How Science Will Revolutionize the 21st Century and Beyond

Visions

MICHIO KAKU

AUTHOR OF HYPERSPACE

'conveys a contagious sense of
the wonder of science'
Chicago Tribune

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Preface

THIS IS A BOOK about the limitless future of science and technology, focusing on the next 100 years and beyond.

A book with the proper scope, depth, and accuracy necessary to summarize the exciting and fast-paced progress of science could not be written without the insights and wisdom of the scientists who are making the future possible.

Of course, no one person can invent the future. There is simply too much accumulated knowledge, there are too many possibilities and too many specializations. In fact, most predictions of the future have floundered because they have reflected the eccentric, often narrow viewpoints of a single individual.

The same is not true of *Visions*. In the course of writing numerous books, articles, and science commentaries, I have had the rare privilege of interviewing over 150 scientists from various disciplines during a ten-year period.

On the basis of these interviews, I have tried to be careful to delineate the time frame over which certain predictions will or will not be realized. Scientists expect some predictions to come about by the year 2020; others will not materialize until much later—from 2050 to the year 2100. As a result, not all predictions are created equal—some are more forward-looking and necessarily more speculative than others. The time frames I've identified in the book, of course, are to be taken only as guidelines, to give readers a sense of when certain trends and technologies can be expected to emerge.

The outline for the book is as follows: In Part I of *Visions*, I discuss the remarkable developments that await us in the computer revolution, which are already beginning to transform business, communications, and our lifestyles, and which I believe will one day give us the power to place intelligence in every part of our planet. In Part II, I turn to the biomolecular revolution, which will ultimately give us the power to alter and synthesize new forms of life, and create new medicines and therapies. Part III focuses on the quantum revolution, perhaps the most profound of the three, which will give us control over matter itself.

I wish to thank the following scientists who have given me their time, advice, and invaluable insights in the course of writing this book:

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Michio Kaku
New York, N.Y.

Part One

Visions

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Choreographers of Matter, Life, and Intelligence

"There are three great themes in science in the twentieth century—the atom, the computer, and the gene."
—HAROLD VARMUS, NIH Director

"Prediction is very hard, especially when it's about the future."
—YOGI BERRA

THREE CENTURIES AGO, Isaac Newton wrote: ". . . to myself I seem to have been only like a boy playing on a seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me." When Newton surveyed the vast ocean of truth which lay before him, the laws of nature were shrouded in an impenetrable veil of mystery, awe, and superstition. Science as we know it did not exist.

Life in Newton's time was short, cruel, and brutish. People were illiterate for the most part, never owned a book or entered a classroom, and rarely ventured beyond several miles of their birthplace. During the day, they toiled at backbreaking work in the fields under a merciless sun. At night, there was usually no entertainment or relief to comfort them except the empty sounds of the night. Most people knew firsthand the gnawing pain of hunger and chronic, debilitating disease. Most people would live not much longer than age thirty, and would see many of their ten or so children die in infancy.

But the few wondrous shells and pebbles picked up by Newton and other scientists on the seashore helped to trigger a marvelous chain of events. A profound transformation occurred in human society. With Newton's mechanics came powerful machines, and eventually the steam engine, the motive force which reshaped the world by overturning agrarian society, spawning factories and stimulating commerce, unleashing the industrial revolution, and opening up entire continents with the railroad.

By the nineteenth century, a period of intense scientific discovery was well underway. Remarkable advances in science and medicine helped to lift people out of wretched poverty and ignorance, enrich their lives, empower them with knowledge, open their eyes to new worlds, and eventually unleash complex forces which would topple the feudal dynasties, fiefdoms, and empires of Europe.

By the end of the twentieth century, science had reached the end of an era, unlocking the secrets of the atom, unraveling the molecule of life, and creating the electronic computer. With these three fundamental discoveries, triggered by the quantum revolution, the DNA revolution, and the computer revolution, the basic laws of matter, life, and computation were, in the main, finally solved.

That epic phase of science is now drawing to a close; one era is ending and another is only beginning.

This book is about this new dynamic era of science and technology which is now unfolding before our eyes. It focuses on science in the next 100 years, and beyond. The next era of science promises to be an even deeper, more thoroughgoing, more penetrating one than the last.

Clearly, we are on the threshold of yet another revolution. Human knowledge is doubling every ten years. In the past decade, more scientific knowledge has been created than in all of human history. Computer power is doubling every eighteen months. The Internet is doubling every year. The number of DNA sequences we can analyze is doubling every two years. Almost daily, the headlines herald new advances in computers, telecommunications, biotechnology, and space exploration. In the wake of this technological upheaval, entire industries and lifestyles are being overturned, only to give rise to entirely new ones. But these rapid, bewildering changes are not just quantitative. They mark the birth pangs of a new era.

Today, we are again like children walking on the seashore. But the ocean that Newton knew as a boy has largely disappeared. Before us lies a new ocean, the ocean of endless scientific possibilities and applications, giving us the potential for the first time to manipulate and mold these forces of Nature to our wishes.

For most of human history, we could only watch, like bystanders, the beautiful dance of Nature. But today, we are on the cusp of an epoch-making transition, from being *passive observers of Nature to being active choreographers of Nature.* It is this tenet that forms the central message of *Visions.* The era now unfolding makes this one of the most exciting times to be alive, allowing us to reap the fruits of the last 2,000 years of science. The Age of Discovery in science is coming to a close, opening up an Age of Mastery.

Emerging Consensus Among Scientists

What will the future look like? Science fiction writers have sometimes made preposterous predictions about the decades ahead, from vacationing on Mars to banishing all diseases. And even in the popular press, all too often an eccentric social critic's individual prejudices are substituted for the consensus within the scientific community. (In 1996, for example, *The New York Times Magazine* devoted an entire issue to life in the next 100 years. Journalists, sociologists, writers, fashion designers, artists, and philosophers all submitted their thoughts. Remarkably, *not a single scientist* was consulted.)

The point here is that predictions about the future made by professional scientists tend to be based much more substantially on the realities of scientific knowledge than those made by social critics, or even those by scientists of the past whose predictions were made before the fundamental scientific laws were completely known.

It is, I think, an important distinction between *Visions*, which concerns an emerging consensus among the scientists themselves, and the predictions in the popular press made almost exclusively by writers, journalists, sociologists, science fiction writers, and others who are *consumers* of technology, rather than by those who have helped to shape and *create* it. (One is reminded of the prediction made by Admiral William Leahy to President Truman in 1945: "That is the biggest fool thing we have ever done. . . . The [atomic] bomb will never go off, and I will speak as an expert in explosives." The admiral, like many "futurists" today, was substituting his own prejudices for the consensus of physicists working on the bomb.)

As a research physicist, I believe that physicists have been particularly successful at predicting the broad outlines of the future. Professionally, I work in one of the most fundamental areas of physics, the quest to complete Einstein's dream of a "theory of everything." As a result, I am constantly reminded of the ways in which quantum physics touches many of the key discoveries that shaped the twentieth century.

In the past, the track record of physicists has been formidable: we have been intimately involved with introducing a host of pivotal inventions (TV, radio, radar, X-rays, the transistor, the computer, the laser, the atomic bomb), decoding the DNA molecule, opening new dimensions in probing the body with PET, MRI, and CAT scans, and even designing the Internet and the World Wide Web. Physicists are by no means seers who can foretell the future (and we certainly haven't been spared our share of silly predictions!). Nonetheless, it is true that some of the shrewd observations and penetrating insights of leading physicists in the history of science have opened up entirely new fields.

There undoubtedly will be some astonishing surprises, twists of fate, and embarrassing gaps in this vision of the future: I will almost inevitably overlook some important inventions and discoveries of the twenty-first century. But by focusing on the interrelations between the three great scientific revolutions, and by consulting with the scientists who are actively bringing about this revolution and examining their discoveries, it is my hope that we can see the direction of science in the future with considerable insight and accuracy.

Over the past ten years, while working on this book, I have had the rare privilege of interviewing over 150 scientists, including a good many Nobel Laureates, in part during the course of preparing a weekly national science radio program and producing science commentaries.

