CHAPTER 1

Big Picture and Principles of the Small World

Nanotechnology means putting to use the unique physical properties of atoms, molecules, and other things measuring roughly 0.1–1000 nm. We are talking about engineering the smallest-ever structures, devices, and systems.

Nanotechnology is also a promise.

A big one. Nobel laureates, novelists, and news anchors alike tell us on a daily basis that nanotechnology will completely change the way we live. They have promised us microscopic, cancer-eating robots swimming through our veins! Self-cleaning glass! Digital threads! Electronic paper! Palm-sized satellites! The cure for deafness! Molecular electronics! Smart dust! What the heck *is* smart dust—and when can we get our hands on some? A promise is a promise. . .

Such things are actually down the road. Nanotechnology has been hyped by techies who cannot wait to order a wristwatch with the entire Library of Congress stored inside; while others bespeak the hysteria of rapidly self-replicating gray goo. Much that is *nano* is burdened with overexpectations and misunderstanding. As usual, the reality lives somewhere between such extremes. Nanotechnology is like all technological development: inevitable. It is not so much a matter of what remains to be seen; the fun question is, who will see it? Will we? Will our children? Their children? Turns out, we will all get to see some. Nanotechnology is already changing the way we live, and it is just getting started.

The "nano" from which this relatively new field derives its name is a prefix denoting 10^{-9}. "Nano" comes from *nanos*, a Greek word meaning dwarf. In the case of nanotechnology, it refers to things in the ballpark of one-billionth of a meter in size. When Albert Einstein was in graduate school in 1905, he took experimental data on the diffusion of sugar in water and showed that a single sugar molecule is about 1 nm in diameter. Prefixes can be applied to any unit of the International System of Units (SI) to give multiples of that unit. Some of the most common prefixes for the various powers of 10 are listed in Table 1.1.

TABLE 1.1 Some Prefixes for SI Units

yotta (Y)	10^{24}	1 septillion
zetta (Z)	10^{21}	1 sextillion
exa (E)	10^{18}	1 quintillion
peta (P)	10^{15}	1 quadrillion
tera (T)	10^{12}	1 trillion
giga (G)	10^{9}	1 billion
mega (M)	10^{6}	1 million
kilo (k)	10^{3}	1 thousand
hecto (h)	10^{2}	1 hundred
deka (da)	10	1 ten
deci (d)	10^{-1}	1 tenth
centi (c)	10^{-2}	1 hundredth
milli (m)	10^{-3}	1 thousandth
micro (μ)	10^{-6}	1 millionth
nano (n)	10^{-9}	1 billionth
pico (p)	10^{-12}	1 trillionth
femto (f)	10^{-15}	1 quadrillionth
atto (a)	10^{-18}	1 quintillionth
zepto (z)	10^{-21}	1 sextillionth
yocto (y)	10^{-24}	1 septillionth

The word “nanotechnology” was first used in 1974 by Norio Taniguchi in a paper titled “On the Basic Concept of Nano-Technology” (with a hyphen) (Taniguchi, 1974). He wrote:

> In the processing of materials, the smallest bit size of stock removal, accretion or flow of materials is probably of one atom or one molecule, namely 0.1–0.2 nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm. . . .“Nano-technology” mainly consists of the processing. . . separation, consolidation and deformation of materials by one atom or one molecule.

By the 1980s, people were regularly using and spreading the word “nanotechnology.”

The late Richard Smalley (Figure 1.1), who shared the 1996 Nobel Prize in Chemistry with Harry Kroto and Robert Curl, was a champion of the nanotech cause. In 1999 he told Congress that “the impact of nanotechnology on the health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering and manmade polymers” (House of Representatives, 1999). Many scientists share Smalley’s bullish assessment.

Nanotechnology has ambitiously been called the next industrial revolution, a wholly different approach to the way human beings rearrange matter. People have always tinkered with what the earth has to offer—there is nothing else with which to work. Technology is in many respects just the rearrangement of chunks of the Earth to suit our needs and our wants. And the Earth is nothing more than atoms. Ever since we dwelled in caves, we have

FIGURE 1.1 Richard Smalley. Until 1985, graphite and diamond were believed the only naturally occurring forms of carbon. Then Dr. Smalley, Harold Kroto, James Heath, Sean O'Brien, and Robert Curl discovered another one. It was a soccer-ball-type arrangement they called buckminsterfullerenes ("buckyballs," for short) after Richard Buckminster Fuller, the renowned architect credited with popularizing the geodesic dome. Similar molecules were soon discovered, including nanotubes. These new forms of carbon are called fullerenes. (Photo used with permission of Dr. Richard E. Smalley and Rice University.)

put atoms over fires to heat them, bashed them against rocks to regroup them, and swallowed them for lunch. We just did not know about them, and we certainly could not see them, nor control them one at a time.

Those days are over.

1.1 UNDERSTANDING THE ATOM: *EX NIHILO NIHIL FIT*

Take a block of gold. If we slice the block into two, it is still gold. Half it again, and again, and again—still gold. But how many times can we divide the chunk and still have gold? And is it made up of *only* gold, or is there also empty space in the block?

In the fifth century B.C., Greek philosophers Democritus (Figure 1.2) and his teacher, Leucippus, were asking questions like these. They posited that all matter was composed of undividable particles called *atomos*, which in Greek means "unbreakable" or "not sliceable." These particles were completely solid, homogeneous, and varied in size, shape, and weight. Between the atoms was void, Democritus said. The famous expression, *ex nihilo nihil fit* (nothing comes from nothing) was his. Although he is credited with writing about 60 books on his theories, none survived.

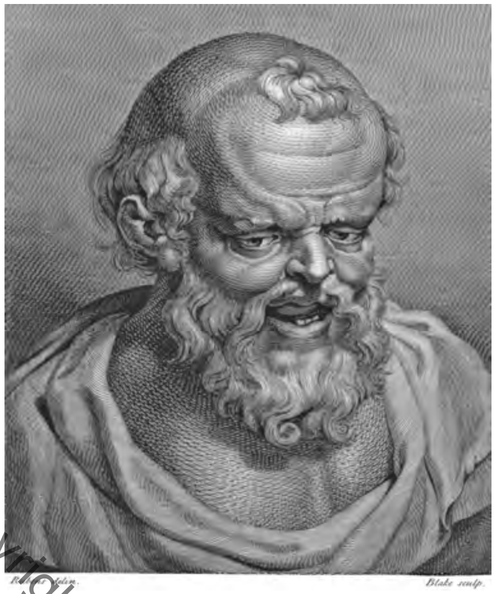

FIGURE 1.2 Greek philosopher Democritus. In the fifth century, he proposed the general idea of atoms, or *atomos*, the Greek word for "unbreakable." (Artist unknown, English eighteenth century Democritus, from *Essays on Physiognomy*, Vol. I by Johann Kaspar Lavater [London: John Murray et al., 1792] engraving and letterpress text, 19.5 × 20.3 cm [plate], 33.6 × 27.0 cm [page]; National Gallery of Victoria Library, Gift of John Cotterell, 1952, National Gallery of Victoria, Melbourne, Australia.) (With permission from National Gallery of Victoria, Melbourne, Australia.)

Plato (ca. 427–347 B.C.) and Aristotle (384–322 B.C.) disagreed with the atom idea and stuck with the prevailing belief that all matter was composed of the four basic elements: earth, water, air, and fire. Epicurus (341–270 B.C.), however, adopted "atomism" as the foundation of his teachings and wrote hundreds of books on the topic. These, like Democritus' works, were lost. But the idea was not, and a Roman named Titus Lucretius Carus (96–55 B.C.) wrote poetry extolling atomism. These writings were unpopular with the Romans and later considered atheistic by many Christians. Carus' books of poetry, unlike the writings of his predecessors, were saved and passed on. French philosopher Pierre Gassendi (1592–1655) read these books and spread the word, penning persuasive treatises on atomism. But the writings were just that—words. His were convincing arguments, but there was no proof.

Robert Boyle (1627–1691), a British scientist, read Gassendi's work and was interested in it. He later provided the arguments that would be the first in a string of physical proofs: Boyle's law. This law states that there is an inverse relationship between the pressure of a gas and its volume (so long as the temperature and the quantity of the gas do not change). The existence of atoms explains this behavior. The pressure in a container of gas is caused by tiny particles (atoms) colliding over and over again with the container walls, exerting a force. If you make the volume of a container larger, the particles collide with the walls less frequently, and the pressure decreases.

Next to come was the French chemist Louis Proust (1754–1826). Proust noticed that copper carbonate—be it native or prepared in a lab—always broke down into the same proportions of copper, carbon, and oxygen by mass. Like Boyle's law, Proust's law of definite proportions jived well with Democritus' concept of indivisible pieces of matter.

Building on the ideas of those who came before him, it would be John Dalton (1766–1844) who at last set the record straightest. Dalton was not formally schooled past the age of 12. (In fact, he began teaching at that age!) It would be Dalton who, in experiments with carbon monoxide and carbon dioxide, realized that one of the gases had one oxygen atom while the other had two oxygen atoms. He eventually expanded Proust's law of definite proportions into a law of multiple proportions. Molecules, Dalton found, were made from fixed numbers of different atoms. Elements combine in ratios of small whole numbers. While carbon and oxygen can react to form CO or CO_2, they cannot form $CO_{2.6}$. As for the elements everyone had been trying to get to the bottom of—well, those were atoms. Different elements are just different atoms with different masses. Modern atomic theory had been established.

