1

The Basics of Nanotechnology

1.1 Definitions and Scales

Before delving into the depths of nanotechnology and nanoscale science, we should be clear what we mean when we use terms such as 'nanotechnology,' 'nanoscience,' and 'nanoscale.' It is a basic nomenclature, used to describe certain attributes of certain systems, and such nomenclatures are typically designed to eliminate confusion and encourage accurate communication among those discussing the system. To be sure, there will be several other variants of words with the prefix 'nano-' used in this book and it is important to make sure that we have our meanings straight if any sort of meaningful discussion is possible.

The prefix 'nano-' is derived from the Greek word *nannos*, meaning "very short man." Most of the measurement prefixes used today originate from Greek and Latin words used in measurements. For example, 'kilo-' is from the Greek word *khilioi* meaning "one thousand" and 'milli-' is from the Latin word *mille* meaning "one thousand." Greek and Latin words for numbers cover the everyday level of measurements from one-thousandth to one thousand. Beyond that, it gets interesting. To describe one billion (1,000,000,000) of something we use the prefix 'giga-' which is from the Greek word *gigas* meaning "giant." We also get the word "gigantic" from this root. On the other end of the spectrum, to describe one millionth (0.000 001) we use the prefix 'micro-' from the Greek word *mikros* meaning "small." To describe one trillionth (0.000 000 000 001) we use the prefix 'pico-' from the Spanish word *pico*, which can mean both a "beak" and a "small quantity." These prefixes are extremely useful when discussing very large or very small values. For example, we could refer to the radius of the Earth at its equator as being 6,378,100 meters, but it is more useful (and requires less effort) to refer to it as 6,378.1 kilometers. The most common scientific prefixes and their derivations are shown in Table 1.1.

Table 1.1 Etymology of scientific prefixes

Prefix	*Language of origin*	*Word*	*Meaning of word*	*Value*
Zetta	Latin	Septem	Seven	$(10^3)^7 = 10^{21}$
Exa	Greek	Hexa	Six	$(10^3)^6 = 10^{18}$
Peta	Greek	Penta	Five	$(10^3)^5 = 10^{15}$
Tera	Greek	Teras	Monster	10^{12}
Giga	Greek	Gigas	Giant	10^9
Mega	Greek	Megas	Great	10^6
Kilo	Greek	Khilioi	One thousand	10^3
Hecto	Greek	Hekaton	One hundred	10^2
Deca	Greek	Deka	Ten	10^1
Deci	Latin	Decem	Ten	10^{-1}
Centi	Latin	Centum	One hundred	10^{-2}
Milli	Latin	Mille	One thousand	10^{-3}
Micro	Greek	Mikros	Small	10^{-6}
Nano	Greek	Nannos	Dwarf	10^{-9}
Pico	Spanish	Pico	Beak, small quantity	10^{-12}
Femto	Danish	Femten	Fifteen	10^{-15}
Atto	Danish	Atten	Eighteen	10^{-18}
Zepto	Latin	Septem	Seven	$(10^{-3})^7 = 10^{-21}$

At its root, the prefix ‘nano-’ refers to a scale of size in the metric system. ‘Nano’ is used in scientific units to denote one-billionth (0.000 000 001) of the base unit. For example, it takes one billion nanoseconds to make a second. In everyday practical use, the term ‘nanosecond’ is not very useful in describing time accurately. Imagine discussing time in these terms: we would say things like “dinner will be ready in 300,000,000,000 nanoseconds.” Instead, the term ‘nanosecond’ is mainly used to refer to a very short period of time. (A nanosecond is to a second as one second is to approximately 30 years.)

When we are talking about *nano*technology, we are talking about a scale – an order of magnitude – of size, or length. We are making a reference to objects that are sized on a scale that is relevant when we discuss *nanometers* (nm). Using this terminology makes it easier to discuss the size of objects that are the main attraction in nanotechnology, namely atoms. If we were to describe the size of atoms and molecules in feet or meters, we would have to say that a hydrogen atom (the smallest atom) is 7.874×10^{-10} feet or 2.4×10^{-10} meters. Instead, we can use nanometers and say that the hydrogen atom is 0.24 nm.

The nanoscale, then, is the size scale at which nanotechnology operates. Though we have a lower limit on this scale size (the size of one atom), pinning down an upper limit on this scale is more difficult. A useful and well-accepted convention is that for something to exist on the nanoscale, at least one of its dimensions (height, width, or depth) must be less than about 100 nanometers. In fact, it is these limits to the nanoscale that the National Nanotechnology Initiative (NNI) uses for its definition of nanotechnology: "Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nm, where unique phenomena enable novel applications."[1] To this, it is useful to add two other statements to form a complete definition. First, nanotechnology includes the forming and use of materials, structures, devices, and systems that have unique properties because of their small size. Also, nanotechnology includes the technologies that enable the control of materials at the nanoscale.

