TO HELP PROMOTE THE TECHNOLOGY behind its “nano-enhanced” downhill skis, a major equipment manufacturer is urging consumers to imagine the size of the nanoscale: “Think very, very small. Now think even smaller.”

“Think even smaller” also could serve as the motto of the burgeoning research field of nanotechnology.

Nanotechnology involves manipulating matter at the scale of a nanometer, one billionth of a meter, or about 80,000 times smaller than the width of a human hair. But considering how the term has recently burst into the popular lexicon—from stain-proof “nano pants” to the State of the Union Address—researchers also are finding encouragement to think very, very big.

Some researchers claim that nanotechnology-derived products have reached the trillion-dollars threshold, while others frame the field as the next industrial revolution, with the potential for staggering advances in pharmaceuticals, semiconductors, optics, environmental remediation, to name a few. Businesses are heavily investing in nanotechnology, with new companies sprouting up today like Internet and biotechnology companies did in the 1980s and 1990s. The U.S. government is also making nanotechnology a priority. But whatever might become of the buzz surrounding this millennial field, one thing is clear: Rensselaer researchers are key players among an international group of scientists working with atomic precision to make new materials and devices.

“Historically, Rensselaer has been known as a powerhouse in materials science and technology,” says Omkaram Nalamasu, vice president for research. “What we are doing with nanotechnology is building on this historic strength and heritage.”

In September 2001, the National Science Foundation selected Rensselaer as one of the six original sites nationwide for a new Nanoscale Science and Engineering Center. A part of the National Nanotechnology Initiative, the center is devoted to realizing the full potential of nanotechnology by creating new materials, architectures, devices, and systems from nanoscale building blocks.

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Early forays into the nano world sometimes produced unexpected results. In 2000, an experiment to grow carbon nanotubes under high-temperature conditions resulted in the growth of a completely different form of carbon. The Rensselaer research team used rapid chemical vapor deposition, creating a forest of pure carbon trees (left). N anotechnology has been called the next industrial revolution, with potential for advances in pharmaceuticals, semiconductors, optics, environmental remediation, and more. Rensselaer researchers are part of a pre-eminent group of scientists around the world behind this small-scale revolution.

IT’S THE LITTLE THINGS THAT MATTER

BY JASON GORSS

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In recent years, scientists have created a variety of nanoscale building blocks from atoms and molecules, but they have only just begun to assemble them into more complex structures. Much of the research at Rensselaer is distinguished by a focus on “directed assembly”—combining these building blocks in a controlled way to create materials with desired properties for a wide variety of applications, from artificial gecko feet to ultra-sensitive devices for detecting airborne toxins.

“Directed assembly of nanoscale building blocks into useful structures is the fundamental gateway to the eventual success of nanotechnology,” says Richard W. Siegel, the Robert W. Hunt Professor of Materials Science and Engineering and director of both the Rensselaer Nanotechnology Center and NSEC. “At Rensselaer, we actually make all of our own nanoscale building blocks, from nanoparticles to nanotubes to hybrid structures comprised of both. That gives us a tremendous advantage in terms of controlling the nature of these structures and how they relate to one another.”

A Comprehensive Vision
Carbon nanotubes are perhaps the most enticing class of nano-materials. These super-tiny cylinders, which bear an uncanny resemblance to rolled-up sheets of chicken wire, have been hailed as some of the lightest, strongest materials ever made.

“Nanotubes are a very versatile material with absolutely fascinating physical properties, all the way from ballistic conduction to really interesting mechanical behavior,” says Pulickel Ajayan, the Henry Burlage Professor of Materials Science and Engineering and aworld-renowned expert in fabricating nanotube materials. “I don’t think we have ever come across a material with such a wide range of possibilities.”

Rensselaer researchers are exploiting this broad portfolio of properties across a variety of fields, beginning with the fundamental building blocks of matter and working up to devices and systems with a multiplicity of applications.

“One of Rensselaer’s unique contributions to nanotechnology is the ability to place the nanotubes where we want, with the control we want, and with the properties we would like to have,” Nalamasu says. “I think it is a very comprehensive vision.”

The vision is fast becoming a reality, as Rensselaer scientists and their collaborators continue to report significant advances in the field. In a 2005 paper published in Science, researchers from Rensselaer, the University of Hawaii at Manoa, and the University of Florida showed that films of vertically aligned carbon nanotubes can act like a layer of “super-compressible” mattress springs, flexing and rebounding in response to a force. But unlike a mattress, which can sag and lose its springiness, these nanotube foams maintain their resilience even after thousands of compression cycles, opening the door to foam-like materials for just about any application where strength and flexibility are needed, from disposable coffee cups to the exterior of the space shuttle.

