V. Fusion Primer—Part One

Understanding Fusion: For Space Travel, New Industries, and Universal Electrical Power

by Ned Rosinsky, MD

This article is intended as a primer for the layman in fusion power. It is the first of three parts.

Part I: Metrics and Varieties of Fusion Energy

Introduction

July 20—A stunning advance in fusion research has repeatedly occurred at Lawrence Livermore National Laboratory (LLNL) for the past 19 months: the production of more energy from a fusion reaction than was put into the reaction. LLNL is the only place in the world that has accomplished this feat. This occurred on 5 occasions from 12/5/2022 to 2/12/2024. Initially 2.05 megajoules of energy were put into the fuel, and 3.15 megajoules were produced by the fusion reaction. Most recently 2.2 megajoules were put in and 5.2 megajoules were produced. One megajoule is the amount of energy that would be used to lift 100 tons approximately 3 feet above the surface of the Earth. The reaction occurred in a pellet of fusion fuel, irradiated with 192 lasers to heat and compress it to burn conditions. For the several billionths of a second that the pellet was irradiated, the energy flow into the pellet was equivalent to that of the entire energy grid of the United States.

At a press conference held at the U.S. Department of Energy on 12/13/2022, one week after the initial fusion success, DOE Secretary Jennifer Granholm called the fusion outcome "One of the most impressive scientific feats of the 21st Century, on a par with the Wright Brothers' first flight at Kitty Hawk." Kim Budil, Director of the LLNL, said at the press conference:

NASA

Figure 1a
Speeds of fusion-driven space rockets will make planetary missions possible; they will be far higher than the speeds of the missions driven by the chemical fuels which have been used since the Apollo Program—here, an Apollo 17 spacewalk in 1972.

> I think it's [fusion] moving into the foreground and, probably with concerted effort and investment, a few decades of research on the underlying technologies could put us in a position to build a power plant).[1]

At a follow-up interview with Reid Hoffman on

1: Secretary of Energy Jennifer Granholm, press release of 12/13/2022, "A shot for the ages: Fusion ignition breakthrough hailed as 'one of the most impressive scientific feats of the 21st century'."

"Possible Podcast" on 7/25/23, Budil stated:

> If the country decided to invest $50 billion over 10 years, then maybe we'd have fusion power on the grid in 20 years.[2]

It is noted that LLNL got $2.7 billion in total annual Federal funding in 2023 for all departments, mostly for strategic weapons lab testing and monitoring. The LLNL fusion program got $16 million in Federal funding in 2023, so this program is severely underfunded.

However, apparently due to the LLNL success and other advancements, private investment into fusion research has surged in the past two years. Such investment has been $4.6 billion worldwide, resulting in a total public-private investment of $6.2 billion. The total number of fusion companies increased from 33 in 2022 to 43 in 2023. Most fusion companies are in the United States. Commonwealth Fusion Systems, General Fusion, TAE Technologies, and Tokamak Energy are four companies that account for 85% of the total investment.

Although private company fusion research is growing explosively, most of the population lacks a basic understanding of what fusion energy is, or how it may be produced. This article aims to provide an overview for the layman of the basic physics involved.

Fusion Promise and Parameters

Fusion has the potential to greatly increase the availability of energy. It is safer than the currently available fission nuclear energy. There are several possible fuels for fusion, and most are readily available at a low cost. Fusion would make a virtually unlimited amount of energy available for major projects, such as lifting the standard of living in Africa by massive desalination of water to green the deserts and increase food production. The energy could be used to build and repair roads, ports, schools, hospitals, and housing. The entire cultural level of the world would be uplifted by the scientific advancements associated with fusion energy, including rapid space travel to the Moon or to a planet (**Figure 1a**).

The main difficulty with building fusion reactors is that the fuel must be heated to a very high temperature, in the range of 100 million degrees Kelvin (K) or more. (100 million degrees K is 180 million degrees Fahrenheit [F]). In addition, some machines require that the pressure must be elevated, and that these conditions must be sustained for a certain amount of time.

The temperature required would destroy any solid container holding the fuel. There are two main approaches to deal with this problem. The first is to put the fuel inside a small solid pellet shell, and then heat the pellet very quickly on all sides with lasers to vaporize the pellet material, causing the pellet material to explode in all directions. This causes the enclosed fuel to react by suddenly recoiling in an opposite direction from the exploding pellet, but because the pellet is set up to explode equally in all directions, the fuel is condensed into a very small space at the center of the pellet. This condensation is equivalent to decreasing a basketball to the size of a pea, but in this case the pellet starts out only 0.5 to 5 millimeters in diameter. This squeezing of the fuel, combined with the heat of the lasers, increases its density and temperature to what is needed for fusion.

This is called inertial confinement fusion. (Inertia is the tendency of matter to remain unchanged in its motion (or rest) unless a force is applied.) This is the type of fusion machine used by Lawrence Livermore in the recent breakthrough.

