PART I

Introduction to Nanotechnology

Part I of this book provides a description of nanotechnology and how it will be commercialized. In Chapter 1, we engage in a technical discussion of nanotechnology and its different applications. In Chapter 2, we construct a model of the industrial structure that is giving rise to nanotechnology. Understanding the materials in these chapters is crucial for readers who wish to clearly digest the concepts and ideas presented in the remainder of the book.

CHAPTER 1

Understanding Nanotechnology

Everything should be made as simple as possible—but not simpler.[1]

—Albert Einstein

In order to explore the business, policy, and legal issues associated with an emerging technology, it is necessary to have a grasp of the scientific underpinnings and potential applications of the technology. This is especially important in the context of nanotechnology, where rhetoric in the popular press has blurred the line between fact and science fiction. This chapter attempts to define what nanotechnology is, explore the history of the field, and then provide a lucid but technical description of the science and some of its potential applications. We hope that it is specific enough to serve as a reference for existing technology and yet general enough that readers may apply its overarching framework in the coming years.

DEFINING NANOTECHNOLOGY

Nanotechnology involves the investigation and design of materials or devices at the atomic and molecular levels. One nanometer, a measure equal to one-billionth of a meter, spans approximately 10 atoms. Formulating a precise definition of nanotechnology, however, is a difficult task. Even scientists in the field maintain that it "depends on whom you ask."[2] Biophysicist Steven M. Block notes that some researchers "reserve the word to mean whatever it is they do as opposed to whatever it is anyone else does."[3] For example, some researchers use the term to describe almost any research where some critical size is less than a micron (1,000 nanometers) while other scientists reserve the term for research involving sizes between 1 and 100 nanometers. There is also debate over whether naturally occurring nanoparticles, such as carbon soot, fall under the rubric of nanotechnology. Finally, some reserve the term "nanotechnology" exclusively for manufacturing with atomic precision whereas others employ the term to describe the use of nanomaterials to construct materials, devices, and systems. According to the Foresight Institute, a nonprofit organization dedicated to preparing society for nanotechnology, molecular nanotechnology "will be achieved when we are able to build things from the atom up, and we will be able to rearrange matter with atomic precision."[4] The National Science Foundation, on the other hand, defines nanotechnology as "research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1– 100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size."[5] Rather than adopt one of the preceding definitions to confine our discussion of nanotechnology, we survey nearly anything and everything that has been described as nanotechnology and provide a new and useful framework for understanding different types of nanotechnology.

UNDERSTANDING NANOSCIENCE

The dawn of the journey into the nano world can be traced back to 1959, when Caltech physicist Richard Feynman painted a vision of the future of science. In a talk titled "There's Plenty of Room at the Bottom," Feynman hypothesized that atoms and molecules could be manipulated like building blocks.[6] The first "proof-of-principle" that atoms could be precisely positioned by a manmade tool (living cells have, of course, been positioning atoms since time immemorial) took place in 1989 when scientists at IBM manipulated 35 xenon atoms to form the letters IBM (Figure 1.1). In the last

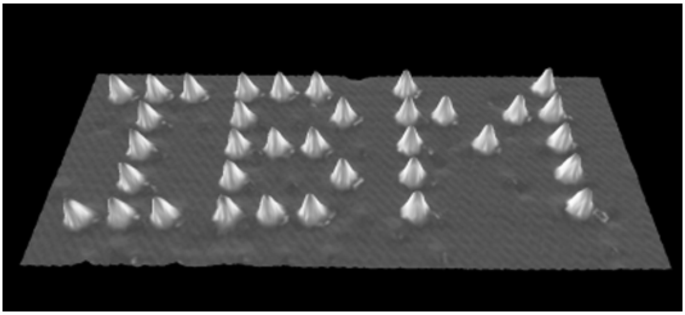

Figure 1.1 Xenon atoms on a nickel substrate positioned by STM.
Courtesy: IBM Research, Almaden Research Center. Unauthorized use not permitted.

few years, exploration within the field of nanotechnology has ramped up substantially.

The nano world is full of surprises and potential. In this realm, the disciplinary boundaries between chemistry, molecular biology, materials science, and condensed matter physics dissolve as scientists struggle to understand new and sometimes unexpected properties. Although these professionals are only on the first leg of the journey, they have made significant progress in synthesizing and understanding the "building blocks" of nanotechnology. In the coming years, the ability to utilize these building blocks for practical purposes will greatly increase. Let us first survey the building blocks of nanotechnology before turning to the potential applications.

The Building Blocks

Throughout this book, we use the term "building blocks" to describe the nanomaterials that can be positioned and manipulated for a variety of different applications. The analogy of building a house is appropriate to understanding nanotechnology. Houses can be comprised of a variety of materials: wood, nails, sheet rock, bricks, and so on. Just as a builder puts together different shapes and pieces of these materials to construct a home, nanotechnologists experiment with a variety of different nanomaterials to build complex materials, devices, and systems.

Atoms are the most basic units of matter. They can be combined to form more complex structures such as molecules, crystals, and compounds. Nanomaterials are arrangements of matter in the length scale of approximately 1 to 100 nanometers that exhibit unique characteristics due to their size. Fabrication, or the making, of nanomaterials falls into one of two categories: *top-down* or *bottom-up*.