The foams are just the latest in a long line of nanotube-based materials that have been produced through collaborations with Ajayan’s lab, including tiny brushes with bristles made from carbon nanotubes. The brushes, which were described in Nature Materials, already have been tested in a variety of tasks that range from cleaning microscopic surfaces to serving as electrical contacts, and they eventually could be used in a whole host of electronic, biomedical, and environmental applications, Ajayan says.

Carbon nanotubes can carry large amounts of electrical current without losing heat, making them ideal materials for nanoscale wires. A long with colleagues in Germany, Mexico, the U.K., and Belgium, Rensselaer researchers have reported a way to weld these tiny tubes together end-to-end, overcoming a major obstacle to realizing nanotube-based electronic devices. By passing a high current through a thin film with nanotubes dispersed across its surface, they generated visible flashes of light—similar to the familiar arc from a welder’s torch. Further investigation revealed that the flashes occur at junctions where overlapping carbon nanotubes are welded together. Current methods to make nanowires require bombarding the surface with electrons or other charged particles, which may not be easily scalable. The team, which is led by Ganapathiraman Ramanath, associate professor of materials...
science and engineering, suggests that their new technique could provide a viable tool for producing nanowires cost-effectively.

In collaboration with researchers from Banaras Hindu University in India, Rensselaer scientists have devised a simple method to produce carbon nanotube filters that can efficiently remove micro- to nano-scale contaminants from water and heavy hydrocarbons from petroleum. Made entirely of carbon nanotubes, the filters are easily manufactured using a new method for controlling the cylindrical geometry of the structure. While activated carbon has long been the standard for removing organic contaminants from drinking water, the new research suggests that carbon nanotubes have significant potential as better materials for water purification.

Researchers also are branching out into new projects that are just starting to yield results. For example, with a $1.15 million grant from the NSF, a team led by Toh-Ming Lu, the R.P. Baker Distinguished Professor of Physics at Rensselaer, is exploring the potential of nanomechanical systems by making and testing springs, rods, and beams on the nanoscale. The past decade has seen an explosion of interest in electronic devices at the molecular level, but less attention has been paid to improving the strength and stiffness of these materials for water purification.

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Researchers have not been able to get the 10- to 20-fold increases in strength and stiffness that have been touted over traditional composites and materials. Ne of the biggest engineering challenges comes when nanotubes are combined with other materials to make composites, according to Koratkar. The interface between the materials is not as strong as one might expect because it is difficult to disperse nanotubes in an orderly way. Single-walled nanotubes are particularly hard to disperse, since they tend to form clusters—like ropes where only the nanotubes on the outside layer come in contact with the other material. Ajan and Koratkar are partnering with researchers across the campus—and around the world—to address some of these challenges.

Tough much of the research has focused on improving the strength and stiffness of nanomaterials, Koratkar and his colleagues have directed their attention to another important property: damping, or the ability of a material to dissipate energy. They have found that dispersing nanotubes throughout traditional materials creates new composites with vastly improved damping capabilities. A nd in a recent paper published in the journal Nano Letters, the researchers have also shown for the first time that these damping properties are enhanced as the temperature increases. Traditional damping polymers perform poorly at elevated temperatures, so the new nanocomposites could fill an important gap for any kind of structure that is exposed to vibration, from high-performance parts for spacecraft and automobile engines, to golf clubs that don’t sting and stereo speakers that don’t buzz.

In 2004, Koratkar received an NSF Faculty Early Career Development Award to fund the development of these new materials, and during the next phase of the grant he plans to move into “hybrid” systems. These structures will combine the high stiffness of carbon fiber composites with the damping properties of nanotubes, leading to a class of materials that truly offers “the best of both worlds.”

Meanwhile, Linda Schadler, professor of materials science and engineering, is leading a group that is working to improve the optical and mechanical behavior of polymers for packaging materials by filling them with nanoparticles. A nd as part of a joint research project with the University of Florida, Schadler and her colleagues are developing a new generation of synthetic lubricant coatings for aircraft and spacecraft. The coatings, which are made of thin layers of carbon nanotubes, polymers, and ceramics, will be sensitive to changes in the environment that a spacecraft experiences, with the potential to reduce the rate of wear by 1,000 times or more.

