NANOTECHNOLOGY APPLICATIONS TO TELECOMMUNICATIONS AND NETWORKING

Daniel Minoli
Managing Director
Leading-Edge Networks Incorporated
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Daniel Minoli
Managing Director
Leading-Edge Networks Incorporated
For Anna

And for my Father and Mother
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This is believed to be the first book that takes a view of nanotechnology from a telecommunications and networking perspective. Nanotechnology refers to the manipulation of materials at the atomic or molecular level. Nanotechnology is getting a lot of attention of late not only in academic settings and in laboratories around the world, but also in government and venture capitalists’ initiatives. There now is a major drive to commercialize the technology by all sorts of firms, ranging from start-ups to Fortune 100 companies.

At the start of the decade, Charles Vest, the president of MIT, observed: “We are just beginning to understand how to use nanotechnology to build devices and machines that imitate the elegance and economy of nature. The gathering nanotechnology revolution will eventually make possible a huge leap in computing power, vastly stronger yet much lighter materials, advances in medical technologies, as well as devices and processes with much lower energy and environmental costs.”

Nanotechnology is a nanometer-level bottom-up\(^1\) assembly approach that allows developers to engineer particles at the molecular level, building them up to the “right size,” with engineered functional properties. A nanometer is one billionth of a meter (a meter being about 3 ft). Bottom-up process technology provides a control mechanism over development of particles with respect to their size, shape, morphology, and surface conditions. Because of the challenges involved in working at this microscopic scale of a few nanometers, research and engineering efforts involving manipulation of components as “large” as 100 nm are typically included in the field of nanotechnology. Atoms are typically between one-tenth and one-half of a nanometer wide.

Research and development topics in nanotechnology range from molecular manipulation to nanomachines (microscopic devices that can themselves carry out tasks at the atomic or sub-atomic level). While nanomachines represent futuristic initiatives with relatively little current (commercial) achievement, nanomaterials, nanomaterial processing, nanophotonics, and nanoelectronics are already resulting (or will do so in the next 3–5 years) in usable technologies.

In this book we focus on developments and technologies that have the potential to be used (or are already being used) in communication and networking environments. Such applications include faster and smaller non-silicon-based processors, faster and smaller switches (particularly optical switches), and MEMSs (microelectromechanical

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\(^1\)In the nanotechnology field the term *bottom-up* is preferred to the (perhaps) more common English-language term *bottoms-up*. 
systems). MEMS are microscale systems (~100 µm) that include both mechanical and electrical devices integrated on a single die or chip. MOEMS are microoptical-electromechanical systems consisting of MEMS devices with integral optical components such as mirrors, lenses, filters, laser diodes, emitters or other optics. A MEMS system may include microfluidic elements, integral microelectronics or ICs, “lab-on-chip” systems, actuators, micromotors, or sensors. Efforts are already underway to create nanoscale MEMSs, also known as NEMSs.

In Chapter 1 we review the basic concepts of nanotechnology and applications. In Chapters 2 and 3 we cover supportive topics such as physics and chemistry basics (e.g., electron, atoms, atomic structures, molecules, bonded structures); electrical properties (e.g., insulators, semiconductors, conductors); and chemical bonds and reactions. Chapter 2 also provides a basic introduction to transistors, in support of the discussion to follow in Chapter 6. It turns out that while classical Newtonian mechanics can predict with precision the motions of masses ranging in size from microscopic particles to stars, it cannot predict the behavior of the particles in the atomic domain; at these dimensions quantum theory (physics) comes into play. Hence, as a spin-off of Chapters 2 and 3, in Appendices D and E we discuss some of the basic scientific principles that support quantum theory; the reader who may find these two appendices somewhat demanding may choose to skip this material and move on to the chapters that follow, which are generally self-contained. In Chapter 4 we look at nanomaterials and nanomaterial processing: Individual nanoparticles and nanostructures (e.g., nanotubes, nanowires) are discussed. Nanophotonics is discussed in Chapter 5 (e.g., nanocrystals, nanocrystal fibers). Nanoelectronics (e.g., metal nanoclusters, semiconducting nanoclusters, nanocrystals, quantum dots) is covered in Chapter 6. Both Chapters 5 and 6 provide a discussion of near-term and longer-term applications in the field of computers, telecommunications, and networking. An extensive glossary is also included. Appendix F discusses nanoinstrumentation, while Appendix G provides detailed information on quantum computing.

