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PHYSICS OF THE FUTURE

HOW SCIENCE WILL SHAPE HUMAN DESTINY AND OUR DAILY LIVES BY THE YEAR 2100

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To my loving wife, Shizue,

and my daughters, Michelle and Alyson

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Empires of the future will be empires of the mind.

—WINSTON CHURCHILL

INTRODUCTION *Predicting the Next 100 Years*

When I was a child, two experiences helped to shape the person I am today and spawned two passions that have helped to define my entire life.

First, when I was eight years old, I remember all the teachers buzzing with the latest news that a great scientist had just died. That night, the newspapers printed a picture of his office, with an unfinished manuscript on his desk. The caption read that the greatest scientist of our era could not finish his greatest masterpiece. What, I asked myself, could be so difficult that such a great scientist could not finish it? What could possibly be that complicated and that important? To me, eventually this became more fascinating than any murder mystery, more intriguing than any adventure story. I had to know what was in that unfinished manuscript.

Later, I found out that the name of this scientist was Albert Einstein and the unfinished manuscript was to be his crowning achievement, his attempt to create a "theory of everything," an equation, perhaps no more than one inch wide, that would unlock the secrets of the universe and perhaps allow him to "read the mind of God."

But the other pivotal experience from my childhood was when I watched the Saturday morning TV shows, especially the *Flash*

Gordon series with Buster Crabbe. Every week, my nose was glued to the TV screen. I was magically transported to a mysterious world of space aliens, starships, ray gun battles, underwater cities, and monsters. I was hooked. This was my first exposure to the world of the future. Ever since, I've felt a childlike wonder when pondering the future.

But after watching every episode of the series, I began to realize that although Flash got all the accolades, it was the scientist Dr. Zarkov who actually made the series work. He invented the rocket ship, the invisibility shield, the power source for the city in the sky, etc. Without the scientist, there is no future. The handsome and the beautiful may earn the admiration of society, but all the wondrous inventions of the future are a byproduct of the unsung, anonymous scientists.

Later, when I was in high school, I decided to follow in the footsteps of these great scientists and put some of my learning to the test. I wanted to be part of this great revolution that I knew would change the world. I decided to build an atom smasher. I asked my mother for permission to build a 2.3-million electron volt particle accelerator in the garage. She was a bit startled but gave me the okay. Then, I went to Westinghouse and Varian Associates, got 400 pounds of transformer steel, 22 miles of copper wire, and assembled a betatron accelerator in my mom's garage.

Previously, I had built a cloud chamber with a powerful magnetic field and photographed tracks of antimatter. But photographing antimatter was not enough. My goal now was to produce a beam of antimatter. The atom smasher's magnetic coils successfully produced a huge 10,000 gauss magnetic field (about 20,000 times the earth's magnetic field, which would in principle be enough to rip a hammer right out of your hand). The machine soaked up 6 kilowatts of power, draining all the electricity my house could provide. When I turned on the machine, I frequently blew out all the fuses in the house. (My poor mother must have wondered why she could not have a son who played football instead.)

So two passions have intrigued me my entire life: the desire to understand all the physical laws of the universe in a single coherent theory and the desire to see the future. Eventually, I realized that these two passions were actually complementary. The key to understanding the future is to grasp the fundamental laws of nature and then apply them to the inventions, machines, and therapies that will redefine our civilization far into the future.

There have been, I found out, numerous attempts to predict the future, many useful and insightful. However, they were mainly written by historians, sociologists, science fiction writers, and "futurists," that is, outsiders who are predicting the world of science without a firsthand knowledge of the science itself. The scientists, the insiders who are actually creating the future in their laboratories, are too busy making breakthroughs to have time to write books about the future for the public.

That is why this book is different. I hope this book will give an insider's perspective on what miraculous discoveries await us and provide the most authentic, authoritative look into the world of 2100.

Of course, it is impossible to predict the future with complete accuracy. The best one can do, I feel, is to tap into the minds of the scientists at the cutting edge of research, who are doing the yeoman's work of inventing the future. They are the ones who are creating the devices, inventions, and therapies that will revolutionize civilization. And this book is their story. I have had the opportunity to sit in the front-row seat of this great revolution, having interviewed more than 300 of the world's top scientists, thinkers, and dreamers for national TV and radio. I have also taken TV crews into their laboratories to film the prototypes of the remarkable devices that will change our future. It has been a rare honor to have hosted numerous science specials for BBC-TV, the Discovery Channel, and the Science Channel, profiling the remarkable inventions and discoveries of the visionaries who are daring to create the future. Being free to pursue my work on string theory and to eavesdrop on the cutting-edge research that will revolutionize this century, I feel I have one of the most desirable jobs in science. It is my childhood dream come true.

But this book differs from my previous ones. In books like *Beyond Einstein, Hyperspace,* and *Parallel Worlds,* I discussed the fresh, revolutionary winds sweeping through my field, theoretical physics, that are opening up new ways to understand the universe. In *Physics of the Impossible,* I discussed how the latest discoveries in physics may eventually make possible even the most imaginative schemes of science fiction.

This book most closely resembles my book *Visions,* in which I discussed how science will evolve in the coming decades. I am gratified that many of the predictions made in that book are being realized today on schedule. The accuracy of my book, to a large degree, has depended on the wisdom and foresight of the many scientists I interviewed for it.

But this book takes a much more expansive view of the future, discussing the technologies that may mature in 100 years, that will ultimately determine the fate of humanity. How we negotiate the challenges and opportunities of the next 100 years will determine the ultimate trajectory of the human race.

PREDICTING THE NEXT CENTURY

Predicting the next few years, let alone a century into the future, is a daunting task. Yet it is one that challenges us to dream about technologies we believe will one day alter the fate of humanity.

In 1863, the great novelist Jules Verne undertook perhaps his most ambitious project. He wrote a prophetic novel, called *Paris in the Twentieth Century,* in which he applied the full power of his enormous talents to forecast the coming century. Unfortunately, the manuscript was lost in the mist of time, until his great-grandson accidentally stumbled upon it lying in a safe where it had been carefully locked away for almost 130 years. Realizing what a treasure he had found, he arranged to have it published in 1994, and it became a best seller.

Back in 1863, kings and emperors still ruled ancient empires, with impoverished peasants performing backbreaking work toiling in the fields. The United States was consumed by a ruinous civil war that would almost tear the country apart, and steam power was just beginning to revolutionize the world. But Verne predicted that Paris in 1960 would have glass skyscrapers, air conditioning, TV, elevators, high-speed trains, gasoline-powered automobiles, fax machines, and even something resembling the Internet. With uncanny accuracy, Verne depicted life in modern Paris.

This was not a fluke, because just a few years later he made another spectacular prediction. In 1865, he wrote *From the Earth to the Moon,* in which he predicted the details of the mission that sent our astronauts to the moon more than 100 years later in 1969. He accurately predicted the size of the space capsule to within a few percent, the location of the launch site in Florida not far from Cape Canaveral, the number of astronauts on the mission, the length of time the voyage would last, the weightlessness that the astronauts would experience, and the final splashdown in the ocean. (The only major mistake was that he used gunpowder, rather than rocket fuel, to take his astronauts to the moon. But liquid-fueled rockets wouldn't be invented for another seventy years.)

How was Jules Verne able to predict 100 years into the future with such breathtaking accuracy? His biographers have noted that, although Verne was not a scientist himself, he constantly sought out scientists, peppering them with questions about their visions of the future. He amassed a vast archive summarizing the great scientific discoveries of his time. Verne, more than others, realized

To understand the difficulty of predicting the next 100 years, we have to appreciate the difficulty that the people of 1900 had in predicting the world of 2000. In 1893, as part of the World's Columbian Exposition in Chicago, seventy-four well-known individuals were asked to predict what life would be like in the next 100 years. The one problem was that they consistently underestimated the rate of progress of science. For example, many correctly predicted that we would one day have commercial transatlantic airships, but they thought that they would be balloons. Senator John J. Ingalls said, "It will be as common for the citizen to call for his dirigible balloon as it now is for his buggy or his boots." They also consistently missed the coming of the automobile. Postmaster General John Wanamaker stated that the U.S. mail would be delivered by stagecoach and horseback, even 100 years into the future.

This underestimation of science and innovation even extended to the patent office. In 1899, Charles H. Duell, commissioner of the U.S. Office of Patents, said, "Everything that can be invented has been invented."

Sometimes experts in their own field underestimated what was happening right beneath their noses. In 1927, Harry M. Warner, one of the founders of Warner Brothers, remarked during the era of silent movies, "Who the hell wants to hear actors talk?"

And Thomas Watson, chairman of IBM, said in 1943, "I think there is a world market for maybe five computers."

This underestimation of the power of scientific discovery even extended to the venerable *New York Times.* (In 1903, the *Times* declared that flying machines were a waste of time, just a week before the Wright brothers successfully flew their airplane at Kitty Hawk, North Carolina. In 1920, the *Times* criticized rocket scientist Robert Goddard, declaring his work nonsense because rockets cannot move in a vacuum. Forty-nine years later, when *Apollo 11* astronauts landed on the moon, the *Times,* to its credit, ran the retraction: "It is now definitely established that a rocket can function in a vacuum. The *Times* regrets the error.")

The lesson here is that it is very dangerous to bet against the future.

