NOTHING SMALL ABOUT NANO-TECH-NOLOGY

Complex functions can be accomplished through machines built at the molecular scale. At left, a design for a computer memory system uses a nanotube probe. Above, this motion controller was developed by Drexler.

INTERVIEW By JEAN THILMANY

J.T: Can you tell us a bit about what you mean by "nanomachinery"?

K.E.D: What I mean by this term is a particular kind of nanomachine-based technology on the horizon today, one that has enormous potential. The best way to understand the potential is by comparing this machine technology to the leading nanoscale technology in the world today.

Today we have a nanotechnology revolution in process, nanoelectronics, the ubiquitous chip technology that has already transformed many industries. It's not commonly called "nanoelectronics" or "nanotechnology," but that's what it is. We still use the prefix "micro," though the technology has gone beyond this.

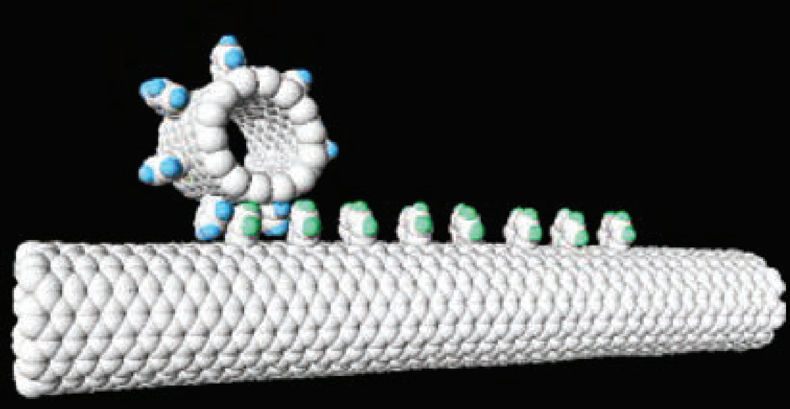
Nanoelectronics today is based on intricate systems with features as small as 20 nanometers. Like future nanoscale machines, these nanoscale electronic systems operate at high speeds and perform useful functions. "Nanoscale" refers to the component level, since chips with billions of devices are built on a centimeter scale, and future nanomachine-based systems with trillions of devices can be much larger.

The impact of electronic nanotechnology has been enormous. Today's digital electronics—cell phones, computers, and so on—are based on nanoelectronic technologies.

These electronic systems are based on arrays of nanoscale components that work together at high frequencies and process little discrete things. In the case of electronics it's bits of information.

Nanomechanical production technology will likewise be based on arrays of nanoscale components that work together at high frequencies and handle small, discrete things. But in the nanomachine world the things aren't bits packaged in bytes, they're atoms packaged in molecules.

This kind of technology is already surprisingly well understood, even though making the actual physical devices is still beyond reach of today's fabrication technologies. What we do have is the modeling tools needed to do detailed computational simulations and explore the design space, and these tools can be used by mechanical engineers to design nanomachines.



Engineered molecules, such as these nanotubes with attached nodules, can act as simple machines. Many working together could make a factory.

J.T: What will nanomachines look like?

K.E.D: In a literal sense, nothing, because the smallest components will be invisible, just a few nanometers in diameter, and only barely resolved by an electron microscope. Useful systems of machines, of course, will often be large.

In terms of their structures, when atomically precise fabrication capabilities become more advanced, it will be possible to build a class of nanoscale machines that is quite extraordinary, with every atom in a position chosen by designers, and densely bonded to form strong, stiff materials. This class of nanoscale machines will have components with shapes and functions very similar to devices designed by mechanical engineers today.

