In Brief

Learning to manipulate and control at the nanoscale — making use of the unique characteristics of that scale — offers a broad array of possible applications. Not only what we make but how we make it can shift as we learn how to harness nanotechnology in self-assembly and directed self-assembly of materials. This article presents an overview of nanotechnology usage and nanoscale applications as well as a note of caution about related potential risks and over-blown projections.

Nanoscale + Technology: Small Stuff Makes Its Mark

Molecular mind-stretching — how can it reshape our world?

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What'll clean your windows, clear harmful bugs from your ailing carcass, self-assemble gizmos, get the gunk out of dirty water, protect your car bumper from dings, prevent nasty foot odor, and do many more wondrous things? If you believe all the hype about nanotechnology and applications at the nanoscale, you can hardly wait for the mammoth wave of molecular- or sub-atomic-level gizmos to hit the market. The good news is that nanoscale applications already help to prevent corrosion as well as increase the strength and reduce the weight of materials, cut the cost of solar cells for significant environmental benefit, and even sort bull semen.

Then there are the realities such as: Some folks can’t agree on a definition of nanotechnology1 much less the ethics and potential risks of its use (food supply benefit or long-term security risk, for example). “Nanoists”’ hopeful and often boastful projections sometimes ring false. No one really knows just how much of the guzillion dollars sunk into this field will pan out or peter out. Yet our competition and other countries are chasing full-blast after this small world, so we can’t afford to ignore it.

No budget to be major R&D player in this arena? Learn how to use and adapt others’ innovative ideas. Here’s a look at some of the happenings in nanotechnology plus a list of selected resources. Warning: Disruptive learning ahead.
Applications: From Diagnostics to Nanopants and Battlefield Intelligence

Nanotechnology involves the ability to manipulate and control at the nanoscale, making use of the unique characteristics of that scale. Exciting stuff includes new and expanded applications, not just new "technology." According to Clayton Teague, director of the National Nanotechnology Coordination Office (NNCO), one of the largest-volume usages of nanotechnology-based products is slurries for chemomechanical polishing of silicon wafers for the microelectronics industry. "Many of the forefront microprocessors on the market today are using circuits within the critical dimensions of nanotechnology," he said. "As defined by the NNI, that means less than 100 nanometers in dimension." Nanotechnology assumes various definitions, depending on the source; it is often defined as the technology and science of controlling the structure of matter at the nanoscale (a billionth of a meter). 2

"We're seeing new products coming on the market from small start-ups to larger companies," continued Teague. Among the nanotech applications he cited are: high-temperature, low-heat products for bonding dissimilar materials; tennis balls incorporating "nanoclays" to decrease the permeability of the shell, plus tennis racquets reinforced with lighter-weight nanofibers; "nanopants" using stain-resistant coatings on fibers; more uniform appearance of paint used on autos; and wear-resistant coatings for machinery and glass. Devices (such as sensors) for homeland and national security applications featuring extraordinarily high sensitivity to chemicals and vapors offer a broad array of applications, said Teague: battlefield intelligence; airport inspection; food safety checks for pathogens; and air quality monitoring in hospitals and other facilities. He commented that not only what we make but how we make it will shift as manufacturers and others learn how to harness nanotechnology in self-assembly and directed self-assembly of materials.

"The potential impact of nanotechnology is very broad. A good general resource is our website, www.nano.gov," Teague said. "In addition to major applications in data processing and storage and biomedical applications, we also anticipate a major impact in the energy field. For example, less expensive solar cells are under development.

"Materials applications is another big area for nanotechnology R&D," he continued. "The use of carbon nanotubes (CNTs — cylinders composed of carbon atoms in a hexagonal network) will provide great strength to weight ratios compared to other materials. Where weight is an issue — autos, aircraft, construction — we anticipate an increasing number of applications. With respect to the environment, one area that looks very promising and exciting is remediating badly-polluted sites. We are seeing new technologies developed at Lehigh University and at other locations in this area."

