Who Gives a Gigabyte?
A Survival Guide for the Technologically Perplexed
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ISBN: 0-471-16293-0

Introduction
Microchips and the Millennium

The watchmaker who lives in our neighborhood retired a few years ago. A German immigrant, he studied his trade for decades, becoming an expert in the finely balanced, exquisitely intricate machinery of Swiss clockwork. He decided to retire as the interlocking gears and cogs inside the timepiece started to be displaced by tiny blocks of silicon without moving parts. "I was an apprentice in Germany for ten years," he used to say. "I don't understand these new things. There is nothing to fix."

The days of the mechanically oriented watchmaker-or even the child tinkerer who pries open an appliance to see how it works-have faded. In their place is a flat, featureless landscape populated by countless electronic circuits. Its topography can only be inspected with powerful microscopes and its description rendered in the obtuse argot of DRAMS, ASICs, and SRAMs.

Microcircuitry surrounds us, not only in watch mechanisms, but in toasters, refrigerators, automobiles, and microwave ovens. The number of transistors in a typical American home outnumbers by far the nails attached to the wooden studs holding up its walls. The average homeowner has driven in a few nails, but has not a clue about the electronic viscera of the digital coffeemaker.

Thus it is with much of the high technology that saturates the modern world: even as the products of applied physics, chemistry, and biology disperse ever more widely, their workings become more obtuse to the consumer who has come to depend upon them. The enabling technologies for the Nintendo game, the gene test, and the pocket cell phone require intimate knowledge of the deepest recesses of the atom, the living cell, and the electromagnetic spectrum.

To create sub-micron-sized electronic circuits that obey the orders of our relatively gigantic fingertips, chip designers tap into precise atomic knowledge of the material and electrical properties of such elements as silicon, germanium, and copper. With ever-more-refined tools and techniques, the genetic engineer manipulates a DNA molecule that would be almost a meter long if unwound from the nucleus of a human cell, yet is so infinitesimally thin that 5 million strands can fit through the eye of a needle.

As anyone knows who reheats a cup of tepid coffee in the microwave, it is entirely possible to enjoy the fruits of this technological age without having any idea of the functioning of the gizmo that excites the water molecules in the cup's recesses. True, many people wrestle with programming the VCR. Yet the majority of new technologies pay lip service to the credo of ease of use. Electronic mail speeds on its way by a simple click of a Send button. The many layers of computer programming that recreate a visual screen-based rendition of an office desktop remain opaque to most of us.

Maybe the inner workings of home appliances and the genetic code that shapes our destiny are best left to the experts. But the extent to which vast numbers of otherwise highly educated people remain technological illiterates periodically surfaces as a matter of societal and even personal concern. Arthur Koestler, a social critic, once described as "urban barbarians" people who own devices they do not understand. Koestler noted that the traditionally humanities-educated Western man will quite cheerfully confess that he does not know how his radio or heating system works, while he would be reluctant to admit that he did not understand a famous painting.

What's in It for You?
There is a list of reasons for trying to educate oneself about the full complement of advanced