Our understanding of the atom has since been refined by the likes of Ernest Rutherford, Niels Bohr, Albert Einstein, and countless others. We are definitely not finished understanding yet. *Ex nihilo nihil fit*—nothing comes from nothing, and the opposite is also true: everything comes from something. The modern model of the atom did not manifest out of thin air. It is the culmination of centuries of work done by creative and diligent thinkers, and those soon to follow.

The significance of atoms cannot be overstated: their form, behavior, and relationships with one another can be used to explain much of the universe. *You* are atoms. So is everything else. Think about a carbon atom in a neuron in your brain, an atom you are using this very second to help you read this sentence and understand it. That same atom was likely once part of an asteroid, then a tree, then a piece of fruit, then maybe a dinosaur, then dirt—on down the line until eventually you came to borrow it for a while.

BACK-OF-THE-ENVELOPE 1.1

Democritus said matter was composed of undividable particles called *atomos*, Greek for "unbreakable." Was he right?

No, atoms are indeed divisible; however, to split one is a messy endeavor and they do not stay divided for long. A process of splitting atoms into smaller pieces is nuclear fission. This process releases tremendous amounts of energy—used in nuclear weapons and nuclear power generation.

Okay, so if atoms can be broken down into smaller parts, will picotechnology and femtotechnology be next?

During fission (and fusion also), certain subatomic particles are released but stable atoms are reformed immediately. Subatomic things—neutrons, protons, electrons—are of great consequence, and as our level of understanding about them deepens, entirely new technological possibilities will emerge. Still, picotechnology and femtotechnology do not make sense in the way that nanotechnology does. The nanoscale is the realm of the atom. With today's technology, you cannot build anything that lasts with smaller stuff. Atoms represent a fundamental frontier. Nanotechnology is not just another step in an ongoing technological trend toward miniaturization. We have reached a boundary.

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the *atomic fact* or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.
>
> RICHARD FEYNMAN, 1963

The composition and behavior of this most important unit of matter have been completely rethought and refined many times over. Two examples of early atom models are shown in Figure 1.3. J. J. Thompson suggested that the atom was a volume of positive charge embedded with negatively charged electrons similar to seeds in a watermelon. Experiments by Ernest Rutherford in 1911 disproved this model and suggested that there must be a concentration of positive charges in the center of the atom, which he called the nucleus, around which the electrons moved in stable orbits much like planets orbiting the Sun. This model was later refined by Niels Bohr, Werner Heisenberg, and others into an atom looking more like the one depicted in Figure 1.4.

Here is what we understand about the atom:

The nucleus occupies the center. It is made of a dense packing of protons and neutrons. As their names indicate, protons have a positive charge and neutrons have a neutral charge. The two particles weigh about the same. Neutrons hold the nucleus together because without them the positively charged protons would repulse each other and the nucleus would break up. The nucleus contains almost all the atom's mass. Negatively charged electrons in

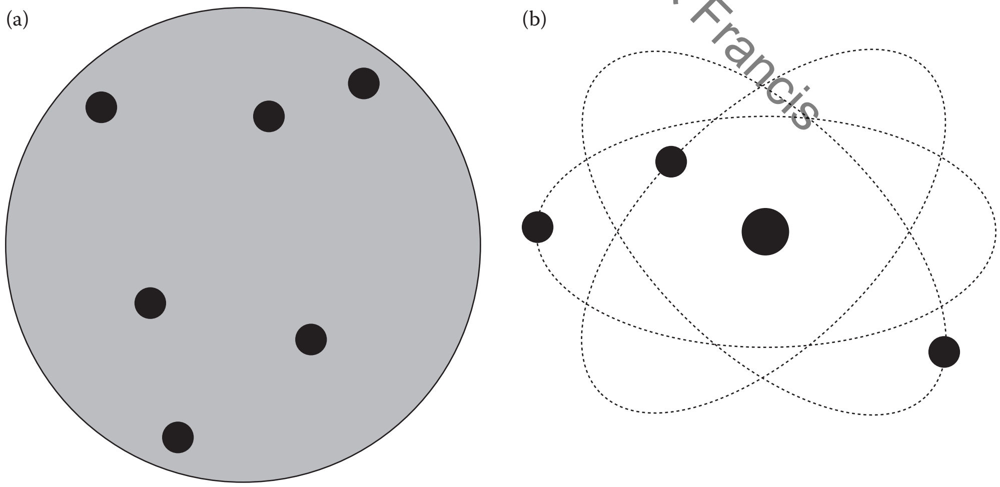

FIGURE 1.3 Early attempts to model the atom. J. J. Thompson's model was that of a positively charged volume embedded with electrons like watermelon seeds (a). Later, Ernest Rutherford hit upon the idea of a nucleus and electrons that orbited it like planets around the Sun (b).

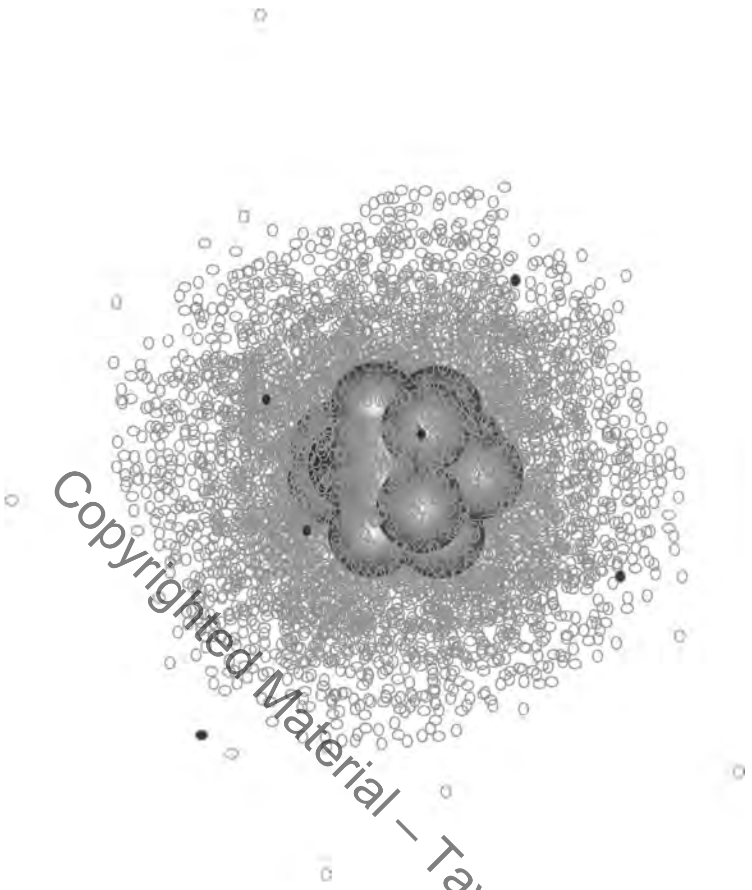

FIGURE 1.4 The atom. The building block of the universe, an atom has a positively charged centralized mass called the nucleus, which is a cluster of neutrons (having no electrical charge) and protons (having positive charge). Negatively charged electrons in perpetual motion enclose the nucleus. In this depiction, the empty dots represent locations where electrons are likely to be found, mostly near the nucleus, and the black dots are locations of the electrons at a particular instant in time.

perpetual motion enclose the nucleus. Electrons are most likely to be found within regions of space called orbitals. These orbitals have differing shapes and sizes, depending on how many electrons there are and how much energy they have. In the case of the simplest atom, hydrogen, which has only one electron, the shape of this orbital is a sphere.

Now consider this: we are the first generation in the history of the world to look right at atoms, to pick them up one at a time, and to put them back down where we like.

Stop! Go back, go back. Reread that last sentence. It may have been too easily swallowed whole. Without tasting anything. Without sliding the i-n-d-i-v-i-d-u-a-l atoms around on your tongue like caviar and bursting them one by one between your molars.

Atoms. Mmmmmmmm.

To get a feel for the significance of this achievement, think of it this way: if you were to take an apple and make it as big as the Earth, then the original apple would be the size of an atom in the earth-sized apple.