The top-down method involves carving nanomaterials out of bulk materials.[7] Approaches in this category are referred to as different forms of lithography. Lithography can be understood through the concepts of *writing* and *replication*.[8] Writing involves designing a pattern on a negative (usually a mask), and replication involves transferring the pattern on the negative to a functional material. There are several types of lithography. Photolithography, which uses different kinds of electromagnetic radiation, is currently used to manufacture computer chips and other microelectronic devices.[9] Photolithography, as currently used, is not an effective tool for fabricating structures with features below 100 nanometers. E-beam lithography, a technique that employs beams of electrons to write, can produce some nanostructures with high resolution, albeit in an essentially serial fashion.[10] Soft lithographic techniques, such as printing, molding, and embossing, involve the physical or chemical deformation of the functional material to yield the desired structure. While soft lithography can be used to construct less planar nanostructures, it may be less precise than other techniques. A novel approach, which

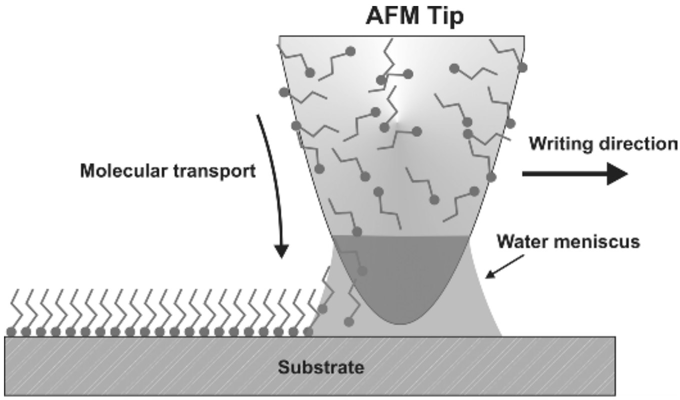

Figure 1.2 "Dip Pen" nanolithography.
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is conceptually different from conventional lithography, is "dip pen" lithography, a technique developed by Chad Mirkin's lab at Northwestern University. As seen in Figure 1.2, different types of molecules can be placed on a nano-sized probe. Water molecules between the probe and a gold substrate act as a bridge over which the molecules are transferred from the probe to the substrate, thus creating a pattern.

A second method of producing nanomaterials, known as the bottom-up approach, describes techniques for coaxing atoms and molecules to form nanomaterials. One bottom up technique, referred to as "positional assembly," involves using a probe to move atoms into certain arrangements. The use of an atomic force microscope to individually position xenon atoms to spell "IBM" is an example of this approach. Although positional assembly allows control over individual atoms, it is time-consuming, cannot presently be used to create complex nanostructures, and does not represent an efficient means for commercial production. Positional assembly, as realized today, is largely a *serial* process: Each step is performed after the previous one is completed. Photolithography, by way of contrast, is a massively *parallel* procedure—a very large number of features are created in each step. Both methods are, however, largely restricted to *planar* constructions or stacks thereof.

Another bottom-up approach is chemical self-assembly. Different atoms, molecules, or nanomaterials are mixed together and, because of their unique geometries and electronic structures, spontaneously organize into stable, well-defined structures. Because self-assembly methods are based on chemical reactions, they are simple and relatively inexpensive. However, they do not offer the precision necessary for constructing designed, interconnected patterns that top-down approaches currently do. Different categorization schemes have been used to describe the building blocks of nanotechnology. For example, some scientists categorize the building blocks into "soft" and "hard" categories. We describe two different, popular ways of classifying nanomaterials. Nanomaterials are often classified in the literature based on dimensionality. Crucial to this classification is the concept of *confinement*, which may be roughly interpreted as a restriction in the ability of electrons to move in one or more spatial dimensions. 0-D nanomaterials, such as quantum dots and metal nanoparticles, are confined in all three dimensions. 1-D nanomaterials are confined in two directions and extended in only one: electrons flow almost exclusively along this extended dimension. Examples of one-dimensional nanomaterials are nanotubes and nanowires. Finally, 2-D nanomaterials, which are confined in one dimension and extended in two, include thin films, surfaces, and interfaces. Interestingly, material structures currently used as elementary semiconductor devices fall under this category. Nanomaterials can also be divided into inorganic and organic classes.

Inorganic Nanomaterials

The term *inorganic nanomaterials* describes nanostructures in which carbon is not present and combined with some other element. We discuss four types of inorganic nanostructures: fullerenes and carbon nanotubes, nanowires, semiconductor nanocrystals, and nanoparticles.

Fullerenes and carbon nanotubes are the most well-known inorganic nanostructures.[11] Fullerene, formally known as buckminsterfullerene, was a new form of carbon discovered by Richard Smalley in 1985.[12] "Buckeyballs," as they are called, are molecules comprised of 60 carbon atoms and have the symmetry of soccer balls. The discovery of fullerenes sparked a raging fire of enthusiasm in the scientific community. It was predicted that the unique properties of fullerenes could be leveraged in everything from windshields to medicine. Although buckeyballs still hold great promise in nanotechnology, the spotlight has shifted to a relative of the fullerene molecule: carbon nanotubes.

Carbon nanotubes, first observed by Sumio Iijima in 1991, are tubular structures that can be thought of as "rolled-up" layers of interconnected carbon atoms. The arrangement of such atoms, because of the electronic structure of carbon, is graphically depicted as a network of hexagons: The lines that form the hexagons represent bonds between adjacent carbon atoms. There are two main types of carbon nanotubes. Multi-walled nanotubes (MWNTs), discovered in 1991, contain a number of hollow cylinders of carbon atoms nested inside one another.[13] Single-walled nanotubes (SWNTs), first synthesized and observed in 1993, consist of a single layer of carbon atoms and a hollow core.[14] (See Figure 1.3.)