This book is intended as an introduction to the field of nanotechnology for telecommunications vendors, researchers, and students who want to start thinking about the potential opportunities afforded by these emerging scientific developments and approaches for the next-generation networks to be deployed 5–10 years in the future. Advanced planning is a valuable and effective exercise. When the author first joined Bell Telephone Laboratories in 1978, he was involved in planning networks 5–10 years into the future. While, recently, advanced planning and strategic development have suffered at the hand of the “next-quarter” mentality, it is indeed advantageous to plan 10 years out, only if for the reason that it takes about 10–15 years to grow a carrier (such as a CLEC, a hotspot provider, a 3G wireless operator) to turn a profit from a cold start.

As noted, this book is intended as an introduction to the field. We hope it will serve as motivation, by raising interest, to continue the line of investigation and research into the field. We have made every effort to make it relatively self-contained by discussing the introductory fundamental principles involved, and by providing an extensive glossary. Most professionals outside the field of basic sciences probably have forgotten freshman college physics and chemistry. The most
basic take-aways from these courses are summarized in the book, to facilitate the discussion of nanotechnology applications.

The reader is encouraged, after reading this text, to seek out additional books that go into greater detail. Each chapter included here can be supported by an entire book just covering each individual chapter-level topic.

Finally, it should be noted that nanotechnology is a highly active burgeoning field at this time, with (hundreds of) thousands of articles, publications, lectures, seminars, and books available. Given this plethora of research, this book is based liberally on industry sources. In this context, we have made every effort to acknowledge the source of the material we cover and provide appropriate credit thereof; we hope, with said diligence, that any unwitting omissions are strictly minimal and/or essentially inconsequential. Hence, while the actual synthesis of the topic(s) as presented here is original, the intrinsic material itself is based on the 750+ references that we cite and utilize throughout the body of the text.

Acknowledgement

I would like to thank Mr. Emile A. Minoli for contributions in Chapters 2 and 3.

The cover page shows Daniel Minoli (center front) with a slide rule next to an AM radio the student trio built based on discrete electronic components. Students Melvin Lee (left front) and Steven Lightburn (right front) part of the student trio are with Mr. Tepper (middle front), electronics teacher in a Technical Electronics Laboratory in High School in Brooklyn, NY in the fall of 1970. Two second-row students are unidentified. As this textbook shows, electronics and electronics density has come a long way in the past 35 years, and will continue to do so under the thrust of nanotechnology.

Daniel Minoli
Daniel Minoli has many years of telecom, networking, and information technology (IT) experience for end-users, carriers, academia, and venture capitalists, including work at ARPA think tanks, Bell Telephone Laboratories, ITT, Prudential Securities, Bell Communications Research (Bellcore/Telcordia), AT&T, NYU, Rutgers University, Stevens Institute of Technology, and Societe General de Financement de Quebec (1975–2001). Recently, he also played a founding role in the launching of two networking companies through the high-tech incubator Leading Edge Networks Inc., which he ran in the early 2000s: Global Wireless Services, a provider of secure broadband hotspot mobile Internet and hotspot VoIP services to high-end marinas; and InfoPort Communications Group, an optical and gigabit Ethernet metropolitan carrier supporting data center/SAN/channel extension and grid computing network access services (2001–2003). In the recent past, Mr. Minoli was involved (on behalf of a venture capitalist considering a $15 million investment) in nanotechnology-based systems using quantum cascade lasers (QCLs) for 10-μm-transmission free space optics communication systems.

