Chapter 3

Elements of Chemistry

THE MAIN IDEA

Elements combine to form compounds, which blend together to form mixtures

3.8 The Advent of Nanotechnology

The age of microtechnology was ushered in some 65 years ago with the invention of the solid state transistor, a device that serves as a gateway for electronic signals. Engineers were quick to grasp the idea of integrating many transistors together to create logic boards that could perform calculations and run programs. The more transistors they could squeeze into a circuit, the more powerful the logic board. The race thus began to squeeze more and more transistors together into tinier and tinier circuits. The scales achieved were in the realm of the micron (10^{-6} meters)—thus the term microtechnology. At the time of the transistor's invention, few people realized the impact microtechnology would have on society—from personal computers to smart phones to the internet.

Today, we are at the beginning of a similar revolution. Technological advances have recently brought us past the realm of microns to the realm of the nanometer (10^{-9} meters), which is the realm of individual atoms and molecules—a realm where we have reached the basic building blocks of matter. Technology that works on this scale is called *nanotechnology*. No one knows exactly what impact nanotechnology will have on society, but people are quickly coming to realize its vast potential, which is likely to be much greater than that of microtechnology.

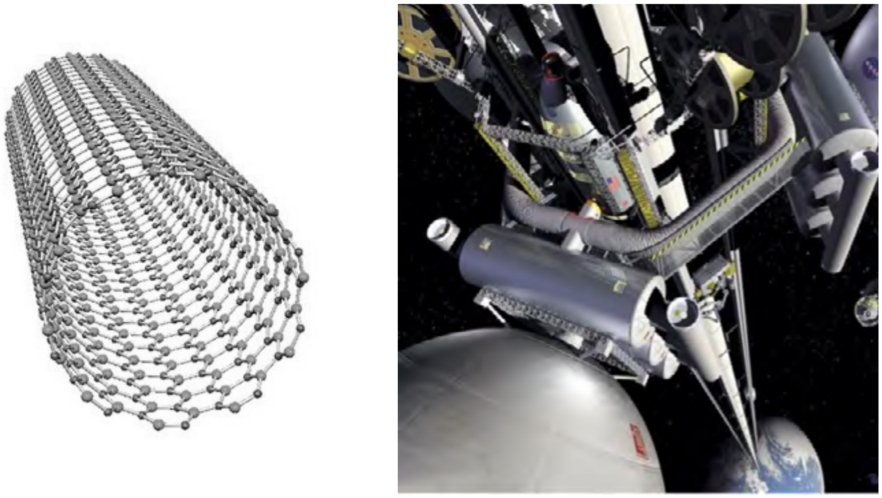
Nanotechnology generally concerns the manipulations of objects from 1 to 100 nanometers in scale. For perspective, a DNA molecule is about 2.0 nm wide (though about a meter long!), while a water molecule is only about 0.2 nm. Like microtechnology, nanotechnology is interdisciplinary, requiring the cooperative efforts of chemists, engineers, physicists, molecular biologists, and many others. Interestingly,

READING CHECK

How large are the objects that are the focus of nanotechnology?

Figure 3.33 >

Carbon nanotubes can be nested within each other to provide the strongest fiber known—a thread 1 millimeter in diameter can support a weight of about 13,000 pounds. A network of such strong fibers could be used to build the once science-fictional space elevator.

