the bulk material. From a technical point of view, what is important to consider is that the ratio between surface and volume that can be obtained when materials of this type are made. As this ratio increases as the diameter of the particle decreases, we observe the confinement of a greater number of atoms on its outer surface. The smaller number of nearest neighbour atoms that can be counted for the atoms on the surface, compared to those inside it, means that fewer chemical bonds are committed to the cohesion between the atoms placed on the surface, therefore these are characterized by a greater reactivity, a characteristic that is then transferred to the whole particle.

Engineered nanoparticles and nanomaterials are part of that group of innovative products that are primarily intended for commercial application. The main ones include fullerene, carbon nanotubes, graphene, quantum dots and dendrimers. Fullerene is a molecule whose three–dimensional structure is made up of 60 carbon atoms, organized at the vertices of pentagons and hexagons, and which closely resembles the shape of an old–fashioned soccer ball. This molecule was discovered in 1985 by four scientists from Rice University, Texas, specifically Richard Smalley, Robert Curl, Sean O'Brien and James Heath, and by Harold Kroto, of the University of Sussex. The discovery earned Kroto, Smalley and Curl the Nobel Prize in Physics in 1996. In fact, the first experimental evidence of the presence of such a molecule must be traced back in time, to the previous year, when Exxon researchers had a tangible proof of the existence of a cluster structure of 60 carbon atoms performing mass spectrometry analyses but, being concentrated on searching for new catalysts, they did not immediately grasp the importance of their observation.

Again, in 1970 Professor Eiji Osawa (Osawa 1970), professor of computational chemistry, was able to predict the existence of a molecule whose carbon atoms would be bound together in space, just like in fullerenes, but the language barrier constituted by Japanese very much limited the diffusion of the article in which Osawa presented his discovery of this molecule. The extremely particular structure of fullerene is the reason for its interesting properties. The most immediate property is the shape of the molecule: if we look at it under an electron microscope, the fullerene molecule really looks like a small soccer ball. A similar thing could not be said for the other molecules, whose formulas are reported on paper to visualize atoms and bonds in an abstract way, but which in fact represent models that we hardly actually observe, especially in conditions of resonance of chemical bonds. In 1991, a Japanese researcher from NEC Corporation, Sumio Iijima, discovered an entirely new class of fullerenes, while trying to make his fullerenes through arc evaporation. This new class of materials consisted of so–called carbon nanotubes. The nanotubes that Iijima discovered are what we can define as multi–walled nanotubes, that is, multiple nanotubes of different diameters, coaxially encased one with each other, such as Russian matryoshka dolls. Actually, the first observation of these structures should be backdated to 1952, when Radushkevich and Lukyanovich first observed similar structures, but once again the linguistic barrier, constituted from the Russian, and the historical situation relating to the Cold War, prevented the spread of their writing to Western scientists. We can think of a carbon nanotube as a single molecule entirely made up of carbon, a single sheet of graphene, with its planar structure of hexagonal cells, rolled up on itself to form a cylinder. Although the diameter of these nanotubes is small, the theoretical limit seems to be around 0.4nm, their length can even reach a few centimetres, like DNA which, despite having a diameter of nanometric dimensions, can extend up to half a meter, in the chromosomes of mammals. The mechanical properties measured on the carbon nanotubes proved to be very interesting. They are as resistant as diamond and their thermal conductivity is comparable to that of the diamond itself. Their strength is greater than that of steel, although the density is reduced to one sixth, nanotubes are flexible, elastic and have some shape–memory that causes them to return to their original shape even after being subjected to deformation, be it elongation or even bending around support structures. Carbon nanotubes are used as additives of the polymeric composites to which they confer resistance and in fact have supplanted previous carbon fibres, which while performing the same mechanical function, were characterized by greater weight and rigidity.

Conceptually, graphene is an easily explained material. It is, in fact, a single sheet of graphite. In other words, graphene is a two–dimensional structure of carbon atoms arranged on the vertices of regular hexagons, which tessellate the plane according to the rules of plane geometry (Fig.).

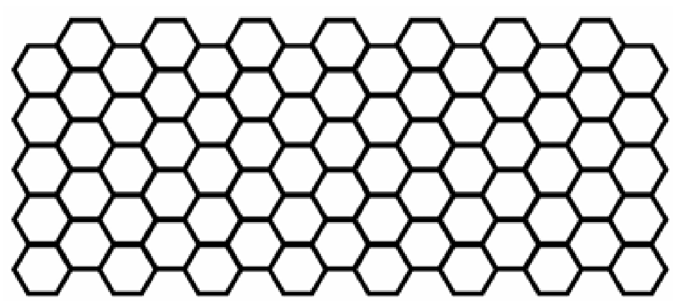


Fig. 1.15 The way we can imagine one single layer of graphene. Source: AD, designed with chemfig LATEX package.

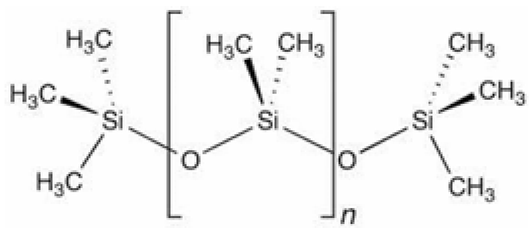
Graphite consists of sp2 hybridized carbon planes, with s and p bonds contained within each individual layer; the different planes are held together by weak Van der Waals interactions, which allows graphite to be an effective writing material. When it is dragged onto the paper, the Van der Waals forces are unable to hold together the individual planes, that settle then on the sheet leaving the trace of the writing. It is also possible that individual layers of graphene may be found on that sheet. One of the simplest and most commonly used methods to obtain this material is the so–called scotch–tape method: a graphite crystal is placed on the surface of an adhesive tape. The ribbon is detached from the crystal and then folded back on itself and opened several times in correspondence with the imprint left by the graphite. In this way it is possible to detach the individual layers from each other, and recover portions of graphene that can be easily transferred to a sample holder for subsequent analysis. Although this system, as a result of the intuition of André Geim, the scientist who with Konstantin Novoselov isolated the first atomic layer of graphene in 2004, is easy to implement in the laboratory, it is not difficult to understand that it cannot be applied on a large scale, for large industrial production. Yet, this stratagem solved an age–old problem that tormented researchers since 1947, when the structure of graphene had been theoretically hypothesized, but, at the same time, being able to isolate a single atomic layer of material seemed impossible.

Nanomaterial Manufacturing Techniques

Nanometric objects have existed in nature since time immemorial, and long before mankind became aware of them. However, when they were discovered, and their high technological potential was revealed in all its importance for the most diverse applications, the industrial development of new production techniques became necessary, in order to manufacture these objects under constant laboratory and technological control. Nanomaterials should not be regarded as a futuristic class of object, but are applied in a variety of products that are available to practically everyone, from nanodevices for electronics to self–cleaning glass, from nanomaterials for medicine to antibacterial fabrics, and the way in which nanometric materials are manufactured depends on their end use. There are two distinct ways to fabricate engineered nanomaterials. The first is called the “top–down” approach and starts with a bulk block of material whose size is progressively reduced until the desired size is achieved. The smallest limit to which one can go depends, of course, on the tools available. The second approach is called “bottom–up” and makes use of building blocks, so to speak, ranging in size from atomic to more complex basic molecules, which are assembled together to create larger objects. The bottom–up method has been chosen by various organisms, for example, as one of the tools suggested by nature to build complex organic higher systems, while the top–down method has become the standard procedure for microtechnology applied to electronics, for example. In top–down machining, when starting from a block of bulk material, it is necessary to be able to intervene selectively on the material. In this mode of operation, selective engravings are made on the material using a lithography process. Masks are then placed on the workpiece, through which a precise pattern is reproduced on the substrate. The top–down methodology for manufacturing nanoscale devices is now widely practised in industry. A number of techniques have been developed using this approach, which is conceptually very simple: it consists of starting with a massive block of material, removing what is superfluous and then working on it, like a sculptor who frees his statue from the inside of a rough block of marble. Top–down processes make it possible to obtain many of the objects that enable our electronic devices to work, such as integrated circuits, which are themselves made up of several billion transistors. Not only transistors but also motion sensors, lab–on–chips used in modern medicine and photonic crystals are examples of nanodevices obtained by this process. Since the transistor is the key element of modern electronics, I will describe the most established top–down techniques for the realisation of this device, in which the components must be arranged in a very precise order, according to a well–defined geometry. In principle, the construction of a transistor is based on the processing of various materials on a substrate of silicon, a semiconductor material whose properties at room temperature make it the most important material in electronics, being obtainable in extremely pure form, in the form of a single crystal. Silicon serves as a substrate for the deposition of other materials in the form of thin films of the order of a few atomic layers, and the techniques that have been developed over time allow extremely fine processing that is practically contaminant–free, thanks to the conditions in which it can be carried out. The technique to be chosen will depend on the object we want to manufacture and the thicknesses which, depending on the object, must be obtained. The top–down approach is applied to chemical and physical procedures.

Soft lithography

Soft lithography uses a stamp made from an elastomer material, on the surface of which structures are modelled to create nanoimprints ranging in size from 30nm to 100pm. Soft lithography is an inexpensive and effective methodology for creating nanostructures. The soft lithography technique uses stamps made from polydimethylsiloxane (PDMS), as stamps of this material adhere well to surfaces and can be easily removed from rigid masters (Fig. 1.16).



The structure pf PDMS. Source: public domain.

