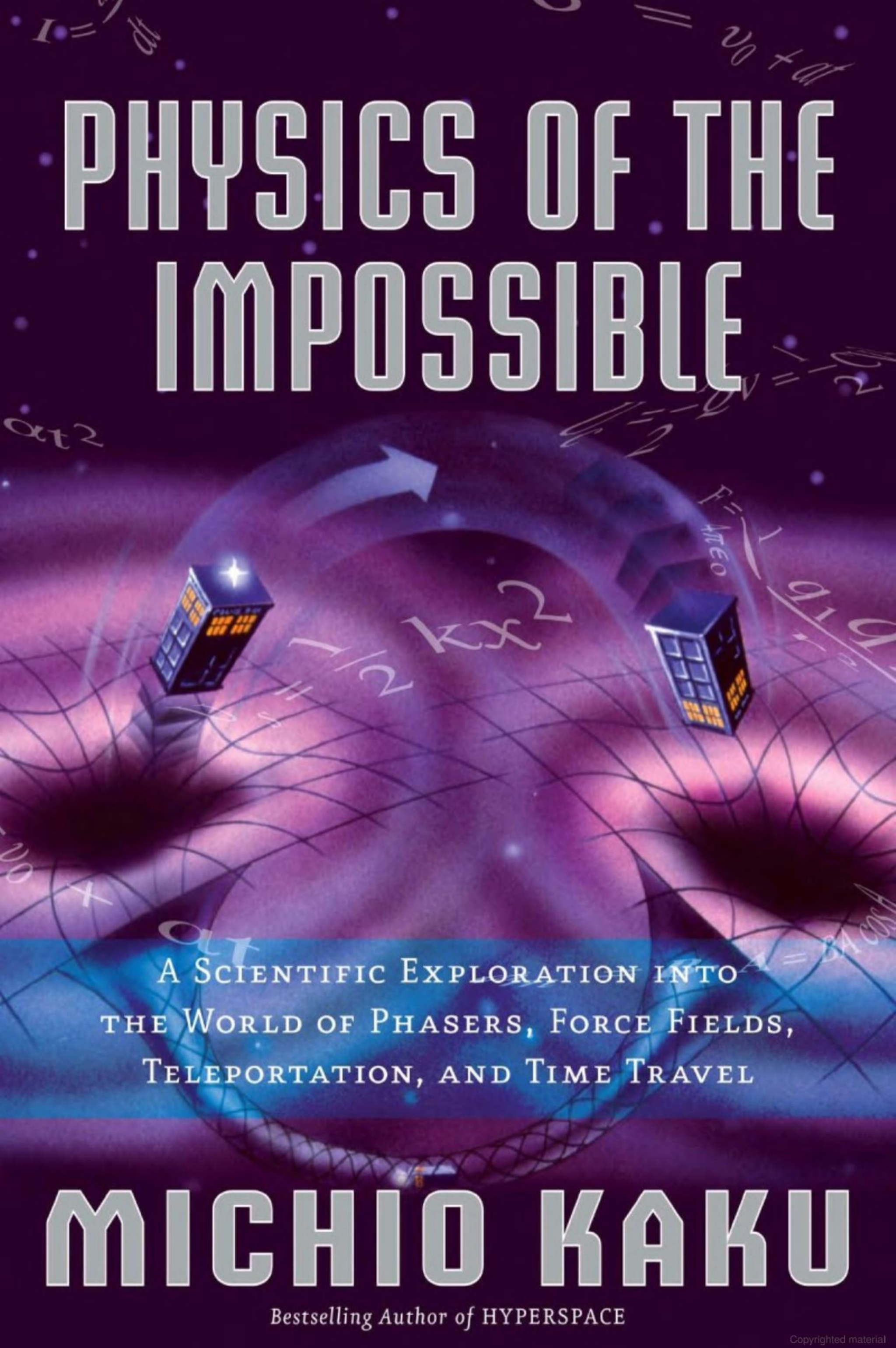
PHYSICS OF THE IMPOSSIBLE
A SCIENTIFIC EXPLORATION INTO THE WORLD OF PHASERS, FORCE FIELDS, TELEPORTATION, AND TIME TRAVEL
MICHIO KAKU
Bestselling Author of HYPERSPACE

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Michio Kaku

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PREFACE

If at first an idea does not sound absurd,
then there is no hope for it.
—ALBERT EINSTEIN

One day, would it be possible to walk through walls? To build starships that can travel faster than the speed of light? To read other people's minds? To become invisible? To move objects with the power of our minds? To transport our bodies instantly through outer space?

Since I was a child, I've always been fascinated by these questions. Like many physicists, when I was growing up, I was mesmerized by the possibility of time travel, ray guns, force fields, parallel universes, and the like. Magic, fantasy, science fiction were all a gigantic playground for my imagination. They began my lifelong love affair with the impossible.

I remember watching the old *Flash Gordon* reruns on TV. Every Saturday, I was glued to the TV set, marveling at the adventures of Flash, Dr. Zarkov, and Dale Arden and their dazzling array of futuristic technology: the rocket ships, invisibility shields, ray guns, and cities in the sky. I never missed a week. The program opened up an entirely new world for me. I was thrilled by the thought of one day rocketing to an alien planet and exploring its strange terrain. Being pulled into the orbit of these fantastic inventions I knew that my own destiny was somehow wrapped up with the marvels of the science that the show promised.

As it turns out, I was not alone. Many highly accomplished scientists originally became interested in science through exposure to science fiction. The great astronomer Edwin Hubble was fascinated by the works of Jules Verne. As a result of reading Verne's work, Hubble abandoned a promising career in law, and, disobeying his father's wishes, set off on a career in science. He eventually became the greatest astronomer of the twentieth century. Carl Sagan, noted astronomer and bestselling author, found his imagination set afire by reading Edgar Rice Burroughs's John Carter of Mars novels. Like John Carter, he dreamed of one day exploring the sands of Mars.

I was just a child the day when Albert Einstein died, but I remember people talking about his life, and death, in hushed tones. The next day I saw in the newspapers a picture of his desk, with the unfinished manuscript of his greatest, unfinished work. I asked myself, What could be so important that the greatest scientist of our time could not finish it? The article claimed that Einstein had an impossible dream, a problem so difficult that it was not possible for a mortal to finish it. It took me years to find out what that manuscript was about: a grand, unifying "theory of everything." His dream—which consumed the last three decades of his life—helped me to focus my own imagination. I wanted, in some small way, to be part of the effort to complete Einstein's work, to unify the laws of physics into a single theory.

As I grew older I began to realize that although Flash Gordon was the hero and always got the girl, it was the scientist who actually made the TV series work. Without Dr. Zarkov, there would be no rocket ship, no trips to Mongo, no saving Earth. Heroics aside, without science there is no science fiction.

I came to realize that these tales were simply impossible in terms of the science involved, just flights of the imagination. Growing up meant putting away such fantasy. In real life, I was told, one had to abandon the impossible and embrace the practical.

However, I concluded that if I was to continue my fascination with the impossible, the key was through the realm of physics. Without a solid background in advanced physics, I would be forever speculating about futuristic technologies without understanding whether or not they were possible. I realized I needed to immerse myself in advanced mathematics and learn theoretical physics. So that is what I did.

In high school for my science fair project I assembled an atom smasher in my mom's garage. I went to the Westinghouse company and gathered 400 pounds of scrap transformer steel. Over Christmas I wound 22 miles of copper wire on the high school football field. Eventually I built a 2.3-million-electron-volt betatron particle accelerator, which consumed 6 kilowatts of power (the entire output of my house) and generated a magnetic field of 20,000 times the Earth's magnetic field. The goal was to generate a beam of gamma rays powerful enough to create antimatter.

My science fair project took me to the National Science Fair and eventually fulfilled my dream, winning a scholarship to Harvard, where I could finally pursue my goal of becoming a theoretical physicist and follow in the footsteps of my role model, Albert Einstein.

Today I receive e-mails from science fiction writers and screenwriters asking me to help them sharpen their own tales by exploring the limits of the laws of physics.

The "Impossible" Is Relative

As a physicist, I have learned that the "impossible" is often a relative term. Growing up, I remember my teacher one day walking up to the map of the Earth on the wall and pointing out the coastlines of South America and Africa. Wasn't it an odd coincidence, she said, that the two coastlines fit together, almost like a jigsaw puzzle? Some scientists, she said, speculated that perhaps they were once part of the same, vast continent. But that was silly. No force could possibly push two gigantic continents apart. Such thinking was impossible, she concluded.

Later that year we studied the dinosaurs. Wasn't it strange, our teacher told us, that the dinosaurs dominated the Earth for millions of years, and then one day they all vanished? No one knew why they had all died off. Some paleontologists thought that maybe a meteor from space had killed them, but that was impossible, more in the realm of science fiction.

