Chapter 1

Introduction to Nanotechnology Concepts

In This Chapter

- Exploring the definition of nanotechnology
- Understanding how nano-sized materials vary from bulk materials
- Examining the bottom-up and top-down approaches to nano
- Following nano's role across disciplines and industries

Nanotechnology has been around as a recognized branch of science for only about fifty years, so it's a baby compared to physics or biology, whose roots go back more than a thousand years. Because of the young age of nanotechnology and our still-evolving understanding of it, defining it is an ongoing process, as you find in this chapter.

In addition, we help you understand nano by comparing it to more familiar concepts, such as atomic structure, and look at how materials change at the nano level.

Finally, the promise nanotechnology holds for the human race ranges from extending our lives by centuries to providing cheap energy and cleaning our air and water. In this chapter, you explore the broad reach that nanotechnology has across several scientific disciplines and many industries.

What Is Nanotechnology, Anyway?

To help you understand exactly what nanotechnology is, we start by providing a definition — or two. Then we explore how nano-sized particles compare with atoms.

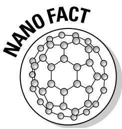
Pinning down a definition

Nanotechnology is still evolving, and there doesn't seem to be one definition that everybody agrees on. We know that nano deals with matter on a very small scale: larger than atoms but smaller than a breadcrumb. We know that matter at the nano scale can behave differently than bulk matter. Beyond that, individuals and groups focus on different aspects of nanotechnology as a discipline. Here are a few definitions of nanotechnology for your consideration.

The following definition is probably the most barebones and generally agreed upon:

> *Nanotechnology is the study and use of structures between 1 nanometer (nm) and 100 nanometers in size.*

To put these measurements in perspective, you would have to stack 1 billion nanometer-sized particles on top of each other to reach the height of a 1-meter-high (about 3-feet 3-inches-high) hall table. Another popular comparison is that you can fit about 80,000 nanometers in the width of a single human hair.



The word *nano* is a scientific prefix that stands for 10^{-9} or 1 billionth; the word itself comes from the Greek word *nanos,* meaning dwarf.

The next definition is from the Foresight Institute and adds a mention of the various fields of science that come into play with nanotechnology:

> *Structures, devices, and systems having novel properties and functions due to the arrangement of their atoms on the 1 to 100 nanometer scale. Many fields of endeavor contribute to nanotechnology, including molecular physics, materials science, chemistry, biology, computer science, electrical engineering, and mechanical engineering.*

The European Commission offers the following definition, which both repeats the fact mentioned in the previous definition that materials at the nanoscale have novel properties, and positions nano vis-à-vis its potential in the economic marketplace:

> *Nanotechnology is the study of phenomena and fine-tuning of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale. Products based on nanotechnology are already in use and analysts expect markets to grow by hundreds of billions of euros during this decade.*

This next definition from the National Nanotechnology Initiative adds the fact that nanotechnology involves certain activities, such as measuring and manipulating nanoscale matter:

> *Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.*

The last definition is from Thomas Theis, director of physical sciences at the IBM Watson Research Center. It offers a broader and interesting perspective of the role and value of nanotechnology in our world:

> *[Nanotechnology is] an upcoming economic, business, and social phenomenon. Nano-advocates argue it will revolutionize the way we live, work and communicate.*

Before nano there was the atom

If you remember your high school science class, you know something about atoms, so we'll take that as our starting point in explaining the evolution of nanotechnology. Figure 1-1 is an illustration of an atom containing positively charged protons and neutral neutrons in the nucleus (center) of the atom, as well as negatively charged electrons in orbit around the nucleus.

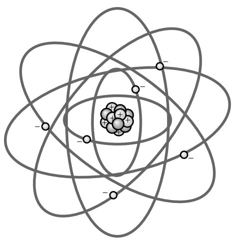


Figure 1-1: Simple model for the structure of an atom.

The word *atom* comes from the Greek word for indivisible, *atomos.* The atomic bomb demonstrated that atoms can indeed be split, but way back in 450 B.C. they were blissfully unaware of such possibilities. In 1803 John Dalton discovered that elements such as water are actually collections of atoms. These collections, called molecules, have different characteristics from the separate atoms (think of two hydrogen atoms combining with one oxygen atom and the wet result of H_2O).

Today we recognize that some of Dalton's original theory of the atom doesn't hold water. Still, the most important concepts, that chemical reactions involve the joining and separating of atoms and that atoms have unique properties, are the basis of today's physical science.

