From materials science to nanotechnology

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At the end of last century, the following question was posed to many scientists, journalists, politicians, intellectuals: "which is, in your opinion, the most important discovery or invention of the last 1000 years?". If you think at the possible answers to this simple question you could figure out a variety of things which had an enormous impact on our life: progresses in surgery and medicine, cars, television, airplanes, electricity, or even basic scientific theories like those of evolution, relativity, genetics, etc. Well, none of these discoveries of the last millennium was selected as the most important one. Rather, most of the people interviewed agreed that the invention that has contributed most to change our life is due to a German librarian who was active in Mainz in the 15th century: Johannes Gutenberg. In 1455 Gutenberg invented the print process with mobile characters. With this seemingly simple system Gutenberg started a real revolution: the free circulation of ideas and knowledge. Until the time of Gutenberg books were hand-written (the famous *incunaboli*) and were extremely costly and preserved in monasteries, but they were not accessible to normal people. It has been estimated that only a 20-30.000 books were existing all over the world at the time of Gutenberg, and most of them were Bibles. Just 50 years after the introduction of the print process, more than 30.000 different titles had been published for a total of 12 million copies. The cost of books dropped, and knowledge and culture started to spread over larger and larger portions of the population. This lead as a consequence to an increasingly rapid development of science and technology, and to the growth of human culture as we know it nowadays.

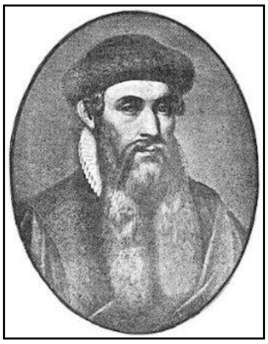


Fig. 1: Johannes Gutenberg(1390-1468)

1. Paper and metal alloys, the basis of books

While everybody knows Gutenberg and his invention, only few know that he was a metallurgist and that the basis for the use of mobile characters is the discovery of an alloy of lead and tin used to fabricate the characters which have to be easy to handle, precise, not deformable under pressure. But there is another aspect which has been essential to spread knowledge in the form of books across the world: this is paper, the support used to print books. Paper is a mixture of vegetable fibers which has been invented in China, around the year 150 a.C. It took a long time however before this material and the technology to produce it arrived in Europe, first in Italy (e.g. in Fabriano) and then in the rest of the continent where it became a common material only around the year 1100. This shows how important revolutions in the history of humanity are based on the introduction of new materials. In the case of Gutenberg these were special metal alloys and paper, nowadays considered "mature" materials which are no longer considered important for our modern style of like (but still, we are not ready yet to replace paper with other more advanced materials!).

Fig. 2: The first printed Bible

One could ask a similar question to that posed at the end of last century, but refereed to the last half a century or so: "which is the most important invention or discovery of the last 50 years?". Also in this case the answer is not easy. The scientific and technological progress in the last decades has been so rapid that it is almost impossible to imagine how the world will look like in 50 years from now. One could consider new technologies like the personal computer, the laser, the possibility to clone cells and living organisms, the DNA world, organ transplant, space travels and satellites, etc.

2. Internet, the modern revolution

The list is long, and one would have a hard choice in selecting one of these advancements. However, if you think a bit more there is one technology which has really completely changed our habits and style of life: internet. In the same way the process of printing with mobile characters has allowed a rapid spread of knowledge, internet has contributed to provide everybody with the possibility to access huge amounts of information, much more of what could be practically used in the entire life of a person. If the diffusion of the Gutenberg invention has been rapid, the diffusion of internet has been extremely fast, almost instantaneous on the time scale of human life. The first web server was set by Tim Berners-Lee at Cern in Geneve in 1992, and the name internet, from the Latin world "intra" and the English world "net", was introduced shortly after. It is only around 1995 that internet started to become used by larger portions of population. This has increased at an incredible rate, and now it is estimated that there are more than 1 billion computers connected in internet, with something like 15 billions of web pages accessible, de facto an unlimited source of information, but also a deep change in the way we communicate and get in touch with other people (just think of phenomena like "second life" or "facebook"). However, in the same way Gutenberg invention was based on novel materials, paper and metal alloys, internet is based on new materials and technologies introduced only in the last 50 years: the transistor, the magnetic supports, the laser, and the optical fibers.

