Global tectonics:
Part 2

Nanotechnology: Small Revolution

BY FARIBORZ GHADAR
AND HEATHER SPINDLER

EXECUTIVE SUMMARY

Nanotechnology is already attracting considerable investment by both governments and private industry worldwide. When perfected, advanced nanotechnology will streamline production and reduce manufacturing costs in significant ways. The result will be a $1 trillion sales market for nanotech components in the next 15 years.

12 TRENDS changing the world

A five-year research project reveals that the future of commerce worldwide will be greatly influenced by a dozen "global tectonics" that will affect business leaders across all industries:

1. Biotechnology
2. **Nanotechnology**
3. Information technology
4. Population
5. Urbanization
6. Disease and globalization
7. Resource management
8. Environmental degradation
9. Knowledge dissemination
10. Economic integration
11. Conflict
12. Governance

Investors are looking at the new technologies that will be the next critical driver of economic growth. Information technology has offered astounding global growth over the past few decades. Biotechnology has developed from its nascent research beginnings into incredible commercial applications and social benefits. The next force that we expect to have a global tectonic effect is, ironically, so small that it cannot be seen with the human eye.

Nanotechnology is used to rearrange molecules so that essentially every atom can be put in its most efficient place. Ralph Merkle, Ph.D., of the Georgia Institute of Technology describes it this way: "Manufactured products are made from atoms, and the properties of those products depend on how those atoms are arranged. If we rearrange the atoms in coal, we can make diamond. If we rearrange the atoms in sand and add a few other trace elements, we can make computer chips. If we rearrange the atoms in dirt, water, and air, we can make potatoes."

3i, a venture capital group, defines nanotechnology as "any application of science that deals with elements between 100 nanometers and a tenth of a nanometer in size in which size is critical to the application's ultimate purpose." One nanometer is one-billionth of a meter. Put another way, there are 1 million nanometers in 1 millimeter. For perspective, the width of a human hair is approximately 80,000 nanometers.

This emerging technology has already attracted considerable investment: More than 30 countries have launched public nanotechnology research and development programs. The Organization for Economic Cooperation and Development reports that government R&D funding grew fivefold between 1997 and 2002, to an estimated $2 billion per year. In the private sector, large multinational firms such as IBM, Dow Chemical, L'Oreal, Hitachi, and Unilever, as well as numerous startups have increased their nanotechnology research initiatives.

George Whitesides, a prolific Harvard chemist, reckons that nanotechnology is now about halfway through the list of discoveries needed for the field to reach maturity. He believes that it will develop much as biotechnology has — through intensive research and experimentation that yield totally new ways of doing things. We are only now beginning to see the wide uses and effects for this nascent technology. Jack Uldrich and Deb Newberry's recently published book *The Next Big Thing is Really Small* put it this way:

"This is not to say that nanotechnology is a far-off, fuzzy, futuristic technology. It is not. It has already established a beachhead in the economy. The clothing industry is starting to feel the effects of nanotech. Eddie Bauer, for example, is currently using embedded nanoparticles to create stain-repellent khakis. This seemingly simple innovation will impact not only khaki-wearers, but dry cleaners, who will find their business declining; detergent makers, who will find less of their product moving off the shelf; and stain-removal makers, who will experience a sharp decrease in customers. This modest, fairly low-tech application of nanotechnology is just the small tip of a vast iceberg — an iceberg that threatens to sink even the 'unsinkable' companies."

In time, nanotechnology could change all of materials science, all of computing, and much of biology. A transformation of that scope could generate serious concerns over nano-ethics.

Perhaps one day there really will be tiny, self-propelling structures that seek out and destroy cancer cells inside the human body. Nanotech could eventually change the nature of health care — moving us from what GE has called a "see and treat" world to a "predict and prevent" world. Hundreds of other applications are under consideration. In time, nanotechnology could change all of materials science, all of computing, and much of biology. A transformation of that scope could generate serious concerns over nano-ethics. It is unlikely, though, that anything would cause the nanotechnology baton to drop. We are watching a classic technological revolution unfold. The critical question for business people is where are we in that revolution.