Today we now know that through plate tectonics the continents do move, and that 65 million years ago a gigantic meteor measuring six miles across most likely did obliterate the dinosaurs and much of life on Earth. In my own short lifetime I have seen the seemingly impossible become established scientific fact over and over again. So is it impossible to think we might one day be able to teleport ourselves from one place to another, or build a spaceship that will one day take us light-years away to the stars?

Normally such feats would be considered impossible by today's physicists. Might they become possible within a few centuries? Or in ten thousand years, when our technology is more advanced? Or in a million years? To put it another way, if we were to somehow encounter a civilization a million years more advanced than ours, would their everyday technology appear to be "magic" to us? That, at its heart, is one of the central questions running through this book; just because something is "impossible" today, will it remain impossible centuries or millions of years into the future?

Given the remarkable advances in science in the past century, especially the creation of the quantum theory and general relativity, it is now possible to give rough estimates of when, if ever, some of these fantastic technologies may be realized. With the coming of even more advanced theories, such as string theory, even concepts bordering on science fiction, such as time travel and parallel universes, are now being re-evaluated by physicists. Think back 150 years to those technological advances that were declared "impossible" by scientists at the time and that have now become part of our everyday lives. Jules Verne wrote a novel in 1863, *Paris in the Twentieth Century,* which was locked away and forgotten for over a century until it was accidentally discovered by his great-grandson and published for the first time in 1994. In it Verne predicted what Paris might look like in the year 1960. His novel was filled with technology that was clearly considered impossible in the nineteenth century, including fax machines, a worldwide communications network, glass skyscrapers, gas-powered automobiles, and high-speed elevated trains.

Not surprisingly, Verne could make such stunningly accurate predictions because he was immersed in the world of science, picking the brains of scientists around him. A deep appreciation for the fundamentals of science allowed him to make such startling predictions.

Sadly, some of the greatest scientists of the nineteenth century took the opposite position and declared any number of technologies to be hopelessly impossible. Lord Kelvin, perhaps the most prominent physicist of the Victorian era (he is buried next to Isaac Newton in Westminster Abbey), declared that "heavier than air" devices such as the airplane were impossible. He thought X-rays were a hoax and that radio had no future. Lord Rutherford, who discovered the nucleus of the atom, dismissed the possibility of building an atomic bomb, comparing it to "moonshine." Chemists of the nineteenth century declared the search for the philosopher's stone, a fabled substance that can turn lead into gold, a scientific dead end. Nineteenth-century chemistry was based on the fundamental immutability of the elements, like lead. Yet with today's atom smashers, we can, in principle, turn lead atoms into gold. Think how fantastic today's televisions, computers, and Internet would have seemed at the turn of the twentieth century.

More recently, black holes were once considered to be science fiction. Einstein himself wrote a paper in 1939 that "proved" that black holes could never form. Yet today the Hubble Space Telescope and the Chandra X-ray telescope have revealed thousands of black holes in space.

The reason that these technologies were deemed "impossibilities" is that the basic laws of physics and science were not known in the nineteenth century and the early part of the twentieth. Given the huge gaps in the understanding of science at the time, especially at the atomic level, it's no wonder such advances were considered impossible.

Studying the Impossible

Ironically, the serious study of the impossible has frequently opened up rich and entirely unexpected domains of science. For example, over the centuries the frustrating and futile search for a "perpetual motion machine" led physicists to conclude that such a machine was impossible, forcing them to postulate the conservation of energy and the three laws of thermodynamics. Thus the futile search to build perpetual motion machines helped to open up the entirely new field of thermodynamics, which in part laid the foundation of the steam engine, the machine age, and modern industrial society.

At the end of the nineteenth century, scientists decided that it was "impossible" for the Earth to be billions of years old. Lord Kelvin declared flatly that a molten Earth would cool down in 20 to 40 million years, contradicting the geologists and Darwinian biologists who claimed that the Earth might be billions of years old. The impossible was finally proven to be possible with the discovery of the nuclear force by Madame Curie and others, showing how the center of the Earth, heated by radioactive decay, could indeed be kept molten for billions of years.

We ignore the impossible at our peril. In the 1920s and 1930s Robert Goddard, the founder of modern rocketry, was the subject of intense criticism by those who thought that rockets could never travel in outer space. They sarcastically called his pursuit Goddard's Folly. In 1921 the editors of the *New York Times* railed against Dr. Goddard's work: "Professor Goddard does not know the relation between action and reaction and the need to have something better than a vacuum against which to react. He seems to lack the basic knowledge ladled out daily in high schools." Rockets were impossible, the editors huffed, because there was no air to push against in outer space. Sadly, one head of state did understand the implications of Goddard's "impossible" rockets–Adolf Hitler. During World War II, Germany's barrage of impossibly advanced V-2 rockets rained death and destruction on London, almost bringing it to its knees.

Studying the impossible may have also changed the course of world history. In the 1930s it was widely believed, even by Einstein, that an atomic bomb was "impossible." Physicists knew that there was a tremendous amount of energy locked deep inside the atom's nucleus, according to Einstein's equation $E = mc^2$, but the energy released by a single nucleus was too insignificant to consider. But atomic physicist Leo Szilard remembered reading the 1914 H. G. Wells novel, *The World Set Free,* in which Wells predicted the development of the atomic bomb. In the book he stated that the secret of the atomic bomb would be solved by a physicist in 1933. By chance Szilard stumbled upon this book in 1932. Spurred on by the novel, in 1933, precisely as predicted by Wells some two decades earlier, he hit upon the idea of magnifying the power of a single atom via a chain reaction, so that the energy of splitting a single uranium nucleus could be magnified by many trillions. Szilard then set into motion a series of key experiments and secret negotiations between Einstein and President Franklin Roosevelt that would lead to the Manhattan Project, which built the atomic bomb.

Time and again we see that the study of the impossible has opened up entirely new vistas, pushing the boundaries of physics and chemistry and forcing scientists to redefine what they mean by "impossible." As Sir William Osler once said, "The philosophies of one age have become the absurdities of the next, and the foolishness of yesterday has become the wisdom of tomorrow."

Many physicists subscribe to the famous dictum of T. H. White, who wrote in *The Once and Future King,* "Anything that is not forbidden, is mandatory!" In physics we find evidence of this all the time. Unless there is a law of physics explicitly preventing a new phenomenon, we eventually find that it exists. (This has happened several times in the search for new subatomic particles. By probing the limits of what is forbidden, physicists have often unexpectedly discovered new laws of physics.) A corollary to T. H. White's statement might well be, "Anything that is not impossible, is mandatory!"

For example, cosmologist Stephen Hawking tried to prove that time travel was impossible by finding a new law of physics that would forbid it, which he called the "chronology protection conjecture." Unfortunately, after many years of hard work he was unable to prove this principle. In fact, to the contrary, physicists have now demonstrated that a law that prevents time travel is beyond our present-day mathematics. Today, because there is no law of physics preventing the existence of time machines, physicists have had to take their possibility very seriously.

The purpose of this book is to consider what technologies are considered "impossible" today that might well become commonplace decades to centuries down the road.

Already one "impossible" technology is now proving to be possible: the notion of teleportation (at least at the level of atoms). Even a few years ago physicists would have said that sending or beaming an object from one point to another violated the laws of quantum physics. The writers of the original *Star Trek* television series, in fact, were so stung by the criticism from physicists that they added "Heisenberg compensators" to explain their teleporters in order to address this flaw. Today, because of a recent breakthrough, physicists can teleport atoms across a room or photons under the Danube River.

Predicting the Future

It is always a bit dangerous to make predictions, especially ones set centuries to thousands of years in the future. The physicist Niels Bohr was fond of saying, "Prediction is very hard to do. Especially about the future." But there is a fundamental difference between the time of Jules Verne and the present. Today the fundamental laws of physics are basically understood. Physicists today understand the basic laws extending over a staggering forty-three orders of magnitude, from the interior of the proton out to the expanding universe. As a result, physicists can state, with reasonable confidence, what the broad outlines of future technology might look like, and better differentiate between those technologies that are merely improbable and those that are truly impossible.

In this book, therefore, I divide the things that are "impossible" into three categories.

The first are what I call *Class I impossibilities.* These are technologies that are impossible today but that do not violate the known laws of physics. So they might be possible in this century, or perhaps the next, in modified form. They include teleportation, antimatter engines, certain forms of telepathy, psychokinesis, and invisibility.

The second category is what I term *Class II impossibilities.* These are technologies that sit at the very edge of our understanding of the physical world. If they are possible at all, they might be realized on a scale of millennia to millions of years in the future. They include time machines, the possibility of hyperspace travel, and travel through wormholes.