Fig. 3: The first web server (1992)

3. The transistor and the birth of the microelectronic era

The first transistor was invented at the end of 1947 by Shockley, Brattain and Bardeen who for this discovery received the Nobel price in 1956. It was made of germanium, a semiconducting element, and its size was quite big, being an object of several cm per side. However, it was the basis of a real and deep revolution: the birth of microelectronics. In a few years after the discovery, in fact, transistors of few mm in size where produced industrially and used in normal devices like radios where they were replacing the old and fragile vacuum tubes. In 1954 the first portable radio, the Regency TR1, was placed on the market and people were able for the first time to walk in a park listening to the music or the latest news. However, transistors were still complicated to be used in computers because they needed to be connected with a large number of electrical wires; furthermore, their size was certainly much smaller than that of vacuum tubes, but still far from a really miniaturized object. A second revolution in the era of microelectronics occurred towards the end of the 50's with the emergence of a new device, the integrated circuit and the so called MOSFET, or metal-oxide semiconductor field effect transistor. This invention is due to two people who arrived more or less simultaneously to the same idea, Kilby and Noyce. Instead of building separate transistors made of silicon and then connect them with electrical wires, they had the idea of fabricating the transistors directly on a silicon wafer, a tiny slice of pure silicon where, by depositing a tin layer of an insulator, silicon dioxide, and a metal gate, it was possible to obtain all the components of the transistor on a common platform. In order to fabricate

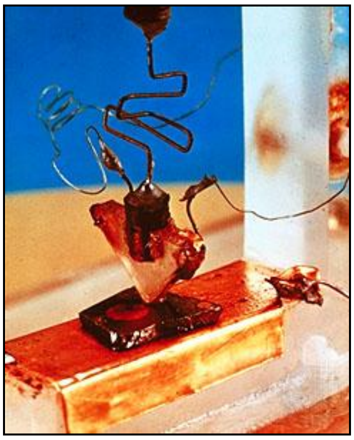


Fig. 4: The first transitor (1947)

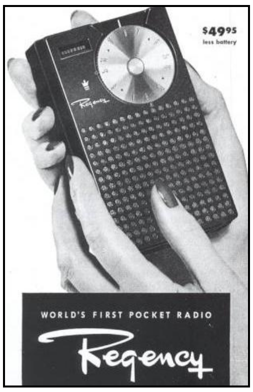


Fig. 5: The first portable radio (1954)

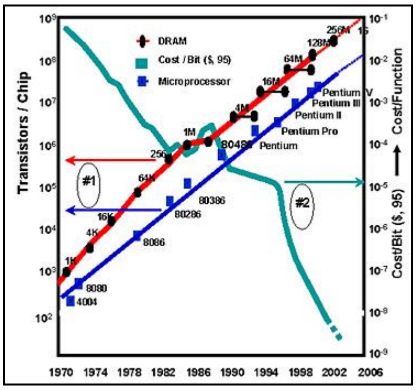


Fig. 6: A diagram illustrating the exponential increase of number of transistors per chip and the drop in cost per transistor from 1970 to 2006

the transistors, however, it was necessary to pattern the wafer by means of a technique known as photolithography, a process used also today to produce industrially integrated circuits. Kilby and Noice had a long dispute about the rights of the patents where this important and new technology was reported. Kilby also got the Nobel price in 2000, while Noyce did not have the opportunity to receive the recognition since he died in 1990.

But the integrated circuit was born, and the possibility to fabricate more and more transistors on the same area, reducing the size of the transistor hence its cost, was started. Also the era of the digital information was going to be deeply changed by this technology. A transistor can be in two states, charged or discharged, on or off, and this electrical signal can be used to manipulate information according to the binary code. The possibility to design powerful computers became reality, and in 1965 Gordon Moore, one of the founders of Intel, formulated a famous empirical low which is known as Moore law. In an article published in Popular electronics Moore stated that the number of transistor per unit of area would have doubled every 18 months leading to an exponential growth of the computing power in the following years.

