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Discovery, Invention, and Science in Human Progress

Nanotechnology is a recent addition to the long history of human efforts to survive and make life better. Nanotechnology is based on the understanding of and tools to deal with very tiny objects, down to the size of atoms [1]. To begin, it is worth reviewing some of the broader history, to put nanotechnology in perspective, so that we can better understand how it can serve as a bridge to the future.

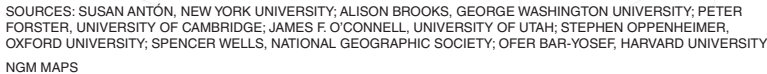
Technology has evolved over tens of thousands of years and more by the activities of humans and their predecessors: the history of technology is almost the history of humanity.

1.1

Origins of Technology, the Need for Human Survival

Struggling for survival and ascendancy for over 50 000 years (a conventional time frame for the migration of “*homo sapiens*” out of Africa [2], (see Figure 1.1), humans invented new and useful ways of doing things.¹ Technology has advanced ever since, in an accelerating fashion, and we hope to provide an understanding of a current forefront of technological advance called *nanotechnology*, which specifically deals with small objects and the laws of nature that describe these small objects [1].

Technology, often based on discovery, is knowledge on how to get things done, and the tools to make use of that knowledge. This is a practical matter, often a matter of life and death. *Stone age* tools have been found dating to about 2.4 million years ago. Then came the *Bronze age* and the *Iron age*. In 1200 BC, the Hittites were the first to use iron in weapons. We can say that advanced metal technology started long ago [3–7].² To understand nanotechnology it is useful to review some of the previous technological advances in the 50 000-year history.



tracked by changes in human DNA. We discuss this in Chapter 4. (NG Maps/National Geographic Stock).

1.2

The development of the wheel, advanced control of fire, and the development of copper, bronze and iron technologies, set the stage for the more recent industrial revolution. The industrial revolution, based on the invention of the steam engine by James Watt in 1776, led quickly to the steam locomotive in 1804. This required a *synthesis* of the technologies for making

fire and elaboration of wheels and axles to include gears and pistons, requiring knowledge of metals to make strong components. The steam engine also brought to the fore knowledge of thermodynamics, a science that could improve the efficiency of engines based upon steam. The concept and measurement of temperature, an aspect of modern science, was part of that advance.

The advance of civilization can be measured by the technology in use and also by the sources of energy that were available at a given time.

A primary source of energy in the mercantile sailing era was wind. Wind has been used since ancient times, to make sailing boats and to power windmills to pump water or grind grain. It is reported that in fourth century BC the Greek wind- and human-powered merchant fleet went all the way from Spain to the Black Sea, and of course Julius Caesar invaded Egypt by sea. A three-masted merchant ship is reported in China in 400 AD. The *compass*, based on magnetite, an iron oxide, was invented in 200 BC in China, and was widely used by the Chinese shipping fleet in 1100 AD. Sailing long distances stimulated the development of better clocks, needed for navigation, and of course, clocks are important in today's information technology.

The technology of sailing ships and worldwide navigation flourished starting from the time of Columbus, who sailed in 1492 to America from Spain. In 1503 Vasco Da Gama of Portugal took 20 ships from Lisbon, around the bottom of Africa and to India, initiating more wide-ranging open-sea commerce, which had earlier been limited, such as to the Mediterranean Sea. Sailing ships remained important until well after 1860, when steam-powered ships were first constructed.

The Dutch were well known for pumping water with windmills, the predecessors of modern wind turbines. Present-day technologies building on the sailing era technology include airfoils on airliners and the space shuttle, helicopters, and wind turbines of 1 MW (megawatt) generating capacity, that cost about \$1 M apiece.

With James Watt's invention of the steam engine in 1776, to begin the industrial era of engines, the source of energy shifted, from wind to fuels to be burned to generate steam and run the engine. Over time, the fuel of choice has changed from wood, to peat and coal, and then to oil and gas. A recent addition is nuclear power, used by nuclear reactors in submarines, aircraft carriers, and electric power plants. This might be looked at as passing industrial leadership from Holland (wind technology) to England (wood and coal steam engines) and then to America (the era of oil and gas, Henry Ford, and the internal combustion engine). Nuclear energy, since about 1945, with the first nuclear reactor in Chicago developed by Enrico Fermi, has been an international effort.