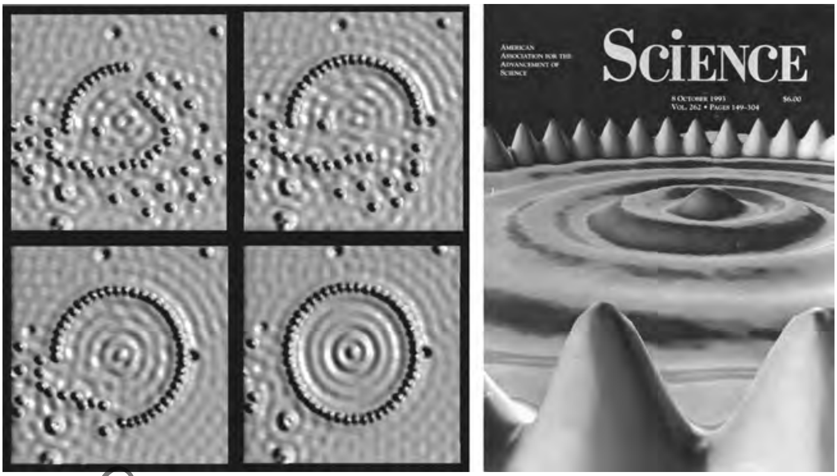

FIGURE 1.5 IBM's Quantum Corral. In 1993, a ring of 48 iron atoms was arranged one at a time (four steps are shown) on a copper surface using the tip of a low-temperature STM. (We will learn more about the STM in Chapters 5 and 6.) The STM was then used to capture an image of the ring, which measures about 14.3 nm across. The iron atoms confine some of the copper's surface electrons, and this barrier forces the electrons into quantum states, visible as concentric standing waves inside the corral. A three-dimensional rendering of this astounding achievement appeared on the cover of *Science*. (Corral image originally created by IBM Corporation. Journal cover from *Science* Vol. 262, No. 5131, October 8, 1993. Reprinted with permission from AAAS.)

We can see and move atoms using the scanning tunneling microscope (STM). This is "bottom-up" engineering, creating something by arranging atoms one by one exactly where we want them, as opposed to "top-down" engineering, where a piece of raw material is drilled, milled, chipped away—reformed—until what is left is what is needed. Nanotechnology is the epitome of bottom-up engineering.

The STM belongs to a family of versatile, small systems tools called scanning probe microscopes. Figure 1.5 shows a ring of atoms arranged and imaged using an STM. This tool is a great example of a small system that bridges the gap between size scales—it has microscale parts used to do nanoscale work. We learn more about the STM later.

BACK-OF-THE-ENVELOPE 1.2

How much does an atom weigh?

This prompts another question: which kind of atom? The periodic table has 116 different elements in it. Each atom has a different number of protons and neutrons, and so their atomic masses are different. Also, since atoms are so minute, we often perform atomic computations using large groups of them. One particularly useful group is called a mole (mol), which consists of Avogadro's number, N_A, of whatever one is counting—atoms, molecules, apples. Avogadro's number is 6.02×10^{23}. It is defined as the number of carbon-12 atoms in exactly 12 g. Therefore, 12 g/mol is the atomic mass of carbon-12. The atomic mass of lead is 207 g/mol, and that of aluminum is 27 g/mol.

To determine the mass of a single atom, divide the atomic mass by Avogadro's number:

$$\text{Mass of 1 aluminum atom} = \frac{27\,\text{g/mol}}{N_A} = 4.5 \times 10^{-23}\,\text{g/atom}$$

So, an aluminum atom weighs 45 yoctograms.

BACK-OF-THE-ENVELOPE 1.3

Proust's work with copper carbonate showed it always broke down in a specific ratio, by mass. This led him to draw his historic conclusion, the law of definite proportions, and furthered our understanding of atoms. What is the ratio Proust measured for this particular substance?

The chemical formula of copper(II) carbonate is $CuCO_3$. Its molecular weight is

$$63.55\,\text{g/mol} + 12.01\,\text{g/mol} + 3(16.00\,\text{g/mol}) = 123.56\,\text{g/mol}$$

The fractional composition by mass of each element is therefore

$$\text{Cu: } \frac{63.55\,\text{g/mol}}{123.56\,\text{g/mol}} = 0.5143$$

$$\text{O: } \frac{3(16.00\,\text{g/mol})}{123.56\,\text{g/mol}} = 0.3885$$

$$\text{C: } \frac{12.01\,\text{g/mol}}{123.56\,\text{g/mol}} = 0.0972$$

Dividing through by the smallest fraction (that of C) gives the relative elemental composition by mass:

Cu: 5.2912
O: 3.9967
C: 1.0000

These are the very same ratios Proust measured over two centuries ago: 5.3 parts copper, 4 parts oxygen, and 1 part carbon.

First, however, let us introduce the first in nanotechnology's cast. If nanotechnology can be said to have a history, then it probably starts with Richard Feynman.

1.2 NANOTECHNOLOGY STARTS WITH A DARE: FEYNMAN'S BIG LITTLE CHALLENGES

Perhaps it was Richard Feynman's (Figure 1.6) enigmatic reputation. Not quite the scientific celebrity he would soon become—he had not won his Nobel Prize for quantum electrodynamics yet—the physicist's ideas and motives were perhaps still enshrouded in enough mystery to keep his colleagues on their toes. When the American Physical Society asked

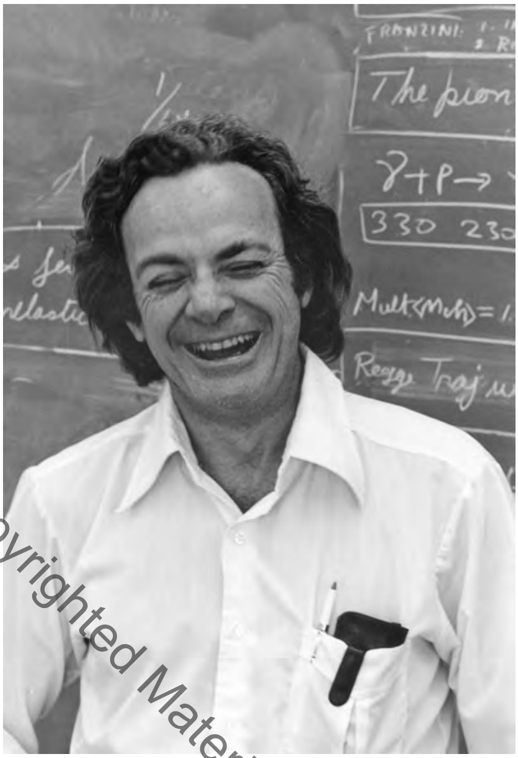

FIGURE 1.6 Richard Feynman. His prophetic talk, “There’s Plenty of Room at the Bottom,” is credited with inspiring the development of nanotechnology. Feynman was a charismatic teacher (and student) of physics. (Photograph by Floyd Clark, courtesy of Caltech Archives, used with permission of Melanie Jackson Agency, LLC.)

him to serve as the featured speaker during its annual banquet, he accepted. The Society’s 1959 meeting was in Pasadena, California—Feynman’s backyard. It was hosted by Caltech on a warm December 29th, a few days before the New Year, a fitting time of the year for predicting the future.

The banquet was downtown at Pasadena’s Huntington-Sheraton. For $4.50 a plate, roughly 300 members of the scientific community ate and drank together. Among the topics of discussion was the title of their guest speaker’s talk: “There’s Plenty of Room at the Bottom” (Feynman, 1960). Some were embarrassed to admit they did not know what the title meant. Had Feynman selected a topic over their heads? Others guessed that Feynman was going to tell them about how there were plenty of lousy jobs left for the taking in the physics industry. When Society President George Uhlenbek welcomed Dr. Feynman to the stage amid the clinking of busy silverware, attendees readied themselves for some kind of elaborate put-on, the kind only Dr. Feynman could conjure.

However, Feynman was utterly serious. And he was talking about a field for which a name had yet to be coined. He was talking about nanotechnology.

Feynman had spent a lot of his own time mulling over the possibilities of small things. Small as in atoms. His tone suggested something akin to disappointment and at the same time hope. His questions: Why has someone not already done this? Why have we yet to think big about the very small? I will tell you what needs to be done, and the best part is: it is doable!

"Now the name of the talk is 'There's *Plenty* of Room at the Bottom'—not just 'There's Room at the Bottom,'" Feynman said. "I will not discuss how we are going to do it, but only that it is possible in principle—in other words, what is possible according to the laws of physics. I am not inventing antigravity, which is possible someday only if the laws are not what we think. I am telling you what could be done if the laws *are* what we think; we are not doing it simply because we haven't gotten around to it" (Feynman, 1960).

In his speech, he would pose challenge after challenge—such as writing the entire 24 volumes of the *Encyclopedia Britannica* on a pinhead, making an electron microscope that could see individual atoms, or building a microscopic computer—and then he would outline the parameters of that challenge. Feynman made many references to examples in nature such as DNA and the human brain where miniaturization was already wildly successful.

Much of what he said has since come to fruition and is commonplace, although in a year when computers took up entire rooms it all sounded quite like fantasy. He explained many of the physical issues and challenges inherent in moving to the small scale, including quantum behavior, van der Waals forces, heat transport, and, of course, fabrication. Still he was intrepid: "I am not afraid to consider the final question as to whether, ultimately—in the great future—we can arrange atoms the way we want; the very *atoms*, all the way down!"

In parting, Feynman offered a pair of $1000 prizes. One was for the first person to create an operating electrical motor no larger than 1/64 in.^{3}. To Feynman's dismay, William McLellan tediously did just that, using tweezers and a microscope, within 4 months of the speech. The motor had 13 parts, weighed 250 μg, and rotated at 2000 rpm. Feynman had been home from his honeymoon less than a week when he had to explain to his wife the promise he had made. They were not exactly financially prepared to divvy out prize money, but he did. (The motor, on display at Caltech, no longer spins.)