Though we have established that the 'nano-' in 'nanotechnology' signifies a particular scale, it is important to get a good idea of what that scale is – that is, what size the nanoscale is in relation to our everyday experience. There are several analogies that we can use to explain the size of a nanometer in relation to sizes that are more commonly known. For example, it takes 50,000 nm to make up the width of a single strand of human hair. Another example is as follows: a nanometer compared to the size of a meter is roughly of the same proportion as a golf ball compared to the size of the Earth. Perhaps the best way to illustrate the nanometer scale is by describing the range of length scales from the centimeter down to the nanoscale. An ant is on the order of 5 mm (10^{-3} meters) in size. The head of a pin is 1–2 mm. A dust mite is 200 μm (10^{-6} meters) in size. A human hair is about half the size of a dust mite, 100 μm wide. The red blood cells that flow in our veins are about 8 μm in diameter. Even smaller than that, the ATP synthase of our cells is 10 nm (10^{-9}) in diameter. The size of the double helix of DNA on the nanoscale is about 2 nm wide. Finally, atoms themselves are typically less than a nanometer in size and are sometimes spoken about in terms of angstroms (10^{-10} meters).

1.2 The Origins of Nanotechnology

Nanotechnology, like any other successful technology, has many founders. In one sense, the very field of chemistry has been working on nanotechnology since its inception, as have materials science, condensed physics, and solid state physics. The nanoscale is not really all that new. But investigating and designing with a specific eye on the nanoscale is new – and revolutionary.

The term 'nanotechnology' can be traced back to 1974. It was first used by Norio Taniguchi in a paper entitled "On the Basic Concept of 'Nano-Technology'."[2] In this paper, Taniguchi described nanotechnology as

[1] "What is Nanotechnology?" National Nanotechnology Initiative. Available at http://www.nano.gov/html/facts/whatIsNano.html (accessed October 11, 2008).

[2] Norio Taniguchi, "On the Basic Concept of Nanotechnology," *Proceedings of the International Conference of Production Engineering, London, Part II*. British Society of Precision Engineering, 1974.

the technology that engineers materials at the nanometer level. However, nanotechnology's history predates this. Traditionally, the origins of nanotechnology are traced back to a speech given by Richard Feynman at the California Institute of Technology in December 1959 called "There's Plenty of Room at the Bottom."[3] In this talk, Feynman spoke about the principles of miniaturization and atomic-level precision and how these concepts do not violate any known law of physics. He proposed that it was possible to build a surgical nanoscale robot by developing quarter-scale manipulator hands that would build quarter-scale machine tools analogous to those found in machine shops, continuing until the nanoscale is reached, eight iterations later. As we will see, this is not exactly the path that nanotechnology research has actually followed.

Feynman also discussed systems in nature that achieve atomic-level precision unaided by human design. Furthermore, he laid out some precise steps that might need to be taken in order to begin work in this uncharted field.[4] These included the development of more powerful electron microscopes, key tools in viewing the very small. He also discussed the need for more fundamental discovery in biology and biochemistry. Feynman concluded this talk with a prize challenge. The first challenge was 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."[5] The second challenge was to make "an operating electric motor – a rotary electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube."[6] He ended the talk by saying "I do not expect that such prizes will have to wait very long for claimants."[7] He was right about one of the prizes: the motor was built fairly quickly and by a craftsman using tools available at the time. However, it was not until 1985 that a graduate student at Stanford named Tom Newman reduced the first paragraph of Charles Dickens' *A Tale of Two Cities* to 1/25,000 its size.

In his paper on the basic concept of nanotechnology, Taniguchi developed Feynman's ideas in more detail. Taniguchi stated, " 'Nano-technology' is the production technology to get the extra high accuracy and ultra fine dimensions, i.e., the preciseness and fineness of the order of 1 nm

[3] Richard P. Feynman, "There's Plenty of Room at the Bottom," *Journal of Microelectromechanical Systems* 1 (1992): 60–6.

[4] Physicists, especially, had not explored this field much. Most physicists at the time were focused on high-energy physics, probing into the atom to look at quarks and subnuclear reactions, astrophysics, or nuclear physics. Much of what fell in between was left to chemists and engineers, as many of the fundamental equations in this area of the natural world were believed to be explained already.

[5] Feynman, "There's Plenty of Room," p. 66.

[6] Ibid.

[7] Ibid.

(nanometer), 10^{-9} m in length. With materials the smallest bit size of stock removal, flow, or design is one atom (generally about 1/5th of a nanometer), so the limit of fineness of materials is on the order of one nanometer."[8] In the paper, Taniguchi discussed his concept of 'nanotechnology' in materials processing, basing this on the microscopic behavior of materials. Taniguchi imagined that ion sputtering would be the most promising process for the technology. As we will discuss later in this section, many tools and techniques are used for the development of this type of nanotechnology.

