Nanotechnology: A Brief Technology Analysis

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Executive Summary

Nanotechnology is the production of materials, pharmaceuticals, or other products that are on the scale of a billionth of a meter in diameter. At such small sizes, materials have the potential to release more of their useful properties and can be employed in almost any product. The market for nanotechnology is generally divided into materials, structures, and systems. Materials are simple particles that can be created at very small sizes, such as drugs or metals. Structures are the combination of multiple materials into a useful structure like a solar cell. Systems are complex combinations that can perform a function like computer memory or machines.

Most of the country's largest companies are pursuing nanotechnology, as well as a large number of start-ups funded by government research grants and venture capital. These competitors hope to create a commercial product like improved suntan lotion and tire rigidifiers, or to capture a patent on a useful material or process.

Introduction

In 1962, Isaac Asimov wrote a novel about a fantastic voyage through the human body (Figure 1). In that book, scientists used a shrinking machine to miniaturize a submarine with three people inside. It became the size of 100 cells and was injected into a human body to allow the submariners to cure a plague that could not be accessed in any other way. Though a work of science fiction, this book was not the first to explore the science of the small. That honor belongs to Richard Feynman who introduced the idea in a 1959 lecture entitled "There's Plenty of Room at the Bottom" (Feynman, 1959). One of his most ambitious statements in that talk was, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big." Though Feynman did not use the term "nano", the field traces its conceptual roots to that lecture.

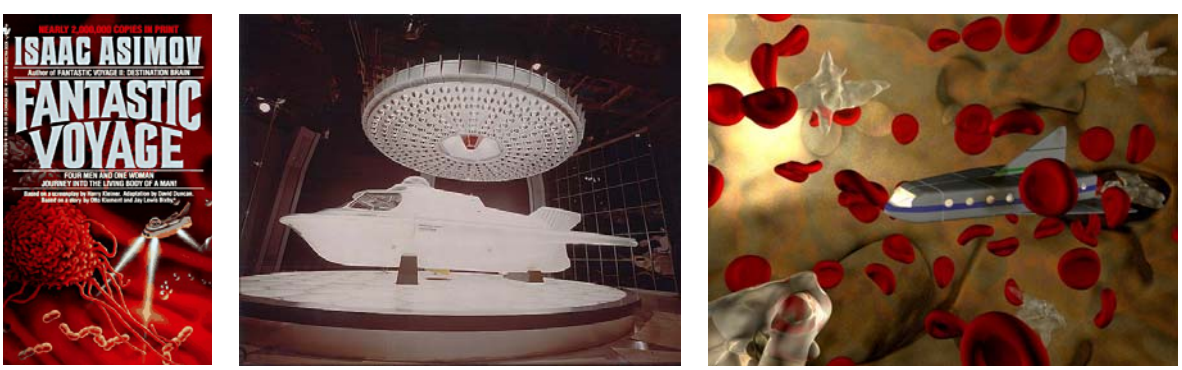


Figure 1. Isaac Asimov's Fantastic Voyage
Sources: Amazon.com, http://www.cloudster.com/Sets&Vehicles/Proteus/ProteusTop.htm, and http://www.foresight.org/Nanomedicine/Gallery/Captions/Image196.html

Since that time, two more recent figures have entered the nanotech spotlight. Eric Drexler actually coined the term "nanotechnology" and explored the power of the science in two of his books, *Engines of Creation* (1986) and *Nanosystems* (1998). The name of the technology is derived from the metric unit nanometer, or one billionth of a meter (10^{-9}). Drexler was most interested in the ability to create very small machines with gears and levers operating at the nano level. He postulated the creation of these through chemical assemblers that used chemical processes to arrange molecules in the necessary configuration or through tiny manipulators like Feynman's "hundred tiny hands."

Drexler also warned of the potential environmental hazards of creating nano products if they were released into the atmosphere. His ideas have been widely discussed and criticized since 1986. Richard Smalley has gone to great lengths to illustrate that the idea of nanoassemblers is impossible (Regis, 2004). However, Bill Joy, one of the founders of Sun Microsystems, has picked up Drexler's ideas and discussed them in a 2000 article in Wired magazine (Joy, 2000). In that article is prophesizes the extinction or enslavement of the human race based on the proliferation of robots and nanotechnology. He sees those as a "superior race" that will emerge to displace humans in the same way that the Neanderthals displaced the Cro-Magnon man.