Both types of nanotubes are narrow and long and exhibit unique electrical, mechanical, and thermal properties. For example, depending on size and

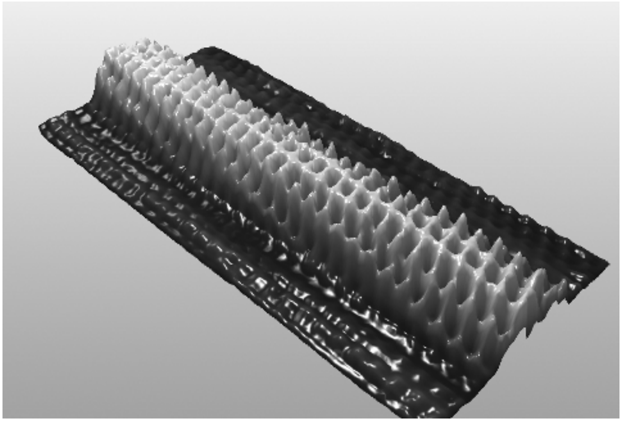

Figure 1.3 STM image of a single-walled carbon nanotube.
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shape, nanotubes can display a range of different conducting properties between metallic and semiconducting.[15] Further, nanotubes have a current carrying capacity of one billion amps per square centimeter while copper wires burn out at one million amps per square centimeter.[16] They also have more than 20 times the tensile strength of high-steel alloys,[17] but are lighter than aluminum.[18] Finally, it is estimated that nanotubes can transmit nearly twice as much heat as pure diamond[19] and are likely to remain stable in higher temperatures than metal wires.[20] At the time of this writing, researchers do not have substantial control over the synthesis of carbon nanotubes. The potential of nanotubes to serve as reliable building blocks is largely contingent on the ability to precisely engineer their size and properties.

Nanowires, also known as "nanorods" or "nanowhiskers," are another potential inorganic building block in nanotechnology. Nanowires are solid wires made from silicon, zinc oxide, and various metals. While their diameters are in the nanometer range, they can have lengths in the tens of micrometers. Nanowires have unique optical and electrical properties that, like those of nanotubes, emerge primarily from their low dimensionality. For example, they can emit laser light, act like optical fibers, and change conductance when bound to different molecules.[21] Unlike carbon nanotubes, researchers have today substantial control over the growth of nanowires.

Semiconductor nanocrystals (Figure 1.4), which are sometimes referred to as quantum dots, are fabricated by both lithography and several different self-assembly methods. Researchers are currently exploring the electrical and optical properties of quantum dots.[22] Altering the sizes of quantum dots can alter the wavelengths of light they can be made to emit.

Other types of inorganic nanoparticles, such as metals, oxides, glass, and clay, are also being developed and researched. They have been produced

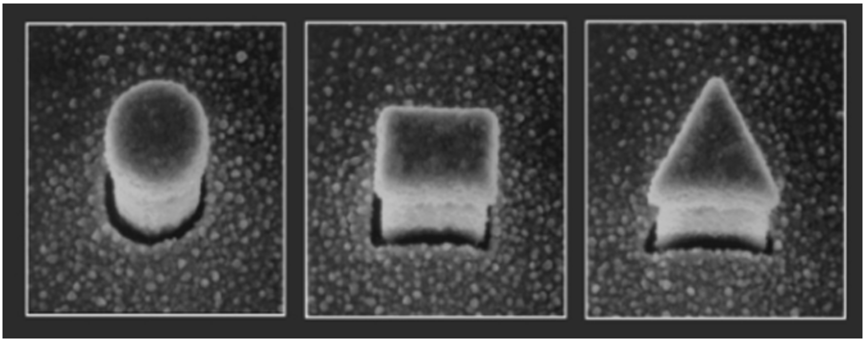

Figure 1.4 Vertical quantum dots of different shapes.
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using both top-down and self-assembly methods.[23] These nanomaterials can have superior properties to their bulk counterparts. For example, nanostructured alloys can be designed to exhibit a greater toughness and creep resistance than conventionally-manufactured alloys.

Organic Nanomaterials

Organic nanomaterials are compounds containing the element carbon. Chemists have long been able to synthesize small complex molecules. Recent advances enable researchers to create organic nanomaterials with specific atoms, geometries, and electronic arrangements. Several different types of organic nanostructures are being tested as potential building blocks. First, some researchers are experimenting with deoxyribonucleic acid (DNA).[24] The molecule is relatively rigid, and several strands can be combined to increase its stiffness. Artificial, repeatable DNA sequences can self-assemble into geometric structures (see Figure 1.5). Researchers have engineered cubic and truncated eight-sided structures from DNA[25] and, more recently, a complete eight-sided structure that is responsive to cloning and, thus, fast replication.[26]

Proteins, which are basic materials of living organisms, might also serve as building blocks. DNA contains the blueprints for proteins. Some scientists are experimenting with altering the DNA of cells to produce proteins that incorporate amino acids not found in nature.[27] Other researchers are experimenting with modified proteins that can form different nanostructures. For example, a group at NASA has shown that “heat shock protein 60” can be induced to self-assemble into tubes, after which the tubes associate to form filaments.[28] Dip pen lithography has also been used to generate protein nanoarrays.[29] Protein-based nanostructures can be made to conduct electricity and might be used in a number of different applications.[30]

