nano technology

Nanomechan

Dr. Ron Lifshitz
School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University

Nano is very small

We operate machines all day. The alarm clock that wakes us up in the morning, the car that takes us to work, the elevator that takes us to our floor, and the computer, printer, or telephone we have in our office, are just a few examples. These machines all have mechanical elements that, either directly or aided by electronics, perform certain tasks for us. They are all built to human scale, enabling us easily to control them and to sense their operation. Nanotechnology promises to make machines that are a million to a billion times smaller.

How small is that? Roughly speaking, the human scale is around a meter. A thousand times smaller is the millimeter which is the scale of tiny insects like ants. A million times smaller is the micrometer, or micron, which is the scale of a single biological cell. A billion times smaller is the nanometer---the scale of a single molecule. It doesn't get much smaller than that because the size of an individual atom, and the distances between adjacent atoms in a crystal or a molecule, are on the scale of a tenth of a nanometer.

So, nanotechnology promises to produce machines that are smaller than a cell and in extreme cases not much bigger than a molecule. Can it be done? If so, is it worth doing? How does one control and observe the operation of such nanomachines? And the main question---is the nanoworld much like our own but a lot smaller, or will these futuristic nanomachines have to operate under a whole different set of physical laws? The emerging science of nanomechanics deals with the mechanical behavior of nanoscale objects and tries to answer these and related questions.

Small is good

There are many obvious benefits for making mechanical or electromechanical devices that are as small as possible. By ``electromechanical'' we refer to devices that contain mechanical elements in combination with some electronics that control and read out the mechanical motion, and possibly perform some additional electronic functions. The smaller the device the more compact it is; the lighter it is; the faster its response is; the less power it uses; and in some cases, the cheaper it is to manufacture it. Electromechanical devices on the micron to millimeter scale, known as microelectromechanical systems (MEMS), have already been around for quite some time. Applications for MEMS are plentiful, ranging from the device that triggers the inflation of safety airbags in cars, through missile guidance systems, to clever video displays based on arrays of micro-mirrors. MEMS devices are normally made from silicon, gallium arsenide, or other similar materials that are in common use in the electronics industry. As a result, the mechanical and the electronic elements can all be conveniently fabricated on a single tiny chip. MEMS devices enjoy all the obvious benefits of smallness, mentioned above. Electromechanical devices on the nanometer to micron scale, or nanoelectromechanical systems (NEMS), will surely utilize these benefits even further. But, are NEMS just smaller and better MEMS, or are there significantly new benefits in the nano regime?

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What is it all about?

First of all, as I described at the beginning, the nano scale is the ultimate in smallness. NEMS are not simply smaller than MEMS---they are as small as it gets. As a consequence the holy grails of many of the NEMS applications contain the word ``single.'' Making electrometers that can measure the charge of a single electron; making calorimeters that can sense the heat produced by a single molecular reaction; or simply detecting the weight of a single molecule. With NEMS scientists can potentially achieve ultimate sensitivity.

Secondly, the fact that NEMS approaches the molecular scale allows fabrication to combine top-down procedures, like the lithography and micromachining used in MEMS, with bottom-up procedures, assembling structures one atom at a time. Like the arms of old record players that were equipped with a sharp needle at their end, scientists can now affix to the end of a NEMS arm a so-called carbon nanotube. This nanotube is a long and stiff tube-like molecule, grown out of carbon atoms, whose diameter is only a few nanometers---the ultimate needle. Assembling complicated elements, at will, one atom at a time is still a vision for the future, but many initial successes have already been demonstrated.

Thirdly, the fact that NEMS are smaller than a living cell, and often not much bigger than single biological molecules, positions them as the natural interface between the inanimate and the living worlds. This opens the door to revolutionary applications in medicine, biology, and biochemistry. The anticipation of such applications is dissolving the traditional boundaries between scientific disciplines, and has prompted Tel Aviv University, as well as scores of other research institutions around the world, to initiate interdisciplinary programs of research where physicists, engineers, chemists, biologists, and physicians will all be working together towards common goals.