Although oil was well known in the Middle East since very early times, the modern large-scale extraction of oil as a fuel dates to 1859, in Titusville, Pennsylvania and 1901, in Spindletop, Texas. US oil production peaked in about 1971, and, with depletion, has fallen ever since. The era of availability of oil may be about 200 years, starting in 1859, because the amount of available oil is definitely limited.

1.3

A Short History of Time: Navigation, Longitudes, Clocks

A *short history of time* involves the technology of devices to measure intervals of time. The earliest clocks were water clocks that date back to the sixteenth century BC in Babylonia and Egypt. These simple useful devices are similar in principle to the sand hourglass, depending upon a steady flow rate of a given mass of water or sand. Accuracy and resolution in clocks was stimulated by the need to know the *longitude* when crossing an open sea, far from sight of land. The distance in going from one time zone to the next is 15 degrees longitude, which is 645 miles at the Latitude of London, England. This information could be used by the sea captain. Suppose, at the wharf in London, as he sets sail, the captain's ship clock reads noon when the sun is directly overhead.

After a day of sailing to the west, noon the next day, the sun might be directly overhead at 12:30 on his ship clock (which was set in London). If so, the captain would know, assuming constant latitude, that he had traveled half a time zone, about 322 miles.

For lack of good clocks, this option was not available to sea captains until after 1760, with the invention of an accurate portable clock, the "marine chronometer," by John Harrison. For centuries before this, sea captains, in practice, had relied on *dead reckoning*.³ The ship's compass indicated the direction of travel, and the distance per day was estimated from the speed multiplied by the time elapsed. This was a laborious and honest, but inaccurate process. Ships went astray and lives and fortunes were lost. The failings in navigation became such a problem that the British government established a Board of Longitude, to fund the development of an accurate clock.

A great advance came in 1759 with the invention of the accurate marine chronometer. This clock, based on a spring oscillator, was invented in stages by John Harrison [8], who won a prize from the British government. Somewhat earlier, in 1656, the pendulum clock was invented by Huygens. The idea of a pendulum as establishing a timescale was known earlier, even to Galileo in the early 1600s. A clock based on a pendulum was not built, however, until 1656. Although it predated the John Harrison chronometer,

the pendulum clock is not useful except in fixed locations. It requires a stable footing not available on a ship.

A major advance in modern timekeeping was made with the miniaturized quartz oscillator in the Bulova watch (see Chapter 3). Here quartz is shaped to form a cantilever or spring, whose resonant frequency, f , near 33 kHz, is governed by a formula $f = (1/2\pi) (K/m)^{1/2}$, where the spring constant K has units Newtons/meter and m is the moving mass. (Here, the Newton is about 0.225 pound force, and m is measured in kilograms. The frequency is in hertz, oscillations per second.) The quartz oscillator has been further miniaturized and still forms the clock in the personal computer (PC), working up to 3 GHz, as we will discuss in Chapter 3.

The *atomic clock*, based Cs (cesium) atoms, is now used as the worldwide standard of timekeeping, accurate on a scale of nanoseconds, billionths of a second.

Our book is about *nanotechnology*, the useful (and profitable) application of small-scale working elements and devices [1].

Present major technologies that benefit most from nanotechnology are the *silicon computer technology*, and *information technology*. Information technology (IT), couples silicon technology with optical fiber transmission of signals, and with advances in data-storage technology, such as the computer disk drive.

Medical technologies including diagnostics such as X-rays, which are also the basis for unraveling the structure of double-helix DNA (the information aspect of biology), drug design and genomic technology; and magnetic resonance imaging (MRI) also benefit from the emerging area of nanotechnology.

High-energy synchrotron light sources, adapted from high-energy physics, giving huge intensities of X-rays, have allowed rapid determinations of molecular structures. This has enabled modern pharmaceutical advances, which also benefit from computer modeling. While polymers (think polyethylene and polystyrene) are definitely chemistry, one can argue that designing drugs for a specific purpose is an exercise in nanotechnology.