Initial commercial applications

The miniaturization of key items or products is a natural first step in the development of this industry. In November 2003, the *New York Times* featured an article about the world's smallest electrical guitar built. Nanotechnology labs around the world are working on Lilliputian-sized everything. Electronics and communications

MOORE'S LAW

The visionary behind Moore's law, which predicts that the number of transistors on a computer chip will double every 18 months, was Intel co-founder Gordon Moore. His 1965 paper from which the law originates is "Cramming More Components onto Integrated Circuits," which can be found on the Web at ***ftp://download.intel.com/research/silicon/moorespaper.pdf***. Since writing that paper, Moore has noted that the cost of a semiconductor manufacturing plant doubles with each generation of microprocessor.

companies are especially interested in this new technology to reduce the size of microprocessors, sensors, transistors, and the like.

The nano-sizing craze is one of the first waves of commercialization of this technology. The information technology industry's relentless pursuit of Moore's Law is leading to the necessary investment for the expensive research and manufacturing investment required. Overall, this is driven by the competitive nature of the industry and an enormous commercial market for nanotech applications.

Despite this development, scientists are still debating what nanotech is exactly. Nano means one-billionth, so 1 nanometer (1nm) is one-billionth of a meter (a DNA molecule measures 2.5nm across); however, the American government's National Nanotechnology Initiative defines nanotechnology as anything involving structures less than 100nm in size.

To bring timely consensus to the field, the Nanotechnology Standards Panel of the American National Standards Institute has initiated the groundwork for establishing standards in this emerging technology.

Small things behave differently

Nanotechnology is not just the miniaturization of products. When moving from the micro level (1 micrometer is one-millionth of a meter) to the nano level, materials exhibit new properties. For example, "large" particles of titanium (on the micron scale) absorb sunlight and are therefore used in some sunscreens. Unfortunately, these large particles show up white on lifeguards' noses. The nanoscale titanium particles absorb exponentially more light due to greater surface area.

The nano-sizing craze is one of the first waves of commercialization of this technology.

As a result, they appear translucent, leaving lifeguards with more natural-looking noses. Nanotech sun block is also longer lasting on the skin. Oxonica, a United Kingdom spin-out from Oxford University, is one of several firms working on sun block that contains such nanoparticles.

In addition to a larger surface area, "nanoparticles in the three-to-five nanometer range behave a lot like gas particles," says Peter Dobson, a professor of engineering science at Oxford and the founder of several nanotechnology startups. Solids this size will float or dissolve more readily than their larger counterparts that sink.

A company called pSiOncology has developed a tiny particle of silicon that is soluble in water. Normally, silicon is not water soluble, but the difference lies in nanoscale irregularities etched onto the particle's surface. The benefit is that drugs can be attached to its surface and then injected into the body. This technology may be used to inject chemotherapy drugs directly into a tumor, which minimizes the damage to other tissues.

Nano-enhanced materials offer new combinations of material characteristics. Scientists can use nanotechnology to produce materials that are both hard and tough, whereas hard materials are usually brittle and tough materials usually soft. General Motors uses a nanoparticle-enhanced polymer to produce a material for a running board on a minivan or sport utility vehicle. This running board is hard and tough enough to withstand use but weighs significantly less than the steel with which most cars are made.

Manufacturing applications

Not only do small things behave differently, they also challenge generally accepted limitations. From frictionless machine bearings that will never wear out to nanomachines that can extract energy from their surroundings, researchers are using nanotechnology to defy the boundaries of materials science to appear to violate the second law of thermodynamics.

When perfected, advanced nanotechnology, also known as molecular manufacturing, is expected to streamline production and reduce manufacturing costs so that they do not greatly exceed the cost of the required raw materials and energy. With every molecule in order, production will generate less waste and be more efficient, producing low-cost, high-quality nano-engineered products. The result would be products that are cheaper to buy and to produce — products that have the potential to raise living standards around the world. Mihail Roco, the National Science Foundation senior advisor on nanotechnology, predicts a future $1 trillion sales market for such nanotech components in the next 15 years.