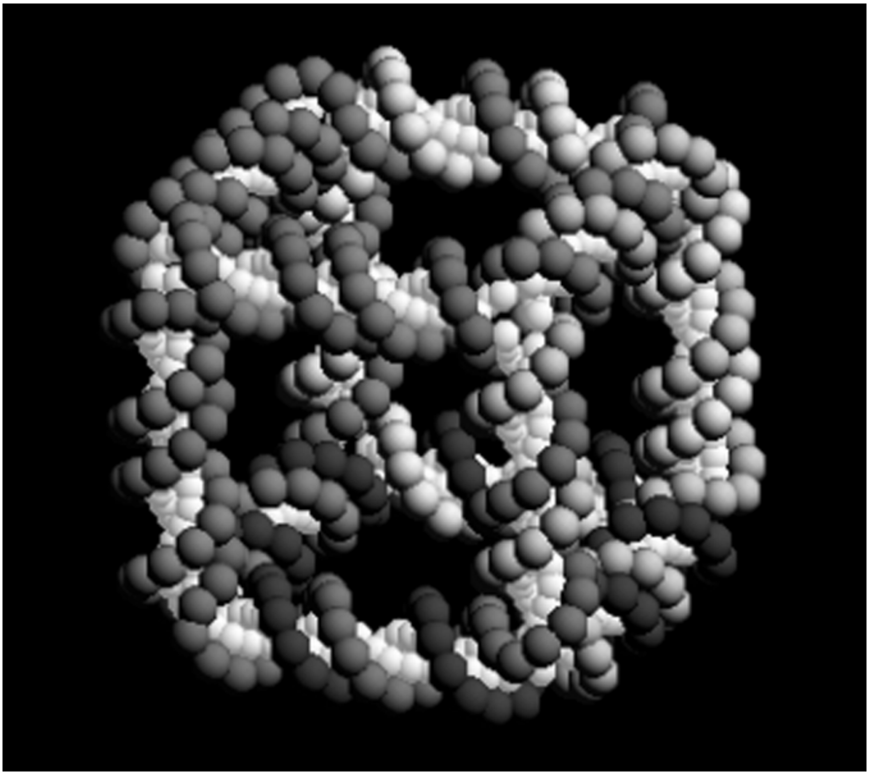

Figure 1.5 Representation of a DNA cube.
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Researchers also have begun experimenting with viruses and virus fragments as potential building blocks for nanotechnology. Viruses are readily available in very large quantities and possess the three-dimensional structure and chemical reactivity to make them suitable templates for building nanoscale devices.[31] Figure 1.6 shows electrically conducting clusters of virus particles (the large, grayish circles) stuck together with small gold particles (the small, bright circles). The viruses are genetically engineered to have sulfur atoms on their surfaces, which stick very well to metallic gold. The different clusters are formed spontaneously when gold and virus are mixed in different amounts.

Other researchers are working with a variety of different types of polymers. For example, block copolymers are formed by combining chemically different polymer species. Altering parameters such as temperature or pressure can cause the copolymers to spontaneously self-assemble into different morphologies.[32] One class of polymers that has received a great deal of attention is dendrimers. They are treelike molecules that can be made to function like a variety of biological structures.[33] They have surface properties that allow them to bind to other molecules and can carry molecules internally.

The Tools

Fullerenes, nanotubes, nanowires, semiconductor nanocrystals, nanoparticles, and polymers are examples of building blocks in nanotechnology. However, returning to the earlier analogy, a builder who has the necessary raw materials (wood, bricks, and so on) is helpless without tools to put together the materials in a fashion that results in a home. Blueprints are necessary, as well as the physical equipment such as hammers, saws, drills, tape measurements, and so on. Similarly, developing materials and devices based on nanomaterials requires the ability to model, observe, and position nanomaterials. Nanotechnologists employ computational tools as well as laboratory tools.

Computational nanotechnology involves designing and modeling nanomaterials and devices. As computational models enable researchers to model experimental results and predict new phenomena, this enterprise plays a critical role in nanotechnology.[34] There are several different computational methods being developed and integrated in different software packages.[35]

There are a variety of tools used by experimentalists to prepare, characterize, manipulate, and test nanostructures. For example, the scanning tunneling microscope (STM) allows researchers to view nanostructures by

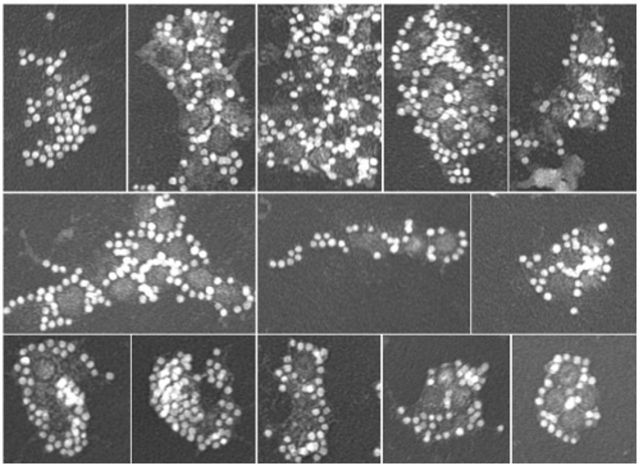

Figure 1.6 Electrically Conducting Clusters of Virus Particles.
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measuring small currents passing between the microscope's tip and the sample under evaluation.[36] Both the STM and the atomic force microscope (AFM) can be utilized to position nanostructures;[37] however, as mentioned before, they are limited on the vertical dimension and also are relatively slow and impractical for large-scale production. Scientists are developing "nanotweezers" to enable researchers to grab nanomaterials, while researchers can move nanomaterials using a movable platform.[38] Rays of light, known as "optical tweezers," are also used to manipulate nanoparticles.[39]

Applications of Nanotechnology

We identify and describe three general classes of nanotechnology applications based on the degree of control over the synthesis, characterization, and positioning of nanomaterials. First, we use the term *simple nanotechnology* to describe applications involving mass production of nanomaterials. Commercial products based on simple nanotechnology do not involve precise fabrication and positioning of nanostructures. We describe the second class of nanotechnology applications as "building small." This category refers to the use of nanomaterials to build advanced materials, devices, and systems. Within the next 5 to 15 years, "building small" nanotechnology could have a major impact on a number of different products in a range of different industries. We term the final class of nanotechnology applications "building large." This category describes the as-yet-unrealized vision of self-replicating nanorobots.