An author of a number of technical references on IT, telecommunications, and data communications, he has also written columns for ComputerWorld, NetworkWorld, and Network Computing (1985–2005). He has taught at New York University (Information Technology Institute), Rutgers University, Stevens Institute of Technology, Carnegie Mellon University, and Monmouth University (1984–2003). Also, he was a Technology Analyst At-Large, for Gartner/DataPro (1985–2001); based on extensive hands-on work at financial firms and carriers, he tracked technologies and wrote around 50 distinct CTO/CIO-level technical/architectural scans in the area of telephony and data communications systems, including topics on security, disaster recovery, IT outsourcing, network management, LANs, WANs (ATM and MPLS), wireless (LAN and public hotspot), VoIP, network design/economics, carrier networks (such as metro Ethernet and CWDM/DWDM), and e-commerce. Over the years he has advised venture capitalists for investments of $150 million in a dozen high-tech companies and has acted as expert witness in a (won) $11 billion lawsuit regarding a wireless air-to-ground communication system.
CHAPTER 1

Nanotechnology and Its Business Applications

1.1 INTRODUCTION AND SCOPE

1.1.1 Introduction to the Nanoscale

Nanotechnology is receiving a lot of attention of late across the globe. The term *nano* originates etymologically from the Greek, and it means “dwarf.” The term indicates physical dimensions that are in the range of one-billionth ($10^{-9}$) of a meter. This scale is called colloquially *nanometer scale*, or also *nanoscale*. One nanometer is approximately the length of two hydrogen atoms. Nanotechnology relates to the design, creation, and utilization of materials whose constituent structures exist at the nanoscale; these constituent structures can, by convention, be up to 100 nm in size.\(^1\)\(^2\)\(^3\) Nanotechnology is a growing field that explores electrical, optical, and magnetic activity as well as structural behavior at the molecular and submolecular level. One of the practical applications of nanotechnology (but certainly not the only one) is the science of constructing computer chips and other devices using nanoscale building elements. This book is a basic practical survey of this field with an eye on computing and telecom applications.

The nanoscale dimension is important because quantum mechanical (non-Newtonian) properties of electronics, photons, and atoms are evident at this scale. Nanoscale structures permit the control of fundamental properties of materials without changing the materials’ chemical status. Nanostructure, such as nanophotonic devices, nanowires, carbon nanotubes, plasmonics devices, among others, are planned to be

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\(^1\) Measures are relatives; hence, one can talk about something being 1000 nanometers (nm), or 1 microm (\(\mu\)m), of 10,000 Angstroms (\(\AA\)). A micron is a unit of measurement representing one-millionth of a meter and is equivalent to a micrometer. An angstrom is a unit of measurement indicating one-tenth of a nanometer, or one ten-billionth of a meter (often used in physics and/optics to measure atoms and wavelengths of light).

\(^2\) Atoms are typically between 0.1 and 0.5 nm wide.

\(^3\) For comparison, a human hair is between 100,000 and 200,000 nm in diameter and a virus is typically 10 nm wide.
incorporated into telecommunication components and into microprocessors in the next few years, leading to more powerful communication systems and computers—these nanostructures are discussed in the chapters that follow. Nanotechnology is seen as a high-profile emerging area of science and technology. Proponents prognosticate that, in the next few years, nanotechnology will have a major impact on society. Recently, Charles Vest [1], the president of MIT, observed: “The gathering nanotechnology revolution will eventually make possible a huge leap in computing power, vastly stronger yet much lighter materials, advances in medical technologies, as well as devices and processes with much lower energy and environmental costs.” There already are an estimated 20,000 researchers worldwide working in nanotechnology today.

In the sections that follow in this chapter we preliminarily answer questions such as: What is nanotechnology? What are the applications of nanotechnology? What is the market potential for nanotechnology? What are the global research activities in nanotechnology? Why would a practitioner (the likely reader of this book), need to care? We then position the reader for the balance of the book, which looks at the nanotechnology topic from an application, and, more specifically, from a telecom- and networking-perspective angle.

While many definitions for nanotechnology exist, the National Nanotechnology Initiative (NNI4), calls an area of research, development, and engineering “nanotechnology” only if it involves all of the following [2]:

1. Research and technology development at the atomic, molecular, or macromolecular levels, in the length scale of approximately 1- to 100-nm range
2. Creating and using structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size
3. Ability to control or manipulate matter on the atomic scale

Hence, nanotechnology can be defined as the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new properties and functions. Nanotechnology can be described as the precision-creation and precision-manipulation of atomic-scale matter [3]; hence, it is also referred to as precision molecular engineering. Nanotechnology is the application of nanoscience to control processes on the nanometer scale, that is, between 0.1 and 100 nm [4]. The field is also known as molecular engineering or molecular nanotechnology (MNT). MNT deals with the control of the structure of matter based on atom-by-atom and/or molecule-by-molecule engineering; also, it deals with the products and processes of molecular manufacturing [5]. The term engineered nanoparticles describes particles that do not occur naturally; humans have been putting together different materials throughout time, and now with nanotechnology they are doing so at the nanoscale.

