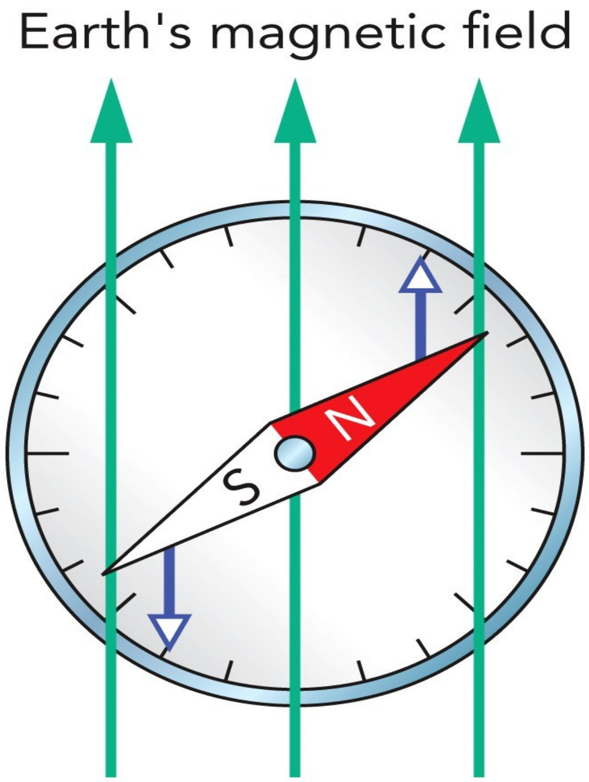
Magnetism

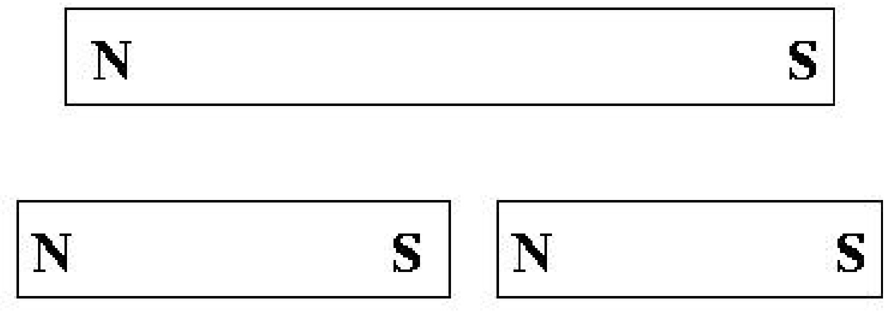


Magnetic forces are somewhat like electric forces. They can attract and repel. Magnets have 'poles' like electric sources have point charges. We label these 'north' and 'south' like we label electric charges positive and negative.

The Earth has a magnetic field. A compass is a small magnet that orients its north and south pole with the earths magnetic poles to show direction. The Earth's magnetic poles are near the north and south geographic poles (spin axis)

Magnetism

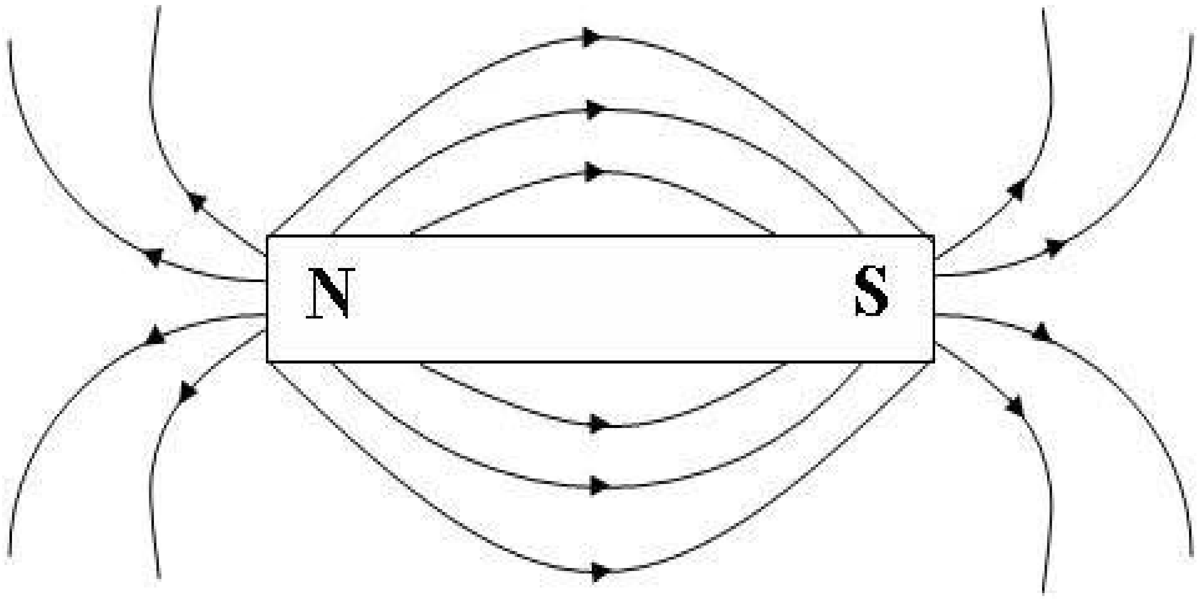
For electricity, we discussed a dipole (equal + and – charge separated by a small distance). Electricity and magnetism are closely related. In fact they are one and the same thing. One major difference with magnetism is that there are no magnetic monopoles (at least that have been found). Magnets always come in dipoles. If you break a magnet with a north and south pole intro two pieces, you end up with two weaker magnets that each have a north and south pole. You not not end up with a single north or south pole.