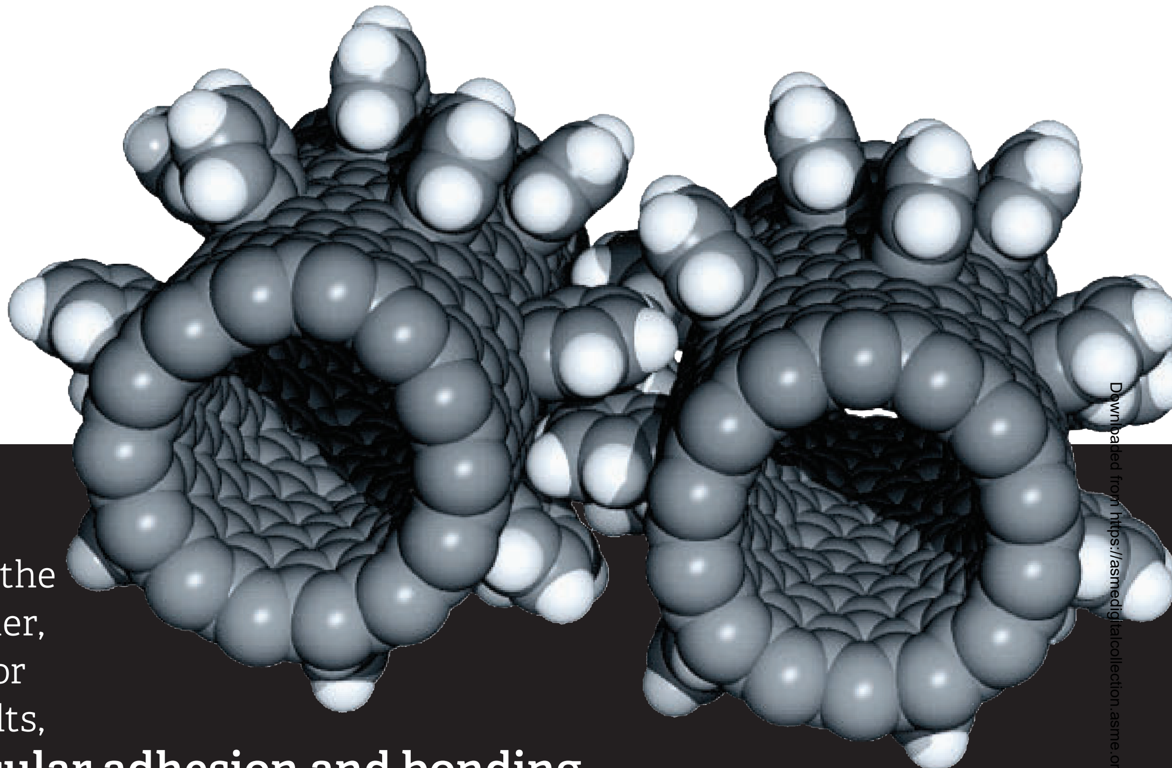
The prospect for this kind of technology includes ultrastrong materials and high-performance mechanical systems of all kinds. The machines will be built on a range of scales, but they'll demonstrate their most extraordinary properties at the nanoscale.

Because of basic mechanical scaling laws, nanoscale machines can operate at high frequencies, and nanoscale production systems will be able to process many times their own mass in a short time. For both energy and materials, there's a factor of one million advantage in throughput per unit mass between nanomachines and similar machinery at the macro level. The consequence is that you don't need a whole lot of machinery to get a large result. A thin-film configuration would be typical.

At this scale, you can get enormously higher power densities in motors and gear boxes—for example, a power density on the order of 100 GW per kilogram is natural, just because of scaling laws. Of course, you couldn't use a kilogram of machines like that all in one in place, because cooling will only be possible with much smaller amounts of hardware or lower power densities.

J.T: Where does the development of nanomachines stand today?

K.E.D: Both the physics and engineering of these technologies are well understood today, but the pathway to their development will depend on



What holds the parts together, isn't rivets, or welds, or bolts,
but molecular adhesion and bonding.

organization and investment, and on all sorts of detailed technological developments. And as all engineers know, these factors are less than predictable.

It's interesting to note that in nanoelectronics, the Moore's law trend, the exponential decline in size and the increase of components on a circuit, have been smooth. But what's delayed nanomachines is that there isn't the same kind of smooth path. The technology has to be built up—not scaled down—starting at the molecular level.

The reason comes down to surfaces: In electronics, charge flows through the interior of a device, and rough surfaces are OK. In machinery, motion depends on having smooth surfaces for bearings, and at the nanoscale, this means having all the atoms in the right place. Lithography just can't do that.

Atomically precise fabrication in the molecular sciences has come a long way, up to millions of atoms, but it has a long way to go before building nanomachinery at this level. The problem isn't scale, but materials.

J.T: It's interesting because in this issue **Yan Wang** of Georgia Tech has written an article about a CAD system his team is working on that would allow engineers to create materials specific to their design.

K.E.D: His work and the kind of work I'm outlining here ultimately fit together. And when you consider nano- and macroscale together, you end up needing multiscale and multiphysics modeling.

This model of a molecular gear set, created at the NASA Ames Research Center, uses carbon nanotubes with teeth added via a known benzyne reaction. Building such nanomachines has been a challenge.

J.T: What needs to happen to advance the state of nanomechanical systems?

K.E.D: What's most needed today is focused research organized around system-level objectives. We need to develop a field of molecular mechanical systems engineering. It's a matter of research, organization, and funding, based in the molecular sciences, but going in new engineering directions.

Some of the roots are in molecular biology, but this field is organized as a science, a branch of biology. But small groups organized around studying and imitating biology don't build the kinds of components needed for a mechanical engineering technology that builds toward more and more advanced nanomechanical systems.

J.T: How would nanoscale production machinery work?

K.E.D: To a remarkable extent, it will work like macroscale production machinery, the kind used to assemble components to make larger components. As components get larger, later in the process, assembly becomes entirely conventional.