Other teams are working to exploit another interesting property of nanotubes called “field emission.” When a voltage is applied to certain materials, electrons are pulled out from the surface, making these materials useful in electronic displays. “Nanotubes are very good field emitters because they have a low threshold for emission and they produce high currents,” says Swastik Kar, a post-doctoral researcher in materials science and engineering. K ar and a team of researchers from Rensselaer, Northeastern, and New Mexico State have developed a new process to make flexible, conducting “nano skins” based on field emission for a variety of applications, from electronic paper to sensors for detecting chemical and biological agents. The materials can be bent, flexed, and rolled up like a scroll, all while maintaining their ability to conduct electricity, which makes them ideal materials for flexible electronics, according to the researchers. Nanotube arrays normally are held together by weak forces that don’t always maintain their shape when transferred, but the team has developed a new procedure that allows them to transfer arrays of nanotubes into a soft polymer matrix without disturbing the shape, size, or alignment of the nanotubes.

A jayan, working with researchers at the University of Akron, is using a similar process to mimic the agile gecko, with its uncanny ability to...
to run up walls and across ceilings. Last year, the team reported a process for creating artificial gecko feet with 200 times the sticking power of the real thing, using nanotubes to imitate thousands of microscopic hairs on a gecko’s footpad.

**Defining New Interfaces**

Rensselaer’s traditional interdisciplinary approach to research also gives the Institute another advantage. “We have tremendous strength in terms of the depth of our scientific knowledge in the various areas of physics, chemistry, materials, and biology,” Siegel says, “but also a tremendous level of interaction that takes place among the group—and that’s actually quite remarkable.”

An example is the interface of medicine and the physical sciences, which is becoming a key focus of many research efforts at Rensselaer. “As an engineering school, we are trying to define new interfaces, and one of the interfaces is nanomedicine,” Nalamasu says. “The nano toolbox is a unique medium to be able to understand this particular interface.”

Shekhar Garde, associate professor of chemical and biological engineering, and Pawel Keblinski, associate professor of materials science and engineering, discovered that heat may actually move better across interfaces between liquids than it does between solids, which could have immediate practical application for cancer therapy. “Scientists are developing cancer treatments based on nanoparticles that attach to specific tissues, which are then heated to kill the cancerous cells,” Keblinski says. “It is vital to understand how heat flows in these systems, because too much heat applied in the wrong spot can kill healthy cells.”

To create artificial bones and other biomaterials, scientists need specially designed scaffolds that can direct how cells grow into body tissues. Siegel and his colleagues are conducting a study that could provide much-needed insight into this process at the intersection of biotechnology and nanotechnology. They are examining the behavior of mesenchymal stem cells (MSCs), which are derived from bone marrow, on a number of ceramic materials that could be used as scaffolds. They have found that the size and chemistry of the nanoparticles that make up the ceramic materials has an impact on the way MSCs stick to the surfaces, and that one protein is primarily responsible for this impact: vitronectin, one of the major adhesive proteins found in human blood. This fundamental knowledge will help tissue-engineering researchers design the next generation of biomaterials for orthopedic applications, according to Siegel.

**Macroseale Effects**

Rensselaer researchers are collaborating with industry to bring this technology to the marketplace. “We are not only developing the fundamental science and engineering concepts related to nanotechnology, but in real time we are exploring the utility of these materials to solve important problems in different disciplines,” Nalamasu says. The Center for Integrated Electronics, for example, is contributing to the science and technology of interconnects, semiconductor devices, architectures, and packaging, by accelerating the production of the next generation of micro- and nanoelectronic devices. The research focuses on discovering solutions to help the semiconductor industry transcend the roadblocks that will come from shrinking device dimensions below 100 nanometers.

And nanotechnology researchers of all fields received a major boon with the establishment of the Computational Center for Nanotechnology Innovations (CCNI)—a partnership between Rensselaer, IBM, and New York state to create the world’s most powerful university-based supercomputing center (see page 7). The $100 million project will provide a platform for researchers to perform a broad range of computational simulations, from the interactions between atoms and molecules up to the behavior of the complete device. These simulations will employ new computational tools that are becoming increasingly central to scientists’ efforts to manipulate matter at the atomic level. In much the same way as cars and planes are designed with computer models before they are built, the tools will allow researchers to build simulations of new nanotechnology-based products.

“The computational and intellectual resources at CCNI will be made available to companies from New York state and across the globe,” Nalamasu says. “The goal of this center is to define a new engineering design paradigm that will provide chip manufacturers the ability to predict device performance through integrated nanoscale simulation and fabrication.”
Rensselaer researchers have discovered a simple method for rapidly creating different shapes of carbon nanotube structures. The new method is based on a commonly used chemical vapor deposition method, resulting in foamlike structures that are stable and elastic. The foams could be used in a variety of applications, including new microchips and wherever strength and flexibility are needed, from repairing bone joints to reinforcing carbon-fiber-based aerospace products.