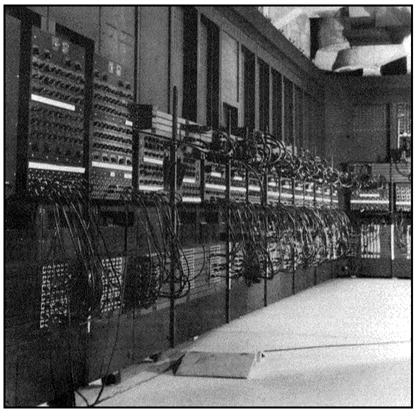


Fig. 7: The computer ENIAC based on bulbs (1946)

With some correction (the number of transistors per surface unit has doubled every 24 months) this law has been valid until very recently. The dimensions of the transistors has decreased to an extent that the modern technologies are based on transistors with size of 60 nm (nm = 1 nanometer = 10^{-9} m). The computing power has literally exploded; the first PCs, which appeared on the marked in the late 70's (like the Commodore, the Apple II, the first PC IBM, or the Olivetti M24) were all more powerful than the largest computer existing in the world in 1946, the ENIAC, with more 17.000 bulbs and a total weight of 30 tons. The microelectronic revolution has occurred in silence, and we entered with the transistors in the nanotechnology era without realizing it.

Fig. 8: The first PC IBM (1981)

The discovery of the transistor and the microelectronic era have deeply changed our habits. However, while the role of the semiconductor technology is well recognized and appreciated, there are other fundamental technologies and materials which have contributed in a decisive way to the advancement of the field and to the revolution in telecommunications, leading finally to internet which has transformed the world in a global village.

4. The role of magnetic materials

When the first computers based on transistors become available, one had to face the same problem that Gutenberg had with his process of mobile printing: where to store information? And in a similar way, the initial way to store data was on paper, using punched cards and punched ribbons.

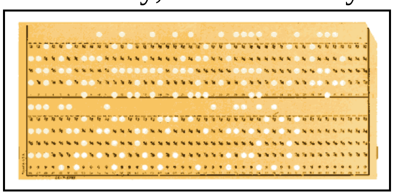


Fig. 9: A punched card

Clearly, the increasing amount of information to store and handle was incompatible with such a procedure: a punched card contains a sequence of 80 characters only! However, already in the 50's material scientists and engineers started to explore another powerful way to store information, the magnetic media. The first magnetic devices in electronic computers were made of ferrite, a material

based on iron oxides which has intrinsic magnetic properties. Magnetic materials were then used in the first magnetic disks which appeared in the mid 50's, and then in magnetic ribbons.
IBM was the first company to introduce this technology to write and read data, and soon become the world leader in producing and developing magnetic disk storage. The capability to store more information in a given space started to grow in a similar way as it was possible to fabricate more transistors per unit of area. Here the problem was similar but the technology different. Also a magnetic device can be in two states, magnetized or non magnetized, which can be translated in the 0 or 1 symbols of the binary code. The smaller is the magnetized area, the larger is the amount of information that can be stored. However, in order to magnetize or demagnetize a given area (usually called a magnetic domain), one needs a magnetic head capable of "writing" (or reading) the magnetic support. Smaller domains require more and more sophisticated and accurate magnetic sensors. Towards the end of the 80's the technology in this direction had more or less reached the physical limits, and it was not clear how to proceed with the miniaturization of the magnetic domains. At the same time, in the early 80's, a completely new technology appeared, which was supposed to fully replace magnetic recording: the optical disk or compact disk (CD). Using another important discovery that we will briefly describe below, the laser, it became possible to "write" and "read" information stored on a support using optical technologies, a beam of light. This opened the possibility to write large amounts of data on a small space. This emerging technology was therefore supposed to replace and substitute completely the "old" magnetic recording supports. It is interesting to note that more or less at the same time when the technology of magnetic recording was considered to be obsolete and therefore in danger and to be replaced by the more promising optical recording media, an important discovery was going to revolutionize the field and to change completely the perspective. In fact, in 1988 two European scientists, the French Albert Fert and the German Peter Grünberg made independently an important observation. A device composed by very thin layers of magnetic and non magnetic metals was exhibiting a particularly high resistance to the flow of current when exposed to an external magnetic field. This effect was therefore called Giant Magneto-Resistance (GMR) and was one of the first important consequences of the possibility to grow films of metals with thickness of the order of the nanometer. In other words, it was the consequence of producing objects at the nanoscale, a largely unexplored world where new phenomena can appear. The discovery of Fert and Grünberg had an important and immediate effect. The GMR effect was a physical phenomenon perfectly suited to design and fabricate new extremely sensitive magnetic heads, giving impulse to the possibility to move from magnetic disks containing Mb of information (1 Mb = 10^6 bytes) to order of magnitude more dense magnetic supports. It was an IBM scientist, Stuart Parkin who did very important progress in the practical application of the GMR. This helped the design and then the production of a new class of magnetic heads, and a few years after the discovery of Fert and Grünberg the first magnetic disks based on GMR were on the marked. By the end of the century practically all disks were based on this technology. Nowadays one can buy a disk containing a Tb of information (1 Tb = 10^{12} bytes) for 100 Euro or so. It is not surprising that the discovery of Fert and Grünberg was awarded the Nobel prize in Physics in 2007. Interestingly, the unsurpassed capability of magnetic disks was also due to a limitation which has not been overcome when dealing with optical disks like the CD: this is the speed to read and write the information, another essential aspect, given the huge amount of data that have to be processed in a computer. So, the story of the magnetic storage, and its competition with the optical storage, which nevertheless has found its way into the market to permanently store data or images like movies and music, is a typical example of how difficult is to predict the development of science and technology.