Predictions for the future, with a few exceptions, have always underestimated the pace of technological progress. History, we are told over and over again, is written by the optimists, not the pessimists. As President Dwight Eisenhower once said, "Pessimism never won a war."

We can even see how science fiction writers underestimated the pace of scientific discovery. When watching reruns of the old 1960s TV series *Star Trek,* you notice that much of this "twenty-third-century technology" is already here. Back then, TV audiences were startled to see mobile phones, portable computers, machines that could talk, and typewriters that could take dictation. Yet all these technologies exist today. Soon, we will also have versions of the universal translator, which can rapidly translate between languages as you speak, and also "tricorders," which can diagnose disease from a distance. (Excepting warp drive engines and transporters, much of this twenty-third-century science is already here.)

Given the glaring mistakes people have made in underestimating the future, how can we begin to provide a firmer scientific basis to our predictions?

UNDERSTANDING THE LAWS OF NATURE

Today, we are no longer living in the dark ages of science, when lightning bolts and plagues were thought to be the work of the gods. We have a great advantage that Verne and Leonardo da Vinci did not have: a solid understanding of the laws of nature.

Predictions will always be flawed, but one way to make them as authoritative as possible is to grasp the four fundamental forces in nature that drive the entire universe. Each time one of them was understood and described, it changed human history.

The first force to be explained was the force of gravity. Isaac Newton gave us a mechanics that could explain that objects moved via forces, rather than mystical spirits and metaphysics. This helped to pave the way for the Industrial Revolution and the introduction of steam power, especially the locomotive.

The second force to be understood was the electromagnetic force, which lights up our cities and powers our appliances. When Thomas Edison, Michael Faraday, James Clerk Maxwell, and others helped to explain electricity and magnetism, this unleashed the electronic revolution that has created a bounty of scientific wonders. We see this every time there is a power blackout, when society is suddenly wrenched back 100 years into the past.

The third and fourth forces to be understood were the two nuclear forces: the weak and strong forces. When Einstein wrote down $E = mc^2$ and when the atom was split in the 1930s, scientists for the first time began to understand the forces that light up the heavens. This revealed the secret behind the stars. Not only did this unleash the awesome power of atomic weapons, it also held out the promise that one day we would be able to harness this power on the earth.

Today, we have a fairly good grasp of these four forces. The first force, gravity, is now described through Einstein's theory of general relativity. And the other three forces are described through the quantum theory, which allows us to decode the secrets of the subatomic world.

The quantum theory, in turn, has given us the transistor, the laser, and the digital revolution that is the driving force behind modern society. Similarly, scientists were able to use the quantum theory to unlock the secret of the DNA molecule. The blinding speed of the biotechnological revolution is a direct result of computer technology, since DNA sequencing is all done by machines, robots, and computers.

As a consequence, we are better able to see the direction that science and technology will take in the coming century. There will always be totally unexpected, novel surprises that leave us speechless, but the foundation of modern physics, chemistry, and biology has largely been laid, and we do not expect any major revision of this basic knowledge, at least in the foreseeable future. As a result, the predictions we make in this book are the product not of wild speculation but are reasoned estimates of when the prototype technologies of today will finally reach maturity.

In conclusion, there are several reasons to believe that we can view the outlines of the world of 2100:

1. This book is based on interviews with more than 300 top scientists, those in the forefront of discovery.
2. Every scientific development mentioned in this book is consistent with the known laws of physics.
3. The four forces and the fundamental laws of nature are largely known; we do not expect any major new changes in these laws.
4. Prototypes of all technologies mentioned in this book already exist.
5. This book is written by an "insider" who has a firsthand look at the technologies that are on the cutting edge of research.

For countless eons we were passive observers of the dance of nature. We only gazed in wonder and fear at comets, lightning bolts, volcanic eruptions, and plagues, assuming that they were beyond our comprehension. To the ancients, the forces of nature were an eternal mystery to be feared and worshipped, so they created the gods of mythology to make sense of the world around them. The ancients hoped that by praying to these gods they would show mercy and grant them their dearest wishes.

Today, we have become choreographers of the dance of nature, able to tweak the laws of nature here and there. But by 2100, we will make the transition to being masters of nature.

2100: BECOMING THE GODS OF MYTHOLOGY

Today, if we could somehow visit our ancient ancestors and show them the bounty of modern science and technology, we would be viewed as magicians. With the wizardry of science, we could show them jet planes that can soar in the clouds, rockets that can explore the moon and planets, MRI scanners that can peer inside the living body, and cell phones that can put us in touch with anyone on the planet. If we showed them laptop computers that can send moving images and messages instantly across the continents, they would view this as sorcery.

But this is just the beginning. Science is not static. Science is exploding exponentially all around us. If you count the number of scientific articles being published, you will find that the sheer volume of science doubles every decade or so. Innovation and discovery are changing the entire economic, political, and social landscape, overturning all the old cherished beliefs and prejudices.

Now dare to imagine the world in the year 2100.

By 2100, our destiny is to become like the gods we once worshipped and feared. But our tools will not be magic wands and potions but the science of computers, nanotechnology, artificial intelligence, biotechnology, and most of all, the quantum theory, which is the foundation of the previous technologies.

By 2100, like the gods of mythology, we will be able to manipulate objects with the power of our minds. Computers, silently reading our thoughts, will be able to carry out our wishes. We will be able to move objects by thought alone, a telekinetic power usually reserved only for the gods. With the power of each unit cost about $1 million each. This was a very expensive fiasco.

And finally, it was thought that the demise of traditional media and entertainment was imminent. Some futurists claimed that the Internet was the juggernaut that would swallow live theater, the movies, radio, and TV, all of which would soon be seen only in museums.

Actually, the reverse has happened. Traffic jams are worse than ever—a permanent feature of urban life. People flock to foreign sites in record numbers, making tourism one of the fastest-growing industries on the planet. Shoppers flood the stores, in spite of economic hard times. Instead of proliferating cyberclassrooms, universities are still registering record numbers of students. To be sure, there are more people deciding to work from their homes or teleconference with their coworkers, but cities have not emptied at all. Instead, they have morphed into sprawling megacities. Today, it is easy to carry on video conversations on the Internet, but most people tend to be reluctant to be filmed, preferring face-to-face meetings. And of course, the Internet has changed the entire media landscape, as media giants puzzle over how to earn revenue on the Internet. But it is not even close to wiping out TV, radio, and live theater. The lights of Broadway still glow as brightly as before.

CAVE MAN PRINCIPLE

Why did these predictions fail to materialize? I conjecture that people largely rejected these advances because of what I call the Cave Man (or Cave Woman) Principle. Genetic and fossil evidence indicates that modern humans, who looked just like us, emerged from Africa more than 100,000 years ago, but we see no evidence that our brains and personalities have changed much since then. If you took someone from that period, he would be anatomically identical to us: if you gave him a bath and a shave, put him in a three-piece suit, and then placed him on Wall Street, he would be physically indistinguishable from everyone else. So our wants, dreams, personalities, and desires have probably not changed much in 100,000 years. We probably still think like our caveman ancestors.

The point is: whenever there is a conflict between modern technology and the desires of our primitive ancestors, these primitive desires win each time. That's the Cave Man Principle. For example, the caveman always demanded "proof of the kill." It was never enough to boast about the big one that got away. Having the fresh animal in our hands was always preferable to tales of the one that got away. Similarly, we want hard copy whenever we deal with files. We instinctively don't trust the electrons floating in our computer screen, so we print our e-mails and reports, even when it's not necessary. That's why the paperless office never came to be.

Likewise, our ancestors always liked face-to-face encounters. This helped us to bond with others and to read their hidden emotions. This is why the peopleless city never came to pass. For example, a boss might want to carefully size up his employees. It's difficult to do this online, but face-to-face a boss can read body language to gain valuable unconscious information. By watching people up close, we feel a common bond and can also read their subtle body language to find out what thoughts are racing through their heads. This is because our apelike ancestors, many thousands of years before they developed speech, used body language almost exclusively to convey their thoughts and emotions.

This is the reason cybertourism never got off the ground. It's one thing to see a picture of the Taj Mahal, but it's another thing to have the bragging rights of actually seeing it in person. Similarly, listening to a CD of your favorite musician is not the same as feeling the sudden rush when actually seeing this musician in a live concert, surrounded by all the fanfare, hoopla, and noise. This means that even though we will be able to download realistic images of our favorite drama or celebrity, there is nothing like actually seeing the drama on stage or seeing the actor perform in person. Fans go to great lengths to get autographed pictures and concert tickets of their favorite celebrity, although they can download a picture from the Internet for free.

This explains why the prediction that the Internet would wipe out TV and radio never came to pass. When the movies and radio first came in, people bewailed the death of live theater. When TV came in, people predicted the demise of the movies and radio. We are living now with a mix of all these media. The lesson is that one medium never annihilates a previous one but coexists with it. It is the mix and relationship among these media that constantly change. Anyone who can accurately predict the mix of these media in the future could become very wealthy.

The reason for this is that our ancient ancestors always wanted to see something for themselves and not rely on hearsay. It was crucial for our survival in the forest to rely on actual physical evidence rather than rumors. Even a century from now, we will still have live theater and still chase celebrities, an ancient heritage of our distant past.