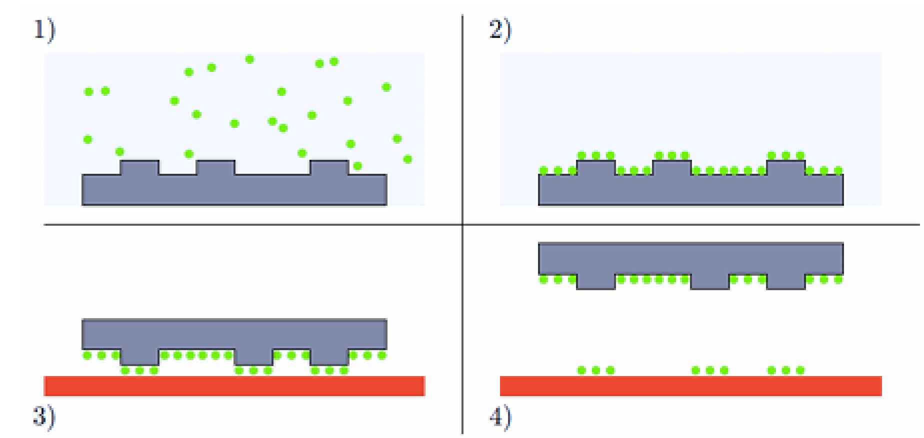


Fig. 1.17 The main phases of the microcontact printing. 1) The ink is deposited on the substrate where 2) it adheres to all the surface. 3) The stamp is put on the substrate and 4) then removed. The ink is transferred from the stamp to substrate. Source: AD, designed with TikZ LATEX package

To obtain the stamp for further processing, the liquid elastomer is poured into a rigid master on which the patterns to be replicated are made. The mixture is then heated to a high temperature and solidifies in the process. Once hardened, the PDMS is peeled off in the form of a stamp shaped according to the pattern made on the starting rigid master. Soft lithography is applied in two preferred ways, microcontact printing and capillary microprinting. With microcontact printing, the pattern is transferred onto the surface of the substrate by means of an inked stamp that is adhered to the substrate. An alcohol–based solution of alkanethiols is the “ink” that is most commonly used in this technique; the traces that are left on the substrate are made from the shaped protrusions on the elastomeric pad, which has been previously modelled (Fig.).

Through the technique of micromoulding in capillaries (MIMIC), channels are cut into the mould which, once the pad has been placed on the substrate, delimit the track into which the liquid to be polymerised is injected. By capillary action, the liquid fills all available cavities along the track and is then polymerised. Once the mould has been removed, the liquid that has solidified remains on the surface of the substrate, leaving the designed track on the substrate (Fig.).

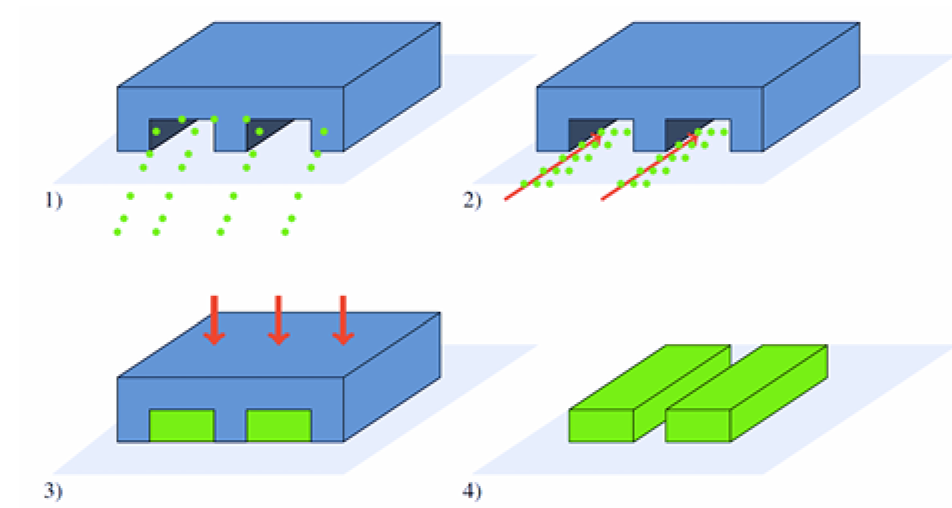
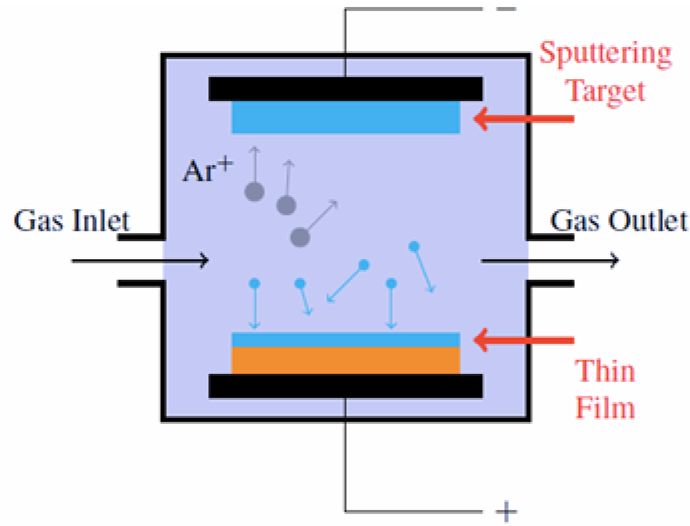


Fig. 1.18 The main phases of the MIMIC. 1) The stamp adheres to the substrate and 2) by capillarity the fluid fills the cavities in the stamp. 3) The stamp is heated to solidify the polymeric fluid and 4) once the stamp is removed, the traces remain on the substrate. Source: AD, designed with TikZ LATEX package

Physical Vapour Deposition

In micro– and nanofabrication of devices, and deposition on a metal substrate, the process of thin film deposition is used. Physical Vapour Deposition (PVD) is the technique of depositing material onto a substrate – called a wafer – both contained within the same clean chamber. This process takes place through a series of sequential steps. First, the material to be deposited is converted into vapour; this vapour is then passed through a low-pressure region from the source to the substrate. On the substrate, the vapour condenses to form a thin film. By controlling the condensation phase, it is possible to adjust the thickness of the film from a few nanometres up to thousands of nanometres. A physical deposition technique is sputtering. A target material is hit with argon atoms, produced in direct current or through a plasma, to eject atoms that are sent towards the substrate where they form a thin film. Through this technique, the deposition of the film is very carefully controlled. In the sputtering technique, a target material is targeted with argon ions; this action removes atoms from the target and ejects them towards the substrate. Argon ions hitting the target are produced using a direct current (DC) or RF plasma. Sputtering allows better control of the composition of multicomponent films, and greater flexibility in the types of materials deposited (Fig.). Plasma–based sputtering is the most common form of sputtering, using positive ions accelerated towards the target, which is held at a negative potential relative to the plasma.



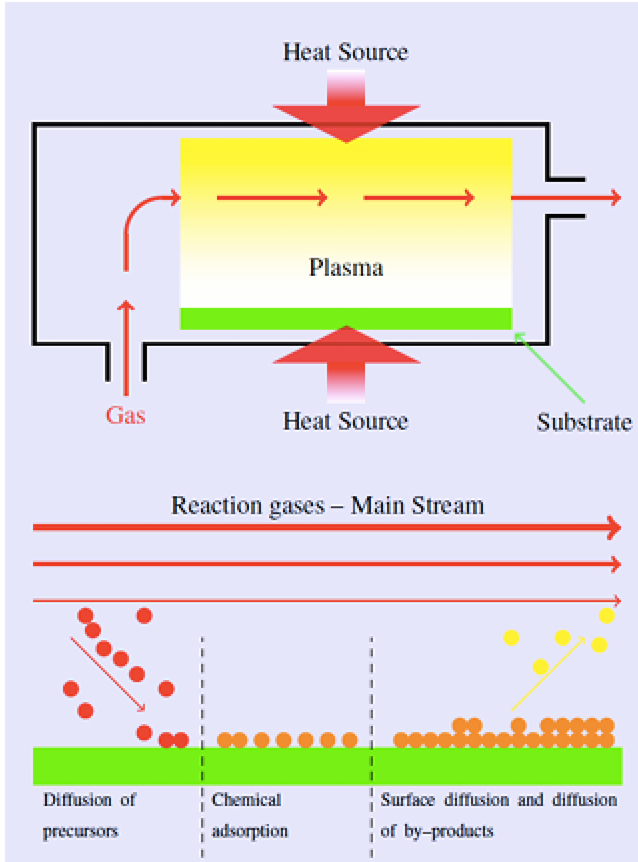
A simplified scheme of the PVD technique. Designed with TikZ LATEX package

The technique based on metal evaporation involves the use of a small melting pot in which the metal to be melted is placed and brought to a temperature where it evaporates. Operating in a high vacuum, inside a camber in which the crucible and substrate are placed, and exploiting the high vapour pressure, the atoms that have evaporated from the liquid are deposited on the substrate.

Chemical Vapour Deposition

It is possible to make nanomaterials from precursors that react chemically in the vapour phase and then deposit and give rise to the required end products. This production technique is Chemical Vapour Deposition (CVD). In CVD, the flow of one or more starting gases is conveyed into an oven in which the reheated object, or objects, to be coated are contained. As they flow past the heated substrate, the materials contained in the gas phase undergo decomposition when they react with the surface. The reaction by–products accompanying the process are removed from the oven in the gas stream that did not take part in the reaction. The precursor gas, typically a hydrocarbon, decomposes due to the high temperature or in the presence of a plasma. Catalysts based on transition metals, the d–block elements (mainly iron, nickel, cobalt or molybdenum), help to increase the reaction rate. CVD processes also include low-pressure CVD (LPCVD) and plasma–enhanced CVD (PECVD). LPCVD is carried out inside low–pressure tubes (kept around 13Pa to 130Pa) heated through electrical systems at temperatures between 550°C and 900°C.

