

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 thou-

sands 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 ap-

pear 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 success. 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 supercon-

ductor 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 fic-

tion 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.