1

AN INTRODUCTION TO NANOCOMPUTING

Elaine Ann Ebreo Cara, Stephen Chu, Mary Mehrnoosh Eshaghian-Wilner, Eric Mlinar, Alireza Nojeh, Fady Rofail, Michael M. Safaee, Shawn Singh, Daniel Wu, and Chun Wing Yip

The continuous shrinking of transistors has made it possible to do amazing feats with computers, and a major theme of the microelectronics era has been ‘‘smaller is better.’’ Today, technology has already shrunk to the nanometer scale, causing many practical challenges and motivating the search for new nanoscale materials and designs. In this chapter, we present a brief introduction to the concept of nanocomputing and provide a high level overview of nanocomputing devices and paradigms. We also discuss some applications of nanocomputing such as biomedical engineering and neuroscience.

1.1. INTRODUCTION

In 1959, Nobel laureate Richard Feynman posed this question to his fellow physicists: *‘‘Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?’’* In that lecture, aptly named ‘‘There’s Plenty of Room at the Bottom,’’ Feynman challenged scientists and engineers to imagine what could be possible using nanoscale structures. He used computing as a prime example, suggesting that wires and circuits could be shrunk to only hundreds of angstroms in size [1], making it possible to combine billions of devices to perform amazing tasks.

The transistor, today’s most prevalent modern computing device, can already be manufactured as small as hundreds of atoms across. This could mark the

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end of the microcomputing era and the beginning of the *nanocomputing era*. Nanocomputing could be fundamentally different from microcomputing: individual particles could play a significant role; quantum effects enter the game much more directly. Even though Feynman's vision has been partially realized with such tiny transistors, researchers are only beginning to explore the fundamental questions: How small can we make computers? How would such computers work? How can we embrace quantum mechanics for computation? What applications are possible with nanocomputing that were not possible with microcomputing? We will explore these questions throughout the book.

In this introductory chapter, we will give a brief overview of devices, paradigms, and applications of nanocomputing. Of course, we cannot include all existing ideas about nanocomputing in the introduction, or even in the entire book. Instead, we aim to inspire the reader with a variety of ideas that appear commonly in nanocomputing research. We will first define computing and nanocomputing and provide some historical context of the microcomputing era. The limitations of today's microcomputers motivate a discussion of nanoscale devices and paradigms, many of which are detailed in later chapters. We then consider two major fields that can greatly benefit from nanocomputing: biology and neurology.

1.2. WHAT IS NANOCOMPUTING?

Computing is the *representation* and *manipulation* of information. Computer games, surfing the Internet, solving complex math equations, and even verbal communication are examples of computing. While we certainly compute using our own thinking power, it is often more useful to create a machine that computes on its own so we can use it to enhance our daily lives. Indeed, our world has become dependent on machines that automatically compute for us. These "computers" are used for entertainment, education, safety, and a vast number of other applications, all of which require manipulation of abstract information.

To build a computing machine, abstract data must eventually be represented by something that physically exists. For example, digital states (such as 1's and 0's) can be represented as high and low voltages on a wire. Similarly, manipulations of abstract data, such as adding two numbers, must eventually be performed by a physical phenomenon that affects the data. Therefore, to explore the world of computing, we must ask the most fundamental question: *How can we use physics to represent and manipulate abstract information?*

Directly or indirectly, researchers from all over the world are exploring this fundamental question. This endeavor spans across several disciplines, including mathematics, computer science, physics, chemistry, and biology. Throughout this book, there are many examples of how physics can be used for computation; some of these ideas may eventually lead to more powerful computers.

Nanocomputing can be interpreted literally as *computing at the nanometer scale*. It is generally agreed that the terms *nanotechnology*, *nanocomputing*, and *nanoscale* are used when considering devices that are at least one dimension smaller than 100 nanometers (nm). Today, devices such as transistors have channels that are well below 100 nanometers in length. Eventually the size of entire computers may also be measured in nanometers.

Just how small is a nanometer? A nanometer is one-billionth of a meter (10^{-9} m). Figure 1.1 shows the approximate size of various physical entities at the nanometer scale. If it were possible to arrange 10 hydrogen atoms side by side, their combined width would measure approximately 1 nanometer. A typical processor found in a modern desktop computer is roughly 10 millimeters wide and 10 millimeters long—in terms of nanometers, this is nearly 10 million nanometers in width and length! Other computers are commonly much smaller; embedded processors used today in cell phones, cars, and many other devices are as small as a fraction of a millimeter squared. Nanocomputers will be even smaller; electrons, atoms, DNA, and proteins are all nanometer scale or smaller and offer a huge variety of ways to represent and manipulate data.

At first this description may seem to be simply a matter of size. For more than 50 years, computers have continued to get smaller and faster, and so it may not be obvious that nanocomputing is drastically different than microcomputing. Looking deeper, however, the nanometer size opens a new world of possibilities. Nanocomputers will be able to fit anywhere, even inside our own bodies. They may be nearly undetectable, certainly invisible to the naked eye. Millions of such computers could work together and intelligently collect data about the world. Quantum physics makes it difficult to continue using old microcomputing techniques, but it also gives us infinitely more possibilities.

With all this in mind, **nanocomputing** can be defined as *the study of devices, paradigms, and applications that surpass the domain of traditional microcomputers by using physical phenomena and objects measuring 100 nm or less*. This definition clarifies that nanocomputing encompasses a large variety of challenges, ranging from effectively fabricating nanoscale devices to creating revolutionary applications for nanocomputers.

In the nanoscale world, it is unlikely that computers will work the same way they work today. Figure 1.2 lists some of the novel paradigms that can be realized with nanoscale physics, roughly estimating how they may be compared to each other given today's understanding of nanocomputing. As the figure shows, there is a vast amount of untapped potential computational power beyond CMOS logic, today's dominant technology.

Another important aspect of nanocomputing is the new set of applications that will be possible with such tiny, powerful computers. In turn, the plethora of applications raises ethical, social, and economic questions that are also of great interest.

The applications and impact of nanocomputing will be discussed later in this chapter, but let us first turn our attention to the fundamental question stated above, that is, exploring how physics can be used for computation. Over the next several sections we will discuss this idea, providing a historical context and generic taxonomy of nanocomputing topics that are detailed in the rest of this book.

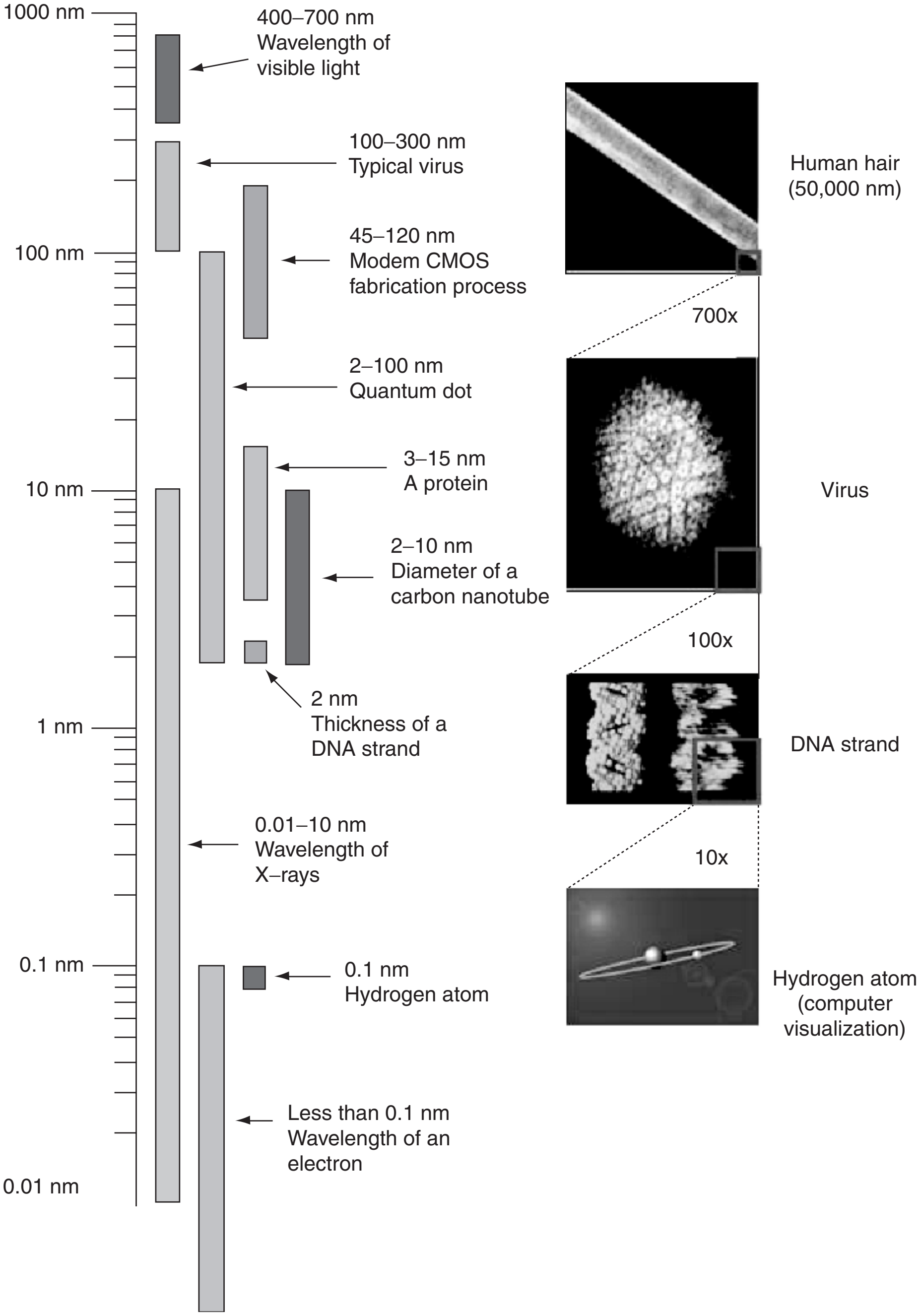

Figure 1.1. Left: Size of various objects, measured on a logarithmic scale. Right: Visual depiction of some of these objects, to compare relative size. Permissions obtained for the DNA strand from CalTech. The human hair and the virus pictures were taken from the Wikipedia public domain.