The final category is what I call *Class III impossibilities.* These are technologies that violate the known laws of physics. Surprisingly, there are very few such impossible technologies. If they do turn out to be possible, they would represent a fundamental shift in our understanding of physics.

This classification is significant, I feel, because so many technologies in science fiction are dismissed by scientists as being totally impossible, when what they actually mean is that they are impossible for a primitive civilization like ours. Alien visitations, for example, are usually considered impossible because the distances between the stars are so vast. While interstellar travel for our civilization is clearly impossible, it may be possible for a civilization centuries to thousands or millions of years ahead of ours. So it is important to rank such "impossibilities." Technologies that are impossible for our current civilization are not necessarily impossible for other types of civilizations. Statements about what is possible and impossible have to take into account technologies that are millennia to millions of years ahead of ours.

Carl Sagan once wrote, "What does it mean for a civilization to be a million years old? We have had radio telescopes and spaceships for a few decades; our technical civilization is a few hundred years old . . . an advanced civilization millions of years old is as much beyond us as we are beyond a bush baby or a macaque."

In my own research I focus professionally on trying to complete Einstein's dream of a "theory of everything." Personally, I find it quite exhilarating to work on a "final theory" that may ultimately answer some of the most difficult "impossible" questions in science today, such as whether time travel is possible, what lies at the center of a black hole, or what happened before the big bang. I still daydream about my lifelong love affair with the impossible, and wonder when and if some of these impossibilities might enter the ranks of the everyday.

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Part I

CLASS I IMPOSSIBILITIES

1: FORCE FIELDS

I. When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.

II. The only way of discovering the limits of the possible is to venture a little way past them into the impossible.

III. Any sufficiently advanced technology is indistinguishable from magic.

—ARTHUR C. CLARKE'S THREE LAWS

"Shields up!"

In countless *Star Trek* episodes this is the first order that Captain Kirk barks out to the crew, raising the force fields to protect the starship *Enterprise* against enemy fire.

So vital are force fields in *Star Trek* that the tide of the battle can be measured by how the force field is holding up. Whenever power is drained from the force fields, the *Enterprise* suffers more and more damaging blows to its hull, until finally surrender is inevitable.

So what is a force field? In science fiction it's deceptively simple: a thin, invisible yet impenetrable barrier able to deflect lasers and rockets alike. At first glance a force field looks so easy that its creation as a battlefield shield seems imminent. One expects that any day some enterprising inventor will announce the discovery of a defensive force field. But the truth is far more complicated.

In the same way that Edison's lightbulb revolutionized modern civilization, a force field could profoundly affect every aspect of our lives. The military could use force fields to become invulnerable, creating an impenetrable shield against enemy missiles and bullets. Bridges, superhighways, and roads could in theory be built by simply pressing a button. Entire cities could sprout instantly in the desert, with skyscrapers made entirely of force fields. Force fields erected over cities could enable their inhabitants to modify the effects of their weather–high winds, blizzards, tornados–at will. Cities could be built under the oceans within the safe canopy of a force field. Glass, steel, and mortar could be entirely replaced.

Yet oddly enough a force field is perhaps one of the most difficult devices to create in the laboratory. In fact, some physicists believe it might actually be impossible, without modifying its properties.

Michael Faraday

The concept of force fields originates from the work of the great nineteenth-century British scientist Michael Faraday.

Faraday was born to working-class parents (his father was a blacksmith) and eked out a meager existence as an apprentice bookbinder in the early 1800s. The young Faraday was fascinated by the enormous breakthroughs in uncovering the mysterious properties of two new forces: electricity and magnetism. Faraday devoured all he could concerning these topics and attended lectures by Professor Humphrey Davy of the Royal Institution in London.

One day Professor Davy severely damaged his eyes in a chemical accident and hired Faraday to be his secretary. Faraday slowly began to win the confidence of the scientists at the Royal Institution and was allowed to conduct important experiments of his own, although he was often slighted. Over the years Professor Davy grew increasingly jealous of the brilliance shown by his young assistant, who was a rising star in experimental circles, eventually eclipsing Davy's own fame. After Davy died in 1829 Faraday was free to make a series of stunning breakthroughs that led to the creation of generators that would energize entire cities and change the course of world civilization.

The key to Faraday's greatest discoveries was his "force fields." If one places iron filings over a magnet, one finds that the iron filings create a spiderweb-like pattern that fills up all of space. These are Faraday's lines of force, which graphically describe how the force fields of electricity and magnetism permeate space. If one graphs the magnetic fields of the Earth, for example, one finds that the lines emanate from the north polar region and then fall back to the Earth in the south polar region. Similarly, if one were to graph the electric field lines of a lightning rod in a thunderstorm, one would find that the lines of force concentrate at the tip of the lightning rod. Empty space, to Faraday, was not empty at all, but was filled with lines of force that could make distant objects move. (Because of Faraday's poverty-stricken youth, he was illiterate in mathematics, and as a consequence his notebooks are full not of equations but of hand-drawn diagrams of these lines of force. Ironically, his lack of mathematical training led him to create the beautiful diagrams of lines of force that now can be found in any physics textbook. In science a physical picture is often more important than the mathematics used to describe it.)

Historians have speculated on how Faraday was led to his discovery of force fields, one of the most important concepts in all of science. In fact, the *sum total of all modern physics* is written in the language of Faraday's fields. In 1831, he made the key breakthrough regarding force fields that changed civilization forever. One day, he was moving a child's magnet over a coil of wire and he noticed that he was able to generate an electric current in the wire, without ever touching it. This meant that a magnet's invisible field could push electrons in a wire across empty space, creating a current.

Faraday's "force fields," which were previously thought to be useless, idle doodlings, were real, material forces that could move objects and generate power. Today the light that you are using to read this page is probably energized by Faraday's discovery about electromagnetism.

A spinning magnet creates a force field that pushes the electrons in a wire, causing them to move in an electrical current. This electricity in the wire can then be used to light up a lightbulb. This same principle is used to generate electricity to power the cities of the world. Water flowing across a dam, for example, causes a huge magnet in a turbine to spin, which then pushes the electrons in a wire, forming an electric current that is sent across high-voltage wires into our homes.

In other words, the force fields of Michael Faraday are the forces that drive modern civilization, from electric bulldozers to today's computers, Internet, and iPods.

Faraday's force fields have been an inspiration for physicists for a century and a half. Einstein was so inspired by them that he wrote his theory of gravity in terms of force fields. I, too, was inspired by Faraday's work. Years ago I successfully wrote the theory of strings in terms of the force fields of Faraday, thereby founding string field theory. In physics when someone says, "He thinks like a line of force," it is meant as a great compliment.

The Four Forces

Over the last two thousand years one of the crowning achievements of physics has been the isolation and identification of the four forces that rule the universe. All of them can be described in the language of fields introduced by Faraday. Unfortunately, however, none of them has quite the properties of the force fields described in most science fiction. These forces are

1. *Gravity*, the silent force that keeps our feet on the ground, prevents the Earth and the stars from disintegrating, and holds the solar system and galaxy together. Without gravity, we would be flung off the Earth into space at the rate of 1,000 miles per hour by the spinning planet. The problem is that gravity has precisely the opposite properties of a force field found in science fiction. Gravity is attractive, not repul-

sive; is extremely weak, relatively speaking; and works over enormous, astronomical distances. In other words, it is almost the opposite of the flat, thin, impenetrable barrier that one reads about in science fiction or one sees in science fiction movies. For example, it takes the entire planet Earth to attract a feather to the floor, but we can counteract Earth's gravity by lifting the feather with a finger. The action of our finger can counteract the gravity of an entire planet that weighs over six trillion trillion kilograms.

2. *Electromagnetism* (EM), the force that lights up our cities. Lasers, radio, TV, modern electronics, computers, the Internet, electricity, magnetism–all are consequences of the electromagnetic force. It is perhaps the most useful force ever harnessed by humans. Unlike gravity, it can be both attractive and repulsive. However, there are several reasons that it is unsuitable as a force field. First, it can be easily neutralized. Plastics and other insulators, for example, can easily penetrate a powerful electric or magnetic field. A piece of plastic thrown in a magnetic field would pass right through. Second, electromagnetism acts over large distances and cannot easily be focused onto a plane. The laws of the EM force are described by James Clerk Maxwell's equations, and these equations do not seem to admit force fields as solutions.

3 & 4. *The weak and strong nuclear forces.* The weak force is the force of radioactive decay. It is the force that heats up the center of the Earth, which is radioactive. It is the force behind volcanoes, earthquakes, and continental drift. The strong force holds the nucleus of the atom together. The energy of the sun and the stars originates from the nuclear force, which is responsible for lighting up the universe. The problem is that the nuclear force is a short-range force, acting mainly over the distance of a nucleus. Because it is so bound to the properties of nuclei, it is extremely hard to manipulate. At present the only ways we

have of manipulating this force are to blow subatomic particles apart in atom smashers or to detonate atomic bombs.