Prospects for environmental and energy-related applications abound. The U.S. Army Space and Missile Command, for example, is sponsoring development (at the Georgia Tech Research Institute) of CNT-based electro-chemical double-layer capacitors, providing more power and energy density as well as longer life than traditional batteries and capacitors storing electrical energy.3

Nanoscale (billionths of a meter) shapes present new opportunities in electrical and thermal transmission, superconductivity, micro-switching devices, and other areas. Argonne National Laboratory researchers, for example, have developed a process where anodized aluminum-oxide (AAO) membranes "synthesize individual and aligned nanostructures with controlled sizes and shapes."4 They created nanowires, nanotubes, etc. from materials such as cobalt, gold, lead, nickel, vanadium oxide, and polymers. Possible applications of this new science include more sensitive sensors.

Last November, Congress OK’d the National Nanotechnology Initiative (NNI), authorizing $3.7 billion in funding over the
next four years, providing for the creation of the National Nanotechnology Coordination Office as well as funding for federal government nanotechnology programs.\(^5\) (Updated information on funding is available by checking online at www.nano.gov/html/about/nnibudget.html) This funding level may seem high. Yet the competition for "getting there first" in nanotechnology is strong, particularly in Asia and Europe, Teague said.

Nanotechnology’s reach will extend to all major U.S. weapons systems, with annual military outlays in the hundreds of millions of dollars. "Nanotechnology is one of the highest priority science and technology programs in the Defense Department," according to Clifford Lau, senior science advisor in the Pentagon’s office of basic research.\(^6\) The U.S. nanomaterials market is projected to top $1 billion in 2007 and $35 billion by 2020.\(^7\)

**Ethical Issues to be Sorted Out**

For all its promise of great reward, nanoscale technology also brings risk. For example, a study at Southern Methodist University, linked synthetic nanoparticles and brain damage in fish. According to John Bucher, head of the toxicology program at the National Institute of Environmental Health Sciences, not much is known about nanotech effects.\(^8\)

In the May 31, 2004 issue of Business Week ("Mega Questions About Nanotech" by Adam Aston), Kristen Kulinowski, a chemistry faculty member at Rice University (Houston, TX) indicated that she believes nanotech scientists are learning from past failures (agricultural biotech offers many "lessons learned," for example). Kulinowski is executive director for education and public policy, Center for Biological & Environmental Nanotechnology (federally funded) at Rice. She identified two broad categories of risk assessment related to nanotechnology that are being examined. The first one is biological systems — from the ways that nanoparticles affect single-celled organisms to their impact on animals such as vertebrates.

Controlling particle toxicity (used to treat disease, etc.) is one of the related issues in this area. The second broad category covers environmental impacts. The impact of nanomaterials accumulating in the water supply, long-term effects on waste streams, ways to engineer production processes for development of environmentally benign product life cycles, and other issues challenge researchers. Kulinowsky noted that within three to five years, researchers will learn much more about preventing environmental damage from nanomaterials, and also about ways to control nanoparticles employed in disease diagnosis, drug delivery, etc.

**Orthovita’s Biomaterials**

Although many promising nanotechnology-related products and applications are on the horizon, current products are already on the market. For example, Orthovita, a Malvern, PA-based biomaterials company, recently gained U.S. FDA clearance to market a new device called the VITOSS® Canister that provides surgeons the means to effectively use its nanoparticle-based bone filler, VITOSS®. Used in bone repair surgery, VITOSS® is a globally marketed, bio-resorbable beta-tricalcium phosphate ($\beta$-TCP) material that can be used for filling gaps or voids in the skeletal system (spine, pelvis, and the extremities). It mimics the chemical composition and structure of cancellous bone, enabling interaction with host bone; an advantage over previous products is that it offers small particles for potentially faster resorption. (See Figure 1.)

Serving the dynamic bone graft market presents many challenges in addition to product development issues. Orthovita’s Senior Manufacturing Manager Dave Dychala noted that all of the company’s biomaterials are manufactured at its Malvern facility. As sales rose rapidly during the past two years, the pressure has increased to streamline production processes. "Working within the physical boundaries of our building is a challenge to meet the significantly increased production requirements," he said.
"We follow current Good Manufacturing Procedures (cGMP) practices as required by the FDA, and we are initiating Six Sigma for better continuous improvement (CI) progress. We have addressed some of our scale-up issues with CI. For example, we have eliminated redundant inspections. This move towards prevention rather than detection is a means to resolve issues before they become problems, and, using three-lot validation runs, we have learned how to improve our sampling techniques, allowing us to make larger production batches."