1.4

The Information Revolution: Abacus to Computer Chips and Fiber Optics

The advance of technology is itself accelerating [9]. To illustrate this, we will consider the timing of advances related to information technology! The first record of bones carved with notches dates to 20 000 BC, and bones carved with prime numbers were found as early as 8500 BC. (Prime numbers cannot be expressed as a product $c = ab$ of two other numbers. This is a

subtle matter, but evidently understood by smart people nearly 10 centuries ago.) The abacus comes from China and Babylonia, around 1000 BC, and has several forms.

But it was not until 1500 AD that Leonardo da Vinci described a mechanical calculator. Logarithms and the slide rule were invented about 1600 AD. The predecessor of the IBM tabulating machine was invented by Hollerith in 1890 for the US census. (If time starts 50 000 years ago, then the 411-year interval (2011 AD–1600 AD) is 0.8% of the life of *Homo sapiens*. If time starts 4.54 billion years ago, with the formation of the earth, this is in the last 0.09 millionth of time on Earth.

Time intervals between inventions in this set have reduced from thousands of years to hundreds of years.

But since 1945 or so, a period of 65 years, we have had many, many inventions related to information technology! The transistor was invented in 1947, the Univac programmable computer in 1951, the atomic clock in 1955, the integrated circuit in 1958, the Xerox machine in 1959, the laser in 1964, the magnetic floppy disk in 1971, the Ethernet in 1973, the personal computer in 1973–1976, the optical fiber in 1970–1975, the injection laser in 1978, the Internet global computer network in 1990 and the Pentium chip in 1993, global positioning system (GPS) in 1993, the Internet search engines in 1993–1998, the Blue Gene chess-playing computer in 1997, the magnetic tunnel junction hard disk reader in 2004, and Watson computer winning the Jeopardy TV competition in 2011.

While earlier inventions were spaced by hundreds or even thousands of years, the inventions listed here since 1945 are spaced by about 4 years, a much shorter interval! It is widely agreed that technology is accelerating [9]. Moore’s law, which has predicted the doubling of the number of transistors per chip each 1.5 years, is an example of “exponential growth,” an accelerating increase. A striking, but hypothetical scenario on growth of computing capacity is “the Singularity,” when computer intelligence may exceed human intelligence. It is suggested, in the work of Ray Kurzweil [9], but hotly debated that computers will become completely equal to humans in all thinking activities in 2045. “Singularity” or not, we live in an age of accelerating technological capacity, much of it based on nanotechnology, the topic of our book.

1.5

Overlap and Accelerating Cascade of Technologies: GPS, Nuclear Submarines

In a more definite historical sense, we have seen that combining two technologies can lead to a third, for example, combining use of fire and wheels

led to the steam engine. (Actually, more developments were needed, including the mining and purification of metals, and their fabrication into gears, pistons, and more.) We can think of the steam engine as a *hybrid* technology, and really this is the norm in the advance of technology. What we see is really a cascade of developments, one upon the other. A recent example is the global positioning system (GPS) depending on atomic clocks, state of the art silicon devices, computers, and space technology.

Another hybrid technology, with a strong nanophysical component, is represented by the nuclear submarine. (We use the term *nanophysics* for the forms of physics that are needed to describe properties and processes on *size scales below 100 nm*; these include atomic and solid-state physics, and nuclear and high-energy physics.)

The nuclear submarine uses an onboard nuclear power reactor to allow long voyages, and nuclear-powered submarines and aircraft carriers have been extremely reliable. The power that drives the propellers on the submarine comes from an electric motor. The electric motor is run from an electric generator. The generator is turned by a steam turbine. The heat that generates the steam comes from a nuclear reactor. The nuclear reactor derives its energy from fission events within uranium nuclei (see Chapter 5). The prototype reaction is the splitting of the ^{235}U , which has $Z = 92$ protons and $N = 143$ neutrons, to release energy of several million electronvolts (MeV) per nucleus. (This is a huge energy release; it is about a million times larger than the energy release in a chemical reaction such as burning hydrogen to make water.) The energy release comes because the Coulomb repulsion between positive proton charges in the resulting nuclei, which might be typified by ^{133}Cs (cesium), with proton number $Z = 55$, is lower after the fission.⁴ The difference in energy can also be calculated by using Einstein's famous relation that the change in energy will be the change in mass multiplied by c^2 , with c the speed of light at $2.998 \times 10^8 \text{ m/s}$.