The second approach for producing fusion is magnetic confinement, which may be fully developed much sooner than inertial confinement. This approach uses magnetic fields to suspend the fuel, so it does not contact the walls of the reactor. As a simple example, think of two magnets suspending a piece of iron between them in midair, with the iron not touching the magnets. Most fusion machines under development around the world are using this approach. There are no high-powered lasers involved, and it is potentially easier than with inertial confinement to produce a longer fusion burn.

2: Statement by Kimberly S. Budil, PhD, Director of Lawrence Livermore National Laboratory, during a 60-minute interview with Reid Hoffman on "Possible Podcast", also called "Possible, Realizing Fusion Energy" and titled "Dr. Kim Budil on the Future of Fusion (full audio)". In this hour-long interview on 7/25/2023, Dr. Budil provides an overview of laser fusion at Lawrence Livermore National Laboratory, as well as a discussion of the spinoffs of science, the role of science in society, and the excitement of participating in scientific advancement. When asked by the interviewer to provide an estimate of when her program might be able to provide energy on the grid, she said "If the country decided to invest $20 billion over 10 years, then maybe we'd have fusion power on the grid in 20 years." She made this statement approximately 18 minutes, 50 seconds into the interview.

Please note that there are several different interviews and partial interviews with Dr. Budil with similar titles. The one with the above quote is here. A transcript is available here.

Most of the current magnetic confinement machines are tokamaks, in which a cylinder that confines the fuel is curved around to form a donut shape (torus). The heated fuel travels around inside the torus, and it is held in place away from the walls by a magnetic field. Tokamaks usually heat fuels with beams of neutral particles, and usually burn fuels that produce neutrons when they react. Energetic neutrons are harmful to humans and damage the walls of the experimental fusion machines trying to contain them.

Another type of machine uses a straight cylinder to confine the fuel. It creates a magnetic field within the cylinder to contain the fuel, in what is called a field-reversed configuration (FRC). It heats the fuel with radio frequency electromagnetic radiation rather than with neutral particles. These machines operate at a higher temperature than tokamaks, so they can use fuels and reactions that do not produce neutrons, and therefore they do not need heavy shields, and are lighter than Tokamaks.

A machine of this type is being developed at Princeton University: the Princeton Field-Reversed Configuration (PFRC). The Princeton machine is more efficient in heating compared to other FRC fusion machines, due to the way it uses radiation to heat the fuel (discussed below); it is therefore considered the world leader among FRC machines. A 1-megawatt machine would be small enough to be mounted on a military Heavy Expanded Mobile Tactical Truck (HEMTT), which has a capacity of ten tons (**Figure 1b**). Therefore, it can be moved easily to severely distressed areas of disaster or poverty.

The PFRC could also be used as a rocket engine for travel to the Moon, Mars, or other planets. Princeton Fusion Systems, the manufacturer of this machine, plans to have a working commercial rocket engine machine in 6-7 years. For these reasons, I will describe the Princeton FRC magnetic confinement fusion machine in some detail in the third and last installment of this article.

To provide the background needed for a general understanding of inertial and magnetic confinement, I will start with a summary of the basic measurement units in physics in **Section 1**: mass, length, and time. I will show how these three basic units can be used to produce the units of force, work and energy. I will then review electricity and magnetism using a simple device, the electromagnet.

Section 1: Mass, Length, and Time

Objects have mass, and mass is measured in two ways, either by weight or inertia. Weight is the force of gravity on the mass, and it is measured in pounds. This use of weight is suitable most of the time in our daily activities. However, in the weightlessness of space, we need another way to measure an object's mass.

A constant measure for mass is inertia, which, as noted above, is the tendency of the motion of a mass, or its rest, to remain unchanged unless a force is applied. Even in outer space, objects retain their inertial mass.

www.princetonfusionsysstems.com

Figure 1b
The Princeton Fusion Engine will be rapidly transportable to areas of disaster or economic need. This artist's rendering shows it mounted on a military HEMTT truck.

In a rocket in space, a large piece of iron may float. But to get it to move requires a force applied to the object. And once it starts moving, to stop the motion requires another force to be applied in the opposite direction.

The kilogram (kg) is the unit of mass in the International System of Units (the metric system), referred to by its French acronym SI. One kilogram of mass weighs 2.2 pounds at the surface of the Earth.

The SI measures length in meters (m), with one meter equal to approximately 39 inches, and measures time in seconds.

Although mass, length and time appear as separate and distinct, there is an underlying reality concerning these units which is far more interesting. Physicist John Archibald Wheeler famously provided a layman's glimpse into Einstein's General Relativity by stating "mass tells space-time how to curve, and curved space-time tells mass how to move." These effects are extremely small in ordinary experience on Earth, but they become important when planning space expeditions which must deal with rapid travel over long distances, with large masses such as planets, and with extended time frames, such as years, for flights. As an example, when an astronaut circles the Earth, his or her wristwatch will slow, so the astronaut loses several seconds of time with each revolution.

This kind of back-and-forth between mass and space-time, which could be understood as having a form similar to a dialogue, can lead to interesting development effects, such as those that support galaxy formation. Lyndon LaRouche elaborated on this point in his article on music, "That which Underlies Motivic Thorough-Composition".[3] We will see something akin to this duet process in the development of plasma structures arising from interactions between electric currents and magnetic fields, described later in this article.