Fig.10: The hard disk 6603 of the Control Data Corporation (1967). The diameter was 66 cm and the capacity of 512 Kb. Here it has been transformed into a table

5. Lasers and optical fibers

Until now we have seen that internet and the modern communication technologies are based on two major advances which have taken us into the nanoworld without being aware of this. The transistor and the magnetic disk are the two key components which allow us to elaborate and store the information, something that we do everyday even when we use our PC or our mobile phone. But transmitting large amounts of data, like when we send to a friend the digitalized picture taken during last holidays, requires two other important technologies, all based on advanced materials specifically designed for this purpose: the laser and the optical fiber. The laser was studied by several people in the 50's and the first patent about a special kind of laser based on ruby, a Cr-doped aluminum oxide crystal, was deposited in 1960 by T. Maiman. Nobody was conscious at that time of the several essential applications that the laser would have experienced in the years to come. Nobody was aware of the fact that at the end of the second millennium huge amounts of data would have been transmitted from computer to computer thanks to a laser which generates ultrafast sequences of photon pulses which transport the information generated in form of electrons by the transistors. But it is thanks to the laser that toady we are able to send in seconds or fractions of second entire books, pictures, movies, music, and so on. The modern lasers are no longer based on the ruby crystal but are done again by ultrathin layers of semiconducting materials each one with a few nanometers thickness. They generate photon pulses which travel with the speed of light thus transferring the information in a very rapid way. But how can light (photons) travel without being absorbed or deviated? For this purpose one uses another system, the optical fiber, a thin, but very long and flexible wire made of ultrapure silica, the basic component of windows. The difference is that while the glass of a window is a made from a mixture of oxides and is transparent for only a few cm thickness, the optical fiber is made of pure SiO_2 and is transparent for kilometers and even hundreds of kilometers. Transparency is the key property of the silica fiber. The pulse of photons generated by the laser need to travel for long distances without being absorbed in order to arrive to another router where it is decoded and translated into an electrical signal. Any absorption of the photons generated by the laser decreases the intensity of the pulse which finally is not detectable any more.

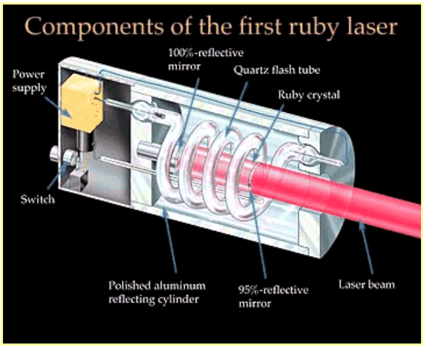


Fig. 11: The ruby laser (1960)

Fig. 12: Optical fibers

This is why the optical fiber needs to be done with special processes able to produce materials which do no absorb light. Pure silica has been the key material in this respect, and the optical fibers represent the "highways" of the modern interconnected world. On these highways huge amounts of data are traveling at the speed of light and allow direct communication between places which are thousand of kilometers apart. Being flexible, the optical fiber can also be bent and adapted to any path and circuit, and represents an excellent solution to the problem of information transport.