Although the force fields used in science fiction may not conform to the known laws of physics, there are still loopholes that might make the creation of such a force field possible. First, there may be a fifth force, still unseen in the laboratory. Such a force might, for example, work over a distance of only a few inches to feet, rather than over astronomical distances. (Initial attempts to measure the presence of such a fifth force, however, have yielded negative results.)

Second, it may be possible to use a plasma to mimic some of the properties of a force field. A plasma is the "fourth state of matter." Solids, liquids, and gases make up the three familiar states of matter, but the most common form of matter in the universe is plasma, a gas of ionized atoms. Because the atoms of a plasma are ripped apart, with electrons torn off the atom, the atoms are electrically charged and can be easily manipulated by electric and magnetic fields.

Plasmas are the most plentiful form of visible matter in the universe, making up the sun, the stars, and interstellar gas. Plasmas are not familiar to us because they are only rarely found on the Earth, but we can see them in the form of lightning bolts, the sun, and the interior of your plasma TV.

Plasma Windows

As noted above, if a gas is heated to a high enough temperature, thereby creating a plasma, it can be molded and shaped by magnetic and electrical fields. It can, for example, be shaped in the form of a sheet or window. Moreover, this "plasma window" can be used to separate a vacuum from ordinary air. In principle, one might be able to prevent the air within a spaceship from leaking out into space, thereby creating a convenient, transparent interface between outer space and the spaceship.

In the *Star Trek* TV series, such a force field is used to separate the shuttle bay, containing small shuttle craft, from the vacuum of outer space. Not only is it a clever way to save money on props, but it is a device that is possible.

The plasma window was invented by physicist Ady Herschcovitch in 1995 at the Brookhaven National Laboratory in Long Island, New York. He developed it to solve the problem of how to weld metals using electron beams. A welder's acetylene torch uses a blast of hot gas to melt and then weld metal pieces together. But a beam of electrons can weld metals faster, cleaner, and more cheaply than ordinary methods. The problem with electron beam welding, however, is that it needs to be done in a vacuum. This requirement is quite inconvenient, because it means creating a vacuum box that may be as big as an entire room.

Dr. Herschcovitch invented the plasma window to solve this problem. Only 3 feet high and less than 1 foot in diameter, the plasma window heats gas to 12,000°F, creating a plasma that is trapped by electric and magnetic fields. These particles exert pressure, as in any gas, which prevents air from rushing into the vacuum chamber, thus separating air from the vacuum. (When one uses argon gas in the plasma window, it glows blue, like the force field in *Star Trek.*)

The plasma window has wide applications for space travel and industry. Many times, manufacturing processes need a vacuum to perform microfabrication and dry etching for industrial purposes, but working in a vacuum can be expensive. But with the plasma window one can cheaply contain a vacuum with the flick of a button.

But can the plasma window also be used as an impenetrable shield? Can it withstand a blast from a cannon? In the future, one can imagine a plasma window of much greater power and temperature, sufficient to damage or vaporize incoming projectiles. But to create a more realistic force field, like that found in science fiction, one would need a combination of several technologies stacked in layers. Each layer might not be strong enough alone to stop a cannon ball, but the combination might suffice.

The outer layer could be a supercharged plasma window, heated to temperatures high enough to vaporize metals. A second layer could be a curtain of high-energy laser beams. This curtain, containing thousands of crisscrossing laser beams, would create a lattice that would heat up objects that passed through it, effectively vaporizing them. I will discuss lasers further in the next chapter.

And behind this laser curtain one might envision a lattice made of "carbon nanotubes," tiny tubes made of individual carbon atoms that are one atom thick and that are many times stronger than steel. Although the current world record for a carbon nanotube is only about 15 millimeters long, one can envision a day when we might be able to create carbon nanotubes of arbitrary length. Assuming that carbon nanotubes can be woven into a lattice, they could create a screen of enormous strength, capable of repelling most objects. The screen would be invisible, since each carbon nanotube is atomic in size, but the carbon nanotube lattice would be stronger than any ordinary material.

So, via a combination of plasma window, laser curtain, and carbon nanotube screen, one might imagine creating an invisible wall that would be nearly impenetrable by most means.

Yet even this multilayered shield would not completely fulfill all the properties of a science fiction force field–because it would be transparent and therefore incapable of stopping a laser beam. In a battle with laser cannons, the multilayered shield would be useless.

To stop a laser beam, the shield would also need to possess an advanced form of "photochromatics." This is the process used in sunglasses that darken by themselves upon exposure to UV radiation. Photochromatics are based on molecules that can exist in at least two states. In one state the molecule is transparent. But when it is exposed to UV radiation it instantly changes to the second form, which is opaque.

One day we might be able to use nanotechnology to produce a substance as tough as carbon nanotubes that can change its optical properties when exposed to laser light. In this way, a shield might be able to stop a laser blast as well as a particle beam or cannon fire. At present, however, photochromatics that can stop laser beams do not exist.

Magnetic Levitation

In science fiction, force fields have another purpose besides deflecting ray-gun blasts, and that is to serve as a platform to defy gravity. In the movie *Back to the Future,* Michael J. Fox rides a "hover board," which resembles a skateboard except that it floats over the street. Such an antigravity device is impossible given the laws of physics as we know them today (as we will see in Chapter 10). But magnetically enhanced hover boards and hover cars could become a reality in the future, giving us the ability to levitate large objects at will. In the future, if "room-temperature superconductors" become a reality, one might be able to levitate objects using the power of magnetic force fields.

If we place two bar magnets next to each other with north poles opposite each other, the two magnets repel each other. (If we rotate the magnet, so that the north pole is close to the other south pole, then the two magnets attract each other.) This same principle, that north poles repel each other, can be used to lift enormous weights off the ground. Already several nations are building advanced magnetic levitation trains (maglev trains) that hover just above the railroad tracks using ordinary magnets. Because they have zero friction, they can attain record-breaking speeds, floating over a cushion of air.

In 1984 the world's first commercial automated maglev system began operation in the United Kingdom, running from Birmingham International Airport to the nearby Birmingham International railway station. Maglev trains have also been built in Germany, Japan, and Korea, although most of them have not been designed for high velocities. The first commercial maglev train operating at high velocities is the initial operating segment (IOS) demonstration line in Shanghai, which travels at a top speed of 268 miles per hour. The Japanese maglev train in Yamanashi prefecture attained a velocity of 361 miles per hour, even faster than the usual wheeled trains.

But these maglev devices are extremely expensive. One way to increase efficiency would be to use superconductors, which lose all electrical resistance when they are cooled down to near absolute zero. Superconductivity was discovered in 1911 by Heike Onnes. If certain substances are cooled to below 20 K above absolute zero, all electrical resistance is lost. Usually when we cool down the temperature of a metal, its resistance decreases gradually. (This is because random vibrations of the atom impede the flow of electrons in a wire. By reducing the temperature, these random motions are reduced, and hence electricity flows with less resistance.) But much to Onnes's surprise, he found that the resistance of certain materials fell abruptly to zero at a critical temperature.

Physicists immediately recognized the importance of this result. Power lines lose a significant amount of energy by transporting electricity across long distances. But if all resistance could be eliminated, electrical power could be transmitted almost for free. In fact, if electricity were made to circulate in a coil of wire, the electricity would circulate for millions of years, without any reduction in energy. Furthermore, magnets of incredible power could be made with little effort from these enormous electric currents. With these magnets, one could lift huge loads with ease.

Despite all these miraculous powers, the problem with superconductivity is that it is very expensive to immerse large magnets in vats of supercooled liquid. Huge refrigeration plants are required to keep liquids supercooled, making superconducting magnets prohibitively expensive.

But one day physicists may be able to create a "room-temperature superconductor," the holy grail of solid-state physicists. The invention of room-temperature superconductors in the laboratory would spark a second industrial revolution. Powerful magnetic fields capable of lifting cars and trains would become so cheap that hover cars might become economically feasible. With room-temperature superconductors, the fantastic flying cars seen in *Back to the Future, Minority Report,* and *Star Wars* might become a reality.

In principle, one might be able to wear a belt made of superconducting magnets that would enable one to effortlessly levitate off the ground. With such a belt, one could fly in the air like Superman. Room-temperature superconductors are so remarkable that they appear in numerous science fiction novels (such as the Ringworld series written by Larry Niven in 1970).