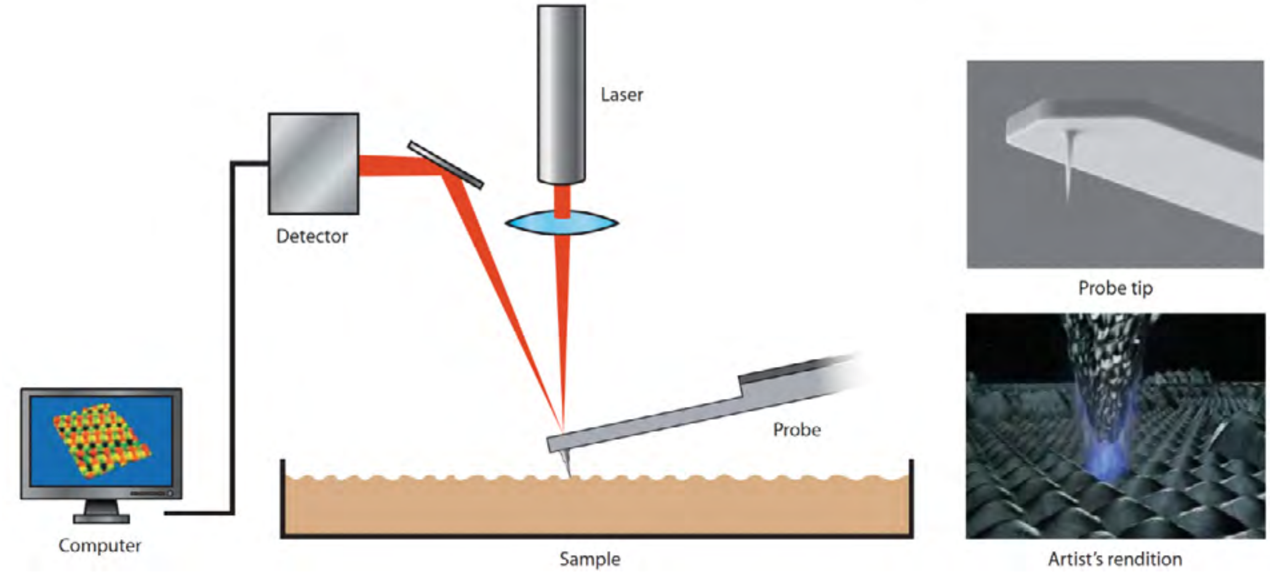


FOR YOUR INFORMATION

Before he died in 2005, Rick Smalley, co-discoverer of the buckyball, advocated that carbon nanotubes, if developed into wires, could be an ideal material for efficiently transporting electricity over vast distances. If such an infrastructure were in place, the wind energy of the Great Plains of the United States would be sufficient to supply the electrical needs of the entire country.

there are already many products on the market that contain components developed through nanotechnology. These include sunscreens, mirrors that don't fog, dental bonding agents, automotive catalytic converters, stain-free clothing, water filtration systems, the heads of computer hard drives, and much more. Nanotechnology, however, is still in its infancy, and it will likely be decades before its potential is fully realized (**Figure 3.33**). Consider, for example, that personal computers didn't blossom until the 1990's, some 40 years after the first solid state transistor.

There are two main approaches to building nanoscale materials and devices: top-down and bottom-up. The top-down approach is an extension of microtechnology techniques to smaller and smaller scales. A nano-sized circuit board, for example, might be carved out from a larger block of material. The bottom-up approach involves building nanosized objects atom by atom. A very important tool for either of these approaches is the **scanning probe microscope**, which detects and characterizes the surface atoms of materials by way of an ultrathin probe tip, as shown in **Figure 3.34**. The tip is mechanically dragged



Λ Figure 3.34

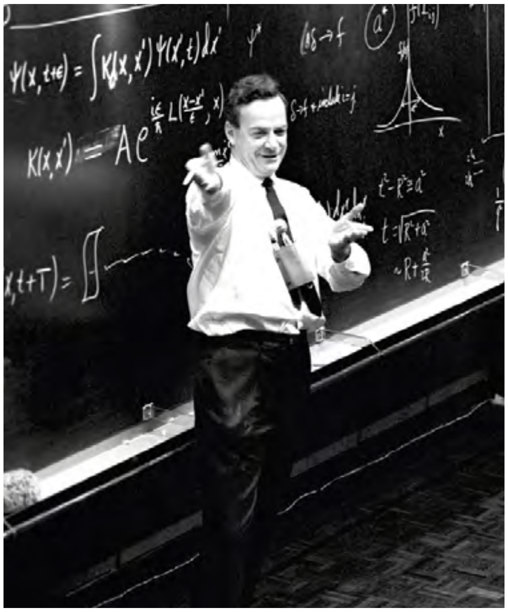
A schematic of a scanning probe microscope that detects and characterizes the surface atoms of a material by way of an ultrathin probe tip attached to a miniature cantilever.

over the surface. Interactions between the tip and the surface atoms cause movements in the probe that are detected by way of a laser beam and translated by a computer into a topographical image. Scanning probe microscopes can also be used to move individual atoms into desired positions.

Nanotechnology will enable the continued miniaturization of integrated circuits needed for ever smaller and more powerful computers. But a computer need not rely on an integrated circuit of nanowires for processing power. A wholly new approach involves designing logic boards in which molecules (not electric circuits) read, process, and write information. One molecule that has proved most promising for such molecular computation is DNA, the same molecule that holds our genetic code. An advantage that molecular computing has over conventional computing is that it can run a massive number of calculations in parallel (at the same time). Because of such fundamental differences, molecular computing may one day outshine even the fastest of integrated circuits. Molecular computing, in turn, may then soon be eclipsed by other novel approaches, such as quantum or photon computing, also made possible by nanotechnology. Consider how this might impact the continued development of artificial intelligence.

The ultimate expert on nanotechnology is nature. Living organisms, for example, are complex systems of interacting biomolecules all functioning on the scale of nanometers. In this sense, the living organism is nature's nanomachine. We need look no further than our own bodies to find evidence of the feasibility and power of nanotechnology. With nature as our teacher, we have much to learn. Such knowledge will be particularly applicable to medicine. By becoming nanotechnology experts ourselves, we would be well equipped to understand exact causes of nearly any disease or disorder (aging included) and empowered to develop innovative cures.