Force, Work and Energy

There are several other units that are derived from the above. A force is a push on an object that can result in a change in the motion of the object, if there is no opposition to the force. The change in motion is called acceleration. In SI units, force is measured in newtons (N). One newton is the force required to increase the motion of one kilogram of mass one by 1 meter per second, for each second that the force is applied. For example, if a car of mass 2,000 kg is already moving at 10 meters per second, a force required to accelerate the car to a speed of 11 meters per second (increase the speed by 1 meter per second) could be 2,000 N applied for 1 second (2000 x 1), or 1,000 N applied for 2 seconds.

Force has both an amount and a direction. It is therefore called a vector. Vectors can be shown in diagrams with arrows. The point where the force is applied is where the arrow originates. The strength of the force is modeled as the length of the arrow. The direction of the force is the direction of the arrow.

Velocity is also a vector, having two components, speed and direction. And acceleration is a vector; change of speed is called longitudinal acceleration, and change of direction is radial acceleration. We will see these forms of acceleration used to create "magnetic bottles" to confine superhot plasmas in fusion machines, described in a subsequent article in this series.

Work is the force applied to an object over a certain distance of its motion, measured as the amount of force times the distance that the object is moved in the direction of the force. Work is measured in joules (J). One joule is one newton of force moving an object for one meter. If a car is pushed with 1,000 newtons of force for 5 meters, this constitutes 5,000 joules of work.

Rate of work is measured in watts (W). One watt is one joule of work per second, so a 1 megawatt (1 MW) nuclear fission plant produces 1 million joules per second. To get a sense of what is required on the energy grid, conventional fission reactors produce approximately 1 billion joules per second, which is 1 gigawatt (1 GW). A small fission reactor produces 300 MW (300 million joules/sec), and a small city uses approximately 500 MW (500 million joules of work per second).

Energy is measured in watt-hours (Wh), the number of hours that 1 watt is being provided. A 100-watt light bulb that is on for 5 hours consumes 500 Wh of energy. Since 1 watt is 1 joule of work per second, and there are 3,600 seconds per hour, 1 watt-hour is 3,600 joules. One thousand watts is 1 kilowatt (kW), and the monthly energy use in a household utility bill is usually measured in kWh.

Composition of Masses

Fusion involves the combination of masses to produce enormous amounts of energy, so a brief description of masses is needed. Masses are made of very small quantities called atoms. One atom of hydrogen, the smallest element, is a tenth of a billionth of a meter in diameter, a length which is called an angstrom. Atoms are composed of particles, such as electrons, protons and neutrons. An electron's diameter is unclear due to the electron behaving as both a particle and a wave. An atom has a central nucleus which is made of protons and neutrons, and the nucleus is surrounded by a cloud of electrons. The nucleus is on average one hundred thousandth the diameter of the atom.

Protons and electrons have the property of electric charge. Protons have positive charge, and electrons have negative charge. Charged particles create electric fields surrounding themselves. Protons create an electric field pointing in straight lines away from the proton in all directions. Electrons create a negative electric field around themselves, with the direction of the field being in straight lines pointing toward the electron from all directions. An electric field can be modeled by

3: LaRouche, Lyndon. "That Which Underlies Motivic Thorough-Composition," *Executive Intelligence Review*, 1995, Vol 22, No. 35, pp. 50-63.

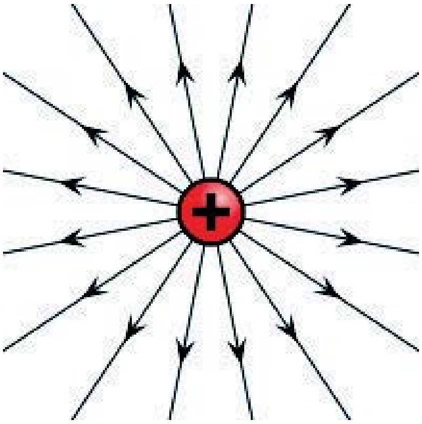

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Figure 2a
Electrical field lines emanating from a positive charge such as a proton. The field is shown as a set of arrows. A positive electrically charged particle has an electric field that points away from the particle in all directions. The field cannot be seen directly, but its effects can be observed and measured, for example, by the motion of dust particles. The field does not change if the particle is in motion.

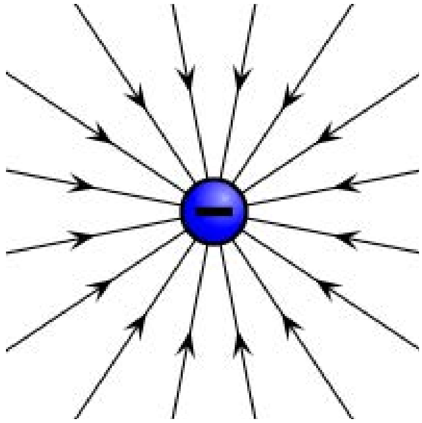

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Figure 2b
Electrical field lines surrounding a negative charge, such as an electron. The direction of the field is towards the charge.