To summarize, we have seen that in a similar way the extraordinary invention of Gutenberg was based on two essential materials, paper and metal alloys, the second revolution in the communication technology, internet, is based on a variety of materials, semiconductors for transistors and lasers, wide-gap insulators for the transparent optical fibers, magnetic materials for storage and recording. All these technologies have pushed our knowledge and our capabilities until the physical limits. This means that many of the systems and devices have been scaled down to reduce the dimensions and increase the power. We have seen that this has been the reason why we can have today in our hands a powerful computer like a palm or that of a digital camera. This was the prediction, or better to say the vision, of Gordon Moore in his famous article of 1965, when he described a future where computers were going to be sold in supermarkets with cosmetics and food.

When the article appeared this prediction looked completely unrealistic to most observers; but this is indeed what we see in our shops and supermarkets in these days.

The history of internet, of the microelectronics era, of the computer, have take us directly into the nanoworld. The word nanotechnology is often used in various contexts, and it has different meanings for different people. It looks like a new announced revolution to many of us, but what it will produce and when remains largely mysterious. However, from what we have said before, nanotechnology is already with us, we are using it, and even since some years, although we may have not been aware of this. Stated differently, nanotechnology has already produced some revolutions, and there is little doubt that others will come. So, it is important to know at least in a broad sense what is nanotechnology and what we can expect from it.

Fig. 13: The picture reported in the famous article of Gordon Moor in "Popular electronics" of 1965 where computers stay in a hand and are sold in supermarkets

6. The birth of nanotechnology

Differently from many other modern fields of research, nanotechnology has a precise birth day, at least in a conventional sense. In fact, on December 29, 1959, the famous American physicist Richard Feynman gave a talk at Caltech which is now considered the start of the nanotechnology era. In his futuristic talk, Feymnan placed emphasis on the potential connected to the manipulation of matter at the level of atoms and molecules: "Now, the name of this talk is "There is *Plenty* of Room at the Bottom" - not just "There is Room at the Bottom". What I have demonstrated is that there *is* room - that you can decrease the size of things in a practical way. I now want to show that there is *plenty* of room. I will not now discuss how we are going to do it, but only what is possible in principle according to the laws of physics" (http://www.zyvex.com/nanotech/feynman.html). With this speech Feynman draw the attention to the fact that the potential connected with the control of operations at the nanoscale is enormous, and that there is no physical law to limit this potential. However, he was aware of the fact that atoms and molecules, with dimensions of the order of the nanometer or below, are extremely small objects and that their manipulation needs to develop extremely sophisticated technologies, not available at the time Feyman gave his famous talk. In fact, it took a few decades before people started to made real progress in this direction. But why there is such a great benefit in manipulating matter at the nanoscale?

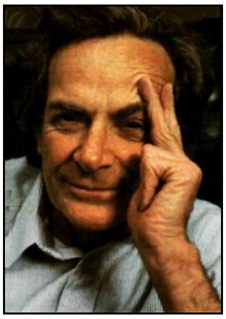


Fig. 14: Richard Feynman

To better understand this we have to consider a number which should be familiar to most of us, but whose dimensions are hard to conceive and imagine for our normal experience. I am referring to the Avogadro number, i.e. the number of molecules contained in a macroscopic amount of substance, the mole, usually a few grams of a substance. While many people have heard of the Avogadro number, only few know that its value has not been defined by Avodagro who, in 1812 only discovered one important law of gases: "Equal volumes of gases at the same temperature and pressure contain the same number of molecules". To establish exactly how many molecules are contained in a mole took nearly a century of efforts, and the most accurate estimate of the Avogadro number was given by Einstein in 1911: 6.0221367×10^{23}. It is a huge number, six hundred thousand billions of billions, hard to imagine. Just to give an idea, it has been estimated that in the entire earth are living about 10^{16}

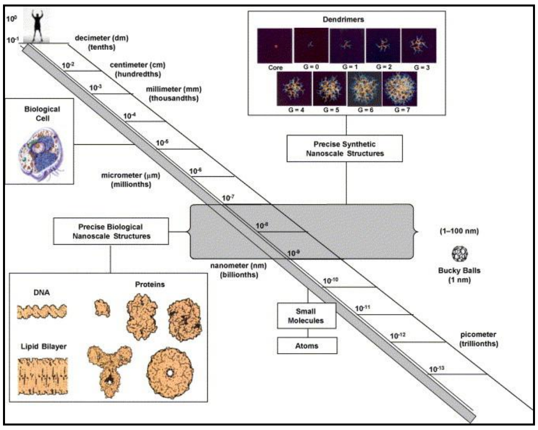


Fig. 15: Dimensionality scale

ants (10 millions of billions). This means that in order to have an Avogadro number of ants, one would need 60 millions of planets like the Earth! These numbers tell us not only that there is plenty of room in the nanoworld, to use Feynman's expression, but also that we have huge numbers of objects. If we are able to let these objects do the work we want (e.g. store or elaborate information) we will have an incredible opportunity.