"Simple Nanotechnology"

We refer to products as "simple nanotechnology" when they are manufactured through mass production and dispersion of nanomaterials in a random fashion. In other words, there is no precise fabrication and positioning of nanostructures. Examples of simple nanotechnology are the use of nanomaterials as catalysts and coatings and in composites and textiles.

Catalysts are substances that regulate the rate at which chemical reactions proceed. When the catalytic rate varies with the surface area of catalysts, nanoparticles that present a large surface area can serve as excellent catalysts in certain reactions. For example, nanoscale metal oxides are currently being utilized in catalytic converters.[40] Aluminum nanoparticles can be found in energetics to enhance the performance of rocket propellants and as lead-free primers in explosives.[41] Finally, researchers are utilizing nanoparticles to develop technology that converts coal directly into liquid fuels.[42]

Coatings and films, traditionally composed of epoxies and paints, are put on objects to make them durable and give them other qualities. Nanofilms serve as invisible coatings that are more durable and cost-effective than traditional coatings. Coatings comprised of nanoparticles can be extremely rough or slippery, or exhibit unusual properties, such as altering color when an electric current is applied. Recent applications of nanoparticles include coatings on walls that make them more resistant to graffiti, a wax used by skiers to increase traction, and transparent suntan lotion.[43] Glassmakers have even begun selling self-cleaning windows coated with dirt-repelling nanoparticles. It is important to distinguish these "macroscopic" thin films from sophisticatedly engineered surfaces or layers—called thin films in a different context—used in certain devices in which the atomic structure is extremely well controlled, such as thin layers of semiconductor materials in devices.

Composites are combinations of materials differing in combination and form. The use of nanomaterials in composites can increase their mechanical properties, decrease their weight, enhance their chemical and heat resistance, and alter their interaction with light and other radiation. As such, they are likely to enhance metals, plastics, textiles, and so on. For example, ceramic composites made of nanoparticles that afford superior performance may be applied as protective coatings in environments subject to harsh thermal and mechanical conditions.

"Building Small" Nanotechnology

We describe the second class of nanotechnology as "building small," because it primarily involves using nanomaterials to construct novel materials, devices, and systems. Unlike "simple" nanotechnology, "building small" requires the ability to precisely fabricate and position nanostructures. The ability to leverage the unique mechanical, electrical, chemical, and optical properties of different nanomaterials could have a major impact on a number of different products in a range of industries. The following discussion provides a brief explanation of some of the different types of products that will be impacted by "building small" nanotechnology. The products we discuss can loosely be grouped into six different classes: sensors and measurement, electronics, communications, energy, life sciences, and aerospace and defense.

Sensors and Measurement: Some of the initial applications of "building small" nanotechnology that will hit the market in the next three to ten years will be a range of different sensing and measurement devices. First, nanostructures are being used to develop better chemical sensors. Such devices can be used for leak detection, medical monitoring, environmental hazard monitoring, and industrial control. Nanotubes and nanowires can serve as the basis for these sensors, because they change their electrical resistance when exposed to alkalis, halogens, and other gases. Several start-up companies are racing to bring nanotechnology sensors to market that are smaller, more sensitive, and use less power.

Nanostructures are also being used to improve biological detection. For example, different-sized quantum dots can be put together in various combinations in latex beads to produce a large number of distinct labels. Each bead can be attached to a different gene. When the "library" of gene-bead structures is exposed to a sample of DNA, the complementary genes bind, and researchers can determine which genes are present in the sample.[44]

In the long run, nanostructures might be used in advanced spectroscopic devices that measure minute concentrations of molecules in different settings. For example, airborne particulates absorb electromagnetic radiation at specific wavelengths. By using quantum dots, researchers could tune a laser to the wavelength at which a certain particle absorbs radiation. Shining the beam through the air would enable researchers to measure the amount of radiation absorbed.

Electronics: A second general category of products that are likely to be substantially improved by "building small" nanotechnology are electronic materials, devices, and systems. We survey the impact of nanotechnology on computer processing, memory, data storage, and display technologies.

Moore's law—an empirical observation rather than actual physical law—holds that the number of transistors that can be fabricated on a silicon-integrated circuit doubles every 18 to 24 months. Microelectronics has progressed along this path for nearly forty years. Modern chips, which are a few square centimeters in size, hold approximately 100 million transistors. Within the next 10 to 12 years, however, silicon electronics will be unable to increase computing speed at the current rate. Stray signals on the chip, thermal instability caused by densely packed transistors, and excessive fabrication costs are predicted to crash the silicon wave.[45]

Semiconductor and computer companies such as Hewlett-Packard (HP), Intel, and IBM have begun to research the possibility of using nanotechnology to build chips in the future. Researchers have demonstrated a field-effect transistor based on a semiconducting single-walled nanotube.[46] In July 2001, a research team at UCLA and HP revealed an electronic switch consisting of a layer of several million rotaxane molecules.[47] Charles Lieber's team at Harvard University announced in January of 2002 a transistor comprised of a silicon nanowire and a gallium nitride nanowire.[48] Cees Dekker's group at Delft University of Technology has observed diode-like properties on a single carbon nanotube that has imperfections in the atomic network.[49] (See Figure 1.7.) And not long before this book went to press, researchers at Stanford University and UC Berkeley created the first integrated silicon circuit with nanotube transistors.[50] The size, cost, and ease of fabrication of nanoscale building blocks make it possible to engineer system architectures with redundancy, an engineering quality that allows for the failure of several individual components without impairing the overall performance of the system.[51]

In addition to making more advanced forms of conventional electronic devices, nanostructures could spawn the creation of entirely novel devices. For example, in a certain regime of transport, electrons maintain their angular momentum, or "spin," as they travel through a nanotube. Spin, much like charge, is a physical quantity that could encode and/or process information. Researchers are attempting to leverage this property by constructing "spintronic" devices that switch on or off in response to electron spin.[52] This approach contrasts with traditional electronic devices, which turn on and off in response to electric charge.