What are the limits of nanotechnology? As a society, how will we deal with the impending changes nanotechnology may bring? Consider the possibilities. Wall paint that can change color or be used to display video. Smart dust that the military could use to seek out and destroy an enemy. Solar cells that capture sunlight so efficiently that they render fossil fuels obsolete. AI models with so much processing power that we begin to wonder whether they experience consciousness. Nanobots that roam our circulatory systems destroying cancerous tumors or arterial plaque. Nanomachines that can "photocopy" 3-dimensional objects, including living organisms. Medicines that more than double the average human life span. Stay tuned for a new revolution in human capabilities.



Λ Figure 3.35

In the 1950s, physicist Richard Feynman foresaw the development of nanotechnology in his talk "There's Plenty of Room at the Bottom" where he noted the great potential of being able to manipulate matter by its individual atoms.

fyi FOR YOUR INFORMATION

An interesting discovery of nanoscience is that the properties of a material at the level of its atoms can be different from its properties in bulk quantities. A bar of gold, for example, is gold in color. A thin sheet of gold atoms, by contrast, is dark red. There is much research currently being directed toward the discovery of the unique nanoproperties of materials. Many novel applications of these nanoproperties are sure to follow.

CONCEPT **CHECK**

How believable would our present technology be to someone living 200 years ago? How believable might the technology of 200 years in the future be to us right now?

CHECK YOUR ANSWER

Hindsight is 20/20. It's always easy to look back over time and see the progression of events that led to our present state. Much more difficult is it to think forward and project possible scenarios. Perhaps the future technology of 200 years from now will be just as unbelievable to us as our present technology is unbelievable to someone of 200 years ago. This assumes we survive as a civilization for that long.

Calculation Corner: How Pure Is Pure?

A 100-gram sample of water contains about 3 × 10^{24} molecules. If this sample were ideally pure, every one of those molecules would be water. Atoms and molecules, however, are so amazingly small, and hence numerous, that the formation of a truly pure sample of macroscopic quantity is virtually impossible.

For example, consider a 100-gram sample of water that is 99.9999 percent pure. What this means is that the sample contains 99.9999 grams of water, which is still nearly 3 × 10^{24} water molecules. Pretty good, right? However, if the remaining 0.0001 grams were made of dissolved lead, Pb, then this would correspond to about 3 × 10^{17} (300,000 trillion) atoms of Pb, which is quite small compared to the number of water molecules but is still an amazingly large number.

Any material that is seemingly pure will inevitably contain impurities. Sometimes these impurities are of particular interest. For example, minor impurities in a solution might be toxic and their presence might need to be monitored. How much is present is frequently measured in units of milligrams per liter (mg/L), micrograms per liter (mg/L), or nanograms per liter (ng/L) of solution.

One liter of water contains one million milligrams of water. Because 1 L of water equals 1 million mg of water, the units of mg/L can also be expressed as 1 mg per 1 million mg. Another way of saying this is one part per million, or simply 1 ppm. The units of mg/L and ppm, therefore, are equivalent. Similarly, "micrograms per liter" is often expressed as parts per billion, ppb, and "nanograms per liter" is often expressed as parts per trillion, ppt. (As Table 1.3 shows, 1 milligram equals 1000 micrograms, while 1 microgram equals 1000 nanograms.)

EXAMPLE

There are about 35 grams of salts in every liter of ocean water. Express this concentration in units of ppm.

ANSWER

Convert grams of salt into milligrams of salt:

(35 g salts)(1000 mg/1g) = 35,000 mg

There are about 35,000 mg of salts in a liter of ocean water, which equals 35,000 ppm.

YOUR TURN

1. Typical levels of fluoride found in fluoridated public drinking water are about 1.0 ppm. If you were to drink a liter of this water, show that you have ingested 1 milligram of fluoride.

2. Aquatic organisms require a dissolved oxygen concentration of about 6 ppm. At this concentration, show that there are 0.006 grams of oxygen present in each liter of water.

3. Chloroform, $CHCl_3$, is a common contaminant of chlorinated drinking water. A usual concentration in municipal tap water may be around 25 ppb. At this concentration, show that there are 0.025 milligrams of chloroform are present in each liter of water.

4. Assume that the population of the United States is 330 million. Show that each U.S. citizen has a concentration of 3.0 ppb. Assume a world human population of 8 billion. Show that each human has a concentration of 125 ppt. If you can imagine how small in number you are compared to national or world populations, then you have a sense of how dilute a dissolved substance is when its concentration is measured by the ppb or ppt.