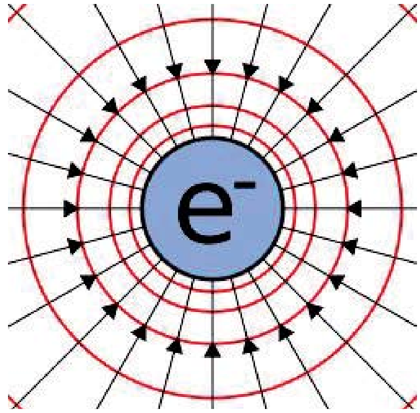

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Figure 2c
The strength of the electric field around an electron is visualized as the spacing of the potential circles. As the circles get closer to the electron, the field lines get closer to each other, indicating that the field is stronger near the electron than it is at a greater distance from the electron.

drawing arrows from chosen points in the field, with the length of the arrow representing the strength of the field at the chosen point, and the direction of the arrow representing the direction of the field at that point (**Figures 2a-2c**).

Two particles with the same charge repel each other, with the repulsive force acting along the electric field lines. Two particles with opposite charges attract each other, with the force acting along the field lines. These forces occur whether the charged particles are moving or not, and the strength of the interaction is not affected by motion of the particles. The force depends on the strength of the electric field and the amount of charge on the particle.

Neutrons have no charge. Since an atomic nucleus is composed of protons and neutrons, the nucleus has an overall positive charge.

There are several physical units of measurement related to charged particles. The quantity of charge is measured in coulombs (C), with one coulomb being approximately 6.2 x 10^{18} times the charge of a proton (10^{18} is a billion billion). One ampere (A) is the flow of 1 coulomb of electric charge moving past a point in 1 second. The strength of a magnetic field is measured in tesla (T), with one tesla being the force of one newton on a one-meter wire carrying one ampere of current perpendicular to the field. A smaller unit of magnetic field is the gauss, 1 ten-thousandth of a tesla. The magnetic field at the surface of the Earth is approximately 0.5 gauss.

There are 118 chemical elements, such as hydrogen, helium, lithium, carbon, oxygen, iron, and uranium. As indicated above, an atom of each type of element contains a nucleus made of protons and neutrons. The number of protons determines the element, while variations in the number of neutrons determine the isotopes of the element. Isotopes of an element are referred to by giving the mass number of the nucleus, the total number of protons and neutrons—for example, carbon-14, which contains 6 protons and 8 neutrons.

Fusion involves the nuclei from two atoms of a relatively light element, such as hydrogen, its deuterium and tritium isotopes, or helium, combining to produce one or two nuclei of other elements—possibly along with other particles, and with electromagnetic radiation such as x-rays. Fusion can release enormous amounts of energy. However, because the nuclei intended for a fusion reaction are both positively charged, they repel each other, so some force is needed to bring them close enough together to combine.

That force comes from moving the atoms rapidly, so they crash into each other, and this is done by heating the atoms to high temperatures where some of the elec-

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Figure 3a
An electromagnet, showing the wiring wrapped around a metal core. The ends of the wire are attached to the positive and negative ends of a battery, which sends an electric current through the wire. The magnet has north and south poles.

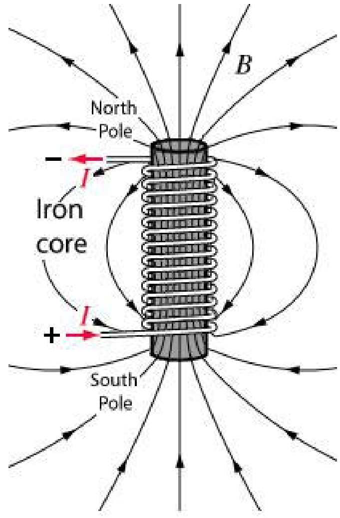

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Figure 3b
The total picture of an electromagnet shows the wire wrapped around the core, an electric current being sent through the wire, and the resulting magnetic field (labeled B) as shown by the field lines.

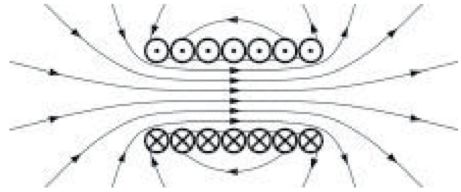

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Figure 3c
Cross section of the electromagnet through the axis of the coil. The wrapped wires are shown in cross sections; the current flowing through circles marked with an X is moving away from the viewer. The circles marked with a dot represent current flowing towards the viewer. The electromagnet produces a magnetic field, which has a strength and direction everywhere around the magnet. The lines and arrows show the location and direction of the magnetic field.

trons separate from the atoms, leaving the positively charged nuclei—a state of matter called a plasma. In some fusion machines, the heated plasma must also be maintained at high pressures to keep the nuclei close together, and these conditions must be maintained long enough for the fusion to occur. This is referred to as getting the plasma "hot enough, and dense enough, for long enough" for fusion to occur which produces more energy than is put into it.

