

@cn:Chapter 9

@ct:Recent Trends in Nanotechnology

@cq:Nanotechnology will make us healthy and wealthy. . . . In a few decades this emerging manufacturing technology will let us inexpensively arrange atoms and molecules in most of the ways permitted by physical law. It will let us make supercomputers that fit on the head of a pin and fleets of medical nanorobots smaller than a human cell able to eliminate cancer, infections, clogged arteries, and even old age. People will look back on this era with the same feelings we have toward medieval times—when technology was primitive and almost everyone lived in poverty and died young.

@cqa:—Ralph Merkle, Principal Fellow, Zyvex

@ics:While some of the earlier chapters have discussed former breakthrough technologies, this chapter presents a perspective on a new breakthrough technology, <I>nanotechnology,</I> which will disrupt and enhance the business world in the years to come. The ability to manipulate individual molecules and atoms will create countless product and process opportunities in the microelectronic and biotechnological fields. Nanotechnology will help create smaller, stronger, and more precise products, as well as more effective delivery systems. It will radically affect industries in both the near and long term.

@\$:The nineteenth century saw an industrial revolution led by an array of inventions. Each creation addressed the shortcomings of its predecessor, fulfilled an unmet need, or developed an entirely new solution. The key contributor to this revolution was technological innovation. The conversion of energy—from heat to steam to movement—spawned many applications, such as the spinning jenny, the steam train, and the combustion engine. The application of that breakthrough became the driving force for improvements in existing infrastructure and the creation of new domains. With rapid progress, however, the development curve eventually reached a plateau, and only marginal improvements could be achieved for mechanical devices.

Then another technological innovation appeared. The ability to store and to communicate information and knowledge electronically with bits and bytes led to the information-technology revolution of the twentieth century. The era redefined our working parameters for distance and timing, as demonstrated with applications like the Internet. A by-product of the underlying technology was the incredible growth of intellectual capital. Although information technology continues to advance, and the industry pushes forward at a rapid rate, the incremental benefits from it will eventually decrease. As in the past, we will reach a plateau on the development curve of improvements to our existing technology and infrastructure. The information-technology age will eventually be displaced.

A new model that fuses the breakthroughs from the two preceding revolutions will accomplish just that displacement. Nanotechnology will apply knowledge and information to the transformation of material or energy. Previous advances focused on using materials to produce energy, which then transported knowledge and information—this is a reactive approach. In the future, we will use our knowledge of molecular structure and energy to produce new materials in a specific and desired state—a truly proactive approach.

@h1:Setting the Stage

@h2:Technical Background

@\$:Nanotechnology designs and manufactures devices from atoms. By definition, devices with minimum feature sizes of 1,000 nanometers (one micron) or less are considered products of nanotechnology, although much of the work focuses on feature sizes smaller than 100nm. The field of nanotechnology encompasses many disciplines, such as computer science, physics, chemistry, and biology. Its aim is to manipulate individual molecules and atoms. Achieving this goal has been a major hurdle, and it has produced substantial skepticism about the feasibility of nanotechnology. Recent theoretical and laboratory progress, however, has been extremely encouraging. There is now

considerable evidence that individual molecules and atoms can be manipulated to build systems at the microscopic scale.

@fn:Ralph Merkle, a pioneer in the field, noted that objects take on particular characteristics depending on how their atoms are arranged. By rearranging the atoms in coal, we can make diamonds. By rearranging the atoms in sand and a few other trace elements, we can make computer chips. By rearranging the atoms in dirt, water, and air, we can make grass. Quoting the Web site for Zyvex Inc., where Ralph Merkle is a Principal Fellow:

@e:Today's manufacturing methods are very crude at the molecular level. Casting, grinding, milling, and even lithography move atoms in great, thundering, statistical herds. It's like trying to make things out of LEGO blocks with boxing gloves on your hands. You can push the LEGO blocks into great heaps and pile them up, but you can't really snap them together. In the future, nanotechnology will let us take off the boxing gloves. We'll be able to snap together the fundamental building blocks of nature easily, inexpensively, and in almost any arrangement that we desire. This will . . . let us fabricate an entire new generation of products that are cleaner, stronger, lighter, and more precise.

@\$: Two of the most important enablers for widespread use and development of nanotechnology are:

@nl: 1. The ability to position essentially every atom in the right place.

Comment: Should be numbered list.

@nlfi: 2. The ability to keep manufacturing costs from greatly exceeding the costs of required raw materials and energy.

@\$: For the first ability, technologists are working on nanomachines with precise positioning and assembly capability at the molecular level. This would allow us to arrange atoms and molecules as desired, much like LEGO blocks. For the second ability, the consensus is that if trillions of nanomachines are needed to make things on a scale useful to us, the cost will be prohibitive unless the devices can self-replicate. When these two challenges are overcome, the possibilities will multiply.