Then, in 1987, K. Eric Drexler published his book, *Engines of Creation: The Coming Era of Nanotechnology*.[9] Aimed at a non-technical audience while also appealing to scientists, Drexler's book was a highly original work describing a new form of technology based on molecular "assemblers," which would be able to "place atoms in almost any reasonable arrangement" and thereby allow the formation of "almost anything the laws of nature allow." This may sound like a fanciful and fantastical idea but, as Drexler points out, this is something that nature already does, unaided by human design, with the biologically based machines inside our own bodies (and those of any biological species). There has been significant debate about the possibilities, promise, and troubles with what is now called "molecular manufacturing." Even the possibility of these machines is widely debated. Suffice it to say, however, that *Engines of Creation* marks a distinct jumping-off point for nanotechnology and the associative scientific research. Even though much of this research had nothing at all to do with molecular manufacturing, the focus on the scale of the research objects became the most important factor. Tools developed to handle individual atoms, such as the scanning probe microscope at IBM, enabled researchers to study and manipulate individual atoms and molecules with a degree never before possible. In a very famous image, researchers at IBM moved xenon atoms around on a nickel substrate with a scanning tunneling microscope. This image used the atoms to spell out the company's logo, "IBM." Electron microscopes developed to the point that they could be in more and more research environments (including, sometimes, in biological applications as Feynman desired). Able to see individual atoms and their arrangements within materials, researchers began to study developing atomically precise materials and devices.

The discovery of novel materials on the nanoscale notably began with the Buckminsterfullerene (also called the buckyball). The buckyball was so named because of the resemblance to the geodesic domes that the architect Richard Buckminster Fuller popularized. Discovered in 1985 at Rice University, it consists of an arrangement of 60 carbon atoms. In 1991,

[8] Taniguchi, "On the Basic Concept."

[9] Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (New York: Broadway Books, 1987).

nanoscale materials became the focus of intense research with the discovery of the carbon nanotubes by Sumio Iijima of NEC. At a somewhat feverish pace, novel nanoscale material after novel nanoscale material has been reported ever since. Nanotechnology is now recognized as the future of technological development. In 2000, the US government developed the National Nanotechnology Initiative (NNI) in order to administer funding and develop nanotechnology as the major research thrust of the twenty-first century.

1.3 The Current State of Nanotechnology

Having looked at the basic history of nanotechnology, we can now investigate where we currently stand. In particular, how is nanotechnology researched in laboratories across the world today? What is the current direction of nanotechnology research? The answer helps us understand the development, characterization, and functionalization of nanoscale materials and the science that governs them. This involves three main thrusts of research: nanoscale science (or "nanoscience" – the science of interaction and behavior at the nanoscale), nanomaterials development (the actual experimental development of nanoscale materials, including their use in device applications), and modeling (computer modeling of interactions and properties of nanoscale materials).

Understanding the underlying science of nanoscale interactions is extremely important to the development of nanotechnology; these interactions constitute one of the main areas of research in the field of nanotechnology. The laws of physics that operate on objects at the nanoscale combine classical (or Newtonian) mechanics, which governs operations of everyday objects, and quantum mechanics, which governs the interactions of very small things. Though many of the fundamental laws of nature that operate on this level have been discovered, science at this scale is still very difficult. Quantum mechanics works at this scale, but the interplay between the high number – that is, greater than two – of atoms in nanoscale materials can make it difficult to predict the actual outcome of these interactions. Furthermore, classical mechanics works on this scale, but the small size of the materials and the close scale of the interactions can make forces that are well understood at large scales (e.g., friction) and/or powerful at those scales (e.g., gravity) mysterious and/or less powerful at the nanoscale. Understanding the forces and theories at play within nanotechnology is just one aspect of nanoscience.

Another very important aspect of nanoscience is understanding the formation of nanoscale materials and devices. In looking at the nanoscale, traditional (non-nano) materials, structures, and devices are often referred to as "bulk technology." To be sure, this "bulk" style of technology has led to many great accomplishments: we easily make wonderful computing devices, ultra-strong steel, and very pure ceramics. Using bulk technology, we can create exquisitely small devices and materials. However, this creation is still done by cutting, chipping, pounding, extruding, melting, and performing other such bulk procedures to materials to create the new device, structure, or material. The main difference with nanotechnology is this creation process. With nanotechnology, we start on the atomic scale and, controlling atomic/molecular placement and arrangement, we build up the technology into unique devices, materials, and structures. This new type of formation requires new types of synthesis, requiring a new understanding of the formation of materials on the nanoscale. Furthermore, many materials have extremely unique properties when they are developed at a nanoscale. Many materials configure themselves in different atomic arrangements not seen in the bulk form of the same materials. Understanding the changes that these materials undergo as they are formed on a smaller scale is vital to developing the use of these materials in devices.

Nanotechnology today focuses, as we have already mentioned, on the development, understanding, and use of materials at the nanoscale, or nanomaterials. Materials are made up by an arrangement of particular atoms – typically in a specific way – which helps define the property of the material. For example, steel is one of the strongest engineering materials, and its strength will increase as carbon is added to it. Steel is made of mostly iron with other elements added: stainless steel, for example, contains 10 percent chromium to protect the material against corrosion.