THE PRESCIENT PHYSICIST: RICHARD FEYNMAN (1918–1988)

Richard Feynman (Figure 1.6) was a zany, independent thinker who restlessly challenged anything he could not prove to himself. As a boy, he often disregarded his textbooks so as to derive the formulas in his own way—sometimes sloppily, and yet sometimes more elegantly than the established derivations. By ignoring so much of what had been posited by his scientific predecessors, he discovered yet untried ways to unravel the thorny conundrums of quantum physics and was for his contributions to the field awarded the 1965 Nobel Prize in Physics.

Feynman was a member of the exclusive Manhattan Project team developing the first atomic bomb, and resisted his scientific quarantine by regularly picking Los Alamos safes full of classified secrets. He communicated with his wife through letters written in code, all for his deciphering amusement and the annoyance of the government censors. He chose to view the first test of the atomic bomb through the windshield of a truck instead of through the standard-issue dark glasses donned by fellow researchers. His own quick calculations had convinced him the blast's ultraviolet light probably would not permanently blind him—making him the only one, he figured, to directly witness the explosion.

When the space shuttle *Challenger* exploded on January 28, 1986, killing all seven astronauts aboard, Ronald Reagan added the iconoclastic physicist to the commission charged with ferreting out the cause of the accident. After many interviews with NASA officials, in which he favored engineers over managers, Feynman concluded that the mechanical fault lay in an O-ring—a thin, rubbery gasket 12 feet in diameter used to seal the solid-fuel rockets. These O-rings lost their malleability at low temperatures and failed to adequately form a seal. This he demonstrated before a throng of reporters during public testimony at the commission's hearings. He dunked a rubbery O-ring in a small cup of frigid water and demonstrated its acquired rigidity. Despite typically warm weather at the Kennedy Space Center in Florida, the day of the launch had been characterized by near-freezing temperatures. Feynman's "minority report" conclusions about the accident were only included in the appendix of the commission's findings.

When he left his Caltech office for good in 1988, he left behind an epigram on the blackboard: "What I cannot create I do not understand."

BACK-OF-THE-ENVELOPE 1.4

What does fitting the *Encyclopedia Britannica* on a pinhead entail?

The head of a pin measures about 1/16th of an inch across; therefore,

$$\text{Area} = \pi\left(\frac{0.0625}{2}\right)^2 = 0.00307\ \text{in.}^2$$

The *Encyclopedia Britannica* has approximately 30 volumes and each volume has about 1000 pages, each measuring 9 in. × 11 in. Thus,

$$\text{Area} = (30)(1000)(9)(11) = 2{,}970{,}000\ \text{in.}^2$$

A pinhead large enough to fit the regular-sized *Encyclopedia Britannica* would need to have a diameter X times bigger than a real pinhead:

$$\text{Area} = \pi\left(\frac{0.0625X}{2}\right)^2 = 2{,}970{,}000\ \text{in.}^2$$

Solving for X shows that the encyclopedia would need to be about 32,000 times smaller in order to fit on the head of a pin. Is that feasible? The diameter of the dot on an "i" in a fine printing of a book is about 1/120 of an inch wide (which, by the way, is about the smallest feature the human eye can resolve). If that dot is reduced 32,000 times, it would be about 7 nm across. In an ordinary metal, an atom is about 0.25 nm in diameter, so the dot would be about 28 atoms wide. The whole dot would contain about 1000 atoms. So there are definitely enough atoms on the head of a pin to accommodate all the letters in the encyclopedia.

The second prize was won by Tom Newman, a Stanford grad student who met Feynman's challenge to "take the information on the page of a book and put it on an area 1/25,000 smaller in linear scale in such a manner that it can be read by an electron microscope" (roughly the scale at which the entire *Encyclopedia Britannica* could squeeze onto a pinhead). Newman and colleague Ken Polasko were at the forefront of electron-beam lithography, approaching the level of quantum effects. They sent a letter to Feynman asking if the prize was still unclaimed, and he phoned them personally in their lab to encourage them to pursue it. They did, using a specialized electron beam writing program to transcribe the full first page of *A Tale of Two Cities* by Charles Dickens.

Feynman's visions were being realized, and at a pace quicker than perhaps even he had expected. The unfathomable was getting more mundane every day.

As with the gradual refinement of atomic theory, the breakthroughs that continue to enable development in nanotechnology are the result of thousands of years of scientific inquiry. Like children, scientists have always been curious, optimistic, and fearless. They continue to tackle nature's toughest puzzles; yet when it comes to nanotechnology, they do it under new auspices. The prospects for prestige, government funding, and the excitement of working at the forefront of a scientific uprising have convinced many scientists and engineers to relabel their nanoscale work—be it thin films, fine fibers, submicron lithography, colloidal particles, and so forth—as nanotech. Condensed-matter physicists and organic chemists are nowadays likely to go by the common job title of nanoscientist.

Nanotechnology is engineering. It is about the practical application of science. Nanotechnology borrows liberally from physics, chemistry, materials science, and biology—ranking it among the most all-encompassing engineering fields. Figure 1.7a shows the relative occurrences of a few nanotechnology topics on the Internet—a quick and intriguing way to estimate the size of these subjects over time. Figure 1.7b shows international interest in nanotechnology based on Google© searches.

In this book, the cluster of nanotech disciplines is broken into eight main areas:

1. Nanomaterials
2. Nanomechanics
3. Nanoelectronics
4. Nanoscale heat transfer
5. Nanophotonics
6. Nanoscale fluid mechanics
7. Nanobiotechnology
8. Nanomedicine

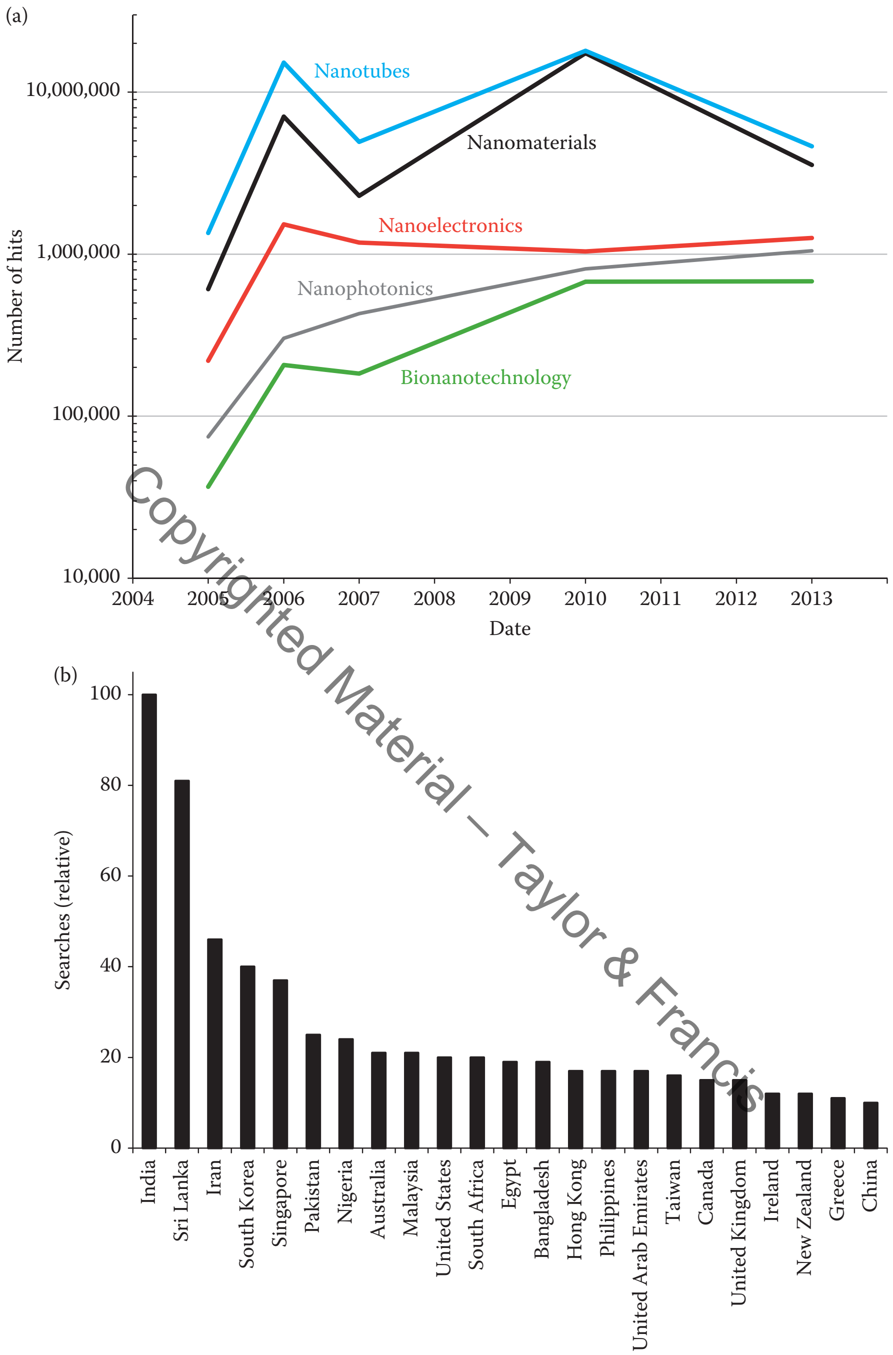

FIGURE 1.7 Googling nano. An interesting way to gauge the relative “size” of a topic is to count the number of hits using the Internet search engine Google©—which over the period from 2005 to 2013 gave the results shown in (a). We can also get a sense of the international interest in nanotechnology with data available from Google Trends about where search queries originated. Graph (b) shows the relative number of searches for the term “nanotechnology” from the top regions for the years 2004–2013. Numbers represent search volume relative to the highest value on the map, which is set as 100.