Nanotechnological developments could also lead to a cleaner environment. The ability to create filtration systems at a molecularly precise level would improve purification of wastewater and gas from fossil fuels. Research is being done to develop nanotechnological components that break down toxic wastes or the development of catalysts that decompose pollutants. Scientists also hope that advances in molecular manufacturing will develop solar power into a cost-effective energy solution.

Advanced nanotechnology, also known as molecular manufacturing, is expected to streamline production and reduce manufacturing costs so that they do not greatly exceed the cost of the required raw materials and energy.

Several energy-saving measures could benefit from a nanotech makeover. Energy experts think that nanotechnology might help reduce transmission losses by rewiring the electricity grid with superconducting cable. More efficient light-emitting diodes could replace wasteful incandescent and fluorescent lighting. Engineering materials that consume large quantities of energy during the manufacturing process, such as steel, aluminum, and titanium, could be replaced by resilient nanocomposites and carbon nanotubes.

Though patent applications and research initiatives have expanded quickly, the application of specific nanotechnologies has been limited. Commercialization depends on the ability to mass produce economically. However, nanotech is very capital intensive, as the tools and equipment to manufacture nanotech products

ENERGY POTENTIAL

When the world population reaches 10 billion inhabitants, the global energy requirement will increase exponentially from today's 14 terawatts (14 million megawatts) to an estimated 30 to 60 terawatts of capacity. Scientists and economists argue about how to meet this energy requirement.

Scientists envision a day when nano-enhanced photovoltaics and fuel cells will make the collection and storage of solar power an efficient and sustainable source of energy. The nanotech giant and winner of a Nobel Prize for his work in nanotechnology Richard Smalley believes that the only remedy for the looming energy crisis is through the use of nanotechnology. His prophecy is the upgrade of the world's energy infrastructure through mass deployment of nanotechnology.

While some dismiss the idea as being unrealistic due to cost restrictions, some foresee nanotechnology as a key to providing an economical electricity alternative to the masses. The current expense of silicon wafers used to harness solar energy raises the price of solar-power to as much as 10 times the price of fossil fuel generation. Researchers are working hard to discover an economical method for harnessing solar energy economically. Researchers at Harvard University in Massachusetts and Cambridge University in England are already at work on nanorods and nanowire to make solar collection and storage more cost effective. Paul Alivisatos, a chemist at the University of California, Berkeley, aims to use nanorods to produce a photovoltaic material that can be spread like plastic wrap or paint and will bring down the cost of solar power to fossil fuel levels. This nano-solar material could be integrated into other building materials or rolled out as a billboard on a bus while doubling as a solar collector.

require a precision found only in very costly machinery. Despite obstacles of high fixed costs and uncertain market demand, MIT's *Technology Review* magazine reports that scientists are making headway. Most initial investment is anticipated in the IT field, where nanotechnology creates considerable interest among computer chip manufacturers.

Where is it all going?

Nanotechnology is now in the pre-competitive stage and has limited applied use. However, a number of industries are using nanotechnology commercially. Nanoscale materials can be found in electronic, magnetic and optoelectronic, biomedical, pharmaceutical, cosmetic, energy, catalytic, and materials applications. Nanotech applications for chemical-mechanical polishing, magnetic recording tapes, sunscreens, automotive catalyst supports, electroconductive coatings, and optical fibers are purportedly producing the highest revenues.

Many nanotech products that consumers use and see are already on the market. Most computer hard drives now contain giant magnetoresistance heads that exponentially increase storage capacity through nano-thin layers of magnetic materials. Companies are combining nanomaterials with other materials to improve existing product functionality. Step assists on vans and bumpers on cars are now stronger and lighter. Paints and coatings now protect against corrosion, scratches, and radiation. Sunscreens and cosmetics, longer-lasting tennis balls, lightweight and stronger tennis racquets, ink, and automobile catalytic converters also benefit from new nano-applications. However, these products and others, like stain-resistant Nano-Care chinos from Eddie Bauer and self-cleaning windows from PPG, are merely incremental improvements to existing products rather than revolutionary new items.

Scientists envision a much cleaner environment due to the proliferation of solar energy and replacement of burning fossil fuels.