Actually, materials throughout history have basically defined the technology of the age. We refer to the Stone Age and the Iron Age because of the types of materials that were used or developed during those eras to make the technology that was used in everyday life. For example, the Bronze Age was a period in civilization's development when the most advanced widespread metalworking consisted of techniques for smelting copper and tin from naturally occurring ore and then alloying those metals in order to cast bronze. In more modern times we can see that the development of methods for using silicon and other semiconductors is essential to developing modern computing devices and many other devices that we use on a daily basis.

On the nanoscale, this association between material, device, and structure only amplifies since these are virtually indistinguishable from each other at that scale. Nanomaterials can also be used in conjunction with other materials, thus augmenting the properties of those other materials. In this sense, nanoscale materials have been important to the materials field for some time. For example, nano-sized carbon black particles have been used to reinforce tires for nearly 100 years. Another, more common, example is precipitation hardening of materials. Precipitation hardening is a heat treatment technique that is used to strengthen materials, particularly some metals. It relies on producing fine, impure nanoscale particles, which then impede the moving of defects within the material. Since these defects are the dominant cause of plasticity in materials, the treatment hardens the material. This accidental discovery in 1906 allowed for significant improvements in the strength of aluminum. At the time, researchers could not image these precipitates. It was later discovered that the precipitates were nano-sized particles.

Materials are the essence of technology at the nanoscale. Because of the scale of the technology, the atomic species and structure define not only the properties of the material but also the function of the device. Furthermore, different materials interact differently with their environment when they are sized on the nanoscale. Bulk materials interact with their environment in a certain way because the vast majority of their atoms are inside the volume of the material rather than on the surface; this makes the surface-to-volume ratio very small. Atoms respond to their environment differently when they are surrounded by other atoms than when they are on a surface and do not have atoms surrounding them. And the relative amount of atoms on the surface can greatly influence the properties of the material as a whole. With nanoscale materials, many of the atoms reside on the surface of the material and therefore the surface-to-volume ratio is much larger. For example, a spherical particle that has a radius of 100 micrometers will have a surface-to-volume ratio of about 30,000. This may seem large, but the percentage of atoms on the surface of the material is very small, only 0.006 percent (that is, only 6 out of every 100,000 atoms are on the surface). Compare this with the surface-to-volume ratio of a particle that has a radius of 10 nm. This ratio would be 300,000,000. Here, the percentage of atoms on the surface of the material is a much larger 6 percent (or 6 out of every 100). This can radically change the properties of the material, how it interacts with its environment, and how it can be used in devices.

Another important aspect of nanotechnology is the modeling of nanoscale devices, materials, and interactions. Modeling has an interesting history, through which initially scientists would build actual physical models of molecules and structures in their offices. With these models they would perform the calculations for each atom, move them around on their model, and then start the process all over again – iteration after iteration. John Desmond Bernal, a scientist who pioneered using X-rays to examine the structure of materials, was one such modeler. As he wrote: "I took a number of rubber balls and stuck them together with rods of a selection of different lengths ranging from 2.75 to 4 inch. I tried to do this in the first place as casually as possible, working in my own office, being interrupted every five minutes or so and not remembering what I had done before the interruption."[10] Clearly, another way to perform these calculations was necessary.

[10] John Desmond Bernal, "The Bakerian Lecture, 1962: The Structure of Liquids," *Proceedings of the Royal Society* 208 (1964): 299–322.

Though the simplest calculations can be done by hand on a sheet of paper, computers are required for understanding and modeling the behaviors of large systems (including biological molecules and chemical systems). For these, a massive amount of computing power is necessary. Modern modeling systems that are used in predicting the behavior of nanoscale systems all rely on the atom as their fundamental unit.[11] Modeling provides an approximate solution. The reason that an exact solution cannot be determined for many arrangements is known as the "many-body problem." This problem is best illustrated by looking at quantum mechanics. When we are trying to determine the energy of an atom, the electrons play a central role. Let us look at a few equations just to see how much more complicated they become as electrons are added; without any technical knowledge about how to solve the equations, this point should still be readily apparent. For example, if we wanted to determine the energy of a hydrogen atom (with one electron and one proton), the equation looks like this:

$$E_\alpha = \frac{<\psi_\alpha|\hat{H}|\psi_\alpha>}{(<\psi_\alpha|\psi_\alpha>)}$$

where the symbols are standard quantum mechanical symbols.[12] This problem can be solved by hand. Now, if we add an electron to the system as in a helium atom, the equation becomes more complicated:

$$\left[-\frac{1}{2}\nabla_1^2 - \frac{1}{2}\nabla_2^2 - \frac{Z}{r_1} - \frac{Z}{r_2} + \frac{1}{|\overline{r_1} - \overline{r_2}|}\right]\psi(\overline{r_1}, \overline{r_2}) = E_{\text{el}}\psi(\overline{r_1}, \overline{r_2})$$

This is still solvable by hand, though it would take a little more work. Beyond this, however, the problem becomes unsolvable exactly; it has to be approximated. The equation for the many electrons looks like the following:

$$\left[-\frac{1}{2}\sum_i \nabla_i^2 - \sum_i \frac{Z}{r_j} + \sum_i \sum_{j>i} \frac{1}{|\overline{r_i} - \overline{r_j}|}\right]\psi(\overline{r_1}, \ldots, \overline{r_n}) = E_{\text{el}}\psi(\overline{r_1}, \ldots, \overline{r_n})$$

This equation is unsolvable when the number of electrons is greater than two. The tabulation of a function of one variable requires about a page, but a full calculation of the wave function (the description) of the element

[11] This may not seem all that special, but physical and chemical law relies on quantum calculations in which the atom is not the fundamental unit. In quantum chemistry, the electron is the fundamental unit; it helps determine the bonding of the atoms and the electrical/magnetic characteristics of the material.