So the nuclear-powered submarine is an example of cascading of technologies, and the origin of its power emphasizes the importance of nanophysics in our modern world.

Understanding the nanophysical properties of the nucleus slowly accumulated by the work of many physicists over decades.

1.6

Silicon and Biotechnologies: Carbon Dating, Artificial Intelligence

Other useful technologies that stem from the knowledge of nanophysics of atomic nuclei include the technique of "carbon dating," which allows us for

example, to date artifacts such as bones of dinosaurs and wooden tools and remains left by early humans. Carbon dating depends upon the presence of small amounts of ^{14}C in the air. The stable form of carbon is ^{12}C . The carbon isotope ^{14}C decays on a regular timescale, and a living organism has its ^{14}C replenished by respiration. When it dies the respiration stops and the ^{14}C decays. The amount of ^{14}C remaining can be determined by counting the rate of electron emissions per second per gram of carbon in the specimen. This knowledge, on which the technology of carbon dating rests, has accumulated slowly by the activity of nuclear physicists. This technology was used, for example, to establish the date of manufacture of the bone flute recently found in a cave in Eastern Europe. The flute was found to have been made 30 000 years ago, from the hollow bones of a large bird. The flute had carefully chiseled openings to place the fingers, and a headpiece to create sound from blowing air.

We suspect that one source of the accelerating advance of technology is the greatly enhanced exchange of information [9]. The Internet global computer network allows the exchange of ideas in an unprecedented fashion. This builds on the silicon technology, the technology for storing information, the optical fiber technology for communications all around the world, and the advance in computer programming.

Human capability and human productivity is basically multiplied by technology. It is definitely rising with the increase in communication capacity. With the Internet, the global computer network, an idea from a remote researcher is often put onto the Web, the Internet, as an Internet archive file that immediately can be read by people all around the world. This is the democratization of science, unquestionably allowing faster progress. There are smart, well-informed people all over the world, and now more of these people can participate in the creation of new knowledge and new technology.

Consider the Google Book project, the ongoing effort of Google Corp at digitizing all the books in the world, to make the texts available as searchable computer PDF files for everyone. There are millions of books in libraries. However, the old books, especially, have been inaccessible, on the whole, limited to those who can walk, for example, to the Library of Congress or the Stanford University Library. Interlibrary loan of books is possible in principle, but difficult in practice, especially for a rare old book.

The Internet (“World Wide Web”) and the Google Books project are revolutionizing access to books. Google Books have digitized millions of books, which are available on the Web, with the great advantage that the digitized sources can be *searched* in a flash (ask the Jeopardy contestants). In his extended family, one of us, EW, had shared a single copy of the “Burgess

Genealogy (1865),” which he finally photocopied. But now photocopying is becoming obsolete, because the “Burgess Genealogy” is on Google Books and can be freely downloaded as a PDF file by anyone. The great advantage is that the computer file can be searched, to find where a given word appears in the book. For example, a search for “Thomaston” immediately finds which relatives named Burgess lived in Thomaston, Maine (William Carey Burgess). There is no need, now, to travel to the one or two libraries in the country that have this book; it is easily available to anyone in a minute on his computer.

EW wrote a book “Quantum Nanoelectronics” [10] for use in his university teaching. This is a long book with facts sometimes forgotten, for which it is a good source. It turns out that the quickest way to find a fact or number from this book is to open the book on Google Books and search it. Putting in “Bohr magneton” (you can try it) gets instantly eight responses, and one can scroll down and see each of the pages that contain that phrase. It is much faster than looking through the index! The use of Google Books online search clearly is easier, once the computer is online, than fumbling through the index and then flipping pages.

This really useful facility is now available for millions of books, a substantial fraction of books in the major libraries in the United States. This provides a big change in the working conditions for scholars worldwide (and for ordinary people who may just want to find their ancestors).

This is a part of the ongoing information technology explosion, which has strong roots in nanotechnology. It seems sensible to call the Google Book search capability a form of *practical artificial intelligence*, or AI from a practical point of view. It does a task that a human might otherwise be needed to perform.

In another example of such *practical artificial intelligence*, Raymond Kurzweil invented a reader for the blind. Given a sheet of text the reader will absorb the information and speak it out in English or any desired language! A complementary capacity, *speech recognition* (for which software is available, for example, from the Nuance Corporation), will take spoken words and turn them into a Word file.