@h2:Timing

@\$:Although it may not be commonly known, nanotechnology has been around for many years. During the 1940s, von Neumann discussed the possibility of self-replicating manufacturing systems that would lower costs. These systems would be able to both manufacture useful products and replicate themselves. In 1959, the transcript of a speech by Richard Feynman called "There Is Plenty of Room at the Bottom" provided the first written description of the subject. In this speech, Feynman stated: "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. We need to apply at the molecular scale the concept that has demonstrated its effectiveness at the macroscopic scale: making parts go where we want by putting them where we want!"

Despite the insights of these inspiring pathfinders, no tangible results or advancements appeared until the 1990s. The late development reflected a series of barriers that prevented major progress or made the need for such progress less urgent. The barriers included the absence of tools to operate and manipulate at the nanoscale, as well as a general lack of knowledge in this area. Sufficient room to optimize existing technology was another important barrier, since the need for new tools was not pressing. The microprocessor industry exemplifies the situation. The ever-evolving miniaturization process of microprocessors seemed to have reached an end every six months; however, only a few months after the roadblock had been identified, there would be new improvements using updated techniques, tools, and methodology. Thus, the incremental advances circumvented the need for progress in nanotechnology because there was no sense of urgency for it.

Nevertheless, the paradigm has begun to change since the late 1990s. The ultimate roadblock might well be on the immediate horizon and, consequently, a look outside the box and into radically new techniques will be necessary. The tools and the budget to explore these new realms have now become available, helping to speed developments. Nanotechnology will be much more

than an incremental improvement; it will be a deep structural improvement, allowing for far-reaching developments.

@h2:Enabling Technologies

@\$:The development of additional enabling technologies will further aid nanotechnology and will result in the emergence of a cluster of related activities. Following are a few initial developments that will complement the value addition of nanotechnology in business applications:

@bl: • <I>Nanoscale microscopes<I>. Further improvement in observation techniques will provide an impetus for nanotechnology research.

@bl2i: • <I>Micromanipulation techniques<I>. Tools and aids to manipulate objects at the nanotechnology level will be necessary—initial work has begun on exponential assembly, which involves using miniature robotic assembly units to help create nanotechnology manufacturing architectures.

• <I>Nanoassemblers<I>. The assembler of nanolevel products to achieve molecular manufacturing will be developed (the current definition of an <I>assembler<I> envisages the construction and synthesis of an unprecedented array of desirable materials).

@blfi: • <I>Computational nanotechnology<I>. Simulation techniques will expedite the development of this new technology, and computational nanotechnology will be to nanotechnology what bioinformatics is to the human genome sequence.

@\$: This limited list of enabling advances in related technologies will be complementary to the development of nanotechnology. Numerous enabling developments will be necessary for nanotechnology applications in specific industries.

@h1:Frameworks and Analysis

@cq:The past may not repeat itself, but it sure does rhyme.

@cqa:—Mark Twain

@\$:This section addresses why nanotechnology will have a tremendous impact on industries, how large this impact will be, which industries will be affected, what the opportunities are, what the implications of this technology are, and how firms can

position themselves to leverage advances in nanotechnology. We do not have to be caught unawares by the proliferation of technology in general, and by nanotechnology in particular. In looking ahead, we have the benefit of the lessons of hindsight. Reviewing the historical impact of prior technological advances can help us evaluate the future effects of this new and revolutionary technology.

We first present a preliminary industrywide approach to the consequences of nanotechnology and identify the areas in which value creation will occur. Next three theoretical models are used to analyze firm-specific issues. Finally, all the issues are incorporated into a single practical framework that shows how firms can best leverage nanotechnology.

The Evolving Value Chain | This section addresses the ambiguity that encompasses nanotechnology. Nathan Rosenberg's framework aids in understanding the uncertainty that accompanies technological progress. This approach helps to identify the sources of ambiguity, which are also the sources of the value creation that will occur as a consequence of the new technology.

Five Ambiguities | A common feature of technological progress is that it is "characterized by a high degree of uncertainty," according to Rosenberg. He presents five dimensions of uncertainty that surround the emergence of new and important technological innovations. Although this approach provides valuable insights, there are a few caveats. First, Rosenberg's analysis is best interpreted within the context of an entire industry. It is not immediately or easily transferable to a firm-specific situation. Second, the framework is easy to apply in retrospect but complex to use in forecasting industry evolution (see Figure 9.1):

[[Au: Please edit figure cites as wanted.]]

1. **Primitive technological capabilities** | The newborn technology is not a fully formed animal. What it will grow up to be is often ambiguous; it is unclear, at its birth, what the implications of the technology will be and where they will manifest themselves. ENIAC, the first

computer ever built, was scarcely an indication of the PC revolution that followed. Similarly, it is difficult to forecast a full host of capabilities of nanotechnology. A few that we can anticipate today are applications that manipulate atoms, drug-delivery systems, and nanophotolithography.