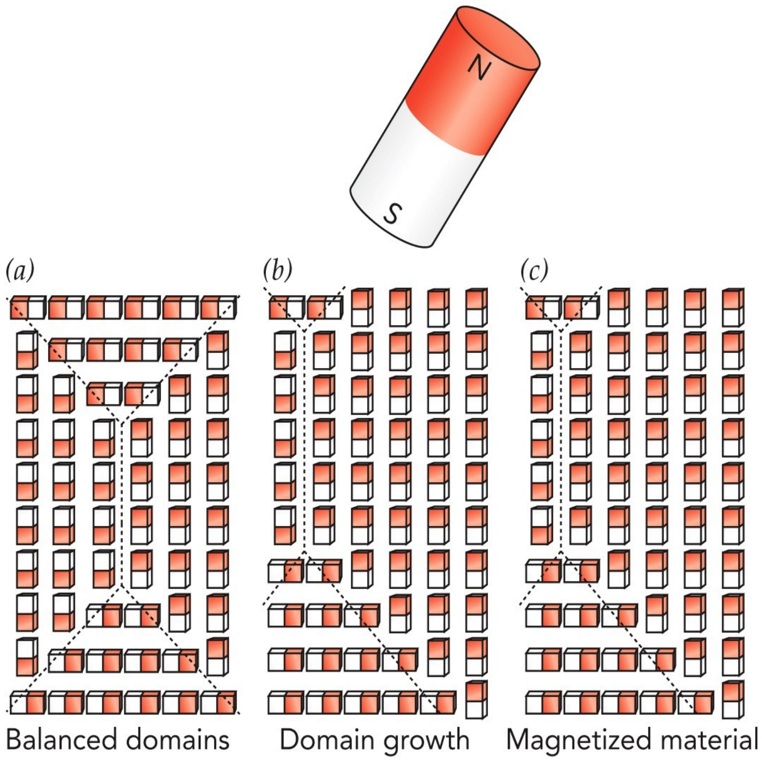
The textbook talks about forces on 'magnetic poles' (monopoles) in the problems. This is not correct. I will not be following the text book on this.

Magnetic Fields

Magnets only come in dipoles so the direction of magnetic field lines looks line an electric dipole with the lines starting at the north pole and terminating at the south pole. We will discuss how the magnitude of the field is calculated and how this produces a force.



Sources of Magnetic Fields



What causes a magnetic field? The short answer is that magnetic fields are produced by currents (moving electric charge). But a refrigerator magnet has no batter or power plug. What causes the magnetic? Electrons 'orbit' around the nucleus of the atom. In some atoms (iron, nickel cobalt) the 'orbiting' electron makes the atom a strong magnet. The 'spin' of the electrons also adds to the effect. Atoms that are near to one another align in a small (pinhead size) region called a 'magnetic domain'. If you align the magnetic domains in a piece of the right type of metal (a 'ferromagnetic material') with another magnet then it can becomes a permanent magnet.

Sources of Magnetic Fields

Permanent magnets come in many types and sizes. A simple refrigerator magnet is just iron or certain iron compounds in rubber that have the domains of the iron aligned. Iron or other elements are used in magnetic recording tape (VCR or cassette tape). The magnetic strip on the back of your ID or credit card has information stored in the magnetic strip of tape. Stereo speakers and headphone have strong permanent magnets ('rare earth' magnets) which interact with the changing current (with the music signal) to produce sound. Small electrical motors use permanent magnets. Most of the worlds information is stored on magnetic material (disk drives.) The list of uses of magnets is almost endless .