In addition, we are descended from predators who hunted. Hence, we love to watch others and even sit for hours in front of a TV, endlessly watching the antics of our fellow humans, but we instantly get nervous when we feel others watching us. In fact, scientists have calculated that we get nervous if we are stared at by a stranger for about four seconds. After about ten seconds, we even get irate and hostile at being stared at. This is the reason why the original picture phone was such a flop. Also, who wants to have to comb one's hair before going online? (Today, after decades of slow, painful improvement, video conferencing is finally catching on.)

And today, it is possible to take courses online. But universities are bulging with students. The one-to-one encounter with professors, who can give individual attention and answer personal questions, is still preferable to online courses. And a university degree still carries more weight than an online diploma when applying for a job.

So there is a continual competition between High Tech and High Touch, that is, sitting in a chair watching TV versus reaching out and touching things around us. In this competition, we will want both. That is why we still have live theater, rock concerts, paper, and tourism in the age of cyberspace and virtual reality. But if we are offered a free picture of our favorite celebrity musician or actual tickets to his concert, we will take the tickets, hands down.

So that is the Cave Man Principle: we prefer to have both, but if given a choice we will chose High Touch, like our cavemen ancestors.

But there is also a corollary to this principle. When scientists first created the Internet back in the 1960s, it was widely believed that it would evolve into a forum for education, science, and progress. Instead, many were horrified that it soon degenerated into the no-holds-barred Wild West that it is today. Actually, this is to be expected. The corollary to the Cave Man Principle is that if you want to predict the social interactions of humans in the future, simply imagine our social interactions 100,000 years ago and multiply by a billion. This means that there will be a premium placed on gossip, social networking, and entertainment. Rumors were essential in a tribe to rapidly communicate information, especially about the leaders and role models. Those who were out of the loop often did not survive to pass on their genes. Today, we can see this played out in grocery checkout stands, which have wall-to-wall celebrity gossip magazines, and in the rise of a celebrity-driven culture. The only difference today is that the magnitude of this tribal gossip has been multiplied enormously by mass media and can now circle the earth many times over within a fraction of a second.

The sudden proliferation of social networking Web sites, which turned young, baby-faced entrepreneurs into billionaires almost overnight, caught many analysts off guard, but it is also an example of this principle. In our evolutionary history, those who maintained large social networks could rely on them for resources, advice, and help that were vital for survival.

And last, entertainment will continue to grow explosively. We sometimes don't like to admit it, but a dominant part of our culture is based on entertainment. After the hunt, our ancestors relaxed and entertained themselves. This was important not only for bonding but also for establishing one's position within the tribe. It is no accident that dancing and singing, which are essential parts of entertainment, are also vital in the animal kingdom to demonstrate fitness to the opposite sex. When male birds sing beautiful, complex melodies or engage in bizarre mating rituals, it is mainly to show the opposite sex that they are healthy, physically fit, free of parasites, and have genes worthy enough to be passed down.

And the creation of art was not only for enjoyment but also played an important part in the evolution of our brain, which handles most information symbolically.

So unless we genetically change our basic personality, we can expect that the power of entertainment, tabloid gossip, and social networking will increase, not decrease, in the future.

SCIENCE AS A SWORD

I once saw a movie that forever changed my attitude toward the future. It was called *Forbidden Planet,* based on Shakespeare's *The Tempest.* In the movie astronauts encounter an ancient civilization unforgiving stare. Even political analyst William F. Buckley had to defend the word processor against intellectuals who railed against it and refused to ever touch a computer, calling it an instrument of the philistines.

It was in this era of controversy that Weiser coined the expression "ubiquitous computing." Seeing far past the personal computer, he predicted that the chips would one day become so cheap and plentiful that they would be scattered throughout the environment—in our clothing, our furniture, the walls, even our bodies. And they would all be connected to the Internet, sharing data, making our lives more pleasant, monitoring all our wishes. Everywhere we moved, chips would be there to silently carry out our desires. The environment would be alive.

For its time, Weiser's dream was outlandish, even preposterous. Most personal computers were still expensive and not even connected to the Internet. The idea that billions of tiny chips would one day be as cheap as running water was considered lunacy.

And then I asked him why he felt so sure about this revolution. He calmly replied that computer power was growing exponentially, with no end in sight. Do the math, he implied. It was only a matter of time. (Sadly, Weiser did not live long enough to see his revolution come true, dying of cancer in 1999.)

The driving source behind Weiser's prophetic dreams is something called Moore's law, a rule of thumb that has driven the computer industry for fifty or more years, setting the pace for modern civilization like clockwork. Moore's law simply says that computer power doubles about every eighteen months. First stated in 1965 by Gordon Moore, one of the founders of the Intel Corporation, this simple law has helped to revolutionize the world economy, generated fabulous new wealth, and irreversibly altered our way of life. When you plot the plunging price of computer chips and their rapid advancements in speed, processing power, and memory, you find a remarkably straight line going back fifty years. (This is plotted on a logarithmic curve. In fact, if you extend the graph, so that it includes vacuum tube technology and even mechanical hand-crank adding machines, the line can be extended more than 100 years into the past.)

Exponential growth is often hard to grasp, since our minds think linearly. It is so gradual that you sometimes cannot experience the change at all. But over decades, it can completely alter everything around us.

According to Moore's law, every Christmas your new computer games are almost twice as powerful (in terms of the number of transistors) as those from the previous year. Furthermore, as the years pass, this incremental gain becomes monumental. For example, when you receive a birthday card in the mail, it often has a chip that sings "Happy Birthday" to you. Remarkably, that chip has more computer power than all the Allied forces of 1945. Hitler, Churchill, or Roosevelt might have killed to get that chip. But what do we do with it? After the birthday, we throw the card and chip away. Today, your cell phone has more computer power than all of NASA back in 1969, when it placed two astronauts on the moon. Video games, which consume enormous amounts of computer power to simulate 3-D situations, use more computer power than mainframe computers of the previous decade. The Sony PlayStation of today, which costs $300, has the power of a military supercomputer of 1997, which cost millions of dollars.

We can see the difference between linear and exponential growth of computer power when we analyze how people viewed the future of the computer back in 1949, when *Popular Mechanics* predicted that computers would grow linearly into the future, perhaps only doubling or tripling with time. It wrote: "Where a calculator like the ENIAC today is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and weigh only 1½ tons."

(Mother Nature appreciates the power of the exponential. A single virus can hijack a human cell and force it to create several hundred copies of itself. Growing by a factor of 100 in each generation, one virus can generate 10 billion viruses in just five generations. No wonder a single virus can infect the human body, with trillions of healthy cells, and give you a cold in just a week or so.)

Not only has the amount of computer power increased, but the way that this power is delivered has also radically changed, with enormous implications for the economy. We can see this progression, decade by decade:

- **1950s.** Vacuum tube computers were gigantic contraptions filling entire rooms with jungles of wires, coils, and steel. Only the military was rich enough to fund these monstrosities.
- **1960s.** Transistors replaced vacuum tube computers, and mainframe computers gradually entered the commercial marketplace.
- **1970s.** Integrated circuit boards, containing hundreds of transistors, created the minicomputer, which was the size of a large desk.
- **1980s.** Chips, containing tens of millions of transistors, made possible personal computers that can fit inside a briefcase.
- **1990s.** The Internet connected hundreds of millions of computers into a single, global computer network.
- **2000s.** Ubiquitous computing freed the chip from the computer, so chips were dispersed into the environment.

So the old paradigm (a single chip inside a desktop computer or laptop connected to a computer) is being replaced by a new paradigm (thousands of chips scattered inside every artifact, such as furniture, appliances, pictures, walls, cars, and clothes, all talking to one another and connected to the Internet).

When these chips are inserted into an appliance, it is miraculously transformed. When chips were inserted into typewriters, they became word processors. When inserted into telephones, they became cell phones. When inserted into cameras, they became digital cameras. Pinball machines became video games. Phonographs became iPods. Airplanes became deadly Predator drones. Each time, an industry was revolutionized and was reborn. Eventually, almost everything around us will become intelligent. Chips will be so cheap they will even cost less than the plastic wrapper and will replace the bar code. Companies that do not make their products intelligent may find themselves driven out of business by their competitors that do.

Of course, we will still be surrounded by computer monitors, but they will resemble wallpaper, picture frames, or family photographs, rather than computers. Imagine all the pictures and photographs that decorate our homes today; now imagine each one being animated, moving, and connected to the Internet. When we walk outside, we will see pictures move, since moving pictures will cost as little as static ones.

The destiny of computers—like other mass technologies like electricity, paper, and running water—is to become invisible, that is, to disappear into the fabric of our lives, to be everywhere and nowhere, silently and seamlessly carrying out our wishes.

Today, when we enter a room, we automatically look for the light switch, since we assume that the walls are electrified. In the future, the first thing we will do on entering a room is to look for the Internet portal, because we will assume the room is intelligent. As novelist Max Frisch once said, “Technology [is] the knack of so arranging the world that we don’t have to experience it.”

Moore’s law also allows us to predict the evolution of the computer into the near future. In the coming decade, chips will be combined with supersensitive sensors, so that they can detect diseases, accidents, and emergencies and alert us before they get out of control. They will, to a degree, recognize the human voice and face and converse in a formal language. They will be able to create entire virtual worlds that we can only dream of today. Around 2020, the price of a chip may also drop to about a penny, which is the cost of scrap paper. Then we will have millions of chips distributed everywhere in our environment, silently carrying out our orders.