@nls: 2. @nl2i:<I>Complementary searches.<I>|en|The birth of a technology gives rise to searches for complementary and/or enabling technologies that broaden the initial impact of the core technology. Fiber-optic technology was made possible by the invention of cables that could carry light pulses, although the laser had been invented many years before. The search for fiber-optic cable was a complementary search. Similarly, using nanotechnology in the semiconductor industry may not be possible until the enabling photolithographic tools are invented.

@nls: 3. @nl2i:<I>Clusters.<I>|en|Often an entire system of complementary inventions follows from the core technology, just as the telephone, the facsimile, and the Internet were created around basic telephone cable. It appears that nanotechnology will prompt the formation of clusters in at least two major industries: biotechnology and microelectronics.

@nls: 4. @nl2i:<I>Specific problems/wider application.<I>|en|Not uncommonly, the invention is made for a particular purpose and developed in a particular context, but something comes along that allows for its use in a different context. The steam engine is a classic example. By definition, it is impossible to accurately predict wider applications of progress in nanotechnology. Some of the more remote applications introduced later in the chapter may be examples.

@nls: 5. @nlfi:<I>Evaluating real needs of customers.<I>|en|Finally, it is impossible to ignore customer preferences in dictating the proliferation of new technologies. Even though, in a technological sense, the Concorde was a success, its tremendous economic failure illustrates how essential it is to have a connection between what is technologically feasible and what customers desire. Examples of customer needs that drive the science of nanotechnology are

faster, smaller, and cheaper computers in the microelectronics industry or improved drug-delivery systems in the biotechnology industry.

@\$: The evolution of nanotechnology will progress through the preceding ambiguities. Rosenberg's analysis allows us to arm ourselves with knowledge of the sources of both uncertainty and value creation, and it is in this revelation that his analysis has most value.

@h2:Models of Innovation

@h3s:Phases of Innovation.@h3:|em|According to James Utterback, there are two forms of innovation: process and product (a concept also attributed to William Abernathy). He maps each of these as three phases of industry evolution: fluid, transitional, and specific (Figure 9.2). The model is straightforward: Product innovation is characterized by major product development; process innovation is characterized by incremental development in process capabilities. The fluid phase occurs in the early stages of an industry's development. The rate of product change is rapid, high technical uncertainty prevails, and competition is generally fierce. The specific phase is characterized by industry consolidation and a shift of focus to process innovation as price competition becomes the primary basis for rivalry. The transitional phase, as the name implies, is the intermediary stage between the fluid and the specific. Industries follow a predictable pattern of evolution from the first stage to the last.

@\$: Utterback's model provides a framework to map the impact nanotechnology will have on different industries and specifically which industries will first receive potentially disruptive threats from this new technology. In addition, nanotechnology is neither a product innovation, nor a process innovation. It is both.

@h3s:Firm Capabilities.@h3:|em|The Henderson-Clark model presents an explanation for why some firms can leverage innovations, whereas others cannot. The essence of their argument involves distinguishing between two kinds of knowledge: component

knowledge and linkage knowledge. The former describes the information a company may possess in a particular product area; the latter describes the company's knowledge base relating to its product. It shows how the product interacts with other products, as well as the synergies that can be created.

@\$: Different innovations hold different implications depending on the type of knowledge a firm possesses. For example, a firm that is weak in the linkage knowledge sphere will be at a disadvantage when it comes to benefiting from an incremental process innovation. This framework is particularly relevant to the puzzle of why incumbent firms face so much difficulty in dealing with minute changes in existing technologies. The Henderson-Clark model can be used to outline the capabilities an individual firm must assemble to leverage nanotechnology (see Figure 9.3).

3@h3s:Disruptive Technologies.@h3:|em|Bower and Christensen developed a framework for grappling with disruptive technologies. They claim that some of the deliberate strategic choices firms make, such as staying close to customers, are the root causes for failure in embracing technological innovations. The Bower-Christensen approach can be simplified into four fundamental questions. We will pose the questions and, to explain them, simultaneously illustrate how nanotechnology will affect the photolithographic-equipment manufacturing industry:

- @nls: 1. @nl:<I>Is the technology disruptive or sustaining?<I>|en|The first step is to determine that the technology is indeed disruptive to the firm's existing business. Nanotechnology will be disruptive to manufacturers of photolithographic equipment, who will have to migrate to manufacturing nanolithographic equipment that is capable of producing structures smaller than 100nm.
- @nls: 2. @nl2i:<I>What is its strategic significance?<I>|en|Why should a photolithographic-equipment manufacturer react? The answer to this question lies in the value creation to the end user. Since nanolithography will result in improved speed and accuracy of building nanolevel structures, it

will eventually result in significantly more powerful microprocessors. There is clear evidence of value creation from the improved process.

3. What is the initial market? How can the photolithographic-equipment manufacturer capture the value it creates? Since the technology creates value for computer users, chip manufacturers would pay for the improved tools. The initial market would be large chip manufacturers.