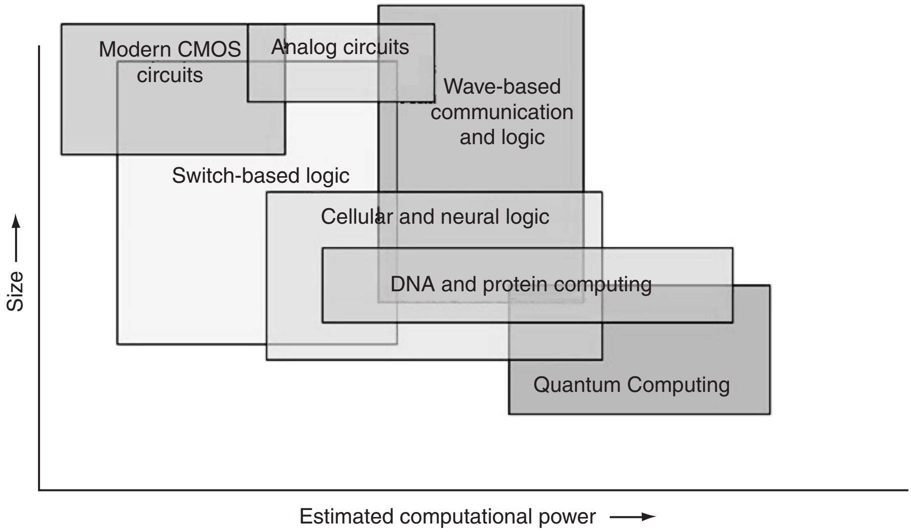

Figure 1.2. Visualization of how future paradigms in nanocomputing may compare to today's CMOS technology.

1.3. THE MICROCOMPUTING ERA: THE TRANSISTOR AS A SWITCH

Traditionally, the most common way to use physics for computation is to cleverly control electricity. Figure 1.3 shows a simplified *transistor*. We can add or remove electrons from the gate. When there is no charge in the gate, the wire can easily transmit its own electrons. If there are electrons in the gate, an electric field of negative charge is created, and this repelling force makes it difficult for electrons to flow through the wire. In a sense, we can control how much current flows through the wire by controlling how much charge we put into the gate.

With this physical device, an abstract 0 or 1 is represented as a low or high current on the wire. This is known as the *digital abstraction*. The transistor's

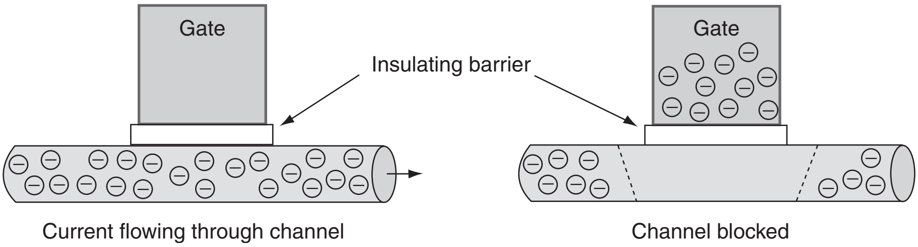

Figure 1.3. A simplified field-effect transistor. Ideally, the gate can "switch" current on or off.

behavior represents a simple *switch*: the gate can allow or prevent current from flowing through the wire. This is the *switch abstraction*. In practice, there are many more abstractions placed on top of these two (for example, representing integers in binary form with a series of 0's and 1's). However, the digital and switch abstractions are particularly significant because they bridge between a physical phenomenon, moving electrons and electric fields, to an entirely abstract world, manipulating 0's and 1's with switches. This use of transistors is the cornerstone of modern computing.

One particularly interesting achievement occurred in 1959, when both Robert Noyce and Jack Kilby independently developed the *integrated circuit*. With integrated circuits, one fabrication process simultaneously creates many transistors, all of them integrated on a single crystalline structure such as silicon. As fabrication techniques began to improve, it became possible to pack more transistors together. By 1965 Gordon Moore, the co-founder of Intel, predicted that the number of transistors that fit into a given area would double every 18 months due to continued improvements in the fabrication process. Following this prediction known as Moore's Law, transistor size, speed, and power consumption have exponentially improved for almost 50 years. Today it is possible to construct hundreds of millions, even billions, of tiny transistors on a small piece of silicon the size of a thumbnail (Fig. 1.4). In turn, it has become practical to create abstract computers that use millions or billions of switches.

Because the fabrication process produces all transistors simultaneously, the cost of fabricating these computers is largely independent of the number of transistors. There is typically a large initial cost, and this initial cost can be amortized over thousands or millions of processors, which can be produced cheaply. The economics of this situation is staggering—with a smaller transistor, performance improves, power consumption decreases, more abstract computation fits onto a single processor, and all this happens as the price of each transistor decreases! With this persistent exponential improvement, it is very easy to manipulate large amounts of abstract information, and computers are used for a prolific number of applications today. All of this has hinged on the fact that transistors continue to get smaller, and this has led to the general trend that "smaller is better."

1.3.1. Difficulties with Transistors at the Nanometer Scale

Transistor sizes are already at the nanometer scale, and this causes many practical difficulties. At the time of publication of this book, many consumer products are using a 45 nm fabrication process, and 32 nm technology has already been demonstrated. At these small sizes, fundamental limitations have to be considered. Entire books have been written on the subject, and here we describe only a few such challenges.

One primary example of these difficulties is a quantum phenomenon known as *tunneling*, visualized in Figure 1.5. Due to the wave nature of particles, electrons can "jump," or tunnel, through barriers with some nonzero probability. This probability increases exponentially as the size of the barrier decreases. The size of

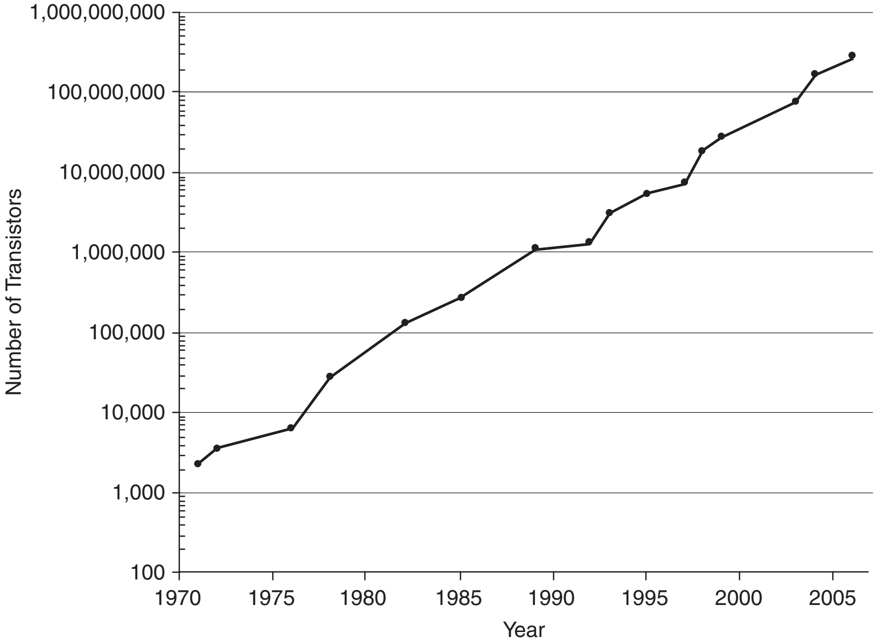

Figure 1.4. The number of transistors found in commercial processors. Note that the y-axis is logarithmic. This exponential trend is mostly due to the decreasing size of transistors. It is expected that very soon transistors will become as small as physically possible, which motivates the exploration of other devices that may be smaller and more powerful. Data acquired from [2].

transistors has decreased so much that in today's tiny transistors, electrons regularly tunnel between the gate and the wire. (Fig. 1.6). Since electrons and charge cannot be controlled as easily at the nanometer scale, the transistor behaves less and less like an ideal switch.

Tunneling has become part of a larger tradeoff between performance and power consumption. The size of transistors has reached the point where traditional models of transistors cannot be applied without a detailed understanding of nonideal characteristics [3]. There are many reasons that electrons can unintentionally leak across the wire, even when the gate tries to block current. Furthermore, the smaller the wires become, the more difficult it becomes for electrons to move through wires; that is, thinner wires have greater resistance. Because of this, even more power is required to push electrons through the wires quickly. Most processors today are limited to about 4 GHz, largely because power requirements beyond this speed are too costly and generate too much heat for a processor to function properly.