Ultimately, the word *computer* itself will disappear from the English language.

In order to discuss the future progress of science and technology, I have divided each chapter into three periods: the near future (today to 2030), the midcentury (from 2030 to 2070), and finally the far future, from 2070 to 2100. These time periods are only rough approximations, but they show the time frame for the various trends profiled in this book.

The rapid rise of computer power by the year 2100 will give us power like that of the gods of mythology we once worshipped, enabling us to control the world around us by sheer thought. Like the gods of mythology, who could move objects and reshape life with a simple wave of the hand or nod of the head, we too will be able to control the world around us with the power of our minds. We will be in constant mental contact with chips scattered in our environment that will then silently carry out our commands.

I remember once watching an episode from *Star Trek* in which the crew of the starship *Enterprise* came across a planet inhabited by the Greek gods. Standing in front of them was the towering god Apollo, a giant figure who could dazzle and overwhelm the crew with godlike feats. Twenty-third-century science was powerless to spar with a god who ruled the heavens thousands of years ago in ancient Greece. But once the crew recovered from the shock of encountering the Greek gods, they soon realized that there must be a source of this power, that Apollo must simply be in mental contact with a central computer and power plant, which then body. But this is just the beginning. Eventually, Parviz envisions the day when we will be able to download any movie, song, Web site, or piece of information off the Internet into our contact lens. We will have a complete home entertainment system in our lens as we lie back and enjoy feature-length movies. We can also use it to connect directly to our office computer via our lens, then manipulate the files that flash before us. From the comfort of the beach, we will be able to teleconference to the office by blinking.

By inserting some pattern-recognition software into these Internet glasses, they will also recognize objects and even some people's faces. Already, some software programs can recognize preprogrammed faces with better than 90 percent accuracy. Not just the name, but the biography of the person you are talking to may flash before you as you speak. At a meeting this will end the embarrassment of bumping into someone you know whose name you can't remember. This may also serve an important function at a cocktail party, where there are many strangers, some of whom are very important, but you don't know who they are. In the future, you will be able to identify strangers and know their backgrounds, even as you speak to them. (This is somewhat like the world as seen through robotic eyes in *The Terminator.*)

This may alter the educational system. In the future, students taking a final exam will be able to silently scan the Internet via their contact lens for the answers to the questions, which would pose an obvious problem for teachers who often rely on rote memorization. This means that educators will have to stress thinking and reasoning ability instead.

Your glasses may also have a tiny video camera in the frame, so it can film your surroundings and then broadcast the images directly onto the Internet. People around the world may be able to share in your experiences as they happen. Whatever you are watching, thousands of others will be able to see it as well. Parents will know what their children are doing. Lovers may share experiences when separated. People at concerts will be able to communicate their excitement to fans around the world. Inspectors will visit faraway factories and then beam the live images directly to the contact lens of the boss. (Or one spouse may do the shopping, while the other makes comments about what to buy.)

Already, Parviz has been able to miniaturize a computer chip so that it can be placed inside the polymer film of a contact lens. He has successfully placed an LED (light-emitting diode) into a contact lens, and is now working on one with an 8 × 8 array of LEDs. His contact lens can be controlled by a wireless connection. He claims, "Those components will eventually include hundreds of LEDs, which will form images in front of the eye, such as words, charts, and photographs. Much of the hardware is semitransparent so that wearers can navigate their surroundings without crashing into them or becoming disoriented." His ultimate goal, which is still years away, is to create a contact lens with 3,600 pixels, each one no more than 10 micrometers thick.

One advantage of Internet contact lenses is that they use so little power, only a few millionths of a watt, so they are very efficient in their energy requirements and won't drain the battery. Another advantage is that the eye and optic nerve are, in some sense, a direct extension of the human brain, so we are gaining direct access to the human brain without having to implant electrodes. The eye and the optic nerve transmit information at a rate exceeding a high-speed Internet connection. So an Internet contact lens offers perhaps the most efficient and rapid access to the brain.

Shining an image onto the eye via the contact lens is a bit more complex than for the Internet glasses. An LED can produce a dot, or pixel, of light, but you have to add a microlens so that it focuses directly onto the retina. The final image would appear to float about two feet away from you. A more advanced design that Parviz is considering is to use microlasers to send a supersharp image directly onto the retina. With the same technology used in the chip industry to carve out tiny transistors, one can also etch tiny lasers of the same size, making the smallest lasers in the world. Lasers that are about 100 atoms across are in principle possible using this technology. Like transistors, you could conceivably pack millions of lasers onto a chip the size of your fingernail.

DRIVERLESS CAR

In the near future, you will also be able to safely surf the Web via your contact lens while driving a car. Commuting to work won't be such an agonizing chore because cars will drive themselves. Already, driverless cars, using GPS to locate their position within a few feet, can drive over hundreds of miles. The Pentagon's Defense Advanced Research Projects Agency (DARPA) sponsored a contest, called the DARPA Grand Challenge, in which laboratories were invited to submit driverless cars for a race across the Mojave Desert to claim a $1 million prize. DARPA was continuing its long-standing tradition of financing risky but visionary technologies.

(Some examples of Pentagon projects include the Internet, which was originally designed to connect scientists and officials during and after a nuclear war, and the GPS system, which was originally designed to guide ICBM missiles. But both the Internet and GPS were declassified and given to the public after the end of the Cold War.)

In 2004, the contest had an embarrassing beginning, when not a single driverless car was able to travel the 150 miles of rugged terrain and cross the finish line. The robotic cars either broke down or got lost. But the next year, five cars completed an even more demanding course. They had to drive on roads that included 100 sharp turns, three narrow tunnels, and paths with sheer drop-offs on either side.

Some critics said that robotic cars might be able to travel in the desert but never in midtown traffic. So in 2007, DARPA sponsored an even more ambitious project, the Urban Challenge, in which robotic cars had to complete a grueling 60-mile course through mock-urban territory in less than six hours. The cars had to obey all traffic laws, avoid other robot cars along the course, and negotiate four-way intersections. Six teams successfully completed the Urban Challenge, with the top three claiming the $2 million, $1 million, and $500,000 prizes.

The Pentagon's goal is to make fully one-third of the U.S. ground forces autonomous by 2015. This could prove to be a lifesaving technology, since recently most U.S. casualties have been from roadside bombs. In the future, many U.S. military vehicles will have no drivers at all. But for the consumer, it might mean cars that drive themselves at the touch of a button, allowing the driver to work, relax, admire the scenery, watch a movie, or scan the Internet.

I had a chance to drive one of these cars myself for a TV special for the Discovery Channel. It was a sleek sports car, modified by the engineers at North Carolina State University so that it became fully autonomous. Its computers had the power of eight PCs. Entering the car for me was a bit of a problem, since the interior was crammed. Everywhere inside, I could see sophisticated electronic components piled on the seats and dashboard. When I grabbed the steering wheel, I noticed that it had a special rubber cable connected to a small motor. A computer, by controlling the motor, could then turn the steering wheel.

After I turned the key, stepped on the accelerator, and steered the car onto the highway, I flicked a switch that allowed the computer to take control. I took my hands off the wheel, and the car drove itself. I had full confidence in the car, whose computer was constantly making tiny adjustments via the rubber cable on the steering wheel. At first, it was a bit eerie noticing that the steering wheel and accelerator pedal were moving by themselves. It felt like there was an invisible, ghostlike driver who had taken control, but after a while I got used to it. In fact, later it became a joy to be able to relax in a car that drove itself with superhuman accuracy and skill. I could sit back and enjoy the ride.

The heart of the driverless car was the GPS system, which allowed the computer to locate its position to within a few feet. (Sometimes, the engineers told me, the GPS system could determine the car's position to within inches.) The GPS system itself is a marvel of modern technology. Each of the thirty-two GPS satellites orbiting the earth emits a specific radio wave, which is then picked up by the GPS receivers in my car. The signal from each satellite is slightly distorted because they are traveling in slightly different orbits. This distortion is called the Doppler shift. (Radio waves, for example, are compressed if the satellite is moving toward you, and are stretched if it moves away from you.) By analyzing the slight distortion of frequencies from three or four satellites, the car's computer could determine my position accurately.

The car also had radar in its fenders so that it could sense obstacles. This will be crucial in the future, as each car will automatically take emergency measures as soon as it detects an impending accident. Today, almost 40,000 people in the United States die in car accidents every year. In the future, the words *car accident* may gradually disappear from the English language.

Traffic jams may also be a thing of the past. A central computer will be able to track all the motions of every car on the road by communicating with each driverless car. It will then easily spot traffic jams and bottlenecks on the highways. In one experiment, conducted north of San Diego on Interstate 15, chips were placed in the road so that a central computer took control of the cars on the road. In case of a traffic jam, the computer will override the driver and allow traffic to flow freely.

wailed that it would gradually replace direct person-to-person contact. The critics were right, but today we don't mind speaking to disembodied voices, because it has vastly increased our circle of contacts and enriched our lives.

This may also change your love life. If you are lonely, your wall screen will know your past preferences and the physical and social characteristics you want in a date, and then scan the Internet for a possible match. And since people sometimes lie in their profiles, as a security measure, your screen will automatically scan each person's history to detect falsehoods in their biography.