Ultimately, the use of nanotechnology to make smaller and denser circuits could lead to "artificial brains" that have intellectual capabilities comparable—or even superior—to those of human beings."[53] Of course, the obstacles on the path to achieving such a goal are monumental. Indeed, several challenges must be overcome before devices based on nanostructures can have a revolutionary impact on computer processing. Researchers must discover how to interconnect nano-sized transistors into complex circuits—a growing challenge even in silicon technology. Further, they must find a mechanism that can mass-produce complex circuits in an efficient and cost-effective manner.

While nanotechnology is unlikely to be used to develop new devices and systems for computer processing in the near future, it could have a more immediate impact on memory devices. Conventional dynamic random-access memory (DRAM) is the short-term electronic memory that a computer uses to run its software. Because information is only stored as long as there is power, stored information must be loaded from the hard drive onto memory every time the machine is turned on. Nano devices are being tested to create new types of RAM that are nonvolatile—that is, that preserve information

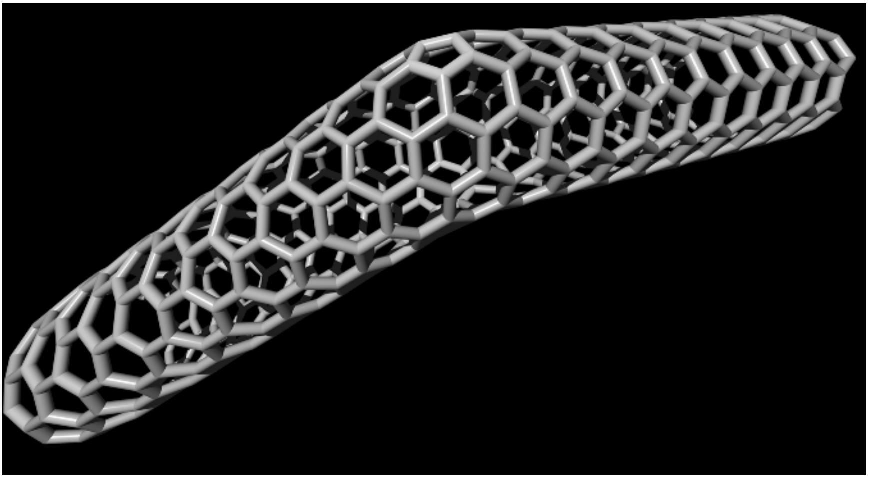

Figure 1.7 Representation of a "kinked" nanotube that exhibits diode-like properties. Reprinted with permission, Cees Dekker, Technical University Delft.

even when the power is turned off.[54] Such devices could conceivably replace current RAM and Flash technologies in the future.[55]

The very concept of nonvolatile memory and the expected storage densities of these devices blur somewhat the distinction between "memory" and "data storage." Nonetheless, applications of nanotechnology to traditional data storage applications such as hard disks have yielded fruitful results: For example, in 2002, IBM announced that it could pack a trillion bits of data onto a chip the size of a postage stamp.[56]

The arena of electronics in which nanotechnology is likely to have the greatest impact in the nearest future is display technologies. Historically, television screens and desktop computer displays used cathode-ray tubes, in which electrically heated wires shoot electrons onto a phosphor-coated screen. Liquid crystal display technology has led to the introduction of flat panel displays for a variety of different devices. Organic light-emitting diodes (OLEDs) are already being marketed as a superior alternative to liquid crystal displays on account of their lower operation costs, ease of fabrication, and superior usability characteristics. As the screen lives of OLEDs lengthen and the costs of production decrease, OLED-based displays will become more popular.

Communications: A third class of products likely to reap substantial benefits from miniaturization are communications devices. Nanotechnology will enable better optical networks, where information is transmitted by light. Already, a clever combination of self- and directed-assembly is used to fabricate photonic crystals, which are essentially semiconductors of light, as opposed to electrical current.[57] A novel approach to optical devices is the use of plasmonic circuits, which utilize light to induce fluctuations in the charge density of a nanostructure and, therefore, the transport of energy and information. This technology would allow for a dramatic scaling of optical components.[58]

Energy: Traditional energy supplies could reach some significant limits in coming years.[59] "Building small" nanotechnology, though, is likely to revolutionize energy conversion and storage. Technology that would enable exploitation of alternative energy sources to supply electric power on a large scale at a lower cost than oil could play a key role in the future of humanity.

Examples of such technology are photovoltaic and photochemical cells. Solar energy can be used to produce electric power directly through the use of photovoltaic cells. It can also be used to produce fuel—hydrogen—by splitting water molecules in a process that closely parallels that of photovoltaic conversion. Nanostructured photovoltaic cells, which include dye-sensitized and organic cells, essentially divide the tasks of absorbing light and generating current between two different entities.[60] This results not only in greater durability but also in an enormous cost advantage vis-à-vis other technologies. The practical challenge that organic cells face for large-scale production is to achieve efficiencies at least three times greater than are possible today. This task, despite several fundamental phenomena that must be better understood, seems within technological reach.[61]

The storage of hydrogen, whether produced by using solar energy to cleave water molecules or, for example, by recuperating it from biological waste, is an area that could also benefit from nanotechnology. Several nanostructures have been studied[62] and some have been successfully demonstrated in the laboratory.[63] Nanomaterials have also been advocated for lithium-ion batteries,[64] now a ubiquitous technology. It is envisioned that large-scale energy storage—necessary to enable solar technology as a mainstream source of electric power—could be accomplished through the use of superconductors, although many fundamental problems must be solved before such use becomes feasible.[65]

Medicine: Some promising applications of nanotechnology are also likely to bear fruit in the world of medicine. Nanotechnology could spawn new drugs, drug delivery systems, diagnostic devices, materials for tissue engineering, and other devices.