4. What can the company do? The firm should create an independent organization to develop the technology. Bower-Christensen would advise the photolithographic-equipment manufacturer to create a separate division to build and sell nanolithographic equipment.

A Practical Roadmap

Some of the frameworks and analytical tools just described apply to industries at large, and others can be applied to firms. How does a firm make the right decisions if it believes nanotechnology will have an impact on the industry in which it operates? How does it apply the frameworks specifically to make strategic decisions? The following interpretations of the models in the context of nanotechnology offer a road map to the corporate reader for navigating through this strange new technology.

Extent of Disruption

The adoption of new technologies is usually characterized by an S-curve, as was described in Chapter 3. This S-curve describes the life cycle of a firm that is creating or marketing a new technology. The beginning of the curve represents the "ferment" stage when no one really understands what is happening. It is characterized by the appearance of an enormous number of new business models or approaches. Eventually, when a company finds out what works, the era of implementation starts. This is called the golden era, in which the company experiences significant growth. Maturity—the top of the curve—is attained when the company is strong and very good at what it does. At this point, should technology change again, the company

might be in trouble. Different kinds of people and skills are needed at different stages of technology life cycles, making it difficult for an established firm to move from one generation of technology to another.

Nanotechnology is in the ferment stage, or the early phase of the S-curve. It is therefore likely that strong incumbents either have never heard of nanotechnology or do not possess the right skills (or do not want to use the necessary resources) to start investigating the impact of this new technology on their businesses. As analyzed in previous sections, nanotechnology will be a disruptive technology: it will affect existing business processes and create new ones. To the extent that incumbents fail to prepare for the takeoff of nanotechnology, the disruptive effect will be exponential.

Knowing the sources of competitive advantage, or core competencies (branding, sales force, IT, etc.), is a critical first step in the management of a disruptive technology. No matter how disruptive the new technology wave, some existing sources of competitive advantages or assets will be critical in the next S-curve. Inevitably, though, some current competitive advantages that sustain the company will become obsolete.

The second step is to establish some distance from the current consumers. Disruptive technologies create problems for established firms because the management rule "focus on your consumer" leads them to miss new opportunities. The rational, analytical investment processes are focused—for all the right reasons—on current customers and markets. The processes are designed to weed out proposed products and technologies that do not address customer needs or that have negative net present value (NPV). The bottom line is that disruptive technologies look financially unattractive to established companies. The potential revenues from discernible markets are small, and it is difficult to project market size over the long term. Any rational resource-allocation process in companies serving established markets will go upmarket rather than downmarket.

All these characteristics, in fact, increase the disruptive potential of nanotechnology. Incumbents will most likely not prepare for the upcoming revolution. This dramatically increases the potential for their displacement. New companies with a relatively small R&D budget, betting on a narrow application segment, may gain a technological competitive advantage that, with some time and consumer education, will be translated into a real customer need. At that point, it will be too late for the incumbents to react. The only way to keep the customer will be to buy either the technology or the company--if it is still possible. That is a risky step.

Different types of technological innovations affect performance trajectories in different ways. <I>Sustaining technologies<I> maintain the rate of improvement, giving customers something more or better in the attributes they already value. Although nanotechnology could drastically improve certain existing processes, its real impact will most likely be as a <I>disruptive technology<I>. It will introduce a package of attributes different from those that customers have historically valued and that often perform worse along one or two dimensions of particular importance to those customers at a certain time.

@h2:Process and Product

@\$:There will be two types of nanotechnology innovations.

<I>Process innovations<I> will be applications to improve existing processes--to make them faster, more efficient, more accurate, more precise, and perhaps more cost-effective. Such innovations can range from lithographic tools in the microelectronics industry to drug-delivery systems in health care. <I>Product innovations<I> will arise from the application of nanotechnology to create revolutionary new products. It is hardly surprising that these will be more difficult to predict.

Nanotechnology process innovations will appear primarily in industries in the specific phase. As industries mature, and cost efficiencies becomes the focus of production, process innovations become more important relative to product innovation.

Nanotechnology product innovations will appear in industries in

the early stages of their development, or the fluid phase, for similar reasons. Although we can make certain predictions about the impacts of nanotechnology on different industries and where they will appear, we cannot predict their timing (see Figure 9.4).

@h2:Risks and Opportunities in Specific-Phase Industries

@\$:The risks posed by nanotechnology as a disruptive force are significant in specific-phase industries. Incumbents will have to incorporate process improvements to remain cost competitive. Likewise, process improvements offer great opportunities to established firms. Product innovations, on the other hand, are a substantially less attractive opportunity. Firms in mature industries will have to develop their knowledge of linkages to fully benefit from incremental process improvements and to prevent their established organizational structure from hindering the adoption of technological progress (see Figure 9.5).