[12] It is not within the scope of this work, nor is it necessary to get into the details of the calculation. Rest assured that this calculation is relatively simple and can be performed by hand on the back of an envelope to receive an exact answer.

iron has 78 different variables in it. Even if we simplified the number of each variable to a number like 10 (a very crude approximation), the full determination would require 10^{78} entries. That's a one with 78 zeros after it for just one iron atom. Imagine if we want to determine the properties and interactions of more complex systems! Clearly, approximation is necessary.

Computer simulation and modeling are not without their limitations. A simulation is at best as good as any underlying assumptions. Oftentimes the assumptions and simplifications are ill-conceived, which can cause the results to be misleading. Furthermore, long simulations can be ill-conditioned (i.e., not well suited for computation) and will accumulate errors. A better choice of algorithm can help relieve this problem, but it cannot eliminate it completely. Also, many of the functions used for simplification are not very good for large systems (because of the problems mentioned earlier), and the molecular dynamics simulations that are based on them will come out flawed. Overall, the larger the system being modeled, the more problematic the simulation will be and the more its results will deviate from physical reality.

1.4 The Future of Nanotechnology

The future of nanotechnology has been the subject of myriad books and articles, which span across many genres. Non-fiction books have included Drexler's *Engines of Creation*, John Storrs Hall's *Nanofuture: What's Next for Nanotechnology*,[13] *The Spike* by Damien Broderick,[14] Ray Kurzweil's *The Singularity Is Near*,[15] and investment books such as *Investing in Nanotechnology* by Jack Uldrich.[16] Fiction works include *Prey* by Michael Crichton[17] and Greg Bear's *Slant*.[18] These works cover nanotechnology in a wide variety of ways, from alarmism over technology run amok to Pollyanna-like predictions of a future utopia.

The discussion of the science and development of nanotechnology in this book emphasizes near-term issues and applications; our priority is more to characterize these properly than to offer speculative commentary which would very likely end up wrong. However, it is important to keep in mind the

[13] J. Storrs Hall, *Nanofuture: What's Next for Nanotechnology* (New York: Prometheus Books, 2005).

[14] Damien Broderick, *The Spike: How Our Lives Are Being Transformed by Rapidly Advancing Technologies* (New York: Forge Books, 2002).

[15] Ray Kurzweil, *The Singularity Is Near: When Humans Transcend Biology* (New York: Viking, 2005).

[16] Jack Uldrich, *Investing in Nanotechnology* (New York: Adams Media Corporation, 2006).

[17] Michael Crichton, *Prey* (New York: HarperCollins, 2002).

[18] Greg Bear, *Slant* (New York: Tor Books, 1998).

longer-term implications of nanotechnology, especially in terms of thinking about how the technology will be developed and the more ambitious applications that are driving that development. Researchers think about this when they apply for grants and when they deliberate what type of research to pursue. Grant managers consider the future of technology when they decide which projects to fund. Companies consider the future of technology when deciding how to develop their own financing and technology development.

Here, we will briefly examine some of the future of nanotechnology, though we will also return to the prospect of its particular applications in subsequent chapters. We want to keep in mind some of the broader developments toward which nanotechnology is working. The discussion will include nanotechnology's impacts on computing and robotics, medicine, and molecular machining. We will find that there is significant overlap between these categories and developments.

Nanotechnology computing development is foreseen in two forms. The first is in the development of much smaller devices with much better properties of the computing circuits. This evolution of computing allows for higher density of circuitry and newer architectures, giving greater and greater computing power. It follows a similar path to that of current computing technology. Most readers are familiar with Moore's law, which predicts the doubling of computing power every 24 months.[19]

Kurzweil has written extensively about what this law means (and accelerating exponential growth) and what it means in relation to the development of nanotechnology:

> Moore's Law of Integrated Circuits was not the first, but the fifth paradigm to provide accelerating price-performance. Computing devices have been consistently multiplying in power (per unit of time) from the mechanical calculating devices used in the 1890 US Census, to Turing's relay-based "Robinson" machine that cracked the German Enigma code, to the CBS vacuum tube computer that predicted the election of Eisenhower, to the transistor-based machines used in the first space launches, to the integrated-circuit-based personal [computers].[20]

The second way in which nanotechnology could bear on computing is far more revolutionary. Smaller and more powerful computing allows for the development of nanoscale machines (sometimes called "nanobots").