For decades physicists have searched for room-temperature superconductors without successs. It has been a tedious, hit-or-miss process, testing one material after another. But in 1986 a new class of substances called "high-temperature superconductors" was found that became superconductors at about 90 degrees above absolute zero, or 90 K, creating a sensation in the world of physics. The floodgates seemed to open. Month after month, physicists raced one another to break the next world's record for a superconductor. For a brief moment it seemed as if the possibility of room-temperature superconductors would leap off the pages of science fiction novels and into our living rooms. But after a few years of moving at breakneck speed, research in high-temperature superconductors began to slow down.

At present the world's record for a high-temperature superconductor is held by a substance called mercury thallium barium calcium copper oxide, which becomes superconducting at 138 K (–135°C). This relatively high temperature is still a long way from room temperature. But this 138 K record is still important. Nitrogen liquefies at 77 K, and liquid nitrogen costs about as much as ordinary milk. Hence ordinary liquid nitrogen could be used to cool down these high-temperature superconductors rather cheaply. (Of course, room-temperature superconductors would need no cooling whatsoever.)

Embarrassingly enough, at present there is no theory explaining the properties of these high-temperature superconductors. In fact, a Nobel Prize is awaiting the enterprising physicist who can explain how high-temperature superconductors work. (These high-temperature superconductors are made of atoms arranged in distinctive layers. Many physicists theorize that this layering of the ceramic material makes it possible for electrons to flow freely within each layer, creating a superconductor. But precisely how this is done is still a mystery.)

Because of this lack of knowledge, physicists unfortunately resort to a hit-or-miss procedure to search for new high-temperature superconductors. This means that the fabled room-temperature superconductor may be discovered tomorrow, next year, or not at all. No one knows when, or if, such a substance will ever be found.

But if room-temperature superconductors are discovered, a tidal wave of commercial applications could be set off. Magnetic fields that are a million times more powerful than the Earth's magnetic field (which is .5 gauss) might become commonplace.

One common property of superconductivity is called the Meissner effect. If you place a magnet above a superconductor, the magnet will levitate, as if held upward by some invisible force. (The reason for the Meissner effect is that the magnet has the effect of creating a "mirror-image" magnet within the superconductor, so that the original magnet and the mirror-image magnet repel each other. Another way to see this is that magnetic fields cannot penetrate into a superconductor. Instead, magnetic fields are expelled. So if a magnet is held above a superconductor, its lines of force are expelled by the superconductor, and the lines of force then push the magnet upward, causing it to levitate.)

Using the Meissner effect, one can imagine a future in which the highways are made of these special ceramics. Then magnets placed in our belts or our tires could enable us to magically float to our destination, without any friction or energy loss.

The Meissner effect works only on magnetic materials, such as metals. But it is also possible to use superconducting magnets to levitate nonmagnetic materials, called paramagnets and diamagnets. These substances do not have magnetic properties of their own; they acquire their magnetic properties only in the presence of an external magnetic field. Paramagnets are attracted by an external magnet, while diamagnets are repelled by an external magnet.

Water, for example, is a diamagnet. Since all living things are made of water, they can levitate in the presence of a powerful magnetic field. In a magnetic field of about 15 teslas (30,000 times the Earth's field), scientists have levitated small animals, such as frogs. But if room-temperature superconductors become a reality, it should be possible to levitate large nonmagnetic objects as well, via their diamagnetic property.

In conclusion, force fields as commonly described in science fiction do not fit the description of the four forces of the universe. Yet it may be possible to simulate many of the properties of force fields by using a multilayered shield, consisting of plasma windows, laser curtains, carbon nanotubes, and photochromatics. But developing such a shield could be many decades, or even a century, away. And if room-temperature superconductors can be found, one might be able to use powerful magnetic fields to levitate cars and trains and soar in the air, as in science fiction movies.

Given these considerations, I would classify force fields as a Class I impossibility–that is, something that is impossible by today's technology, but possible, in modified form, within a century or so.

2 : INVISIBILITY

You cannot depend on your eyes when
your imagination is out of focus.

—MARK TWAIN

In *Star Trek IV: The Voyage Home,* a Klingon battle cruiser is hijacked by the crew of the *Enterprise.* Unlike the starships in the Federation Star Fleet, the starships of the Klingon Empire have a secret "cloaking device" that renders them invisible to light or radar, so that Klingon ships can sneak up behind Federation starships and ambush them with impunity. This cloaking device has given the Klingon Empire a strategic advantage over the Federation of Planets.

Is such a device really possible? Invisibility has long been one of the marvels of science fiction and fantasy, from the pages of *The Invisible Man,* to the magic invisibility cloak of the Harry Potter books, or the ring in *The Lord of the Rings.* Yet for at least a century, physicists have dismissed the possibility of invisibility cloaks, stating flatly that they are impossible: They violate the laws of optics and do not conform to any of the known properties of matter.

But today the impossible may become possible. New advances in "metamaterials" are forcing a major revision of optics textbooks. Working prototypes of such materials have actually been built in the laboratory, sparking intense interest by the media, industry, and the military in making the visible become invisible.

Invisibility Throughout History

Invisibility is perhaps one of the oldest concepts in ancient mythology. Since the advent of recorded history, people who have been alone on a creepy night have been frightened by the invisible spirits of the dead, the souls of the long-departed lurking in the dark. The Greek hero Perseus was able to slay the evil Medusa armed with the helmet of invisibility. Military generals have dreamed of an invisibility cloaking device. Being invisible, one could easily penetrate enemy lines and capture the enemy by surprise. Criminals could use invisibility to pull off spectacular robberies.

Invisibility played a central part in Plato's theory of ethics and morality. In his philosophical masterpiece, *The Republic*, Plato recounts the myth of the ring of Gyges. The poor but honest shepherd Gyges of Lydia enters a hidden cave and finds a tomb containing a corpse wearing a golden ring. Gyges discovers that this golden ring has the magical power to make him invisible. Soon this poor shepherd is intoxicated with the power this ring gives him. After sneaking into the king's palace, Gyges uses his power to seduce the queen and, with her help, murder the king and become the next King of Lydia.

The moral that Plato wished to draw out is that no man can resist the temptation of being able to steal and kill at will. All men are corruptible. Morality is a social construct imposed from the outside. A man may appear to be moral in public to maintain his reputation for integrity and honesty, but once he possesses the power of invisibility, the use of such power would be irresistible. (Some believe that this morality tale was the inspiration for J. R. R. Tolkien's Lord of the Rings trilogy, in which a ring that grants the wearer invisibility is also a source of evil.)

Invisibility is also a common plot device in science fiction. In the *Flash Gordon* series of the 1930s, Flash becomes invisible in order to escape the firing squad of Ming the Merciless. In the Harry Potter novels and movies, Harry dons a special cloak that allows him to roam Hogwarts Castle undetected.

H. G. Wells put much of this mythology into concrete form with his classic novel *The Invisible Man,* in which a medical student accidentally discovers the power of the fourth dimension and becomes invisible. Unfortunately, he uses this fantastic power for private gain, starts a wave of petty crimes, and eventually dies desperately trying to evade the police.

Maxwell's Equations and the Secret of Light

It was not until the work of Scottish physicist James Clerk Maxwell, one of the giants of nineteenth-century physics, that physicists had a firm understanding of the laws of optics. Maxwell, in some sense, was the opposite of Michael Faraday. Whereas Faraday had superb experimental instincts but no formal training whatsoever, Maxwell, a contemporary of Faraday, was a master of advanced mathematics. He excelled as a student of mathematical physics at Cambridge, where Isaac Newton had done his work two centuries earlier.

Newton had invented the calculus, which was expressed in the language of "differential equations," which describe how objects smoothly undergo infinitesimal changes in space and time. The motion of ocean waves, fluids, gases, and cannon balls could all be expressed in the language of differential equations. Maxwell set out with a clear goal, to express the revolutionary findings of Faraday and his force fields through precise differential equations.

Maxwell began with Faraday's discovery that electric fields could turn into magnetic fields and vice versa. He took Faraday's depictions of force fields and rewrote them in the precise language of differential equations, producing one of the most important series of equations in modern science. They are a series of eight fierce-looking differential equations. Every physicist and engineer in the world has to sweat over them when mastering electromagnetism in graduate school.

Next, Maxwell asked himself the fateful question: if magnetic fields can turn into electric fields and vice versa, what happens if they are constantly turning into each other in a never-ending pattern? Maxwell found that these electric-magnetic fields would create a wave, much like an ocean wave. To his astonishment, he calculated the speed of these waves and found it to be the speed of light! In 1864, upon discovering this fact, he wrote prophetically: "This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself . . . is an electromagnetic disturbance."

It was perhaps one of the greatest discoveries in human history. For the first time the secret of light was finally revealed. Maxwell suddenly realized that everything from the brilliance of the sunrise, the blaze of the setting sun, the dazzling colors of the rainbow, and the firmament of stars in the heavens could be described by the waves he was scribbling on a sheet of paper. Today we realize that the entire electromagnetic spectrum–from radar to TV, infrared light, visible light, ultraviolet light, X-rays, microwaves, and gamma rays–is nothing but Maxwell waves, which in turn are vibrating Faraday force fields.