Many creative solutions have kept transistors useful despite these limitations. For example, by placing the appropriate stress or strain on the crystalline

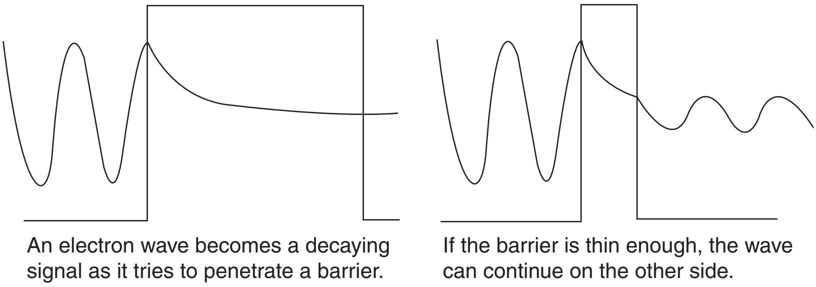

Figure 1.5. Visualization of the tunneling phenomenon. Mathematically, the wave changes into an exponential decay when it enters a region of "high potential"—the barrier—and resumes as a wave after it exits. The probability that an electron will tunnel across the barrier is related to how much amplitude the wave has left once it exits the barrier.

structure of silicon, electrons can move through a transistor more easily. This can be done by adding materials on top of transistors that naturally want to bend, thus pulling or pushing on the silicon. The so-called *strained silicon* [4] has quickly become a standard technique to improve the performance of transistors at 90 nm or less. Another example is the development of better insulating materials, known as *high-K dielectrics* [5]. The right combination of conducting and insulating materials can reduce the amount of undesirable tunneling between the gate and channel, even when the barrier is only a few layers of molecules thick. This advancement has been the key towards 45-nm technology. In the future, it may be necessary to use multiple gates to reliably control the current along a wire. *FinFETs* [6] or *trigate transistors* [7] are two multigate variations of transistors that may take us beyond 45 nm.

There are several more limitations when using tiny transistors that motivate the nanocomputing ideas presented in this book. First, the wiring that interconnects transistors is becoming a very signficant limitation for performance, power, and size of devices. There are even theoretical limitations about how much

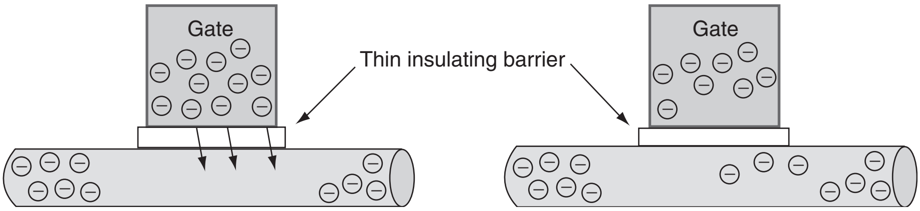

Figure 1.6. One of many nonideal effects in a transistor is that electrons in the gate may tunnel into the wire. This occurs more often as the thickness of the insulating barrier decreases.

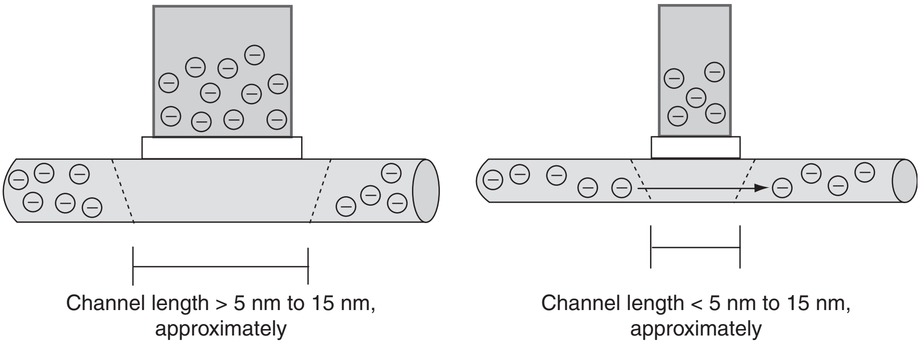

Figure 1.7. When transistors become very tiny, electrons can tunnel across the channel when the gate tries to block current flow. If the channel length is small enough, electrons will regularly tunnel in this way, and the gate would no longer effectively control current flowing through the wire.

area interconnections require as long as we connect transistors with traditional wires [8]. As we will see in the next few sections, there are many ideas in this book that reduce the limitations of wiring.

Second, variations during fabrication are now becoming a very significant problem. Relative to such tiny transistors, variations in geometry or chemical concentrations can easily change or break the behavior of the transistor. This variability decreases the yield and reliability of devices. *Fault-tolerant methodology* (Chapter 10) is desired for computing under unreliable conditions, and new fabrication methods, such as *self-assembly* (Chapter 12), may be better for reliable fabrication at the nanometer scale. Furthermore, *reconfigurability* (Chapter 5) offers a way to keep a device useful by updating or fixing its functionality.

Finally, when transistors become very small (below 5 to 15 nm approximately), electrons will be able to tunnel in a different, much more challenging way: electrons would be able to tunnel through the channel itself, even when the gate tries to block current, defeating the purpose of a gate entirely (Fig. 1.7). It is currently not clear how to overcome this upcoming problem, except to find a better nanoscale device that can behave like a switch [9].

1.4. BEYOND THE TRANSISTOR: NANOSCALE DEVICES

In practice, the use of transistors has been so successful that so far it remains unchallenged as the “best way” to use physics for computation. However, as mentioned above, it is not clear that the transistor will continue to be the best device to use as a switch at the nanometer scale. One major facet of nanocomputing research is finding new devices that exhibit switching or other behaviors that are useful for computing. Unlike the classical transistor, these devices very directly embrace the properties of quantum physics to serve their function. In this section, we briefly describe various nanoscale device technologies, referring to the specific chapters where topics are discussed in more detail.

It should be noted that this introductory material is not intended to be a comprehensive list of nanoscale devices; such information can be found in later chapters. In fact, this section only describes a mere fraction of the devices that are being explored at the nanometer scale. Instead, the purpose of this section is to give an intuitive understanding for several common aspects of nanoscale devices.

1.4.1. Molecular Devices

In general, there are a huge variety of molecules and structures that can be explored (for example DNA, proteins, rotaxanes, nanotubes, and more) [10]. In some sense, atoms and molecules are just highly complicated toy blocks: there are an infinite number of ways to assemble molecules into something useful, limited only by the creativity of future research.

Molecular structures can be used to create very tiny switches, ranging from 1 to 10 nm in size. One possible approach is to control how easily electrons can flow through the molecule, very much like a transistor, but with different underlying physics (e.g., [11]). Another possible approach is to control how light is absorbed or scattered by the molecules (e.g., [12]). These interactions with molecules can be controlled in many different ways, for example, by applying a nearby voltage or by changing the structure of molecules. Molecular switches and molecular computing are discussed further in Chapter 11.

A big challenge with molecular switches—and many nanoscale devices—is to effectively fabricate and interconnect them to perform complex logic functions. In an attempt to circumvent these problems, one proposed molecular device is the *NanoCell* [13]. The NanoCell tolerates defects and variability that occur during self-assembly fabrication. To provide reliability, the NanoCell depends on post-fabrication ‘‘training’’ to create the desired logic function. This approach is interesting for two reasons. First, the logic function of the NanoCell can (ideally) be reconfigured instead of permanently fixed; second, it allows the use of larger and fewer wires to connect between different cells. The function implemented by a single cell would be equivalent to using many transistors, thus simplifying the arrangement of large-scale computations.

1.4.2. Nanotubes

One interesting class of molecular devices is nanotubes, particularly *carbon nanotubes*. Recall that pure carbon has two common crystalline forms: diamond, where carbon atoms form a three-dimensional structure; and graphite, where carbon atoms form flat sheets that can easily slide and peel from each other. A single-wall carbon nanotube (Fig. 1.8) can be visualized as a single sheet of graphite rolled into a tube (though it is not created in this way), with a diameter of only a few nanometers.

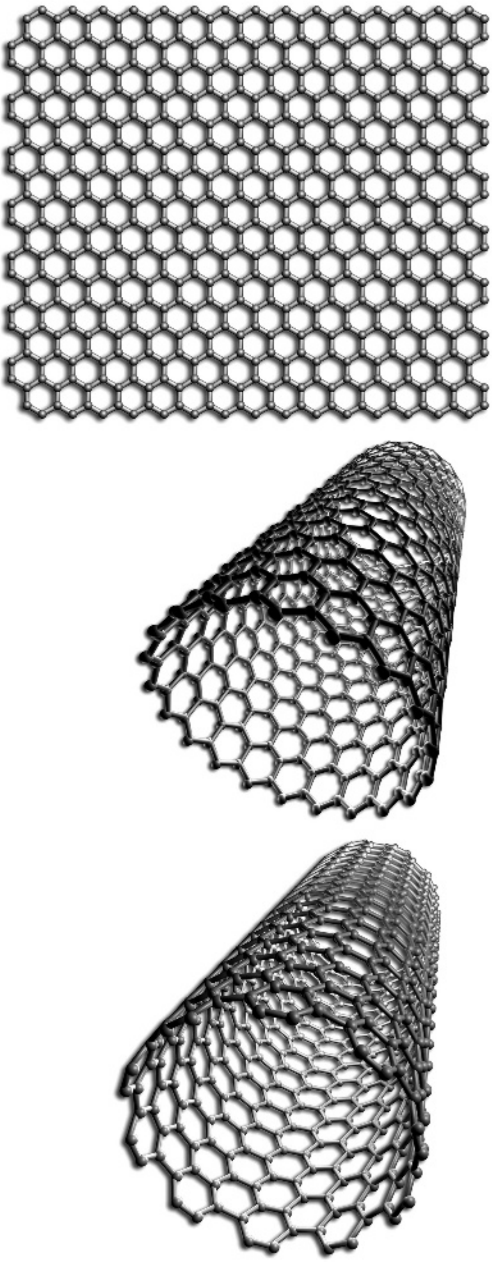

Figure 1.8. Visualization of carbon nanotubes (CNT), an exciting class of molecular devices. CNTs can be visualized as a sheet of graphene (top) rolled into a tube, though they are not created this way. Note that these two nanotubes have slightly different configurations. Various configurations of nanotubes can result in drastically different physical properties. Images created by Gabriele Nateneli.