Richard Feynman, CalTech

Bill Joy, Sun Microsystems

K. Eric Drexler, Foresight Institute

Figure 2. Prominent Public Catalysts of Nanotechnology Ideas

Whether the chemical assembly of nanomachines will become possible remains a topic for futurists and science fiction writers. Today, scientists are more interested in the creation of products with nanosized ingredients and the incorporation of near-nano machines for commercial purposes. Miniature ingredients are leading to major product improvements in medicine, computer science, consumer products, and weapons.

Applications

Nanotechnology has made significant progress since 1956 and is no longer just a research topic. A recent search of the databases of the US Patent and Trademark Office revealed 89,153 patent applications that used nanotechnology terms between 1976-2002 (Rensselaer, 2004). Nano is joined by a related technology called Micro-Electro-Mechanical Systems (MEMS). These systems are similar to nanosystems in that they are extremely small. They also achieve some of the machine-like capabilities envisioned by Drexler. However, they are on the micro scale (10^{-6}) rather than the nano scale (10^{-9}). MEMS systems at Sandia National Laboratories are created using chemical deposition and lithography techniques that are very similar to those used to create computer chips.

Consumer Products

Since a nanoparticle exposes a larger surface area of the material of interest, it presents an opportunity to more fully exploit the capabilities of that agent. In one simple product, nanosized particles of UV reflectant have been embedded in a suntan lotion. This allows the material to block more UV rays with less product. The same principle is being used to create an inner sealant for tennis balls so they will maintain the optimum bounce for a longer period of time. Other rigidifiers are being explored for use in aircraft frames and wing surfaces because they provide more strength with a lower weight of materials.

Medicines

Nanoparticles can serve as more efficient medicines and can be targeted to specific organs and cells. In one application, nanoparticles can enter the cellular structure of the body and block the absorption of proteins. Cancerous cells are overloaded by the barrage of signals that are created around a blocked cell and die off. However, healthy cells are more resilient and recover once the inhibitor has dissolved (Figure 3).

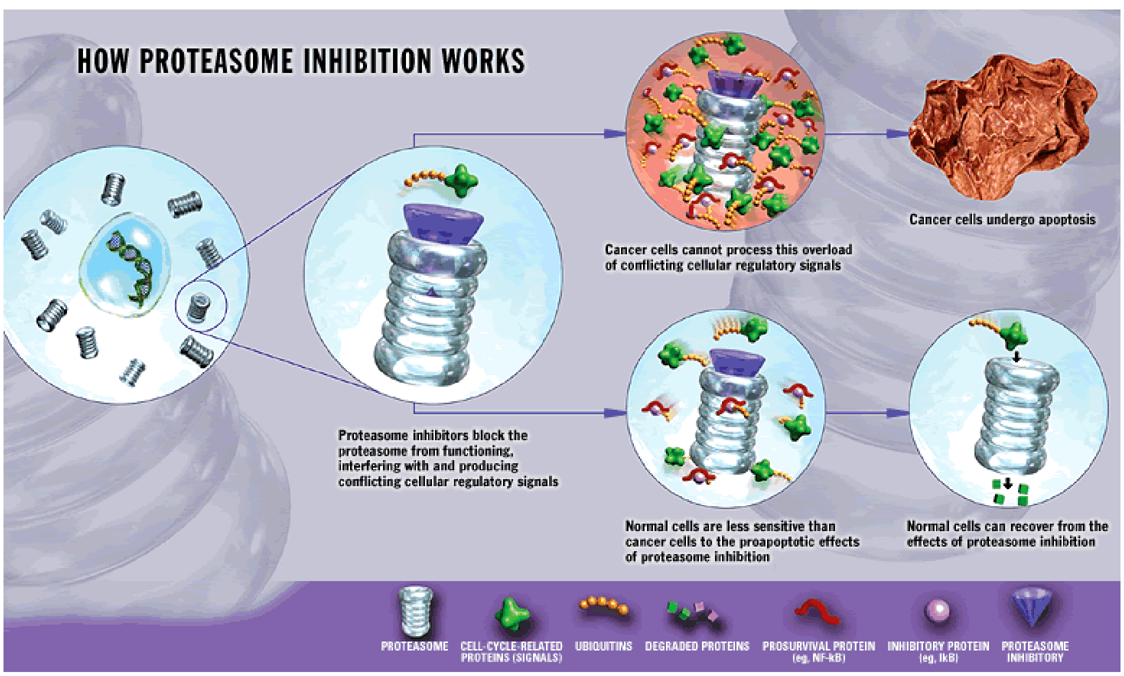


Figure 3. Nanotechnology for Proteasome Inhibition

Source: Unknown

Experiments are also being conducted in which nanoparticles are used to repair damaged surfaces of the eye. The damaged area presents a rough surface to which nanoparticles can attach, leaving a layer against external irritation and infection (Figure 4).