1.3 WHY ONE-BILLIONTH OF A METER IS A BIG DEAL

At one-billionth of a meter, the world does not behave in quite the ways we are used to. We are familiar with the physical behavior of things we can hold in our hands, like a baseball, or, more accurately, the trillions of trillions (not trillions *and* trillions—trillions *of* trillions) of atoms of which the baseball is comprised. Toss it up, and it comes down. Put it near another ball, and that is probably where it will stay—near the other ball.

However, an atom does not behave like a baseball. It is beholden to laws of physics that really only kick in below 100 nm, where matter becomes a foreign substance we do not understand quite as well. Gravity, for example, has little effect. However, intermolecular forces, such as van der Waals forces, play a large role when the atom nears its neighbors. Quantum effects manifest also. In the quantum regime, electrons no longer flow through conductors like water through a hose, but behave instead more like waves; electrons can hop, or "tunnel," across insulating layers that would have barred passage if conventional, macro-scale physics were in charge. Strange phenomena such as size confinement effects and Coulomb blockage are relevant below 30 nm.

When you move through a swimming pool, your body feels like it is gliding through the water. The wetness is continuous. However, if you were a chlorine atom in the same pool, you would find a discreteness to your motion as you went bumping around between molecules.

As we gain unprecedented control over matter, entirely new devices are possible. Think of atoms as bricks and electrons as mortar, and begin tailoring things from the bottom up, using nature's building blocks. The human body is nothing but a bunch of oxygen, hydrogen, nitrogen, carbon, and other atoms; but when you combine these ingredients properly, the resulting object is exponentially more significant and miraculous than the sum of its parts. The primary challenge here is the integration of objects over diverse size scales, the overlapping of bottom-up engineering with top-down approaches to realize real devices with nanoscale functionality. Right now, it is difficult to work at the nanoscale. It is expensive and tedious and hit-or-miss. It is difficult. Imagine building something as mechanically straightforward as the gear assembly shown in Figure 1.8—a simple machine on the macroscale but quite a challenge when the teeth of the gears are molecules, or even individual atoms.

However, it is not impossible. Nanosized particles have for a century been used to reinforce tire rubber, long before nanotechnology went by that name. Chemists design nanoscale catalysts to accelerate thousands of chemical transformations every day, including the conversion of crude oil into gasoline for cars, organic molecules into pills for fighting disease, graphite into diamond for cutting tools. Engineered vaccines contain proteins with nanoscale dimensions. Computer disk drives have nanometer layers for memory storage.

These applications are a glimpse into how one might use nanotechnology in the future. The tenet of this gradual conversion to bottom-up thinking is: Do More with Less. Molecular-scale manufacturing ensures that very little raw material is wasted and that we make only what we intend to make, no more. Factories begin to look more like clean rooms.

All manufactured products already consist of atoms. Theoretically, this fact leaves no product unaffected by nanotechnology. Whereas machines have always been a means of

FIGURE 1.8 Molecular gears. This schematic representation shows how molecules might be employed in a gear mechanism. (Image courtesy of NASA.)

outperforming human strength, nanotechnology will enable us to overcome our limitations in the opposite direction—below our physical size limits.

Nanotechnology could make for healthier, wealthier nations. Governmental preparedness and foresight are crucial and should coincide with scientific and engineering progress. James Canton, President of the Institute for Global Futures, has said of nanotechnology's disruptive economic potential that "those nations, governments, organizations, and citizens who are unaware of this impending power shift must be informed and enabled so that they may adequately adapt" (Canton, 1999). Materials, manufacturing, electronics, medicine, health care, energy, information technology, national security—the list of industries nanotechnology will influence is long.

The sooner we understand what nanotechnology is, the quicker we can temper any expectations or fears we may have. It is going to take teamwork to realize its many brilliant promises.

1.4 THINKING IT THROUGH: THE BROAD IMPLICATIONS OF NANOTECHNOLOGY

Like all technological trends throughout history, nanotechnology has been subjected to vigorous overstatement, speculation, and opposition. The chain of events has been typical. A handful of paradigm-shifting scientific breakthroughs in otherwise disparate disciplines (such as the invention of the STM and the discovery of carbon buckminsterfullerenes—both of which we will discuss in more detail later in this book) leave scientists at once awed by new possibilities and at the same time suspicious. It has been said that extraordinary claims require extraordinary proof. Bolstered by a breakthrough, but scientifically skeptical, scientists worldwide work quickly to verify or refute a new idea. The ideas that take hold are those that emerge intact from the spotlight of scrutiny.

This is not to say that skeptics cannot be wrong, or that they are completely objective in their evaluation of new ideas; the history of technological development is littered with people, including scientists, eventually proven wrong by persistent optimists with great ideas. The Wright brothers and the inventors of the STM were both hounded by criticism from their peers before and after their breakthroughs. Copernicus' belief about the Sun being the center of the solar system, and not the Earth, met with great opposition from religious leaders.

Technological and scientific breakthroughs represent giant leaps in our understanding of the world. At the same time, they often reveal giant gaps. Discovery is not only about finding answers, but also new questions.

Some of the new ideas regarding nanotechnology have weathered decades of skepticism. Some, such as nanotube semiconductance, have been demonstrated enough times to warrant widespread acceptance and now application development. Others, such as the possibility of a molecular assembler that could piece together specific molecules over and over again, are still being publicly debated. (See Section 1.4.1.)

However, it is not only the scientific merit of a new idea that must face opposition. The ethical implications are also considered, or at least they should be. As is often the case, the excitement of discovery and our innate desire to alter the world to better suit ourselves (sometimes at the expense of the planet) quickens the pace of development, and ethical considerations lag behind, hustling to keep up. Before anyone has had time to think through the ramifications of a new idea, it is not new anymore. The world has already absorbed it, for better or for worse.

During World War II, scientists secretly building and testing the first nuclear weapon were among the only ones who knew about the technology. The billions of people affected by the emergence of such a weapon had no say in how it was developed or deployed until after it was dropped on Hiroshima toward the end of the war. So began the nuclear arms race, with nations competing to build better and better weapons in the hope that no other nation would ever use them: the only foreseeable outcome of nuclear war was mutually assured destruction, or "MAD." Was this the best course of development for nuclear technology?

Vehement backlashes against biotechnologies such as stem cell research, cloning, and genetically modified foods suggest that people find such things important enough to debate, or outright oppose.

That which is new can be frightening—oftentimes because it is unknown. The more we learn about new technologies, the better equipped we are to decide how to use (or not use) them. The potential uses of nanotechnology, both good and bad, remain topics of debate. Ethical issues such as these do not necessarily have right or wrong answers. Since the topic is the future, the debate is fueled by speculation.

Careful attention is best paid to the environmental, psychological, social, legal, and political implications of nanotechnology *throughout* its evolution in order to ease society toward new techniques in the safest way possible, and without backlash or unintended consequences.

Insight into this process can be gained by examining our experiences with similarly revolutionary fields like biotechnology and information technology. One lesson we can learn from these fields is that the study of the social implications of nanotechnology should not be conducted in isolation. Instead, it should have an intersectoral approach: those studying ethical and social implications should have regular opportunities to interact with and debate scientists, activist groups, governments, and major industry players. Journalists need to be invited to report on even the most nascent stages of research, as they have an important influence on public perception and can help disseminate facts instead of rumors. Early and continuing public engagement is critical. Innovative engagement mechanisms including movies, plays, and books can help spark conversations and even educate. Science museums, libraries, laboratories, and industrial sites can develop exhibits and host interactive educational programs about the broader impacts of nanotechnology and its risks on both a global and a neighborhood scale. Governments must also intervene where necessary and appropriate in order to mitigate potentially harmful outcomes of nanotechnology, and facilitate positive ones.

All of these avenues of communication can help ensure that those who stand to benefit from nanotechnology are included in early, balanced discussions of the potential harms, and can help steer the ship.

The 21st Century Nanotechnology Research and Development Act, signed by President George W. Bush in December 2003, authorized billions of dollars in funding for nanotechnology research and development. The act appropriated money not only for research and development, but also to ensure that "ethical, legal, environmental, and other appropriate societal concerns ... are considered during the development of nanotechnology" and are called for "public input and outreach to be integrated into the program by the convening of regular and ongoing public discussions, through mechanisms such as citizens' panels, consensus conferences, and educational events." Groups such as the Center for Responsible Nanotechnology and the Foresight Institute often weigh in on political and policy-related issues.