Researchers are experimenting with nanomaterials to develop a variety of new drugs. For example, NanoBio Corporation is developing an antimicrobial material that is effective against a wide range of microbial pathogens. The company is in clinical trials for use of the material to treat herpes and toenail fungus and expects to bring products to market within five years. Another company, C Sixty Inc., is investigating the use of the fullerene molecule as a drug. Fullerene can interact with cells, proteins, and viruses, and can be altered to perform specific tasks. The company hopes to develop several therapies, including a novel treatment for HIV.

Nanotechnology could also give rise to new mechanisms for delivering drugs. The most basic drug delivery systems under development enhance the effectiveness of drugs by targeting certain types of cells, speeding up delivery time, and preventing digestive enzymes from breaking down the medication. Researchers are also experimenting with more advanced delivery systems, such as a dendrimer device that can infiltrate cells and detect premalignant and cancerous changes in the cells, release a chemical substance to kill the cell, and verify destruction of the cell by becoming fluorescent in the presence of enzymes released by fatally wounded cells. Dendrimers might also be used as delivery vehicles for introducing genes into cells in the body to treat different diseases. For years, researchers have been experimenting with gene therapy procedures that involve wrapping genes in viruses or coatings of fat, but these methods often elicit dangerous immune responses. Because dendrimers are so small, they may be able to insert a gene into a targeted cell without provoking an immune reaction. Other researchers are developing implantable devices that can periodically dispense medicines, such as insulin or morphine. These devices, composed of copolymer-nanoshell composites, are capable of holding medicine. When the nanoshells are exposed to infrared light, the drug is released into the surrounding tissue.[66]

In conjunction with yielding better drugs and drug delivery systems, nanotechnology could significantly improve diagnostic capabilities. One way that it could accomplish this is with devices that perform highly parallel analysis of genetic material. High-throughput assaying is likely to be a valuable aid in identifying variations in the sequence of DNA and thus diagnosing diseases of a hereditary nature. Rapid analytical methods for characterization will also be valuable in studying protein structure and function in order to arrive at a molecular-level understanding of cellular behavior. Finally, molecular assaying will also enable the discovery of highly specific drugs. [67]

Alternatively, nanostructures could be used to build noninvasive devices that can enter the body to determine glucose levels, distinguish between normal and cancerous tissue, and provide genetic screening for multiple diseases. For example, researchers are working with a nanoscale needle that can probe cells for carcinogenic chemicals.[68] Exploratory research in this area includes a pill that would travel through the body and provide a comprehensive diagnosis of the patient's health.[69]

Nanotechnology could also enhance tissue engineering and cell therapy, which involve the use of living cells and other natural or synthetic compounds to develop implantable parts for the restoration, maintenance, or replacement of the body's tissues and organs. To treat patients whose pancreatic cells do not produce enough insulin, researchers have experimented with implanting insulin-producing cells from a pig. The primary problem associated with such a procedure is that the immune system attacks the foreign pig cells. Researchers are conducting clinical trials using a silicon capsule with nano-sized pores that prevents the immune system from identifying the foreign cells. The pores, which are only a few nanometers wide, are small enough to screen out the antibodies employed by the immune system while large enough to allow insulin molecules to exit into the bloodstream.[70] Nanoporous fabrication technology could also be used to direct the growth of tissue[71] and facilitate the integration of synthetic materials into the human body.[72]

Nanomedical research could also result in an array of different medical devices. In the short run, it seems likely that surgical tools will be enhanced by nanotechnology. For example, nanotechnology has resulted in a surgical scalpel based on a nanostructured diamond that slices more neatly into eyeballs.[73] In the more distant future, nanotechnology could result in miniature devices that can be implanted to correct auditory, visual, and sensory impairment. For example, researchers are working on a tiny film that can be implanted on the retina of a blind patient, where it absorbs light and delivers electrical signals that are relayed to and interpreted by the brain.[74] This might emulate to some extent the sensory input from eyesight.

Aerospace and Defense: A final class of products that will be improved by "building small" nanotechnology are products in the aerospace and defense sector. To some extent, the impact of nanotechnology on this class of products will primarily be the culmination of the impact of nanotechnology on other industries. NASA perceives miniaturization as the key to exploring new frontiers in space. The agency envisions that future spacecraft will be comprised of ultrasmall sensors, advanced electronic and photonic systems for communication and navigation, lightweight and strong surface materials, and highly efficient power sources. Meyya Meyyappan, director of the Center for Nanotechnology at the NASA Ames Research Center, declares that nanotechnology "presents a whole new spectrum of opportunities to build device components and systems for entirely new, bold space architectures."[75]

The Defense Department is also making substantial investments in nanotechnology. For example, the Army contracted with Massachusetts Institute of Technology (MIT) to design futuristic combat gear for American soldiers.[76] The envisioned battle suits will purportedly change color to blend in with the surrounding environment and transform from a soft fabric to bulletproof armor. Sensors in the suit would detect when the soldier is wounded, devices would transmit vital signals to a distant medic, and antidotes would be released as needed.

"Building Large" Nanotechnology

We refer to the final class of nanotechnology as "building large," because it attempts to revolutionize macroscopic manufacturing capabilities.[77] Molecular manufacturing, as this type of nanotechnology is sometimes called, was conceived by K. Eric Drexler at MIT in the late 1970's.