These are the scientists who are tirelessly working in the trenches, who are laying the foundations of the twenty-first century, many of whom are opening up new avenues and vistas for scientific discovery. In these interviews, as well as through my own work and research, I was able to go back over the vast panorama of science laid out before me and draw from a wide variety of expertise and knowledge. These scientists have graciously opened their offices and their laboratories and shared their most intimate scientific ideas with me. In this book, I've tried to return the favor by capturing the raw excitement and vitality of their scientific discoveries, for it is essential to instill the romance and excitement of science in the general public, especially the young, if democracy is to remain a vibrant and resonating force in an increasingly technological and bewildering world.

The fact is that there *is* a rough consensus emerging among those engaged in research about how the future will evolve. Because the laws behind the quantum theory, computers, and molecular biology are now well established, it is possible for scientists to generally predict the paths of scientific progress in the future. *This is the central reason why the predictions made here, I feel, are more accurate than those of the past.*

What is emerging is the following.

The Three Pillars of Science

Matter. Life. The Mind.

These three elements form the pillars of modern science. Historians will most likely record that the crowning achievement of twentieth-century science was unraveling the basic components underlying these three pillars, culminating in the splitting of the nucleus of the atom, the decoding of the nucleus of the cell, and the development of the electronic computer. With our basic understanding of matter and life largely complete, we are witnessing the close of one of the great chapters in the history of science. (This does not mean that all the laws of these three pillars are completely known, only the most fundamental. For example, although the laws of electronic computers are well known, only some of the basic laws of artificial intelligence and the brain are known.)

The first of these twentieth-century revolutions was the *quantum revolution*, the most fundamental of all. It was the quantum revolution that later helped to spawn the two other great scientific revolutions, the *biomolecular revolution* and the *computer revolution.*

THE QUANTUM REVOLUTION

Since time immemorial, people have speculated what the world was made of. The Greeks thought that the universe was made of four elements: water, air, earth, and fire. The philosopher Democritus believed that even these could be broken down into smaller units, which he called "atoms." But attempts to explain how atoms could create the vast, wondrous diversity of matter we see in Nature always faltered. Even Newton, who discovered the cosmic laws which guided the motion of planets and moons, was at a loss to explain the bewildering nature of matter.

All this changed in 1925 with the birth of the quantum theory, which has unleashed a thundering tidal wave of scientific discovery that continues to surge unabated to this day. The quantum revolution has now given us an almost complete description of matter, allowing us to describe the seemingly infinite multiplicity of matter we see arrayed around us in terms of a handful of particles, in the same way that a richly decorated tapestry is woven from a few colored strands.

The quantum theory, created by Erwin Schrödinger, Werner Heisenberg, and many others, reduced the mystery of matter to a few postulates. First, that energy is not continuous, as the ancients thought, but occurs in discrete bundles, called "quanta." (The photon, for example, is a quantum or packet of light.) Second, that subatomic particles have both particle and wavelike qualities, obeying a well-defined equation, the celebrated Schrödinger wave equation, which determines the probability that certain events occur. With this equation, we can mathematically predict the properties of a wide variety of substances before creating them in the laboratory. The culmination of the quantum theory is the Standard Model, which can predict the properties of everything from tiny subatomic quarks to giant supernovas in outer space.

In the twentieth century, the quantum theory has given us the ability to understand the matter we see around us. In the next century, the quantum revolution may open the door to the next step: the ability to manipulate and choreograph new forms of matter, almost at will.

THE COMPUTER REVOLUTION

In the past, computers were mathematical curiosities; they were supremely clumsy, messy contraptions, consisting of a complex mass of gears, levers, and cogs. During World War II, mechanical computers were replaced by vacuum tubes, but they were also monstrous in size, filling up entire rooms with racks of thousands of vacuum tubes.

The turning point came in 1948, when scientists at Bell Laboratories discovered the transistor, which made possible the modern computer. A decade after that, the laser was discovered, which is essential to the Internet and the information highway. Both are quantum mechanical devices.

In the quantum theory, electricity can be understood as the movement of electrons, just as droplets of water can make a river. But one of the surprises of the quantum theory is that there are "bubbles" or "holes" in the current, corresponding to vacancies in electron states, which act as if they are electrons with positive charge. The motion of these currents of both holes and electrons allows transistors to amplify tiny electrical signals, which forms the basis of modern electronics.

Today, tens of millions of transistors can be crammed into an area the size of a fingernail. In the future, our lifestyles will be irrevocably changed when microchips become so plentiful that intelligent systems are dispersed by the millions into all parts of our environment.

In the past, we could only marvel at the precious phenomenon called intelligence; in the future, we will be able to manipulate it according to our wishes.

THE BIOMOLECULAR REVOLUTION

Historically, many biologists were influenced by the theory of "vitalism"—i.e., that a mysterious "life force" or substance animated living things. This view was challenged when Schrödinger, in his 1944 book *What Is Life?*, dared to claim that life could be explained by a "genetic code" written on the molecules within a cell. It was a bold idea: that the secret of life could be explained by using the quantum theory.

James Watson and Francis Crick, inspired by Schrödinger's book, eventually proved his conjecture by using X-ray crystallography. By analyzing the pattern of X-rays scattered off a DNA molecule, they were able to reconstruct the detailed atomic structure of DNA and identify its double-helical nature. Since the quantum theory also gives us the precise bonding angles and bonding strength between atoms, it enables us to determine the position of practically all the individual molecules in the genetic code of a complex virus like HIV.

The techniques of molecular biology will allow us to read the genetic code of life as we would read a book. Already, the complete DNA code of several living organisms, like viruses, single-cell bacteria, and yeast, have been completely decoded, molecule for molecule.

The complete human genome will be decoded by the year 2005, giving us an "owner's manual" for a human being. This will set the stage for twenty-first century science and medicine. Instead of watching the dance of life, the biomolecular revolution will ultimately give us the nearly godlike ability to manipulate life almost at will.

From Passive Bystanders to Active Choreographers of Nature

Some commentators, witnessing these historic advances in science over the past century, have claimed that we are seeing the demise of the scientific enterprise. John Horgan, in his book *The End of Science*, writes: "If one believes in science, one must accept the possibility—even the probability—that the great era of scientific discovery is over. . . . Further research may yield no more great revelations or revolutions, but only incremental, diminishing returns."

In one limited sense, Horgan is right. Modern science has no doubt uncovered the fundamental laws underlying most of the disciplines of science: the quantum theory of matter, Einstein's theory of space-time, the Big Bang theory of cosmology, the Darwinian theory of evolution, and the molecular basis of DNA and life. Despite some notable exceptions (e.g., determining the nature of consciousness and proving that superstring theory, my particular field of specialization, is the fabled unified field theory), the "great ideas" of science, for the most part, have probably been found.

Likewise, the era of reductionism—i.e., reducing everything to its smallest components—is coming to a close. Reductionism has been spectacularly successful in the twentieth century, unlocking the secrets of the atom, the DNA molecule, and the logic circuits of the computer. But reductionism has probably, in the main, run its course.

However, this is just the beginning of the romance of science. These scientific milestones certainly mark a significant break with the ancient past, when Nature was interpreted through the prism of animism, mysticism, and spiritualism. But they only open the door to an entirely new era of science.

The next century will witness an even more far-reaching scientific revolution, as we make the transition from unraveling the secrets of Nature to becoming masters of Nature.

Sheldon Glashow, a Nobel Laureate in physics, describes this difference metaphorically when he tells the story of a visitor named Arthur from another planet meeting earthlings for the first time:

"Arthur [is] an intelligent alien from a distant planet who arrives at Washington Square [in New York City] and observes two old codgers playing chess. Curious, Arthur gives himself two tasks: to learn the rules of the game, and to become a grand master." By carefully watching the moves, Arthur is gradually able to reconstruct the rules of the game: how pawns advance, how queens capture knights, and how vulnerable kings are. However, just knowing the rules does not mean that Arthur has become a grand master! As Glashow adds: "Both kinds of endeavors are important—one more 'relevant,' the other more 'fundamental.' Both represent immense challenges to the human intellect."