[19] Moore's law is variously formulated with differences in the doubling time quoted (from one to two years) and the actual measure that is being doubled (from the number of transistors on a single chip to computing power). The law owes to Intel co-founder Gordon Moore, who used the two-year figure for the doubling of transistors on a chip. See Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics* 38.8 (1965): 56–9. See also Intel's website at http://www.intel.com/technology/mooreslaw/ (accessed August 17, 2007).

[20] Ray Kurzweil, "The Law of Accelerating Returns," March 7, 2001. Available at http://www.kurzweilai.net/articles/art0134.html (accessed April 25, 2007).

These machines could be autonomous – as envisioned in Crichton's *Prey* – or they could require outside control. The small nature of these machines would provide for significant advantages over larger robots. For example, nanobots could venture to places previously unthinkable for machines, such as into the bloodstream or into cells. They could be used on rescue missions, searching in places that are too dangerous or too small for larger robotics or humans to venture. They could serve as a laboratory on a chip and be sent to study environments that are harmful for humans, such as the inside of volcanoes, tornadoes, and hurricanes or even outside the Earth's atmosphere. Consider the success of the two rovers that have been studying Mars for the past four years (at the time of writing). They have helped us investigate and learn more about the planet Mars than have years of study by telescope. Smaller-scale (nanoscale) robotics could be made with less material, which would ultimately make them cheaper and require less energy. Though a single nanobot may not be able to provide the level of analysis that a larger robot could, networks of these machines working together could use effective parallel processing to study much more.[21]

Nanoscale robots could also assist with medical treatments; we will discuss this in more detail in Chapter 11 (esp. §11.3), but offer some preliminary discussion here. A nanoscale machine could be programmed to flow through the bloodstream and seek out diseased cells. These cells could then be destroyed specifically. Alternatively, new medicines that target only very specific cells or parts of the body (highly selective medicines) could be developed to eliminate many of the adverse side effects of treatments. Chemotherapy is one treatment that could greatly benefit from this. Traditionally chemotherapy essentially involves a race to kill the diseased cancerous cells before the healthy cells are killed as well.[22] Being able to target only tumor cells with treatments would be a great boon to fighting cancer. In fact, much of the research in nanomedicine focuses on cancer treatment. Consider the use of dendrimers. A dendrimer is a synthetic macromolecule comprising branched repeating units, much like a tree that grows in three dimensions from a core root; the properties of this molecule are controlled by the surface functional groups.[23] Using dendrimers, James Baker at the University of Michigan has shown how to transport a powerful drug inside tumor cells. Folic acid is attached to the surface of the material, and in this way the dendrimer is selectively absorbed by the cancer cells. The

[21] These nanobots may not even require powering their own locomotion once they are on the surface. As light as and smaller than dust, the "nanobots" could simply be blown about by the winds on the planet. Of course we would lose some control over *where* the nanobots are, but a much greater portion of the surface of the planet could be covered in much less time.

[22] Of course, this is an extreme oversimplification of cancer treatments.

[23] See §7.5 for further uses of dendrimers in medical applications, specifically HIV/AIDS prevention.

surface also has anti-cancer drugs attached to it, thereby achieving selective delivery of the drug.[24] Also, sensor test chips containing nanowires made to selectively detect different diseases and irregularities in blood can be developed to detect, *in vivo* and in parallel, many other different diseases.

Of course, the idea of "nanomedicine" is not limited to curing diseases. Using nanoscale and nano-enabled robots to assist in surgery could allow for more precise and safer surgery; already robots with steadier hands than humans are used to perform certain surgeries. Nanoscale robots could enter the body and perform controlled surgery on individual cells, tissues, or organs without requiring an external incision. Human enhancement is another area where nanomedicine is being developed: mankind has a long history of using tools and technology to enhance and augment the natural ability of humans, and nanotechnology can easily be imagined to enhance many different aspects of human performance, from memory to physical ability. We discuss enhancement in greater detail in Chapter 12 (though also see §9.2 for military applications).

Molecular manufacturing was described in detail by Drexler. In particular, he used the biological assembler as supposed proof of the feasibility of assembling atoms and molecules in extremely precise arrangements. According to Drexler:

> Nature shows that molecules can serve as machines because living things work by means of such machinery. Enzymes are molecular machines that make, break, and rearrange the bonds holding other molecules together. Muscles are driven by molecular machines that haul fibers past one another. DNA serves as a data-storage system, transmitting digital instructions to molecular machines, the ribosomes, that manufacture protein molecules. And these protein molecules, in turn, make up most of the molecular machinery.[25]

This vision, while exciting, nevertheless faces challenges. The primary contention is over the feasibility of molecular manufacturing; i.e., whether it is scientifically possible. A well-publicized "debate" between Drexler and Richard Smalley – a Nobel Prize winner and the discoverer of the buckyball – appeared in the pages of *Chemical and Engineering News*.[26] The two have very different views concerning what nanotechnology is and how it works. The scientific objections to the idea of molecular assemblers are summed up as the "fat fingers problem" and the "sticky fingers problem."