But permanent magnets are not the only way to make a magnet which we will discuss later. (Most magnets are electromagnets)

Super-Conductivity

In 1911 H. K Onnes discovered a curious effect. When some materials are cooled to very low temperatures near absolute zero (-273^{o} C), they conduct electricity like they have no resistance.   Super-conductivity can be used to make very powerful magnets. Most super-conducting magnet are cooled by liquid helium (4K). Some types of super-conductors become super-conducting liquid nitrogen (77K). These super-conducting magnets are used in MRI medical imaging devices and most particle accelerators (LHC, CEFAF etc).

Super-conducting magnets exclude an external magnetic field. This is known as the Meissner effect. This can create very large forces which can be used to 'levitate' something as heavy as a train. Maglev trains are in operation in other contries and have been proposed for use in this country.

Magnetic Forces

What is the force law for magnetic forces? We could define a force law like:

$$F = \frac{p_1 \, p_2}{4\pi r^2}$$

Where p_1 or p_2 is a 'magnetic pole' with units of ampere-meter. The problem is there are no magnetic (mono)poles! The constant μ_o is a fundamental constant in magnetism known as the permeability of free space and is equal to $4\pi \times 10^{-7}$ N/A^2.

The motion of a compass needle is no translational but rotational. A magnetic dipole in a magnetic field experiences a torque:

$$\tau = \mu B$$

Where τ is the torque, B is the magnetic field and μ is the 'dipole moment' of the magnet.

Electric Currents and Magnetic Fields

Courtesy Lou Bloomfield

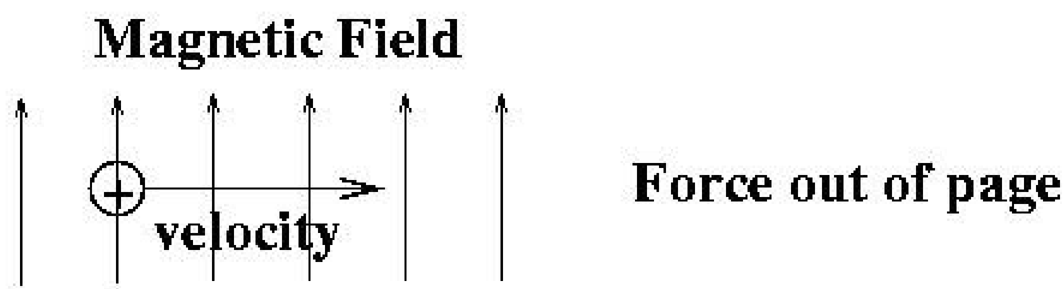
Magnetic field are made by currents (moving charges). Magnetic fields are routinely created and used in motors and generators by a current in a wire. The magnetic field depends on the current and the configuration of the wire. Such a device is called an electromagnet. For example the magnetic field of around a wire is given by:

$$B = \frac{\mu_o I}{2\pi r}$$

B is the magnetic field in Tesla, mo is the permeabilty of free space, I is the current (ampere) and r is the distance from the wire (meters)

Magnetic Forces on Moving Changes

Place a stationary charged particle in a magnetic field and nothing happens. There is not force. However, a moving charged particle experiences a force. For a positive charge moving to the right in a vertical magnetic field, the force is out of the page. The direction is given by the 'right hand rule'.



If the charged particle's velocity is perpendicular to the direction of the magnetic field, the magnitude of the force is:

$$F = q\,v\,B$$

where F is the force (Newtons), q is the charge in Coulombs, v is the velocity in m/s and B is the magnetic field in Tesla. A Tesla is a Newton/(ampere · Meter).