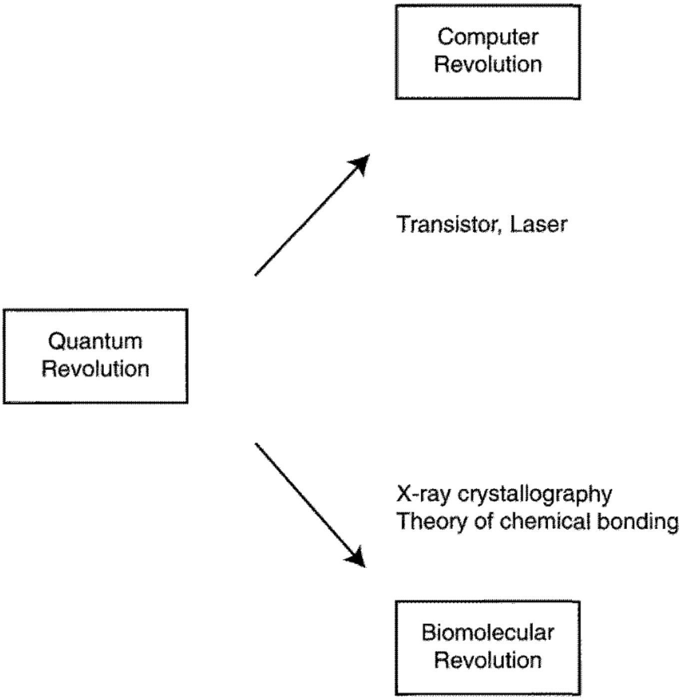
In some sense, science has finally decoded many of the fundamental "rules of Nature," but this does not mean that we have become grand masters. Likewise, the dance of elementary particles deep inside stars and the rhythms of DNA molecules coiling and uncoiling within our bodies have been largely deciphered, but this does not mean that we have become master choreographers of life.

In fact, the end of the twentieth century, which ended the first great phase in the history of science, has only opened the door to the exciting developments of the next. We are now making the transition from amateur chess players to grand masters, from observers to choreographers of Nature.

From Reductionism to Synergy

Similarly, this is creating a new approach in the way in which scientists view their own discipline. In the past, the reductionist approach has paid off handsomely, eventually establishing the foundation for modern physics, chemistry, and biology.

At the heart of this success was the discovery of the quantum theory, which helped to spark the other two revolutions.



The quantum revolution gave birth to the computer and biomolecular revolutions via the transistor, laser, X-ray crystallography, and the theory of molecular bonds.

But since the quantum theory helped to initiate these other revolutions in the 1950s, they have since matured and grown on their own, largely independent of physics and of each other. The watchword was specialization, as scientists probed deeper and deeper into their subdisciplines, smugly ignoring the developments in other fields. But now the heyday of reductionism has probably passed. Seemingly impenetrable obstacles have been encountered which cannot be solved by the simple reductionist approach. This is heralding a new era, one of *synergy* between the three fundamental revolutions.

This is the second main theme of this book.

The twenty-first century, unlike the previous ones, will be typified by synergy, the cross-fertilization between all three fields, which will mark a sharp turning point in the development of science. The cross-pollination between these three revolutions will be vastly accelerated and will enrich the development of science, giving us unprecedented power to manipulate matter, life, and intelligence.

In fact, it will be difficult to be a research scientist in the future without having some working knowledge of all these three areas. Already, scientists who do not have some understanding of these three revolutions are finding themselves at a distinct competitive disadvantage.

The new relationship between the three revolutions is an intensely dynamic one. Often, when an impasse is reached in one area, usually a totally unexpected development in another field is found to contain the solution. For example, biologists once despaired of ever deciphering the millions of genes which contain the blueprint for life. But the recent torrent of genes being discovered in our laboratories is being driven largely by a development in another field: the exponential increase in computer power, which is mechanizing and automating the gene-sequencing process. Similarly, silicon computer chips will eventually hit a roadblock as they become too clumsy for the computer of the next century. But new advances in DNA research are making possible a new type of computer architecture which actually computes on organic molecules. Thus, discoveries in one field nourish and fertilize discoveries in totally unrelated fields. The whole is more than the sum of its parts.

One of the consequences of this intense synergy between these revolutions is that the steady pace of scientific discovery is accelerating at an ever-increasing rate.

The Wealth of Nations

This acceleration of science and technology into the next century will necessarily have vast repercussions on the wealth of nations and our standard of living. For the past three centuries, wealth was usually accumulated by those nations which were endowed with rich natural resources or which amassed large amounts of capital. The rise of the Great Powers of

Europe in the nineteenth century and the United States in the twentieth century follows this classic textbook principle.

However, as Lester C. Thurow, former dean of MIT's Sloan School of Management, has stressed, in the coming century, there will be a historic movement in wealth away from nations with natural resources and capital. In the same way that shifts in the earth's tectonic plates can generate powerful earthquakes, this seismic shift in wealth will reshape the distribution of power on the planet. Thurow writes: "In the twenty-first century, brainpower and imagination, invention, and the organization of new technologies are the key strategic ingredients." In fact, many nations which are richly endowed with abundant natural resources will find their wealth vastly reduced because, in the marketplace of the future, commodities will be cheap, trade will be global, and markets will be linked electronically. Already, the commodity prices of many natural resources plummeted some 60 percent from the 1970s to the 1990s, and, in Thurow's estimation, will plummet another 60 percent by 2020.

Even capital itself will be reduced to a commodity, racing around the globe electronically. Many nations which are barren of natural resources will flourish in the next century because they placed a premium on those technologies which can give them a competitive edge in the global marketplace. "Today, knowledge and skills now stand alone as the only source of comparative advantage," Thurow asserts.

As a consequence, some nations have drawn up lists of the key technologies which will serve as the engines of wealth and prosperity into the next century. A typical list was compiled in 1990 by Japan's Ministry of International Trade and Industry. That list included:

- microelectronics
- biotechnology
- the new material science industries
- telecommunications
- civilian aircraft manufacturing
- machine tools and robots
- computers (hardware and software)

Without exception, every one of the technologies singled out to lead the twenty-first century are deeply rooted in the quantum, computer, and DNA revolutions.

The point is that these three scientific revolutions are not only the key to scientific breakthroughs in the next century; they are also the dynamic engines of wealth and prosperity. *Nations may rise and fall on their ability to master these three revolutions.* In any activity, there are winners and losers. The winners will likely be those nations which fully grasp the vital importance of these three scientific revolutions. Those who would scoff at the power of these revolutions may find themselves marginalized in the global marketplace of the twenty-first century.

Time Frames for the Future

In making predictions about the future, it is crucial to understand the time frame being discussed, for, obviously, different technologies will mature at different times. The time frames of the predictions made in *Visions* fall into three categories: those breakthroughs and technologies that will evolve between now and the year 2020, those that will evolve from 2020 to 2050, and those that will emerge from 2050 to the end of the twenty-first century. (These are not absolute time frames; they represent only the general period in which certain technologies and sciences will reach fruition.)

TO THE YEAR 2020

From now to the year 2020, scientists foresee an explosion in scientific activity such as the world has never seen before. In two key technologies, computer power and DNA sequencing, we will see entire industries rise and fall on the basis of breathtaking scientific advances. Since the 1950s, the power of our computers has advanced by a factor of roughly *ten billion*. In fact, because both computer power and DNA sequencing double roughly every two years, one can compute the rough time frame over which many scientific breakthroughs will take place. This means that predictions about the future of computers and biotechnology can be quantified with reasonable statistical accuracy through the year 2020.