7. The discovery of fullerenes

The idea of Feynman, however, remained basically a dream for at least two decades. It was only from 1980 to 1990 that a few fundamental discoveries opened the way for the rapid revolution that we call now nanotechnology. One of these discoveries occurred more or less by chance in 1985 in the laboratory of Rich Smalley, today considered one of the fathers of this new field. Smalley was studying gas-phase clusters, very small aggregates of atoms produced with a sophisticated equipment specifically designed by his group. Clusters represent an new state of matter, not atoms and not yet condensed phases like liquids or solids, and present several interesting and unusual properties. They can contain from a few to a few thousand of atoms, and their characteristics change by changing the dimension.

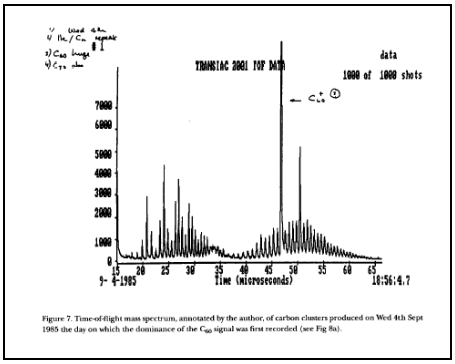
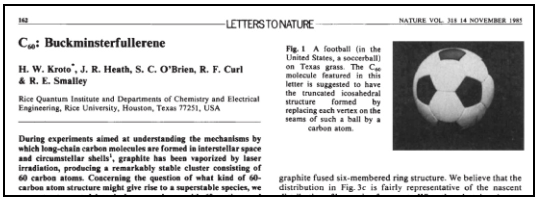


Fig. 16: The mass spectrum showing the intense peak corresponding to the formation of the C_{60} cluster (1985)

During a visit to Smalley's group in Huston, Texas, the British scientist Harold Kroto decided to investigate clusters of carbon atoms using Smalley's equipment. The experiment showed the formation of a particularly stable aggregate, containing exactly 60 carbon atoms. This observation, which by the way had been done by another group a year before without realizing its importance, lead Smalley and Kroto to try to understand the nature of this particularly stable cluster. In order to do this, Smalley tried to figure out which particular arrangement could result in a stable, hence unreactive, aggregate. He became inspired by some structures, the geodesic domes, invented by an American architect, Backminster Fuller. Smalley realized that if one connects 60 atoms forming hexagons and pentagons one obtains a spherical object which closely resembles a soccer ball in use in those years. The illuminating idea that the carbon atoms are disposed in this way led Smalley and Kroto to propose that this is in fact the reason for the special stability of the carbon aggregate C_{60}. They formulated for this new molecule the name "fullerene", in honor of the American architect.


162 LETTERS TO NATURE NATURE VOL. 318 14 NOVEMBER 1985

C_{60}: Buckminsterfullerene

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During experiments aimed at understanding the mechanisms by which long-chain carbon molecules are formed in interstellar space and circumstellar shells[1], graphite has been vaporized by laser irradiation, producing a remarkably stable cluster consisting of 60 carbon atoms. Concerning the question of what kind of 60-carbon atom structure might give rise to a superstable species, we

Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.

graphite fused six-membered ring structure. We believe that the distribution in Fig. 3c is fairly representative of the nascent

Fig. 17: The article of Nature reporting the first observation of C_{60} (1985)

This discovery lead in a few years to a real explosion of this field, with the discovery of new methods to prepare these nanoobjects, and with other surprising findings like the possibility to produce even elongated structures, the carbon nanotubes, kind of electrical wires with molecular dimensions. Today, carbon nanotubes are produces industrially and are used in a variety of applications, in mixture with polymers to form new robust composite materials, but are studied also for applications in microelectronics and even in biology and medicine. For they discovery, Smalley and Kroto received the Nobel price in chemistry in 1996.