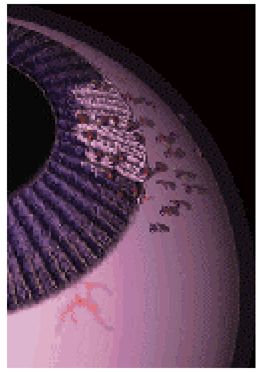


Figure 4. Nanotech Coatings for Eye Injuries

Source: Unknown

Explosives

Scientists at Los Alamos National Laboratories are exploring the potential to release energy from nanoparticles – nano explosives. Nanoenergetics is a new field in which nanoaluminum particles are used as more effective explosives. Just as with the suntan products, the nanoaluminum presents a higher surface area to volume of the material. This means that when ignited a greater volume of the aluminum achieves chemical reaction, releasing its energy, and generating a larger explosion per pound of material. Nuclear weapons achieve their destructive power in this same way at the very lowest atomic level. This means that nanoaluminum and the “superthermite” that is made from it are presenting significantly more powerful weapons than those in use today. Details on this power and ongoing projects are not publicly available. But, it is instructive that the experiments are being carried out at the same laboratory that created the designs for most of the nuclear weapons in the US arsenal (Gartner, 2005).

Micro-Electro-Mechanical Systems

Sandia National Laboratories has turned their expertise in creating computer chips into the creation of MEMS devices. These are not strictly nanomaterials or nanomachines because they are 1,000 times larger than the traditionally accepted nano-threshold of 100 nanometers. But, these tiny machines are the smallest than can be achieved at this time. The process for creating these MEMS machines is similar to the chemical deposition and lithography methods used to create computer chips. Careful designs leave behind tiny gears, levers, and energy transfer devices at the chip-size (Figure 5).

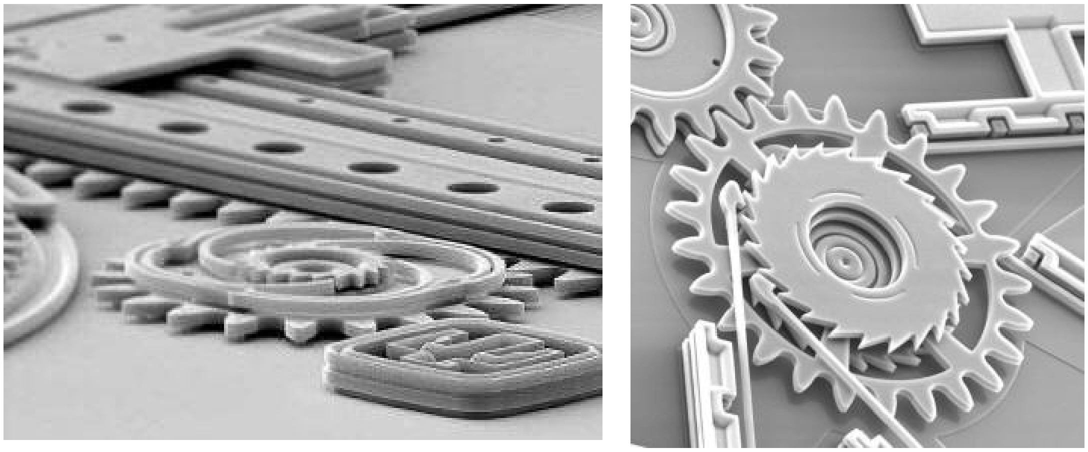


Figure 5. Sandia's Micro-Electro-Mechanical Systems
Source: Sandia National Laboratories, http://www.fantasyarts.net/nanotechnology-gallery.htm

MEMS devices can be used in conjunction with computer chips to create devices than can perform computational and physical operations. Early commercial products from this technology are found in the motion detectors that deploy automobile airbags.

Hybrid Materials

Scientists have also created hybrid materials, one of the most recent being “metal rubber”. Using chemical deposition methods, they have been able to create a material with the properties of both rubber and metal. It retains the flexibility, stretchability, and resilience of rubber. But, it can also conduct electricity like a metal. Scientists in robotics and prosthetics are hoping that this material can be used as an artificial muscle that will contract when stimulated with electricity (Hoffman, 2005).