There is a pressing need to answer, or at least discuss, the many concerns surrounding nanotechnology. It is important not to pick a side, but rather to be able to understand both sides of the debate. By exploring and acknowledging the potential risks of nanotechnology, a track record of honesty and openness can be established.

Here are some questions about nanotechnology still being answered:

1. How will the military use nanotechnology?
2. How might pervasive, undetectable surveillance affect our privacy?
3. Might nanotechnology be used in acts of mass terror?
4. How do we safeguard workers from potentially dangerous fabrication processes?

5. How will our attempts to better our bodies with nanotechnology affect later generations and society as a whole?
6. Who will define what is ethical about nanotechnology?
7. Who will regulate nanotechnology?
8. Should we limit research in areas that could be dangerous, even if this prevents beneficial technologies from being developed as well?
9. How will the benefits (financial, health, military, etc.) of nanotechnology be distributed among the world's nations?
10. To what extent will the public be involved in decision making? Legislators? Scientists? Businesspeople?
11. Will nanotechnology reduce the need for human workers and cause unemployment?
12. How will intellectual property (patents) be handled?
13. Who will profit from nanotech innovations? Universities? Businesses? Individuals?

1.4.1 Gray Goo

It has been suggested that self-replicating "nanobots" could become a new parasitic life-form that reproduces uncontrollably, remaking everything on Earth into copies of itself. The result would be undifferentiated "gray goo." The gray goo idea is one that has received much press and has sparked vehement arguments within the scientific community. K. Eric Drexler (Figure 1.9), one of nanotechnology's earliest advocates and thinkers, once quipped that gray goo's catchy, alliterative name fuels the interest (as with the oft-mentioned "digital divide") and that there is really nothing gray or gooey about the scenario.

The majority of scientists who have weighed in on gray goo discount its possibility as no possibility at all. Most importantly, no self-replicating machine has ever been built, on any scale, let alone the nanoscale. Richard Smalley penned an editorial in *Scientific American* in 2001 that fueled an ongoing debate with Drexler about the feasibility of a nanoscale assembler that could self-replicate. When would we see such a thing, Dr. Smalley asked rhetorically. "The simple answer is never" (Smalley, 2001).

1.4.2 Environmental Impact: Risks to Ecosystems and Human Health

Dichlorodiphenyltrichloroethane (DDT) was first synthesized in 1873. In 1939, the Swiss scientist Paul Hermann Müller discovered that DDT was an effective insecticide, earning him the 1948 Nobel Prize in Physiology and Medicine. During the 1940s and 1950s, DDT was widely used to kill mosquitoes and thereby prevent the spread of malaria, typhus, and other insect-borne human diseases. It seemed a perfect synthetic pesticide: toxic to a broad range of insects, seemingly safe for mammals, and inexpensive.

Silent Spring by Rachel Carson (1962) described the ill effects of pesticides on the environment, including birds, whose reproduction was harmed by thinning egg shells.

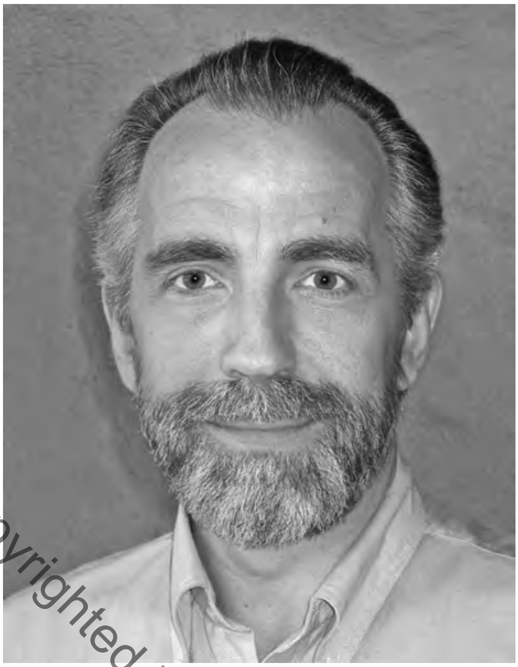

FIGURE 1.9 K. Eric Drexler. He is founder and chairman of the Foresight Institute, a think tank and public interest institute on nanotechnology founded in 1986. (Photo courtesy of K. E. Drexler.)

Studies revealed that DDT was toxic to fish and mammals, including humans, and that it accumulated through the food chain. It is now banned in the United States and most other countries. The publication of Carson's book is considered one of the first events in the environmental movement.

The plight of DDT provides a valuable lesson about how a synthetic product—bestowed with accolades, proven effective, and seemingly safe—can wreak havoc in the environment. It also illustrates how scientists and businesspeople tend to focus on breakthroughs and bottom lines, sometimes at nature's expense.

Nanotechnology has been touted as an ecofriendly approach to making things. Little raw material would be needed and very little would be wasted by nanotech processes. However, there are valid concerns as to how nanosized products such as nanoparticles would accumulate in nature. For example, could large amounts be ingested by fish? And if so, would it be harmful? Would the particles be passed along the food chain like DDT? Could genetically modified microorganisms reproduce uncontrollably into a *green* goo that clogs the environment?

Such questions remain mostly unanswered. Environmental and health impact studies are lacking for manufactured nanomaterials, which are increasingly prevalent in consumer products like paint, fabrics, cosmetics, treated wood, electronics, sports equipment, and sunscreen. Such materials are new to the environment in type and quantity, and constitute a new class of nonbiodegradable pollutants, already showing up in our air and our water. Also, recapturing these materials after they get "out" is exceedingly difficult.

Studies on the fate, transport, transformation, and recyclability of nanomaterials in the environment must be done—and indeed, such studies have begun in earnest, including full, "life-cycle" evaluations. It is important we learn how to detect nanomaterials as they enter and move through ecosystems, and how to remove them if they become problematic. Exposure thresholds will need to be determined. Also, new techniques for raw material extraction, handling, and disposal will likely be necessary. As yet, no clear guidelines exist.

Lacking data, scientists have found it challenging to make real conclusions at this stage. It would be premature to pronounce any particular material too toxic for use yet. Still, early studies suggest health risks that need to be considered. Table 1.2 provides an overview of the potential risks identified so far for some of the most widely deployed nanomaterials. While the threats mentioned in this table are by no means exhaustive or conclusive, they certainly need to be considered.

Airborne nanomaterials—such as particles, spherical carbon fullerenes, and fibrous nanotubes and nanorods—are of particular concern, as they can enter the body easily via the respiratory system. Their size range overlaps with that of the ultrafine particles (<0.1 μm) characteristic of urban air pollution and known to have both long-term and immediate health effects, such as increased illness and death from lung and cardiovascular problems. Such particles rarely aggregate or land on surfaces; instead they tend to remain airborne for days at a time. They can therefore be carried in the atmosphere for thousands of kilometers. The high surface-to-volume ratio of such small particles enables them to collectively carry large amounts of adsorbed pollutants. Though few worldwide health standards exist, a 2011 international workshop made recommendations on exposure limits to granular nanomaterials based on a mass concentration of 0.1 mg/m^3. (This equates to ~1 million 50-nm C_{60} carbon fullerenes per cubic centimeter of air, or 45,000 100-nm titanium dioxide particles per cubic centimeter of air.)

Normally, foreign particles that enter our bloodstream are absorbed by cells or phagocytes responsible for protecting the body. However, things smaller than about 200 nm are not typically absorbed by phagocytes. Nanoparticles therefore have nearly unlimited access to the human body. This can be used to advantage for medical applications but, unfettered, this is concerning. Nanoparticles can easily pass into cells or through the blood–brain barrier, or become lodged in mitochondria, and may even evade detection by the human body's immune system.

So what becomes of nanoparticles in the body? Do they accumulate? Do they aggregate? Are they eventually excreted? The exact distribution and fate of foreign matter in the body often depends on the material's surface chemistry. The high surface-area-to-mass ratios of nanomaterials tend to give them increased chemical reactivity, which can lead to chemical damage of surrounding tissues; other influences on a nanomaterial's toxicity include its surface functionalization, solubility, shape, and its ability to generate oxidant species and adsorb, or bind to, biological molecules. Initial studies have focused on materials roughly 1–100 nm in size and suggest that smaller size (and therefore higher surface-to-volume ratio) generally leads to higher toxicity, but larger materials up to 100s of nanometers may also pose risks.