The picture is of nanoscale machinery making nanoscale parts and of those parts being put together to make microscale parts by microscale machinery, and parts on the centimeter-scale assembling centimeter-scale components, and so on.

At the bottom, at the start, the key is to apply nanoscale mechanical systems to move things—molecules—and put them together. This is entirely parallel to what we see in factories, but what holds the parts together isn't rivets, or adhesives, or welds, or bolts, or snap fittings, but molecular adhesion and bonding. Different in many details, but the same function. Also, the smallest parts at the start of assembly, instead of being cut from bar stock or injection molded or stamped out of sheet metal, will be reactive molecules of the kind used in chemical synthesis.

Considering these earliest steps in the process, the best parallel today is continuous-motion assembly machines, the machines used to assemble things like the mechanisms of plastic spray bottles. These assembly machines process a continuous stream of parts and some of them produce as many as 50 assembled products per second. The assembly isn't done with little arms. Instead, the parts are carried and transferred by spinning disks with gripping fixtures around the circumference. What's most like "programming" is in the shape of the cam surfaces that guide some of the motions.

This principles of these continuous-motion assembly machines could be applied on a nanoscale, then the nanoscale products would be handed off to larger machines. These would naturally be organized much like a factory, with parts passed from machine to machine and conveyors moving them along. The final products used by people would be on the familiar human scale, like today's products, even though the parts they are made from would be much smaller, and the properties of the small parts can result in high performance on the macroscale.

This kind of manufacturing process is somewhat like additive manufacturing or 3-D printing which is also about building small bits of materials together under programmable control to make any of an unlimited range of larger objects.

J.T: So the end product would be something you could see and touch. What is an example?

K.E.D: Well, some examples of potential products are photovoltaic arrays, cars, computers, spacecraft, and small medical devices that can work at the level of cells—a list would go on and on. Bottom-up atomically precise manufacturing is a general-purpose manufacturing technology.

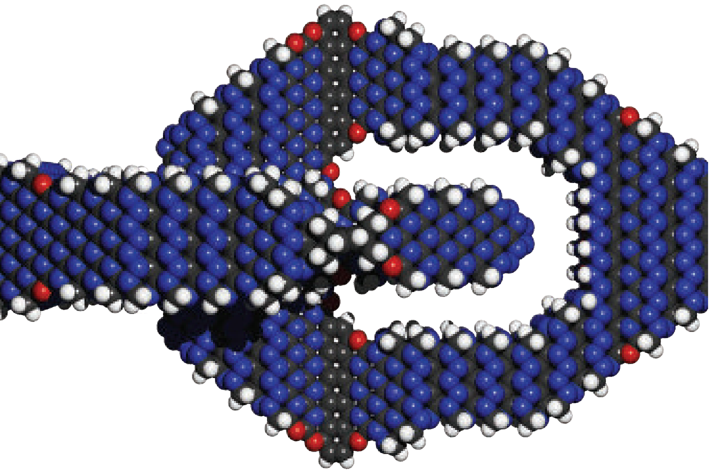
Think of the very general applications of computers. They have totally transformed areas as different as photography, music, scientific equipment, and mail. At the heart of a cell phone are sets of small, fast devices that transform patterns of information at the smallest bits. Using nanoscale devices to build up from molecules is similar in many ways, and will also have very general applications and products.

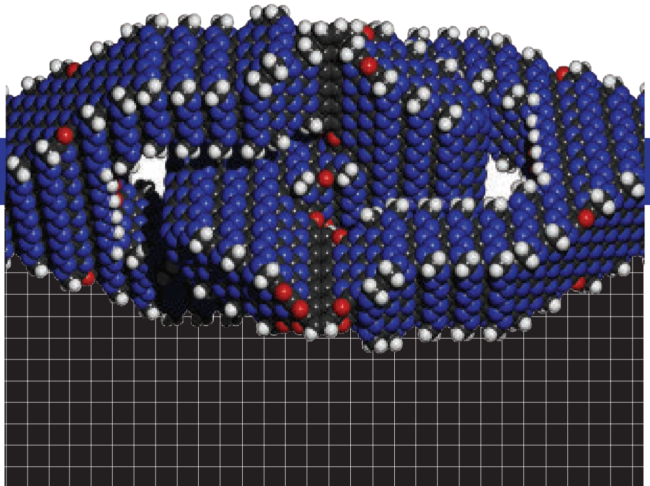
J.T: How should mechanical engineers think about nanomachinery?

K.E.D: Scaling laws tell us that machine-parts that move at equal speeds with similar shapes and patterns of motion will have the same dynamics (and stresses and strains), except for a scale factor in space and time. This means that much of mechanical engineering translates directly to the nanoscale.