Small is difficult

The mechanical elements found in typical current-day NEMS are fairly simple and include cantilevers, beams, and torsion balances. More sophisticated devices include arrays or other clever combinations of these building blocks. The individual elements of a NEMS device usually vibrate or deflect in response to applied forces. The smaller they are, the higher are their natural frequencies of vibration, and the faster they respond to external signals.

State-of-the-art nanolithography is capable today of fabricating elements with cross sections down to the 10 nanometer scale. Such elements vibrate with frequencies reaching the GHz range---comparable to the clock speed of a modern personal computer.

These extremely small devices are not yet to be found on industrial production lines. They are only being produced in a small number of research laboratories worldwide. Many difficult problems still need solving before today's delicate fabrication processes can be transformed into tomorrow's robust manufacturing schemes. Many obstacles need to be overcome before the basic elements of today can be combined into sophisticated nanomachines. Some of the problems are more of a technical nature and will most likely be solved as more experience is gained. But some problems are unique to NEMS, and pose fundamental challenges.

If a single molecule, adsorbed onto the surface of a NEMS resonator, is enough to change its frequency of vibration by a measurable amount, then tiny variations in any fabrication process can easily affect the device that is being made. At 10 nanometers across, any tiny irregularity like a few misplaced atoms can change the mechanical behavior of a NEMS element. This makes device reproducibility an almost unattainable goal. Another frequently encountered difficulty is the surprisingly high rate of energy loss during the vibration of NEMS resonators. We all know that if we pluck a guitar string then after a little while its vibration dies away and we stop hearing it. The same is true for any resonator, and it turns out that the smaller the resonator, the worse it is in retaining its vibration energy. The reason for this effect is not yet fully understood, and is the focus of current research, but there is growing evidence that surface imperfections play an important role. As devices shrink the fraction of atoms that are at the surfaces of the device increases. At 10 nanometers across, or about a 30 atom by 30 atom cross section, more than 10% of the atoms are at the surface. It is therefore crucial to achieve clean and perfect surfaces in NEMS devices.

Finally, there is the problem of communicating with the mechanical elements of the nanomachine. At 10 nanometers across, and frequencies of a few gigahertz, the elements performing the communication, called transducers, must be able to sense motion on a sub-nanometer length scale at nanosecond times scales. Improving on standard MEMS transducing schemes doesn't always work, simply because they don't scale down properly. Observing an object which is much smaller than the wavelength of the light used to observe it or the width of the optical fiber carrying the light is a difficult task. Sending even minute electric currents through certain NEMS elements can heat them enough to reach their melting point. It seems that new ingenious schemes will be required to properly interface with the smallest NEMS devices.

Small is different and exciting

In conclusion, scientists clearly have the motivation to develop nanomachines. Some basic building blocks of NEMS devices are already working in research laboratories, and work is on its way to try to overcome the difficulties outlined above. It is only a matter of time that NEMS will offer us a host of fascinating and revolutionary applications. But that is not all. Depending on size and temperature, NEMS devices can operate in a regime where the rules of classical physics, which govern the mechanical behavior of large objects, are gradually replaced by the rules of quantum physics, which govern the behavior of atoms and molecules. This intermediate regime of operation, called by physicists the ``mesoscopic'' scale, has the potential for opening the door to exciting new physical discoveries. These new scientific discoveries will, in turn, affect potential NEMS applications. One example is that of thermal transport, where it has recently been demonstrated by researchers at Caltech, that quantum mechanics imposes an upper limit on the rate at which heat can flow through certain nanoscale beams. Designers of nanomachines that require cooling for proper operation will have to be aware of this quantum mechanical limit. It is likely that many of the nanomachines of the future will be operating in the mesoscopic regime, where the rules are set by quantum rather than classical mechanics. Physicists are only beginning to explore this regime of mechanical behavior, and are likely to discover even more new physical effects. These, in turn, will lead to more applications. The field of nanomechanics is clearly only at its infancy.

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Further reading

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