FLEXIBLE ELECTRONIC PAPER

The price of flat-screen TVs, once more than $10,000, has dropped by a factor of about fifty just within a decade. In the future, flat screens that cover an entire wall will also fall dramatically in price. These wall screens will be flexible and superthin, using OLEDs (organic light-emitting diodes). They are similar to ordinary light-emitting diodes, except they are based on organic compounds that can be arranged in a polymer, making them flexible. Each pixel on the flexible screen is connected to a transistor that controls the color and intensity of the light.

Already, the scientists at Arizona State University's Flexible Display Center are working with Hewlett-Packard and the U.S. Army to perfect this technology. Market forces will then drive down the cost of this technology and bring it to the public. As prices go down, the cost of these wall screens may eventually approach the price of ordinary wallpaper. So in the future, when putting up wallpaper, one might also be putting up wall screens at the same time. When we wish to change the pattern on our wallpaper, we will simply push a button. Redecorating will be so simple.

This flexible screen technology may also revolutionize how we interact with our portable computers. We will not need to lug heavy laptop computers with us. The laptop may be a simple sheet of OLEDs we then fold up and put in our wallets. A cell phone may contain a flexible screen that can be pulled out, like a scroll. Then, instead of straining to type on the tiny keyboard of your cell phone, you may be able to pull out a flexible screen as large as you want.

This technology also makes possible PC screens that are totally transparent. In the near future, we may be staring out a window, and then wave our hands, and suddenly the window becomes a PC screen. Or any image we desire. We could be staring out a window thousands of miles away.

Today, we have scrap paper that we scribble on and then throw away. In the future, we might have "scrap computers" that have no special identity of their own. We scribble on them and discard them. Today, we arrange our desk and furniture around the computer, which dominates our office. In the future, the desktop computer might disappear and the files will move with us as we go from place to place, from room to room, or from office to home. This will give us seamless information, anytime, anywhere. Today at airports you see hundreds of travelers carrying laptop computers. Once at the hotel, they have to connect to the Internet; and once they return back home, they have to download files into their desktop machines. In the future, you will never need to lug a computer around, since everywhere you turn, the walls, pictures, and furniture can connect you to the Internet, even if you are in a train or car. ("Cloud computing," where you are billed not for computers but for computer time, treating computation like a utility that is metered like water or electricity, is an early example of this.)

VIRTUAL WORLDS

The goal of ubiquitous computing is to bring the computer into our world: to put chips everywhere. The purpose of virtual reality is the opposite: to put us into the world of the computer. Virtual reality was first introduced by the military in the 1960s as a way of training pilots and soldiers using simulations. Pilots could practice landing on the deck of an aircraft carrier by watching a computer screen and moving a joystick. In case of a nuclear war, generals and political leaders from distant locations could meet secretly in cyberspace.

Today, with computer power expanding exponentially, one can live in a simulated world, where you can control an avatar (an animated image that represents you). You can meet other avatars, explore imaginary worlds, and even fall in love and get married. You can also buy virtual items with virtual money that can then be converted to real money. One of the most popular sites, Second Life, registered 16 million accounts by 2009. That year, several people earned more than $1 million per year using Second Life. (The profit you make, however, is taxable by the U.S. government, which considers it real income.)

Virtual reality is already a staple of video games. In the future as computer power continues to expand, via your glasses or wall screen, you will also be able to visit unreal worlds. For example, if you wish to go shopping or visit an exotic place, you might first do it via virtual reality, navigating the computer screen as if you were really there. In this way, you will be able to walk on the moon, vacation on Mars, shop in distant countries, visit any museum, and decide for yourself where you want to go.

You will also, to a degree, have the ability to feel and touch objects in this cyberworld. This is called “haptic technology” and allows you to feel the presence of objects that are computer generated. It was first developed by scientists who had to handle highly radioactive materials with remote-controlled robotic arms, and by the military, which wanted its pilots to feel the resistance of a joystick in a flight simulator.

To duplicate the sense of touch scientists have created a device attached to springs and gears, so that as you push your fingers forward on the device, it pushes back, simulating the sensation of pressure. As you move your fingers across a table, for example, this device can simulate the sensation of feeling its hard wooden surface. In this way, you can feel the presence of objects that are seen in virtual reality goggles, completing the illusion that you are somewhere else.

To create the sensation of texture, another device allows your fingers to pass across a surface containing thousands of tiny pins. As your fingers move, the height of each pin is controlled by a computer, so that it can simulate the texture of hard surfaces, velvety cloth, or rough sandpaper. In the future, by putting on special gloves, it may be possible to give a realistic sensation of touch over a variety of objects and surfaces.

This will be essential for training surgeons in the future, since the surgeon has to be able to sense pressure when performing delicate surgery, and the patient might be a 3-D holographic image. It also takes us a bit closer to the holodeck of the *Star Trek* series, where you wander in a virtual world and can touch virtual objects. As you roam around an empty room, you can see fantastic objects in your goggles or contact lens. As you reach out and grab them, a haptic device rises from the floor and simulates the object you are touching.

I had a chance to witness these technologies firsthand when I visited the CAVE (cave automatic virtual environment) at Rowan University in New Jersey for the Science Channel. I entered an empty room, where I was surrounded by four walls, each wall lit up by a projector. 3-D images could be flashed onto the walls, giving the illusion of being transported to another world. In one demonstration, I was surrounded by giant, ferocious dinosaurs. By moving a joystick, I could take a ride on the back of a

Tyrannosaurus rex, or even go right into its mouth. Then I visited the Aberdeen Proving Ground in Maryland, where the U.S. military has devised the most advanced version of a holodeck. Sensors were placed on my helmet and backpack, so the computer knew exactly the position of my body. I then walked on an Omnidirectional Treadmill, a sophisticated treadmill that allows you to walk in any direction while remaining in the same place. Suddenly I was on a battlefield, dodging bullets from enemy snipers. I could run in any direction, hide in any alleyway, sprint down any street, and the 3-D images on the screen changed instantly. I could even lie flat on the floor, and the screens changed accordingly. I could imagine that, in the future, you will be able to experience total immersion, e.g. engage in dogfights with alien spaceships, flee from rampaging monsters, or frolic on a deserted island, all from the comfort of your living room.

MEDICAL CARE IN THE NEAR FUTURE

A visit to the doctor's office will be completely changed. For a routine checkup, when you talk to the "doctor," it will probably be a robotic software program that appears on your wall screen and that can correctly diagnose up to 95 percent of all common ailments. Your "doctor" may look like a person, but it will actually be an animated image programmed to ask certain simple questions. Your "doctor" will also have a complete record of your genes, and will recommend a course of medical treatments that takes into account all your genetic risk factors.

To diagnose a problem, the "doctor" will ask you to pass a simple probe over your body. In the original *Star Trek* TV series, the public was amazed to see a device called the tricorder that could instantly diagnose any illness and peer inside your body. But you do not have to wait until the twenty-third century for this futuristic device. Already, MRI machines, which weigh several tons world.) Because computers are revealing the genes that control our bodies, we will be able to reengineer our bodies, replacing organs and changing our appearance, even at the genetic level, like the beast in "Beauty and the Beast."

Some futurists have even feared that this might give rise to a return to the mysticism of the Middle Ages, when most people believed that there were invisible spirits inhabiting everything around them.

MIDCENTURY (2030 TO 2070)

END OF MOORE'S LAW

We have to ask: How long can this computer revolution last? If Moore's law holds true for another fifty years, it is conceivable that computers will rapidly exceed the computational power of the human brain. By midcentury, a new dynamic occurs. As George Harrison once said, "All things must pass." Even Moore's law must end, and with it the spectacular rise of computer power that has fueled economic growth for the past half century.

Today, we take it for granted, and in fact believe it is our birthright, to have computer products of ever-increasing power and complexity. This is why we buy new computer products every year, knowing that they are almost twice as powerful as last year's model. But if Moore's law collapses—and every generation of computer products has roughly the same power and speed of the previous generation—then why bother to buy new computers?

Since chips are placed in a wide variety of products, this could have disastrous effects on the entire economy. As entire industries grind to a halt, millions could lose their jobs, and the economy could be thrown into turmoil.

Years ago, when we physicists pointed out the inevitable collapse of Moore's law, traditionally the industry pooh-poohed our claims, implying that we were crying wolf. The end of Moore's law was predicted so many times, they said, that they simply did not believe it.

But not anymore.

Two years ago, I keynoted a major conference for Microsoft at their main headquarters in Seattle, Washington. Three thousand of the top engineers at Microsoft were in the audience, waiting to hear what I had to say about the future of computers and telecommunications. Staring out at the huge crowd, I could see the faces of the young, enthusiastic engineers who would be creating the programs that will run the computers sitting on our desks and laps. I was blunt about Moore's law, and said that the industry has to prepare for this collapse. A decade earlier, I might have been met with laughter or a few snickers. But this time I only saw people nodding their heads.

So the collapse of Moore's law is a matter of international importance, with trillions of dollars at stake. But precisely how it will end, and what will replace it, depends on the laws of physics. The answers to these physics questions will eventually rock the economic structure of capitalism.