Commenting on the importance of Maxwell's equations, Einstein wrote that they are "the most profound and the most fruitful that physics has experienced since the time of Newton."

(Tragically, Maxwell, one of the greatest physicists of the nineteenth century, died at the early age of forty-eight of stomach cancer, probably the very same disease that killed his mother at the same age. If he had lived longer, he might have discovered that his equations allowed for distortions of space-time that would lead directly to Einstein's relativity theory. It is staggering to realize that relativity might possibly have been discovered at the time of the American Civil War had Maxwell lived longer.)

Maxwell's theory of light and the atomic theory give simple explanations for optics and invisibility. In a solid, the atoms are tightly packed, while in a liquid or gas the molecules are spaced much farther apart. Most solids are opaque because light rays cannot pass through the dense matrix of atoms in a solid, which act like a brick wall. Many liquids and gases, by contrast, are transparent because light can pass more readily between the large spaces between their atoms, a space that is larger than the wavelength of visible light. For example, water, alcohol, ammonia, acetone, hydrogen peroxide, gasoline, and so forth are all transparent, as are gases such as oxygen, hydrogen, nitrogen, carbon dioxide, methane, and so on.

There are some important exceptions to this rule. Many crystals are both solid and transparent. But the atoms of a crystal are arranged in a precise lattice structure, stacked in regular rows, with regular spacing between them. Hence there are many pathways that a light beam may take through a crystalline lattice. Therefore, although a crystal is as tightly packed as any solid, light can still work its way through the crystal.

Under certain circumstances, a solid object may become transparent if the atoms are arranged randomly. This can be done by heating certain materials to a high temperature and then rapidly cooling them. Glass, for example, is a solid with many properties of a liquid because of the random arrangement of its atoms. Certain candies can become transparent via this method as well.

Clearly, invisibility is a property that arises at the atomic level, via Maxwell's equations, and hence would be exceedingly difficult, if not impossible, to duplicate using ordinary means. To make Harry Potter invisible, one would have to liquefy him, boil him to create steam, crystallize him, heat him again, and then cool him, all of which would be quite difficult to accomplish, even for a wizard.

The military, unable to create invisible airplanes, has tried to do the next best thing: create stealth technology, which renders airplanes invisible to radar. Stealth technology relies on Maxwell's equations to create a series of tricks. A stealth fighter jet is perfectly visible to the human eye, but its radar image on an enemy radar screen is only the size of a large bird. (Stealth technology is actually a hodgepodge of tricks. By changing the materials within the jet fighter, reducing its steel content and using plastics and resins instead, changing the angles of its fuselage, rearranging its exhaust pipes, and so on, one can make enemy radar beams hitting the craft disperse in all directions, so they never get back to the enemy radar screen. Even with stealth technology, a jet fighter is not totally invisible; rather, it has deflected and dispersed as much radar as is technically possible.)

Metamaterials and Invisibility

But perhaps the most promising new development involving invisibility is an exotic new material called a "metamaterial," which may one day render objects truly invisible. Ironically, the creation of metamaterials was once thought to be impossible because they violated the laws of optics. But in 2006 researchers at Duke University in Durham, North Carolina, and Imperial College in London successfully defied conventional wisdom and used metamaterials to make an object invisible to microwave radiation. Although there are still many hurdles to overcome, for the first time in history we now have a blueprint to render ordinary objects invisible. (The Pentagon's Defense Advanced Research Projects Agency [DARPA] funded this research.)

Nathan Myhrvold, former chief technology officer at Microsoft, says the revolutionary potential of metamaterials "will completely change the way we approach optics and nearly every aspect of electronics . . . Some of these metamaterials can perform feats that would have seemed miraculous a few decades ago."

What are these metamaterials? They are substances that have optical properties not found in nature. Metamaterials are created by embedding tiny implants within a substance that force electromagnetic waves to bend in unorthodox ways. At Duke University, scientists embedded tiny electrical circuits within copper bands that are arranged in flat, concentric circles (somewhat resembling the coils of an electric oven). The result was a sophisticated mixture of ceramic, Teflon, fiber composites, and metal components. These tiny implants in the copper make it possible to bend and channel the path of microwave radiation in a specific way. Think about the way a river flows around a boulder. Because the water quickly wraps around the boulder, the presence of the boulder has been washed out downstream. Similarly, metamaterials can continuously alter and bend the path of microwaves so that they flow around a cylinder, for example, essentially making everything inside the cylinder invisible to microwaves. If the metamaterial can eliminate all reflection and shadows, then it can render an object totally invisible to that form of radiation.

Scientists successfully demonstrated this principle with a device made of ten fiberglass rings covered with copper elements. A copper ring inside the device was rendered nearly invisible to microwave radiation, casting only a minuscule shadow.

At the heart of metamaterials is their ability to manipulate something called the "index of refraction." Refraction is the bending of light as it moves through transparent media. If you put your hand in water, or look through the lens of your glasses, you notice that water and glass distort and bend the path of ordinary light.

The reason that light bends in glass or water is that light slows down when it enters a dense, transparent medium. The speed of light in a pure vacuum always remains the same, but light traveling through glass or water must pass through trillions of atoms and hence slows down. (The speed of light divided by the slower speed of light inside the medium is called the index of refraction. Since light slows down in glass, the index of refraction is always greater than 1.0). For example, the index of refraction is 1.00 for a vacuum, 1.0003 for air, 1.5 for glass, and 2.4 for diamond. Usually, the denser the medium, the greater the degree of bending, and the greater the index of refraction.

A familiar example of the index of refraction is a mirage. If you are driving on a hot day and look straight toward the horizon, the road may seem to be shimmering, creating the illusion of a glistening lake. In the desert one can sometimes see the outlines of distant cities and mountains on the horizon. This is because hot air rising from the pavement or desert has a lower density than normal air, and hence a lower index of refraction than the surrounding, colder air, and therefore light from distant objects can be refracted off the pavement into your eye, giving you the illusion that you are seeing distant objects.

Usually, the index of refraction is a constant. A narrow beam of light is bent when it enters glass and then keeps going in a straight line. But assume for the moment that you could control the index of refraction at will, so that it could change continuously at every point in the glass. As light moved in this new material, light could bend and meander in new directions, creating a path that would wander throughout the substance like a snake.

present, the smallest components that one can create with this etching process are about 30 nm (or about 150 atoms across).

A milestone in the quest for invisibility came when this silicon wafer etching technology was used by a group of scientists to create the first metamaterial that operates in the visible range of light. Scientists in Germany and at the U.S. Department of Energy announced in early 2007 that, for the first time in history, they had fabricated a metamaterial that worked for red light. The "impossible" had been achieved in a remarkably short time.

Physicist Costas Soukoulis of the Ames Laboratory in Iowa, with Stefan Linden, Martin Wegener, and Gunnar Dolling of the University of Karlsruhe, Germany, were able to create a metamaterial that had an index of –.6 for red light, at a wavelength of 780 nm. (Previously, the world record for radiation bent by a metamaterial was 1,400 nm, which put it outside the range of visible light, in the range of infrared.)

The scientists first started with a glass sheet, and then deposited a thin coating of silver, magnesium fluoride, and then another layer of silver, forming a "sandwich" of fluoride that was only 100 nm thick. Then, using standard etching techniques, they created a large array of microscopic square holes in the sandwich, creating a grid pattern resembling a fishnet. (The holes are only 100 nm wide, much smaller than the wavelength of red light.) Then they passed a red light beam through the material and measured its index, which was –.6.

These physicists foresee many applications of this technology. Metamaterials "may one day lead to the development of a type of flat superlens that operates in the visible spectrum," says Dr. Soukoulis. "Such a lens would offer superior resolution over conventional technology, capturing details much smaller than one wavelength of light." The immediate application of such a "superlens" would be to photograph microscopic objects with unparalleled clarity, such as the inside of a living human cell, or to diagnose diseases in a baby inside the womb. Ideally one would be able to obtain photographs of the components of a DNA molecule without having to use clumsy X-ray crystallography.

So far these scientists have demonstrated a negative index of refraction only for red light. Their next step would be to use this technology to create a metamaterial that would bend red light entirely around an object, rendering it invisible to that light.

Future developments along these lines may occur in the area of "photonic crystals." The goal of photonic crystal technology is to create a chip that uses light, rather than electricity, to process information. This entails using nanotechnology to etch tiny components onto a wafer, such that the index of refraction changes with each component. Transistors using light have several advantages over those using electricity. For example, there is much less heat loss for photonic crystals. (In advanced silicon chips, the heat generated is enough to fry an egg. Thus they must be continually cooled down or else they will fail, and keeping them cool is very costly.) Not surprisingly, the science of photonic crystals is ideally suited for metamaterials, since both technologies involve manipulating the index of refraction of light at the nanoscale.