A doctor may use such a program to get a written record of his discussions with patients. The accuracy of such programs is definitely improving. So a computer can now take your spoken words and turn them into a file and a written page. A computer can also look at a written page and speak it out in any language you might like. These activities are valuable and would in earlier times require a human to carry them out. We consider these to be examples of *practical artificial intelligence*, and my inclination would be to call this simply AI, for artificial intelligence.

Other people disagree, and offer a different definition of (strong) artificial intelligence, AI, which does not exist as far as we know.

This hypothetical form of AI, which we will call *strong* or *sentient* AI, would be a self-aware conscious independent entity that some people think (and/or fear) might arise from a computer system. This hypothetical kind of artificial intelligence, AI, was described long ago by Isaac Asimov in his book entitled “I, Robot.” Asimov’s hypothetical robot knows who it is and will defend its own interests!

If a big robot looking like Arnold Schwarzenegger strides into the room and says “I am in charge here,” you will know that *strong* AI has arrived.

Asimov’s robot has not happened yet. This “strong” or “sentient” AI has not occurred, but it is part of the Singularity hypothesis. (The machine called “Watson” that has recently won on the TV show “Jeopardy” is not likely to stride into anyone’s room, since it comprises two rooms of computer racks, costing millions of dollars [9] and requiring megawatts of power to run.)

But the practical form of artificial intelligence is certainly helping the acceleration of technology. This is part of what we are talking about. All of the elements of the practical form of artificial intelligence incorporate nanotechnology: Fast computers with lots of storage, fiber-optic networks connecting to cloud computers all incorporate basic nanotechnological inventions.

One of us was driving a rental car in summer 2010 in Colorado, using a GPS unit carried in a carry-on bag from New York. On the highway, a casual query to the GPS about “driving home” (to a New York apartment) led quickly to a voice from the GPS describing the requested trip as “1875 miles and would take 38 hours.” This is pretty amazing; it did a search of all the routes from an immediate location in Colorado, using maps stored in its extensive database. The selected route was measured and an estimate of the time was produced, all in a few seconds. (The spoken answer could as easily have been given in German or in Hindi, according to the manual with the inexpensive GPS device.)

This seems to be an extraordinary artificial intelligence! Nanotechnology enters this story in fast computing, large databases, and in the atomic clocks in the GPS.

The New York Times recently ran a story [11] about a commercial computer program, called “Creative Artificial Intelligence (CAI),” for writing advertisements or ads. This program, developed by an arm of Havas, an international communications group, will produce ads on request, based on the selection of a product category (e.g., “soft drinks”) followed by a brief dialog. This CAI software can generate an estimated 200 000 ads.

In a recent demonstration, according to the New York Times story, the software “brought forth bland and formulaic—but perfectly acceptable—ads that could be run in magazines or newspapers, or as banners on Websites or billboards.” The story [5] was not particularly complimentary, describing as “mediocre” ads produced in a typical ad agency and also as “mediocre” ads produced by the software program that was being described.

With regard to reactions from people who did trials in use of the software, trial users were, generally, at first, amused. But, the notable quote was “they get a little scared when they see that a software program can create the same (mediocre) results *in just 10 seconds* as several hours of strategic meetings and production” in an agency! (*italics added*).

It was commented that this CAI program “generates fun ads,” and also that it “sometimes leads to random accidents that could stimulate the creative process.”

Nanotechnology enters this scenario in fast computation and rapid access/search to a large database; the large database was probably collected by using Internet search as pioneered by Google, which again has roots in nanotechnology.

A program to generate classical music has been written by Prof. David Cope, a music professor at the University of California. As in the advertising software, the style of the requested music can be adjusted (Bach or not Bach?). The current version of the software is called “Emily Howell,” an earlier version was called Emmy, and the output of new music written by these programs includes *1500 symphonies, 1000 piano concertos and 1000 string quartets!* An article on this subject (*I’ll be Bach*) [12] written by Chris Wilson appeared in Slate, dated May 19, 2010.