To understand this situation, it is important to realize that the remarkable success of the computer revolution rests on several principles of physics. First, computers have dazzling speed because electrical signals travel at near the speed of light, which is the ultimate speed in the universe. In one second, a light beam can travel around the world seven times or reach the moon. Electrons are also easily moved around and loosely bound to the atom (and can be scraped off just by combing your hair, walking across a carpet, or by doing your laundry—that's why we have static cling). The combination of loosely bound electrons and their enormous speed allows us to send electrical signals at a blinding pace, which has created the electric revolution of the past century.

Second, there is virtually no limit to the amount of information you can place on a laser beam. Light waves, because they vibrate much faster than sound waves, can carry vastly more information than sound. (For example, think of stretching a long piece of rope and then vibrating one end rapidly. The faster you wiggle one end, the more signals you can send along the rope. Hence, the amount of information you can cram onto a wave increases the faster you vibrate it, that is, by increasing its frequency.) Light is a wave that vibrates at roughly 10^{14} cycles per second (that is 1 with 14 zeros after it). It takes many cycles to convey one bit of information (a 1 or a 0). This means that a fiber-optic cable can carry roughly 10^{11} bits of information on a single frequency. And this number can be increased by cramming many signals into a single optical fiber and then bundling these fibers into a cable. This means that, by increasing the number of channels in a cable and then increasing the number of cables, one can transmit information almost without limit.

Third, and most important, the computer revolution is driven by miniaturizing transistors. A transistor is a gate, or switch, that controls the flow of electricity. If an electric circuit is compared to plumbing, then a transistor is like a valve controlling the flow of water. In the same way that the simple twist of a valve can control a huge volume of water, the transistor allows a tiny flow of electricity to control a much larger flow, thereby amplifying its power.

At the heart of this revolution is the computer chip, which can contain hundreds of millions of transistors on a silicon wafer the size of your fingernail. Inside your laptop there is a chip whose transistors can be seen only under a microscope. These incredibly tiny transistors are created the same way that designs on T-shirts are made.

Designs on T-shirts are mass-produced by first creating a stencil with the outline of the pattern one wishes to create. Then the stencil is placed over the cloth, and spray paint is applied. Only where there are gaps in the stencil does the paint penetrate to the cloth. Once the stencil is removed, one has a perfect copy of the pattern on the T-shirt.

Likewise, a stencil is made containing the intricate outlines of millions of transistors. This is placed over a wafer containing many layers of silicon, which is sensitive to light. Ultraviolet light is then focused on the stencil, which then penetrates through the gaps of the stencil and exposes the silicon wafer.

Then the wafer is bathed in acid, carving the outlines of the circuits and creating the intricate design of millions of transistors. Since the wafer consists of many conducting and semiconducting layers, the acid cuts into the wafer at different depths and patterns, so one can create circuits of enormous complexity.

One reason why Moore's law has relentlessly increased the power of chips is because UV light can be tuned so that its wavelength is smaller and smaller, making it possible to etch increasingly tiny transistors onto silicon wafers. Since UV light has a wavelength as small as 10 nanometers (a nanometer is a billionth of a meter), this means that the smallest transistor that you can etch is about thirty atoms across.

But this process cannot go on forever. At some point, it will be physically impossible to etch transistors in this way that are the size of atoms. You can even calculate roughly when Moore's law will finally collapse: when you finally hit transistors the size of individual atoms.

Around 2020 or soon afterward, Moore's law will gradually cease to hold true and Silicon Valley may slowly turn into a rust belt unless a replacement technology is found. According to the laws of physics, eventually the Age of Silicon will come to a close, as we enter the Post-Silicon Era. Transistors will be so small that quantum theory or atomic physics takes over and electrons leak out of the wires. For example, the thinnest layer inside your computer will be about five atoms across. At that point, according to the laws of physics, the quantum theory takes over. The Heisenberg uncertainty principle states that you cannot know both the position and velocity of any particle. This may sound counterintuitive, but at the atomic level you simply cannot know where the electron is, so it can never be confined precisely in an ultrathin wire or layer and it necessarily leaks out, causing the circuit to short-circuit.

disappear. This is not true invisibility, since it works only if you wear special goggles that merge two images. However, it is part of Professor Tachi's grand program, which is sometimes called "augmented reality."

By midcentury, we will live in a fully functioning cyberworld that merges the real world with images from a computer. This could radically change the workplace, commerce, entertainment, and our way of life. Augmented reality would have immediate consequences for the marketplace. The first commercial application would be to make objects become invisible, or to make the invisible become visible.

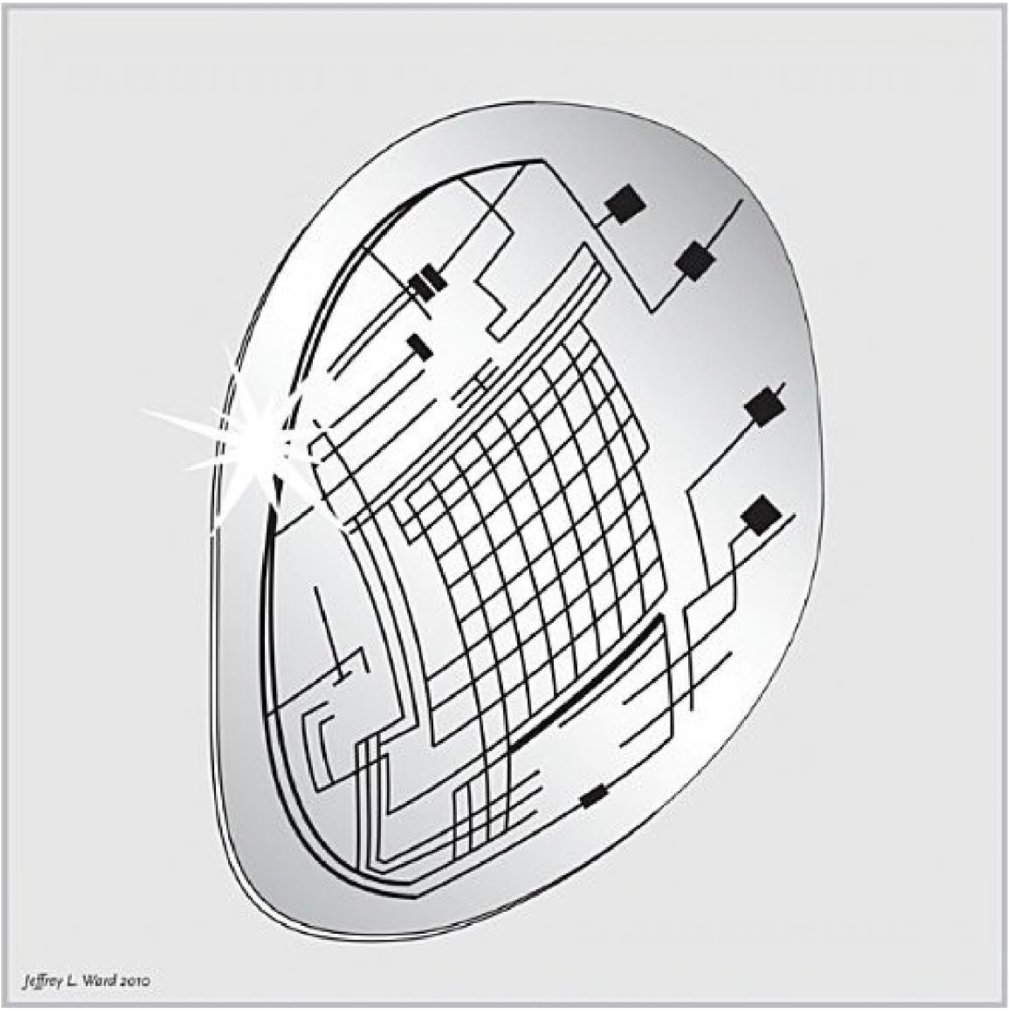
For example, if you are a pilot or a driver, you will be able to see 360 degrees around yourself, and even beneath your feet, because your goggles or lens allow you to see through the plane's or car's walls. This will eliminate blind spots that are responsible for scores of accidents and deaths. In a dogfight, jet pilots will be able to track enemy jets anywhere they fly, even below themselves, as if your jet were transparent. Drivers will be able to see in all directions, since tiny cameras will monitor 360 degrees of their surroundings and beam the images into their contact lenses.

If you are an astronaut making repairs on the outside of a rocket ship, you will also find this useful, since you can see right through walls, partitions, and the rocket ship's hull. This could be lifesaving. If you are a construction worker making underground repairs, amid a mass of wires, pipes, and valves, you will know exactly how they are all connected. This could prove vital in case of a gas or steam explosion, when pipes hidden behind walls have to be repaired and reconnected quickly.

Likewise, if you are a prospector, you will be able to see right through the soil, to underground deposits of water or oil. Satellite and airplane photographs taken of a field with infrared and UV light can be analyzed and then fed into your contact lens, giving you a 3-D analysis of the site and what lies below the surface. As you walk across a barren landscape, you will “see” valuable mineral deposits via your lens.

In addition to making objects invisible, you will also be able to do the opposite: to make the invisible become visible.

If you are an architect, you will be able to walk around an empty room and suddenly “see” the entire 3-D image of the building you are designing. The designs on your blueprint will leap out at you as you wander around each room. Vacant rooms will suddenly come alive, with furniture, carpets, and decorations on the walls, allowing you to visualize your creation in 3-D before you actually build it. By simply moving your arms, you will be able to create new rooms, walls, and furniture. In this augmented world, you will have the power of a magician, waving your wand and creating any object you desire.