For computers, this staggering growth rate is quantified by Moore's law, which states that computer power doubles roughly every eighteen months. (This was first stated in 1965 by Gordon Moore, co-founder of the Intel Corp. It is not a scientific law, in the sense of Newton's laws, but a rule-of-thumb which has uncannily predicted the evolution of computer power for several decades.) Moore's law, in turn, determines the fate of multibillion-dollar computer corporations, which base their future projections and product lines on the expectation of continued growth. By 2020, microprocessors will likely be as cheap and plentiful as scrap paper, scattered by the millions into the environment, allowing us to place intelligent systems everywhere. This will change everything around us, including the nature of commerce, the wealth of nations, and the way we communicate, work, play, and live. This will give us smart homes, cars, TVs, clothes, jewelry, and money. We will speak to our appliances, and they will speak back. Scientists also expect the Internet will wire up the entire planet and evolve into a membrane consisting of millions of computer networks, creating an "intelligent planet." The Internet will eventually become a "Magic Mirror" that appears in fairy tales, able to speak with the wisdom of the human race.

Because of revolutionary advances in our ability to etch ever-smaller transistors onto silicon wafers, scientists expect this relentless drive to continue to generate newer and more powerful computers up to 2020, when the iron laws of quantum physics eventually take over once again. By then, the size of microchip components will be so small—roughly on the scale of molecules—that quantum effects will necessarily dominate and the fabled Age of Silicon will end.

The growth curve for biotechnology will be equally spectacular in this period. In biomolecular research, what is driving the remarkable ability to decode the secret of life is the introduction of computers and robots to automate the process of DNA sequencing. This process will continue unabated until roughly 2020, until literally thousands of organisms will have their complete DNA code unraveled. By then, it may be possible for anyone on earth to have their personal DNA code stored on a CD. We will then have the Encyclopedia of Life.

This will have profound implications for biology and medicine. Many genetic diseases will be eliminated by injecting people's cells with the correct gene. Because cancer is now being revealed to be a series of genetic mutations, large classes of cancers may be curable at last, without invasive surgery or chemotherapy. Similarly, many of the microorganisms involved in infectious diseases will be conquered in virtual reality by locating the molecular weak spots in their armor and creating agents to attack those weak spots. Our molecular knowledge of cell development will be so advanced that we will be able to grow entire organs in the laboratory, including livers and kidneys.

FROM 2020 TO 2050

The prediction of explosive growth of computer power and DNA sequencing from now through 2020 is somewhat deceptive, in that both are driven by known technologies. Computer power is driven by packing more and more transistors onto microprocessors, while DNA sequencing is driven by computerization. Obviously, these technologies cannot indefinitely continue to grow exponentially. Sooner or later, a bottleneck will be hit.

By around 2020, both will encounter large obstacles. Because of the limits of silicon chip technology, eventually we will be forced to invent new technologies whose potentials are largely unexplored and untested, from optical computers, molecular computers, and DNA computers to quantum computers. Radically new designs must be developed, based on the quantum theory, which will likely disrupt progress in computer science. Eventually, the reign of the microprocessor will end, and new types of quantum devices will take over.

If these difficulties in computer technology can be overcome, then the period 2020 to 2050 may mark the entrance into the marketplace of an entirely new kind of technology: true robot automatons that have common sense, can understand human language, can recognize and manipulate objects in their environment, and can learn from their mistakes. It is a development that will likely alter our relationship with machines forever.

Similarly, biotechnology will face a new set of problems by 2020. The field will be flooded with millions upon millions of genes whose basic functions are largely unknown. Even before 2020, the focus will shift away from DNA sequencing to understanding the basic functions of these genes, a process which cannot be computerized, and to understand polygenic diseases and traits—i.e., those involving the complex interaction of multiple genes. The shift to polygenic diseases may prove to be the key to solving some of the most pressing chronic diseases facing humanity, including heart disease, arthritis, autoimmune diseases, schizophrenia, and the like. It may also lead to cloning humans and to isolating the fabled "age genes" which control our aging process, allowing us to extend the human life span.

Beyond 2020, we also expect some amazing new technologies germinating in physics laboratories to come to fruition, from new generations of lasers and holographic three-dimensional TV to nuclear fusion. Room-temperature superconductors may find commercial applications and generate a "second industrial revolution." The quantum theory will give us the ability to manufacture machines the size of molecules, thereby opening up an entirely new class of machines with unheard-of properties called nanotechnology. Eventually, we may be able to build ionic rocket engines that may ultimately make interplanetary travel commonplace.

FROM 2050 TO 2100 AND BEYOND

Last, *Visions* makes predictions about breakthroughs in science and technology from 2050 to the dawn of the twenty-second century. Although any predictions this far into the future are necessarily vague, it is a period that will likely be dominated by several new developments. Robots may gradually attain a degree of "self-awareness" and consciousness of their own. This could greatly increase their utility in society, as they are able to make independent decisions and act as secretaries, butlers, assistants, and aides. Similarly, the DNA revolution will have advanced to the point where biogeneticists are able to create new types of organisms involving the transfer of not just a few but even hundreds of genes, allowing us to increase our food supply and improve our medicines and our health. It may also give us the ability to design new life forms and to orchestrate the physical and perhaps even the mental makeup of our children, which raises a host of ethical questions.

The quantum theory, too, will exert a powerful influence in the next century, especially in the area of energy production. We may also see the beginnings of rockets that can reach the nearby stars and plans to form the first colonies in space.

Beyond 2100, some scientists see a further convergence of all three revolutions, as the quantum theory gives us transistor circuits and entire machines the size of molecules, allowing us to duplicate the neural patterns of the brain on a computer. In this era, some scientists have given serious thought to extending life by growing new organs and bodies, by manipulating our genetic makeup, or even by ultimately merging with our computerized creations.

Toward a Planetary Civilization

When confronted with dizzying scientific and technological upheaval on this scale, there are some voices that say we are going too far, too fast, that unforeseen social consequences will be unleashed by these scientific revolutions.

I will try to address these legitimate questions and concerns by carefully exploring the sensitive social implications of these powerful revolutions, especially if they aggravate existing fault lines within society.

In addition, we will address an even more far-reaching question: to where are we rushing? If one era of science is ending and another is just beginning, then where is this all leading to?

This is exactly the question asked by astrophysicists who scan the heavens searching for signs of extraterrestrial civilizations which may be far more advanced than ours. There are about 200 billion stars in our galaxy, and trillions of galaxies in outer space. Instead of wasting millions of dollars randomly searching all the stars in the heavens for signs of extraterrestrial life, astrophysicists engaged in this search have tried to focus their efforts by theorizing about the energy characteristics and signatures of civilizations several centuries to millennia more advanced than ours.

Applying the laws of thermodynamics and energy, astrophysicists who scan the heavens have been able to classify hypothetical extraterrestrial civilizations into three types, based on the ways they utilize energy. Russian astronomer Nikolai Kardashev and Princeton physicist Freeman Dyson label them Type I, II, and III civilizations.

Assuming a modest yearly increase in energy consumption, one can extrapolate centuries into the future when certain energy supplies will be exhausted, forcing society to advance to the next level.

A Type I civilization is one that has mastered all forms of terrestrial energy. Such a civilization can modify the weather, mine the oceans, or extract energy from the center of their planet. Their energy needs are so large that they must harness the potential resources of the entire planet. Harnessing and managing resources on this gigantic scale requires a sophisticated degree of cooperation among their individuals with elaborate planetary communication. This necessarily means that they have attained a truly planetary civilization, one that has put to rest most of the factional, religious, sectarian, and nationalistic struggles that typify their origin.

Type II civilizations have mastered stellar energy. Their energy needs are so great that they have exhausted planetary sources and must use their sun itself to drive their machines. Dyson has speculated that, by building a giant sphere around their sun, such a civilization might be able to harness their sun's total energy output. They have also begun the exploration and possible colonization of nearby star systems.

Type III civilizations have exhausted the energy output of a single star. They must reach out to neighboring star systems and clusters, and eventually evolve into a galactic civilization. They obtain their energy by harnessing collections of star systems throughout the galaxy.

(To give a sense of scale, the United Federation of Planets described in *Star Trek* probably qualifies for an emerging Type II status, as they have just attained the ability to ignite stars and have colonized a few nearby star systems.)

