Nanoscience and Nanotechnology: A Personal View of a Chemist**

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- devices
- molecular machines
- nanoscience
- nanotechnology
- supramolecular chemistry

Introduction

Nanotechnology is a frequently used word both in the scientific literature and in common language.[1] It is a word that stirs up enthusiasm and fear since nanotechnology is expected, for the good and for the bad, to have a strong influence on the future of mankind. Everybody seems to know what nanotechnology is, but even within the scientific community the meaning of this word is not yet well established. In fact, nanotechnology has apparently different meanings in different fields of science, for example, in physics and chemistry. Perhaps surprisingly, the term *nanoscience* is much less commonly used, but it is all the same rather poorly defined.

In this essay, I will briefly discuss what nanoscience and nanotechnology mean for a chemist. It is easy to forecast that my view will not be shared by physicists and engineers, and perhaps also by some chemists. It is, in fact, not only a chemical, but also a personal view. Whether right or wrong, the concepts expressed in this essay will hopefully open a debate that proves helpful in underscoring the scope of *Small*.

I will start with a few comments on the meanings of the component words: science, technology, and "nano".

Science

My own definition of science is the following: *Science is a human activity aimed at knowing the laws of Nature and then using such a knowledge to change the world*. This definition reflects the fact that science operates and develops along two directions; discovery and invention. On one hand, science aims at discovering what already exists, but is still unknown; for example, how sunlight is converted into chemical energy by green plants (natural photosynthetic process). On the other hand, science aims at inventing what did not exist before; for example, the way in which water can be split into hydrogen and oxygen by sunlight (artificial photosynthesis). Science is the most powerful means that mankind has to understand the working principles of the material world, as well as to change the world. In the early age of science, most of the scientists were engaged in discovering Nature. As time proceeds, scientists move more and more from discovering to inventing. Most of the papers published in *Small* will likely deal with inventions.

Technology

Technology has a quite different meaning from an apparently similar word, technique. Technique is the method of doing or performing, with skill acquired by experience, something that has already been established. Technology can be defined as *the ability of taking advantage of the progress of science to create novel opportunities for practical applications*. Technology is the main driving force for the progress of mankind since it provides a wealth of novel materials, devices, and machines capable of improving the quality of life. Unfortunately, however, technology can also be exploited for negative purposes, for example, violence, war, and terrorism. As technology advances, the welfare of mankind improves, but at the same time the world becomes more fragile. This is an implicit consequence of the "great asymmetry" principle pointed out by S. J. Gould:[2] *"The essential human tragedy, and the true source of science's potential misuse for destruction, lies in a great asymmetry in our universe of natural laws. We can only reach our pinnacles by laborious steps, but destruction can occur in a minute fraction of the building time, and can often be truly catastrophic. A day of fire destroyed a millennium of knowledge in the li-*

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brary of Alexandria, and the shot of one assassin can launch a preventable war. … We have no choice, for humans must wonder, ask and seek—and science must break through the strictures of custom—to become either our greatest glory, and our most potent engine of benevolent change, or an accelerator of destruction on the wrong side of the great asymmetry".

This concept is of topical interest. In the last few decades there has been tremendous technological development, and at the same time, we have realized that it is practically impossible to protect all of our technological achievements from terrorist attack: aircraft, power plants, skyscrapers, hazardous biomaterials, and so on. Since it is clear that war propagates terrorism, it is now clear that peace is not only a moral command, but also a necessity for the survival of our highly technological society.

"Nano"

Nano, like micro, pico, and so on, is a prefix used in front of a macroscopic unit to change its value by orders of magnitude. Nano means one billionth, or 10^{-9}. Thus, one nanometer is one billionth of a meter. When placed in front of words like science and technology, however, the meaning of nano is not that obvious (nanoscience cannot be one billionth of science!). Since experimental science and technology deal with material objects, it seems fair to say that *nanoscience and nanotechnology are science and technology concerning objects of nanometer dimensions*, which are atoms (on a scale of tenths of nanometers) and molecules (on a scale of nanometers). Since everything is made of atoms and molecules, nanoscience and nanotechnology could, in principle, be thought to cover all the branches of science and technology. Another possibility is that of limiting these words to define the branches of science and technology that are specifically related to the atomic and molecular structure of macroscopic matter. Both proposals, however, are unsatisfactory and neither physicists nor chemists would agree on defining nanoscience and nanotechnology in this way.

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A more satisfactory definition of nanoscience and nanotechnology can be achieved by focusing on the intrinsic properties of the nanoscale objects and on the possibility of using, manipulating, or organizing them into assemblies in order to perform specific functions. These concepts can be better explained in the frame of a discussion on miniaturization.