Internet contact lenses will recognize people's faces, display their biographies, and translate their words as subtitles. Tourists will use them to resurrect ancient monuments. Artists and architects will use them to manipulate and reshape their virtual creations. The possibilities are endless for augmented reality.

AUGMENTED REALITY: A REVOLUTION IN TOURISM, ART, SHOPPING, AND WARFARE

As you can see, the implications for commerce and the workplace are potentially enormous. Virtually every job can be enriched by augmented reality. In addition, our lives, our entertainment, and our society will be greatly enhanced by this technology.

For example, a tourist walking in a museum can go from exhibit to exhibit as your contact lens gives you a description of each object; a virtual guide will give you a cybertour as you pass. If you are visiting some ancient ruins, you will be able to "see" complete reconstructions of the buildings and monuments in their full glory, along with historical anecdotes. The remains of the Roman Empire, instead of being broken columns and weeds, will spring back to life as you wander among them, complete with commentary and notes.

The Beijing Institute of Technology has already taken the first baby steps in this direction. In cyberspace, it re-created the fabulous Garden of Perfect Brightness, which was destroyed by British-French forces during the Second Opium War of 1860. Today, all that is left of the fabled garden is the wreckage left by marauding troops. But if you view the ruins from a special viewing platform, you can see the entire garden before you in all its splendor. In the future, this will become commonplace.

An even more advanced system was created by inventor Nikolas Neecke, who has created a walking tour of Basel, Switzerland. When you walk around its ancient streets, you see images of ancient buildings and even people superimposed on the present, as if you were a time traveler. The computer locates your position and then shows you images of ancient scenes in your goggles, as if you were transported to medieval times. Today, you have to wear large goggles and a heavy backpack full of GPS electronics and computers. Tomorrow, you will have this in your contact lens.

If you are driving a car in a foreign land, all the gauges would appear on your contact lens in English, so you would never have to glance down to see them. You will see the road signs along with explanations of any object nearby, such as tourist attractions. You will also see rapid translations of road signs.

A hiker, camper, or outdoorsman will know not just his position in a foreign land but also the names of all the plants and animals, and will be able to see a map of the area and receive weather reports. He will also see trails and camping sites that may be hidden by brush and trees.

Apartment hunters will be able to see what is available as you walk down the street or drive by in a car. Your lens will display the price, the amenities, etc., of any apartment or house that's for sale.

And gazing at the night sky, you will see the stars and all the constellations clearly delineated, as if you were watching a planetarium show, except that the stars you see are real. You will also see where galaxies, distant black holes, and other interesting astronomical sights are located and be able to download interesting lectures.

In addition to being able to see through objects and visit foreign lands, augmented vision will be essential if you need very specialized information at a moment's touch.

For example, if you are an actor, musician, or performer who has to memorize large amounts of material, in the future you will see all the lines or music in your lens. You won't need teleprompters, cue cards, sheet music, or notes to remind you. You will not need to memorize anything anymore.

Other examples include:

- If you are a student and missed a lecture, you will be able to download lectures given by virtual professors on any subject and watch them. Via telepresence, an image of a real professor could appear in front of you and answer any questions you may have. You will also be able to see demonstrations of experiments, videos, etc., via your lens.
- If you are a soldier in the field, your goggles or headset may give you all the latest information, maps, enemy locations,

that can bathe a room. Then they bounce off the walls, and pass from behind through the object you want to examine. Your goggles are sensitive to the X-rays that have passed through the object. Images seen via backscattered X-rays can be just as good as the images found in the comics. (By increasing the sensitivity of the goggles, one can reduce the intensity of the X-rays, to minimize any health risks.)

UNIVERSAL TRANSLATORS

In *Star Trek,* the *Star Wars* saga, and virtually all other science fiction films, remarkably, all the aliens speak perfect English. This is because there is something called the "universal translator" that allows earthlings to communicate instantly with any alien civilization, removing the inconvenience of tediously using sign language and primitive gestures to communicate with an alien.

Although once considered to be unrealistically futuristic, versions of the universal translator already exist. This means that in the future, if you are a tourist in a foreign country and talk to the locals, you will see subtitles in your contact lens, as if you were watching a foreign-language movie. You can also have your computer create an audio translation that is fed into your ears. This means that it may be possible to have two people carry on a conversation, with each speaking in their own language, while hearing the translation in their ears, if both have the universal translator. The translation won't be perfect, since there are always problems with idioms, slang, and colorful expressions, but it will be good enough so you will understand the gist of what that person is saying.

There are several ways in which scientists are making this a reality. The first is to create a machine that can convert the spoken word into writing. In the mid-1990s, the first commercially available speech recognition machines hit the market. They could recognize up to 40,000 words with 95 percent accuracy. Since a typical, everyday conversation uses only 500 to 1,000 words, these machines are more than adequate. Once the transcription of the human voice is accomplished, then each word is translated into another language via a computer dictionary. Then comes the hard part: putting the words into context, adding slang, colloquial expressions, etc., all of which require a sophisticated understanding of the nuances of the language. The field is called CAT (computer assisted translation).

Another way is being pioneered at Carnegie Mellon University in Pittsburgh. Scientists there already have prototypes that can translate Chinese into English, and English into Spanish or German. They attach electrodes to the neck and face of the speaker; these pick up the contraction of the muscles and decipher the words being spoken. Their work does not require any audio equipment, since the words can be mouthed silently. Then a computer translates these words and a voice synthesizer speaks them out loud. In simple conversations involving 100 to 200 words, they have attained 80 percent accuracy.

"The idea is that you can mouth words in English and they will come out in Chinese or another language," says Tanja Schultz, one of the researchers. In the future, it might be possible for a computer to lip-read the person you are talking to, so the electrodes are not necessary. So, in principle, it is possible to have two people having a lively conversation, although they speak in two different languages.

In the future, language barriers, which once tragically prevented cultures from understanding one another, may gradually fall with this universal translator and Internet contact lens or glasses.

Although augmented reality opens up an entirely new world, there are limitations. The problem will not be one of hardware; nor is bandwidth a limiting factor, since there is no limit to the amount of information that can be carried by fiber-optic cables.

The real bottleneck is software. Creating software can be done only the old-fashioned way. A human—sitting quietly in a chair with a pencil, paper, and laptop—is going to have to write the codes, line for line, that make these imaginary worlds come to life. One can mass-produce hardware and increase its power by piling on more and more chips, but you cannot mass-produce the brain. This means that the introduction of a truly augmented world will take decades, until midcentury.

HOLOGRAMS AND 3-D

Another technological advance we might see by midcentury is true 3-D TV and movies. Back in the 1950s, 3-D movies required that you put on clunky glasses whose lenses were colored blue and red. This took advantage of the fact that the left eye and the right eye are slightly misaligned; the movie screen displayed two images, one blue and one red. Since these glasses acted as filters that gave two distinct images to the left and right eye, this gave the illusion of seeing three dimensions when the brain merged the two images. Depth perception, therefore, was a trick. (The farther apart your eyes are, the greater the depth perception. That is why some animals have eyes outside their heads: to give them maximum depth perception.)

One improvement is to have 3-D glasses made of polarized glass, so that the left eye and right eye are shown two different polarized images. In this way, one can see 3-D images in full color, not just in blue and red. Since light is a wave, it can vibrate up and down, or left and right. A polarized lens is a piece of glass that allows only one direction of light to pass through. Therefore, if you have two polarized lenses in your glasses, with different directions of polarization, you can create a 3-D effect. A more sophisticated version of 3-D may be to have two different images flashed into our contact lens.

3-D TVs that require wearing special glasses have already hit the market. But soon, 3-D TVs will no longer require them, instead using lenticular lenses. The TV screen is specially made so that it projects two separate images at slightly different angles, one for each eye. Hence your eyes see separate images, giving the illusion of 3-D. However, your head must be positioned correctly; there are "sweet spots" where your eyes must lie as you gaze at the screen. (This takes advantage of a well-known optical illusion. In novelty stores, we see pictures that magically transform as we walk past them. This is done by taking two pictures, shredding each one into many thin strips, and then interspersing the strips, creating a composite image. Then a lenticular glass sheet with many vertical grooves is placed on top of the composite, each groove sitting precisely on top of two strips. The groove is specially shaped so that, as you gaze upon it from one angle, you can see one strip, but the other strip appears from another angle. Hence, by walking past the glass sheet, we see each picture suddenly transform from one into the other, and back again. 3-D TVs will replace these still pictures with moving images to attain the same effect without the use of glasses.)

But the most advanced version of 3-D will be holograms. Without using any glasses, you would see the precise wave front of a 3-D image, as if it were sitting directly in front of you. Holograms have been around for decades (they appear in novelty shops, on credit cards, and at exhibitions), and they regularly are featured in science fiction movies. In *Star Wars,* the plot was set in motion by a 3-D holographic distress message sent from Princess Leia to members of the Rebel Alliance.

The problem is that holograms are very hard to create.

Holograms are made by taking a single laser beam and splitting it in two. One beam falls on the object you want to photograph, which then bounces off and falls onto a special screen.