How It Works

In his 1986 book, Eric Drexler imagined an assembly process for nanodevices that was driven through either chemical reactions or through tiny manipulators. Based on these, he was able to imagine both nanoparticles and nanomachines. However, further exploration has revealed that our ability to create such products is very limited. Chemical processes can be used to create nanoparticles for medicines, tanning lotion, and explosives. But, the ingredients and their chemical properties determine what type of particles can be created. Therefore, scientists must combine the discovery of natural processes with their own manipulation of these conditions to encourage the desired mixtures and shapes of particles.

Nanosys in Palo Alto, California has been using chemical processes to create nanoparticles that operate as efficient solar panels. They describe their production process as similar to that used to create rock candy. They supersaturate a liquid with the semi conducting materials and then allow the mixture to cool. As it does so, the silicates organize themselves into nanostructures in the same way that sugar creates the large crystals in rock candy (Huang, 2003).

Other scientists envision small desktop machines that combine materials in specific sequences to build up nanoparticles and nanomachines. These devices may become the equivalent of desktop printers that create computer chips (Figure 6).

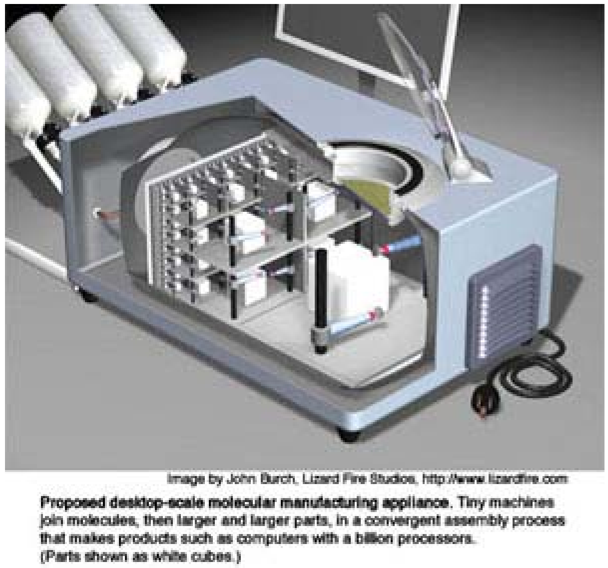


Figure 6. Desktop Nanofactory Concept

Source: http://www.foresight.org/NanoRev/nanofactory.html

Currently, the creation of nanomachines remains out of our reach. The chemical deposition of materials to create MEMS devices at the micro level is the smallest we can achieve right now.

Technical Challenges

Unlike e-business and the software explosion, nanotechnology requires significant investments in laboratories, equipment, ingredients, and scientists. This is one reason that nanotech has not generated the same number of new companies that came out of the computer and Internet explosions.

Nanotech remains an expensive and complicated production process that requires significant investments. There are few nanotech companies operating in a garage in their back yards. Instead new companies rely on government and venture capital funding to establish their laboratories and stake their claims at the patent office.