Figure 1.20 shows the main steps of a CVD process. First, the precursor gas is introduced into the furnace and then decomposed through heat or plasma. Then the gas is adsorbed onto the surface of the substrate and reacts there to form the required nanostructures. The reaction sub pipelines are ejected from the furnace. Radio frequencies are used in PECVD to create the reactive species within the plasma that will also adhere to the substrate. In this way, the operating temperatures of the chamber are lower, because part of the plasma energy replaces the heat, allowing the precursor to decompose at a lower temperature.



The diagram of CVD process. In the upper part of the picture a simplified apparatus is depicted, while in the lower part I represent a schematic process of what happens on the substrate. Source: AD, designed with TikZ LATEX package

Etching

The etching process allows traces to be made on the surface of the material to be processed-. The traces describe the topography of the object to be produced. Surface processing can be carried out by means of physical devices, or through well–defined chemical attacks. The etching technique uses liquids or gases, and the resulting engraving is called isotropic if it is uniform in all directions, or anisotropic if there is a preferred direction of engraving. In the first case, the walls obtained in the material have a characteristic semi–circular shape and are wider than the opening of the tracing mask. Conversely, if the incision to be made is anisotropic, the dissolution of the material being attacked occurs more quickly in the vertical direction and the incision has almost straight vertical walls. The etching technique can be carried out dry, so–called dry–etching, or by immersion in liquid solvents, so–called wet–etching. Wet–etching is based on immersion of the wafer in a reactive solution, from which the solution diffuses over the surface of the material to be processed. At this point, the chemical attack on the oxide and the removal of the reaction by–products takes place. It must be said, however, that the minimum size of the material that can be obtained is limited to 3pm, due to undercutting phenomena, i.e. the presence of areas of material that prove to be inaccessible. The dry–etching technique allows the oxide to be worked with little undercut and therefore the incisions that are made are sharper and smaller than those obtained through wet–etching. In addition, dry–etching avoids the use of solvents or acids, which can be dangerous for the operator. From a plasma, ions are obtained which are directed towards the wafer to perform the processing. The action of the ions breaks the bonds of the surface atoms, removing them out of position and leaving them free. Since the ions are strongly vertically directed, collisions occur preferentially with the horizontal surface and, as a result, the engraving is characterised by very sharp vertical grooves. The transfer of the pattern from the mask to the wafer is thus very precise and only takes place at the location of the pattern (Fig).

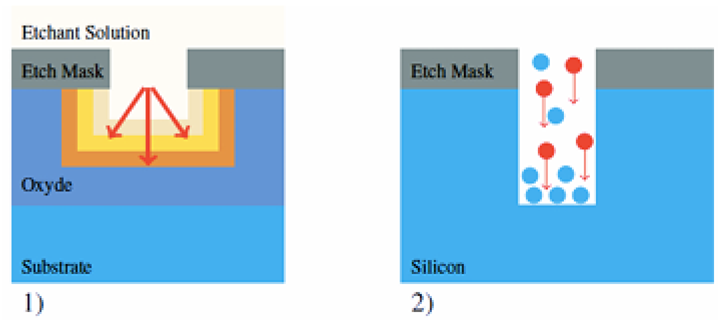


Fig. 1.21 The etching process. 1) wet–etching, 2) dry–etching. It has to be noticed how the dry attack results in a more precise pattern transfer. Source: AD, designed with TikZ LATEX package

Electron Beam (E–Beam) Lithography

Integrated circuits, channels for injecting nanofluids and photonic crystals are just some of the devices that are manufactured using a technique known as electron beam lithography. Using an electron beam, it is possible to carry out extremely precise processing between 5 and 7 nanometres. The operating principle of Electron Beam Lithography is simple: the electron beam is passed through a region of a substrate, which is itself covered with a material called resist, forming the desired pattern. When the resist is exposed to the beam, the chemical bonds of the atoms involved in the passage of electrons change. In particular, it is the solubility of these atoms that is altered during the process. Once the resist has been traced, the material is subjected to a developing solution which acts either on the areas that have been exposed to the electrons or on those that have not, removing, depending on the solution, the resist that has been exposed or that has not been exposed (Fig).

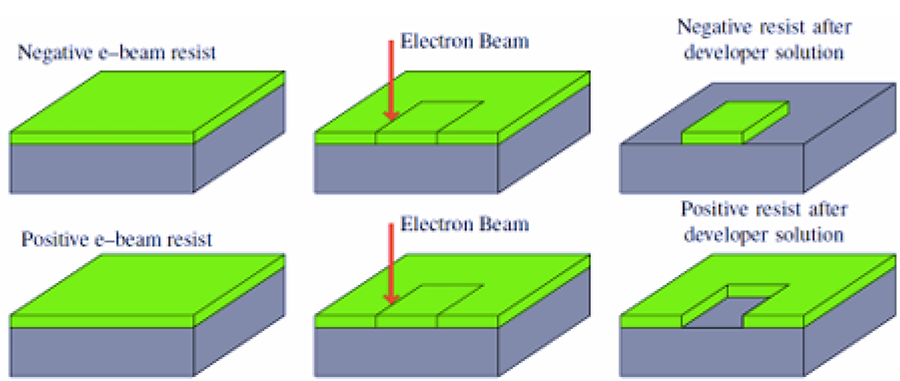


Fig. 1.22 Electron Beam Lithography for negative and positive resist. Source: AD, designed with TikZ LATEX package

Electron beam lithography has many features that are common to scanning electron microscopy (SEM). In fact, it also works with an electron beam that sweeps over a portion of the sample. In this technique, the electrons are obtained from a source that can be thermionic or by using field electron emission sources. The electron beam is collimated with lenses that can be electrostatic or magnetic. It should be noted that magnetic lenses are preferred to electrostatic lenses because the latter suffer from aberration phenomena and do not allow the electron beam to be focused with extreme precision. The system basically consists of an electron source, as described, a chamber housing the sample to be processed, and a column containing the electromagnetic lenses. The column and the sample chamber are kept under high vacuum.

Focused Ion Beam

A technique known as Focused Ion Beam (henceforth FIB) has made its way into materials science or the semiconductor industry. With FIB, sites in biological tissue can be precisely analysed, materials can be selectively deposited, or material can be selectively removed from the sample; in fact, this technique is preferably used for milling samples. FIB also has features that make it similar to SEM microscopy, however, the major difference is that whereas an SEM microscope uses an electron beam to scan the sample, FIB uses an ion beam. FIM preferentially uses gallium ions, although it is possible to use gold or iridium sources. The sensitivity of this technique is very high, as the ion beam that will be collimated by the electronic lens can be narrowed down to 2nm at the source. When the beam strikes the sample, the ions interact with the sample atoms, resulting in collisions that are both elastic and inelastic. Elastic collisions lead to sputtering of atoms, while inelastic collisions produce secondary electron and X–ray emission. The ions and electrons extracted from the sample can be used to create an image of the sample (Pradeep 2007).

Photolithography

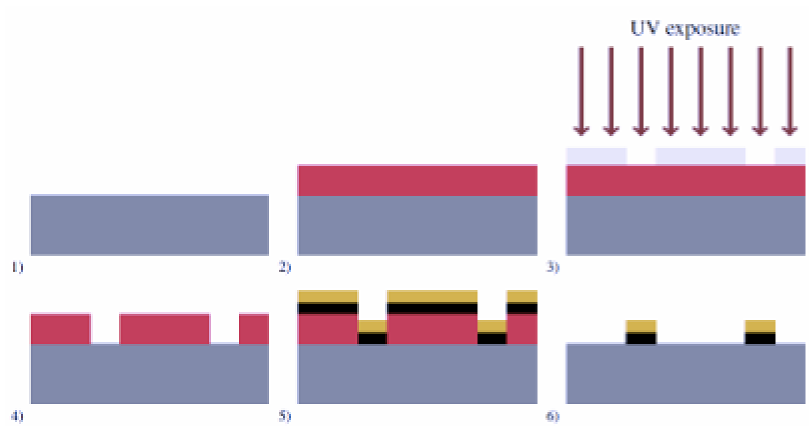


Fig. 1.23 The phases of photolithography. The substrate 1) is covered with the resist 2). After the deposition the mask is applied and the sample is radiated with UV light 3). The exposed substrate is removed 4) (positive resist). 5) Gold is evaporated on the surface and 6) the remaining resist is removed. Source: AD, designed with TikZ LATEX package

Increasing the power of electronic devices and simultaneously decreasing their size are two fundamental achievements that have been made possible by the processing of materials using a technique known as photolithography. As the name of this technique suggests, photolithography is a technique based on a photographic process. Light is projected onto a mask which reproduces the circuit model to be produced. In this way, the light projects, through the mask, the trace to be made onto a wafer covered with a photoresist material, which is sensitive to light. Resolution accuracy is achieved by varying the wavelength of the incident light: shorter wavelengths – and therefore higher radiation energies – correspond to better resolutions. To prepare the wafer, a technique known as spin coating is used: a small part of the coating material is placed on the centre of the wafer, which has a circular geometry. The wafer is then spun around its own axis in a vacuum chamber. In this way, the coating is spread evenly over the substrate by centrifugal force, without bubbles or other imperfections forming. The vacuum ensures the adhesion of the coating material to the substrate. To print the designed pattern, a photomask is placed on the substrate and irradiated with ultraviolet light to transfer the pattern onto the wafer. The wavelengths used range from near UV (350nm–500nm) to deep ultraviolet (150nm–300nm) or extreme ultraviolet (10nm–14nm). Exposure to light causes a chemical change in the coating, which can be removed by a solution called the developer (Fig.).