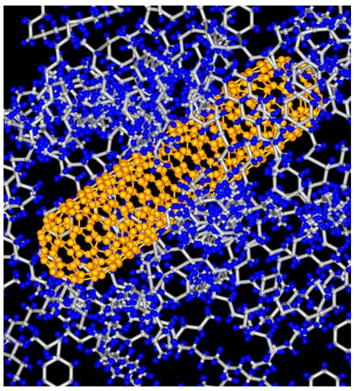

Fig. 19: A simulated structure of a composite material formed by carbon nanotubes and polymers

8. Microscopes to "see" the atoms

But more or less at the same time when fullerenes were discovered, another important breakthrough occurred. Two scientists at the IBM research center in Zurich, Gerd Binnig and Heinrich Rohrer, designed and finally realized a revolutionary instrument, the scanning tunneling microscope, or STM in short. It took some years of work to Binnig and Rohrer to transform a fantastic idea into a practical tool. The idea was that if one is able to produce an extremely tiny tip and to place it at very close distance from a conductive surface, one may apply a small voltage and measure a flow of electrons, a current, between the tip and the surface. If the two objects are not in contact, however, this electron flow occurs through the air (an electrical insulator) in between the tip and the surface, by means of a mechanism known as quantum-mechanical tunnel effect. The extent of the current will depend on the distance of the tip from the surface, so that if one can measure this tiny current, one can obtain a topographic image of the surface. Stated differently, with some elaboration of the signal one can obtain an image at atomic resolution of the surface, or, in common words, one can see the atoms! Notice that while the atomic theory of matter was well established at the beginning of the 20th century, until the discovery of the STM, around 1982, nobody has never seen a single atom! The method implemented by Binnig and Rohrer, that for this discovery received the Nobel prize in Physics in 1986, was opening a completely new area and was producing, for the first time, direct images of the world at the nanoscale. A few years later, another scientist from IBM, Don Eigler, working at the research center in Almaden, California, implemented a new version of the STM able to operate at very low temperatures. With this new instrument he performed an extraordinary experiment: he used the tip of the STM to pick-up single atoms and move them in a different position following a precise scheme. Eigler used this procedure to move a series of Xenon atoms on a surface of nickel and put them in a sequence to create the logo of IBM, only written with just a few atoms! One has to realize that given the extremely small dimensions of a single atom, the possibility to manipulate them and to place them in desired positions was something closer to science fiction than to reality. Since then, STM technology has advanced rapidly and it is now currently used to study materials at the nanoscale.

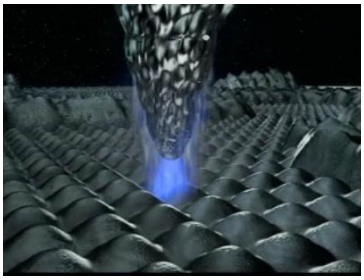

Fig. 20: A simulated image of the tip of an STM moving on a surface

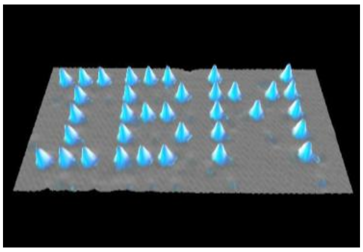

Fig. 21: The IBM logo written with a STM tip using Xe atoms on a nickel surface (1990)

The STM has thus represented a major step towards the possibility to manipulate and observe matter in the nanoworld. However, since this particular microscopy is connected to an electron flow from the tip to the surface to investigate, its use is restricted to conducting materials, a rather severe limitation if one is interested, for instance, in living organisms or insulating materials. To overcome these problems, Gerd Binnig, the same year he was awarded the Nobel prize for the design of the STM, had another brilliant idea. His goal was to fabricate another type of "microscope" able to recognize the topography and the profile of any object, even of non-conducting samples. To reach this ambitious objective, he had to make use of the extremely weak forces which are established between any object of molecular dimensions when these objects are at very short distance, typically below a nanometer. These forces are known as van der Waals forces, from the name of the Dutch scientists who identified them in the early years of the 20th century. These forces are responsible for instance for the transformation of rare gases in liquids at very low temperature. Binnig designed a special cantilever terminating with a very small tip. This cantilever was vibrating when the tip was getting close to the surface under the effect of the attractive van der Waals forces. By measuring these tiny