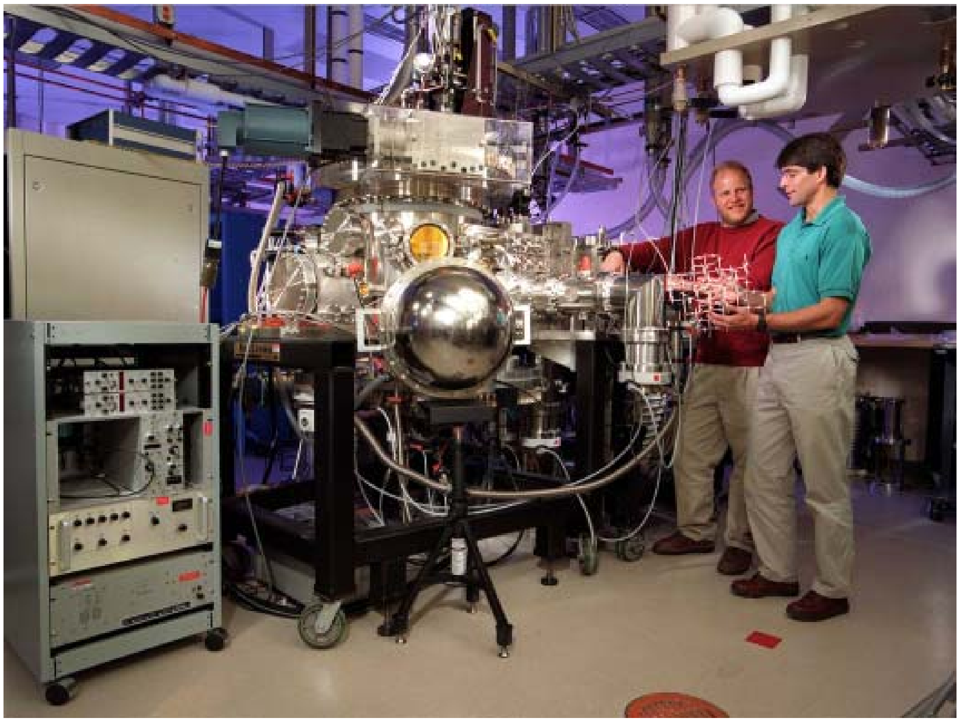


Figure 7. Nano-production Equipment at the University of Washington

Source: Harrill, 2001

Self-assembly through a chemical process or tiny manipulators remains a dream of researchers like Drexler. But, these are currently limited to simple nanoparticles and larger MEMS devices.

Market Leaders

Investments in nanotechnology have been healthy by many governments and venture capitalists. In 2004 the US government invested $710 million and VC's invested a little over $1 billion. These numbers are expected to continue to increase in the future. All of this money has created a number of new companies vying for a specific place in the emerging industry. Some of these companies are striving to bring products to market. Others are trying to build a portfolio of patents on particles, processes, and knowledge that may become licensable intellectual property in the future. Table 1 shows some of the start-ups identified in the references cited.

Table 1. Nanotechnology Startup Companies

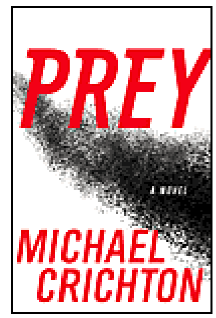
Category	Leading Companies
Medicine	iMedd, Flamel, BioSante, Elan, CytImmune, FeRX, Targesome, Nanospectra Biosciences, NanoBio Corp, Engene, Nanosys, Nanosphere, Quantum Dot, Combimatrix, Fluidigm
Electronics & IT	NanoOpto, Nanosys, Nantero, Zettacore, Samsung, Konarka
Materials Science	Applied Nanomaterials, Argonide, Lightyear, NanoSonic

Particles & Catalysts	NanoMix, Medis Technologies, NEC, Xoliox, nTera, NanoGram, Konarka
Tools	Veeco, NanoDevices, AngstroVision, FEI, Nanometrics, NanoTitan, Vyzx, NanoInk, Reactive NanoTech, Zyvex
Information Sources	Foresight Institute, Nanotechnology Now

Sources: Moore, 2004 and Gartner, 2005

Like RFID and grid computing, large multinational companies like IBM, Hewlett Packard, and General Electric are also investing in nanotech. Nineteen of the Dow Jones 30 companies have entered the field and are looking for ways to create nano improvements to their current products and to introduce new products to the marketplace (Baker, 2005).

Financial, Social, Legal, & Regulatory Issues



In 2002, Michael Crichton reintroduced the general public to the science of the small with his novel *Prey*. He adopted many of the ideas presented by Drexler concerning the assembly of tiny machines and gave each of them the intelligence of tiny robots. With this intelligence and a malevolent spirit, the nanoparticles became a swarm of mobile, reasoning, and hostile opponents to the human race. This also reflected some of the concerns from Drexler's book and Bill Joy's 2000 Wired magazine article entitled "The Future Doesn't Need Us" (Joy, 2000).

Most nanotechnologists do not believe that we will have the capability to create nanomachines like those described by Crichton anytime soon. Nor do they accept that those machines could evolve any form of intelligent behavior. However, there are concerns about a much more passive threat to human, animal, and plant life. The "grey goo" in Crichton's novel kills by obstructing the airways of its prey. This reflects a real concern about the effect that nanoparticles will have on the human body. These particles are so small that once airborne, they could remain suspended until inhaled by an animal. The mucous system that is designed to rid the body of dust, smoke, and other particles may not be able to cleans the lungs of nanosized particles.

At this point we do not know what effects these particles will have on the human body. Donaldson (2004) suggests that a new field of nanotoxocology must emerge to study this issue. The medical profession is already very familiar with the effects of inhaled particles in the form of asbestos, coal dust, silica, smoke, and other "large" particles. Nanoparticles may induce similar effects, but the additional impact of their extremely small size is simply not known.