technologies that drive modern industrial society. The foremost motivation is a selfish one. The creation of smaller and cheaper microcircuits and the diciphering of the genetic code are among the most exciting and stimulating challenges in science and engineering. In short, they hold an innate interest to the intellectually curious. One can follow the travails of solid-state physicists and engineers as they borrow hand-me-down methods from ancient lithographers to pattern circuit lines on a silicon chip that are less than one hundredth the width of a human hair. On a more basic level, will the breakneck pace of development of faster and cheaper chips continue? Or will technologists stumble on physical limits that will force designers to make radical changes in the way they build chips? Those hurdles could threaten the inexorable decline in the cost of microcircuits, which will have seen the price of an electronic memory circuit drop from $10 in the 1950s to an estimated hundred thousandth of a cent somewhere around the turn of the millennium.
Similarly, one of the few remaining "big science" projects-the Human Genome Project-faces equally daunting challenges. In the next few years it plans to elicit the codes for the roughly 80,000 genes for the stuff from which we are made, the proteins that constitute everything from brain cells to toenails. But unraveling the human genetic code will not be enough. For decades afterward, scientists will labor to determine, perhaps with only limited success, what the genes are used for. Behavioral traits that explain why some are optimists while others resemble Pooh's friend Eeyore may be determined by the complex interactions of different genes with one another and with a host of environmental influences. But the difficulties of understanding the effects of genes, or of nature versus nurture, may make human character ultimately unfathomable.
Another compelling rationale for learning as much as possible about things technical is that this knowledge can serve as a membership card to a societal elite fluent in such concepts as DRAMs and base pairs. Political and financial institutions are increasingly dominated by the technically and scientifically savvy. In the highly competitive business world, financial success frequently hinges on technological leadership.
Of course, this book will not furnish you with a specialist's credential, which is conferred only after the years of toil that result in an advanced degree in engineering or the sciences. But it will provide a gateway of sorts into the major disciplines-computers, biotechnology, materials science, and others-that have become the bulwark of the postindustrial society.
Becoming a technological heathen remains a danger, even for the specialist. The expert in one field may retain only a passing awareness of what occurs down the hall or at the company across the street. The pace of change makes it difficult to eschew the feeling of being the outsider. Fiddling with human genes to produce therapeutic proteins had the aura of science fiction thirty years ago, a period that falls within the life span of nearly half of all Americans.
In the new millennium, success as a manager or a project leader may depend on a multifaceted understanding of the interrelationships among technologies-how the computers made possible by novel material designs may process enough information to engineer new drugs from thousands or even millions of molecular candidates with slightly varying chemical properties.
Technological literacy also enables us to become better citizens. A knowledgeable public means that decisions on genetic testing, filtering of Internet content for minors, or placement of toxic waste sites will not be made by only a few business leaders, government officials, scientists, and engineers who understand and control these technologies. It does not take deep insight to realize that technologies are not just tools to make our lives richer and more convenient, but powerful forces that have a substantial impact on the whole planet. A basic understanding of the scope and limitations of new technology makes it easier for us to grasp related social issues free from hysteria and misconceptions. Protection of the diversity of species can be justified on ethical and scientific grounds. But it is also a potential source of genetic richness that may benefit agricultural and medical biotechnology.
We need to understand the power of technology as well as its limitations. Despite our ability to simulate life as computer-based representations, we are still creatures of the natural world, dependent on energy cycles and food chains. Carbon-based industrial emissions may cause catastrophic warming of the Earth's atmosphere. Here technology can assume a legitimate role, separated from its Frankenstein image. The prize could be nonpolluting energy generation and

transportation and genetically engineered crops that can feed the world's billions without the water-table depletion and pollution caused by current intensive farming techniques. Advances in materials science hold the promise of manufacturing lighter and stronger materials that do not generate toxic wastes.

From Computer Hardware to Bioremediation

The word *technology* is increasingly associated with computers and communications equipment manufacturers. The computer section of a well-stocked bookstore is filled with stack after stack of overthick volumes that explain the ins and outs of Microsoft's Windows operating system. This book is not geared toward the reader who wants to learn about setting up a personal Web site or mastering the intricacies of a programming language. Rather, it attempts to provide a concise survey of the workings of some of the most important advanced technologies.

The range of technology-from paper clips to big-screen televisions to nuclear power plants-is enormous. So we have tried to select the machines and processes that may most affect our lives today and beyond the dawn of the new millennium-and to explain the underlying physical, chemical, and biological concepts that make them a reality.

Chapters on computer hardware, software, and communications come first, not only because of the importance of these technologies for the ordinary citizen, but also because of their influence on every other engineering endeavor. The Human Genome Project, which is intended to decode all human genes, would not be possible without high-powered processors and database software. Digital technologies exert the same leverage in our age that steam power did in the early years of the Industrial Revolution. Understanding computers may constitute the foundation of technical literacy in the closing years of the twentieth century. "All technologies have consequences," writes computer scientist Gregory E. Rawlings, in a meditation on the seductions of computer technology. "But because our brain is the source of all our technology, and because computers let our brains think better and faster and cheaper, they have consequences all out of proportion to those of most technologies. Take computers away and the pace of biotechnological change would slow to a crawl. As would the pace of change in every other technical field."

The first chapter examines the basics of computer hardware logic, explores how microcircuits are manufactured, and forecasts future directions in computer hardware that move beyond conventional electronics. Our look at software details the process whereby ever more complex programming has made software simpler to use. It ends by chronicling the still-unsuccessful attempts to make software function more like the human mind. A chapter on telecommunications and data networks chronicles how millions of computers, distributed from San Jose to Kuala Lumpur, can add up to more than the sum of their parts. The Network, with a capital *N*, dictates that a single computer becomes just one neuron in a vast global megasystem for exchanging numbers, words, pictures, and speech.