Over the next few years, the market should watch for product technologies made more economical via nanotechnology. Nanotechnology-driven solar cells in roofing tiles and siding could provide electricity for homes and facilities more economically than traditional energy sources. Many scientists envision a much cleaner environment due to the proliferation of solar energy and replacement of burning fossil fuels. In addition, these noble goals include a higher standard of living for parts of the world that do not currently have access to efficient, reliable energy.

The market can also expect crossover of nanotechnology applications that will provide greater demand and help defray the large fixed costs. One example is prototype tires with improved skid resistance and longer wear. While these tires have not hit the market yet, scientists have already identified several additional uses for the nanocomposites used in tires, including high-performance footwear, exercise equipment, and other car parts such as belts, wiper blades, and seals.

The pharmaceutical and chemical industries are being affected greatly by nanotechnology, as well. New commercial applications of nanotechnology that are expected in two to five years include advanced drug delivery systems (including implantable devices that automatically administer drugs and sensor drug levels) and medical diagnostic tools (such as cancer-tagging mechanisms).

Consumer companies have taken great interest in nanotechnology and its potential benefits for their products. A survey of 30 Dow Jones companies was conducted to determine whether companies were investigating or using nanotechnology. The findings indicate a rapidly growing corporate presence in the next decade. While nanotech might not alter Coca Cola's classic formula, nanotech-based advances in packaging materials for cans may provide better insulation to maintain cold temperatures and carbonation levels, resulting in increased product shelf life.

The next two decades will see more sophisticated uses of nanotechnology and better integration. While it's hard to predict the commercial impacts of nanotechnology, consumer products, health products, chemicals, and electronics will be among the most affected.

A survey of 30 Dow Jones companies was conducted to determine whether companies were investigating or using nanotechnology. The findings indicate a rapidly growing corporate presence in the next decade.

Nanotechnology takes time

Purists in the field want to move to a future of nanodevices that interact with one another. Components will need to interact actively in a stable manner and then be reproduced economically before the true promised benefits of nanotechnology can be realized.

However, there are two big obstacles to overcome. The first is developing an interface between living entities and electronic devices. Nanotech components are merely novelties until they can communicate with other components to achieve the necessary process.

The second challenge is how to design and build nanodevices. Right now much still needs to be understood about the behavior of nanoscale objects before we can build them. One of the world's first nanotech firms, Nanophase, was founded for the sole purpose of commercializing a nanosubstance. This company was started in 1989 and went public in 1997. They developed nanosubstances that were useful in cosmetics and sunscreen, but it took years before they figured out how to manufacture these products cheaply.

Despite these challenges, nanotechnology's spread into materials seems inevitable. Scientists will learn how to assemble atoms with stable structures predictably and profitably, and nano-tech applications will take off. They will turn it over to engineers who will then develop prototypes and expertise that can be transferred to the manufacturing foremen and the marketers. But before investors get our their checkbooks, they need to be aware that these issues could take years to solve. And as with most new technologies, the resolutions will owe much to trial and error with a good

NANOTECHNOLOGY roots

In 1959, renowned physicist Richard Feynman shared his vision of nanotechnology. However, for decades, researchers could only conjecture about this technology that would allow them to manipulate things so small as to put a book on the head of a pin. It wasn't until 1980 that two researchers at IBM's Zurich Research Laboratory filed a patent for a scanning tunneling microscope. Four years later, the atomic force microscope was developed, and these two devices let researchers view and monitor particles at a scale that had been impossible before. Like the microscope enabled people to first detect germs, these super-microscopes made nanotechnology possible by enabling scientists not only to see nano-scale building blocks but also manipulate them.

Once researchers had the technology to observe and manipulate atoms at the nanoscale, other breakthroughs quickly followed suit. A new form of carbon, carbon-60, was invented. Scientists began postulating about miniature self-assembling machines and other previously implausible notions. The effect was intoxicating, and the scientific community took on the frenetic momentum not unlike the late1990's Internet bubble. However, as Internet businesses were still subject to the basic laws of commerce, nanotechnology is subject to the effects of quantum mechanics or the laws of physics that explain the behavior of very small things. This technology does have its limits even though we may not understand them fully right now.

dose of luck.