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4The National Nanotechnology Initiative (NNI) is a U.S. government-funded R&D and commercialization initiative for nanoscience and nanotechnology. The 21st Century Nanotechnology Research and Development Act of 2003 put into law programs and activities supported by the initiative.
As it might be inferred, nanotechnology is highly interdisciplinary as a field, and it requires knowledge drawn from a variety of scientific and engineering arenas: Designing at the nanoscale is working in a world where physics, chemistry, electrical engineering, mechanical engineering, and even biology become unified into an integrated field. “Building blocks” for nanomaterials include carbon-based components and organics, semiconductors, metals, and metal oxides; nanomaterials are the infrastructure, or building blocks, for nanotechnology.

The term nanotechnology was introduced by Nori Taniguchi in 1974 at the Tokyo International Conference on Production Engineering. He used the word to describe ultrafine machining: the processing of a material to nanoscale precision. This work was focused on studying the mechanisms of machining hard and brittle materials such as quartz crystals, silicon, and alumina ceramics by ultrasonic machining. Years earlier, in a lecture at the annual meeting of the American Physical Society in 1959 (There’s Plenty of Room at the Bottom) American Physicist and Nobel Laureate Richard Feynman argued (although he did not coin or use the word nanotechnology) that the scanning electron microscope could be improved in resolution and stability, so that one would be able to “see” atoms. Feynman proceeded to predict the ability to arrange atoms the way a researcher would want them, within the bounds of chemical stability, in order to build tiny structures that in turn would lead to molecular or atomic synthesis of materials [6]. Based on Feynman’s idea, K. E. Drexler advanced the idea of “molecular nanotechnology” in 1986 in the book Engines of Creation, where he postulated the concept of using nanoscale molecular structures to act in a machinelike manner to guide and activate the synthesis of larger molecules. Drexler proposed the use of a large number (billions) of roboticlike machines called “assemblers” (or nanobots) that would form the basis of a molecular manufacturing technology capable of building literally anything atom by atom and molecule by molecule. Quite a bit of work has been done in the field since the publication of the book, although the concept of nanobots is still speculative.5

At this time, an engineering discipline has already grown out of the pure and applied science; however, nanoscience still remains somewhat of a maturing field. Nanotechnology can be identified precisely with the concept of “molecular manufacturing” (molecular nanotechnology) introduced above or with a broader definition that also includes laterally related subdisciplines [7]. This text will encompass both perspectives; the context should make clear which of the definitions we are using. The nanoscale is where physical and biological systems approach a comparable dimensional scale. A basic “difference” between systems biology and nanotechnology is the goal of the science: systems biology aims to uncover the fundamental operation of the cell in an effort to predict the exact response to specific stimuli and genetic variations (has scientific discovery focus); nanotechnology, on the other hand, does not attempt to be so precise but is chiefly concerned with useful design

5The possibility of building tiny motors on the scale of a molecule appears to have been brought one step closer of late: researchers recently have described how they were able—using light or electrical stimulation—to cause a molecule to rotate on an axis in a controlled fashion, similar to the action of a motor [8].
Figure 1.1 depicts the current evolution of various disciplines toward a nanoscale focus. Figure 1.2 places “nano” in the continuum of scales, while Figure 1.3 depicts the size of certain natural and manmade objects (Table 1.1, loosely based on [10] depicts additional substances, entities, and materials). A nanometer is about the width of four silicon atoms (with a radius of 0.13 nm) or two hydrogen atoms (radius of 0.21 nm); also see Figure 1.4. Figure 1.5 depicts an actual nanostructure. For comparison purposes, the core of a single-mode fiber is 10,000 nm in diameter, and a 10-nm nanowire is 1000 times smaller than (the core of) a fiber. The nanoscale exists at a boundary between the “classical world” and the “quantum mechanical world”; therefore, realization of nanotechnology promises to afford revolutionary new capabilities. In this context, the following quote is noteworthy [11]:

When the ultimate feature sizes of nanoscale objects are approximately a nanometer or so, one is dealing with dimensions an order of magnitude larger than the scale exploited by chemists for over a century. Synthetic chemists have manipulated the constituents, bonding, and stereochemistry of vast numbers of molecules on the angstrom scale, and physical and analytical chemists have examined the properties of these molecules. So what is so special about the nanoscale? There are many answers to this question, possibly as many as there are people who call themselves nanoscientists or nanotechnologists. A particularly intriguing feature of the nanoscale is that this is the scale on which
biological systems build their structural components, such as microtubules, microfilaments, and chromatin. The associations maintaining these and the associations of other cellular components seem relatively simple when examined by high-resolution structural methods, such as crystallography or Nuclear Magnetic Resonance—shape complementarity, charge neutralization, hydrogen bonding, and hydrophobic interactions. A key property of biological nanostructures is molecular recognition, leading to self-assembly and the templating of atomic and molecular structures. Those who wish to create defined nanostructures would like to develop systems that emulate this behavior.
TABLE 1.1 Scale of Some Substances and Entities

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Planck length (the smallest measurement of length that has meaning)</td>
<td>$1.616 \times 10^{-35}$ m</td>
</tr>
<tr>
<td>One fermi (aka a femtometer: a unit suitable to express the size of</td>
<td>$1 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>atomic nuclei)</td>
<td></td>
</tr>
<tr>
<td>Diameter of proton</td>
<td>$1.66 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>Classical diameter of neutron</td>
<td>$2.2 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>Diameter of the nucleus of a helium atom</td>
<td>$3.8 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>Classical diameter of an electron</td>
<td>$5.636 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>Diameter of the nucleus of an aluminum atom</td>
<td>$7.2 \times 10^{-15}$ m</td>
</tr>
<tr>
<td>Diameter of the nucleus of a gold atom</td>
<td>$1.4 \times 10^{-14}$ m</td>
</tr>
<tr>
<td>Wavelength of $\gamma$ rays</td>
<td>$1 \times 10^{-12}$ m</td>
</tr>
<tr>
<td>Diameter of flourine ion</td>
<td>$3.8 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Most likely distance from electron to nucleus in a hydrogen atom (bohr radius)</td>
<td>$5.29 \times 10^{-11}$ m</td>
</tr>
<tr>
<td>Distance between bonded hydrogen atoms</td>
<td>$7.41 \times 10^{-11}$ m</td>
</tr>
<tr>
<td>One angstrom</td>
<td>$1 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Van der Waals radius of hydrogen atoms (max distance between atoms that are not bonded)</td>
<td>$1.2 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Resolution (size of smallest visible object) of a transmission electron microscope</td>
<td>$2 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Distance between bonded iron atoms</td>
<td>$2.48 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Van der Waals radius of potassium atoms (max distance between atoms that are not bonded)</td>
<td>$2.75 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Diameter of water molecule</td>
<td>$3 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Distance between base pairs in a DNA molecule</td>
<td>$3.4 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Diameter of xenon ion</td>
<td>$3.8 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>Distance between bonded cesium atoms</td>
<td>$5.31 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>One nanometer</td>
<td>$1 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Size of glucose molecule</td>
<td>$1.5 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Diameter of DNA helix</td>
<td>$2 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Diameter of insulin molecule</td>
<td>$5 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Diameter of a hemoglobin molecule</td>
<td>$6 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Thickness of cell wall (Gram-negative bacteria)</td>
<td>$1 \times 10^{-8}$ m</td>
</tr>
<tr>
<td>Size of typical virus</td>
<td>$7.5 \times 10^{-8}$ m</td>
</tr>
<tr>
<td>Thickness of gold leaf</td>
<td>$1.25 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>Diameter of smallest bacteria</td>
<td>$2 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>Resolution (size of smallest visible object) of an optical microscope</td>
<td>$2 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>Length of the smallest transistor in a Pentium 3 chip</td>
<td>$2.6 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>Wavelength of violet light</td>
<td>$4.1 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>Wavelength of red light</td>
<td>$6.8 \times 10^{-7}$ m</td>
</tr>
<tr>
<td>One micrometer (micron)</td>
<td>$1 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Size of typical bacterium</td>
<td>$1 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Diameter of average human cell nucleus</td>
<td>$1.7 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Thickness of typical red blood cell</td>
<td>$2.4 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Length of the smallest transistor in an Intel 286 chip</td>
<td>$3 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Diameter of typical capillary</td>
<td>$4 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Length of the smallest transistor in an Intel 8086 chip</td>
<td>$6 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Diameter of a single yeast organism</td>
<td>$7 \times 10^{-6}$ m</td>
</tr>
</tbody>
</table>
INTRODUCTION AND SCOPE