Donaldson suggests that there are a number of ways for a human to come into contact with nanoparticles. The most obvious is during the manufacturing process of the particles or the products that incorporate them. A second comes from the degradation of the products under use. Nanoparticles used to strengthen tires would be freed from the material as the rubber in the tires is worn down. These particles may become airborne or waterborne and be transmitted to humans and other animals through the ecological system. A third avenue is through the direct use of the product. For example, nanoparticles in suntan lotions will be spread directly on the body. It is possible that these very small particles will be absorbed through the skin.

Figure 8 illustrates the systems within the body that may be subject to the absorption of nanoparticles introduced through inhalation – the brain, airways, blood vessels, blood, heart, and liver.

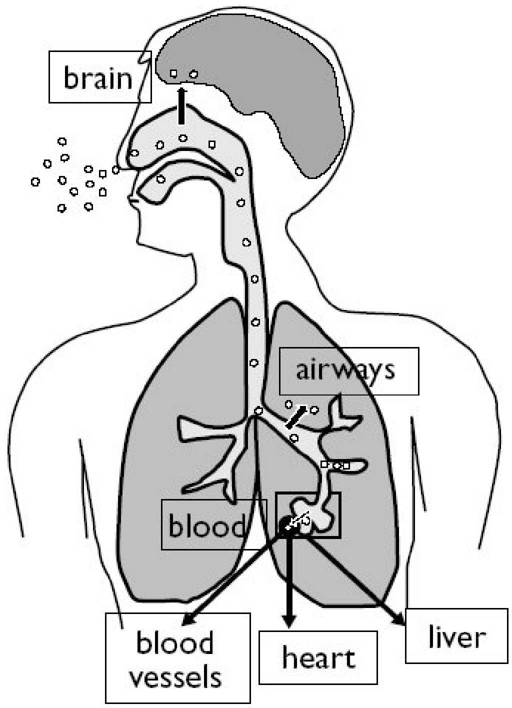


Figure 8. Nanoparticle Absorption Through Inhalation

Source: Donaldson, 2004

Donaldson does not explore the possible impacts of nanoparticles on vegetation, though Joy did speculate on this. In small numbers, they may simply enter the ecological system and be transmitted from one source to another. As described above, they may be harmful in the same way that fish-borne mercury is carried to humans - or they may be benign. In large numbers, they may act as a coating over plants that will kill them, whereupon the particles would enter the ecological system and spread to other hosts.

The key point is that the impact of these particles on living things is completely unknown at this time. Bill Joy (2000) seized on these ideas to paint an image of a future in which humans would been killed off, enslaved, or marginalized by more capable robots, while plant life would be displaced by self-assembling nanoparticles as the basic material of nature. This doomsday scenario plays on people's fears of the unknown, but does little to help us understand and deal with the inevitable proliferation of these products.

Market Size

In spite of the doomsayers, governments and venture capitalists are investing in the technology. They can see its potential to improve nearly every type of product. Lux Research predicts the market to be $13 billion in 2005 and as high as $292 billion by 2010 (Baker, 2005).