Magnetic Forces on Moving Changes

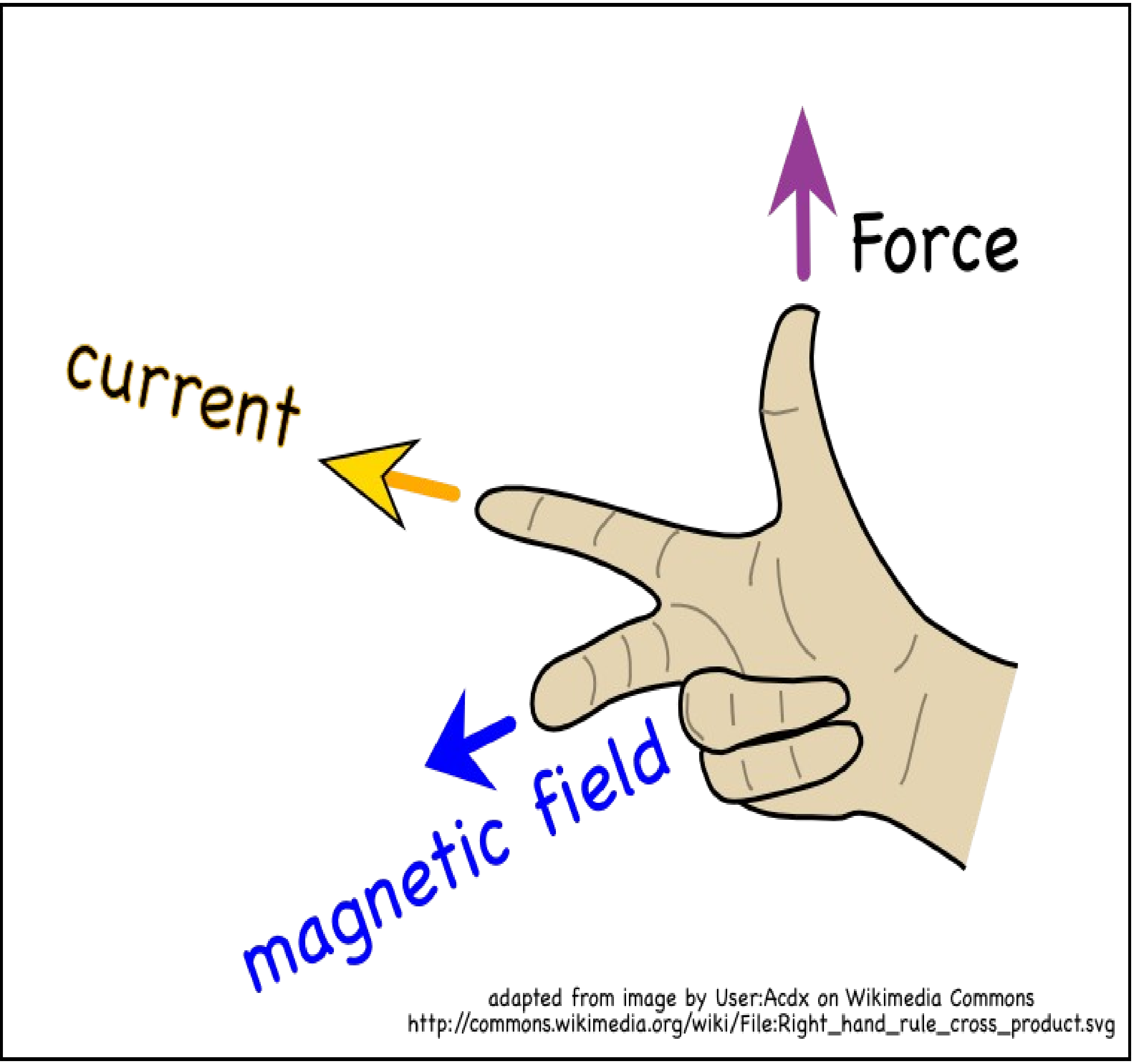
If the directions of the velocity and magnetic field is not perpendicular, then we need to find the component of the magnetic field perpendicular to the velocity. The magnitude of the force is then $F = qvB\sin\theta$.

A wire with a current is essentially the same thing as a moving charge. (Remember we defined the current to be in the direction a positive charge would flow). The force on a current carrying wire is then just:

$$F = i\,L\,B$$

where F is the force on the wire, i is the current in amperes, B is magnetic field in Tesla and L is the length of the wire affected by the magnetic field.

Right Hand Rule



The right hand rule (rhr) gives the direction of the force when the direction of the magnetic field and current (or the velocity of a positive charge) are know. The force is in the direction of the thumb, the current (or qv) is in the direction of the first finger and the magnetic field is along the second finger.