Miniaturization: Top-Down and Bottom-Up Approaches

The miniaturization of components for the construction of useful devices and machines is currently pursued by the top-down approach. This approach, which leads physicists and engineers to manipulate progressively smaller pieces of matter by photolithography and related techniques, has operated in an outstanding way up until this time. It is becoming increasingly apparent, however, that the top-down approach is subject to drastic limitations for dimensions smaller than 100 nm.[3] This size is very small by the standards of everyday experience (about one thousandth of the width of a human hair), but it is very large on the scale of atoms and molecules. Therefore, "there is plenty of room at the bottom" for further miniaturization, as Richard Feynman[4] stated in a famous talk to the American Physical Society in 1959, but the top-down approach does not seem capable of exploiting such an opportunity.

An alternative and most promising strategy to exploit science and technology at the nanometer scale is offered by the bottom-up approach, which starts from nano- or subnanoscale objects (namely, atoms or molecules) to build up nanostructures. The bottom-up approach is largely the realm of nanoscience and nanotechnology. This is the reason why chemists, being able to manipulate atoms and molecules, are in an ideal position to contribute to the development of nanoscience and nanotechnology.

Bottom-Up Approach

In the bottom-up approach to miniaturization one can distinguish two different limiting cases:

Case 1: Nanoscale "objects" are very simple from a chemical viewpoint and do not exhibit any specific intrinsic function (atoms, clusters of atoms, small molecules). Functions arise from ensembles of such objects. I will only mention a couple of examples; a) atoms or very simple molecules can be used to write a word of nanoscale dimension on a surface. Figure 1 shows how the new millennium was celebrated by writing the figure "2000" on a Cu(211) surface using 47 individually placed CO molecules.[5] b) Metal nanoparticles can be used to cover a surface. A metal nanoparticle is made of metal atoms, as is a metal leaf, but in the nanoparticle most of the atoms, being on or close to the surface, are exposed to interactions with other species. Covering a macroscopic piece with metal leaves (technology) or with metal nanoparticles (nanotechnology) leads to materials characterized by quite different properties.[6]

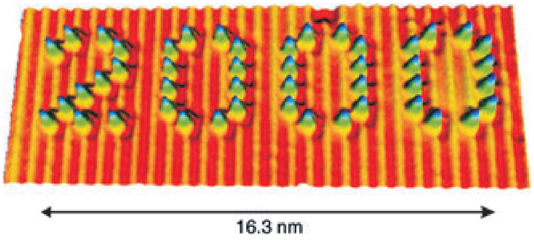


Figure 1. The number 2000, celebrating the new millennium, has been written by using 47 CO single molecules. Each protrusion represents an individual CO molecule and the background vertical lines are the intrinsic Cu surface step edges.[5]

This field of nanoscience and nanotechnology is of greatest interest to physicists and engineers (nanoparticles, nanostructured materials, nanoporous materials, nanopigments, nanotubes, nanoimprinting, quantum dots, and so on) and has already led to many innovative applications, particularly in materials science.[7] For basic investigations, an important role is played by manipulation or imaging nanoscale techniques (e.g., AFM and STM).

Case 2: Nanoscale "objects" have complex chemical composition (supramolecular[8] or multicomponent[9] systems), exhibit characteristic structures, show peculiar properties, and perform specific functions. All of the artificial molecular devices and machines[10] belong to this category. Examples of such nanoscale "objects" are the light-driven rotary motors based on the geometrical isomerization of alkene-type compounds containing chiral centers (Figure 2),[11] the prototype of a molecular muscle (Figure 3),[12] the light-driven molecular shuttles,[13] the artificial molecular elevator (Figure 4),[14] the light-driven hybrid systems for producing ATP and pumping calcium ions,[15] and the DNA biped walking device.[16,17] All of the natural molecular devices and machines,[18,19] from the light-harvesting antennae of the photosynthetic systems to the linear and rotary motors present in our bodies, also belong to this category.