At the very bottom, the atoms do matter. They can't be scaled. The meshing teeth of the smallest machines will be on the atomic scale, just rows of atoms. Bearings are a special case, because ordinary lubricants won't work. Instead, properly structured surfaces can slide over one

A universal joint (below) and bearing (opposite) designed with atomic precision.
(Images copyright: Institute for Molecular Manufacturing, imm.org)





another, in direct contact, with the "bumpiness" of individual atomic interactions adding up in a way that results in smooth motion. This phenomenon is called "superlubricity" and has been demonstrated in a lab.

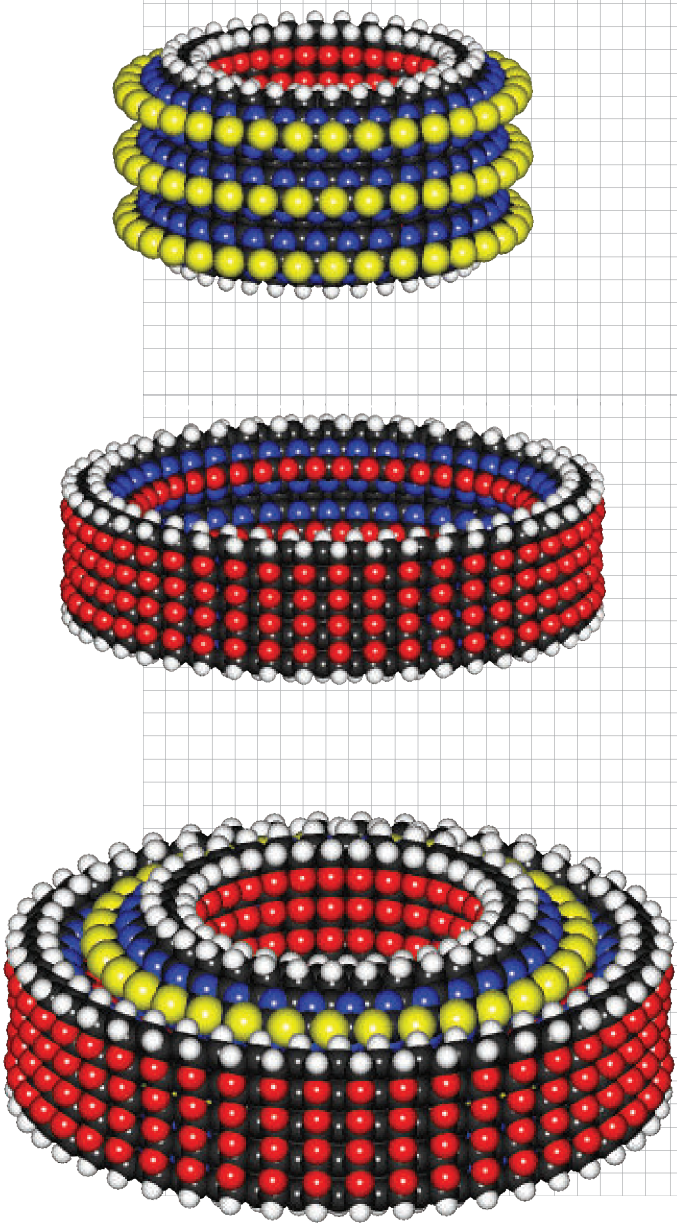
Thermal fluctuations are a special concern at the nanoscale, but they're statistically predicable and are part of standard dynamic models. In mechanical engineering terms, thermal motion amounts to an especially well-understood source of vibrations—but ones that are impossible to damp!

Today, however, the modeling software used to describe and test atomically precise machines machine designs comes straight out of the molecular sciences, and it doesn't directly support abstractions at the component level. The description is very fine-grained.

Traditional CAD would then apply at scaling levels not too far above the nanoscale. At much less than a micron non-atomistic solid models become realistic. Atomistic models can establish elastic properties, friction properties, and so on, and these can then be used to parameterize conventional models. Likewise, atomistic machine designs can be characterized as lumped components, in terms of properties like gear ratios, torque, elastic compliance, friction, and so on.

Mechanical engineers today can work with the existing atomistic models, and can make an enormous contribution to understanding the potential of advanced nanomachinery. In these models, they can build parts and machines, and after testing in simulation, they can calculate performance parameters, then try to come up with better designs. This could make a great area for online competition.

There's a lot to learn in this area of technology, even before we can actually build the machines. I hope that today's mechanical engineers will learn about nanomachinery and help explore this new domain. It's important, exciting, and fun. **ME**



At the very bottom, the atoms do matter. They can't be scaled.
The meshing teeth of the smallest machines will be
on the atomic scale, just rows of atoms.

Properly structured surfaces **can slide over one another,** with the **individual atomic interactions** resulting in smooth motion.