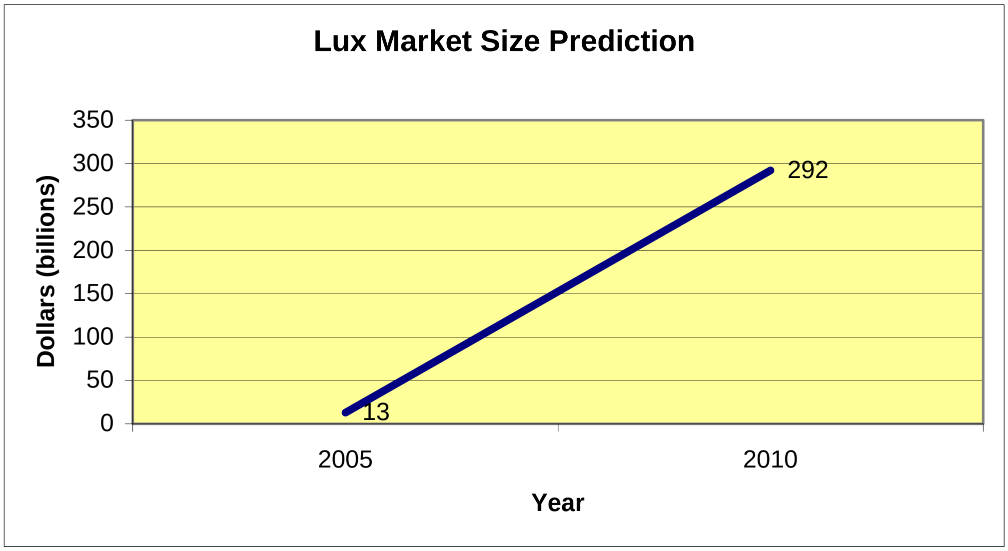


Figure 9. Lux Research Nano Market Estimate

Source: Baker, 2005

They also indicate that VC's have invested over $1 billion in companies pursuing applications of the technology so far and that spending is expected to increase. Governments around the world invest approximately $4.7 billion in this field every year. This investment is divided nearly evenly between North America, Europe, and Asia (Baker, 2005). So the pursuit of nanotechnology is a worldwide enterprise.

Adding to the 2010 prediction above, the US Nanotechnology Initiative estimates that the market will climb to over $1 trillion by 2015 (Figure 10). They see the leading areas of application to be materials, electronics, and pharmaceuticals.

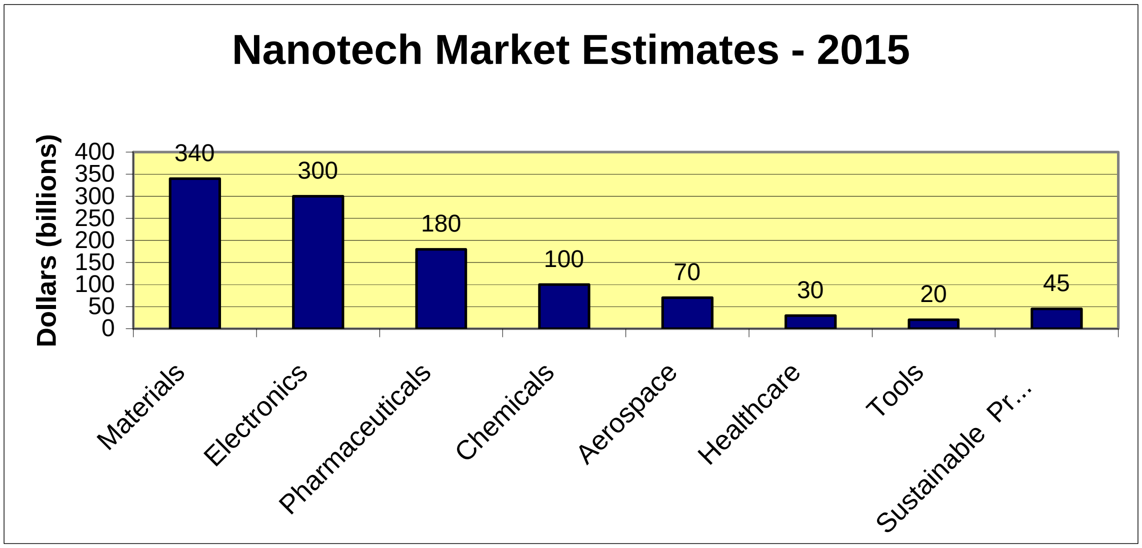


Figure 10. Nanotechnology Market Estimate for 2015
Source: Moore, 2004

The US Nanotechnology Initiative has been investing aggressively in nanotech since 2000 (Figure 11). They began at $270 million annually and expect to provide $850 million in 2005 (Moore, 2004).