There is also a *strong force* which can hold two protons together, and which operates only at very close distances, approximately the diameter of a proton. The strong force is also involved with keeping the nuclei of atoms stable in general, since nuclei are composed of protons and neutrons and would otherwise be expected to blow apart due to repulsion between the protons.

"Hot enough" for fusion depends on the type of fuel, and it is approximately 100 million degrees K or more. The cleanest fusion, with the most abundant fuel material, is hydrogen-boron, which uses the isotope 11-boron, but this requires at least 1.5 billion degrees K and runs best at 6 billion degrees K. The high temperatures involved in plasmas sometimes use a different unit for measuring the temperature, which is the electron-volt (eV). One eV equals 11,600 K. One keV is one thousand eV (one kiloelectron-volt) or 11,600,000 K, and one MeV (one megaelectron-volt) is one million eV or 11,600,000,000 degrees K. The temperature required for fusion in eV therefore usually starts in the range of approximately 9-10 keV.

When atoms are heated to high temperatures, some of the electrons separate from the atoms, resulting in a group of the negatively charged electrons, and the remaining positively charged atomic nuclei, which are termed ions. The heated charged particles are rapidly moving due to the high energy, and they are in a state of matter which is termed "plasma". Our Sun is a hot plasma, with the high temperature created and maintained by the energy from fusion reactions, and the high pressure due to the strong gravity caused by the large mass of the Sun.

Although the electron and proton carry the same amount of charge, the proton is approximately 1850 times heavier. This means that if the two particles are the same temperature, meaning that they have approximately the same energy, the electron travels through space with a higher velocity than the proton because it is lighter. The energy in a moving mass is equal to the mass times the square of the velocity speed, divided by two. (Remember that velocity is a vector that includes both speed and direction.)

Electricity and Magnetism

To make the discussion of electricity and magnetism concrete and observable, I would like to describe a simple device that is easy to construct: an electromagnet. I will review how to put together an electromagnet, and then take it apart to see how the electric and magnetic fields are formed.

An electromagnet consists of an insulated wire wrapped around a cylinder core (**Figures 3a-c**). The cylinder can be made of metal or plastic pipe or other

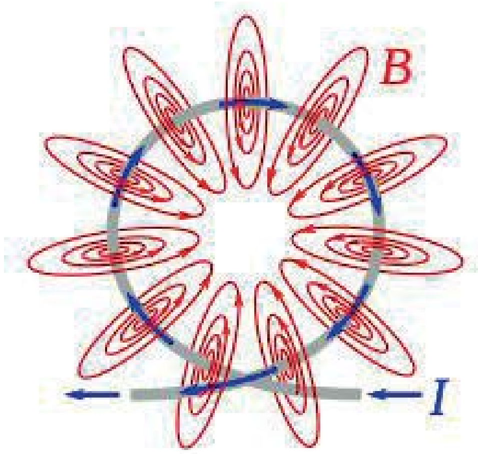

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Figure 4

A magnetic field is created by an electric current flowing through a single loop of wire. Shown here is the single wire loop, with magnetic field lines circling around the wire loop. The electric current is indicated by the capital letter I, with the arrows indicating the direction of the electric current. The magnetic field is labeled as B.

materials, but the resulting magnetic field is stronger if the cylinder is made of a metal such as iron. The wrapped wire extends from one end of the cylinder to the other, and usually consists of 20-100 or more turns around the cylinder.

The two ends of the wire are then connected to the two terminals of a battery, which sends an electric current through the wire, resulting in the current rotating around the cylinder. The rotating current creates a magnetic field inside the core of the cylinder. The magnetic field within the cylinder is parallel to the central axis of the cylinder core. The field extends out of one end of the cylinder, spreads out in all directions, and then doubles back to reenter the cylinder at the other end, so the field lines are closed. The end where the field comes out is the north pole of the magnet, and the end where the field reenters is the south pole.

This demonstrates a basic principle of electricity and magnetism: that a rotating current of electricity creates a magnetic field. The cylinder with the coil of wire is called a *solenoid*.

The magnetic field cannot be directly observed, but we know it is there because it affects the motion of certain visible materials, such as pieces of iron. The magnetic field has a direction and strength at every point, which can be visually represented with a vector, by drawing an arrow from representative points in the field. The arrow starts at the representative point, the direction of the arrow indicates the direction of the magnetic field, and the length of the arrow indicates the strength of the field at that point. The overall magnetic field may also be pictured as consisting of lines of field that connect the vectors, with the closeness of the lines indicating the strength of the field.

Let us now take another look at the electromagnet, to gain some insight into how the charged particles behave and how this behavior is related to fusion. Imagine removing some of the coils, so there are fewer wraps around the core. The solenoid continues to produce a magnet field within the cylinder that is parallel to the cylinder, though weaker. The field continues to extend out from one end of the cylinder and loop around in all directions from the north to the south pole to reenter the cylinder.