This system of classifying civilizations is a reasonable one because it relies on the available supply of energy. Any advanced civilization in space will eventually find three sources of energy at their disposal: their planet, their star, and their galaxy. There is no other choice.

With a modest growth rate of 3 percent per year—the growth rate typically found on earth—one can calculate when our planet might make the transition to a higher status in the galaxy. For example, astrophysicists estimate that, based on energy considerations, a factor of ten billion may separate the energy demands between the various types of civilizations. Although this staggering number at first seems like an insurmountable obstacle, a steady 3 percent growth rate can overcome even this factor. In fact, we can expect to reach Type I status within a century or two. To reach Type II status may require no more than about 800 years. But attaining Type III status may take on the order of 10,000 years or more (depending on the physics of interstellar travel). But even this is nothing but the twinkling of an eye from the perspective of the universe.

Where are we now? you might ask. At present, we are a Type 0 civilization. Essentially, we use dead plants (coal and oil) to energize our machines. On this planetary scale, we are like children, taking our first hesitant and clumsy steps into space. But by the close of the twenty-first century, the sheer power of the three scientific revolutions will force the nations of the earth to cooperate on a scale never seen before in history. By the twenty-second century, we will have laid the groundwork of a Type I civilization, and humanity will have taken the first step toward the stars.

Already the information revolution is creating global links on a scale unparalleled in human history, tearing down petty, parochial interests while creating a global culture. Just as the Gutenberg printing press made people aware of worlds beyond their village or hamlet, the information revolution is building and forging a common planetary culture out of thousands of smaller ones.

What this means is that our headlong journey into science and technology will one day lead us to evolve into a true Type I civilization—a planetary civilization which harnesses truly planetary forces. The march to a planetary civilization will be slow, accomplished in fits and starts, undoubtedly full of unexpected twists and setbacks. In the background always lurks the possibility of a nuclear war, the outbreak of a deadly pandemic, or a collapse of the environment. Barring such a collapse, however, I think it is safe to say that the progress of science has the potential to create forces which will bind the human race into a Type I civilization.

Far from witnessing the end of science, we see that the three scientific revolutions are unleashing powerful forces which may eventually elevate our civilization to Type I status. So when Newton first gazed alone at the vast, uncharted ocean of knowledge, he probably never realized that the chain reaction of events that he and others initiated would one day affect all of modern society, eventually forging a planetary civilization and propelling it on its way to the stars.

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Part Two

The Computer Revolution

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2

The Invisible Computer

"Long-term, the PC and workstation will wither because computing access will be everywhere: in the walls, on wrists, and in 'scrap computers' (like scrap paper) lying about to be grabbed as needed."
—MARK WEISER, Xerox PARC

THE XEROX PARC (Palo Alto Research Center) lies nestled in the quiet, rolling hills overlooking Silicon Valley, surrounded by acres of golden-brown fields lying under a brilliant sky. With a herd of horses grazing quietly nearby, one might never suspect that Xerox PARC sits in the eye of a hurricane that may help to reshape the twenty-first century. Anyone who doubts Xerox PARC's uncanny ability to predict the future of computer technology need only examine its remarkable history of picking winners.

Outside the front entrance, there is no sign or poster that properly introduces visitors to the historic significance of this lab. But by rights, Xerox PARC could claim, "The PC was invented here," not to mention laying the foundation for the laser printer and the program that eventually became the basis for the Macintosh and Windows operating systems.

Even in the fiercely competitive Silicon Valley, Xerox PARC has built up a formidable reputation in an industry moving at breakneck speed. If we are experiencing a tidal wave of new products and high-tech gadgets coming from Silicon Valley, it's because Xerox PARC built the foundation that led to their invention.

If anyone has seen the future, it is Mark Weiser, former head of the

Computer Science Laboratory of Xerox PARC, and his team of engineers. They belong to an elite cadre of highly select computer scientists located in Silicon Valley and Cambridge who have the rare knack of combining raw technical ability with creative, artistic virtuosity. Weiser is short, with thinning hair, with an animated, engaging style and an impish smile. (He also has a mischievous side; he bangs on the drums for a raucous rock and roll band—appropriately called Severe Tire Damage—which is famous for its prankster-like antics on the Internet.) When he is not jamming with his rock and roll band, he is busily constructing the computer architecture of the twenty-first century. The goal of his team is to foresee the next stage in the evolution of the computer.

Because microchips are becoming so powerful and so cheap, Weiser and computer scientists like him believe that microchips will quietly disappear by the thousands into the fabric of our lives, and will be incorporated into the walls, the furniture, our appliances, our home, our car, even our jewelry. A simple necktie may one day contain more computing power than today's supercomputer. Already, prototypes of these devices have been built which silently follow our movements from room to room and building to building, seamlessly carrying out our commands invisibly.

The computer, far from being the demanding taskmaster it can be today, will be a truly liberating force in our lives. As Weiser notes: "Machines that fit the human environment instead of forcing humans to enter theirs will make using a computer as refreshing as taking a walk in the woods." These invisible devices will communicate with each other and tap in automatically to the Internet; gradually, they will become intelligent and will be able to anticipate our wishes and, by accessing the Internet, bring the wisdom of the planet to us.

The full implications of this vision are astounding. By comparison, the PC is just a computing appliance.

The ideas of the people at places like Xerox PARC have attracted enormous attention because the fortunes of a multibillion-dollar industry may one day ride on the silly doodlings and idle daydreams of these engineering wizards. A consensus is growing among America's top computer experts. Computers, instead of becoming the rapacious monsters featured in science fiction movies, will become so small and ubiquitous that they will be invisible, everywhere and nowhere, so powerful that they will disappear from view. Weiser has christened this idea "ubiquitous computing."

The Disappearing PC

This push toward invisibility may well be a universal law of human behavior. As Weiser says: "Disappearance is a fundamental consequence not of technology but of human psychology. Whenever people learn something sufficiently well, they cease to be aware of it."

If that seems far-fetched, think of the evolution of electricity and the electric motor. In the nineteenth century, electricity and the electric motor were so precious that entire factories were designed to accommodate the presence of lightbulbs and bulky motors. The placement of workers, machine parts, tables, and so on were all designed around the needs of electricity and the motor.

Today, however, electricity is everywhere, hidden in the walls and stored in tiny batteries. Motors are so small and prevalent that scores of them are concealed inside the frame of a car, moving the windows, mirrors, the radio dial, the tape deck, and antennas. Yet while we are driving, we are blissfully unaware that we are surrounded by up to twenty-two motors and twenty-five solenoids.

To use an analogy, the next stage of the computer can be compared to the evolution of writing. Several thousand years ago, writing was a secret art jealously controlled by a small caste of scribes who were trained to write on clay tablets. These tablets were very scarce and were laboriously baked and carefully guarded by the king's soldiers. When paper was first invented, it too was an extremely precious commodity, taking hundreds of hours to produce a simple scroll. Paper was so expensive that only royalty had access to it. Most people only rarely caught fleeting glimpses of paper in their lives.

Today, we are not even aware that we are surrounded by a world brimming with paper and writing. Strolling down the street, we see nothing special in the writing on billboards, gum wrappers, or street signs. Every day, we grab scrap sheets of paper, scribble on them, and then throw them away. Writing has progressed from being a labor-intensive, sacred form of communication jealously guarded by kings and scribes into becoming invisible, disposable, and ubiquitous. (In fact, one of the single largest sources of waste in modern society is paper, almost all of it with writing on it.)

While this vision of powerful but invisible computers hidden in our environment sounds impractical and very expensive, that's an illusion. With the falling cost of microchips relentlessly driving down the costs of computers, computers will be so cheap, Weiser claims, "that we'll think nothing of going to the grocery store to pick up a six-pack of computers, just like we pick up batteries today."

In the computer industry, it takes roughly fifteen years, on the average, from the conception of an idea to its entering the marketplace. The first PC, for example, was built at Xerox PARC in 1972, but it wasn't until the late 1980s that the PC caught the public's fancy. Ubiquitous computing was conceived in 1988; it may take until the year 2003 to begin to see these ideas affect our lives in an appreciable way. And it may be years after that before they reach "critical mass" and ignite the marketplace. But by 2010, one can expect to see ubiquitous computing becoming of age. By 2020, it will dominate our lives.