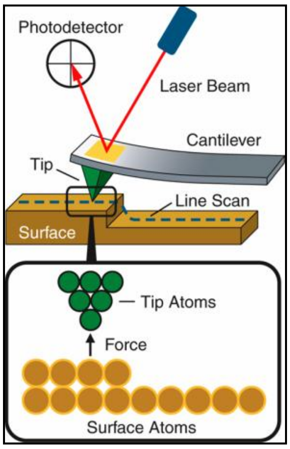

Fig. 22: A schematic view of the structure of a AFM microscope

vibrations, Binnig succeeded in producing an image of the surface under the tip. He called the new instrument atomic force microscope, or AFM. Today, with various improvements, it has been possible to reach atomic resolution even in AFM images, and the AFM has become of even more generalized use than the STM for the investigation of nanosystems. For instance, IBM has developed a new technology to store data which is based on the AFM idea; it is called millipede, and it consists of thousand of cantilevers with a needle at the end. These needles are used to indent a substrate and create a hole. The presence or the absence of the hole corresponds to a bit of information, 0 or 1. Since the size of the tips and of the holes is of few nanometers, it is expected that with this technology very high densities of information can be stored.

9. Lessons from nature

There is another aspect of this story which is worth mentioning. We have seen that the AFM is based on the weak van der Waals forces existing when objects are at very short distance. For almost a century scientists have tried to figure out how the gecko, a small reptile leaving in several continents, can walk on wall or roofs with great mobility and facility. Several hypotheses have been formulated: the secretion of a special glue, the existence of special sucker at the end of its fingers, the existence of electrostatic forces, etc. None of these hypotheses survived a serious verification. It is only recently that it has been observed, thanks to accurate electron microscopy, that the legs of the gecko are ending with very small filaments, each one of the dimension of few hundreds of nanometers. The last part of the gecko fingers is therefore nanostructured. Each of these filaments in contact with a surface produces a very small interaction, a van der Waals force. A single filament generates a tiny adhesion energy, but since there are 14000 of these filaments per millimeter square, the final effect is a strong adhesion. This example, which has become a classic in the anecdotes of nanotechnology, is however a typical case where nature is providing us with practical demonstrations of the usefulness of nanostructured materials.

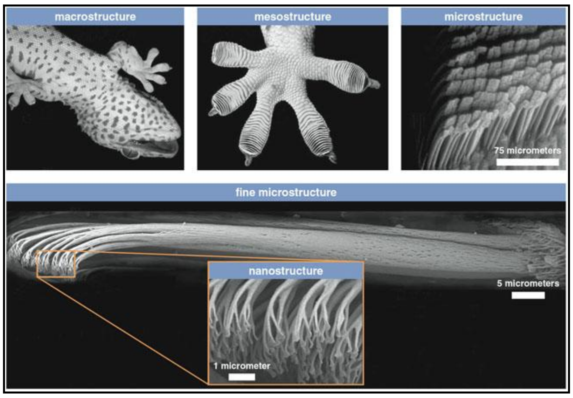

Fig. 23: Images taken at the electron microscope (bottom) of the filaments at the fingers of the gecko.

And this bring us to the most recent and most relevant aspect of nanoscience and nanotechnology, at least for practical implications. Nanotechnology is in fact the science which aims to generate, by exploiting the small dimensions of atoms and molecules, new materials with unprecedented properties. These materials are going to be used in several fields, like energy production from solar light, molecular electronics to replace the classical microelectronic devices based on silicon, fabrication of very accurate sensors to indicate the presence of specific polluting substances in the atmosphere, synthesis of new ultrastrong materials or materials with exceptional thermal properties, etc. Materials science is going to be deeply changed by the introduction of nanostructures. But the nanotechnology revolution is not restricted to materials or devices. It will also have a strong impact on other human activities, like medicine. One speaks already of nanomedicine. In a near future it will be possible to develop specific nanosensors capable to identify the parts of the body where cell tissues have to be removed or repaired; it will be possible to deliver drugs in a selective way only to cancerogenous cells without damaging the other cells; it will be possible to construct kind of molecular machines able to repair the body without the need of a surgery operation. And so on. Of course, some of these objectives look rather fantastic and one may wonder if this will ever occur. As we mentioned before, predicting the future is a difficult and dangerous exercise. Twenty years ago nobody would have even guessed the revolution introduced by internet, but today we could hardly live without it. In the same way, it is very difficult to predict how life will look like in twenty years from now. There is little doubt, however, that nanotechnology is one of the fields which is expected to produce the deepest changes. Knowing more about it, is a way to be prepared for the changes to come.