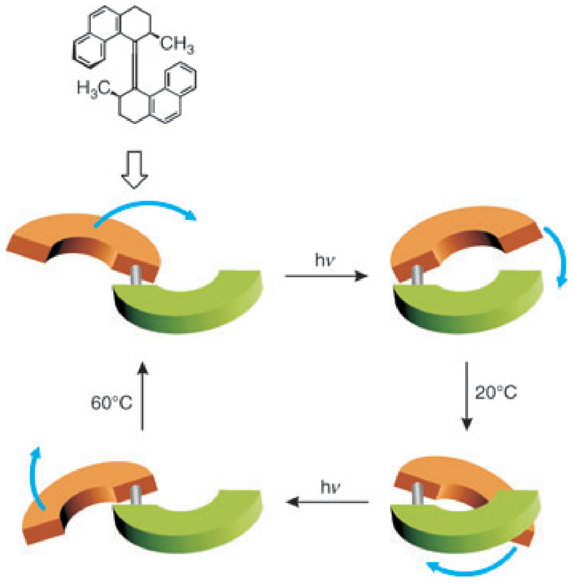


Figure 2. Structural formula and schematic representation of a molecular motor, based on the photoisomerization of an alkene-type compound containing chiral centers, that exhibits light-induced unidirectional rotation.[11]

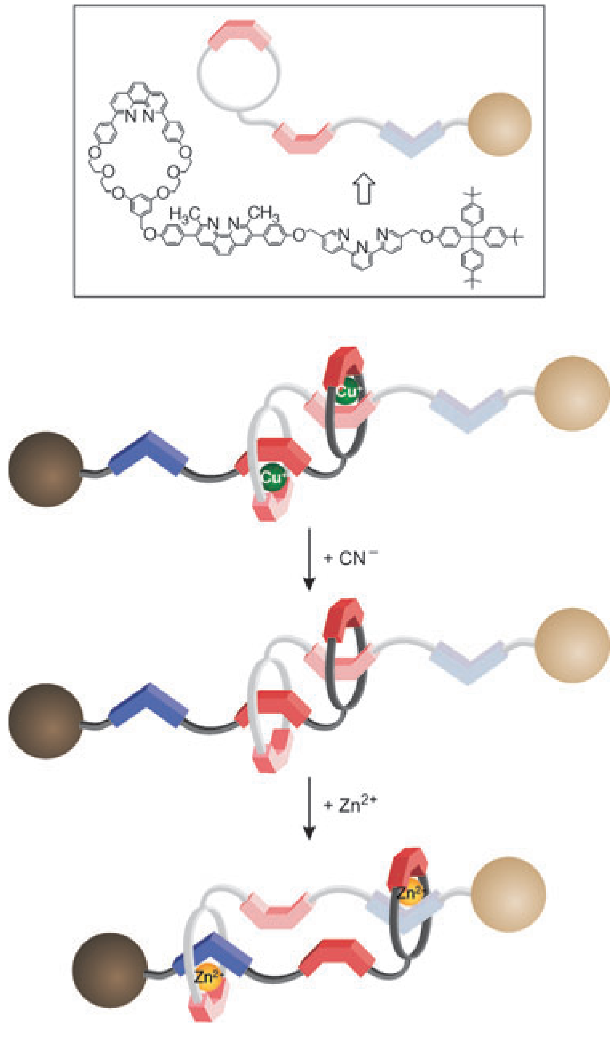


Figure 3. A prototype of a molecular muscle based on the chemically driven contraction of a rotaxane dimer.[12]

Bottom-Up Construction of Nanoscale Devices and Machines

Nanoscale devices and machines are either present in nature,[18,19] or must be synthesized starting from more simple components.[10–17,20,21]

The idea that atoms could be used to construct nanoscale devices and machines was first raised by Feynman in the previously mentioned address "There is plenty of room at the bottom".[4] A key sentence of Feynman's talk is the following: *"The principles of physics do not speak against the possibility of maneuvering things atom by atom"*.

The advent of nanotechnology was depicted in an exciting and visionary way by Eric Drexler in mid-1980s.[22]

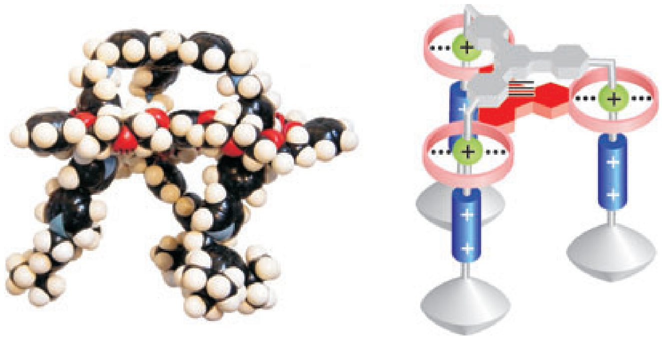


Figure 4. A molecular elevator: the red platform moves up and down upon the addition of acid and base, respectively.[14]