Three Phases of Computing

It may be helpful to put the evolution of the computer into a larger historical context. Many computer analysts divide the history of the computer into three or more distinct phases.

The first phase was dominated by the clunky but powerful mainframe computer, pioneered by IBM, Burroughs, Honeywell, and others. Computers were so expensive that an entire division of scientists and engineers was forced to share one giant mainframe. The ratio of computers to people was often one computer for a hundred scientists. "Machines were so scarce and so expensive that man approached the computer the way an ancient Greek approached an oracle," said John Kemeny, former president of Dartmouth University. "There was a certain degree of mysticism in the relationship, even to the extent that only specially selected acolytes were allowed to have direct communication with the computer."

As with clay tablets, an entire "priesthood" developed around servicing and programming each computer; to outsiders, they seemed to jealously guard their power and their access to the mainframe by dreaming up inscrutable incantations and rituals.

The second phase of computing began in the early 1970s, when the engineers at Xerox PARC realized that computer power was exploding even as the size of chips was imploding. They envisioned a ratio of computers to people that would eventually reach one-to-one. To test their ideas, in 1972 they created ALTO, the first PC ever built.

The engineers at Xerox PARC realized that one bottleneck to computing was the fiendishly complicated commands and clumsy manuals, often as thick as the Manhattan telephone book and just as illuminating. Computers were not "user-friendly." They were "user-belligerent." Why not, they mused, create a computer screen which was based entirely on pictures or "icons," where you would simply point a "mouse" at these pictograms to open programs and manipulate them.

In one masterful stroke, computers, instead of being a painful rite of passage, could be operated from scratch even by children. Using a computer could become a pleasant, playful, even enjoyable journey of discovery navigating through unexplored and uncharted menus and playful icons.

Later, the ideas of Xerox PARC were borrowed by Apple Computer, which eventually created the Macintosh computer. Eventually, the Microsoft Corporation adopted Xerox PARC's ideas again in their Windows program, which has since become almost the universal operating system for IBM-based computers sold throughout the world. One wag dubbed this process of raiding the ideas of Xerox PARC "inventing the past." (Ironically enough, Apple tried to sue Microsoft for piracy of its Macintosh operating system, which, in turn, was pirated from Xerox PARC.)

The transition between these phases has never been easy. Even giant multibillion-dollar corporations have been mercilessly crushed like eggshells because they were unable or unwilling to understand and adapt to these phases of computing. Not very long ago, the IBM, Digital, and Wang corporations were the towering giants of the computer business, with lucrative markets in the mainframe, minicomputer, and word processing businesses, respectively. But they mistakenly thought this phase would last forever. Like lumbering dinosaurs, all three thought the personal computer was a passing fad. In the end, all three were shaken to their foundations. Wang is all but bankrupt, and both IBM and Digital were forced to throw out their corporate leadership after devastating and humiliating multibillion-dollar losses.

The Third Phase and Beyond

The third phase of computers is now known as ubiquitous computing, which refers to a time when computers are all connected to each other and the ratio of computers to people flips the other way, with as many as one hundred computers for every person.

Even today's software giant, Microsoft, is trembling in the face of the tidal wave of the third phase that began with the Internet. As Bill Gates admitted: "It's a little scary that as computer technology has moved ahead there's never been a leader from one era who was also a leader in the next. Microsoft has been a leader in the PC era." Suddenly realizing that Microsoft could be relegated to the dustbin of history by the Internet, Gates wrenched his giant corporation completely around to accommodate the new advances in computer networks, a move he hadn't anticipated in the original edition of his 1995 book, *The Road Ahead.*

By 2020, the era of ubiquitous computing should be in full flower. However, even this phase cannot continue forever. Beyond 2020, it is likely that the reign of silicon will end and entirely new computer architectures will have been created.

Some computer analysts believe that this will lead to a fourth phase, the introduction of artificial intelligence into computing systems. From 2020 to 2050, the world of computers may well be dominated by invisible, networked computers which have the power of artificial intelligence: reason, speech recognition, even common sense.

Some commentators believe that computing devices may even enter a fifth phase beyond 2050, when machines become self-aware and even conscious. The computing world from 2020 to 2100 will be discussed in more detail in later chapters.

The implications of these phases are truly profound, affecting every aspect of our lives. A few of the technological wonders which await us, especially in the next ten years, have already been profiled in the media, as in Gates's book, such as the wallet PC and the smart home. Readers may be familiar with some of these developments, which I will briefly review in this chapter. However, I will go far beyond this, focusing on developments which will take us well past the coming decade to the end of the twenty-first century.

Moore's Law

To appreciate the remarkable increase in computer power that is propelling us from one phase to the next, it is important to remember that from 1950 to the present, there has been an increase in computer power by a factor of about *ten billion.* At the heart of this explosive growth is Moore's law, which states that computer power doubles every eighteen months. A rapid increase in power on this scale is almost unheard of in the history of technology.

In order to better appreciate the size of this massive increase, it is helpful to realize that it is larger than the transition from chemical explosives to the hydrogen bomb! In fact, if we go back eighty years, computer power has increased by a factor of *one trillion.* These are the astronomical numbers that are inevitably driving us into the third phase of computing. Using Moore's law, we can reasonably predict the future of computer technology for the next twenty-five years. Moore's law is deceptive because our brains function linearly, rather than exponentially. In the short term, we often see very little change year by year, so we erroneously conclude that not much is happening. But over a period of five to ten years the changes can become monumental.

Two of the most powerful forces in the world favor the long-term vision of ubiquitous computers: the laws of economics and the laws of physics.

As the price of microprocessors continues its plunge, many predict that the sheer power of economics will drive the computer industry into the next phase. Ron Bernal, president of MIPS Technologies, predicts that the price of the microchip will drop to 10 cents by the year 2000, 4 cents in 2005, and 2 cents in 2010. Thomas George, general manager of semiconductor products with Motorola, basically agrees, estimating that the microchip will cost 50 cents in 2000, 7 cents in 2005, and 1 cent in 2010. Eventually, microprocessors will be as *cheap as scrap paper*, and just as plentiful.

This steady exponential explosion in computer power, in turn, will spawn entire industries that have no counterpart in today's market. When the price of a computer chip is just one penny, the financial incentive to include them everywhere, from our appliances to our furniture, our cars, and our factories, will be enormous. *In fact, companies that don't include a few computer chips in their products will be at a severe competitive disadvantage.* (Already, for example, musical greeting cards, which contain disposable music-making chips, have more computer power than the computers that existed before 1950.) In the same way that practically every product on the planet contains writing on it, in the third phase of computers every product may contain a penny microprocessor.

As Andrew Grove, CEO of the giant Intel Corp. says, in the future computing power will be "practically free and practically infinite."

But to understand the dynamics and limits of Moore's law, one must understand the power of the quantum theory—the most fundamental physical theory of the universe.

What Drives Moore's Law?

The secret behind the success of Moore's law lies in the transistor—how it behaves and the way it is manufactured. The transistor is basically a valve which controls the flow of electricity. In the same way that firemen can control huge torrents of water flowing in a fire hose by turning a valve, tiny voltages on a transistor can control the flow of large currents of electricity. The dynamics of semiconductor transistors, in turn, is governed by the quantum theory. (According to the quantum theory, the absence of an electron within a semiconductor acts like an electron of opposite charge, i.e. a "hole." The quantum theory dictates how these electrons and holes move in the transistor.)

What drives the success of Moore's law has been the struggle to miniaturize these transistors. The original transistors were crude electrical components, about the size of a dime, and were connected by wires. Transistors were originally built by hand. Today, transistors are made by using beams of light to make microscopic grooves and lines on silicon wafers (a process called "photolithography").