The processing of the material depends on the type of resist used, as it can undergo two different transformations under UV light. If the photoresist that is affected by ultraviolet light is positive, the bonds of the atoms in the exposed regions will be attached and will be more soluble in the developing solution. If the photoresist is negative, the atoms will cross–link when exposed to UV radiation and become insoluble in the developing solution, not being removed, unlike the areas not exposed to light.

The production of ever–smaller integrated circuits requires manufacturing techniques that keep pace with electronic progress. For this reason, Extreme Ultraviolet Lithography (henceforth EUV or EUVL) was developed, a technique that differs fundamentally from conventional lithography. Since there are no materials with transparent behaviour for the wavelengths used (around 13.5nm), concave and convex mirrors must be used, each containing alternating layers of molybdenum and silicon, capable of reflecting radiation of 13.5nm wavelength. Machining down to a size of 11nm is possible with this technique. The wavelengths required for the EUVL technique are obtained through plasmas produced by laser devices, when a target is irradiated by a pulsed laser beam. Compared to the conventional lithography technique, EUVL has a number of advantages. These include:

- construction of structures with maximum detail;
- for the same amount of space, an increase in the number of transistors with a consequent increase in the speed of the devices;
- production of objects of minimum dimensions.

Pioneers in Nanotechnology

The History of Science is made up of dates and characters that have characterized the salient moments. Similarly, the History of Nanoscience and Nanotechnologies is made up of characters and discoveries that, in the last seventy years, have definitively changed the perception of the nanoworld, through results that influence the existence of man, day by day. In this paragraph we take into consideration those who can be considered the leading figures in the History of Nanotechnology: Richard Feynman, who is considered to be the father of Nanotechnology; Eric Drexler, who took up and expanded the ideas proposed by Feynman and, finally, Norio Taniguchi, who first coined the term Nanotechnology.

Richard Feynman, Eric Drexler and Two Debates

Richard Feynman (1918–1988) is very often referred to, in the literature, as the founder of Nanotechnology as it is known today. His name appears in texts, articles, essays, as that of the main inspirer of this new physics. The reason for this can be found in a famous 1960 article called There’s Plenty of Room at the Bottom (POR) in which Feynman predicts the wonders of the nanoworld, at a time when the tools that are now part of this science still had to be perfected or made. Actually, this is not an article20 designed for publication in a specialized journal, but a meticulous transcription of a recording, made on December 29, 1959. On that date, Feynman gave a lecture at the Californian Institute of Technology, Caltech, for the American Physical Society Annual Meeting. At that event, an avid attendant of Feynman's lectures taped every word of the future Nobel Prize winner, producing a paper that would be published shortly after, in February 1960, in the Caltech Engineering and Science journal. Later in the same year, The New Scientist magazine reported the impressions of the audience attending the lecture.

The Professor literally spun the idea off the top of his mind in an after–dinner talk at an American Physical Society meeting in Pasadena last December. If any news reporters heard it, they betrayed no interest. But the scientific audience was captivated. Those who afterwards asked for copies of the remarks learned that there hadn't even been notes beforehand. Professor Feynman had just talked on a subject considered important. Fortunately, a foresighted admirer had lugged a tape recorder to the session. The transcription was pocked with typical Feynman jokes; after they had been extracted, the Caltech house organ, Science and Engineering, published what remained under a corny title, "There Is Plenty of Room at the Bottom" (Lear 1960).

These few words convey very well the effect of Feynman's intervention on the audience. On the other hand, the Professor's ability to entertain the participants to a conference is well known. It appears that the contents of POR justify the enthusiasm of those who support the figure of Richard Feynman as the inspiring father of modern Nanotechnology. In fact, the characteristics that are sought today within nanostructured materials, as totally new specifications due to the nanometric dimension, compared to the material at the macroscopic scale, seem to have been, in some way, anticipated in 1959. In the first paragraph, Feynman quotes Heike Kamerlingh Onnes (1853–1926), the scientist whose research on helium granted him the Nobel Prize for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium.

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of ever higher vacuum was a continuing development of the same kind (Feynman 1960).

Now that we know the entire history of POR, could we ask if Feynman was aware of the impact he expected from the talk, and if he was thinking of obtaining a temporary monopoly in this new field of Physics? The following famous paragraphs give the reader an idea of how revolutionary the concepts that Feynman presented, that evening of December 29, 1959, would have sounded to the ears of the people present.

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, "What are the strange particles?") but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications. What I want to talk about is the problem of manipulating and controlling things on a small scale. As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on *the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction. Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica21 on the head of a pin? (ibidem)*

His words are about manipulating and controlling things on a small scale. Feynman's perspective – anyway – was not only about materials and nano chances but on what people in the future might have thought about his times and the discoveries made in the Sixties (or more likely what he would have thought about the research in the Sixties, if he was alive in 2000).

In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction (ibidem).

Was it the prophetic ability to see a new science in the future that made Richard Feynman the first visionary of Nanotechnology? This is what is strongly reiterated in many texts, from popular ones to the most authoritative, that deal with the history of Nanoscience and Nanotechnology at various levels, and a point that I shall discuss later. Richard Feynman's article seemed to find new life when it was rediscovered by an MIT student, Kim Eric Drexler, who, coming from engineering studies, was able to draw a very interesting parallel between the world of mechanics and the world of biology. He did this by combining more or less complex mechanical objects, or parts of them, with biological structures whose function was in some way attributable to engineering objects (Drexler 1981). His imagination was greatly stimulated by Molecular Biology, to the point that he was able to coin, starting from the term "Engineering" and the term "Molecular biology", a new expression: "Molecular engineering". These are the two words that open his 1981 article. Throughout all his articles, and although already present in the scientific dictionary, Drexler never refers to manipulation of objects to the nanoscale, never using the prefix "nano" or any nano–word. This is already made clear from his abstract.

Development of the ability to design protein molecules will open a path to the fabrication of devices to complex atomic specifications, thus sidestepping obstacles facing conventional microtechnology. This path will involve construction of molecular machinery able to position reactive groups to atomic precision. It could lead to great advances in computational devices and in the ability to manipulate biological materials. The existence of this path has implications for the present (Drexler 1981).

In his description of what molecular engineering could be, Drexler does not proceed through formal demonstrations, such as those of mathematics, but through analogies between the ideas he proposes, what is observable in Nature and what has been possible to achieve with the help of technology. Where the similarities are compatible and strong, according to Drexler, the new devices will be considered feasible. It is also interesting to note how Drexler proposes, as Nature's approach to the fabrication of its systems, what is now called the Bottom–Up process, rather than what is called the Top–Down process. In fact, he observes that biochemical systems are subject to this type of "microtechnology": starting from the molecular level they develop higher systems through a series of "tools" to create "devices" to be copied. From this point on, gene synthesis and recombinant DNA technology could direct ribosomes, for example in bacteria, towards the synthesis of absolutely new proteins that can serve as building blocks for larger molecular structures. Drexler then suggests a comparison between macroscopic and biochemical mechanical components.

Through multiple combinations of structural elements, moving parts, bearings and with the use of a driving force, Drexler expects that mechanical systems characterized by great versatility can be created. The assemblages of atoms in molecules can act as solid structures, occupying a certain region of space and being characterized by a predefined shape. However, while rigid structures can behave as structural elements, they can also act as moving parts. Sigma bonds, which are characterized by a low steric footprint, can act as rotating bearings, capable of withstanding a stress of up to 10–9N. A succession of sigma bonds can instead perform the functions of a hinge. Proteins capable of changing their conformation can serve, in Drexler's idea, as sources of driving force for motion along a linear trajectory. The reversible motor of a bacterium's flagellum can serve as a source of driving force to trigger a rotational motion. The existence, in Nature, of this range of components makes it possible to imagine the feasibility of making mechanical systems driven by some motor organ, whose dimensions are measured with a molecular scale. Similarly to macroscopic devices, Drexler provides for molecular machine manipulation devices, capable of handling different instruments, controlled by human operators or macroscopic machines. Molecular–scale tools may also evidently be capable of producing macroscopic signals, indicating the feasibility of feedback control in molecular manipulations. All these arguments, taken together, are a clear indication that it is possible to obtain devices capable of moving molecular objects, positioning them with atomic precision, applying forces to them to effect a change and inspecting them to verify that the change in shape or position imposed by the external operator has actually been carried out. Drexler then creates the following correspondences (Table 1.1), where he reports the macroscopic and microscopic components, together with the description of their functions, a description that, in his imagination, acts as a bridge between the two worlds.

Table. 1.1 Comparison of macroscopic and microscopic components (Drexler 1981).