Later, he presented his ideas on nanosystems and molecular manufacturing in a more scientific (but essentially theoretical) way claiming the possibility of constructing a general-purpose nanodevice, nicknamed the *assembler*.[23,24] Such a nanorobot should be able to build almost anything, including copies of itself, by atomic-scale precision, "pick-and-place" machine-phase chemistry (mechanosynthesis).[25]

The fascinating but, admittedly, somewhat abstract ideas of Drexler about the construction, futuristic use, and also frightening potential of nanomachines have been skeptically received by a large part of the scientific community.[26] In fact, the ideas of maneuvering atoms or making molecular mechanosynthesis, that seem so appealing to physicists, do not convince chemists who are well aware of the complexity and subtlety of bond-breaking and bond-making processes.[27]

In the late 1970s, a new branch of chemistry called *supramolecular chemistry* emerged and expanded very rapidly.[8,9] In the same period, research on molecular electronic devices began to flourish[28] and the idea arose[8,9,29] that molecules are much more convenient building blocks than atoms to construct nanoscale devices and machines. The main reasons that provide the basis of this idea are as follows: 1) Molecules are stable species, whereas atoms are difficult to handle; 2) Nature starts from molecules, not from atoms, to construct the great number and variety of nanodevices and nanomachines that sustain life; 3) most laboratory chemical processes deal with molecules rather than with atoms; 4) molecules are objects that already exhibit distinct shapes and exhibit device-related properties (e.g., properties that can be manipulated by photochemical and electrochemical inputs); 5) molecules can self-assemble or can be covalently connected to make larger structures.

In the following years it became clear[30] that the "bottom-up" approach opens virtually unlimited possibilities[31] regarding the design and construction of artificial molecular devices and machines capable of performing specific functions upon stimulation with external energy inputs (see, for example, Figures 2–4).[10] Furthermore, such an approach can provide invaluable contributions to give a better understanding of the molecular-level aspects of the extremely complicated devices and machines that are responsible for biological processes.[18,19]

Energy Supply

Molecular devices and machines operate via electronic and nuclear rearrangements, that is, through some kind of chemical reaction. Like their macroscopic counterparts, they are characterized by 1) the kind of energy input supplied to make them work, 2) the way in which their operation can be controlled and monitored, 3) the possibility to repeat the operation at will, 4) the timescale needed to complete a cycle of operation, and 5) the function performed.[10]

The problem of finding the energy supply to make artificial molecular devices and machines work is of the greatest importance.[32] Since their operation is always based on some kind of chemical reaction, the most obvious way to supply energy to these systems is through the addition of suitable reactants. In his address to the American Physical Society, Feynman observed:[4] "*An internal combustion engine of molecular size is impossible. Other chemical reactions, liberating energy when cold, can be used instead*". This is exactly what happens in our body, where the chemical energy supplied by food is used in long series of slightly exergonic reactions to power the biological machines that sustain life.

If an artificial molecular device or machine has to work by inputs of chemical energy, it will need the addition of fresh reactants ("fuel") at any step of its working cycle, with the concomitant formation of waste products. Accumulation of waste products, however, will compromise operation unless they are removed from the system, as is what happens in our body as well as in macroscopic internal combustion engines. The need to remove waste products introduces noticeable limitations in the design and construction of artificial molecular devices and machines based on "chemical fuel" inputs.

Chemists have known for a long time that photochemical and electrochemical energy inputs can cause the occurrence of chemical reactions. In recent years, the outstanding progress made by supramolecular photochemistry[9] and electrochemistry[33] has led to the design and construction of molecular devices and machines powered by light (see, for example, Figure 2) or electrical energy, which work without the formation of waste products.[10]

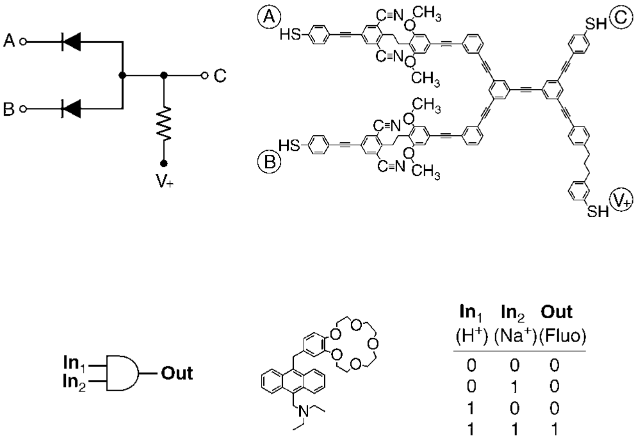
Towards a Molecular (Chemical) Computer

One of the most important objectives of nanoscience and nanotechnology is a further miniaturization of information processing devices. Present computers are based on miniaturized electronic circuits fabricated by solid-state physicists and electronic engineers on semiconductor chips. As mentioned above, progressive miniaturization has been pursued up until now by the top-down approach, which has intrinsic limitations for dimensions smaller than 0.1 μm. The alternative strategy to reach miniaturization up to the nanometer scale is that based on the previously described bottom-up approach that could open the way to the design and construction of "molecular computers" much smaller and much powerful than the presently used silicon-based computers.