This process can be compared to making colorful T-shirts. The old-fashioned way is to paint each T-shirt by hand. But a more efficient method is to place a stencil over each T-shirt and then spray it with ink. In this way, one can repeatedly imprint images on T-shirts and mass-produce them in unlimited quantity. (Similarly light is projected through a special stencil called a "mask," containing the desired pattern of complex lines and circuitry, which is placed over a silicon wafer. The light beam focused through the mask imprints the pattern on the wafer, which is photosensitive. The wafer is then treated with special gases, which etch the circuitry into the wafer where it was exposed to light. The basic skeleton of the circuit is carved out this way. The transistors are created on these grooves by spraying the wafer with special ions. This process is repeated about twenty times, fashioning a multilayer system of silicon wafers containing wires and transistors.)

Philosophers used to debate how many angels could dance on the head of a pin. Computer experts today debate how many transistors can be crammed into a microprocessor by means of this etching process. The Motorola Power PC 620, for example, has almost seven million transistors squeezed into silicon chips smaller than a postage stamp. This miniaturization process, however, cannot continue indefinitely. There is a limit to how many wires can be etched on a wafer. That limit is the result, in part, of the wavelength of the light beam.

Typically, the etching of silicon wafers is done by light beams from a mercury lamp, which have wavelengths measured in microns (a micron is a millionth of a meter). Over the last few decades, Moore's law has been driven by using increasingly smaller and smaller wavelengths of mercury light to manufacture microprocessors. Mercury lamps emit light of wavelength .436 micron (in the visible range) and .365 micron (in the ultraviolet range). These distances are about 300 times thinner than a human hair.

The technology that may dominate the first few years of the next century, perhaps until 2005, is based on the pulsed excimer laser, which can push the wavelength down to .193 micron (in the deep ultraviolet range). But beyond 2020, this process will end and entirely new technologies will be required, which will be discussed in Chapter 5.

Sensors and the Invisible Computer

The idea of ubiquitous computing has been amplified and embellished by many of the key thinkers in the computer field. Paul Saffo, director of the

Institute for the Future and one of the leading futurists in the country, is one of many computer experts who feel that some form of ubiquitous computing is inevitable, given the proliferation of cheap microchip technology. His particular version of this future is called the "electronic ecology."

When we analyze the ecology of a forest, we treat it as a collection of animals and plants which exist in harmony and interact dynamically with each other. To Saffo, every ten years or so there is a key technological advance which changes the relationship between the creatures in what he terms the electronic ecology.

The driving force behind the PC revolution in the 1980s, for example, was the microchip. In the 1990s, by contrast, the explosive growth in the Internet (which I will turn to in more detail in the next chapter) was driven by marrying the power of microprocessors with cheap lasers, which can carry trillions of bits of data at the speed of light along glass fibers.

In the twenty-first century, he thinks, the next revolution will be driven by cheap sensors coupled to microprocessors and lasers.

In Saffo's version of the third phase, we will be surrounded by tiny, invisible microprocessors sensing our presence, anticipating our wishes, even reading our emotions. And these microprocessors will be connected to the Internet. Equipped with these sensors, the "animals" of his "electronic forest" will be able to do what most computers cannot: sense our presence and even our mood. He points out wryly that toilets can now recognize our presence (via infrared sensors). But even the most advanced Cray supercomputer is totally unaware of who, what, or where the person using the computer is. Saffo says, "If a meteor smashed into my house and struck me while I was sitting next to my PC, it wouldn't have the slightest clue as to what happened. It will still be awaiting my next instruction!"

In Saffo's third phase, we will interact with our invisible computers by using our gestures, our voice, our body heat and electric field, and our body motions. Invisible computers will sense the world around them via two invisible media, sound and the electromagnetic spectrum. Different invisible media will be used for different purposes. For example, sensors will pick up our voice commands to carry out our wishes. Using hidden video cameras, computers will be able to locate our presence and even recognize our facial gestures. The location of our hands and body can be detected by measuring their electric fields. Smart cars will use radar to sense the presence of other cars. Infrared light sensors will be able to locate where we are by the heat we give off. Computers will communicate with each other and with the Internet via radio and microwaves.

The Smart Office and Home of the Future

The first step in the long but exciting journey toward ubiquitous computing is to create marketable computer devices called tabs, pads, and boards, which are roughly an inch, a foot, and a yard in size. Perhaps 100 tabs, 10 to 20 pads, and one or two boards per room will likely be a fixture of the office of the future.

Tabs are tiny, inch-size clip-on badges that employees will wear—similar to an employee's ID badge, except that they will carry an infrared transmitter and have the power of a PC. Prototypes have already been built by Olivetti Cambridge.

As an employee moves within a building, the tabs can keep track of his or her precise location. Doors magically open up when they are approached, lights come on as people enter a room (and turn off automatically as they leave). Receptionists can actually locate anyone in the building. An intercom badge allows employees to verbally communicate orders or make inquiries to the master computer.

There are endless possibilities for computer tabs. They may be able to scan the Internet for important news and alert the wearer to crucial developments in industry or the stock market, to important calls, to family emergencies, and so on. Tabs will be able to communicate with other tabs as well, silently exchanging business information. Eventually, they may become so tiny they can be concealed in our cuff links or tie clasps.

The larger, foot-size *pads* are the counterparts of disposable scrap paper that we scribble on. In appearance, they will resemble extremely thin computer monitors, and will eventually become almost as thin as paper itself. Instead of employees lugging a heavy workstation from room to room, each room will have such "disposable" pads. These pads will have no individual identity at all. As with sheets of scrap paper, we might have scores of them scattered around our desk. Unlike ordinary sheets of scrap paper, however, each of these pads will be fully operational PCs connected to the main computer. It is, in a sense, the beginning of smart paper.

When we scribble on such smart paper, the graphics program inside will be able to convert our idle doodles into beautiful graphics or use editing capabilities to convert our notes into grammatically correct text. And after we are finished with it and have saved our work on the main computer, we simply toss it in the stack of pads on our desk.

Yard-long *boards* are huge computerized screens which are hung on a wall. At home, such boards can function as wall-size video screens for interactive TV or the Web. At the office, they serve as bulletin boards and "white boards" on which we can scribble notes and post notices or which we can use as a full-fledged PC connected to the Internet. They will also be used for teleconferencing. Instead of spending thousands of dollars flying a staff from distant offices, a manager will be able to simply convert the board into a large wall screen and teleconference with his or her staff. Or doctors will be able to use them to supervise surgery from distant locations.

Historically, one of the first devices in our office or home to become "smart" was the typewriter. When a chip was first inserted into the typewriter, it was christened the word processor. Today, although a few primitive chips may be scattered throughout the house, they are still not connected to each other. In the future, if a big storm is predicted, your house will pick up the weather forecast from the Internet and make the proper preparations, raising the temperature, alerting family members, and providing the latest updates. The smart bathroom will monitor family members' health. In Japan, a computerized toilet is being marketed which can diagnose simple medical problems. A person's pulse can be taken by the toilet seat by sensing the tiny pulse in the thighs. Urine can be chemically analyzed for diabetes.

Although these medical diagnostic tools are still primitive, in the future scientists expect them to blossom into sophisticated medical analyzers, acting as an electrocardiogram for the heart and detecting proteins emitted by precancerous tissues. In the distant future, the smart home may serve as a computerized nurse, carefully analyzing a person's state of health and sending the information silently and automatically to his or her doctor.

The MIT Media Lab

Perhaps the institute most dedicated to bringing about the unification of media, art, and technology is the MIT Media Laboratory, founded by Nicholas Negroponte. Hidden among the austere, faceless buildings that make up the MIT campus, the Media Lab is housed in an ultramodern, white-tiled building designed by architect I. M. Pei. (Because of its distinctive design, the locals fondly refer to the building as the "Pei toilet.")

The director of what is probably its most ambitious and provocative enterprise inspired by ubiquitous computing, the Things That Think project, is physicist Neil Gershenfeld, who envisions a day when most inanimate things around us will think.

A young man in a hurry, Gershenfeld is tall, lanky, with a light beard and curly brown hair; he is a lively, intense man who has several irons in the fire at any one time. He can speak more rapidly on three subjects than most of us can on one.