Carbon nanotubes have very interesting mechanical and electrical properties. Mechanically, they are extremely strong and versatile. The tensile strength and stiffness of carbon nanotubes are extremely high, especially relative to their weight. Also, two tubes arranged with one inside the other can have a very low friction interface, similar to the way two flat sheets of graphite can very easily slide over each other. Therefore, two nanotubes can have very efficient telescoping and rotation motions, useful for nanomachines [14].

Electrically, a nanotube can potentially behave as a *ballistic conductor*. This means that an electron travels through the tube with small, quantized levels of resistance. The typical levels of resistance are much lower than traditional conductors. Nanotubes can exhibit properties of a metal or a semiconductor, depending on how the sheet of graphite is rolled into a tube. It has even been suggested that nanotubes can behave like a *waveguide*, guiding the wave-like properties of an electron similar to the way electromagnetic (optical) waves are guided through a fiber-optic cable [15]. All of these properties are being investigated for future switches and wires. In fact, switches, wires, and support structures have all been demonstrated with carbon nanotubes, but, as with many nanoscale devices, the ability to fabricate a practical nanoscale device with nanotubes and nanowires is still an open challenge. Carbon nanotubes are discussed further in several chapters in this book. See Chapter 2, Chapter 12, and Chapter 18.

1.4.3. Quantum Dots and Tunneling Devices

Many quantum phenomena occur when confining electrons to a very small space, such as the nanoscale range. For example, an electron confined to a small area can only have a select few discrete levels of energy, similar to the discrete levels of energy that an electron may have as part of an atom. When a group of electrons is confined in all axes of movement (i.e., in three dimensions), a *quantum dot* is formed. Similarly, a *quantum wire* is a group of electrons confined along a 1-dimensional line, and a *quantum well* restricts electrons to a 2-dimensional plane. These structures can exhibit properties similar to electrons in atoms or molecules, even if there is no nucleus of protons and neutrons. Their properties can be fine-tuned with more freedom than atoms or molecules, making them very interesting structures to use for computing.

Often, the phenomenon of tunneling, described previously, is combined with quantum dots, wires, and wells to create useful devices. This is in contrast to traditional transistors, where tunneling is very undesirable. Three such nanoscale devices are the *resonant tunneling diode* (RTD), the *single electron transistor* (SET), and *quantum-dot cellular automata* (QCA). An RTD is a device that has a quantum well where electrons can be confined; therefore, electrons in this region can assume only a few possible discrete energy states. When the energy of an incoming electron is close to one of these “resonant” discrete energy states, the electron can tunnel through with high probability. This device can emit extremely high frequencies, in the hundreds of GHz, making it interesting for high-speed applications. RTDs can also be arranged to perform logic functions, digital or otherwise. For example, RTDs have been used to implement cellular automata and cellular nonlinear networks [16, 17], two paradigms described below.

A single-electron transistor, or SET [18], operates on a principle similar to a conventional transistor: a gate can control the flow of electrons through a channel. However, unlike the classical transistor, in a SET the flow of a precise number of electrons is controlled. The device consists of a quantum dot between two barriers. When the gate has a negative electric field, the properties of the quantum dot are changed, effectively preventing electrons from entering (Fig. 1.9). When the gate does not block the flow of electrons, the space between two barriers accepts only a few electrons, typically allowing single electrons to tunnel through one at a time. In addition to quantum phenomena, an important mechanism that is generally dominant in SETs is the so-called coulomb blockade, which is essentially a classical effect, arising from the fact that charge is not continuous, but comes in packets of one electron each. The mutual repulsion of individual electrons, when confined to very small regions, leads to this effect. Currently, the smallest SETs are just as large as transistors, but it is expected that SETs will be able to shrink well beyond the limits of classical transistors. RTDs, SETs, quantum dots, and many other related devices are discussed further in Chapter 2.

Another interesting use of quantum dots is in *quantum-dot cellular automata* (QCA) [19]. A single QCA cell is a container that has several quantum dots. Electrons in this container tunnel between the dots in order to try and find the "ground state," that is, the state where the cell is at its lowest energy. A QCA cell has only two stable states, as shown in Figure 1.10. With two states, a QCA cell can realize the digital abstraction (i.e., logic 0's and 1's). However, there is no switching behavior in this concept. Instead, QCA are based on the property that adjacent cells prefer to have the same ground state. At the inputs, the cells can be constrained. Depending on how cells are arranged, the constrained inputs will propagate in

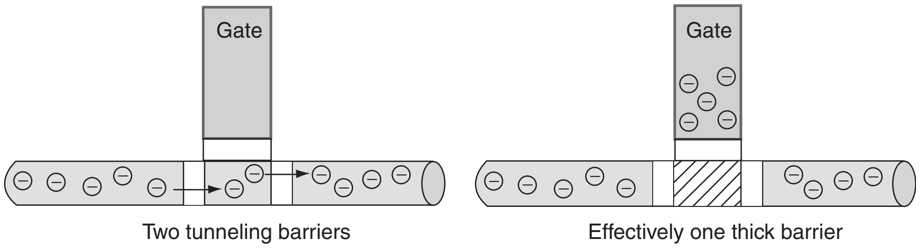

Figure 1.9. Conceptual illustration of a single-electron transistor (SET). A quantum dot (small confined space containing electrons) exists between two tunneling barriers, and electrons can tunnel in and out of the dot, one at a time. When the gate has electrons, the quantum dot changes and no electrons can flow from one side to the other.

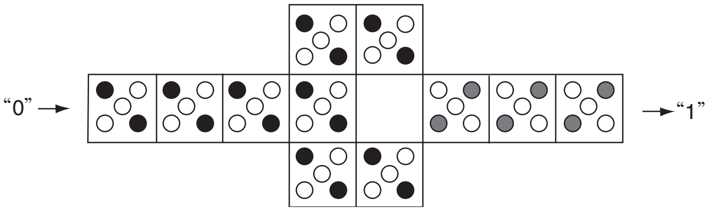

Figure 1.10. Depiction of quantum-dot cellular automata (QCA). Each cell has several quantum dots (in this case five). A cell can have two possible states, where electrons are diagonally oriented. When the input value is changed, the change propagates over time, this particular arrangement of cells represents a logic function that inverts the input.

different ways, allowing for many interesting logic functions. Since there are no wires interconnecting various cells, they can be arranged very compactly, in turn allowing for compact logic functions. Note that quantum dots are only one of serveral ways to implement QCA cells. QCA are discussed in Chapter 4.

1.4.4. Spin Devices

Electron spin is another interesting quantum effect that can be used to create nanoscale switching devices. Various particles can have different types of spin, but electrons in particular can have only two types: *spin up* and *spin down*. This is a natural way to introduce the digital abstraction. Furthermore, electron spin is a main nanoscale property that results in macroscopic magnetic fields. For example, if most of the electrons in a metal object assume a polarized spin state (either all spin up or all spin down), the metal object will be magnetic. One interesting phenomenon that is a result of the relationship between magnetism and electron spin is the *magnetoresistive effect*: the resistance of some materials can change depending on the surrounding magnetic field.

Magnetoresistance is already widely used as the mechanism to read data from a disk drive that stores information magnetically. Manufacturers are also considering the possibility of magnetic random-access memory (MRAM), which would use magnetoresistance to implement nanoscale memory cells. MRAM may have a number of advantages over other types of memory storage. It is expected to have the high storage density of today's dynamic RAM technology, while providing the high speed and power savings of today's static RAM technology. Magnetoresistance can also be used to create a switching device. This sort of switch is called a *spin transistor*, or *transpinnor* [20]. Recall that a classical transistor uses an electric field to make it difficult for electrons to travel across the wire. Similarly, a spin transistor uses magnetoresistance to drastically increase the resistance of the wire, effectively blocking current like a switch. Magnetic storage is discussed in Chapter 6, and spin devices are discussed further in Chapters 7 and 9.

1.5. BEYOND THE SWITCH ABSTRACTION: NANOSCALE PARADIGMS

The use of switches has fundamental limits. At some point, researchers may achieve a switch that is plainly as small as possible. This would mean that the exponential decrease in size of transistors would stop—the end of Moore's Law. It would be desirable to find a new way of continuing Moore's Law, not in the literal sense that transistors could get smaller, but rather that technology could continue to exponentially improve. Furthermore, the complexity of interconnecting switches is a fundamental limitation; even today, the wires are becoming the limiting factor when making high performance nanoscale transistors. In fact, there is no indication that switches, binary logic, or transistors are the best way to compute.

This motivates the search for entirely new paradigms of computing that could eventually replace the digital and switch abstractions. Of course, the common thread in the ideas we consider is that they can be realized at the nanoscale level. Here we briefly describe some of the major paradigms of computing that are part of nanocomputing research, as well as mention the corresponding chapters where they are discussed further. As before, this section is not intended to be comprehensive; instead it aims to inspire the reader by illustrating some novel approaches to computing and how drastically different they are than today's computing technology.