The idea that atoms combine to form molecules such as water is key to chemistry, biology, and nanotechnology. The work of Dalton and many other scientists has allowed chemists to develop useful materials, such as plastics, as well as destructive materials, such as explosives. All bulk materials are made up of atoms, so it was necessary to first understand atoms to learn how to make new materials. Scientists could draw conclusions about atoms based on the properties of the materials they produced, even though they couldn't see inside an atom.

An important point to underscore is that nobody has ever seen the structure of an atom. Even today's most sophisticated microscopes don't reveal the details of atoms, just fuzzy pictures of tiny orbs. All the information about the structure of atoms is based on empirical evidence. Scientists determined that each type of atom absorbed different frequencies of light and then used those differences to make a model of the structure of electrons around the nucleus of each atom. Other scientists bombarded atoms with very small high-energy particles and analyzed what type of particles resulted from collisions with the atomic nucleus to guess at what was inside the nucleus of each type of atom. Then scientists did the math and developed a model of each atom to match their results. The way we describe atoms to our high school students today continues to evolve as physicists probe atoms with higher and higher energy particles to provide more details about the components of the atomic nucleus.

So how does all this information about atoms relate to nanotechnology? *Nanoparticles* (particles whose diameter, width, or length is between 1 nanometer and 100 nanometers) are bigger than atoms and, like atoms, are around us everyday. They are given off by candle flames, wood fires, diesel engines, laser printers, vacuum cleaners, and many other sources. Scientists worked with nanoparticles for centuries before these particles had a name. But unlike atoms — and this is a big difference — we can now see the structure of nanoparticles. This breakthrough came a few decades ago with the advent of electron microscopes. Figure 1-2 shows the structure of some key nanoparticles (such as the DNA molecule in the bottom left) and their size in relation to other materials.

With our understanding of atomic theory and the ability to see things at the nanoscale, we now have knowledge in place that allows us to manipulate matter in ways never before possible.

See Chapter 3 for more about nanoparticles and materials and Chapter 4 for information about how these can be manipulated.

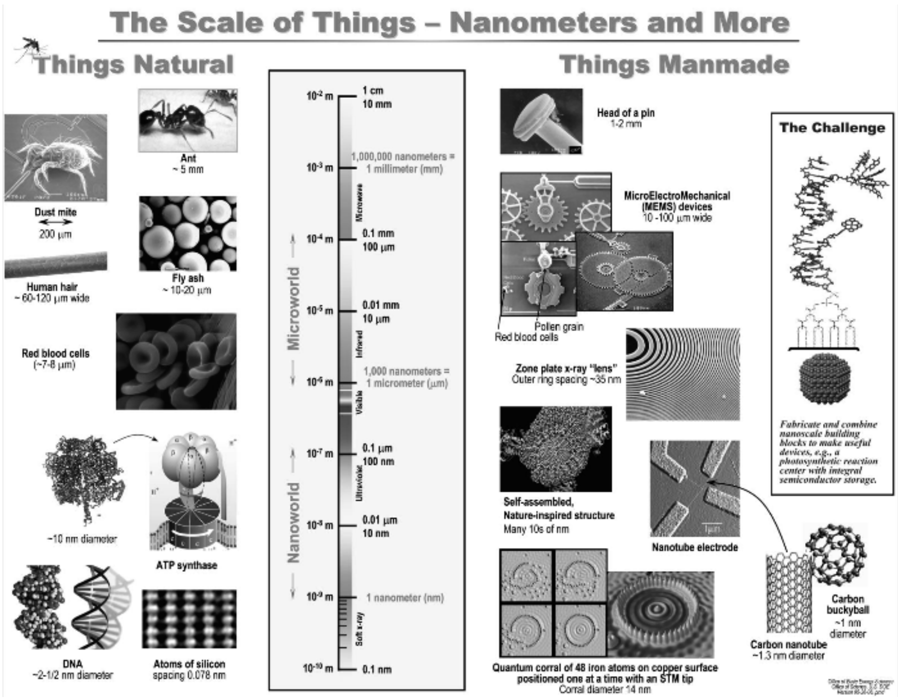


Figure 1-2: The scale of things.