@h2:Risks and Opportunities in Fluid-Phase Industries

@\$:Firms in the fluid-phase industries face a different risk-opportunity profile. They are positioned to benefit from the potential opportunities of disruptive technologies and product innovations, and they also benefit from the absence of an organizational heritage that can act as a burden. Product innovations pose a risk to these firms, however, since at this early stage of the industry, it is unclear which products will become industry standards. Finally, developing a linkage knowledge base is an opportunity for future process innovations, but firms have less to fear from its absence (see Figure 9.6).

@h2:Capabilities to Build and Deploy

@\$:Extending the Henderson-Clark argument, it is apparent that firms in the specific phase must focus on fostering linkage knowledge and firms in the fluid phase must focus on building component knowledge.

Fortunately, this is not a revelation. Competitive forces often prompt firms in the specific phase to focus on process innovations. The Henderson-Clark argument, however, carries an

implication for the allocation of research and development budgets. A specific-phase firm operating under a defensive strategy must expend its R&D dollars to explore the ways in which its manufacturing inputs and components and finished products relate. A thorough understanding of these linkages can enable it to discern opportunities to apply the emerging discipline of nanotechnology. A firm might improve operations processes by following a cost-minimization strategy. Alternatively, it might follow a product-differentiation strategy by improving product features.

On the other hand, a fluid-phase firm following a first-to-market and volume strategy might devote its R&D budget to increasing component knowledge as opposed to linkage knowledge. It is important to note that R&D refers not only to a determination of what is technologically feasible, but also to an analysis of customer requirements. Value capture occurs at the intersection of technical feasibility and customer desirability.

The precise capabilities that a firm must build are dictated by the phase in which it finds itself, but it must also consider a second input-strategy. A specific-phase firm in a defensible position may be able to devote a higher proportion of its R&D budget toward building component knowledge and attempt to further both process and product innovation. The reverse, however, is rarely true. A fluid-phase firm is rarely in a sufficiently defensible position to spend budget funds on expanding linkage knowledge.

@h1:Applications

@\$:The following framework (Figure 9.7) attempts to identify the areas where the new technologies will arise. Process innovations relying on nanotechnology will be dominant in mature industries, whereas new-product innovations incorporating nanotechnology will essentially see the light in industries in their early development stage.

The rationale behind this segmentation is that mature industries rely on current core competencies and installed customer bases, but new applications in these industries must stay closer to the

current product line and are therefore labeled process innovations. New-product applications, on the other hand, will emanate from new companies, potentially spun off from mature players. These new companies will focus on the new technology, without having to please an installed customer base. They are likely to experiment with more radical ideas and products, and thus product innovations are classified in the early stage of industry development.

@h2:Microelectronics

@\$:The idea of mechanical computing devices is not new. In fact, the first known computing device did not use electronics at all. The difference engine, created by Charles Babbage in 1822, was solely mechanical. The device, which required close to two thousand parts, served the single function of fixing entries for tables on the steam engine. The purely mechanical computing device gave way to electronics in the twentieth century, driving the machinery Babbage created into obsolescence. Today, the idea of returning to Babbage's concept at first seems comical, but the emergence of nanotechnology provides new motivation for studies of mechanical computers. Nanotechnology will lead to microscopic computer systems at the molecular and, eventually, the atomic scale. At present, we do not know how to design electronic components of that size, although if Moore's law (see Chapter 3) prevails, and smaller, faster devices are required, a nanocomputer constructed by solely molecular mechanical nanodevices may be on the horizon.

Even if an abrupt shift from electronics back to pure mechanics is doubtful, the arrival of nanotechnology will lead to a strong combination of the two in the near future. Carbon nanotubes, discovered in 1991 by Sumio Iijima of NEC Corporation, are an exciting example. These tubular structures impart mechanical and electronic properties that become an exotic variation of common graphite. A short list of their attributes includes super strength combined with low weight, stability, flexibility, good heat conduction, large surface area, and intriguing electronic properties. Today's nanotechnology has

already proven able to create material many times stronger and lighter than steel. The following microelectronic applications could emerge from these advances in both the short and long term.

@h3s:Plastics

@\$:Nanotechnology will most likely have its first significant industry impact in the area of materials science. Through process innovation, it will create stronger and lighter plastics from nanoclay. The nanomaterials are layered, often chemically modified, clays consisting of nanometer-thick platelets up to 1,000nm in diameter. Implementation will lead to improvements in staple products such as countertops, auto parts, toys, and nylon-packing applications. Though experts estimate that the current market demand for such products is only \$10 million, they predict that the global market will expand to \$500 million by 2010. [[Au: Source?]]

Several companies have already entered this space. Nanocor, a subsidiary of Amcol International, has patented technology and development agreements with Bayer, Eastman Chemicals, and Toyota. The five-year-old group plans to produce 20,000 tons of nanoclay this year [[Au: Identify year.]]for packaging applications and auto parts. Another group, RTP Company, focuses on plastic components for film and sheet applications. Others, such as Dow Chemical and Magna International, are developing production technology for automotive applications. Even if these innovations do not lead to new products, they will change the standards of existing ones.