Now remove all the coils but one. There is still a magnetic field produced, including the looping around (**Figure 4**). Now remove the cylinder and increase the distance between the wires to make a letter C figure, and then to make a straight wire. The field continues to wrap around the wire, but now that the wire is straight, the magnetic field has a cylinder shape circling around the wire

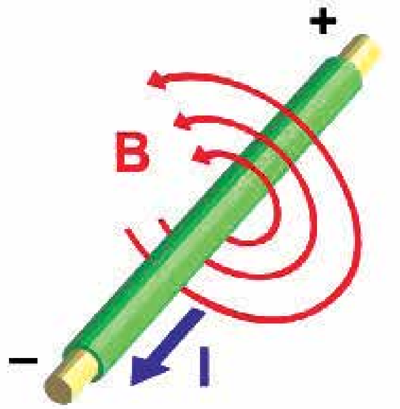

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Figure 5a

A single straight wire carrying an electric current produces a magnetic field (B). The field forms a cylinder shape around the wire; the field lines (red) revolve in the direction shown if the direction of electric current is the vector I. The positive and negative ends of the wire are attached to the terminals of a battery.

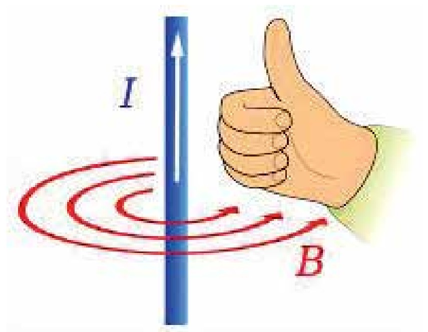

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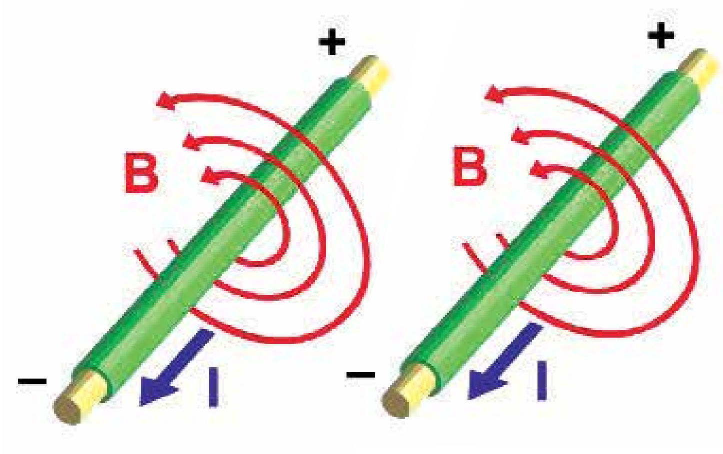
Figure 5b

If you wrap your fingers around a wire carrying a current with your thumb pointing in the direction of the current, your fingers will circle around the wire in the direction of the magnetic field created by the current.



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Stannered from an original rendering by Wapcaplet

Figure 6
In these two wires, the magnetic field above the wire is pointing to the left, and the magnetic field below it is pointing to the right, so these field lines would add, and produce total magnetic fields in these directions. But between the wires, the magnetic field created by the left wire is pointing up, while the magnetic field created by the right wire is pointing down. These two parts of the fields would cancel each other, creating zero magnetic field.

If more parallel wires were added to form a sheet of wires one wire thick, the total field would be going to the left across the top of the sheet and going to the right across the bottom of the sheet. If you wrap such a sheet once around a cylinder, that will produce a solenoid, with the magnetic field inside the cylinder going one way, and the magnetic field outside the cylinder going the other way.

(**Figure 5a**). There is a Right-Hand Rule associated with this situation: if you wrap your fingers around a wire that is carrying a current and point your thumb in the direction of the current, then the magnetic field will circle around the wire following the circling pattern of your fingers (**Figure 5b**).

To summarize, this result shows that an electric current in a straight wire produces a magnetic field in the form of a magnetic cylinder positioned around the current. The direction of the field at each point is along a circle on the magnetic cylinder that the field is making around the wire.

Even a single electron traveling in a wire can produce a magnetic field which revolves around the path of the electron. This magnetic field can also occur around an electron's path even if there were no wire, and the electron is moving in free space. This will also occur if the space is in a plasma.

Now let us consider two parallel wires carrying current in the same direction (**Figure 6**). They generate two rotating, cylindrical magnetic fields. The magnetic field region directly above the wires will be pointing to the left, so these left-pointing vectors will add, to form a total left-pointing vector; the opposite will happen in the region below the wires, with the resulting vector pointing to the right. Midway between these regions the left field will be pointing up, and the right field will be pointing down, so they will cancel. Adding the field vectors to get a total field at each point around the wires results in a generally symmetric oval magnetic field around the wires.

If more parallel wires are added, a sheet of wires one wire thick can be formed. The field above the sheet will go one way perpendicular to the direction of the wires, and the field below the sheet will go the opposite direction perpendicular to the wires.