The term molecular computer sounds strange to most chemists in spite of the fact that 20 years ago the Pimentel report[34] explicitly forecasted the construction of such a device: *"There are those who dismiss as far-fetched the idea of man-made molecular scale computers. … But since we know that molecular computers are routine accessories of all animals from ants to zebras, it would be prudent to change the question from* whether *there will be man-made counterparts to questions concerning* when *they will come into existence and* who *will be leading in their development. The* when *question will be answered on the basis of fundamental research in chemistry; the* who *question will depend on which countries commit the required resources and creativity to the search".*

In the past decade, many systems that could prove useful for information processing at the molecular level have indeed been constructed and studied. As research is progressing, however, it becomes clear that two quite different bottom-up strategies can be exploited towards designing and constructing molecular computers.

One strategy relies on the use of molecules to construct nanoscale electric circuits that would replace those used in the current microelectronic solid-state technology (see, for example, Figure 5, top).[35] Along this line, many investigations have been performed on the electrical conductivity and electrical switching properties of molecules and a variety of molecular wires, rectifiers, switches, and logic gates have been proposed and constructed.[36]



In$_1$ (H$^+$)	In$_2$ (Na$^+$)	Out (Fluo)
0	0	0
0	1	0
1	0	0
1	1	1

Figure 5. Top: molecular implementation of a diode–diode AND logic gate.[35] Bottom: a molecule that performs in solution according to AND logic.[37a]

An alternative strategy[37] refers to the working principles of information-transfer processes in living organisms that operate in solution on the basis of chemical input and output signals. In artificial information processing systems, chemical input and output signals can be easily generated by photochemical and electrochemical reactions and can also be profitably combined with simple light inputs and outputs (see, for example, Figure 5, bottom).

These two strategies are clearly different for philosophical reasons; one is driven by the idea that the successful concepts that govern artificial macroscopic information processing devices can be extended to the molecular level, whereas the alternative, less-defined approach takes inspiration from the natural world where a wealth of nanoscale (admittedly, quite complex) "wet" devices are already operating. The two strategies are also different from a chemical viewpoint, in spite of the fact that in both cases molecular components must be assembled by bottom-up techniques to obtain systems capable of performing the desired function: Molecules to be used as components of a nanoscale electrical circuit in the solid state must be irreversibly linked together (e.g., by using covalent bonds), whereas signal exchange among molecules in solution is more likely to take place by reversible association/dissociation processes.

The approach based on molecules used as simple circuit components has the potential advantage of being strictly related to the paradigms of current microelectronics technology.[35] On the other hand, the "chemical" approach provides an opportunity of implementing even complex logic operations with one molecule or supramolecular species.[37] It is difficult at the present stage to predict which one of these two strategies will have the greater technological impact.

Conclusion

Nanoscience and nanotechnology are still in their infancy. At present, new exciting results[38] and, sometimes, disappointments[39] alternate on the scene, as always happens in fields that have not yet reached maturity. Surely, as Feynman said,[4] *"when we have some control of the arrangement of things on a molecular scale, we will get an enormously greater range of possible properties that substances can have"*, and these new properties will lead to a wide variety of applications which we cannot even envisage today. Hopefully, nanoscience and nanotechnology will contribute in finding solutions for the four big problems that face a large part of the earth's population: food, health, energy, and pollution. In developing nanoscience and nanotechnology, however, we should not forget the above-mentioned "great asymmetry" principle.[2]

Scientific education is producing many people who are able to *make* science, and this is good. Even more important, however, would be to produce people who are able to *distinguish what is worth making* with science. As scientists and citizens we have a great social responsibility.[40] We must teach and check that science and technology are used for peace, not for war; for alleviating poverty, not for maintaining privileges; for reducing, not for increasing the gap between developed and underdeveloped countries; for protecting, not for destroying our planet that, even after the development of nanoscience and nanotechnology, will most likely remain the only place where mankind can live.

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