Gershenfeld made a significant breakthrough when he found an entirely new way for computers to sense our presence. The space around our bodies is filled by an invisible electric field, like a spiderweb. This electric field is generated by electrons which accumulate on our skin like static electricity. When our bodies move, this electric-field "aura" moves with it.

In the past, this aura was considered useless from a commercial point of view. It was Gershenfeld who reasoned that if we have a sensor that can detect electric fields in the space around our bodies, they can be used to locate our arms and fingers.

As a result, the "smart table" was born. Gershenfeld likes to give demonstrations of this new piece of technology. He waves his hands over the computerized table like a symphony conductor. Nearby, a computer screen shows a ghostlike hand moving inside a cube, giving the precise coordinates of his hand in three dimensions. Gershenfeld calls this "electric-field sensing."

The phenomenon can have immediate applications, as it is a more versatile and powerful way to communicate with a computer than the two-dimensional mouse commonly found on PCs. It can also be used to enhance virtual reality, so that people don't have to wear clumsy gloves to locate the position of their hands. (The illusion of virtual reality is enhanced, in fact, without having to be wired up like a Christmas tree. Cyber shoppers of the future may be able to wave their fingers to navigate through virtual shopping malls on their computer screens.)

Gershenfeld's strategy by which he approaches computers of the next century is to ask himself, "Where can I find empty space that is not being used and how can I animate it?" One location, which has been overlooked for years, is the shoes we wear, which have valuable, unused workspace just waiting to be made intelligent.

In the future, our shoes may replace the computer batteries we are likely to need. Carrying bulky batteries around whenever we need to energize the computer in our tie clasp would be a nuisance. But the human body, Gershenfeld points out, generates about 80 watts of usable energy by its motions; about 1 watt of that can easily be drawn from the movements of the shoe alone.

Gershenfeld has found another use for our shoe. It may be possible in the future to put an electrode in one's shoe which will be able to transmit biographical data to others. Rather than exchange business cards, all one would have to do is shake a person's hands. Because skin is salty and conducts electricity, a résumé can travel electrically from shoe to hands and then to one's acquaintance's hand and shoe. This may ultimately prove to be a convenient way to exchange large computer files with someone on the street.

One motto of the Things That Think lab, not surprisingly, is:

> In the past, shoes could stink.
> In the present, shoes can blink.
> In the future, shoes will think.

Wearable Computers

Another essential element of the Things That Think concept is the glasses many of us wear. The MIT Media Lab has already perfected a way to include a miniature computer screen over one's glasses. They do this by placing over the glasses a strange eyepiece resembling a jeweler's lens which contains a complete PC screen, illuminated by tiny LEDs (light emitting diodes). Peering into this tiny screen, barely half an inch wide, one can clearly see bright symbols appearing on a full-sized PC screen.

On nice days in Cambridge, one can sometimes see MIT students from the Media Lab dressed up like cyborgs, complete with helmets, goggles, special eyepieces, and a tangle of electrodes in their clothes. They carry a simplified keyboard which allows them to input data into their computer screens, which are located in their eyepieces.

These crude beginnings that make up part of the Wearable Computers project of the Media Lab will ultimately make any individual a walking node of the World Wide Web. Steve Mann of the Media Lab has connected the video images on his eyepiece to the Internet, so others too can instantly view exactly what he is seeing, even thousands of miles away. In the future, people in distant locations might be able to instantly share what we see through our glasses in this manner.

Wearable computers in many respects represent a merger of cellular phones with the laptop computer. Rocketing sales of laptops, which now account for almost a quarter of all PC sales, prove that mobile computers are no longer a niche market, but are an essential part of the computer landscape. As the costs continue to plunge, many of these users would likely leap at the opportunity to replace their cellular phones and laptops with an invisible smart device with the power of a supercomputer.

This could prove to be immensely liberating for people who ride in cabs, shop at the mall, or travel by airplane. Some of those who may require wearable computers are doctors who need access to emergency medical records, police who need access to files, reporters who need data to file reports, stockbrokers who need twenty-four-hour stock quotes, and so on.

Someday, wearable computers may also save lives. If you have a heart attack somewhere far from a hospital or phone, your wearable computer, by silently monitoring your heartbeat, will be able to recognize unusual patterns consistent with a heart attack and alert the EMS. After a car accident, a wearable computer could automatically call for an ambulance. By hooking up to the GPS satellite, which I'll discuss later, it will also be able to transmit your exact location. At present, tens of thousands die needlessly because there is no one around to alert the EMS when a heart attack or car accident occurs.

The Smart Room

One long-range goal of the Media Lab is to be able to design machines that can identify and imitate the full range of ways people interact with each other. People don't use language alone; we employ a rich, complex body language to communicate with others consisting of a surprisingly wide variety of signals, including eye contact, facial gestures and grimaces, arm motions, voice intonations, and posture. One step in this direction is to design a "smart room" which can recognize not only people but also their signals and emotions.

The Media Lab's prototype smart room of the future is a very ordinary den with small cameras placed in the ceiling and a giant wall-sized screen on the floor.

"Imagine a house that always knows where your kids are and tells you if they are getting into trouble. Or an office that sees when you are having an important meeting and shields you from interruptions. Or a car that senses when you are tired and warns you to pull over," writes Alex Pentland of the MIT Media Lab.

Today's computers cannot reliably recognize a person's face from different angles. Faces are among the most difficult things to identify by computer. However, the Media Lab's computer takes a shortcut to this difficult problem. It already has a series of key faces stored in its memory. If the computer scans a stranger's face and matches it with a face already filed away in its memory, then it can correctly find a match 99 percent of the time in a group of several hundred people.

Computers at the Media Lab can also identify a person's mood by means of the face. Emotions are etched into our faces by the motions they induce in our facial features. By placing sensors on people's faces and having them smile, laugh, smirk, or scowl, the sensors are able to detect how much our facial muscles move. Scientists have found that emotions can be recognized by computers as a result of the well-defined stretching motions they cause in the face. A smile, for example, leads to a broad stretching of our mouth muscles. Surprise leads to rising eyebrows. Anger leads to a contorting forehead. Disgust creates motion throughout the entire face. Therefore when the computer focuses only on the parts of the face that are in motion, it has been able in tests to correctly identify the emotional state of the subject about 98 percent of the time.

Smart Cards, Digital Money, and Cyber Cash

Money is already going digital.

As James Gleick of the *New York Times* commented, digital money "is money incarnated, finally, as pure information." For the big banks and international corporations, this is already a reality. Of the $4 trillion circulating in the U.S. money supply, only one-tenth is in the form of actual cash and coins stored in bank vaults and people's pockets. "People today do not put $5 billion in a truck and drive it from one bank to another—that's irrational," comments Kawika Daguio of the American Bankers Association. In the future, even that one-tenth will disappear into electronic bits.

In the years ahead, as microchip costs plunge to mere pennies, there will be enormous economic pressure for people to convert to smart cards and digital money. This is because maintaining a society based on cash is very expensive. According to Carol H. Fancher, who is researching smart cards for Motorola: "Counting, moving, storing, and safeguarding cash costs about 4 percent of the value of all transactions. The interest lost by holding cash instead of keeping money on deposit is also substantial."

"Money is the current liability of a bank," says Sholom Rosen of Citibank. "It's as simple as that. It's not gold, it's not silver." Cash sitting in a bank is money that is not collecting interest or appreciating in value and that has to be constantly guarded.

Europe has taken the lead in mass-producing primitive versions of smart cards which contain up to a few kilobytes of memory. The value of these smart cards to consumers, who have used them mainly as telephone cards, has already been demonstrated in France (which has over 20 million smart cards in use) and the rest of Europe, where most of the 250 million smart cards in circulation have been issued.

Germany has begun to issue a smart card that carries basic health information to all its citizens. The 1996 Olympics in Atlanta featured the largest trial of smart cards in the United States, with over a million smart cards issued that were honored by restaurants, shops, and the subway system.

In the future, smart cards will replace ATM cards, telephone cards, train and transit passes, credit cards, as well as cards for parking meters,