[24] Jolanta F. Kukowska-Latallo et al., "Nanoparticle Targeting of Anticancer Drug Improves Therapeutic Response in Animal Model of Human Epithelial Cancer," *Cancer Research* 65.12 (2005): 5317–24.

[25] K. Eric Drexler, "Appendix A: Machines of Inner Space," in B.C. Crandall and James Lewis (eds), *Nanotechnology: Research and Perspectives* (New York: MIT Press, 1993), pp. 325–6.

[26] K. Eric Drexler and Richard Smalley, "Point–Counterpoint: Nanotechnology," *Chemical and Engineering News* 81.48 (2003): 37–42.

The "fat fingers problem" refers to the lack of space available to build a molecular assembly. To assemble a structure one molecule at a time, multiple manipulators are necessary. There simply is not enough room in the nano-sized reaction region to account for all of the atomic-sized "fingers" of all the manipulators necessary to have complete control of the chemistry involved. The "sticky fingers problem" refers to how atoms stick to each other via bonding: this adhesion makes the atoms of the manipulator hands adhere to the atom that is being moved around. Even despite these problems, future nanotechnology may still take a wide range of paths leading to radical new types of technology.

We now turn to familiar forms of nanoscale technology used in the world around us.

1.5 Nanotechnology in Nature and Applications

Natural nanotechnology

Nanotechnology has emerged as a discipline only recently. Like many other technological disciplines, it draws a significant amount of inspiration from nature. With many more years of development than human technology and a very large "laboratory" in which to test new ideas, nature has inspired innovations in technology for a very long time. Going back to the designs of Leonardo da Vinci, inspiration by nature for technologies to help humans are very evident. For example, da Vinci studied in extensive detail the flight of birds to help him design his plans for a helicopter and a hang glider. The wings of many of his hang gliders were based upon those of bats. Modern technology also draws on many concepts observed in nature.

Understanding how nature uses nanoscale forces and materials to achieve some very remarkable things can be used to design engineered devices serving other purposes. Biomimetics (the research field that deals with recreating and mimicking nature's mechanisms in technology) attempts to take advantage of nature's billions of years of evolutionary experience in order to make more effective materials and technology. By looking at how evolutionary pressures have created efficient and adapted traits and structures, scientists can try to use some of those traits and structures in their own designs. Or, as a corollary, failed designs would have been eliminated in nature, so, by copying nature, scientists will avoid at least some of those failures.

One of the more famous examples of biomimetic technology is Velcro. Velcro was developed in 1941 by Georges de Mestral after he noticed burdock seeds sticking to his clothes and his dog's fur. On examining the ball-like seeds, he noticed the hook-ended nature of their fibers that allowed them to stick to other materials. This evolutionary trick allows the seeds to travel and spread: the hooks of the burrs "grab" onto loops of thread or fur. Evolution designed this to help spread the seed, but de Mestral used it in order to aid in adhesion and create the common application, Velcro, that we know and use today.

Scientists have recognized the special functionality of nanoscale materials for some time. In the natural world, the impact of design on the nanoscale is well known and nature has evolved some very interesting uses for nanomaterials. For example, some bacteria have magnetic nanoparticles inside them, which are used as a compass and help provide a sense of direction to the bacterium. Even larger creatures have taken advantage of nanoscale design. Gecko foot hair, nanoscale in size, has been shown to be central in the gecko's exceptional ability to climb rapidly up smooth vertical surfaces. Even the most basic building blocks of biological things are an example of nanoscale design. Most forms of movement in the cellular world are powered by molecular motors that use sophisticated intramolecular amplification mechanisms to take nanometer steps along protein tracks in the cytoplasm.

Gecko feet are an interesting example of nanoscale design providing functionality on a larger scale. Geckos can hang out on a wall and effortlessly cling to just about anything. As far back as Aristotle, it was observed how they can "run up and down a tree in any way."[27] Until recently it was not known exactly how the geckos accomplished such feats, but a 2002 research article in the *Proceedings of the National Academy of Sciences*[28] explained it as a dry adhesion mechanism. The mechanism relies on a force known as the van der Waals force. This force will be discussed in more detail in §2.2, but it implies that the gecko's adhesive properties are not the result of surface chemistry or an epoxy. Instead, they are the result of the size and shape of seta tips. Greater adhesive strength is achieved simply by having a greater surface area (that is, by subdividing the setae).

Another example of nanotechnology in nature is magnetotactic bacteria. "Magnetotactic" is the name of a class of bacteria that orient themselves along the magnetic field lines of the Earth's magnetic field, in much the same way that a compass does. These bacteria were first reported in 1963. This ability to orient themselves arises from the presence of chains of magnetic materials inside their cells. This magnetic material is typically either magnetite (Fe_3O_4) or greigite (Fe_3S_4). That nature uses such a chain of materials that look much like nanowires implies that such magnetic nanoscale wires could be used in technological applications as well.