Finished goods phase purity must be maintained to meet ASTM requirements. The manufacture of \( \beta \)-TCP, while a straightforward process for Orthovita, requires ensuring continual accuracy in the preparation of precursor formulation and is an ongoing program as the company scales up production quantities. "We need to work smarter, not harder," Dychala said.

The company portfolio also includes IMBIBE\textsuperscript{®} Bone Marrow Aspiration Syringe and CORTOSS\textsuperscript{®} Synthetic Cortical Bone Void Filler, along with other products. Orthovita plans to launch up to 12 new products based on the core VITOSS\textsuperscript{®} technology, including various FOAM Bone Graft Materials in 2004. VITOSS\textsuperscript{®} derived nano-sized \( \beta \)-TCP has been found to readily disperse within resorbable organic materials, yielding shape-conforming composites that provide true synthetic solutions for orthopedic applications. Corporate sales are projected to increase 40 to 48 percent in 2004.

The quickening pace of biomedical applications spawns hope for improved diagnostics and treatment (removing toxins from blood, targeting and destroying cancerous cells using nanoparticles in site-specific probes, traversing membrane boundaries in therapeutics and drug delivery, etc.). Quantum dots (semiconductor nanocrystals) provide researchers new tools for treating diseases and disorders, for example. French researchers recently employed quantum dots to track glycine receptor molecules in living cells for extended periods of time, opening expanded drug treatment options for epilepsy and depression. Quantum Dot Corporation manufactured the semiconductor nanocrystals used in this study, as reported in the October 17, 2003 issue of Science and in the December 2003 issue of Nanoparticle News.

**PPG: Making the Extraordinary Affordable**

"We are a materials company with a diverse product line — photochromic eyewear (Transitions lenses), glass and fiberglass, chemicals, coatings, etc. We are the largest supplier of coatings to the transportation market in the world. Nanotech will impact 90 percent of what we do," said Dave Diehl, senior scientist, PPG, Pittsburgh, PA. PPG’s sales were $8.8 billion in 2003. "Our differentiator is what we can do with various products and technologies to make them better. We see this area not as something we’d like to do, but that we need to be doing, or our sales will not continue to grow domestically."

Diehl noted that PPG’s R&D activities spawn nanotechnology-related and other new products, yet the best way to innovate, sometimes, is to put others great ideas to
work. "Look at SunClean, for example," he said. "We didn't invent it. We took the application and transformed it to work in our products." A transparent coating on SunClean self-cleaning glass has photocatalytic properties. Energized by UV rays from the sun, it can break down and loosen grime, with minimal streaking. The surface of the glass is coated with a permanent layer of nano-sized titania that are activated by sunlight.

Working with Mercedes-Benz, PPG also co-developed CeramiClear clearcoat, used to protect automotive color and maintain a glossy finish. Incorporating nanoparticle technology, the clearcoat incorporates a cross-linked, glass-like or "ceramic" network at the surface of the coating for improved resistance to environmental hazards, car washes, etc. (scratches from car keys and fender benders can still damage an auto's clearcoat — no one's figured out how to prevent damage from human error). Another PPG product incorporating nanomaterials: They recently introduced a rain sensor for auto windshields.

Offering innovative, extraordinary products sounds like a great premise for R&D efforts. Yet Diehl cautioned, "Developing the extraordinary can be risky. Although our core competency in innovation is here in the United States, we need to follow our customers — what they need and want in global markets. We also have to reduce costs, so that your new ideas can become affordable. We look increasingly towards mass customization; everyone wants things customized for themselves."

Butterflies and birds come to mind, said Diehl. What's the connection? The vibrant colors of these flighty creatures are created with refractive structures, potentially yielding ideas for development of customized coatings, etc. "We're in materials, and when we think about ways to customize coatings or paint, such as the color of your car, we look at ways through nanotechnology that could enable you to flip a switch and have it change from one color to another, depending on your mood," said Diehl.