Invisibility via Plasmonics

Not to be outdone, yet another group announced in mid-2007 that they have created a metamaterial that bends visible light using an entirely different technology, called "plasmonics." Physicists Henri Lezec, Jennifer Dionne, and Harry Atwater at the California Institute of Technology announced that they had created a metamaterial that had a negative index for the more difficult blue-green region of the visible spectrum of light.

The goal of plasmonics is to "squeeze" light so that one can manipulate objects at the nanoscale, especially on the surface of metals. The reason metals conduct electricity is that electrons are loosely bound to metal atoms, so they can freely move along the surface of the metal lattice. The electricity flowing in the wires in your home represents the smooth flow of these loosely bound electrons on the metal surface. But under certain conditions, when a light beam collides with the metal surface, the electrons can vibrate in unison with the original light beam, creating wavelike motions of the electrons on the metal surface (called plasmons), and these wavelike motions beat in unison with the original light beam. More important, one can "squeeze" these plasmons so that they have the same frequency as the original beam (and hence carry the same information) but have a much smaller wavelength. In principle, one might then cram these squeezed waves onto nanowires. As with photonic crystals, the ultimate goal of plasmonics is to create computer chips that compute using light, rather than electricity.

The Cal Tech group built their metamaterial out of two layers of silver, with a silicon-nitrogen insulator in between (with a thickness of only 50 nm), which acted as a "waveguide" that could shepherd the direction of the plasmonic waves. Laser light enters and exits the apparatus via two slits carved into the metamaterial. By analyzing the angles at which the laser light is bent as it passes through the metamaterial, one can then verify that the light is being bent via a negative index.

The Future of Metamaterials

Progress in metamaterials will accelerate in the future for the simple reason that there is already intense interest in creating transistors that use light beams rather than electricity. Research in invisibility can therefore "piggyback" on the ongoing research in photonic crystals and plasmonics for creating replacements for the silicon chip. Already hundreds of millions of dollars are being invested in creating replacements for silicon technology, and research in metamaterials will benefit from these research efforts.

With breakthroughs occurring in this field every few months, it's not surprising that some physicists see some sort of practical invisibility shield emerging out of the laboratory perhaps within a few decades. In the next few years, for example, scientists are confident that they will be able to create metamaterials that can render an object totally invisible for one frequency of visible light, at least in two dimensions. To do this would require embedding tiny nano implants not in regular arrays, but in sophisticated patterns so that light would bend smoothly around an object.

Next, scientists will have to create metamaterials that can bend light in three dimensions, not just for flat two-dimensional surfaces. Photolithography has been perfected for making flat silicon wafers, but creating three-dimensional metamaterials will require stacking wafers in a complex fashion.

After that, scientists will have to solve the problem of creating metamaterials that can bend not just one frequency but many. This will be perhaps the most difficult task, since the tiny implants that have been devised so far bend light of only one precise frequency. Scientists may have to create metamaterials based on layers, with each layer bending a specific frequency. The solution to this problem is not clear.

Nevertheless, once an invisibility shield is finally made, it might be a clunky device. Harry Potter's cloak was made of thin, flexible cloth and rendered anyone draped inside invisible. But for this to be possible the index of refraction inside the cloth would have to be constantly changing in complex ways as it fluttered, which is impractical. More than likely a true invisibility "cloak" would have to be made of a solid cylinder of metamaterials, at least initially. That way the index of refraction could be fixed inside the cylinder. (More advanced versions could eventually incorporate metamaterials that are flexible and can twist and still make light flow within the metamaterials on the correct path. In this way, anyone inside the cloak would have some flexibility of movement.)

Some have pointed out a flaw in the invisibility shield: anyone inside would not be able to look outside without becoming visible. Imagine Harry Potter being totally invisible except for his eyes, which appear to be floating in midair. Any eye holes on the invisibility cloak would be clearly visible from the outside. If Harry Potter were totally invisible, then he would be sitting blindly beneath his invisibility cloak. (One possible solution to this problem might be to insert two tiny glass plates near the location of the eye holes. These glass plates would act as "beam splitters," splitting off a tiny portion of the light hitting the plates, and then sending the light into the eyes. So most of the light hitting the cloak would flow around it, rendering the person invisible, but a tiny amount of light would be diverted into the eyes.)

As daunting as these difficulties are, scientists and engineers are optimistic that an invisibility shield of some sort can be built in the coming decades.

Invisibility and Nanotechnology

As I mentioned earlier, the key to invisibility may be nanotechnology, that is, the ability to manipulate atomic-sized structures about a billionth of a meter across.

The birth of nanotechnology dates back to a famous 1959 lecture given by Nobel laureate Richard Feynman to the American Physical Society, with the tongue-in-cheek title "There's Plenty of Room at the Bottom." In that lecture he speculated on what the smallest machines might look like, consistent with the known laws of physics. He realized that machines could be built smaller and smaller until they hit atomic distances, and then atoms could be used to create other machines. Atomic machines, such as pulleys, levers, and wheels, were well within the laws of physics, he concluded, though they would be exceedingly difficult to make.

Nanotechnology languished for years, because manipulating individual atoms was beyond the technology of the time. But then physicists made a breakthrough in 1981, with the invention of the scanning tunneling microscope, which won the Nobel Prize in Physics for scientists Gerd Binnig and Heinrich Rohrer, working at the IBM lab in Zurich.

Suddenly physicists were able to obtain stunning "pictures" of individual atoms arrayed just as in the chemistry books, something that critics of the atomic theory once considered impossible. Gorgeous photographs of atoms lined up in a crystal or metal were now possible. The chemical formulae used by scientists, with a complex series of atoms wrapped up in a molecule, could be seen with the naked eye. Moreover, the scanning tunneling microscope made possible the mavideo projector that lights up the front of the cloak, so it appears as if light has passed through the person.

Prototypes of the optical camouflage cloak actually exist in the lab. If you look directly at a person wearing this screenlike cloak, it appears as if the person has disappeared, because all you see is the image behind the person. But if you move your eyes a bit, the image on the cloak does not change, which tells you that it is a fake. A more realistic optical camouflage would need to create the illusion of a 3-D image. For this, one would need holograms.

A hologram is a 3-D image created by lasers (like the 3-D image of Princess Leia in *Star Wars*). A person could be rendered invisible if the background scenery was photographed with a special holographic camera and the holographic image was then projected out through a special holographic screen placed in front of the person. A viewer standing in front of that person would see the holographic screen, containing the 3-D image of the background scenery, minus the person. It would appear as if the person had disappeared. In that person's place would be a precise 3-D image of the background scenery. Even if you moved your eyes, you would not be able to tell that what you were seeing was fake.

These 3-D images are made possible because laser light is "coherent," that is, all the waves are vibrating in perfect unison. Holograms are produced by making a coherent laser beam split in two pieces. Half of the beam shines on a photographic film. The other half illuminates an object, bounces off, and then shines on the same photographic film. When these two beams interfere on the film, an interference pattern is created that encodes all the information of the original 3-D wave. The film, when developed, doesn't look like much, just an intricate spiderweb pattern of whirls and lines. But when a laser beam is allowed to shine on this film, an exact 3-D replica of the original object suddenly appears as if by magic.

The technical problems with holographic invisibility are formidable, however. One challenge is to create a holographic camera that is capable of taking at least 30 frames per second. Another problem is storing and processing all the information. Finally, one would need to project this image onto a screen so that the image looks realistic.

Invisibility via the Fourth Dimension

We should also mention that an even more sophisticated way of becoming invisible was mentioned by H. G. Wells in *The Invisible Man*, and it involved using the power of the fourth dimension. (Later in the book I will discuss in more detail the possible existence of higher dimensions.) Could we perhaps leave our three-dimensional universe and hover over it from the vantage point of a fourth dimension? Like a three-dimensional butterfly hovering over a two-dimensional sheet of paper, we would be invisible to anyone living in the universe below us. One problem with this idea is that higher dimensions have not yet been proven to exist. Moreover, a hypothetical journey to a higher dimension would require energies far beyond anything attainable with our current technology. As a viable way to achieve invisibility, this method is clearly beyond our knowledge and ability today.

Given the enormous strides made so far in achieving invisibility, it clearly qualifies as a Class I impossibility. Within the next few decades, or at least within this century, a form of invisibility may become commonplace.

3: PHASERS AND DEATH STARS

Radio has no future. Heavier-than-air flying machines are impossible. X-rays will prove to be a hoax.

–PHYSICIST LORD KELVIN, 1899

The (atomic) bomb will never go off. I speak as an expert in explosives.