Direct Current Motors

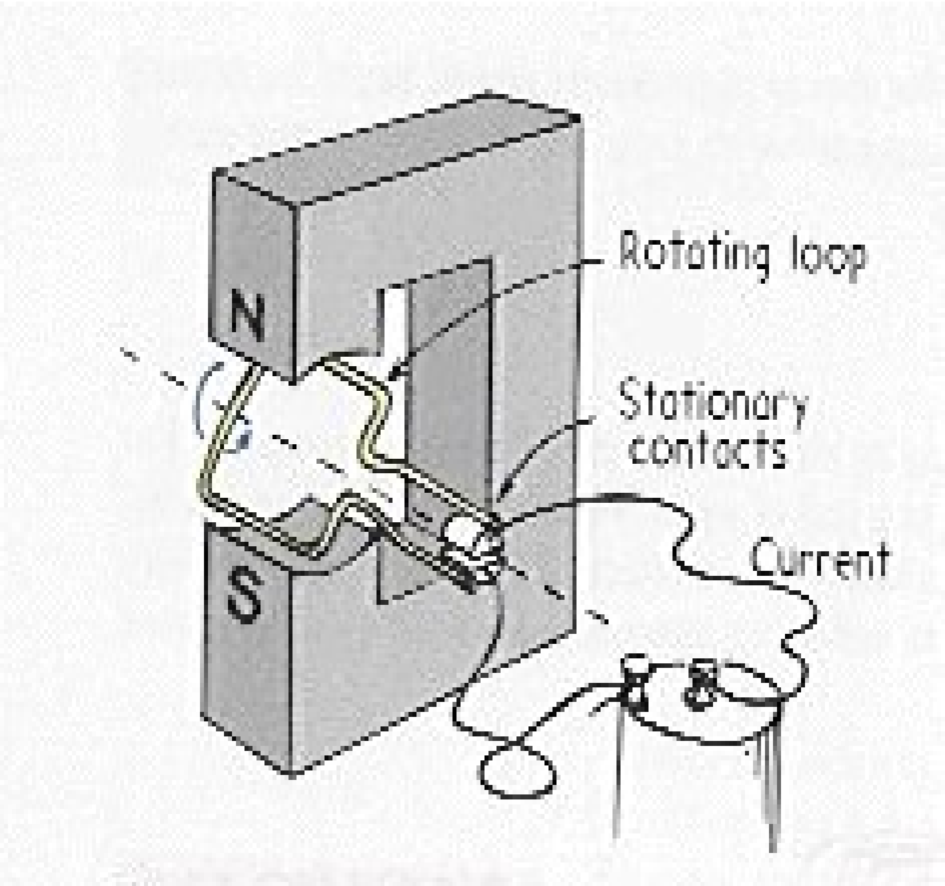
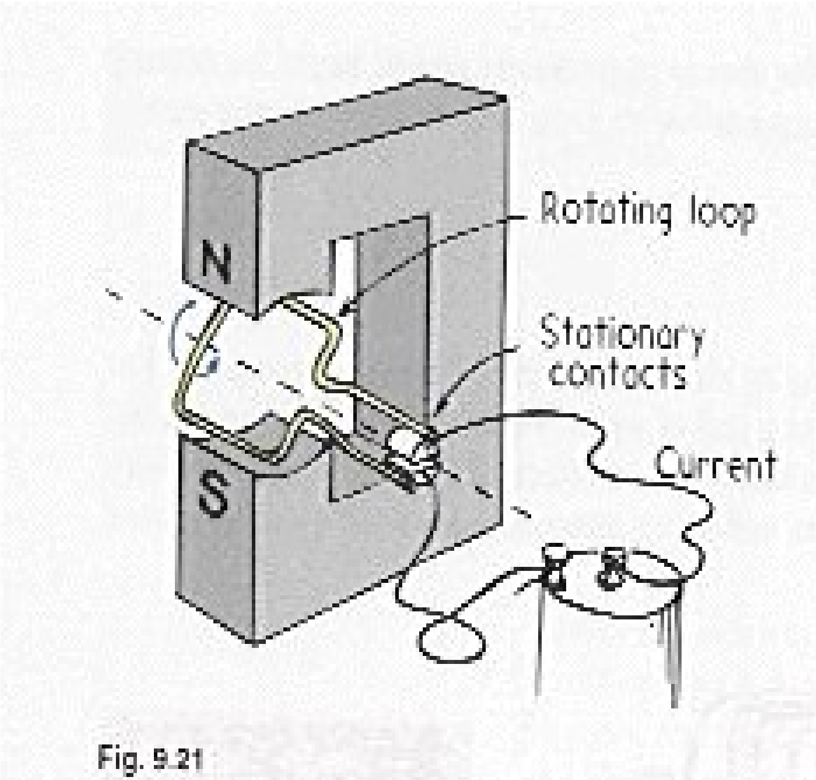


Fig. 9.21

Many small electrical motors use a continuous electric current ('direct' current of DC). These motors have a permanent magnet to produce a magnetic field around a coil of wire (normally many 'turns' or loops)When a current flows through the coil, the forces on the current carrying wire produce a torque which rotates the coil by ½ turn. At this point the stationary contacts reverse the direction of the current flow. This reverses the magnetic forces on the wires which cause the coil to rotate another ½ turn. At this point the coil is back to its initial position.

Direct Current Motors



Note we could really call an 'electric' motor a 'magnetic' motor since the force that produce the torque are magnetic and not electrical.