Technology	**Function**	**Molecular example(s)**
Struts, beams, casings	Transmit force, hold positions	Microtubules, cellulose, mineral structures
Cables	Transmit tension	Collagen
Fasteners, glue	Connect parts	Intermolecular forces
Solenoids, actuators	Move things	Conformation–changing proteins, actin/myosin
Motors	Turn shafts	Flagellar motor
Drive shafts	Transmit torque	Bacterial *flagella*
Bearings	Support moving parts	σ bonds
Containers	Hold fluids	Vesicles
Pipes	Carry fluids	Various tubular structures
Pumps	Move fluids	*Flagella*, membrane proteins
Conveyor belts	Move components	RNA moved by fixed ribosome (partial analog)
Clamps	Hold workpieces	Enzymatic binding sites
Tools	Modify workpieces	Metallic complexes, functions groups
Production lines	Construct devices	Enzyme systems, ribosomes

The Feynman paper can be quite simply schematized: it opens with an introduction and develops in ten subparagraphs, before the conclusions. In the introduction it is possible to read very clearly Feynman's mission statement, regarding the lecture *[…] what I want to talk about is the manipulating and controlling things on a small scale (Feynman 1960).*

It is interesting to note, from an epistemological point of view, how Feynman never uses the prefix nano in any of the terms of his talk. In fact, the nano prefix, although first introduced in 1947 at the 14th congress of the Union Internationale de Chimie as a thousandth–millionth of a part, was incorporated into the International System of Units in 1960 only. Furthermore, the term nanometre, as a measure of the billionth part of the meter, appeared for the first time in 1963, this measure being formerly known as the *millimicrometer*. When he needs to measure "at the bottom", Feynman refers to 10 angstroms, for example. Then, with a rather precise description, Feynman illustrates a process by which letters can be reduced by 25,000 times using an electron microscope. Once the plastic moulds of the text were prepared, it would have been sufficient to reproduce them in silicon to be able to read them, again with the aid of an electron microscope. In the following, Feynman moves the discussion from the strictly practical level to that relating to the compatibility of his statements with what is known, from the scientific point of view.

I will not discuss how we are going to do it, but only what is possible in principle – in other words, what is possible in principle according to the laws of Physics (ibidem).

Five times he remarks to his audience that what he proposes is always consistent with the laws of physics. Further on, it is possible to read this line.

I am not inventing anti–gravity, which is possible someday only if the laws are not what we think. I am telling you what could be done if the laws are what we think; we are not doing it simply because we haven't yet gotten around to it (ibidem).

or:

I would like to try and impress upon you, while I am talking about all of these things on a small scale, the importance of improving the electron microscope by a hundred times. It is not impossible; it is not against the laws of diffraction of the electron (ibidem).

Yet:

There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now (ibidem).

All these statements indeed appear very prophetic. POR condenses within it some forecasts on what will happen, in effect, "we could arrange atoms one by one the way we want them" with other statements that almost express a desire for a more advanced scientific future "Is there no way to make the electron microscope more powerful?" Feynman expresses his thought always remarking that he cannot know exactly how to achieve certain results, but that these are not impossible, in principle. A first reading of POR, always thinking of the histrionic figure of Richard Feynman, would certainly lead most of the readers to think that they are facing the inspiring vision of a science that in a few decades has revolutionized our world. It is not possible to deny that several ideas are suggested in the writing, and some of them have actually been realized today. If POR is believed to be the historically inspiring document for Nanotechnology, notable remarks to this point of view are given by well–known researchers such as, for example, Kim Eric Drexler. In his 1981 article Molecular Engineering, Drexler immediately makes it clear that he is aware of the contents in POR, from the copy published in the magazine Miniaturization, and from this he draws inspiration for his subsequent arguments:

Feynman's 1959 talk entitled "There's Plenty of Room at the Bottom" discussed microtechnology as a frontier to be pushed back, like the frontiers of high pressure, low temperature, or high vacuum. He suggested that ordinary machines could build smaller machines that could build still smaller machines, working step by step down toward the molecular level; he also suggested using particle beams to define two–dimensional patterns. Present microtechnology (exemplified by integrated circuits) has realized some of the potential outlined by Feynman by following the same basic approach: working down from the macroscopic level to the microscopic (Drexler 1981).

Later, in his authoritative volume Engines of Creation, Drexler again quotes POR as a text in which Feynman's inspiring ideas, relating to nanomachines capable of controlling and directing chemical syntheses, are reported, although "[Feynman] could foresee neither the time nor the cost of doing so" (Drexler 1986). Again, in his doctoral thesis, in 1991, Drexler pays tribute to the ability of Feynman and POR to inspire research:

The body of the talk focuses on miniaturization and microtechnology; this section anticipates capabilities like those that are now basic to the microelectronics industry and proposes an alternative approach to miniaturization (using machines to build smaller machines, which build still smaller machines, and so forth) that has not, in fact, been followed (Drexler 1991).

Before going on, considering those witnesses that open the historiographical debate, I find it important to first underline that considering POR as the inspiring document of the ideas that led to Nanotechnology, as we know it today, is not incorrect; this is simply one of the interpretations possible, and which finds its validity in the fact that several of Feynman's words on this subject have found a realization in the contemporary world. Furthermore, it is essential to keep in mind that the considerations I am carrying out here do not in any way concern the figure of Feynman as a researcher, much less as a scientist or populariser. My description of the facts is based upon the interpretation of POR as the cornerstone of Nanotechnology. Now, in order to better understand what influence POR had on researchers, Toumey himself interviewed distinguished scholars in Nanosciences/Nanotechnology to discover if Feynman's paper was (really) of some inspiration or even illuminating. Three researchers were chosen for the interviews, for their close relationship with three of the most important (according to Toumey's opinion) discoveries in Nanotechnology: the invention of the STM microscope, the invention of the AFM and the first atom manipulation using a STM microscope. Probably, most people would cite these three events as the most significant ones for Nanotechnology.

Heinrich Rohrer (1933–2013), Nobel Laureate in 1986 for his research in STM together with Gerd Binnig, wrote:

Binnig and I neither heard of Feynman's paper until Scanning Tunneling Microscopy was widely accepted in the scientific community a couple of years after our first publication, nor did any referee of our papers ever refer to it… It might have been even after the Nobel [Prize] […] I think it had no influence whatsoever (Toumey 2008).

Gerd Binnig, Nobel Laureate with Rohrer for STM, suggested:

I have not read ["Plenty of Room"]… I personally admire Feynman and his work but for other reasons than for his work on Nanotechnology (which actually does not exist) [Binnig's brackets]. I believe people who push too much his contribution to this field do harm to his reputation. His contribution to science is certainly not minor and he needs not to be lifted [posthumously] onto the train of Nanotechnology (ibidem).

Calvin Quate (1923–2019), who contributed to the development of AFM, wrote that:

None of this work derived from the publications of Feynman. I had not read the Feynman article and I don't think Binnig or Rohrer had read it. All they wanted was a better method for examining microdefects in oxides (ibidem).

Donald Mark "Don" Eigler, the physicist that in 1989 arranged 35 xenon atoms to spell out the letters IBM, a worldwide famous picture also known as "The Beginning", said that he might have read "Plenty of Room" when he was a graduate student, a long time before manipulating atoms with STM but he also says that: *The technical aspects of my work have not been influenced by Feynman's paper (ibidem).*

Toumey's work appears to be important as it contains several extracts from interviews by the author with the protagonists of the recent history of Nanotechnology. This adds a particular value to a new possible interpretation of a work that has been widely credited as the one and only that indicated the way to go throughout the research. Submitting such results to public opinion triggers, in an almost inevitable way, heated debates which, however, can be traced back to two fundamental levels of discussion. The first level is what I have analysed up to this point and collects the ideas of those in favour and against the idea that POR is the document from which it all originated, as regards Nanotechnology. The opinions of the debates, at this level, dwell on the content of the POR and the ideas expressed in it, to establish whether they constituted, to all intents and purposes, the essential starting points for the developments that would come. The testimonies in this sense are discordant, as I have reported through the work of Toumey; indeed, authoritative researchers have had no difficulty in affirming that they were not aware of the publication of POR, or that they did not draw illuminating opinions from it. It should be noted that such a point of view in no way diminishes the historical significance of POR, nor does it prevent other researchers from affirming the exact opposite, and considering it as a milestone in the historiography of science. In fact, our considerations are based on the analysis, in terms of contents, of a scientific article and do not enter into the merits of the historical interpretation of the figure of its author, Richard Feynman. In other words, it is possible to consider POR not to be a "prophetic" text, lifting the figure of Feynman from the paternity of Nanotechnology, without, on the other hand, diminishing the historical significance of Feynman himself as a scientist, Nobel laureate and populariser.