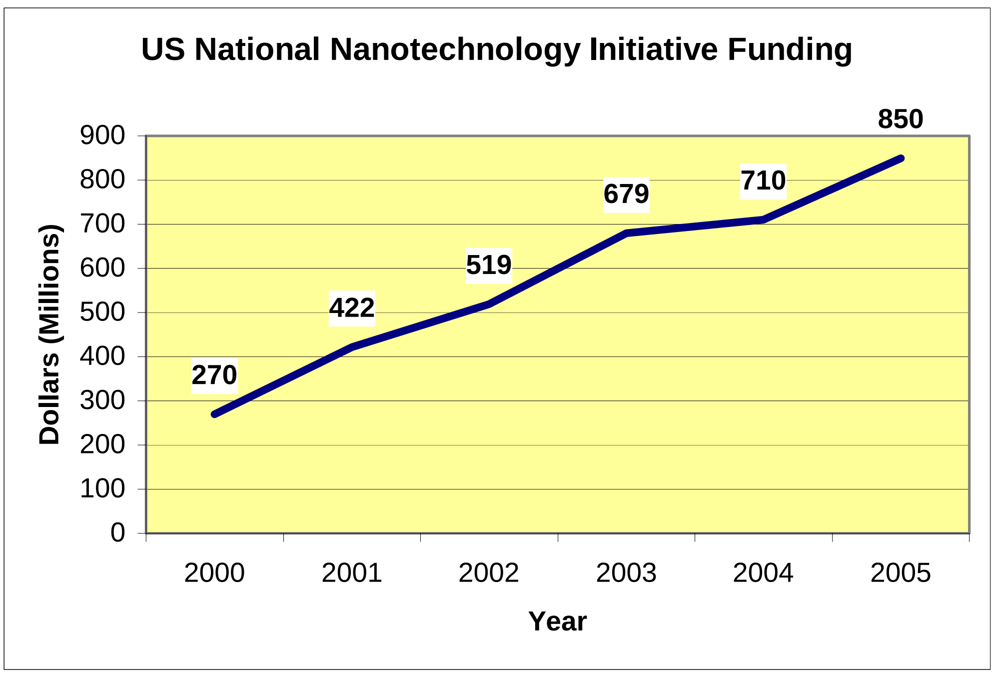


Figure 11. Annual Nanotech Investment by US Nanotechnology Initiative

Source: Moore, 2004

Strategic Positions

From all of the data collected, it appears that the best strategic position is in the creation of nanomaterials, such as sun blocker, rigidifiers, and protease inhibitors. Simpler materials are easier to make, present a broader array of commercial opportunities, and require less investment in equipment and expertise. However, these areas are also the most prone to competition and any valuable materials must have a carefully constructed patent barrier to control them as a source of competitive advantage.

Figure 12 illustrates the relationship between product complexity, regulations, life cycles, and the time to maturity. Passive materials are shown as the least complex, least regulated, and most imminent. All of these are desirable characteristics for nanoparticles, coatings, catalysts, and tools. The authors at Rensselaer Polytechnic Institute (2004) expect the field to mature into more complex structures like computer displays and then into functional systems like computer memory.

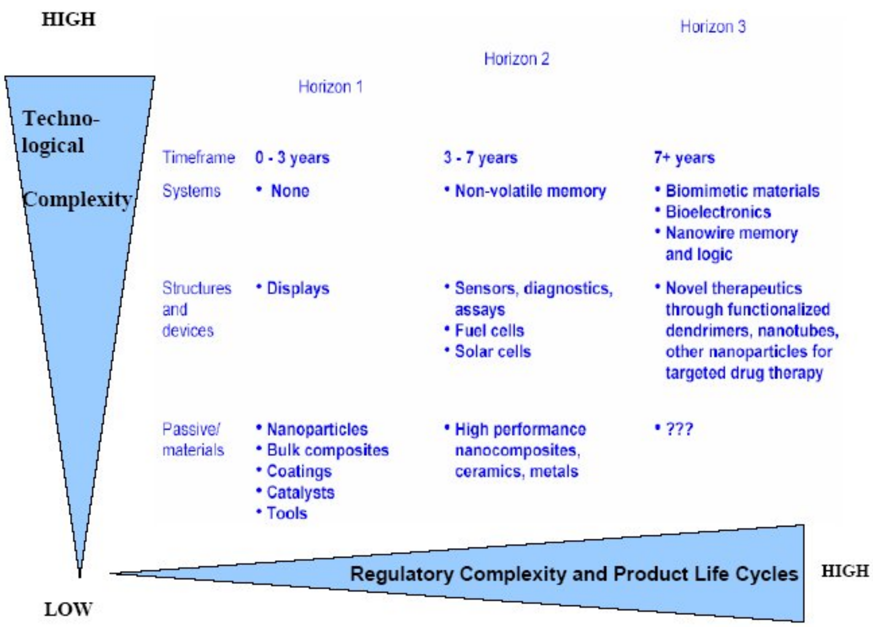


Figure 12. RPI's Estimate of Market Penetration for Nanotech Products

Source: Rensselaer, 2004

Many of the Dow 30 companies are aggressively pursuing nanotech and are an attractive partner for small companies that can provide progress in a specific area. Small companies can also thrive through government and VC funding if they are prepared to launch a unique product or stake an IP claim on a specific technology.

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