TABLE 1.2 The Uses and Potential Risks of Key Nanomaterials

Nanomaterial	Commonly Used In	Potential Risks
Carbon nanotubes, buckyballs	Vehicles, sports equipment, electronics, television screens	Preliminary studies show nanotubes may behave like asbestos when inhaled. (Asbestos causes mesothelioma, a cancer of the lungs.) Other studies report brain damage in fish and small crustaceans exposed to buckyballs. Buckballs have also been shown to travel unhindered through soil, where they could be absorbed by earthworms, an entry point to our food chain.
Cerium oxide	Electronics, biomedical supplies, energy and fuel additives	Typical applications of CeO2 nanoparticles tend to disperse them widely into the environment, increasing risk of exposure. For example, new diesel fuels use additives containing CeO2, with unknown environmental and health impacts.
Titanium dioxide	Sunscreens, cosmetics, paints, coatings, as an agent for removing arsenic from drinking water	Little is known about the biological effects of titanium dioxide nanoparticles. Studies have shown controversial results. Concerns have been raised that nanoscale titanium dioxide/zinc oxide in some sunscreens may migrate through the stratum corneum—the protective, outermost layer of the skin made up of dead skin cells—and reach the living cells, where the particles can generate reactive oxygen species (ROS) and damage the cells' DNA and/or kill the cells.
Silver	Disinfectant sprays, textiles, clothing, food packaging, consumer product surfaces (to eliminate bacteria and odor)	The toxicity of nanosilver on bacteria is well studied. While data on larger organisms are scarce, some studies with marine organisms reveal toxic effects. Humans ingesting very high levels of colloidal silver can suffer from gastrointestinal distress, seizures, and neurotoxicity.
Gold	Tracers in medical imaging and diagnostics	Studies on the uptake and toxicity of gold nanoparticles and nanorods give conflicting data, yet there is some indication that certain concentrations and particle sizes may be harmful.
Iron	"Smart fluids" for optics polishing, nutrient supplements, systems to remove contamination from groundwater	Iron oxide nanoparticles have been shown to be toxic in human cells under certain conditions in early studies.
Copper	Catalysts, electronics, additives, antibacterial/antimicrobial coatings	Copper oxide nanoparticles have been shown to be toxic in human cells under certain conditions in early studies.

Natural biodegradable substances are usually decomposed and their waste products excreted by the kidneys and intestines. However, studies performed using nonbiodegradable nanoparticles have shown that they tend to accumulate in certain organs, especially the liver. It is not known how long the deposits stay, the potential harm they may trigger, or the dosage that can cause harm—making this a huge area of concern. Special attention has to be paid to vulnerable organs such as the brain, where the potential to impair health is generally greater.

As you may see, our current and future problems with nanomaterial toxicity arise from a shortage of information. Studies need to determine what, if any, risks these new materials pose, so we can make informed purchases, draft-informed legislation, develop effective mitigation and collection methods, and leave ecosystems unharmed. Better disclosure and transparency (e.g., through more explicit product labeling) will help consumers know what they're breathing and rubbing into their skins and dumping down their drains.

Still, caution, not fear, seems the best stance.

1.4.3 The Written Word

Nanotechnology's reputation has been authored not only by scientists and technologists, but also by novelists. By surveying our present capabilities and then extrapolating to the extreme of possible outcomes, fantastic fictions emerge. Such stories create public fascination and help focus attention on the subject of nanotechnology—both good and bad. Publicity of this sort can stimulate ideological debate, foster industry growth, or generate fear.

Prey by Michael Crighton (2002). Although not fiction, the book was imaginatively forward-looking and discussed the potential of nanotechnology to give us unprecedented control of matter. Self-replicating nanomachines, Drexler said, might be used to produce any material good, pause global warming, cure diseases, and dramatically prolong human life spans. These visions were the stuff of science fiction, but also fodder for ridicule. Still, the book stirred the imagination of many of today's leading nanotechnologists and is considered a seminal work.

Novelists also were intrigued by Drexler's book. *Engines of Creation* by K. Eric Drexler, Anchor Books (1986) (Figure 1.10), quotes Drexler in the opening of the book. *Prey* does for nanotechnology what Crichton's *Jurassic Park* did to heighten concerns over cloning. The story is about a company developing nanoscale surveillance technology. The spying nanoparticles eventually become a predatory swarm, evolve rapidly, run amok, and feed on people in the Nevada desert—not exactly good public relations for nanotechnology but an awareness booster nonetheless. Other science fiction books involving nanotechnology include *The Diamond Age* by Neal Stephenson, *Slant* by Greg Bear, and *Idoru* by William Gibson.

Novelists are not the only writers weighing in. In a widely quoted article from *Wired Magazine* (April 2000), "Why the Future Doesn't Need Us," Bill Joy, cofounder of Sun Microsystems, wrote that nanotech, genetic engineering, and robotics together make for a bleak outlook for the human race, and possibly our extinction. The arguments have met

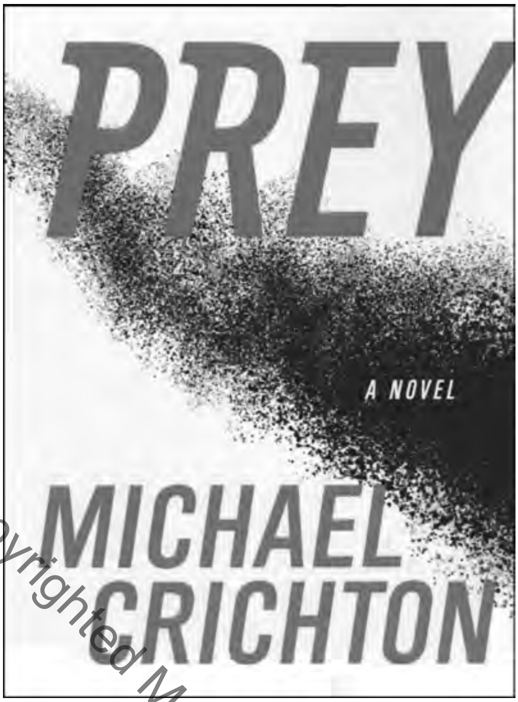

FIGURE 1.10 The novel *Prey*. Author Michael Crichton: "The creators of technology often do not seem to be as concerned about the effects of their work as outsiders think they ought to be. But this attitude is changing. Just as war is too important to be left to the generals, science is too important to be left to the scientists." (Book cover from *Prey* by Michael Crichton. Copyright © 2002 by Michael Crichton. Reprinted by permission of HarperCollins Publishers.)

strong criticism. *Fantastic Voyage* by Ray Kurzweil and Terry Grossman (who met at a Foresight Institute conference in 1999) discusses the use of nanobots to improve and repair the human body.

1.5 THE BUSINESS OF NANOTECH: PLENTY OF ROOM AT THE BOTTOM LINE TOO

As technology drivers, curiosity and the thrill of innovation are often no match for the lure of big profits. Money is the primary force pushing nanotechnology development worldwide. Faster, smaller, cheaper—like a mantra, these long-standing engineering goals aimed at displacing existing products are the same reasons nanotechnology will figure into the balance sheets of so many companies in the coming decades. If a better product can be built in a small clean room instead of a gigantic factory, using less raw material, and shipped in envelopes instead of on pallets, it is going to earn the company money. In terms of products, "nano" also spells "new"—new ideas, new markets, and new ways to turn a profit.

The investment in tech development, paradoxically, costs a fortune. Governments around the world are among the only investors who can afford to take the long-term financial plunge. Private industry usually expects investments to pay off in 5–10 years, sometimes even faster. As such, federal nanotech funding in the United States, Europe, and Asia tends to support fundamental research, intended to build the scientific knowledge base upon which businesses can later capitalize. Governmental investments in science do not necessarily require *immediate* economic benefits.

Still, large multinational research and development giants such as IBM, General Electric, and Hewlett-Packard have made significant internal investments in research and development programs. While the outcomes are historically difficult to predict, basic research is vital to technological growth. It is where the lucrative scientific surprises come from. It is not surprising, then, that more than half of the 30 companies in the Dow Jones Industrial Index have launched some type of nano initiative.

Estimates pegged the number of people working in nanotech research in 2005 at around 20,000. Within 15 years, this number is expected to reach 2 million. Your next job may be nanorelated. The National Science Foundation predicts that by 2015 the need for technology professionals in nanotechnology will be 800,000 employees in the United States and more than 2 million worldwide.

In 2004, manufactured goods incorporating nanotechnology accounted for just over $10 billion in sales—the equivalent of a rounding error on the global economy. But it is a ripple that over the coming years is expected to grow into a more disruptive wave, especially as the prices of nanoengineered materials drop.

Figure 1.11 shows how the price of nanotubes has come down since their introduction as a commercial product. There are now numerous companies selling all varieties of

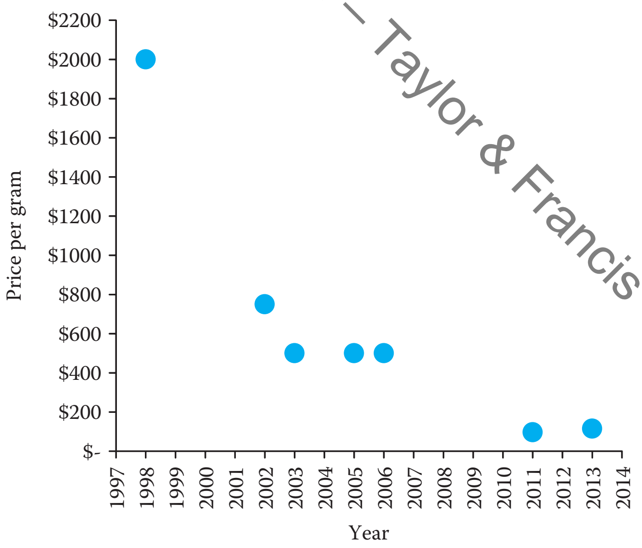

FIGURE 1.11 Carbon nanotube prices over time. Nanotube production processes originally developed at Rice University were later used for production and sale of nanotubes by Tubes@Rice (1998) and subsequently by Carbon Nanotechnologies Incorporated (CNI). The price shown is for a single gram of pure, single-walled nanotubes (SWNTs). All data for 1998–2006 are from Tubes@Rice and CNI. The 2011 and 2013 data points are the average price of a single gram quantity of >90% pure SWNTs from three suppliers—Nano-C, MKnano, and CheapTubes.

nanotubes. This is but one example. Global Industry Analysts predicts the annual market for products incorporating nanotechnology to reach $2.4 trillion by 2015.