Governments are investing

Like information technology and biotechnology, the burgeoning nanotechnology has the potential to change our economy profoundly and to improve our standard of living. Some commercial products are just starting to come to market, but the major applications for nanotechnology remain five to 10 years out.

Unfortunately, only large private investors can absorb the risk and timeline for these returns on investment. As a result, most governments recognize that support for basic research and development in its early stages is critical to realize nanotechnology's full potential. Governments that want to maintain a competitive position in the global nanotechnology marketplace are making significant investments now.

In the late 1990s, the U.S. government created the National Nanotechnology Initiative. At a time when funding for basic research was being cut, federal funding for nanotechnology research and development increased sixfold, from $116 million in 1997 to an estimated $961 million in 2004. This agency now spans 15 government agencies, from NASA to the Pentagon, and the proposed 2005 budget requests a 2 percent increase, bringing it to $982 million.

The United States is not the only country to recognize the tremendous economic potential of nanotechnology. More than 30 countries have launched public nanotechnology research and development programs. The OECD reports that government R&D funding grew fivefold between 1997 and 2002, to an estimated $2 billion per year.

More than 30 countries have launched public nanotechnology research and development programs.

Asian countries, including Japan, China, and Korea, as well as several European countries have made leadership in nanotechnology a national priority. In Japan, the government committed 75 billion yen in fiscal 2002 to fund nanotechnology R&D. Working with the government, large corporations such as Mitsui and Mitsubishi plan to build plants to ramp up carbon nanotube production from ounces to tons.

The European Union proposed a budget of 1.3 billion euros for nanotechnology research from 2002 to 2006. Many European countries, including the United Kingdom, Germany, France, and Ireland, are coordinating this initiative with their own national nanotech plans.

Governments around the world are spending money on nanotech research. Every big university in the world seems to be building their own curriculums around nanotechnology. All the large high-tech companies from IBM and Hewlett-Packard to NEC and Sony have accelerated their nanotech research and development. And they are seeing results from their investments. Patenting activity has risen, with European Patent Office applications relating to nanotechnology tripling between 1990-1998, from 100 to 300 patents per year. The OECD believes this trend in patenting reflects the potentially large economic benefits from nanotechnology research.

Education and regulation

As with all new technologies, nanotechnology must be developed and implemented with proper risk assessment and regulation. Accidents caused by careless research and development can be avoided through the implementation of appropriate safety guidelines in both the public and private sectors. Public education, business-sponsored, and government-sponsored discourse remain critical to the successful emergence of new nanotech applications. Such dialogue will result in improved regulation and safety enforcement as well as wider public support for new products and processes using the technology.

Despite significant breakthroughs in nanotechnology and its much touted potential applications in biomedical and materials sciences, questions still remain in the scientific community whether nanotechnology will present unique health and environmental dangers. The U.S. Environmental Protection Agency's National Center for Environmental Research recently funded $4 million to 12 universities for the purpose of investigating potential health and environmental impacts of nanomaterials.

The incredible diversity of nano particles complicates the data-gathering process. Essentially, anything can be made nanoscale, and all materials will not be as safe as water. Determination of safe or not safe will need to be made on the specific basis of the material and the application. Ultimately, cost-benefit analyses will determine where nanoresearch efforts will be focused.

Alternative energy supplies or new treatments for cancer may outweigh certain risks, but the use of nanomaterials in cosmetic products may not.

Alternative energy supplies or new treatments for cancer may outweigh certain risks, but society may determine that the use of nanomaterials in cosmetic products may not.

Regardless, nanotechnology has entered the public sphere and public education and transparency will be vital to its acceptance. People are now seeing nanotech play a role in such movies as *Spiderman* and *Minority Report*, and it is the villain in Michael Crichton's novel *Prey*. Public fear is a growing concern in the nanotechnology field.

While scientists and the federal government recognize the potential benefits of nanotechnology and it will not be possible to say that all nanotech applications are safe or are dangerous, it will be important to listen and address public concerns. And although much more data will be available in 10 years that will facilitate the decision, society will be forced to make a decision before then in the absence of complete data. And the adoption of nanotechnologies will be a very diverse and complex problem.❖