Edward L. Wolf and Manasa Medikonda

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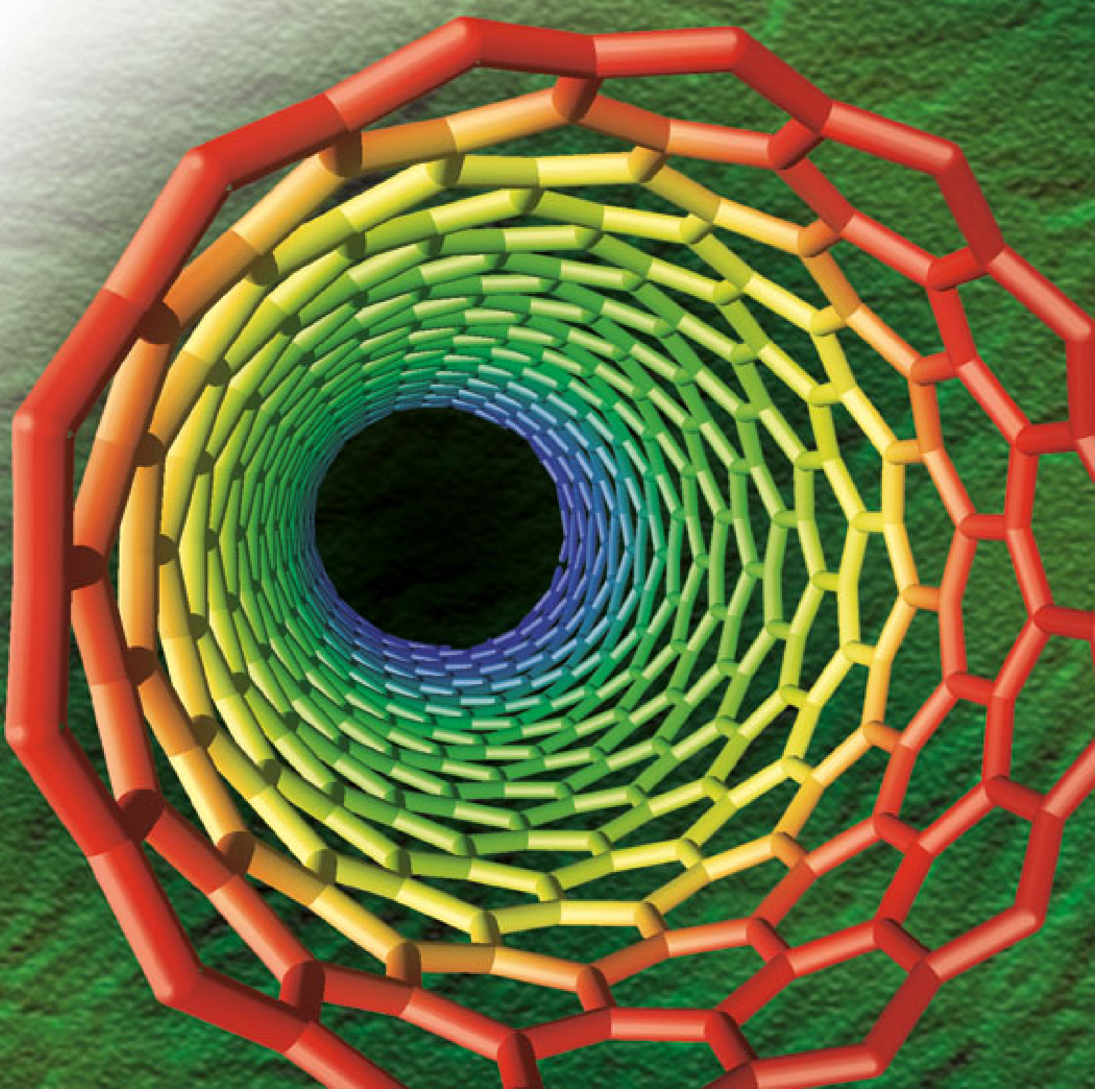

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Understanding the Nanotechnology Revolution

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Contents

Preface

A revolution has occurred over the past several decades in the availability and uses of information. This is perhaps the strongest reminder that we live in a time of accelerating technological change. This book explains one aspect of technological change, related to very small devices, devices approaching the atomic scale in their size. The technology related to small devices is called nanotechnology. But our aim in this book is broader, to put nanotechnology into the context of earlier scientific advances concerning very small objects. The contributions of the enlarged field of "nanotechnology" have been particularly great in information technology, the technology of computers, wireless communication, fiber optics, the Facebook phenomenon, and thinking machines like the "Watson" computer that can win on the television game "Jeopardy." We will argue that the greatest success of nanotechnology is really the silicon chip, with its billion transistors. Although Moore's law appeared before the word "nanotechnology," these developments in silicon technology clearly now fall within the definition of "engineered systems, at least one dimension being in the scale from 100 to 1 nanometers." The best way to view these developments is as part of nanotechnology. Many people, we think, will benefit, beyond seeing that silicon technology is a leading example of nanotechnology, by recognizing the longer common thread of competences that we believe are best regarded as "nanotechnology." These have the common aspect of harnessing tiny objects, to include the electron spins in cesium atoms that are the basis for the atomic clock, the use of proton spins in successful magnetic resonance imaging, and other topics as we will mention.