The impact of nanotechnology in the present and future, we argue, comes in part through its participation in the technology of the information explosion,⁵ and a leading example is artificial intelligence of a practical kind. A further example of nanotechnology-enabled practical artificial intelligence, in the form of the IBM Deep Blue computer, reached a peak when it outplayed the chess master Gary Kasparov. More recently, IBM has coupled its most powerful computer, Blue Gene, to a huge database, equipped with algorithms to direct extremely fast searches as on Google, to make “Watson,” the supercomputer that can play the TV game Jeopardy in a winning fashion [3, 7].

When human contestants in test trials play Jeopardy against “Watson,” they tend to refer to “Watson” as He. You may ask, “Who is ‘Watson?’”, and, of course, “Watson” in reality is a roomful of advanced computers [13], very expensive, with a large electric power bill, and there is absolutely no chance



Figure 1.2 The show Jeopardy in February 2011 pitted Watson against two star players, Ken and Brad. Watson won by the numbers, but made a few spectacular goofs, including placing Toronto, Canada, in the United States [14].

of “Watson” reproducing. (Although a “Watson”-type machine might be able to *design* a better version of itself) (Figure 1.2).

In modern business practice, this type of capacity is called an “expert system,” designed to serve as a consultant, for example, to inform decisions in business or medical diagnosis. IBM’s “Watson” programmed supercomputer/database is at the apex of the development of such expert systems [9]. Clearly the advance of Moore’s law will make this capacity more available in the future. At the moment “Watson,” however, is a multimillion dollar capital item, although time sharing may well evolve as a practical alternative.

Clearly there is a big disconnect between a hypothetical robot looking like Arnold Schwarzenegger and the real IBM “Watson,” which is a roomful of computers completely tied to the power grid. So even if “Watson” should decide that “he is in charge,” “he” would be immobile, and his owners at IBM could unplug him if they felt he was getting out of hand.

By any measure [1], the Pentium computer chip and its billion-transistor successors, used by the millions (nearly a thousand servers) in a system such as the IBM Watson, are products of nanotechnology. Open access to, and the facility of rapid searching, much of the knowledge of our civilization, is

a recent and ongoing development. It is hard to escape the conclusion that will have an astounding effect in technological advance.

Also, in many countries, detailed reports were made freely available to public listing out the risks and benefits and the areas of technology that still need investigation. And a lot of investment is being put into nanotech toxicology research to fully understand the toxicology implications of the materials [15].

1.7

Nanotechnology: A Leading Edge of Technological Advance, a Bridge to the Future

What is nanotechnology? It is the knowledge and methods to deal with and engineer particles and systems that range from 100 nm in size down to the sizes of individual particles, including, from our point of view, the particles in the atomic nucleus. The definition offered by the National Science Foundation in the United States describes controlled engineered elements whose extent at least in one dimension is in the range of 1–100 nm. The Royal Society Report [1] extends the range to 0.2 nm “because at this scale the properties of materials can be very different from those at larger scale.” This report [1] (p. vii) also comments that “nanotechnologies have been used to create tiny features on computer chips for the past 20 years.” This report clearly identifies the information revolution as a beneficiary of nanotechnology. We are reminded of the reality of this revolution by the recent valuation estimates of Facebook, *ca* \$50 billion, and by a report in the Egyptian newspaper “Al-Ahram” that an Egyptian father, Jamal Ibrahim, had named his newborn daughter “Facebook” to honor the social media site’s role in Egypt’s revolution [14].

Conventional engineering, based on machine tools making three-dimensional objects, such as tiny Ti screws for dental implants, really extends only to about 1 mm, the size of parts in mechanical wristwatches or sophisticated dental implants made of titanium.

There are six orders of magnitude, a factor of 1 million, in length from 1 mm to 1 nm. These size scales, from 1 mm to 1 nm, largely remain to be exploited to make useful devices and systems. In this context, the physicist Richard Feynman said, “there is lots of room at the bottom.” The potential benefits of miniaturization are illustrated by Moore’s law, which describes the road to billion-transistor chips at continuously falling prices and vastly improved chip performance. Consider that semiconductor counters now work at frequencies up to 200 GHz! (3 GHz is 3 billion cycles per second and is now a typical clock frequency in personal computers.)

But most areas of technology remain to be extended into the nanotechnology domain.

We believe it is reasonable, certainly for the benefit of the readers of this informational book, to *broaden our view of nanotechnology* to include devices and systems whose operation is based on the quantum laws of nature, which we call nanophysics, which come into play on size scales below 100 nm and apply all the way down to 1 femtometer, 10^{-15} m, one millionth of a nanometer.