"We need more emphasis on mainstream, affordable applications of nanotechnology," added Diehl. Noting the "valley of death" for new products and applications ideas — university researchers take their ideas to a certain point and then their innovations founder when they fail to hook up with the vision and the means to use them — he said the government can play a greater role in bridging the gap. "In other countries, there are initiatives sponsored by government about coupling nanotechnology research and making these ideas useful; the big issue is technology transfer," he said.

**Office of Naval Research: Fighting the Enemy — Wear**

Dr. Lawrence Kabacoff, a program officer at the Office of Naval Research (ONR) in Arlington, VA noted that a new coating material has come out of the nanotechnology world, a composite containing very small grains of aluminum oxide and titanium oxide. "Most people think of nanotechnology as making very small objects or structures (like an electric motor the size of a flea or a computer memory that stores a bit of information in a single molecule). It also includes making ordinary-sized (bulk) materials (things you can hold in your hand or even things too big to pick up without help) which get their unusual properties because they contain very small structures (which can be grains, fibers, or particles of another material entirely). This material is ceramic, like a coffee mug, but it adheres to a surface much better and is remarkably resistant to cracks. Ceramics are very useful because they are hard and inert (they don't corrode or react with chemicals), however you can't use them in many places you would like to because they are brittle and break easily." He noted that this is important for the Navy "because we are always fighting corrosion from seawater and because mineral deposits like to form on exposed metal surfaces. Our new ceramic coating solves this problem."

Kabacoff cited an example of a propeller shaft. "Sometimes, hard particles in seawater like bits of shells or perhaps sand get into the works and actually grind away at propeller shafts," he said. "To be more
precise, this happens to bronze shafts, not steel, which is harder. Shafts twist and vibrate a lot, and ordinary ceramic would fall off in minutes. These coatings have been tried on four ships so far and are still working after almost a year. Unlike most bulk nanomaterials under development, these are already commercially available.

"The term 'nanotechnology' may or may not apply," said Kabacoff. Yet the size of the crystals in the coatings he describes is approximately 20-60 nanometers, or billionths of an inch — much smaller than conventional materials. "This is not as new as people think," Kabacoff said. "Automobile tires are nanomaterials! The black color comes from nanoparticles of carbon."

**More Prospects, Collaborative Efforts**

*Nanosized liposomes filled with medicine can allow more accurate, effective drug therapy. "A new method for producing uniform, self-assembled nanocells has been developed by researchers at the National Institute of Standards and Technology (NIST)," as reported in the *Journal of the American Chemical Society*, March 10, 2004; the method can provide an improved means to encapsulate various drug therapies.*

*Several research and development reports presented at the NanoCommerce 2003 meeting, Chicago, IL, noted opportunities for learning how to tailor nano-sized drug delivery methods to a broad range of individual patient factors.* Researchers are working on designer molecules that can carry remedial molecules to the target cell and penetrate it, offering prospects for faster diagnosis and treatment in personalized lot sizes of one. Will Big Pharma companies lead this revolution, or perhaps, more nimble startups?

*Arryx, Inc., Chicago, IL employs holographic laser steering at nanoscopic and microscopic levels, with applications in manufacturing and processing. Its BioRyx® 200 system can apply multiple "tractor" beams to grab, hold, rotate, separate, stretch, join and otherwise manipulate objects as small as 1/1000th the diameter of a human hair, according to Lewis Gruber, president and CEO. Gruber also described the Arryx CelRyx™ system, which is designed to sort large samples of cattle semen for gender and viability using a nanomanufacturing technology which grasps the sperm by nanoscopic features. Arryx is one of many companies developing nanosensors to detect chemicals, biological agents, and other potential hazards for food safety, animal health, and homeland security applications. "Our model is partnering with other industries to improved products or solve their problems," said Gruber; his company is in discussion with companies on applications in displays, pharmaceutical purification, etc.*

*Small tech offers improved performance for passenger cars as well as racing cars and other vehicles, with potential for crossover applications. Although a common perception is that auto racing innovations migrate to passenger cars, the reverse can also happen. Steve Wickam, who's the electronics manager for Toyota Racing Development (providing R&D for Toyota Motor Sports), noted instances where they replaced pricey, proprietary racing sensors with off-the-shelf MEMS devices (microelectromechanical machines which were repackaged and modified).*