Drexler has predicted that molecular nanotechnology will eventually allow scientists to prevent death by cellular repair, build everything from computers to space shuttles, eliminate pollution, rebuild extinct plants and animals, and efficiently produce food to end hunger on the planet.[78] Others have envisioned nanorobots that will travel throughout the human body (Figure 1.8) using molecular motors and computers, treat pathogens, eliminate cancer and HIV as life-threatening conditions, reverse trauma and injury from burns and accidents, enhance mental capabilities and physical abilities, and slow down aging.[79] A common idea in these applications is the concept of *mechanosynthesis*, which is to have positional control over the site of chemical reactions.[80]

Given a description of a structure's atomic constituents and their arrangement, mecanosynthesis would require a tool that could be programmed to perform specific reactions at specific sites, namely binding each atom to its neighbors as per the specification. This tool, called an *assembler*, should be able to position atoms to within a fraction of a nanometer—a rough estimate

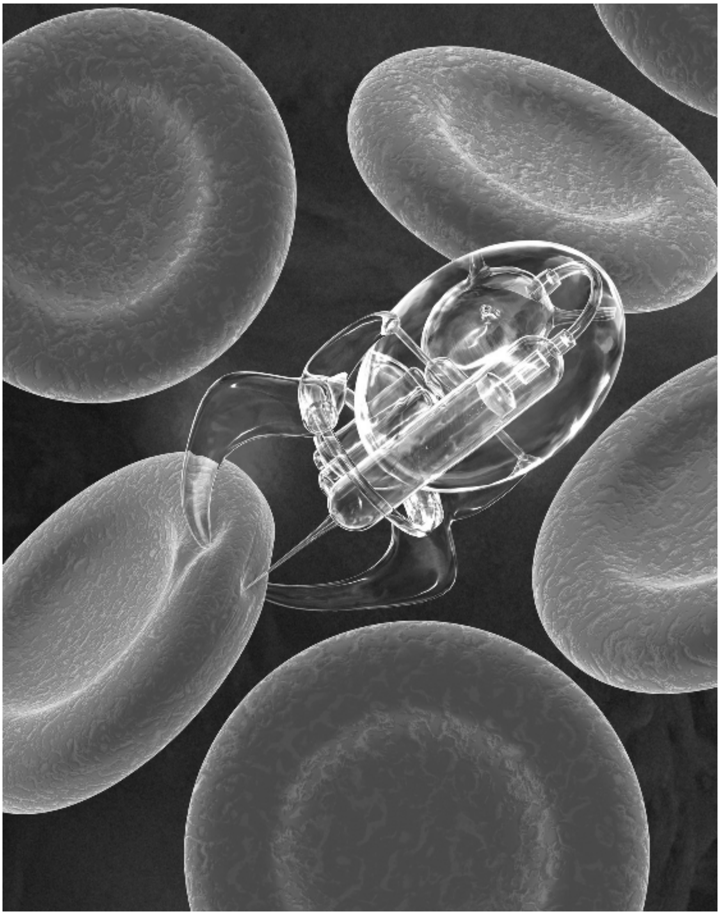

Figure 1.8 Artist's impression of a futuristic nanorobot.
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for the average size of an atomic diameter.[81] As there are by this estimate on the order of 1024 atoms in a cubic inch, a large number of rapid assemblers must be employed to assemble anything of macroscopic proportions. To gain a sense of the scales involved, an example might be useful. If one were to employ a billion such assemblers, and if each took, on average, a billionth of a second per positioning/binding operation, then a rather trivially structured and lightweight cubic inch of matter would result after about eleven days.[82] Employing a thousand assemblers that take a thousandth of a second per operation for the same task would take longer than *twice* the current age of the universe.[83]

To be feasible, then, molecular nanotechnology would need to demonstrate precise, small, fast, inexpensive, and plentiful positioning/synthesizing assemblers. A characteristic that cuts across the last two categories is that of *replication*, the notion that some degree of exponential growth in assembler number—growth that is proportional to the quantity present at any given time—may compensate for the astronomical number of operations that must be performed to assemble a macroscopic product.[84] Indeed, Drexler has claimed that an object weighing one kilogram could be assembled in less than three hours.[85]

Assemblers, as defined by Drexler, are yet to be demonstrated. Certain proponents of manmade molecular machinery also point to living cells as a proof-of-principle for the central idea of building complex microscopic structures from elementary precursors. The way in which biological systems accomplish this, however, is fundamentally different from the mechanical, "dry" approach advocated by Drexler.[86]

Nobel-Prize-winning scientist Richard Smalley has made a vocal case against self-replicating nanorobots, noting that they "will never become more than a futurist's daydream."[87] Smalley's central argument, presented as the "fat fingers" and "sticky fingers" problem, is that the attempt to position individual atoms to guide chemical reactions will fail because unwanted reactions—with other neighboring atoms—will occur. Drexler has countered that his approach involves molecules, not single atoms; furthermore, he argues that if such unwanted reactions were to happen under particular conditions, then it would be necessary to turn to other configurations of building blocks. Smalley finalizes his argument by saying to Drexler that, "in all of your writings, I have never seen a convincing argument that this list of conditions and synthetic targets that will actually work reliably with mechanosynthesis can be anything but a very, very short list."[88] In the end, however, the feasibility of assemblers is not a philosophical issue. Scientific questions are only settled by experiment, and the physical realization of Drexler's ideas will be the ultimate test of their validity.

Meanwhile, there are other obstacles in the path to molecular nanotechnology. On one hand, a number of influential researchers seem to be hostile to Drexler's ideas. If this indifference is shared by a large group of scientists, it might significantly stall technological progress towards the eventual construction of an assembler. On the other hand, even if an assembler is technically possible, other factors might hinder its development. The sum total of the decisions society makes will determine the incentives, opportunities, public interest, and risks for "build large" nanotechnology. In the end, if mechanosynthesis is ever demonstrated, social forces will likely have a substantial hand in its development.