Photo by the United States Department of Energy's Office of Basic Energy Sciences

Moving from half-baked to Bakelite

Have you ever wondered what the first entirely man-made (synthetic) substance was? Turns out it was a resin-based material called Bakelite, the very first plastic. Bakelite was developed by a chemist named Leo Baekeland. Producing Bakelite involves the application of heat and pressure while mixing two chemicals. Bakelite hardens to form the shape of any mold you pour it into. Its unique composition means that you can't burn it or dissolve it with any commonly available acid. The United States military saw Bakelite as the basis for producing lightweight weapons, and Bakelite became a part of most weapons used in World War II.

Bakelite also found its way into products such as electrical insulators and dishware. The stuff doesn't break, crack, or fade. (Okay, this sounds like an infomercial, but this stuff is really amazing.) Today other plastics have largely replaced Bakelite in general use, but it was a big breakthrough in its time.

Approaching Nanotechnology from Above and Below

How we should use our knowledge of nanoparticles has been a subject of much debate. Nanotechnologists have offered two approaches for fabricating materials or manipulating devices using nanotechnology: top down and bottom up.

Imagine you need to build the tiniest computer chip possible. Using the *bottom-up* approach, you would use nanotechnology to assemble the chip atom by atom, placing each type of atom in a specific location to build the circuit. With the *top-down* approach, you would instead create the computer chip by carving away at bulk material — much like a sculptor and his artwork — to create nano-sized features, never dealing with the atomic level of matter.

The top-down method is currently in use to manufacture computer chips as well as other products you use every day. The bottom-up method is in the theoretical stage, with researchers doing initial experiments to develop these techniques.

TECHNICAL STUFF

Nanotechnologists also use a technique called self-assembly, discussed in Chapter 4, to build structures using nanoparticles. *Self-assembly* involves creating conditions such that atoms and molecules arrange themselves in a specific way to create a material. Some consider this one form of the bottom-up approach.

Examining four generations of nano development

Mihail (Mike) Roco of the Nanotechnology Initiative has suggested that nanotechnology development will occur in four generations. Currently, according to Roco, we're in an era of passive nanostructures, which he describes as "materials designed to perform one task." In the second generation, which we have already entered, we are using "active nanostructures for multitasking." These nanostructures would include devices to deliver drugs in a targeted way. The third generation would include nanosystems that might involve thousands of components interacting with each other. Finally, several years in the future, we may see integrated nanosystems, including systems within systems that could accomplish far more than we can today, such as sophisticated molecular manufacturing of genes inside the DNA of targeted cells and nanosurgery for healing wounds on the cellular level.

Understanding How Nano Changes Things

We've stated that materials at the nano level have different characteristics than so-called bulk materials. That's a key concept worthy of a little more explanation.

Nanoparticles are so small they contain just a few atoms to a few thousand atoms, as opposed to bulk materials that might contain many billions of atoms. This difference is what causes nano materials to have unique characteristics, including how they react with other materials, their color, and even how they melt at high temperatures.

In this section, we explore these differences and help you begin to understand the changes they make possible.

Reacting with other elements

One aspect of how nano-sized particles act differently is how they behave in chemical reactions. One of the most interesting examples of this involves gold.

Gold is considered an inert material in that it doesn't corrode or tarnish (which is why you paid so much for that ring on your finger). Normally, gold would be a silly material to use as a catalyst for chemical reactions because it doesn't do much. However, break gold down to nanosize (approximately 5 nanometers) and it can act as a catalyst that can do things like oxidizing carbon monoxide.

This transformation works as follows. The smaller the nanoparticle, the larger the proportion of atoms at the surface, and the larger proportion of atoms at the corners of the crystal. While in the bulk form, each gold atom (except the small percentage of them at the surface) is surrounded by twelve other gold atoms; even the gold atoms at the surface have six adjacent gold atoms. In a gold nanoparticle a much larger percentage of gold atoms sits at the surface. Because gold forms crystalline shapes, as shown in Figure 1-3, gold atoms at the corners of the crystals are surrounded by fewer gold atoms than those in the surface of bulk gold. The exposed atoms at the corners of the crystal are more reactive than gold atoms in the bulk form, which allows the gold nanoparticles to catalyze reactions.

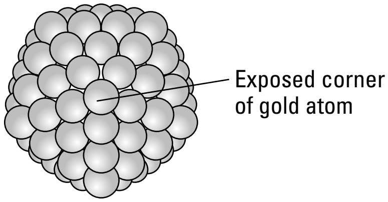


Figure 1-3: A gold nanoparticle.