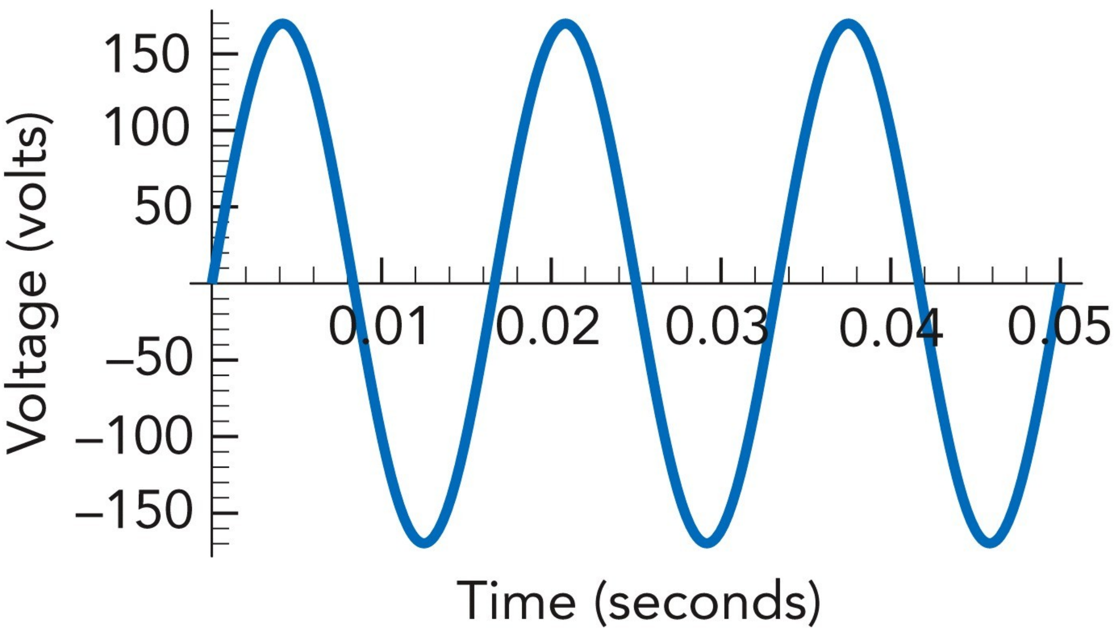
Larger 'DC' motors often replace the permanent magnet with coils to produce the magnetic field.

In a real electric motor there are often more than one coil. In this case, each coil turns the motor ¼ turn (two coil) , 1/6 of a turn (3 coils) etc.

With modern electronic, the 'commutator' contacts (coils) and 'brushes' (stationary contacts) are replace by electronic controls to reduce electronic noise.

Alternating Current - AC

The flow of charge (current) can be DC (steady) or can change in time. There are several advantages to have the current alternate back and forth. Current which is changing is called 'alternating' current or AC. With a AC current the flow of current is first in one direction and then the the opposite direction. Because the current and voltage is always changing, it is more difficult to define the values. A standard US wall plug has a voltage that changes from +170 volts to -170 volts and back to +170 volts 60 times per second (Hz).



Why do we call it '100' volts? The rms (root mean square) of the voltage is 110 volts. (The average is zero!).

Alternating Current - AC

Using the rms value of the voltage and current has the advantage that everything we did with DC voltage and current works the same way. We still have Ohm's law ($V = IR$) and the power consumed is $P = IV$.

Another advantage of AC voltage current is that it is much easier to move from one place (the power plant) to another (your house).   When electricity was introduced in the late 1800's, Thomas Edison tried to use DC. The power plants had to be near the consumer. George Westinghouse and Nikola Tesla used AC power and eventually replaced the DC systems of Thomas Edison. To understand how this works, we need to look at a magnetic effect called 'induction'

Induction (Faraday's Law)

In the 19th century, Henry and Faraday discovered that a changing magnetic field can produce a current in a closed loop of wire. Faraday's Law can be stated as:

- The induced voltage in a coil is proportional to the number of loops times the rate at which the magnetic field changes in those loops.

We can find the the current if we know the resistance of the coil from Ohm's Law.

You can move the coil into and out of a magnetic field or you move (change) the magnetic field in the coil. It is only the relative motion that matters.