In a greater sense, the mechanisms that control any biological cell operate at the nanoscale and represent a source of inspiration for a whole array of nanotechnology applications. If nanomedicine is to have any impact, we must understand and control movement through cells, bloodstreams, and

27 Richard McKeon and C.D. Reeve, *The Basic Works of Aristotle* (New York: Modern Library, 2001), p. 140.

28 Kellar Autumn et al., "Evidence for van der Waals Adhesion in Gecko Setae," *Proceedings of the National Academy of Sciences U.S.A.* 99.19 (2002): 12252–6.

biological environments. What better place to draw inspiration than from nature itself, which has been grappling with these problems for eons?

It is important, however, to understand that biology and evolutionarily designed solutions can only take us so far in technological development. Because nature has evolved mechanisms suited for certain purposes (e.g., survival and reproduction), human intuition and guidance are needed in order to use technology for other particular purposes. Furthermore, though nature may have highly optimized solutions for problems, they may not be the *most* optimal solutions. From one generation to the next, nature has a limited toolkit upon which to draw. Humans will not, all of a sudden, develop solid state memory storage simply because it is "better" in some sense than our biological memory storage. We will not develop, through evolution, the ability to walk on walls as geckos have. Where evolution has brought us from has a large impact on where we will go. Our toolkit of biological solutions determines, to a large extent, the toolkit that we will develop through evolution.

Historical nanotechnology

Nanotechnology has not only been present in nature, but has also been used unwittingly in human-made technology for centuries. For example – and as already mentioned in §1.3 – nanoscale carbon black particles, basically high-tech soot, have been used as a reinforcing additive in tires for nearly 100 years. Nanomaterials have also been used unwittingly by artisans for centuries. When gold is significantly reduced in size, it no longer retains its familiar yellow-metallic appearance, but can take on an array of colors. The red paint used on Chinese vases as far back as the Ming dynasty is the result of Chinese artisans grinding up gold particles until they are on the order of 25 nm in size. Separately, medieval artisans in Europe discovered that by mixing gold chloride into molten glass they could create a rich ruby color. By varying the amount of gold put in the mixture, different colors are produced. Though the cause was unknown at the time, the tiny gold spheres were being tuned to absorb and reflect the sunlight in slightly different ways, according to the size of these particles. Nanomaterials have been used unknowingly to make stained glass by grinding up gold and silver nanoparticles to small sizes. Both gold and silver nanoparticles change color significantly according to their size and shape. At 25 nm in diameter and spherical, gold is red, at 50 nm and spherical, it is green, and at 100 nm and relatively spherical, it is orange. Silver is blue at 40 nm when spherical, yellow at 100 nm when spherical, and red at 100 nm when prismatic.

Though these are early examples of using the nanoscale size to enhance or change the property of a material, they at best qualify as accidental nanotechnology. In order to categorize them as nanotechnology, they would have to have been intentional. The main difference between the modern push for technology and these previous historical examples of nanoparticle use is that the modern use is intentional and with an understanding of the underlying mechanisms that produce the new properties.

The multidisciplinary world

We have written a lot about materials because they are central to the nanoscale world and, therefore, to the development of nanotechnology. However, nanotechnology draws from a wide range of disciplines. Because it requires extensive knowledge of chemical interactions to manipulate matter at the molecular scale, chemistry is very important to nanotechnology. Because, on the nanoscale, the laws of nature merge the laws of the very small (quantum mechanics) and the laws of the large (classical physics), physics is very important to understanding nanotechnology. Because the material is vital to the function of device and structure, the science and engineering of materials are vital to developing nanotechnology. Specific applications require even more disciplines. Medical applications such as drug delivery require knowledge of biomedical applications. Even more, because nanoscale devices will have to move through a bloodstream, fluid dynamics becomes important.

The point is that this wide range of disciplines brings interesting opportunities and challenges to researchers. There are opportunities for nearly any scientist to be involved in developing nanoscale science and technology. One of the true revolutionary effects of developing nanotechnology is that scientists of all different stripes are working together on a wide variety of projects. Physicists are providing insight into curing cancer, chemists are developing new types of lights, and many more bridges are built between disciplines that once were separated from each other.

The challenges are also numerous. Each field brings its own expertise and terminology. This makes communication between practitioners in these fields difficult. Consequently, a large amount of overlap in research occurs and insights take some time to be shared and understood. In order to solve this challenge, many multidisciplinary centers are being established. In these centers, biologists and physicists work side by side in hopes that proximity will breed cooperation in research, understanding of the different fields, and innovation from fresh perspectives on the problems of the fields. For example, the University of Chicago established an Interdisciplinary Research Building in 2003 in order to create such a cooperative environment. This environment is necessary because, as we have seen and will see, nanotechnology draws from many different disciplines. In subsequent chapters – and especially in the first unit of this book – we will provide a more scientific context for nanotechnology, thus elaborating on the themes developed in this chapter. The second and third units of this book will build on that context and show some uses to which nanotechnology is applied, as well as the associative social and ethical dimensions of those uses.