*Looking at ways to partner more effectively goes hand-in-hand with innovative nanotechnology R&D, according to Nanophase Technologies Corporation President and CEO Joseph Cross. The Romeoville, IL-based company develops and manufactures nanocrystalline materials, with applications in sunscreen products, environmental catalysts, antimicrobial products, and polishing applications (semiconductors, hard disk drives, and optics). (See Figure 2.) "We are using continuous improvement, modeling our processes after the Toyota Production System (TPS), as we look for ways to collaborate with other organizations, understand our actual costs, reduce our variable costs, and compete more effectively in our markets," Cross said. "We've started with Six Sigma training. An example of our progress is that we have learned how to produce as much material in*
two shifts as we previously made in three shifts. We reduce cycle time for innovation by co-developing nanoengineered solutions for customer applications. Nanophase seeks strategic partnerships with companies occupying market channels. Examples include supplying Rodel (a division of Rohm and Haas Company) with zinc oxide nanoparticle dispersions for semiconductor polishing applications and supplying BASF with nanomaterials for sunscreen applications. His “lessons learned” for effective partnering: Synergy and trust are essential, as well as a market focus; also, commit to a planned approach with decision points and milestones.

Does this approach sound familiar? As we are bombarded by announcements of the latest in nanotechnology applications, not to mention the wonders of new communications systems, software innovation, and the like, the “basics” of continuing improvement and collaboration still apply. Otherwise, the unfolding possibilities for nanotechnology will turn out to be nano-smoke and mirrors, more nano-hype than nano-hope.

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Footnotes:
1. James D. Plummer, professor of electrical engineering, Stanford University, noted the lack of a universally-accepted definition of nanotechnology; the broadest definition of nanostructure, according to Plummer, is something smaller than 0.1 micron, or 100 nanometers (billionths of a meter), as noted in the article, “How far are we from realizing practical benefits from nanotechnology?” on the Scientific American website (www.sciam.com). Adding to the potential for confusion is the definition for micromanufacturing, a relative newcomer; the article, “Micromanufacturing is Growing” by Robert B. Aronson in Manufacturing 2004 (published by the Society of Manufacturing Engineers, website www.sme.org) indicates that common references of micro as one millionth of a unit, nano as one billionth of a unit, and mezzo as generally larger than a micro, with small parts generally in the micro/mezzo ranges and products at the atomic and molecular level in the “nano” area.
5. Passage by the U.S. House of Representatives of the Nanotechnology Research and Development Act prompted F. Mark Modzelowski, executive director of the NanoBusiness Alliance, to say, “When one looks at the next 100 years of human development and the growth of the global economy, no vote taken by Congress in the past decade will have a greater effect than today’s overwhelming passage of the nanotechnology bill.”

Resources:
www.asme.org; among the nanotechnology resources on this website is information about the ASME B46.1-2002 standard concerned with geometric irregularities of surfaces, billed as the “world’s first metrology standard to address the nanotechnology challenge.” Also, the ASME Nanotechnology Institute (website www.nanotechnologyinstitute.org).

Foresight Institute; its goal is to "guide emerging technologies to improve the human condition;" readings on topics such as "Nanotechnology: The Coming Revolution in Molecular Manufacturing" are found at its website, www.foresight.org

Nanoparticle News, a BCC Inc. newsletter, covers the fine, ultrafine, and nanopowder industry; website www.bccresearch.com

Nanotechnology Now; Gateway to Everything Nanotech; online newsletter offering a wealth of information from varied sources, "reporting on disruptive technologies such as MEMS, NEMS (nanoelectromechanical systems), Nanoscale materials, Molecular Manufacturing, Computing, Nanomedicine, Nanoelectronics, Nanotubes, Self Assembly, and Molecular Biology" (website www.nanotech-now.com).

National Nanotechnology Initiative; information on government nanotech activities as well as links to many other resources are offered at its website, www.nano.gov

Smalltimes; Big News in Small Tech.; check this online resource for updates on nanotechnology applications in biotech, defense, energy, consumer goods, transportation, IT and telecom, environment, etc.; opinion columns and company/individual profiles are also featured at http://www.smalltimes.com; and a Small Tech Business Directory is online at www.smalltechdirectory.com

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