Let us return to the solenoid. Start with the sheet of parallel wires carrying current. If this sheet is wrapped once around a cylinder, with the wires perpendicular to the axis of the cylinder, the result will be a magnetic field inside the cylinder going one way, and another magnetic field outside the cylinder going the other way, which is the field of a solenoid. At the end of the cylinder the field will loop around, analogous to the situation with the solenoid (**Figure 3b**). Now instead of using individual parallel wires, use one wire wrapped repeatedly around the cylinder (**Figure 3a**), and that completes the solenoid.

The formation of magnetic fields around sheets of current is important in understanding the formation of vortex filaments and vortex rings, which are composed of sheets of current and plasma. They will be discussed in a subsequent article in this series.

Magnetic Fields

Magnetic fields exert a force on moving charged particles. The direction of the force can be determined by another right-hand rule, which for clarity I will call the Second Right-Hand Rule (**Figure 7**). The index finger is held in the direction of charge movement. The middle finger is held in the direction of the magnetic field vector. The thumb is then the axis along which the magnetic field exerts a force on the charged particles. The angle between the index finger and middle finger depends on the situation, so they do not have to be perpendicular to each other. The thumb must be perpendicular to the other two fingers. That is, the direction of the magnetic force is perpendicular to the direction of particle motion, and it is also perpendicular to the direction of the magnetic field.

The strength of the *magnetic* force on a charge is different from the strength of the force exerted by an

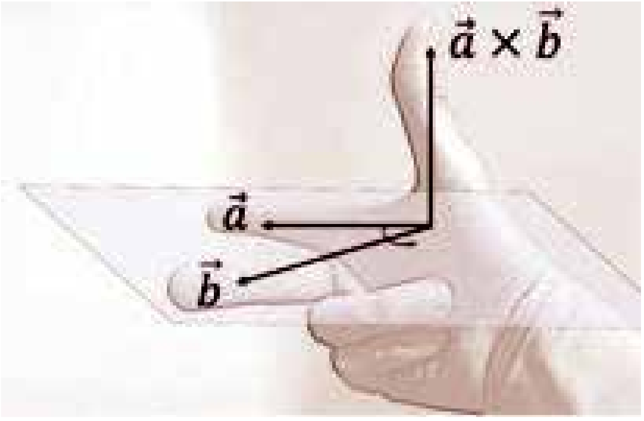

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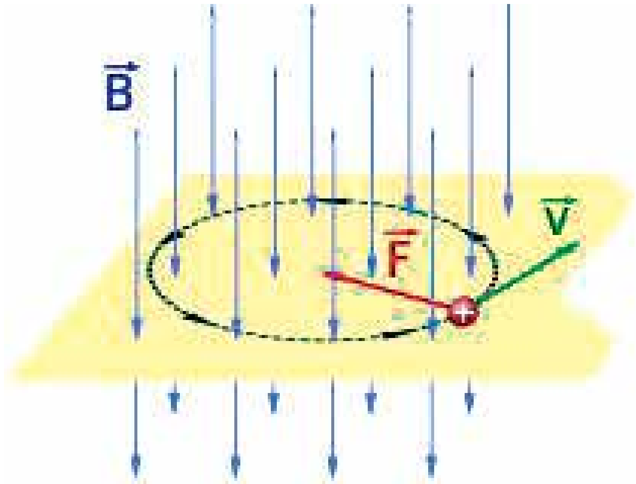
Figure 7

The second Right Hand Rule uses the index finger to point along the path of a particle (vector a); the middle finger to point to the direction of the magnetic field (vector b); the thumb shows the direction of the resulting force on the particle (Vector a×b). The The direction of vector a does not have to be perpendicular to the direction of vector b, but the direction of vector a×b must be perpendicular to the other two.



Wikipedia.

Figure 8

Shown is a positively charged particle moving with a velocity v in a constant magnetic field. The field is indicated by the parallel downward pointing vectors, and is named B. The force on the particle is perpendicular to the particle's direction of motion, and is also perpendicular to the field, and is indicated by the red vector F. This force turns the particle motion to the left. The particle then encounters another field line, which again turns the particle to the left. The repeated left turns combine to form a circular path.

electric field. The magnetic force varies directly with the speed of the particle. For example, twice the speed produces twice the force. The force also varies depending on the angle between the particle path and the field, between the index finger and the middle finger. If the path and field are parallel to each other (zero degrees), there will be no force; if they are in opposite directions (180 degrees), there will also be no force. If the angle is perpendicular (90 degrees), the force will be maximal.

As with the electric field, the strength of the magnetic field's effect on the particle increases with the strength of the field, and with the amount of charge on the particle.