@h3s:Nanomemory Computers

@\$:According to Moore's Law, computer-chip sizes decrease exponentially with time. This trend indicates that atomically precise computers will arrive by about 2010 to 2015. Nanotechnology will be required to work at this scale. In the near future, devices with nanoscale computer memory will provide orders-of-magnitude improvements in RAM density along with picosecond switching speeds.

Faster computer processors and increased memory storage improve the product. Although the major players still primarily

seek improvements through electronic innovation, they are aware of nanotechnology. Players such as David Tomanek's group at Michigan State University [[Au: As meant?]] have a patent pending on the design of Nano-memory, a computer that will be 1,000 times smaller than our standard today, yet hold the same amount of memory. The design employs nanotubes that literally change the state of the computer's on and off functions. Although this device or a different prototype may not emerge in the next 10 years, the trend is clear. A day will arrive when a standard personal computer will have enough storage to literally keep track of every conversation a person has ever had from birth to death, and the individual will be able to access the information quicker than the blink of an eye.

@h3:Batteries and Cell Phones @\$:The emergence of nanotubes could have a significant impact on the global \$2.8 billion battery market. They will create ion storage for batteries, improving the performance of rechargeable batteries through changes in the molecular electrochemical behavior. Since this technology has already been created, it should have an immediate impact on cell phones and computer batteries. In addition, innovations for batteries in electric cars will significantly cut down on the hours it takes to recharge. In fact, nanotechnology could make recharging quicker than refueling. A high-performance capacitor could store an electrical charge when two conductors are placed close together with an insulating layer. Such devices could be instantly recharged with large amounts of electrical energy, which could then be drawn off slowly by a motor.

The introduction of nanotechnology to computer and cell-phone batteries will happen soon. Tokyo-based Ulvac recently announced it had found a way to "grow" nanotubes in specific arrays and positions that will allow manufacturers of lithium batteries and computer displays to start using nanotubes within the next year[[Au: Need to define year and "recently" in this sentence]].

@h3:Fuel Cells

@\$:If electric cars do not emerge, many people believe that nanotechnology will enable environmentally improved and efficient fuel cells to power automobiles and other motor-driven devices in the future. Many fuel cells operate by oxidation involving hydrogen, oxygen, and a catalyst—hydrogen is introduced at the anode of the fuel cell, and oxygen at the cathode. Nanotubes may be able to absorb hydrogen in fuel tanks, compressing hydrogen more densely than is possible today. This will lead to increased power and efficiency, as more hydrogen fuel cells can be added.

In 2001, companies including NEC and Sony announced work on fuel-cell battery technology using nanotechnology. Though revenues for this technology are small today, analysts predict that the market will grow to \$14 to \$17 billion for distributed generation in North America in 2010 and \$40 to \$50 billion worldwide. Ballard Power, a leader in this industry, has a market capitalization of close to \$4 billion, yet had revenues of only \$55 million in 2000. As an enabler, nanotechnology should have a strong impact on the portable-power industry.

@h3s:Other Potential Applications @\$:Flat-screen TVs and optical-switch improvements are also areas of potential microelectronic applications. Today's television sets are so large because three electron guns are firing electrons from the back. Molecule-sized nanotubes could emit the electrons with the precision of one nanotube per pixel, resulting in a television with the depth of a framed print. Also, it would use far less power than present-day electron guns, in which silicon does the electron emitting.

The boom in optical telecommunications, spurred by the explosive growth of the Internet, has been provoking the growth of micromirrors and microlenses to bounce a laser beam around on the surface of a chip for routing optical signals. This process eliminates the need to switch from photons to electrons for routing data signals and thereby reduces transmission time. As innovative as optical switches sound, nanotechnology can miniaturize these switches, making them more effective and efficient. In addition, there is room to make intelligent photons

that carry their own destination information with them, thereby making optical switches redundant.

[[Au: Okay to move following material from health care section? Supply subhead?]]

@\$: The information-technology age saw precision farming, which used global-positioning systems (GPS) and geographic-information systems (GIS) to create yield maps for harvesting. The \$800 billion U.S. food industry targeted several products for improvements. Genetic engineering eliminated some of the potential problems. The first generation of products resulting from genetic engineering has focused on making plants (seeds) stronger and more robust without much change in functionality or the nature of the product.

The advent of nanotechnology will bring second-generation products that alter the very structure and function of those products to make them more useful and convenient. For example, in addition to making cotton more robust and pest resistant, nanotechnology will make it possible to grow colored cotton or wrinkle-free cotton right from the seed. These changes will not be limited to cotton but will be applied across multiple agricultural products, enhancing their nutritional and commercial value. Moreover, nanotechnology will allow us to grow these products artificially on a large scale that could compete with traditional agriculture.