1.5.1. Cellular and Neural Logic

One paradigm is the use of *emergent properties*. The idea is to use a large number of extremely simple processors. Alone, each processing element can be extremely small, and it can do only a limited number of trivial functions. However, powerful computers "emerge" from a group of such processors. Cellular automata, cellular nonlinear networks, and artificial neural networks are major examples of this paradigm. *Cellular automata* (CA) [21, 22] can be understood as a regular grid of identical cells, where each cell changes its state depending on its own state and the state of its neighbors (Fig. 1.11). *Cellular nonlinear networks* (CNN) [23] are similar to cellular automata, the main difference being that each cell in a CNN is an analog processor. *Neural networks* [24], unlike CA or CNN, use simple units that simulate the behavior of biological neurons.

Figure 1.11 shows an example of how a behavior can emerge from a cellular automaton. At each step, every cell changes depending on the previous state of its neighboring cells. The pattern shown in this figure repeats every four steps, but gradually moves diagonally as well. This diagonal movement is a property that emerges from the group of cells. The rules that define how all cells behave are very simple, but the result is a rich, complex world of emergent properties that are being studied by many mathematicians and scientists and can be used for computation.

In nanocomputing, the idea of having a huge number of very simple nanoscale structures is appealing for many reasons. The challenge of how to fabricate such

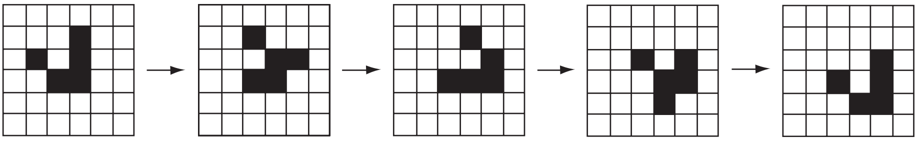

Figure 1.11. Example of a simple cellular automaton. Each cell can be "on" (black) or "off" (white). Depending on its neighbors, a cell may turn on or off in the next time-step. This specific example shows a "glider," a structure that emerges from rules defined by the famous "Game of Life" by John Conway [25]. As time goes forward, the glider moves diagonally. More complex cellular automata can compute anything that a traditional computer can, and possibly more.

a computer becomes much easier because the same nanoscale structure can be repeated in a regular pattern. Most of the ideas in this paradigm are also fault-tolerant, that is, able to handle a few defective cells or neurons. This alleviates the problem of variability when fabricating nanoscale devices. Their regular structure usually implies that they can perform different functions depending on the context, instead of being permanently hard coded with a fixed function; in other words, such computers are highly reconfigurable. Most importantly the potential computing power that is available with emergent properties is immense and only beginning to be explored.

Even with the limited understanding of emergent properties, this paradigm already has many applications. Cellular automata and cellular nonlinear networks have been mostly used for image processing applications due to the highly parallel nature and intuitive correspondence between each simple processor and pixels on an image. Neural networks have been extensively studied for their applications in artificial intelligence and are useful practically anywhere uncertainty is encountered in computation. It has also been shown theoretically that cellular automata and neural networks can do anything that today's computers can do [26, 27]. With all this in mind, one of the main challenges of this paradigm is to find a way to harness emergent properties for a wider variety of applications.

Nanoscale devices that implement cellular automata, cellular nonlinear networks, and neural networks are actively being researched. NanoCells, quantum-dot cellular automata (QCA), and RTDs, described in the previous section, are just a few possible ways to realize this paradigm. Quantom-dot cellular automata are discussed in Chapter 4, and nanoscale neural networks are discussed in Chapter 17.

1.5.2. Wave Computing

Waves are an elegant but complicated way to communicate and manipulate abstract data. One of the most powerful features of waves is the phenomenon of *diffraction*, or the behavior of light as it propagates around objects or through a nonuniform medium. Perhaps the best known example of the power of diffraction is seen—literally—in holography. To display a hologram, light waves are diffracted through patterns that were previously recorded. The diffraction of light actually reproduces all the waves of light that were originally recorded. Because of this, visual holograms are well known to have accurate details and amazing realism. Holography has found many other important engineering applications because diffraction can manipulate light waves in a flexible, powerful way.

Equally important is the *superposition* of waves. Consider two waves that are traveling in opposite directions (Fig. 1.12). The waves continue with the same direction and speed, unaffected by each other. However, if desired, one could measure the *intensity* of the point where both waves cross. The propagation of the waves remains unaffected, but the intensity measured at a point where two waves overlap would be the sum of both waves, a result of constructive or destructive interference.

This provides a convenient way to overcome the significant limitation of wiring: use waves for communication instead of particles. Because of superposition, waves can cross over each other without destroying the information being carried. In addition to guided waves, one could also use waves in free space, removing dependence on wiring. This may seem like a small matter at first, but as shown later in this book, it allows for significant improvements in *theoretical algorithmic performance* of computations. Note that improving algorithmic performance is usually more beneficial than simply making a processor "smaller and faster."

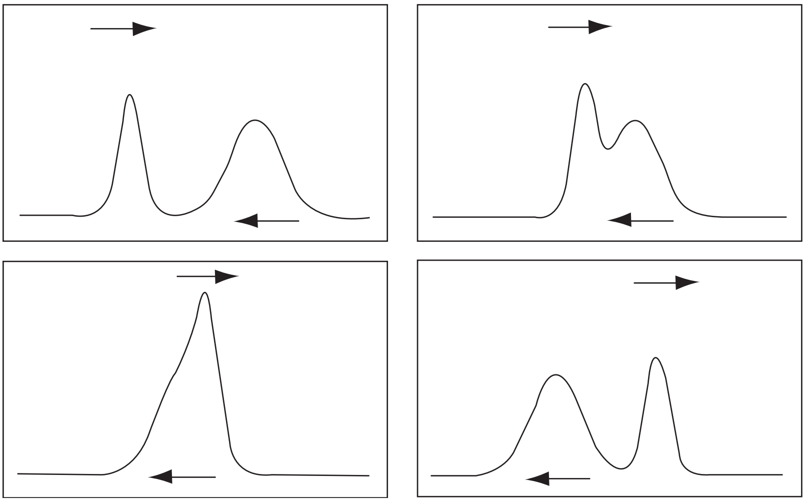

Figure 1.12. Visualization of how two waves cross. Unlike wires carrying an electrical signal, waves can occupy the same space while propagating. However, even though propagation over time remains unaffected, as they cross, the waves do interfere.

In addition to being used for communication, waves can also be used for computation by using interference. For example, constructive and destructive interference can result in either a high intensity or low intensity—introducing the digital abstraction without any switches. Furthermore, several waves can be combined at a single point, an occurence that can be advantageous over traditional logic that requires many transistors to handle many inputs. By combining the benefits of waves over wires with the functionality of waves over transistors, many limitations, theoretical and practical, can be overcome.

The visual portion of the electromagnetic spectrum has wavelengths on the order of hundreds of nanometers, slightly larger than the nanoscale level. The principles of diffraction and interference, however, apply to any type of wave, including X-rays and electrons that have nanoscale or smaller wavelengths (recall from Fig. 1.1). Another useful nanoscale wave, known as a *spin wave*, occurs when the spin state of previous electrons affects the spin state of nearby electrons, causing a propagation of the change in magnetic field (recall that magnetism is the macroscopic property of spin). In addition to the many benefits of wave computing described above, a key benefit of spin waves is that they can conveniently communicate with electronic devices as well. Spin waves for computation are described in Chapters 7, 8, 9, 14, and 19.

1.5.3. DNA and Protein Computing

DNA and protein are nanoscale molecular structures found in almost all existing biological life that we know. Recall that DNA is essentially a sequence of four primitive molecular structures: adenine (A), cytosine (C), guanine (G), and thymine (T), attached to a molecular "backbone." The main property that can be exploited for computing is that adenine bonds only to thymine, and cytosine bonds only to guanine. This means that a sequence of these base pairs has exactly one complementary sequence that will bond to it. By setting up specific sequences of DNA, many clever interlocking "tiles" can be created, and the way these tiles interact is used for computation.

Proteins are complex molecules comprised of a string of amino acids. Biologically, the sequence of amino acids that create a protein is defined by a sequence of DNA. Various proteins can interact to perform useful computations, for example, by exploiting the way a protein structure folds. Proteins are much more complex than DNA, and their use for computation has so far only been simulated [28].

The power of this paradigm is the principle of *constraint satisfaction*. Here, instead of representing abstract operations as physical phenomena, abstract rules are enforced (in this case with molecular structure), and physical phenomena (in this case, bonding between structures) do their best to find the lowest state of energy within the constraints. Performing constraint satisfaction in this way makes it possible to compute many things that are otherwise very difficult. The best example is a demonstration of DNA computing to solve the Hamiltonian Path Problem [29]. This is a well known problem in theoretical computer science for which the best known solutions currently take exponential amounts of time. Because of this high complexity, only very small, trivial inputs can be solved by a traditional computer. To solve a large exponential problem on a traditional computer can take years, or even decades, even with all the computing power available in the world! Many real world problems are also exponentially difficult, and being able to quickly solve these problems would profoundly impact the world. While DNA computing still performs an exponential amount of computation, by using constraint satisfaction of nanoscale physics, this paradigm can quietly bypass many of the limitations of traditional computers, allowing the solution of the Hamiltonian Path Problem to be computed in a tractable amount of time.

Note that constraint satisfaction is implicit in all physical phenomena used for computing. For example, a QCA cell in Figure 1.10 had two stable states because of the way electrons were constrained within quantum dots. The difference here is that the constraint itself is used for computation, rather than to make devices that can be used for computation. Another place that constraint satisfaction is useful is for self-assembly. By specifying tiles of DNA to connect in certain ways, the DNA can automatically assemble itself into structures that satisfy the constraints. DNA self-assembly has been demonstrated as a way to fabricate nanoscale structures [30, 31], which can then be used for other purposes (e.g., as a template to fabricate other integrated devices at the nanometer scale).