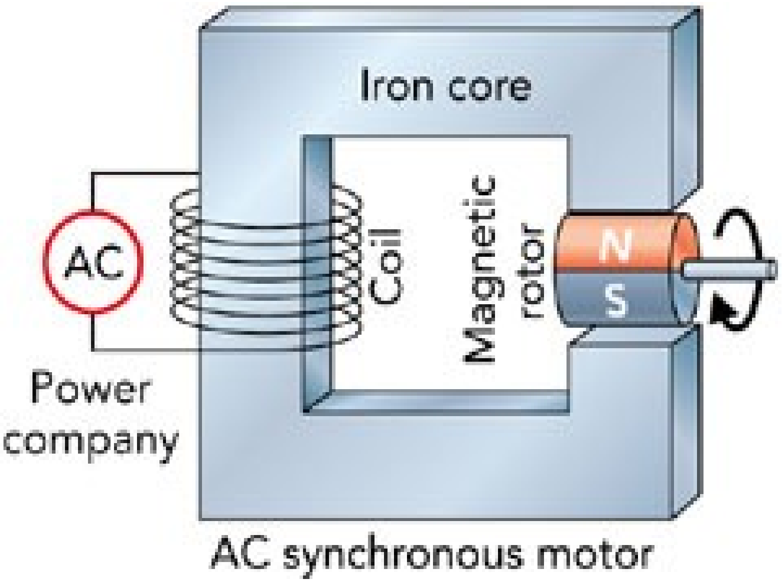
Energy Stored in a Magnetic Field

A magnetic field stores energy. A current flowing in a coil or wire creates a magnetic field. The magnetic field stores energy. (A coil of wire which stores magnetic field energy is called an inductor.) If the current stops flowing, the magnetic field will collapse which induces a potential and current in the coil and releases the stored magnetic energy. The magnetic energy stored in a volume of space is given by:

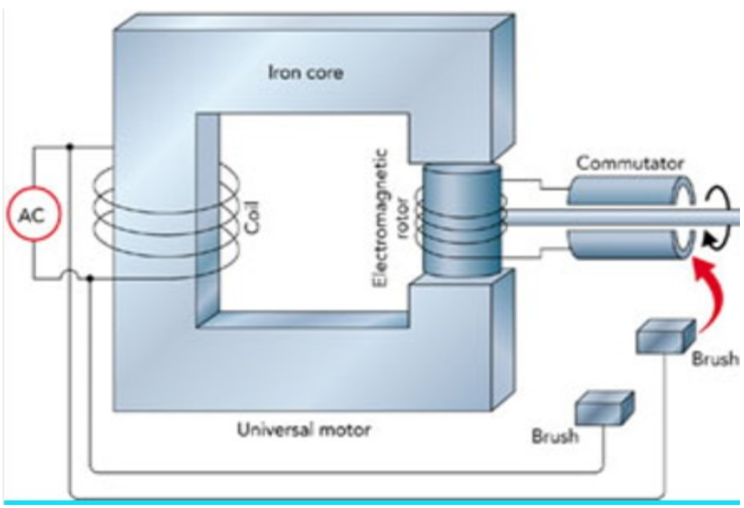
$$U = \frac{B^2 v}{2\mu_o}$$

Where U is the stored magnetic energy in Joules, B is the magnetic field in Tesla, v is the volume (m^3) and μ_o is the permeability of free space.

AC Motors



A simple AC (synchronous) motor is a magnetic rotor in the changing magnetic field produced by an AC electromagnet. Each time the field changes direction, the rotor turns ½ turn. The motor turns at the frequency of the AC current (60 Hz).

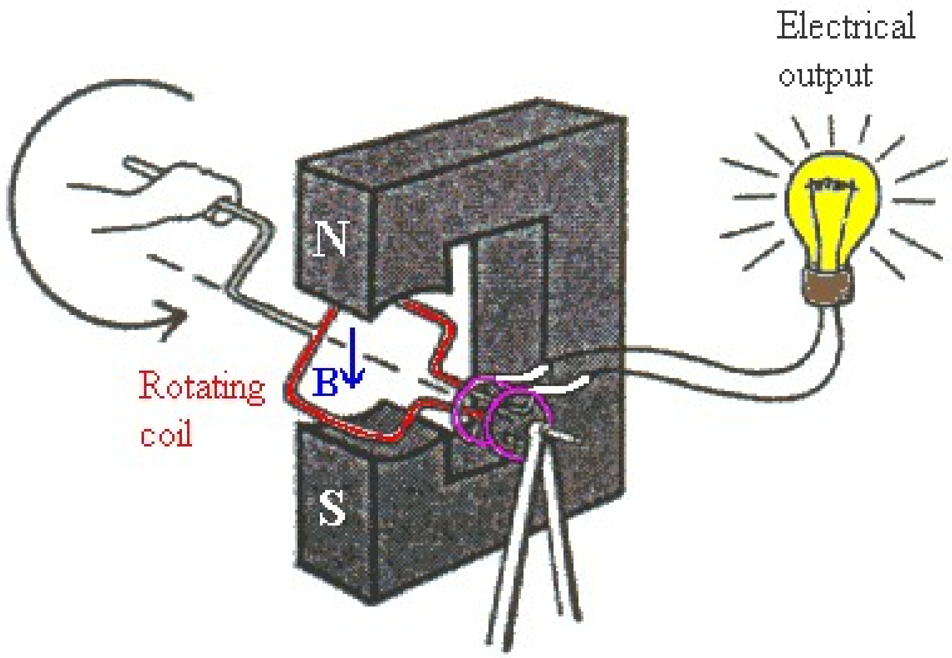


A universal motor can use AC or DC. The rotor is an electromagnet as is the AC magnetic field. For AC each time the current reverses the rotor reverses. For DC mode, the magnetic field is static and the rotor changes each ½ turn.