Changing color

It turns out that gold's capability to catalyze reactions is not the only thing that changes at the nanoscale. Gold can actually change color depending on the size of the gold particles.

One of the characteristics of metals is that they are shiny because light reflects off their surfaces. This reflectivity has to do with electron clouds at the surface of metals. Because photons of light can't get through these clouds and therefore aren't absorbed by the electrons bound to atoms in metals, the photons are reflected back to your eye and you see that shiny bling quality.

In addition to this shininess, metals have different colors because different colors are reflected more strongly than others. Gold and copper, for example, have lower reflectivity for shorter wavelengths, such as blue, than for longer wavelengths, such as yellow, green, and red, causing a gold tone. Silver has a more constant reflectivity across wavelengths, so it reflects all colors, making it seem more like an absence of color (white).

In bulk form, gold reflects light. At the nanoscale, the electron cloud at the surface of a gold nanoparticle resonates with different wavelengths of light depending upon their frequency. Depending on the size of the nanoparticle, the electron cloud will be in resonance with a particular wavelength of light and absorb that wavelength. A nanoparticle of about 90 nm in size will absorb colors on the red and yellow end of the color spectrum, making the nanoparticle appear blue-green. A smaller-sized particle, about 30 nm in size, absorbs blues and greens, resulting in a red appearance.

Nanotechnologists are debating the possible use of this color-changing characteristic to build sensors in fields such as medicine.

Melting at lower temperatures

Another characteristic that varies at the nano level is the temperature at which a material melts. In bulk form, a material, such as gold, has a certain melting temperature regardless of whether you're melting a small ring or a bar of gold. However, when you get down to the nanoscale, melting temperatures begin to vary by as much as hundreds of degrees.

Gold nanoparticles melt at relatively low temperatures (~300 degrees celsius for 2.5 nm size) whereas a slab of gold melts at a toasty 1064 °C.

This difference in melting temperature again relates to the number of atoms on the surface and corners of gold nanoparticles. With a greater number of atoms exposed, heat can break down the bond between them and surrounding atoms at a lower temperature. The smaller the particle, the lower its melting point.

Nano Is Everywhere

Nanotechnology is sometimes referred to as a general-purpose technology because in its more advanced stages it will have a significant impact on almost all industries and all areas of society.

Nanotechnology is unlike other scientific disciplines you may be familiar with in its breadth. It pulls in information from physics, chemistry, engineering, and biology to study and use materials at the nano level to achieve various results.

It turns out that being able to see and work with things on a very small level has some very big ramifications not isolated to one industry or field. In this section you get an idea of the types of applications and future changes nano is making possible.

Applying nano in various settings

Nanotechniques can be applied in many different settings and many different applications. It crosses industries, enabling achievements in areas such as manufacturing, medicine, space travel, energy, and the environment. The techniques being developed for creating and manipulating particles at the nano level hold out the hope for curing diseases such as cancer, cleaning our air, and producing cheap energy.

Think of some other scientific disciplines. Medicine pertains only to healthcare; astronomy is lost in the stars; zoologists focus on animals. But nanotechnology doesn't have that single focus; in that respect, it's more like physics or chemistry, scientific disciplines whose discoveries can be used in many areas and many industries and with many other sciences.

This range of effect is indicated by the many federal agencies that participate in the *National Nanotechnology Initiative,* whose web site is shown in Figure 1-4. These agencies include the Departments of Agriculture, Defense, Energy, Labor, Transportation, and Treasury, as well as organizations such as the National Institute of Health, Forest Service, NASA, and the Environmental Protection Agency.