Such a diminishment absolutely does not constitute the goal of those who have distanced themselves from POR, as an inspiring document for their research. On the other hand, it is equally possible to consider POR as a fundamental article, as some of the ideas expressed in it have been realized, and nothing prevents them from being considered as direct inspiration for research. The second level of discussion arises, as Toumey's direct experience confirms, when the focus of the debate shifts from the objective vision of the speech – whether or not POR is an inspiring document – to a subjective interpretation that completely distorts the object of the matter itself. That is, when the reader no longer considers POR at all, and Richard Feynman becomes the subject of the debate, as if the considerations on POR may be considered a simple prelude to a more decisive attack on Feynman. Toumey summarizes these concepts in a paragraph of his article which he titles The evil anti–Feynman. This, in fact, is the interpretation to attributed to Toumey, following the publication of his article, by some thinkers whose attention shifted dramatically from POR to its author, a move Toumey never intended, as we read from his own words. The outcry in defence of Feynman allows us to infer how the object of the dispute was completely misrepresented, and how some felt compelled to defend Feynman from accusations which, on closer inspection, are completely absent. By reflecting on this aspect, it is possible to broaden the discussion further. The author and his writing are not one and the same thing. Those who felt compelled to defend Feynman have in fact combined Feynman's words and thought and figure together into one, considering POR to be an absolutely indisputable work. To question not Feynman, not his work but only the possible influence of one of his articles – not even the article itself, at this point – and not in an abstract way, but supporting the ideas with the direct testimonies of those who, while expressing the highest esteem for Feynman himself, confirmed that the ideas of POR did not address their research at all, this constitutes an intellectual scandal for some. I believe I can consider this fact as breaking the scientific paradigm that has long being accepted: Feynman is the father of Nanotechnology because in POR he foresaw, in some way, some of the results we have achieved today in this subject. This paradigm has been reinforced for decades by all those authors who inaugurated and still open their writings with the words "In 1959 Richard Feynman gave a lecture…". I do not believe that it is a question of choosing one path rather than the other but rather accepting the plurality of points of view, without thinking of undermining – this is absolutely not the purpose – the figure of Feynman or the validity of POR itself. A second crucial debate, the one concerning the practical feasibility of the molecular assembly mechanism, an achievement that seems to be the key to the most wonderful results promised by nanotechnology, involved one of its founding fathers, Eric Drexler, and Richard Smalley, a Rice University professor and Nobel Prize winner. Drexler argued that it was possible to manufacture molecular–sized objects with extreme accuracy, and this idea, with its developments, was the basis of Smalley's criticism. The publication of the observations and counter-responses at later dates fuelled the discussion between the two scientists. According to one of the most simplistic interpretations, the basic promise of nanotechnology is to provide mankind with the tools to design a completely new world by allowing, at the limit, the repair of any device, including the human body in its most delicate organs such as the brain, by manipulating elements on an atomic or molecular scale. Kurzweil (Kurzweil 1990) argued that the linear dimension, one of the key features of technology, is shrinking by a factor of 4 every decade and sets 2020 as the year by which most electronic and many mechanical technologies will be considered as nanotechnologies, with dimensions below 100 nanometres. In reality, electronic achievements are already below this threshold, even if they are not self–assembling structures. The last few years have also been devoted to preparing the conceptual framework within which new ideas and projects in nanotechnology can be developed. The focus point of the discussion between Drexler and Smalley concerns the realisation of self–assembling devices of molecular dimensions. To better understand how Drexler developed his idea of the molecular assembler, it is historically interesting to go back to the late 1940s, when information theorist John Von Neumann (1903–1957), inspired by the concepts of construction, universality and evolution, proposed a model of a self–replicating system consisting of a universal constructor combined with a universal computer. In his idea, the purpose of the computer is to execute a program that directs the actions of the constructor, which makes one copy of the computer, one of the self–replicating program and one of the constructor. Interesting as it is, this idea, not one of those for which Von Neumann is remembered, understandably remains very abstract. It is not clear, in fact, how the computer and the constructor are to be made, many solutions are possible, and the materials that can be used are different. Later, he elaborated the concept of the "kinematic builder", a robot characterised by at least one manipulator, or arm, capable of building a replica of itself from a so–called "sea of parts". Eric Drexler is credited with founding the field of modern nanotechnology in the mid 1980s with the draft of his doctoral thesis, which laid the foundations for nanotechnology and provided the road map that is still followed today. In his work, Drexler presents a Von Neumann Kinematic Constructor that works with atoms and fragments of molecules, in turn taking inspiration from the ideas contained in POR. Drexler calls this constructor the "universal assembler", where the word "universal" refers directly to the device's ability to operate practically at will in performing its functions. The products of a universal assembler must necessarily follow the laws of physics and chemistry, so only atomically stable structures are feasible. Moreover, any specific assembler is limited to building products from his available “sea of parts”, even though the feasibility of using individual atoms has been repeatedly demonstrated. In his work, it must be said, Drexler has not provided a detailed blueprint of what he understands as an assembler, and there does not yet appear to be any such blueprint, yet, as indicated above, each of its components can be associated with an object found in nature. A further plausible classification is based on the following points.

- **The computer**: this is needed to provide what Drexler calls “intelligence”, to control the assembly process; it must be small and simple. Drexler describes an intriguing mechanical computer with molecular “locks” instead of transistors. Each lock requires only 5 cubic nanometres of space and switches 20 billion times per second. This proposal remains more competitive than any known electronic technology, although it could be overtaken by electronic computers built from three-dimensional arrays of carbon nanotubes.
- **The architecture of the instructions**: Drexler and his colleague Ralph Merkle have proposed a Single Instruction Multiple Data (SIMD) architecture in which a single database records instructions to be transmitted simultaneously to trillions of molecular–sized assemblers (each with its own simple computer). In this way, it is not necessary for each assembler to store the entire program to create the desired product. This “broadcast” architecture makes it possible to deal with a key security problem, namely the threat of self–replication, which can be nipped in the bud by inhibiting the single central database. Drexler, however, points out that a nano–sized assembler need not be self–replicating. The Foresight Institute therefore sets up a series of ethical blocks that contain explicit prohibitions against self replication, which in the worst–case scenario is unlimited, especially when operating in the natural environment.
- **Transmission of instructions**: the transmission of instructions from the centralised data archive to each of the many assemblers is carried out electronically, if the computer is electronic, or through mechanical vibrations if a mechanical computer is used, which is also provided for in Drexler’s vision.
- **The builder robot:** the builder is a simple molecular robot with a single arm, similar to Von Neumann’s kinematic builder, but on a smaller scale. In later years, Drexler would demonstrate how mechanical organs can be replicated by molecular–based structures.
- **The tip of the robotic arm: Nanosystems:** molecular machinery, manufacturing, and computation, is the 1992 book in which Drexler provided a series of chemicals that could be used for the tip of the robotic arm which would be able to grasp, using appropriate atomic force fields, a molecular fragment, or even a single atom, and then deposit it where required by the program. Having developed a deposition process to make artificial diamonds, it is known that it is possible to remove individual carbon atoms, as well as molecular fragments that include carbon, and then place them in another position through very precisely controlled chemical reactions. The creation of an artificial diamond involves trillions of atoms, but the process behind it has been exploited to design the tip of a robotic arm that can remove hydrogen atoms from a starting material and deposit them in the desired position in a molecular machine under construction. In doing so, the machines are constructed from a diamond–like material (called “diamondoid”). As well as possessing great strength, the material can be doped with impurities, very precisely, to make electronic components such as transistors. Simulations have shown that mechanical elements such as gears, levers, motors and other systems can be built from these carbon matrices. In the following years, several proposals were made, including several innovative designs proposed by Ralph Merkle (Merkle 1996). In recent years, three–dimensional

carbon nanotubes, capable of providing both mechanical and electronic functions at the molecular level, made up of hexagonal arrays, have received a great deal of attention.

- The internal environment of the assembler: environmental impurities that interfere with the delicate assembly process must be carefully avoided. Drexler proposes to maintain an almost total vacuum and build the walls of the assembler from the same diamondoid material that the assembler itself is capable of producing.
- The energy required for the assembly process: this can be provided either by electricity or chemical energy. Drexler proposed a chemical process in which the fuel is woven into the raw construction material. More recent proposals use nano–engineered fuel cells incorporating hydrogen and oxygen, or glucose and oxygen.

Many different configurations have been proposed; generally speaking, the typical assembler is described as a desktop unit that can manufacture any physically possible product that can be described in some way by software. The products that can be made can vary in kind: computers, clothes and artwork, even cooked meals. Larger products, such as furniture, cars or even houses, can be built in a modular way, or using larger assemblers. A key point of discussion concerns the fact that an assembler can create copies of itself. The cost of creating any physical product, including the assemblers themselves, would basically be the cost of raw materials. The real cost, of course, would be the value of the information through which each type of product is described, namely the software that controls the assembly process. In this way, everything of value in the world, including physical objects, would be composed essentially of information. We are not so far from this situation today, as the "information content" of products is rapidly reaching 100% of their value.

Once operational, the centralised data repository simultaneously sends commands to all robots dedicated to assembly. Trillions of robots make up an assembler, each executing the same instruction at the same time. The assembler creates these molecular robots by starting with a small number and then using these robots to create others, iteratively, until the required number is reached.