–ADMIRAL WILLIAM LEAHY

4–3–2–1, fire!

The Death Star is a colossal weapon, the size of an entire moon. Firing point-blank at the helpless planet Alderaan, home world of Princess Leia, the Death Star incinerates it, causing it to erupt in a titanic explosion, sending planetary debris hurtling throughout the solar system. A billion souls scream out in anguish, creating a disturbance in the Force felt throughout the galaxy.

But is the Death Star weapon of the *Star Wars* saga really possible? Could such a weapon channel a battery of laser cannons to vaporize an entire planet? What about the famous light sabers wielded by Luke Skywalker and Darth Vader that can slice through reinforced steel yet are made of beams of light? Are ray guns, like the phasers in *Star Trek*, viable weapons for future generations of law enforcement officers and soldiers?

In *Star Wars* millions of moviegoers were dazzled by these original, stunning special effects, but they fell flat for some critics, who panned them, stating that all this was in good fun, but it was patently impossible. Moon-sized, planet-busting ray guns are outlandish, and so are swords made of solidified light beams, even for a galaxy far, far away, they chanted. George Lucas, the master of special effects, must have gotten carried away this time.

Although this may be difficult to believe, the fact is there is no physical limit to the amount of raw energy that can be crammed onto a light beam. There is no law of physics preventing the creation of a Death Star or light sabers. In fact, planet-busting beams of gamma radiation exist in nature. The titanic burst of radiation from a distant gamma ray burster in deep space creates an explosion second only to the big bang itself. Any planet unfortunate enough to be within the crosshairs of a gamma ray burster will indeed be fried or blown to bits.

Beam Weapons Through History

The dream of harnessing beams of energy is actually not new but is rooted in ancient mythology and lore. The Greek god Zeus was famous for unleashing lightning bolts on mortals. The Norse god Thor had a magic hammer, Mjolnir, which could fire bolts of lightning, while the Hindu god Indra was known for firing beams of energy from a magic spear.

The concept of using rays as a practical weapon probably began with the work of the great Greek mathematician Archimedes, perhaps the greatest scientist in all of antiquity, who discovered a crude version of calculus two thousand years ago, before Newton and Leibniz. In one legendary battle against the forces of Roman general Marcellus during the Second Punic War in 214 BC, Archimedes helped to defend the kingdom of Syracuse and is believed to have created large batteries of solar reflectors that focused the sun's rays onto the sails of enemy ships, setting them ablaze. (There is still debate even today among scientists as to whether this was a practical, working beam weapon; various teams of scientists have tried to duplicate this feat with differing results.)

Ray guns burst onto the science fiction scene in 1889 with H. G. Wells's classic *War of the Worlds,* in which aliens from Mars devastate entire cities by shooting beams of heat energy from weapons mounted on their tripods. During World War II, the Nazis, always eager to exploit the latest advances in technology to conquer the world, experimented with various forms of ray guns, including a sonic device, based on parabolic mirrors, that could focus intense beams of sound.

Weapons created from focused light beams entered the public imagination with the James Bond movie *Goldfinger,* the first Hollywood film to feature a laser. (The legendary British spy was strapped onto a metal table as a powerful laser beam slowly advanced, gradually melting the table between his legs and threatening to slice him in half.)

Physicists originally scoffed at the idea of the ray guns featured in Wells's novel because they violated the laws of optics. According to Maxwell's equations, the light we see around us rapidly disperses and is incoherent (i.e., it is a jumble of waves of different frequencies and phases). It was once thought that coherent, focused, uniform beams of light, as we find with laser beams, were impossible to create.

The Quantum Revolution

All this changed with the coming of the quantum theory. At the turn of the twentieth century it was clear that although Newton's laws and Maxwell's equations were spectacularly successful in explaining the motion of the planets and the behavior of light, they could not explain a whole class of phenomena. They failed miserably to explain why materials conduct electricity, why metals melt at certain temperatures, why gases emit light when heated, why certain substances become superconductors at low temperatures—all of which requires an understanding of the internal dynamics of atoms. The time was ripe for a

(Picture a line of dominoes. Dominoes in their lowest energy state lie flat on a table. Dominoes in a high-energy, pumped-up state stand up vertically, similar to the pumped-up atoms in the medium. If you push one domino, you can trigger a sudden collapse of all this energy at once, just as in a laser beam.)

Only certain materials will "lase," that is, it is only in special materials that when a photon hits a pumped-up atom a photon will be emitted that is coherent with the original photon. As a result of this coherence, in this flood of photons all the photons are vibrating in unison, creating a pencil-thin laser beam. (Contrary to myth, the laser beam does not stay pencil-thin forever. A laser beam fired onto the moon, for example, will gradually expand until it creates a spot a few miles across.)

A simple gas laser consists of a tube of helium and neon gas. When electricity is sent through the tube the atoms are energized. Then, if the energy is suddenly released all at once, a beam of coherent light is produced. The beam is amplified by using two mirrors, one placed at either end, so the beam bounces back and forth between them. One mirror is completely opaque, but the other allows a tiny amount of light to escape on each pass, producing a beam that shoots out one end.

Today lasers are found almost everywhere, from grocery store checkout stands, to fiber-optic cables carrying the Internet, to laser printers and CD players, to modern computers. They are also used in eye surgery, to remove tattoos, and even in cosmetic salons. Over $5.4 billion worth of lasers were sold worldwide in 2004.

Types of Lasers and Fusion

New lasers are being discovered almost every day as new materials are found that can lase, and as new ways are discovered for pumping energy into the medium.

The question is, are any of these technologies suitable for building a ray gun or a light saber? Is it possible to build a laser powerful enough to energize a Death Star? Today a bewildering variety of lasers exist, depending on the material that lases and the energy that is injected into the material (e.g., electricity, intense beams of light, even chemical explosions). Among them are

- *Gas lasers.* These lasers include helium-neon lasers, which are very common, creating a familiar red beam. They are energized by radio waves or electricity. Helium-neon lasers are quite weak. But carbon dioxide gas lasers can be used for blasting, cutting, and welding in heavy industry and can create beams of enormous power that are totally invisible.
- *Chemical lasers.* These powerful lasers are energized by a chemical reaction, such as a burning jet of ethylene and nitrogen trifluoride, or NF_3. Such lasers are powerful enough to be used in military applications. Chemical lasers are used in the U.S. military's airborne and ground lasers, which can produce millions of watts of power, and are designed to shoot down short-range missiles in midflight.
- *Excimer lasers.* These lasers are also powered by chemical reactions, often involving an inert gas (e.g., argon, krypton, or xenon) and fluorine or chlorine. They produce ultraviolet light and can be used to etch tiny transistors onto chips in the semiconductor industry, or for delicate Lasik eye surgery.
- *Solid-state lasers.* The first working laser ever made consisted of a chromium-sapphire ruby crystal. A large variety of crystals will support a laser beam, in conjunction with yttrium, holmium, thulium, and other chemicals. They can produce high-energy ultrashort pulses of laser light.
- *Semiconductor lasers.* Diodes, which are commonly used in the semiconductor industry, can produce the intense beams used in industrial cutting and welding. They are also often found in checkout stands in grocery stores, reading the bar codes of your grocery items.
- *Dye lasers.* These lasers use organic dyes as their me-

dium. They are exceptionally useful in terms of creating ultra-short pulses of light, often lasting only trillionths of a second.

LASERS AND RAY GUNS?

Given the enormous variety of commercial lasers and the power of military lasers, why don't we have ray guns available for use in combat and on the battlefield? Ray guns of one sort or another seem to be standard-issue weaponry in science fiction movies. Why aren't we working to create them?

The simple answer is the lack of a portable power pack. One would need miniature power packs that contain the power of a huge electrical power station yet are small enough to fit on your palm. At present the only way to harness the power of a large commercial power station is to build one. At present the smallest portable military device that can contain vast amounts of energy is a miniature hydrogen bomb, which might destroy you as well as the target.

There is a second, ancillary problem as well–the stability of the lasing material. Theoretically, there is no limit to the energy one can concentrate on a laser. The problem is that the lasing material in a handheld ray gun would not be stable. Crystal lasers, for example, will overheat and crack if too much energy is pumped into them. Hence to create an extremely powerful laser, the kind that might vaporize an object or neutralize a foe, one might need to use the power of an explosion. In that case, the stability of the lasing material is not such a limitation, since such a laser would be used only once.

Because of the problems in creating a portable power pack and a stable lasing material, building a handheld ray gun is not possible with today's technology. Ray guns are possible, but only if they are connected by a cable to a power supply. Or perhaps with nanotechnology we might be able to create miniature batteries that store or generate enough energy to create the intense bursts of energy required of a handheld device. At present, as we have seen, nanotechnology is quite