Chapter 4, "Lasers: The Light Fantastic," describes the centerpiece of both futuristic warfare scenarios and the mundane bar-code scanner. The laser epitomizes the union between advanced scientific knowledge and sophisticated engineering. Beginning with its quantum physical principles, we proceed to the manifold uses of this artifact of James Bond movies.

Genetic engineering, the subject of chapter 5, has been called the discipline that will produce the milestones of the new millennium, rivaling the accomplishments of computers in the twentieth century. Ever since the 1953 discovery of the structure of DNA by the Nobel Prize-winning biochemists James Watson and Francis Crick, researchers have been probing and manipulating this helical-shaped molecule. Their discoveries have profound implications for human life and commerce. There are now techniques for cutting, pasting, and copying pieces of DNA. Deciphering the codes of life has fostered burgeoning industries that encompass agriculture, medicine, and waste management. Issues that we cover range from the Human Genome Project, which aims to spell out every base letter of our genetic inheritance, to the implications of altering the genes of important agricultural products like soybeans, corn, and cotton.

In chapter 6 we describe how growing knowledge of molecular biology-the biochemical basis of natural processes-drives new methods of drug development. A section on new directions in cancer treatment describes the evolution of new strategies for attacking malignant cancer cells without producing the damaging side effects of traditional treatments.

Despite the revolutionary impact of genetic engineering, the health sciences remain more than just gene-fiddling. The ability to see inside the body has become routine with such advanced diagnostic and imaging methods as magnetic resonance imaging and positron emission tomography. Chapter 7, "Spare Parts and High-Tech Flashlights," also highlights other areas in which science and technology play an important role in modern medical practice, including telemedicine and tissue engineering, a new field that holds the promise of developing replacement body parts.

The standard-issue personal computer is just one item brought to you through the insights of materials science, the multidisciplinary field outlined in chapter 8. Materials scientists meld chemistry, solid-state physics, and metallurgy to investigate the properties of solids. Their discoveries turn up not just in microchips, but in snack-food packaging, golf clubs, new bicycle models, and cooking utensils. "Intelligent" materials, incorporating sensors that respond and adjust to temperature or excessive vibrations, have begun to find their way into exercise equipment and downhill skis. In the future, material advances may be built right into the infrastructure of buildings, so that they can signal areas of stress and wear, and even possibly repair themselves.

The ability to extract and shape exotic materials depends on propitious energy usage and a benign environmental impact-topics explored in chapters 9 and 10. Without cheap, efficient energy, technical advance remains stultified. The industrial world's insatiable appetites may translate into overheating of the atmosphere, which may only be rectified through radical alterations to the status quo. Debates about global warming tie intimately to arguments about the availability of nonpolluting energy sources. The environmental sciences will help to examine the way that industry organizes itself. The nascent field of industrial ecology foresees waste products of one industry becoming the feedstock of another. A further trend toward "green" technology examines the retooling of production processes to use more environmentally benign chemicals and to minimize waste.

We conclude with a glance toward the forces that both foster and inhibit the pace of technological innovation-how science translates into consumer implements, how government can help or hurt, and how expectations for technological utopia often founder because of cost, practicality, and the gap between inventors' dreams and the limits imposed by the laws of physics. Throughout the text, timelines and glossaries are provided where we considered them to be important.

This volume is intended as both a survey of important technologies and a simple reference. It is not by any means a comprehensive tour. The waning of the Cold War has meant that civilian technology now outstrips military research and development in importance. So munitions-and related space technologies-have largely been left aside here. Advanced transportation is covered as it relates to how it may help the environment and produce energy savings. But some superstars of yesteryear, such as magnetically levitated trains, have been ignored because their prospects appear to have waned, given cost constraints, practicality, and the emergence of alternatives like high-speed conventional trains.

This book, of course, can be nothing more than a beginning. To those who wish to probe further, suggested readings, including many that we found helpful in our research, follow at the end of the book. We have omitted World Wide Web links because of their transient nature, but any key word or phrase in the text-*polymerase chain reaction*, for instance-should yield a wealth of material when entered in a Web-based search engine.