Specifically, this small book was stimulated by the invitation of "The Modern Scholar" series of audio lectures of Recorded Books, LLC, to one of us to provide a series of audio lectures on the topic "Understanding Nanotechnology: A Bridge to the Future." We have benefited from interactions with many people in this project. We thank Ed White of Recorded Books;

Ed Immergut, Consulting Editor in Brooklyn, NY; Vera Palmer, Commissioning Editor at Wiley VCH; Ulrike Werner of Wiley-VCH; Prof. Lorcan Folan; and Ms. DeShane Lyew at the Physics Department of NYU-Poly. In particular, E.W. thanks Carol, Ph.D. in Mathematics and Prof. of Computer Science, for help in many ways and for comments on the abacus and more generally on the history of mathematical inventions. M.M. wants to thank her family and friends for their tremendous support.

The book is dedicated to pioneers in the nanotechnology-enabled information revolution. John V. Atanasoff invented the digital programmable computer, arguably the most important invention of the twentieth century, as detailed in Note N4 to Chapter 2. (*Notes* follow Chapter 14 in the organization of this book.) John Bardeen was a coinventor of the transistor, which made the digital computer a practical matter and led to the Moore's law growth of computing capacity. S.S.P. Parkin did essential developmental research allowing the quantum-mechanical magnetic tunnel junction, based on the spin ½ of electrons, to be manufactured as the data-reading element in today's computer memory, the basis for cloud computing. Sir Timothy John "Tim" Berners-Lee is a principal architect of the World Wide Web, the global computer network that connects people in today's world.

Brooklyn, NY, May 1, 2011 *E. Wolf and M. Medikonda*

1
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 ascendency 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.

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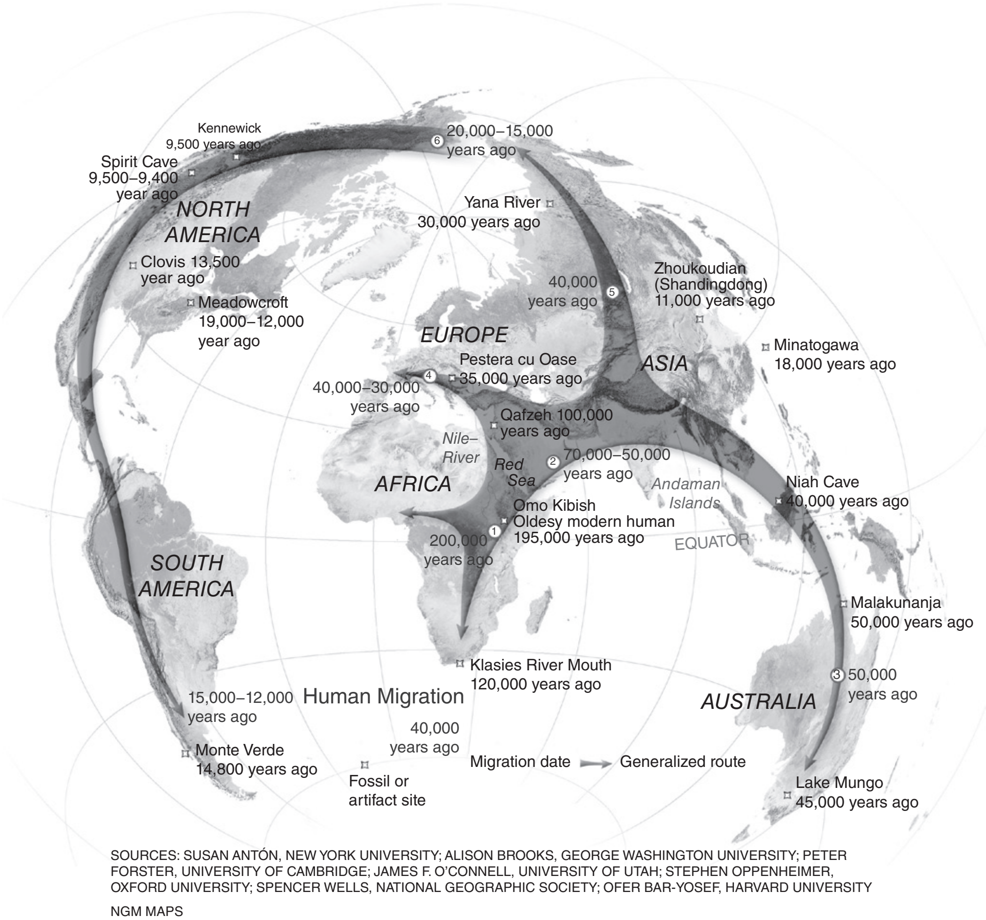

Figure 1.1 A speculative *but data-based* map of human migrations, from genomic technology. *Homo sapiens* migrations, with approximate dates in thousands of years, are tracked by changes in human DNA. We discuss this in Chapter 4. (NG Maps/National Geographic Stock).

1.2
The Industrial Revolution: Watt's Steam Engine, Thermodynamics, Energy Sources

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 2.998×10^8 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.