Whereas the Internet has proved a singular phenomenon with definite uses and boundaries, the marketplace for nanotechnology does not appear so easily constrained; it is difficult to draw a boundary around it because it affects no single industry, but rather the scale of engineering in general. It offers thousands of new possibilities for materials and devices that already exist. This makes market speculation even more speculative. Burned by dot com failures, investors have been weary of overhype and simultaneously allured by the promise of new markets, new customers. Venture capitalists have thus far invested about $1 billion in nano companies and more than 1000 start-ups have formed around the world, about half of them in the United States.

However, investors are scrupulous. They have found themselves asking: What does nano even mean? In April 2004, Merrill Lynch introduced a Nano Index, featuring 25 companies in the nanotech business. Critics pounced on the index, debating the nanoness of, for example, the pharmaceutical companies on the roster. These companies make molecules for drugs, a common industry practice, but is that truly *nano*? Merrill revised the index to include only companies with publicly disclosed nanotech initiatives representing a significant component of their future business strategy. Reshuffling, they dropped six companies and added three new ones.

Meanwhile, using the same old periodic table of raw materials, nanoscientists are inventing new things. A deluge of patent applications has resulted in what some are calling a “land grab” for intellectual property. This gold-rush mentality has led to thousands of U.S. patents issued, with thousands awaiting judgment. Most of these fall into five nanomaterials categories: (1) dendrimers, (2) quantum dots, (3) carbon nanotubes, (4) fullerenes, and (5) nanowires. Reviews of these patents have revealed much overlap and fragmentation, meaning that to avoid infringement, many entrepreneurs will first need to strike agreements with numerous patent holders before cashing in on the technology.

There are also other challenges facing nanotech companies. Things taken for granted with traditional size scales—quality control, inventory—are difficult to manage when the products are practically invisible. Industry standards and enforcement practices are needed, as are assurances that the products sold are safe in the body and in the environment.

1.5.1 Products

Chances are that you have already bought something that uses nanotechnology. Companies of all sizes are hurrying small science from labs to the marketplace. The primary markets are for nanoparticles that bolster products such as the rubber in tires and the silver used in photography. Specialized coatings on glass reduce glare and make it easier to clean. Other products incorporating nanotechnology include burn and wound dressings, water filtration systems, dental bonding agents, car parts including bumpers and catalytic converters, sunscreens and cosmetics, tennis balls, golf clubs and tennis rackets, stain-free clothing and mattresses, and ink.

Further along the nanotech timeline, expect to see more ubiquitous energy generation. Ideas in the works include solar cells in roofing tiles and siding. Computers also will become more pervasive as nanotech breakthroughs make circuits small and cheap enough to build into fabrics and other materials. Look for better drug-delivery systems, including implantable devices that release drugs and measure drug levels while inside the body.

HOMEWORK EXERCISES

1.1 What is the definition of nanotechnology?

1.2 The number 1,234,567 written out is one million, two hundred thirty-four thousand, five hundred sixty seven. Write out this number: 1,200,300,400,500,600,700, 800,901.

1.3 Rank the following things from largest to smallest: polio virus, drop of water, mercury atom, *Escherichia coli* bacterium, helium atom, human red blood cell.

1.4 Approximately how long ago was the concept of the atom introduced?

1.5 What are the three main components of an atom?

1.6 What are the main components of an atom's nucleus?

1.7 What is the law of definite proportions?

1.8 What is the law of multiple proportions?

1.9 Boyle's law states that $PV = C$, where P is the pressure of a gas, V is the volume, and C is a constant (assuming constant temperature). Consider a gas held in a 4-m^3 container at 1 kPa. The volume is then slowly doubled.

   a. What is the new pressure?

   b. Use atoms to explain how a larger container leads to a lower pressure.

1.10 a. What is the mass of a square piece of aluminum foil 100 μm thick and 10 cm wide (aluminum = 2.7 g/cm^3)?

   b. How many atoms are in the piece of foil (aluminum = 27 g/mol)?

1.11 Calculate the mass of an atom of

   a. Hydrogen (1.0 g/mol)

   b. Silver (107.87 g/mol)

   c. Silicon (28.09 g/mol)

1.12 What are the mass ratios of the elements in these chemical compounds? (*Note:* nitrogen = 14 g/mol; hydrogen = 1 g/mol; carbon = 12 g/mol; oxygen = 16 g/mol.)

   a. Ammonia, NH_3

   b. Ethanol, C_2H_6O

   c. Toluene, C_7H_8

1.13 What now-famous talk did Feynman give to stimulate development in nanotechnology? What year did he give it?

1.14 What less optimistic topic did some of those in the audience suspect was meant by the title of Feynman's talk?

1.15 Many computers use one byte (8 bits) of data for each letter of the alphabet. There are 44 million words in the *Encyclopedia Britannica*.

a. What is the bit density (bits/in.^{2}) of the head of a pin if the entire encyclopedia is printed on it? Assume the average word is five letters long.

b. What is the byte density?

c. What is the area of a single bit in nm^2?

d. A CD-ROM has a storage density of 46 megabytes/in.^{2} and a DVD has a storage density of 329 megabytes/in.^{2}. Is the pinhead better or worse than these two storage media? How much better or worse?

1.16 What is meant by "gray goo"?

1.17 For a gray goo scenario to play out, what entirely new type of machine would be necessary?

1.18 What year was the word "nanotechnology" first used?

1.19 A baseball is made of trillions of trillions of atoms.

a. Write out the number for one trillion trillion.

b. NASA estimates that there are about 10^{21} stars in the universe. Is this number higher or lower than the number of atoms in a baseball?

1.20 The distance between the nuclei of two iron atoms is about 4 Å (1 Å = 10^{-10} m).

a. How many nanometers is that?

b. How many iron atoms at this spacing would it take to reach 2 µm (1 µm = 10^{-6} m)?

1.21 What five categories are the most popular areas for nanotechnology patents in the United States?

Short Answers

1.22 Name three things you are familiar with (easy for you, personally, to identify with) that are roughly 1 mm (millimeter) in size. Name something that is approximately 1 µm (micrometer) in size. Name something that is 1 nm (nanometer) in size.

1.23 Based on your education and interests, describe the role you might be best suited to play in the multidisciplinary arena of nanotechnology.

1.24 Perform your own topic search using an Internet search engine. Use the same search terms as Figure 1.7 and reconstruct the chart. How have the results changed, and what does this suggest?

1.25 Make a list of at least five name-brand products that incorporate nanotechnology.

1.26 Search *Science* magazine's online table of contents. Find the percentage of issues from the previous year with at least one article whose title contains the prefix "nano."

1.27 The concept of the atom was ridiculed by Romans; the idea that the Earth revolved around the Sun was initially shunned also. What scientific ideas are at the heart of controversy these days? What are the implications of these ideas? Which groups are at odds? How much is proven about the idea and how much is conjecture?

Writing Assignments

1.28 Nanotechnology is multidisciplinary; it draws from, and requires expertise in, numerous scientific and engineering fields. So the question becomes: Is there such a thing as nanotechnology? Are there any applications, research fronts, concepts, or overarching goals that are unique to nanotechnology and not just an advancement in another field (chemistry, physics, medicine, biology, etc.)? Or is nanotechnology really just the name for where all these other fields overlap? Citing and quoting evidence from credible sources (including at least two that are nontechnical in nature such as a newspaper article, a book review, or a governmental document) and those more geared toward scientists and engineers (e.g., an editorial or an article from a scientific journal or a speech from a convention) take one side of this issue and argue it in 500 words. It would also certainly be worth interviewing an expert on the topic (a professor or government official perhaps).

1.29 Technological progress in nuclear power and biotechnology has been thwarted to a degree by public distrust, misinformation, and resistance to change. There are very real dangers and ethical issues involved in such technological progress, and at the same time, very real advantages. How is nanotechnology similar? How is it different? What lessons can be taken from the manner in which nuclear power and biotechnology are understood by the general public to make for a safer, more productive transition period in the case of nanotechnology?

1.30 Richard Feynman thought that the atomic hypothesis was the best single sentence to summarize all of scientific knowledge. Write your own sentence at the top of a page and use the rest of the page to convince the reader that your choice makes sense.

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