The challenge with DNA and protein computing is to manage these complex molecules. Even though DNA computing solves the Hamiltonian Path Problem, extracting the computation from the reactions takes many hours of manual effort, and the constraints to set up do not scale well. For proteins, it is not yet fully understood how they fold to develop complex structures. The number of permutations with sequences of base pairs or amino acids can be astronomical, and finding sequences that result in useful structures is like trying to find a needle in a haystack. As future research overcomes these challenges, DNA and protein computing may become an essential paradigm to solving very difficult problems. Such topics are discussed further in Chapters 13 and 14.

1.5.4. Quantum Computing

Further on the horizon of nanocomputing is the very powerful yet challenging field of quantum computing [32]. Recall that the fundamental question we have been discussing is how physics can be used for computation. All the ideas discussed above, even though they use properties of quantum physics, are only used to represent intuitive, essentially “classical” abstractions, such as digital 1’s and 0’s. Quantum computing, on the other hand, uses the general principles and mathematics of quantum mechanics as the abstraction itself.

In this paradigm, the leap from physics into an abstract world is accomplished by a *qubit*: the quantum analogy to the digital abstraction. Recall that a classical bit can have one of two possible states, usually denoted as 0 and 1. A qubit also has two such states, often denoted as $|0\rangle$ and $|1\rangle$, but in this case the qubit actually is a combination of both states simultaneously! This combination of two states, however, is something that cannot be measured directly. When trying to observe the state of a qubit, we receive a $|0\rangle$ or $|1\rangle$ with some probability. This probability is the actual information contained by a qubit, and it is almost as if nature teases us by making this information impossible to measure. One of the key tasks of quantum computing is to manipulate this hidden information in such a way that it is meaningful to measure the qubit as only a $|0\rangle$ or $|1\rangle$.

The states $|0\rangle$ and $|1\rangle$ are actually just one "frame of reference" in understanding the actual underlying quantum system. One of the interesting powers of quantum computing is that we can freely decide which frame of reference we want in which to manipulate the qubit. For example, we could view the same qubit as a combination of $|+\rangle$ and $|-\rangle$, two other states that give us a different way of looking at the same qubits. Even more peculiar, two or more qubits may be completely unrelated in one frame of reference, but in another frame of reference, the qubits become *entangled*. This means that a change in one qubit will unavoidably affect the other qubit, and even though this complicates matters, it allows a powerful way to manipulate multiple qubits. Often, a useful quantum circuit first manipulates qubits in one frame of reference, where they are entangled, and then uses another frame of reference where the state of the qubits can be observed.

Perhaps the best known example of the power of quantum computing is its use in finding the prime factors of a given number. Traditional algorithms can take extremely long for large numbers. A quantum algorithm known as Shor's Algorithm [33] uses quantum computing to factor prime numbers. A physical implementation of this algorithm has been demonstrated using 7 qubits, triumphantly factoring the number 15 into the prime numbers 5 and 3 [34]. While the number 15 is not large and it seems like a trivial task that could have been done with any other computer, the real landmark of this result is to demonstrate that quantum computers can indeed work as theoretically proposed.

With every next qubit, the amount of hidden information in a quantum system effectively doubles. With 7 qubits, there are 128 hidden "numbers" that represent a combination of 128 different states. With 20 qubits, there are more than a million such hidden numbers. It might take 30–40 qubits to represent computations that exceed the potential of traditional computers, and each qubit could possibly be represented by a single nanoscale particle! While this is currently a distant dream, the foundations towards realizing this dream are being studied extensively today.

Despite this awe inspiring amount of power that seems possible with quantum computation, there are many daunting challenges to be addressed before quantum computing becomes more practical. First, physically implementing a quantum computer is a tricky task. While it would be ideal to isolate a single quantum system in reality as we can do mathematically, in practice a quantum system also interacts with the rest of the world. Therefore, it is difficult to keep the *coherence* of a quantum system, where coherence is a measure of how long the quantum system can stay intact before it gets disrupted by the surrounding environment. On the other hand, quantum phenomena such as photons of light have a good coherence, but then it becomes difficult to get the photons to interact at all. Another problem is the difficulty of understanding how to develop algorithms for quantum computation. Some algorithms have been proposed that use quantum computation, and a few general computing framework are being proposed for using qubits in a practical setting. Chapter 3 gives a detailed history of the contributions in quantum computing as well as a discussion of its theoretical and practical limitations.

1.6. BIOMEDICAL APPLICATIONS

Recent developments in the field of nanocomputing have laid the groundwork for technology that will revolutionize modern medicine. The most important biomedical research in the latter half of the twentieth century, which culminated in the publication of the human genome, was driven by an understanding of DNA, our genetic code. Similarly, nanotechnology has the potential to usher in an age of nanomedicine, creating a paradigm shift in the way we study and treat disease.

This technology will not come without a heavy price. There are obvious financial impediments and technical challenges, but moral and ethical concerns will also play an important role in the development of this field. An excellent comparison can be drawn with genetically modified foods. A significant amount of the produce and livestock grown in the United States has been subject to genetic engineering. While many consider these modifications to be safe, some are still skeptical. Various nations, particularly some in the European Union, are hesitant to embrace such technology because of a fear that genetically modified foods are inherently unsafe and may damage local ecosystems. Some say nanomedicine may suffer a similar fate. Will governments and health care professionals trust and endorse this technology? Will individuals be comfortable with nanoscale devices circulating through their bodies?

Regardless of the public's willingness to accept nanomedicine, few will dispute its potential to revolutionize the biomedical research. By providing scientists with new techniques for targeting and attacking virtually every human ailment, nanocomputing will usher in an age of medicine in which physicians and scientists can treat disease at a molecular level and attack it in a way never thought possible. As nanotechnology provides more versatile tools, the rules of engagement for diseases will change. Physicians and scientists will no longer be hindered by the small size and tremendous complexity of the human cell, but rather utilize these features to develop therapies that are more specific and effective, producing better outcomes with fewer side effects.

1.6.1. Vaults

The future of nanocomputing knows no bounds and its merger with biomedical research provides unlimited pathways to discovery. It is difficult to imagine an area in which there is more promise and a greater potential to revolutionize the scientific field. It is also important to emphasize the importance of cooperation between scientists, physicians, and engineers to ensure the success of biomedical and nanotechnology related research.

Perhaps the most intriguing development in this field was the discovery of nanoparticles called vaults. Groundbreaking work on vaults was performed at the University of California, Los Angeles, where these nanocapsulses have fascinated scientists since their discovery [35]. Current studies have shown that vaults are found in all eukaryotic cells and are composed of protein and RNA [36]. Through precise genetic manipulation, scientists predict that vaults may be used as structural support for nanomachines as well as integral parts of nanocircuits. Perhaps most appealing is the potential of vaults to serve as vehicles for drug delivery. These nanocapsulses may one day deliver precise amounts of drug to specific cells in the body, increasing their efficacy and eliminating the potential for certain adverse reactions. While this type of technology seems to be straight out of a science fiction film, it is indeed very real and has a tremendous potential to usher in the age of nanomedicine. Vaults may also be used as biological sensors, detoxification centers, and aid in environmental restoration [36]. Equally important will be their contributions to biomedical research as a whole. It is impossible to predict the full potential of vaults but they may revolutionize drug delivery, treatment of disease, and fundamentally change the way we practice medicine.

Imagine for a moment a day in which vital signs, blood chemistries, and even disease progression can be monitored remotely by nanomachines. These safe and affordable nanorobots would be capable of transmitting data to a local physician and may even calculate complete blood counts, cholesterol levels, and search for invading pathogens. Some speculate that such robots could also be used to treat heart attacks and strokes by analyzing and neutralizing blood clots that pose a threat to the patient. Nanotechnology can provide physicians with more accurate and less invasive techniques for treating everything from the common cold to the most severe and debilitating diseases. Medicine would never be the same.

1.6.2. Molecular Motors

In analyzing the problem of providing power for future nanocomputing devices, researchers are exploring the use of molecular motors. These motors, instrumental in the functioning of biological systems such as muscle contraction, will allow for the movement of nanorobots within organisms. All motors consume a form of energy to perform work; in the case of molecular motors, it is some form of chemical energy, such as ATP [37]. Molecular motors are attractive because they are smaller and more efficient than any other man-made motor [37]. Numerous molecular motors exist, the most well-known being the proteins myosin and kinesin. Myosin lies along actin filaments in muscle cells and utilize a single ATP molecule per cycle to perform a power stroke [38]. Kinesin carries cargo in the intercellular space and uses 1 ATP to move 8 nm. The development of effective and reliable molecular motors will be essential for the utilization of nanorobots in biomedical applications.

A focal point of such research is treating motor neuron diseases, such as Amyotrophic Lateral Sclerosis (Lou Gehrig's Disease) and other types of atrophy [38]. Motor neuron diseases typically result in the degradation of neurons that control voluntary muscle, which are critical in performing tasks such as speaking and swallowing. Researchers have discovered a mutation in a molecular motor gene that leads to the buildup of improperly folded proteins in the cell. Many hypothesize that nanorobots and molecular motors may prove useful in preventing such degradation by restoring normal function to the cell and preventing the buildup of protein [37]. Scientists are currently attempting to construct nanoscale devices for this application, but they face many challenges. By studying molecular motors, they hope to discover ways for powering and mobilizing future nanodevices.