@h2:Health Care and Biotechnology

Comment: Should be h2 head.

@\$: Diseases are caused largely by damage at the molecular and cellular level. Today's surgical tools are, at that scale, large and crude. From the viewpoint of a cell, even a fine scalpel is a blunt instrument better suited to tear and injure than to heal and cure. Modern surgery works only because cells have a remarkable ability to regroup, cleanse their dead, and heal over the injury.

@\$: Nanotechnology should let us economically build a broad range of complex molecular tools much smaller than a human cell and constructed with the accuracy and precision of drug molecules. Such tools will let medicine intervene in a

sophisticated and controlled way at the cellular and molecular level: they could remove obstructions in the circulatory system, kill cancer cells, or take over the function of subcellular organelles. Just as today we have the artificial heart, so in the future we could have the artificial mitochondrion.

Equally dramatic, nanotechnology will provide new instruments to examine tissue in unprecedented detail. Sensors smaller than a cell could allow an inside and exquisitely precise look at ongoing function. Tissue that was either chemically fixed or flash frozen could literally be analyzed down to the molecular level, giving a completely detailed snapshot of cellular, subcellular, and molecular activities.

Nanotechnology will also enable genetic medicine with a far-reaching impact on the health care industry and how pharmaceutical companies conduct business.

@h3s:Inside versus Outside.@h3:|em|Today's medicine attempts to find a weapon that works against a given health threat.

Tomorrow's medicine, enabled by nanotechnology, will largely replace the current approach and reveal the actual cause and biomedical pathways of disease. An ability to understand the causes and work "inside" the human body versus "outside" will lead to a new form of medicine that will succeed through the genetic prevention of disease rather than treatment of the disease itself. The health care industry and subsequent applications will move toward understanding the human genome and its relation to diseases and consequently provide customized medication.

@h3s:"Pharmacogenomics."@h3:|em|Body Text Indent 2|:In the near term, pharmacogenomics will develop precise drugs that treat specific genetic sets of patients. At present, \$8 billion worth of prescribed medicines do not work on all patients or need to be discontinued because of adverse side effects. Instead of a one-size-fits-all approach, wherein one drug is meant for everyone, precise drugs will be configured for distinctive gene types, leading to custom treatments that are more effective and have fewer side effects. Herceptin, developed by Genentech, which

Comment: PDC—Okay?

targets the 25 percent to 30 percent of breast-cancer patients who have a gene called HER2, is already on the market. In the future, a doctor will meet a patient and prescribe or even configure the exact treatment needed for a particular gene type.

Cancer Cures | About 1.2 million cases of cancer were diagnosed in this country in 20xx[[Au: Identify year]], but 60 percent of those cases had no therapy. After several years of research, there are over 350 biotech cancer therapies in clinical trials, 57 of those in final phase 3. Most of those therapies work with viruses or proteins. For example, tumor necrosis therapy (TNT), from Techniclone, uses a genetic smart bomb, which is injected into the bloodstream and finds its way to the tumor, delivering precise radiation treatment to the inside of the tumor, killing it from the inside and leaving the surrounding issue intact. Nanotechnology promises to provide scalability and cost-effectiveness for these solutions by helping the production of smart bombs.

Artificial Red Blood Cells and Mitochondria | Once scientists can manipulate at the molecular level, they will be able to provide metabolic support in the event of impaired circulation by providing artificial red blood cells. Not only could these cells be produced externally, but genetic enhancements to the immune system would allow for immediate recognition of tissue damage or blood clotting, resulting in restored blood flow at an appropriate level. An alternate possibility is a nanotechnology-enabled artificial device that releases oxygen at a constant rate to maintain metabolism and keep tissues healthy.

Biomachinery for Drug Delivery | In the classic 1966 science-fiction film *Fantastic Voyage*, a submarine and its crew are shrunk to microscopic size and travel through the bloodstream of a scientist to remove a clot in his brain with an onboard laser. Nanotechnology holds the promise of making an adaptation of this concept a reality: Miniaturization techniques will enable innovative drug-delivery systems to serve as doctors inside a human body and provide effective medical treatment by

enhancing the immune system or supplanting corrective-surgery methods.

@h1:Conclusion

@\$:Nanotechnology is more than an enabling technology; it is a revolutionary technology that will have a great impact not only on early stage industries, but also on mature industries. Early-stage industries will see product innovations, and mature industries will see process innovations in the form of nanotechnology applications. Developing internal capabilities for relevant process innovations in nanotechnology should appear on the agenda of companies in mature industries. On the other hand, companies in early-stage industries should direct resources toward product innovations. It is important to keep in mind that these are guidelines rather than rules. Other strategic options, such as external technology acquisitions and outsourcing of research and development, are also available.