When the magnetic field lines are all parallel to each other, and the path of a charged particle is at 90 degrees from the magnetic field lines, a magnetic force occurs that is perpendicular to the particle path, so the path will be turned by the force. Think of turning the steering wheel on a car, which turns the front wheels and pushes the front of the car sideways, turning the direction of the car's motion. If the particle's path is turned to a new direction and the particle moves forward, the new path will then face another field line at 90 degrees, a field line that is parallel to the first magnetic field line, so by

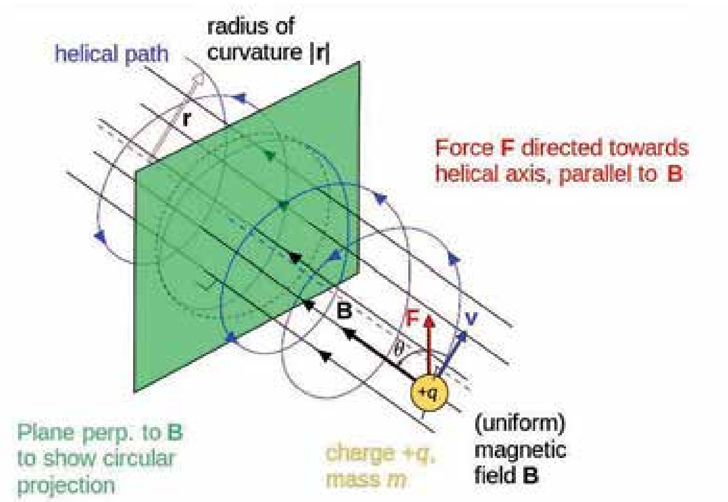


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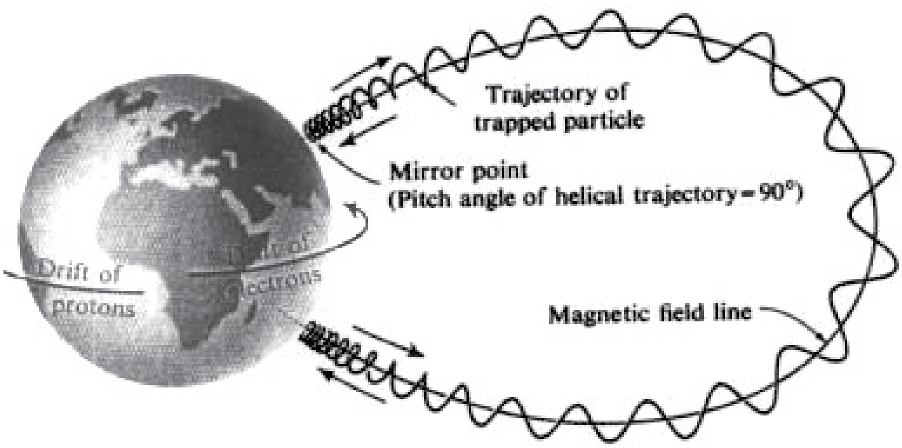
Figure 9

A particle spiraling around a line of magnetic field B. The particle has a positive charge +q. The charge has a velocity at this moment indicated as v. The angle between v and B is indicated by θ, which is less than 90 degrees. The velocity vector can be thought of as composed of two parts which are not shown, one parallel to the magnetic field B, and one perpendicular to it. The effect of the field is only on that part of the velocity that is perpendicular to the field; the field changes the angle of the particle's motion, like turning the steering wheel of a car, which tends toward a circular motion. The velocity vector part that is parallel to the field is not affected by the field, so this vector continues in a straight line. This results in the motion of the particle following both a circle in one direction, and a straight line that is perpendicular to the circle, which adds up to create a spiral.



Public Domain

Figure 10

A charged particle's spiral path following a curved magnetic field line. Shown is a diagram of a magnetic field line from the earth's magnetic field, with the path of a trapped particle moving in a spiral around the curved field line.

the Second Right-Hand Rule, the turning process will repeat. If the same process of turning continues, this will result in the particle moving in a circle (**Figure 8**).

If the particle approaches the field line at an angle between zero and 90 degrees, the effect on the particle can be visualized by considering that the particle motion vector (the motion arrow) can be considered as composed of two parts, one that is parallel to the field line and one that is perpendicular to the field line (**Figure 9**). The magnetic field force affects only the part of the vector that is perpendicular, so that part is turned, but the part that is parallel to the field is not affected and so is not turned. The resulting two vectors can then be added to form the final vector of the effect on the particle. If that process continues, the particle's path will form a spiral around the field line.

Think of a child tying a string around a stone and whirling it around his head. The stone will travel in a circle in the air. Now put the child on a trampoline. As the child bounds up, the stone travels in a spiral, a combination of rotation and upward straight-line motion.

If all the nearby field lines curve by the same amount, remain locally parallel to each other, and stay the same distance apart, the particle will continue to spiral around them. In this way, magnetic field lines can "grab" particles in plasma, causing charged particle currents, as well as flows of plasma containing the particles, to follow magnetic field lines (**Figure 10**).

This is a way that fusion machines can use curved magnetic fields to form "magnetic bottles" which capture charged particles—including positive ions which are the ones that fuse—and confine them while the ions are heated, to produce fusion without the ions contacting the confinement walls. The shapes of some of these magnetic bottles are discussed in the next article in this series.

So far, we have seen situations in which electrical currents tell magnetic fields how to curve, such as the magnetic field that curves around a wire carrying an electrical current, and curved magnetic fields tell electrical currents how to move, such as magnetic fields "grabbing" charged plasma particles to follow the magnetic field lines.