1.6.3. Nanorobots

Based on the existence of vaults, it is clear that nature has created its own nanoparticles. But what about man-made nanomachines? As nanocomputing advances, the field of nanorobotics is sure to progress as well. Approximately 10 years ago, the first theoretical design of a nanorobot for medicinal purposes was presented to the scientific community. The device utilized 18 billion precisely arranged atoms to form a diamonoid vessel with active pumping capabilities [41]. This has the potential to deliver over 200 times more oxygen to tissues than red blood cells. Theoretical designs also exist for synthetic white blood cells that are able to digest blood-borne pathogens. These nanorobots would have the ability to operate faster and more reliably than naturally occurring white blood cells.

Other designs include nanorobots with platelet functions that will allow hemostasis in as little as a single second. This complex machine would be invaluable in treating patients with severe hemorrhaging, especially in traumatic injuries. Perhaps most intriguing is the idea of a chromallocyte, a hypothetical mobile repair nanorobot capable of performing chromosome replacement therapy (CRT) [41]. This process involves the replacement of the entire chromatin content of a living cell with a prefabricated set of error-free chromosomes. This may allow for the treatment of entire organs such as the liver or heart and will without a doubt revolutionize the way we treat disease.

These nanomachines will be the core of nanocomputing and nanotechnology's biomedical applications; they represent a fundamental change in the way engineers and doctors will communicate. Indeed, it is essential for researchers on both sides of this fascinating technology to exchange ideas and strategies if they are to fully utilize the potential of nanotechnology. Nanorobotics is discussed in detail in Chapter 15.

1.6.4. Pharmaceuticals

Pharmaceuticals are a multibillion dollar a year industry, evolving daily with the discovery and patenting of new drugs. Developers are constantly seeking stronger and more effective medicines that will also reduce side effects. Nanotechnology and nanocomputing stand as beacons of hope for fulfilling these goals as they encompass several areas of pharmaceuticals, including “discovery, development, delivery and even post-delivery” [39]. Currently, several short- and long-term projects are underway to revolutionize the industry, as well as talks with large pharmaceutical corporations [39]. The National Cancer Institute has also created a nanotechnology branch to allow companies to expedite the processing of their drugs. Presently, many of the benefits achieved by this technology are decreased toxicity and reduction of side effects [39]. Two anti-cancer drugs, Doxil and Abraxane, have had their adverse effects reduced nanoformulation. Other applications include improved targeting of drugs by both oral and parenteral means [40].

These present developments are minuscule compared to the limitless long-term applications of nanocomputing and nanotechnology. Three crucial applications are in the areas of design, delivery, and drug monitoring [40]. Monitoring the efficiency of pharmaceuticals remains an persistent obstacle to both pharmaceutical corporations as well as medical practitioners. The use of nanorobots composed of “diamondoid nanometer-scale nanosensors” may allow imaging after drug delivery [41]. This would enable physicians to consistently monitor patients and evaluate the efficacy of certain medicines over a broad spectrum of individuals. Additionally, by using recently pioneered nanodelivery systems, several drugs may be combined into a single “package.” [42].

1.6.5. The Future of Biomedical Nanotechnology

The future of nanotechnology is bright and every day new and important advancements are made in the field of nanocomputing. The merger with biomedical research will bring in a new age of scientific development unlike anything we have ever seen. Like the biotechnology revolution of the 1960s and 1970s, biomedical nanotechnology will revolutionize research and provide an almost infinite supply of techniques for treating the most challenging ailments. Even the simplest tasks may be delegated to nanomachines, which make fewer mistakes and will monitor parts of the human body not possible by physicians. The brain, heart, liver, kidneys, and other vital organs may be under the constant watch of millions of nanorobots that can take precise and accurate measurements in real time. This data can be sent to a local computer where it is processed and transmitted to a healthcare professional for analysis. Doctors will change their approach to treating disease, and computing in nanotechnology will make diagnoses more accurate, treatments more effective, and lives more fulfilling. The technology is real. The potential is real. All we need is time. Chapters 15, 16, and 18 provide additional information.

1.7. NANOCOMPUTING AND NEUROSCIENCE

Nanotech applications in biology and medicine now allow for surgeons to induce desired physiological responses in the human body throughout the central nervous system (CNS). Pioneer work being done in this novel field may one day bring us numerous new therapeutic choices that hold much less risk for patients, as well as prove a more convenient means for surgeons to handle molecular machinery. According to Dr. Gabriel A. Silva, technological advancements must occur alongside clinical neuroscience advancements [43, 44] simply because of the highly interdisciplinary nature. An emerging field of neuroscience nanocomputing is the production of materials and devices designed to interact with neurons at the molecular level. The developing platform technology of nanowires that is to be discussed in this section may prove to have broad applications in neuroscience and, of greater importance, possess the potential to save lives much sooner than expected.

1.7.1. Nanomachinery: Opportunities and Challenges

Imagine wires that were hundreds or thousands of times thinner than the human hair, utilizing blood vessels in the body as conduits towards adjacent individual neurons. These are what we would call nanowires [45]. Dr. Charles M. Leiber, an interested researcher at Harvard University in the field of nanocomputing, invented a nanowire transistor that can detect, stimulate, and inhibit neuronal signals [46]. This gives rise to the question of what a nanowire is. In simple terms, a nanowire is a wire of dimensions in the order of a nanometer. These range in makeup, being either metallic, semiconducting, or insulating. Some previous technology was available in this area but was too large in size. Micropipette electrodes were previously available but were harmful to cells in that they destructively poked cells. By contrast, the tiny nanowire transistors developed by Lieber and colleagues gently touch a neuronal projection to form a hybrid synapse, making them noninvasive and thousands of times smaller than the electronics now used to measure brain activity [46]. In addition to being nonintrusive, nanowires can be biodegradable, biocompatible, and capable of producing diagnostic test results in minutes instead of days.

A great effort has already been invested in this nanomachinery, and a series of promising results have thus been revealed. One such opportunity is the silicon nanowires' precision in its detection of bioterrorism threats. When discussing neuropathological disease processes at a molecular level, scientists can observe that there is potential in a nanowire's ability to limit such disease processes with early detection. Unlike conventional DNA sensors, such nanowire techniques provide much more detailed information on the scale of neurons, as well as give a sharper focus of disease markers in perhaps any bodily fluid in humans [47]. Likewise with degenerative diseases such as Parkinson's and Alzheimer's, nanowires provide hope for treatment rid of damaging side effects (brain tissue scars) by stimulating the affected area of the brain with wires tinier than capillaries themselves. Many researchers envision nanowires connected to a catheter tube and able to be guided throughout the circulatory system to the brain, where nerve-to-nerve interactions will allow neuroscientists to make earlier diagnoses and provide earlier treatment without the cost of time consuming procedures.

Through electrophysiological measurements of brain activity, made possible by nanowires, important signal propagation through individual neurons and neural networks can be understood. Sophisticated networks between the brain and external prosthetic technology can be produced through this revolutionary manipulative technique. Much of this technology has great potential in the field because it can be used to monitor signaling among larger networks of nerve cells, thereby allowing doctors to detect electrical activity going on between neurons, tumors, and brain abnormalities; to localize seizures; and to pinpoint damage caused by injuries and stroke [47]. Eventually, the technology will be used to detect the diverse kinds of neurotransmitters that leap synapses from neuron to neuron. The mystery behind many neural system disabilities such as mental illnesses and certain paralysis diseases could be unraveled with this amazing invention in the scientific community.

Working at the molecular level with nanowires still has its shortcomings and is an incredible challenge in the field of neuroscience and nanocomputing. The extremely intricate composition of the CNS poses obvious challenges to nanocomputing's applications in neuroscience. Specifically, these include cellular heterogeneity and multi-dimensional cellular interactions which explain the basis of its extremely complex information processing [43]. There is also the challenge of guiding nanowire probes to a predetermined location among the thousands of capillary branches in the human brain that reside in the brain's vascular system. And because it is considerably more difficult to manipulate materials on the nanoscale level, it is also difficult to measure the electrical and mechanical properties of the nanomaterials themselves.

Along with developing the functions of engineered machinery to carry out neural regeneration, neuroprotection, and other tasks of the sort, there is an evident need for precise and proper synthesis of such machinery. These "tailored nanotechnologies" cannot provide any solution to neurobiological complications unless they are designed by the most skilled and competent specialists, which in this case is not the role of the neuroscientist [44]. We know that materials scientists, chemists, and specialists of other similar disciplines have, unlike neuroscientists, devoted their careers to the synthesis of such technologies. Neuroscientists in turn contribute to this interdisciplinary science through their wealth of knowledge in neurobiology, neuropathology, and other areas. In this book, an implementation of neural network with nanotechnology is studied in Chapter 17. Evidently, these challenges have the potential to improve what may have otherwise been overlooked in synthesizing machinery. Often such obstacles help us to be more focused on the safety behind clinical neuroscience advancements.

1.7.2. Current Work and Research

Functional nanotechnology, including nanocomputing, is still at its infancy stages, with numerous institutions of various scientific fields finding ways to make nanotechnology as safe and effective as can be. The government has given research grants to scientists from different universities such as Brown, Stanford, MIT, and CIT in order to facilitate research in such a promising field. Leading researchers such as Dr. Charles M. Lieber of Harvard University have contributed greatly to the advancement of nanocomputing. Dr. Lieber, along with his associate Jong-in Hahm, Ph.D., recently helped start a company called NanoSys, Inc., which is currently in the process of developing nanowire technology and other nanotech products. Other researchers include neuroscientist Rodolfo R. Llinas of the New York University School of Medicine and Masayuki Nakao of the University of Tokyo [45, 47]. As the general public can see, the advent of nanotechnology is one that will affect the lives of people worldwide and not simply arrive to us as a packaged fad whose hype is short lived.