Examples of nanophysically based devices include the magnetic tunnel junction disk reader, leading to 1-TB hard disks (1 TB is 10^{12} bytes), the cesium atomic clock used in the GPS and in Wall Street computers, and the MRI (magnetic resonance imaging) medical imaging apparatus, whose operation is based on the nanophysics of a spin- $\frac{1}{2}$ particle, the proton.

The laser, powering optical fiber communication, is based on the quantum photon of light and on the quantum phenomenon of stimulated emission first described by physicist Albert Einstein in 1905. These developments are based on quantum physics, the underlying science of nanotechnology. Nanotechnology, in its strongest form, would allow engineering of devices in this entire size range. It would be engineering knowledge applicable to size scales from 100 nm down to 1 femtometer, the size of the nucleus of an atom. Although femtometer engineering is not possible, intelligent applications of femtometer systems as in magnetic resonance imaging (MRI) and nuclear reactors can be viewed as “nanotechnology.”

In our beginning chapter, we have sketched a review of the history of technology, learning that technology is an accumulating bank of know-how and devices that various aspects of technology combine or form hybrids. We have seen that technological advance is accelerating. Nanotechnology is expertise and methods relating to small-size objects, on sizes below 100 nm, or about 0.1% the size of a human hair. A leading example of nanotechnology is the silicon chip that may contain a billion units that operate at frequencies above 1 GHz, a billion operations per second. It is reasonable to include in our discussion of nanotechnology those devices that depend upon engineering knowledge of atomic-scale phenomena, including electron and proton spins, in modern disk-drive readers and in magnetic resonance imaging (MRI), respectively. Nanotechnology has been, and will continue to be, a leading part in the advances in communication and computing, components of the information technology and Internet advances that are transforming our way of life.

Our hope in writing this book is to promote broader understanding of the existing nanotechnology and its underlying nanophysics, and its role in

the ongoing information revolution, and to help show how it may provide a bridge to the future.

1.8

How to Use This Book

The central theme of our book, stated in Chapter 1, continues in Chapters 2, 3, 5–7, and 14. Important illustrations of the central theme are given in Chapter 4 and Chapters 8–13. Chapter 4, on biology as successful nanotechnology, and Chapters 8–13 outline the present state of nanotechnology in several important areas. These chapters are factual and reasonably independent of one another. For the reader who wishes to sample highlights among these, we suggest that Chapter 4 stands apart.

Scaling to small sizes is central to our topic, and involves some mathematics. Chapter 3 shows on a case-by-case basis how the operating frequency f of oscillators (and other devices) increases as the typical size scale L is reduced. If the numerical examples in Chapter 3 become tedious, be sure to look at Figure 3.5, which shows how typical frequencies increase from 0.5 Hz for a grandfather clock to 10^{14} for a hydrogen molecule as a mechanical oscillator. (Don't miss Figure 3.1 either.) The latter portion of Chapter 3, explaining why small objects like pollen particles float and don't follow trajectories like baseballs, may be more mathematical and optional, unless you are curious as to why a bumblebee can't "fly" in an aeronautical sense. Chapters 8, 9, and 11–13, illustrative of our central theme, describe the most important present and future devices of electrical nanotechnology. These topics are up-to-date and are introduced with the minimum mathematics to convey their essence. Chapter 10, however, is a little different, it explains how the MRI machine works and how it is based on the quantum mechanics or "nanophysics" of the proton spin $1/2$. Chapter 10 also explains how a less costly MRI machine can be made using a quantum-mechanical sensor device, the "superconducting quantum interference detector" (SQUID). (We include quantum mechanically based devices in our broadened category of nanotechnology.) The operating element of the MRI machine is the proton, whose radius is about a femtometer, one millionth of a nanometer. Chapters 7 (including carbon nanotubes and C_{60} molecules), 12, and 13 cover in some detail topics highlighted in the new book by Michio Kaku, "Physics of the future: How science will shape human destiny and our daily lives by the year 2100" (2011), which is part of our concluding discussion in Chapter 14. Our comments on the hypothetical "Singularity" (which may already have happened?) are limited to Chapter 1 and Chapter 14.

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