Each local robot has a local data memory that specifies the type of mechanism it is building. This local data storage is used to mask global instructions that are sent from the centralised database, so that some instructions are blocked while only local instructions are executed. In this way, even though all assemblers receive the same sequence of instructions, there is a level of customisation of the part built by each molecular robot. Each robot extracts the raw materials it needs from the source material. These include single carbon atoms and molecular fragments. The required chemical fuel is also included in the source material. All the requirements that go into the design, including the routing of instructions and the source material, have been described in detail in Drexler's two works. It is Life itself that provides us with the ultimate proof of the feasibility of a molecular assembler. Indeed, as we deepen our understanding of the information base of life processes, we discover specific ideas to address the design requirements of a general molecular assembler. For example, proposals have been made to use a molecular energy source of glucose and ATP similar to that used by biological cells. Biology is capable of solving each of these assembler design challenges. Ribosomes represent, for example, both the computer and the building robot, as Life does not store data centrally, but provides the entire code to each cell. However, the ability to limit a nanorobot's local data storage to only a small part of the assembly code, particularly in cases of self–replication, is one way in which one can think of designing a nanotechnology with greater safety mechanisms than Nature. In these years in which nanotechnology has taken hold, the potential is available to replace the genetic information repository of biology in the cell nucleus with a nanosystem capable of storing the genetic code and simulating the actions of RNA, ribosomes and other computer elements in the assembler. Doing this might bring significant advantages. It could eliminate the accumulation of DNA transcription errors, a major source of the ageing process, or introduce DNA modifications to essentially reprogram our genes using gene therapy techniques. The ethical implications of such radical interventions in the human genome and the question of ethics will be discussed in detail in Chapter VI. With such a system, the recommended transmission architecture could enable us to stop unwanted replication, thereby defeating cancer, autoimmune reactions and other pathological processes. Although most of these disease processes will already have been defeated by genetic engineering, re–engineering the computer of life using nanotechnology could remove any remaining obstacles and create a level of durability and flexibility far beyond the inherent capabilities of biology. If, over time, nano–replicators become more and more sophisticated, more capable of extracting carbon atoms and carbon-based molecular fragments from source materials that are themselves less controlled, and are able to operate outside defined boundaries, as is the case in the world of biology, they will potentially be a serious threat, particularly if we consider on the one hand their resistance, and on the other hand the speed of replication with which they are endowed, a characteristic that we have already pointed out many times to be considerably greater than that of biological systems. This is, of course, the source of the great controversy alluded to in the article regarding the Drexler–Smalley debate and the letters that followed. In the decade since the publication of Nanosystems, every aspect of Drexler's proposed projects on a purely conceptual level has been reinforced by further proposals for design, supercomputer simulations and, above all, the actual construction of molecular machines. Ross Kelly, professor of chemistry at Boston College, described in the journal Nature his creation of a chemically powered nanomotor consisting of 78 atoms (Kelly, De Silva, Silva 1999). A biomolecular research group led by C. D. Montemagno (*In 2003, Dr. Montemagno was awarded the Feynman Prize for Nanotechnology)* (1956–2018) has, in turn, created a nanomotor powered by ATP (Montemagno, Bachan, Stelick and Bachand 1999). Another molecular–sized motor, powered by solar energy, was created by Ben Feringa, at the University of Groningen in the Netherlands and granted him the Noble Prize. Molecular–scale mechanical components such as gears, rotors and levers have been developed extensively, from Drexler's initial ideas to the present day. Systems demonstrating how chemical energy or acoustic energy can be used, exactly as originally described by Drexler, have been designed, simulated and, in many cases, actually built. Substantial progress has been made in the development of various types of electronic components made from molecular–scale devices, particularly in the area of carbon nanotubes, an area pioneered by Smalley. Under the light of the rapid development of practically every aspect of nanotechnology, from the simplest to the most futuristic, it is interesting to note that the concept of the nano assembler proposed by Drexler has no defects of its own that have been discovered and then described in the literature. In Scientific American (Smalley 2001), Smalley objected strongly to Drexler, but based his ideas on a distorted description of Drexler's proposal, ignoring the numerous results obtained in the last decade. Being rightly counted among the pioneers of nanotechnology for his expertise on carbon nanotubes, Smalley has constantly moved between enthusiasm and scepticism, having written that "nanotechnology holds the answer, insofar as there are answers, to most of our pressing material needs in energy, health, communication, transport, food, water ....". Smalley describes an assembler "according to Drexler" as a device consisting of five to ten "fingers" (or manipulator arms) capable of holding, moving and positioning each atom in the machine being built. Later, he objects that there it would be no room for so many fingers in the confined environment in which a nanobot assembler device is supposed to work. Smalley refers to this situation as to the "fat fingers" problem; these fingers would also have difficulty releasing their atomic load due to the forces of molecular attraction, this is what he called the “sticky fingers” problem. Smalley then describes the “intricate three dimensional waltz that is performed” by five to fifteen atoms in a typical chemical reaction. In fact, Drexler’s idea of assemblers bears no resemblance to Smalley’s description and the subject of his criticism. Drexler’s idea, as well as most of those that followed from it, is of an assembler possessing only one probe, or “finger”. The History of Science has shown us how similar devices have been made, and reference is made to Scanning Probe Microscopes (SPM) and the more sophisticated Atomic Force Microscope. This puts Smalley’s criticism to rest: if it were supported by experience, Life itself would be impossible. Furthermore, there have been extensive descriptions and analyses of possible fabrication techniques that do not involve picking up and placing atoms as if they were mechanical parts to be deposited in place. For example, the feasibility of moving hydrogen atoms using Drexler’s “propynyl hydrogen abstraction” (Drexler 1992) has been widely confirmed in subsequent years. The ability of the scanning probe microscope (SPM), developed at IBM in 1981, and the more sophisticated atomic force microscope to position individual atoms through specific reactions of a tip with a molecular–scale structure provide further evidence of feasibility. Smalley also objects that despite “frantic work... generating even a tiny amount of a product would require [for a nanobot]... millions of years of work”. Here it must be admitted that reason is on Smalley’s side: an assembler consisting of a single nanobot would not be able to produce any appreciable amount of a product. The basic nanotechnological concept is that we will need trillions of nanobots to achieve significant results. Such a large number of nanobots poses significant safety problems. Creating trillions of nanobots at a reasonable cost will require the nanobots to make themselves, this self–replication solves the economic problem on the one hand while introducing serious dangers on the other. Biology has used the same solution to create organisms with trillions of cells, but virtually all diseases result from a biological self–replication process gone wrong. Previous challenges to the concepts behind nanotechnology have also been addressed and resolved successfully. Critics have pointed out that nanobots would be subject to bombardment by thermal vibrations of nuclei, atoms and molecules. For this reason, conceptual designers of nanotechnology have emphasised the construction of structural components in diamondoids or carbon nanotubes. Increasing the strength or stiffness of a system reduces its susceptibility to thermal effects. Analysis of these designs has shown that they are thousands of times more stable in the presence of thermal effects than biological systems, and can therefore operate over a much wider temperature range (Merkle 2001). Similar challenges have also been faced with regard to the uncertainty of position resulting from the inevitable quantum effects, based on the nanometric size of the engineered devices. Quantum effects are significant for an electron, but a single nucleus of a carbon atom is more than 20,000 times more massive than an electron. A nanobot will be constructed of anywhere from hundreds of thousands to millions of carbon and other atoms, so a nanobot will be billions of times more massive than an electron. Plugging this ratio into the fundamental quantum equation for positional indeterminacy shows that this is an insignificant factor. Providing power to the devices presented a further challenge. Drexler’s original proposals involved glucose–oxygen fuel cells, which have held up well in feasibility studies. The glucose–oxygen approach has one major advantage: nanomedicine applications can exploit the glucose, oxygen and ATP resources already provided by the human digestive system. A nanoscale engine has been created using helices made of nickel and powered by an ATP–based enzyme (Montemagno, Bachan, Stelick and Bachand 1999). However, advances in the implementation of hydrogen–oxygen fuel cells at the MEMS and even nanoscale have provided an alternative approach. Hydrogen–oxygen fuel cells, with hydrogen supplied by a safe methanol–based fuel, have advanced in recent years. A small Massachusetts company, Integrated Fuel Cell Technologies, Inc. (Kurzweil 2003) has demonstrated an operational fuel cell based on MEMS. Each device, approximately the size of a postage stamp, contains thousands of microscopic fuel cells and includes power lines and electronic controls. NEC planned to introduce nanotube–based fuel cells in 2004 for laptops and other portable electronic devices. They claimed that their small power sources would power the devices for up to 40 hours before the user needs to change the methanol canister. Back to the debate, on 16 April 2003, Drexler responded to Smalley's article in Scientific American with an open letter. He cited 20 years of his and other scientists' research and specifically responded to the fat–finger objection and the sticky–finger objection. As mentioned above, molecular assemblers have never been described as having actual fingers, but rather a precise location of reactive molecules. Drexler cited biological enzymes and ribosomes as examples of precise molecular assembly in the natural world. Drexler concluded by quoting Smalley's own observation that "when a scientist says something is possible, he is probably underestimating how long it will take. But if scientists say it's impossible, they're probably wrong". Three more rounds of this debate have published to date. Smalley responded to Drexler's open letter by backtracking on his objections to fat fingers and sticky fingers and acknowledging that enzymes and ribosomes are indeed engaged in the precise process of molecular assembly that Smalley had previously indicated was impossible. Smalley states that biological enzymes function only in water and that such water–based chemistry is limited to biological structures such as "wood, flesh and bone". This is incorrect and Drexler stated this assumption. Many enzymes, even those that normally operate in water, can also function in anhydrous organic solvents, and some enzymes can act on substrates in the vapour phase, without the presence of any liquid (Zaks and Klibanov 1984). Smalley goes on to say (but without making any deductions or quotations) that enzyme type reactions can only take place with biological enzymes. This is also incorrect. It is easy to see why biological evolution adopted water–based chemistry: it is the most abundant substance on our planet, and also comprises 70 to 90% of our bodies, our food and all organic matter. Most people think of water as something quite simple, but it involves far more complex phenomena than conventional wisdom suggests. The three–dimensional electrical properties of water, for example, are quite powerful and can break the strong chemical bonds of other compounds. Consider what happens when we put salt in water. Salt is quite stable when it is dry, but it is rapidly broken down into its ionic components when put into water. The negatively charged oxygen side of the water molecules attracts positively charged sodium ions ($Na+$), while the positively charged hydrogen side of the water molecules attracts negatively charged chlorine ions ($Cl–$). In the dry form of the salt, the sodium and chlorine atoms are tightly bound together, but these bonds are easily broken by the electrical charge of the water molecules. Water is considered the "universal solvent" and is involved in most biochemical pathways in our bodies. So we can consider the chemistry of life on our planet mainly as water chemistry. However, the primary thrust of our technology has been to develop systems that are not limited by the restrictions of biological evolution, which has adopted only water chemistry and proteins as its basis. Biological systems can fly, but if we want to fly at 30,000 feet and hundreds or thousands of miles per hour, we will use our modern technology, not proteins. Biological systems like human brains can remember things and do calculations, but if we want to do data mining on billions of pieces of information, we would want to use our electronic technology, not unassisted, though efficient, human brains. Here Smalley is avoiding considering the last decades of research that has investigated alternatives for placing molecular fragments using precisely guided molecular reactions. The synthesis of diamondoid (the diamond–like material formed in precise patterns, as also mentioned before) that can be very finely controlled has been extensively studied, for example, at Caltech's Materials and Process Simulation Center; North Carolina State University's Department of Materials Science and Engineering; the Institute for Molecular Fabrication, University of Kentucky; the U.S. Naval Academy; and the Xerox Palo Alto Research Center (Kurzweil 2003). Smalley is also ignoring the established scanning probe microscope mentioned above, which uses precisely controlled molecular reactions. Based on these concepts, Ralph Merkle has described reactions, at the microscope tip, that can involve up to four reactants (Merkle 1997). There is an extensive literature on reactions that occur at very precise sites, can be accurately guided, and would be feasible for a molecular assembler. Smalley ignores all this literature when he claims that reactions in water carried out by biological enzymes in water are the only ones possible. Recently, many tools beyond SPMs are emerging that can reliably manipulate molecular atoms and fragments. On 3 September 2003, Drexler responded to Smalley's reply by once again alluding to the vast body of literature that Smalley was ignoring, citing the analogy of a modern factory, only made at the nanoscale. Drexler also cited analyses of transition state theory, according to which positional control would be feasible at megahertz frequencies for appropriately selected reactants. The final step in this debate is a follow–up letter from Smalley. This letter does not abound in scientific specifics and citations, but dabbles in imprecise metaphors that avoid the key issues. He writes, for example, that "just as you can't make a boy and a girl fall in love simply by pushing them together, you can't make precise chemistry take place as desired between two molecular objects by a simple mechanical movement... it can't be done simply by putting two molecular objects together". Smalley again acknowledges that enzymes do in fact accomplish this, but refuses to acknowledge that such reactions could occur outside of a biological type system: "this is why I led you... to talk about real chemistry with real enzymes... any such system will need a liquid medium. For the enzymes we know, that liquid will have to be water, and the kinds of things that can be synthesized with water around can't be much broader than the flesh and bones of biology." Drexler's frustration in this debate is understandable because many critics do not bother to read or understand the data and arguments presented to describe future technologies. Smalley's argument is of the form "we don't have 'X' today, so 'X' is impossible". Simply because some things are not available to us today does not mean that they cannot be available to us in the future. Indeed, some realities that will be manifest in the future may be unavoidable, but the fact that they are not before us today makes them easy to deny. Denying the feasibility of an imminent technological transformation is a short–sighted strategy. In the early twentieth century, some thinkers saw the flight of heavier–than–air objects as an entirely possible technological advancement, but proponents of what we would now call mainstream thinking were quick to denigrate them by claiming that it had not been demonstrated at all. Today, flying is one of the most common modes of travel and is done by means that are clearly heavier than air. In 1990, Garry Kasparov scoffed at the idea that a computer or artificial intelligence could beat him in a game of chess, yet when he was beaten by the Deep Blue computer in 1997, observers dismissed it as saying that chess was not such a big deal after all. Those of us who try to project into the future based on well–founded methodologies are at a disadvantage. Smalley reveals at least part of his motivation at the end of his most recent letter when he writes:

A few weeks ago I gave a lecture on nanotechnology and energy entitled "Be a Scientist, Save the World" to about 700 middle and high school students from Spring Branch ISD, a large public school system here in the Houston area. Before my visit, the students were asked to "write an essay on why I am a Nanogeek". Hundreds responded, and I had the privilege of reading the top 30 essays, choosing my 5 favorites. Of the essays I read, almost half assumed that self–replicating nanobots were possible, and most were deeply concerned about what would happen in their future when these nanobots spread around the world. I did what I could to allay their fears, but there is no doubt that many of these young people have been told a bedtime story that is deeply disturbing. You and the people around you have frightened our children (Kurzweil 2005).

Smalley should note that previous critics have also expressed scepticism that both global communications networks and the software viruses that spread through them are viable. Today, we have both the benefits and the harms of both these realisations. However, along with the danger of software viruses, a technological immune system has also emerged. Even if it does not protect us completely, few people would advocate eliminating the Internet to eliminate software viruses. We are getting far more benefit than harm from this latest twist of promise and danger.

Smalley's approach of reassuring the public about the potential abuse of this future technology is not the right strategy. Denying the feasibility of both the promise and the danger of molecular assembly will ultimately prove counterproductive and fail to steer research in the necessary constructive direction. Molecular assembly will provide tools to effectively fight poverty, clean up our environment, defeat disease, extend human longevity, and many other useful activities. Like any other technology humanity has created, it can also be used to amplify and enable us to unleash our destructive side. It is important that we approach the new developments in technology, and nanotechnology in particular, in a conscious way to gain the profound benefits it promises, while avoiding the dangers to which it inevitably exposes us. Drexler and his colleagues at the Foresight Institute have been at the forefront of developing the ethical guidelines and design considerations needed to steer the technology in a safe and constructive direction (Kurzweil 2003).

Norio Taniguchi

Professor Norio Taniguchi was born in 1912 and passed away in 1999. He was professor of Tokyo University of Science and, in 1999, just a few months before his death, he was awarded in Bremen the 1st Lifetime Achievement Award by the European Society for Precision Engineering and Nanotechnology (euspen) (*The Mention on the award reads: "In recognition of his unique and outstanding contributions to research and development in the ultra precision materials processing technologies and in 1974, being the first to formulate and use the term Nanotechnology. Through his vision, writings and example of total dedication to his field of endeavour he has stimulated the development of what will be one of the dominant technologies of the 21st Century").* In 1974, he coined the term nano–technology to describe semiconductor processes such as thin film deposition and ion beam milling, both processes exhibiting characteristic control on the order of a nanometer. The abstract of his article (Taniguchi 1974) can be undoubtfully considered a milestone in History of Science, and it is worth reading.

Nano–technology is the production technology to get the extra high accuracy and ultrafine dimensions, i.e. the preciseness and fineness of the order of 1nm (nanometer), 10 m in length. The name of Nano–technology originates from this nanometer. In the processing of materials, the smallest bit size of stock removal, accretion or flow of materials is probably of one atom or molecule, namely 0.1~0.2nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm. Accordingly, Nano–technology mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule. Needless to say, the measurement and control techniques to assure the preciseness and fineness of 1 nm play very important role in this technology. In the present paper, the basic concept of Nano–technology in materials processing is discussed on the basis of microscopic behaviour of materials and, as a result, the ion sputter–machining is introduced as the most promising process for the technology (ibidem).

In his article, Taniguchi focuses his attention on the need of ultra–fine finishing when manufacturing integrated circuits, electronic devices and opto–electronic devices. He points out also that the grade of fineness required must be of 1nm in length and such a grade can be achieved operating on one atom or one molecule at the time. Back to his article, we read his ideas.

[…] on the manufacturing of mechanical parts of high precision machineries, for instance, block gauge, injection pump, pneumatic or hydraulic bearing, memory disc or drum of electronic computer, aspheric lens, precision diamond tools, etc., such a high grade finishing in dimension and surface roughness has also become to be necessary to improve their qualities to the extreme24 limit. From the emergent needs based on these industrial requirements, the system of ultra fine finishing or "Nano–technology" has been introduced. The usual precision finishing technology has aimed to get the preciseness and fineness of 1µm, i.e. 10–6m in length, hence it says "micro–technology", not so accurate in meaning. Consequently, in contrast, the finishing technology aimed to get the preciseness and fineness of 1nm would be called "Nano–technology". Needless to say, the technology includes the systems of materials processing, measurement and control for the preciseness and fineness of 1nm (ibidem).

According to his ideas, Taniguchi states that Nano–technology must pursue one objective, i.e. to achieve a process of ultra–fine finishing whose precision and fineness is about 1nm in length. Taniguchi's idea is to work on one atom or one molecule at the time, removing it from what he calls the work–piece materials, concentrating the processing energy to the particular atom or molecule we want to take away, this particular energy being at least the molecular bonding energy necessary to remove the atom or the molecule off the surface of the bulk piece. In the article we can find information about the fact that in 1974 some processes were already developed as reported in the table below.

Table. 1.2 The processes on materials capable to intervene on one atom/molecule, according Taniguchi.

Mechanism		Kinds of processing
(Removing) Separation process	Chemical decomposition	Chemical etching (photo–etching), chemical polishing
	Electro–chemical decomposition	Electrolytic polishing, electro–chemical machining
	Evaporation, dissolution (thermal)	Electron beam machining, laser ray machining, electro discharge machining, dissolution machining
	Sputtering (dynamical)	Ion sputter machining
(Accreting, joining) Consolidation process	Physical and thermal accretion	Vapour deposition, sputter deposition, ionic deposition
	Chemical accretion	Chemical plating or deposition
	Electro–lytic accretion	Electro–plating, electrocasting
	Chemical and electro–chemical composition	Thin film (anodic oxidation, oxidation, nitration; gaseous, liquid)
	Implantation (dynamical)	Ion implantation
	Diffusion (thermal)	Surface treatment, sintering
	Crystal growth (thermal)	Epitaxial, molecular beam
	Fusion (thermal)	Dip plating, thermal fusion
(Flow) Deformation process	Surface flow (thermal)	Flow finishing (gas flame, high frequency, heat ray, electron beam, laser ray)
	Viscous flow and abrasion (dynamical)	Flow finishing (vibration sliding, liquid, gas)

Here it is of historical interest to notice how precisely Taniguchi guides the reader among removing processes, accreting ones and flow processes, also detailing which processes are dynamical or thermal. The figure of Norio Taniguchi must appear in every text that concerns the History of Nanoscience and Nanotechnology, because the honour of christening a new science must be credited to him, whose aim was then to improve the techniques used to operate on single atoms and molecules, which today has proved to be of maximum impact in mankind's everyday life.