The great deal of research that is currently being done on the neurological applications of nanotechnology was bolstered when six scientists at Brown University were awarded $4.25 million to begin research on such interactions in the mammalian nervous system. Along with many professionals from an array of different fields—surgery, chemistry, physics, and others—these brilliant minds are collaborating to help advance knowledge and further discovery of nanotechnology and nanocomputing. This commitment to research, coupled with a great amount of popular sentiment towards nanotechnology and nanocomputing, may further our own knowledge as observers and students and accelerate the progress of this exciting phenomenon. For more information on funding and patenting issues, see Chapter 20.

1.8. CONCLUSIONS

For the past 50 years, transistors have been shrinking consistently, and we have entered the era of nanocomputing. In this new era, transistors are only a small portion of the technologies that are available at nanoscale. There is a vast landscape of nano devices and paradigms that are currently being studied. In this chapter, we gave a brief introduction to nanocomputing and presented a high level overview of nanocomputing devices and paradigms. Nanocomputing has a potential to provide a remedy for some traditional problems in microelectronics. We also discussed some applications of nanocomputing such as bio medical engineering and neuroscience. The rest of this book will take the reader on a journey from low level device physics to architecture-level, bio-inspired architectures, all of which have the potential to be used for implementing various devices, such as biomedical and biomimetic nanoscale integrated circuits.

REFERENCES

1. R. P. Feynman. There's plenty of room at the bottom: an invitation to enter a new field of physics. *Engineering and Science*, 23(5): 1960.
2. Wikipedia. List of Intel Microprocessors. 2007. http://en.wikipedia.org/w/index.php?title = List_of_Intel_microprocessors&oldid = 181278285.

3. N. Weste and D. Harris. *CMOS VLSI Design: A Circuits and Systems Perspective*. Reading, MA: Addison Wesley, 2004.
4. C. K. Maiti, N. B. Chakrabarti, and S. K. Ray. *Strained Silicon Heterostructures: Materials and Devices*. Piscataway, NJ: IEEE, 2001.
5. M. Houssa. *High k Gate Dielectrics*. New York: AIP, 2004.
6. X. Huang, W. C. Lee, C. Kuo, D. Hisamoto, L. Chang, J. Kedzierski, E. Anderson, H. Takeuchi, Y. K. Choi, K. Asano, V. Subramanian, T. J. King, J. Bokor, and C. Hu. Sub 50-nm finFET: PMOS. Electron Devices Meeting, 1999. *IEDM Technical Digest International*: pp 67–70, 1999.
7. B. S. Doyle, S. Datta, M. Doczy, S. Hareland, B. Jin, J. Kavalieros, T. Linton, A. Murthy, R. Rios, and R. Chau. High performance fully depleted tri-gate CMOS transistors. *IEEE Electron Device Letters*, 24(4): pp 263–265, Apr 2003.
8. Harold Abelson and Peter Andreae. Information transfer and area-time tradeoffs for VLSI multiplication. *Communications of the ACM*, 23(1): pp 20–23, 1980.
9. J. Wang and M. Lundstrom. Electron Devices Meeting, 2002. Does source-to-drain tunneling limit the ultimate scaling of MOSFETs? In: *IEDM '02 Digest*. *International*: pp 707–710, 2002.
10. V. Balzani, A. Credi, and M. Venturi. *Molecular Devices and Machines: A Journey into the Nanoworld*. Weinheim: Wiley-VCH, 2003.
11. Y. Chen, G. Y. Jung, D. A. A. Ohlberg, X. Li, D. R Stewart, J. O. Jeppesen, K. A. Nielsen, J. F. Stoddart, and R. S. Williams. Nanoscale molecular-switch crossbar circuits. *Nanotechnology*, 14(4): pp 462–468, 2003.
12. B. L. Feringa. *Molecular Switches*. Weinheim: Wiley-VCH, 2001.
13. J. M. Tour, W. L. Van Zandt, C. P. Husband, S. M. Husband, L. S. Wilson, P. D. Franzon, and D. P. Nackashi. Nanocell logic gates for molecular vomputing. *Nanotechnology*, 1(2): pp 100–109, Jun 2002.
14. J. Cumings, A. Zettl. Low-friction nanoscale linear bearing realized from multiwall carbon nanotubes. *Science*, 289(5479): pp 602–604, 2000.
15. W. Liang, M. Bockrath, D. Bozovic, J. H. Hafner, M. Tinkham, and H. Park. Fabry–Perot interference in a nanotube electron waveguide. *Nature*, 411: pp 665–669, June 2001.
16. A. Khitun and K. L. Wang. Multifunctional edge driven nanoscale cellular automata based on semiconductor tunneling nanostructure with a self-assembled quantum dot layer. *Superlattices and Microstructures*, 37(1): pp 55–76, 2005.
17. A. Khitun and K. L. Wang. Cellular nonlinear network based on semiconductor tunneling nanostructure. *IEEE Transactions on Electron Devices*, 52(2): pp 183–189, Feb 2005.
18. M. A. Kastner. The single electron transistor and articial atoms. *Annalen der Physik*, 9: pp 885–894, Nov 2000.
19. C. S. Lent, P. D. Tougaw, W. Porod, and G. H. Bernstein. Quantum cellular automata. *Nanotechnology*, 4(1): pp 49–57, 1993.
20. M. Johnson. Bipolar spin switch. *Science*, 260(5106): pp 320–323, 1993.
21. S. Wolfram. *A New Kind of Science*. Wolfram Media, 2002.
22. A. Ilachinski. *Cellular Automata: A Discrete Universe*. Singapore: World Scientific, 2002.
23. L. O. Chua and L. Yang. *Cellular Neural Networks*. *Circuits and Systems*, 1988.

24. C. M. Bishop. *Neural Networks for Pattern Recognition*. Oxford, UK: Oxford University Press, 1994.
25. M. Gardner. Mathematical games: the fantastic combinations of john conway's new solitaire game 'life.' *Scientific American*, 223(4): pp 120–123, 1970.
26. M. Cook. Universality in elementary cellular automata. *Complex Systems*, 15(1): pp 1–40, 2004.
27. T. Roska and L. O. Chua. The CNN universal machine: an analogic array computer. *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, 40(3): pp 163–173, Mar 1993.
28. C. N. Eichelberger and K. Najarian. Simulating protein computing: character recognition via probabilistic transition trees. *IEEE International Conference on Granular Computing, 2006*. pp 101–105, May 2006.
29. L. M. Adleman. Molecular computation of solutions to combinatorial problems. *Science*, 266(11).
30. P. W. Rothemund, N. Papadakis, and E. Winfree. Algorithmic self-assembly of DNA sierpinski triangles. *PLoS Biology*, 2(12): Dec 2004.
31. P. W. Rothemund. Folding DNA to create nanoscale shapes and patterns. *Nature*, 440: pp 297–302, 2006.
32. M. A. Nielsen and Isaac L. Chuang. *Quantum Computation and Quantum Information*. Cambridge: Cambridge University Press, 2000.
33. P. W. Shor. Algorithms for Quantum Computation: Discrete Logarithms and Factoring. *IEEE Symposium on Foundations of Computer Science*: pp 124–134, 1994.
34. L. M. Vandersypen, M. Steffen, G. Breyta, C. S. Yannoni, M. H. Sherwood, and I. L. Chuang. Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance. *Nature*, 414: pp 883–887, Dec 2001.
35. N. L. Kedersha, D. F. Hill, K. E. Kronquist, L. H. Rome. L.H. Subpopulations of liver coated vesicles resolved by preparative agarose gel electrophoresis. *Journal of Cell Biology*, 103: pp 287–297, 1986.
36. National Science Foundation. "Vaults: From Biological Mystery to Nanotech Workhorse?" *Biological Sciences*, Arlington, VA: The National Science Foundation. http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id = 104106&org = MCB, 2007.
37. Regents of the University of Michigan. Molecular Motors. http://www.umich.edu/news/MT/04/Fall04/story.html?molecular. Jan 16, 2007.
38. Y. E. Goldman. Functional studies of individual myosin moleculares. *Annals of the New York Academy of Sciences*, 1(18): 2006.
39. C. McCarthy, Nano Science and Technology Institute. Pharma Explores Business Opportunities for Nanotech. http://www.nsti.org/news/item.html?id = . Mar 13, 2007.
40. Cirrus Pharmaceuticals. Pharmaceutical Nanotechnology. http://www.cirruspharm.com/pdf/brochures/Nanotechnology.pdf. Mar 13, 2007.
41. R. A. Freitas. Computational Tasks in Medical Nanorobotics. Insitute for Molecular Manufacturing, 2007.
42. P. Chapman. Nanotechnology in the pharmaceutical industry. *Expert Opinion on Theraperutic Patients*. 15(3): pp. 249–255, 2005.
43. G. A. Silva. Introduction to nanotechnology and its applications to medicine: applying nanotechnology to medicine. *Surgical Neurology*, 61: pp 216–220, 2004.

44. G. A. Silva. Neurosicence nanotechnology: progress, opportunities, and challenges. *Nature Reviews Neuroscience*, 7: pp 65–74, 2006.
45. National Science Foundation. Nanowires in blood vessels may help monitor,sStimulate neurons in the brain. http://www.nsf.gov/news/newssumm.jsp?cntnid = 104288&org = ENG. July 7, 2005.
46. F. Patolsky, B. P. Timko, G. Yu, Y. Fang, A. B. Greytak, G. Zheng, and C. M. Lieber. Detection, stimulation, and inhibition of neuronal signals with high-density nanowire transistor arrays. *Science*, 313: pp 1100–1104, 2006.
47. Tiny Nanowire Could be Next Big Diangostic Tool for Doctors. *Science Daily*: Dec. 18, 2003.