The second laser beam falls directly onto the screen. The mixing of the two beams creates a complex interference pattern containing the "frozen" 3-D image of the original object, which is then captured on a special film on the screen. Then, by flashing another laser beam through the screen, the image of the original object comes to life in full 3-D.

There are two problems with holographic TV. First, the image has to be flashed onto a screen. Sitting in front of the screen, you see the exact 3-D image of the original object. But you cannot reach out and touch the object. The 3-D image you see in front of you is an illusion.

This means that if you are watching a 3-D football game on your holographic TV, no matter how you move, the image in front of you changes as if it were real. It might appear that you are sitting right at the 50-yard line, watching the game just inches from the football players. However, if you were to reach out to grab the ball, you would bump into the screen.

The real technical problem that has prevented the development of holographic TV is that of information storage. A true 3-D image contains a vast amount of information, many times the information stored inside a single 2-D image. Computers regularly process 2-D images, since the image is broken down into tiny dots, called pixels, and each pixel is illuminated by a tiny transistor. But to make a 3-D image move, you need to flash thirty images per second. A quick calculation shows that the information needed to generate moving 3-D holographic images far exceeds the capability of today's Internet.

By midcentury, this problem may be resolved as the bandwidth of the Internet expands exponentially.

What might true 3-D TV look like?

One possibility is a screen shaped like a cylinder or dome that you sit inside. When the holographic image is flashed onto the screen, we see the 3-D images surrounding us, as if they were move anything but a few facial muscles and his eyelids, with nurses holding up his limp head and pushing him around. It takes him hours and days of excruciating effort to communicate simple ideas via his voice synthesizer. I wondered if it was not too late for him to take advantage of the technology of BrainGate. Then John Donoghue, who was also in the audience, came up to greet me. So perhaps BrainGate is Hawking's best option.)

Another group of scientists at Duke University have achieved similar results in monkeys. Miguel A. L. Nicolelis and his group have placed a chip on the brain of a monkey. The chip is connected to a mechanical arm. At first, the monkey flails about, not understanding how to operate the mechanical arm. But with some practice, these monkeys, using the power of their brains, are able to slowly control the motions of the mechanical arm—for example, moving it so that it grabs a banana. They can instinctively move these arms without thinking, as if the mechanical arm is their own. "There's some physiological evidence that during the experiment they feel more connected to the robots than to their own bodies," says Nicolelis.

This also means that we will one day be able to control machines using pure thought. People who are paralyzed may be able to control mechanical arms and legs in this way. For example, one might be able to connect a person's brain directly to mechanical arms and legs, bypassing the spinal cord, so the patient can walk again. Also, this may lay the foundation for controlling our world via the power of the mind.

MIND READING

If the brain can control a computer or mechanical arm, can a computer read the thoughts of a person, without placing electrodes inside the brain?

It's been known since 1875 that the brain is based on electricity moving through its neurons, which generates faint electrical signals that can be measured by placing electrodes around a person's head. By analyzing the electrical impulses picked up by these electrodes, one can record the brain waves. This is called an EEG (electroencephalogram), which can record gross changes in the brain, such as when it is sleeping, and also moods, such as agitation, anger, etc. The output of the EEG can be displayed on a computer screen, which the subject can watch. After a while, the person is able to move the cursor by thinking alone. Already, Niels Birbaumer of the University of Tübingen has been able to train partially paralyzed people to type simple sentences via this method.

Even toy makers are taking advantage of this. A number of toy companies, including NeuroSky, market a headband with an EEG-type electrode inside. If you concentrate in a certain way, you can activate the EEG in the headband, which then controls the toy. For example, you can raise a Ping-Pong ball inside a cylinder by sheer thought.

The advantage of the EEG is that it can rapidly detect various frequencies emitted by the brain without elaborate, expensive equipment. But one large disadvantage is that the EEG cannot localize thoughts to specific locations of the brain.

A much more sensitive method is the fMRI (functional magnetic resonance imaging) scan. EEG and fMRI scans differ in important ways. The EEG scan is a passive device that simply picks up electrical signals from the brain, so we cannot determine very well the location of the source. An fMRI machine uses "echoes" created by radio waves to peer inside living tissue. This allows us to pinpoint the location of the various signals, giving us spectacular 3-D images of inside the brain.

The fMRI machine is quite expensive and requires a laboratory full of heavy equipment, but already it has given us breathtaking details of how the thinking brain functions. The fMRI scan allows scientists to locate the presence of oxygen contained within hemoglobin in the blood. Since oxygenated hemoglobin contains the energy that fuels cell activity, detecting the flow of this oxygen allows one to trace the flow of thoughts in the brain.

Joshua Freedman, a psychiatrist at the University of California, Los Angeles, says: "It's like being an astronomer in the sixteenth century after the invention of the telescope. For millennia, very smart people tried to make sense of what was going on up in the heavens, but they could only speculate about what lay beyond unaided human vision. Then, suddenly, a new technology let them see directly what was there."

In fact, fMRI scans can even detect the motion of thoughts in the living brain to a resolution of .1 millimeter, or smaller than the head of a pin, which corresponds to perhaps a few thousand neurons. An fMRI can thus give three-dimensional pictures of the energy flow inside the thinking brain to astonishing accuracy. Eventually, fMRI machines may be built that can probe to the level of single neurons, in which case one might be able to pick out the neural patterns corresponding to specific thoughts.

A breakthrough was made recently by Kendrick Kay and his colleagues at the University of California at Berkeley. They did an fMRI scan of people as they looked at pictures of a variety of objects, such as food, animals, people, and common things of various colors. Kay and colleagues created a software program that could associate these objects with the corresponding fMRI patterns. The more objects these subjects saw, the better the computer program was at identifying these objects on their fMRI scans.

Then they showed the same subjects entirely new objects, and the software program was often able to correctly match the object with the fMRI scan. When shown 120 pictures of new objects, the software program correctly identified the fMRI scan with these objects 90 percent of the time. When the subjects were shown

1,000 new pictures, the software program's success rate was 80 percent.

Kay says it is "possible to identify, from a large set of completely novel natural images, which specific image was seen by an observer. ... It may soon be possible to reconstruct a picture of a person's visual experience from measurements of brain activity alone."

The goal of this approach is to create a "dictionary of thought," so that each object has a one-to-one correspondence to a certain fMRI image. By reading the fMRI pattern, one can then decipher what object the person is thinking about. Eventually, a computer will scan perhaps thousands of fMRI patterns that come pouring out of a thinking brain and decipher each one. In this way, one may be able to decode a person's stream of consciousness.

PHOTOGRAPHING A DREAM

The problem with this technique, however, is that while it might be able to tell if you are thinking of a dog, for example, it cannot reproduce the actual image of the dog itself. One new line of research is to try to reconstruct the precise image that the brain is thinking of, so that one might be able to create a video of a person's thoughts. In this way, one might be able to make a video recording of a dream.

Since time immemorial, people have been fascinated by dreams, those ephemeral images that are sometimes so frustrating to recall or understand. Hollywood has long envisioned machines that might one day send dreamlike thoughts into the brain or even record them, as in movies like *Total Recall.* All this, however, was sheer speculation.

Until recently, that is.

Scientists have made remarkable progress in an area once thought to be impossible: taking a snapshot of our memories and possibly our dreams. The first steps in this direction were taken by scientists at the Advanced Telecommunications Research (ATR) Computational Neuroscience Laboratory in Kyoto. They showed their subjects a pinpoint of light at a particular location. Then they used an fMRI scan to record where the brain stored this information. They moved the pinpoint of light and recorded where the brain stored this new image. Eventually, they had a one-to-one map of where scores of pinpoints of light were stored in the brain. These pinpoints were located on a 10 × 10 grid.

Then the scientists flashed a picture of a simple object made from these 10 × 10 points, such as a horseshoe. By computer they could then analyze how the brain stored this picture. Sure enough, the pattern stored by the brain was the sum of the images that made up the horseshoe.

fMRI, and electrodes on the brain itself) require close contact with the subject.

Nonetheless, laws may eventually be passed to limit unauthorized mind reading. Also, devices may be created to protect our thoughts by jamming, blocking, or scrambling our electrical signals.

True mind reading is still many decades away. But at the very least, an fMRI scanner might function as a primitive lie detector. Telling a lie causes more centers of the brain to light up than telling the truth. Telling a lie implies that you know the truth but are thinking of the lie and its myriad consequences, which requires much more energy than telling the truth. Hence, the fMRI brain scan should be able to detect this extra expenditure of energy. At present, the scientific community has some reservations about allowing fMRI lie detectors to be the last word, especially in court cases. The technology is still too new to provide a foolproof lie-detection method. Further research, say its promoters, will refine its accuracy. This technology is here to stay.

Already, there are two commercial companies offering fMRI lie detectors, claiming a more than 90 percent success rate. A court in India already has used an fMRI to settle a case, and several cases involving fMRI are now in U.S. courts.

Ordinary lie detectors do not measure lies; they measure only signs of tension, such as increased sweating (measured by analyzing the conductivity of the skin) and increased heart rate. Brain scans measure increased brain activity, but the correlation between this and lying has still to be proven conclusively for a court of law.

It may take years of careful testing to explore the limits and accuracy of fMRI lie detection. In the meantime, the MacArthur Foundation recently gave a $10 million grant to the Law and Neuroscience Project to determine how neuroscience will affect the law.