The science of nanotechnology exists on the frontiers of technological innovation. Many of the applications considered in this chapter will become reality only in a mid-to-long-term time frame. However, two principal decisions are necessary in the short term. The first is which developments to choose among the nanotechnology-enabling products and services. The second involves the allocation of resources and must take into consideration any implications that nanotechnology will have for a company's future processes and products. These decisions may alter the business model.

Nanotechnology will change the existing paradigm of thinking and have more profound effects than any previous technology. It will touch every facet of the economy and have a wide-ranging impact across all industries. Some industries, such as health care and electronics, will feel the effects earlier than the others because of the short product cycles and the need for innovation.

In typical industries, value is created when new technology is matched to customer needs. Common questions in evaluating a project are, Does the customer want it? How big will the market

be? Is this a positive net-present-value project? However, those are not the appropriate questions for evaluating nanotechnology initiatives—nanotechnology is an object of "causal ambiguity." The existing customer may reject nanotechnology for its discontinuous or radical nature. Initially, the market might not capture a sizable chunk, and the opportunity cost of capital might not favor the nanotechnology initiatives. Thus, it is imperative that organizations understand its strategic significance by estimating the initial performance level of the technology. Once the exponential benefits are identified, the organization should locate the initial market and consider the potential of developing the technology independent of its current operations.

@h1:References

@r:Bauschlicher, Charles W., Jr., Alessandra Ricca, and Ralph Merkle. "Chemical Storage of Data." <I>Nanotechnology<I> (March 1997).

Bauschlicher, Charles W., Jr., and M. Rosi. "Differentiating between Hydrogen and Fluorine on a Diamond Surface." Submitted to <I>Theor. Chem. Acta.<I>

Brown, Eric. "A Better Optical Switch." <I>MIT Technology Review<I> (2001).

Brown, Kathryn. "Hugs Biotech Trees." <I>MIT Technology Review<I> (2001).

Christensen, Clayton, and Joseph Bower. "Disruptive Technologies: Catching the Wave." In John Seely Brown (ed.) <I>Seeing Differently: Insights on Innovation.<I> Harvard Business Review Book, 1997.

Drexler, K. Eric. <I>Journal of the British Interplanetary Society<I> (1992).

3. <I>Nanosystems: Molecular Machinery, Manufacturing, and Computation.<I> John Wiley & Sons, 1992.

Drexler, K. Eric, Chris Peterson, and Gayle Pergami. <I>Unbounding the Future.<I> William Morrow and Company, 1991.

Hyman, Anthony. <I>Charles Babbage: Pioneer of the Computer.<I> Princeton University Press, 1982.

Iijima, Sumio. "Helical Microtubules of Graphitic Carbon." <I>Nature<I> (November 7, 1991).

Kurzweil, Ray. "The Story of the 21st Century." <I>MIT Technology Review<I> (2000).

Leo, Alan. "Wiring Up Nanoelectronics." <I>MIT Technology Review<I> (2001).

Merkle, Ralph C. "How Long Will It Take to Develop Nanotechnology?" [[Web address]]

3. "Nanotechnology and Medicine." In <I>Advances in Anti-aging Medicine,<I> vol. 1, Ronald M. Klatz (ed.). Liebert Press, 1996.

3. "Two Types of Mechanical Reversible Logic." <I>Nanotechnology<I> (1993).

Merkle, Ralph C., and Drexler, K. Eric. "Helical Logic." <I>Nanotechnology<I> (1996).

Moore, Geoffrey. "Crossing the Chasm." <I>Harper Business,<I> 2d ed., 1999.

NanoInk, Incorporated. Presentation at Digital Frontier Conference, Kellogg Graduate School of Management, Northwestern University (2001).

"Nanotubes Show Promise from TVs to Velcro." <I>MSU Media Communications: News Releases<I> (February 18, 2000).

National Nanotechnology Initiative. "The Initiative and Its Implementation Plan." National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology, 2000.

Oliver, Richard W. <I>The Coming Biotech Age.<I> New York: McGraw Hill, 2000.

Piner, Richard D., et al. "Dip-pen Nanolithography." <I>Science<I> (1999).

Rosenberg, Nathan. "Uncertainty and Technology Change." In Landau, Taylor, and Wright (eds.). <I>The Mosaic of Economic Growth.<I> Stanford: Stanford University Press, 1996.

Shapiro, Carl, and Hal Varian. <I>Information Rules.<I> Boston: Harvard Business School Press, 1998.

Smalley, Richard. "Wires of Wonder." <I>MIT Technology Review<I> (2001).

Taylor, R., and Walton, D.R.M. "The Chemistry of Fullerenes." *Nature* (June 24, 1993).

Thayer, Ann M. "Firms Find a New Field of Dreams." *Chemical & Engineering News* (October 16, 2000).

Utterback, James. *Mastering the Dynamics of Innovation*. Boston: Harvard Business School Press, 1994.

Voss, David. "Nanomedicine Nears the Clinic." *MIT Technology Review* (2000).

Wang, Linda. "Live Wires." *MIT Technology Review* (2000).