TABLE 1.1 (Continued)

<table>
<thead>
<tr>
<th>Description</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of a single yeast organism</td>
<td>$7 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Diameter of typical red blood cell</td>
<td>$8.4 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>Diameter of average cell in human body</td>
<td>$1 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Size of a grain of talcum powder</td>
<td>$1 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Length of the smallest transistor in the first 6502 chips</td>
<td>$1.6 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Length of the smallest transistor in an Intel 4004 (the first microprocessor)</td>
<td>$2 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Diameter of a small grain of sand</td>
<td>$2.0 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Diameter of a typical human hair</td>
<td>$2.5 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Thickness of typical sheet of paper</td>
<td>$8.38 \times 10^{-5}$ m</td>
</tr>
<tr>
<td>Optical resolution: minimum size of object that can resolved by unaided eye</td>
<td>$1 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Size of a grain (crystal) of salt</td>
<td>$1 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Diameter of a period printed at end of typical sentence</td>
<td>$3 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Diameter of the most common type of optical fiber (including cladding)</td>
<td>$3.7 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Size of largest known bacterium</td>
<td>$7.5 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Diameter of the head of the average pin</td>
<td>$1.7 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>Diameter of a large grain of sand</td>
<td>$2 \times 10^{-3}$ m</td>
</tr>
</tbody>
</table>

~ 125 Carbon atoms (diam. = 1.8 Å)
~ 15 Hydrogen atoms (diam. = 4.1 Å)

FIGURE 1.4 What one gets at the nanometer scale.

1.1.2 Plethora of Potential Applications

Nanotechnology is an enabling and potentially disruptive technology that can address requirements in a large number of industries. Developments in nanoscale science and engineering promise to impact, if not revolutionize, many fields and lead to a new technological base and infrastructure that can have major impact on telecom, computing, and information technology (in the form of optical networking/nanophotonics, nanocomputing/nanoelectronics, and nanostorage); health care and biotechnology; environment; energy; transportation; and space exploration, among
Nanotechnology will enable manufacturers to produce computer chips and sensors that are considerably smaller, faster, more energy efficient, and cheaper to manufacture than their present-day counterparts. Specifically, nanotechnology is now giving rise to many new applications such as quantum computing, surface and materials modification, novel separations, sensing technologies, diagnostics, and human biomedical replacements.

The technology will also open up completely new areas of research because, as already stated, matter behaves differently at this physical scale. Interfacing materials with biology is widely believed to be the exciting new frontier for nanotechnology. For example, the National Aeronautics and Space Administration (NASA) foresees a zone of convergence between biotechnology, nanotechnology, and information technology; consequently, NASA, is funding basic nanoscience, as well as work on nanostructured materials, nanoelectronics, and research into sensors. As another example, the U.S. Army is funding soldier nanotechnologies to develop products to substantially reduce the weight that soldiers must carry while increasing physical protection.

Nanomaterials give impetus to new applications of the (nano)technology because they exhibit novel optical, electric, and/or magnetic properties. The first generation of nanotechnology (late 1990s–early 2000s) focused on performance enhancements to existing micromaterials; the second generation of nanotechnology (slated for 2006–2007) will start employing nanomaterials in much more significant and radical ways. Industry observers assert that nanotechnological advances are essential...