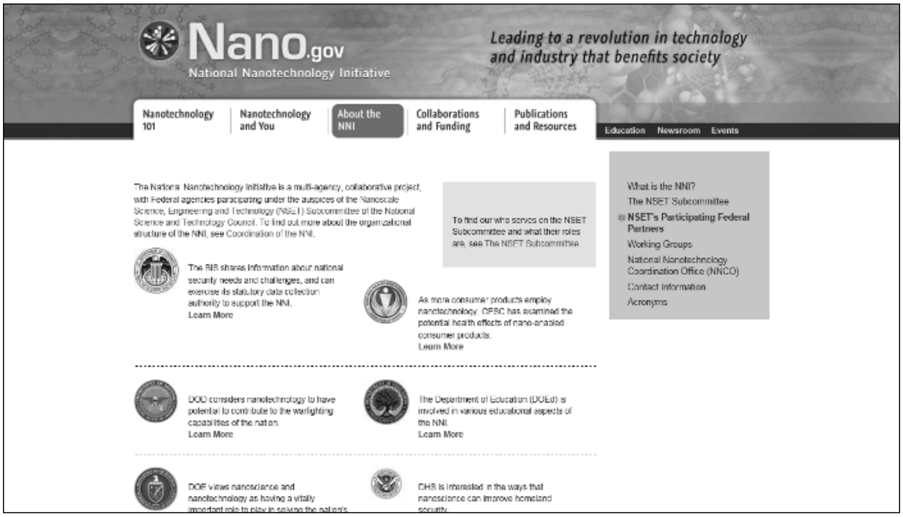


Figure 1-4: Some of the agencies participating in the National Nanotechnology Initiative.

Nano is also used in many commercial settings, many of which you'll hear about in more detail in subsequent chapters. For example, nano materials are used to

- Add strength to materials used in products ranging from tennis rackets to windmills
- Act as catalysts in chemical manufacturing
- Help absorption of drugs into the body
- Add stain resistance to fabrics used in clothing
- Make medical imaging tools such as MRIs function more accurately
- Improve the efficiency of energy sources such as batteries and fuel cells
- Purify drinking water and clean up our air

There may even be nanoceramics in your dental implants, taking advantage of the fact that their properties can be adjusted to match the properties of the tissue surrounding them. And just about every electronic gadget you own probably has some type of *nanomaterial* in it, especially in the chips used in computing devices.

Taking a clue from educators

If you want to find out whether a field involves various disciplines, check out the university programs offered for those interested in the field. What you'll find is that nanotechnology is such an interdisciplinary field that many educational programs accept students from a range of disciplines.

Mahbub Uddin and Raj Chodhury, in a conference paper on Nanotechnology Education, make this statement about the challenge of providing nanotechnology education: "Nanotechnology is truly interdisciplinary. An interdisciplinary curriculum that encompasses a broad understanding of basic sciences intertwined with engineering sciences and information sciences pertinent to nanotechnology is essential."

NANO RESOURCE

If you'd like to read the full article, go to this URL: `www.actionbioscience.org/education/uddin_chowdhury.html`.

Various programs at institutions such as Northeastern University, Rice University (see Figure 1-5), and Penn State offer courses and degrees in everything from nanomedicine to nanobusiness. These programs are available to students majoring in such disciplines as Biology, Chemistry, Physics, Chemical Engineering, Mechanical/Industrial Engineering, Electrical/Computer Engineering, Pharmaceutical Sciences, Materials Science and Engineering, Integrative Biosciences, and Applied Chemistry.

It's clear from these examples that preparing students for a career in nanotechnology can involve knowledge of both nanotechnology and the specialty of their choosing.

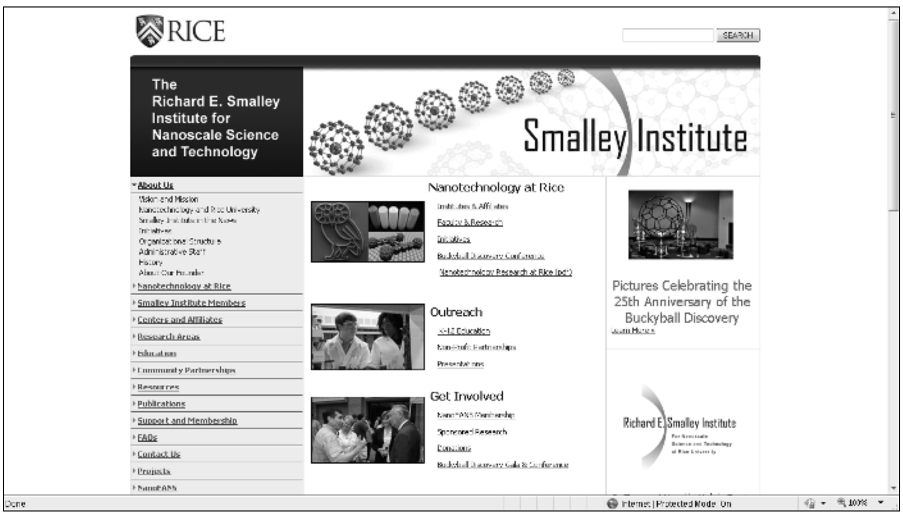


Figure 1-5: The Smalley Institute at Rice University.