AC Motors

An AC induction motor is often used in industrial settings and where efficiency and power are required. In an induction motor, the coils in the rotor are closed circuits. There are no brushes or contacts which flip the direction of the current. Using electronics, the magnetic field produced by electromagnets is rotate around the rotor. This induces a current in the closed rotor windings which cause the rotor to turn. It takes a fair amount of engineering to make the magnetic fields rotate in a uniform way. Normally these motors operate at a fixed speed but modern electronics has made variable speed induction motors more common. Because there are no brushes the electronic noise is minimal.

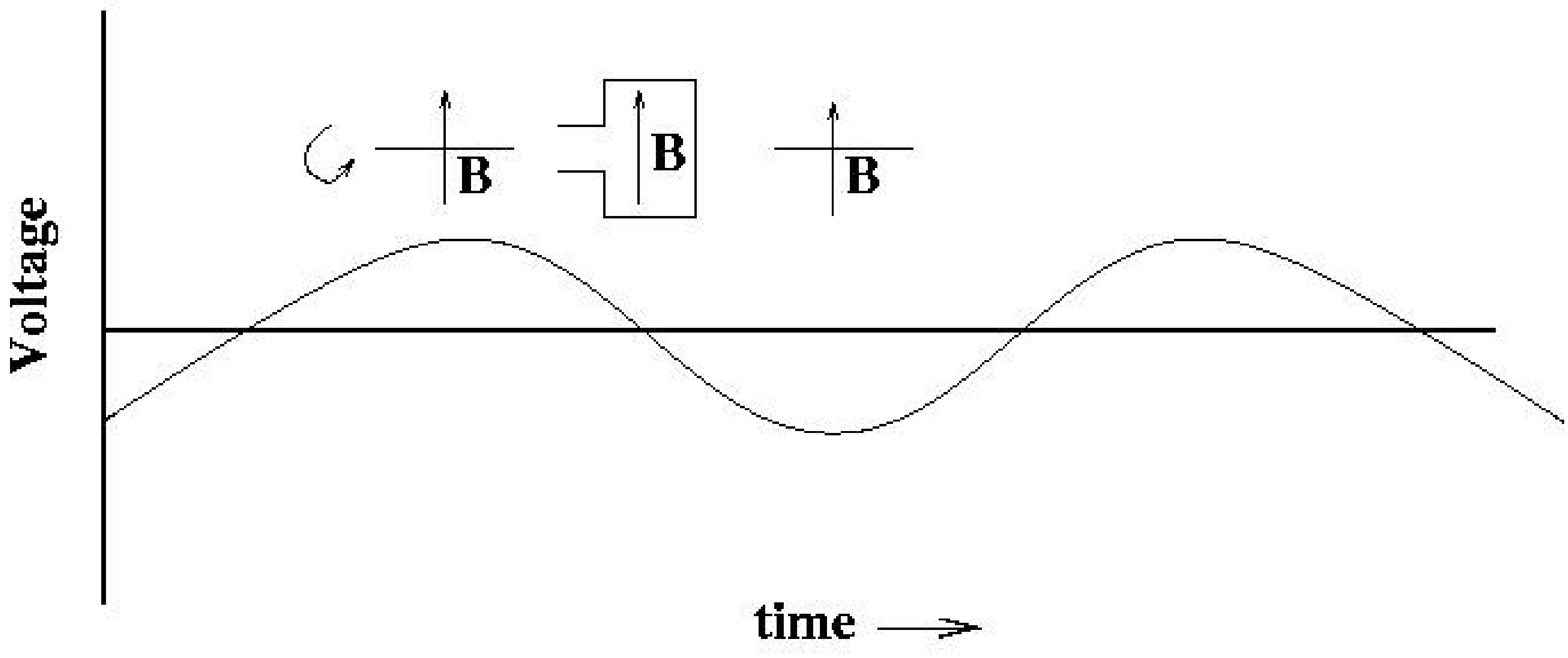
Generators



A generator is basically the same as electric motor when power is supplied to turn the rotor. When the coil is turned, the magnetic field inside the coil changes and a current is induced in the coil. The current is an AC current. Most of the electrical power used is produced in this manner. All power plants (hydroelectric, nuclear, coal, natural gas) rotate a generator to produce electrical power.

Generators

The current produced is AC because of the rotation of the coil. In fact if you think about it the variation is sinusoidal. If the magnetic field is vertical and the plane of the coil is horizontal, all of the magnetic field goes through the loop. When the plane of coil rotates to the vertical position, there is no magnetic field through the coil. Another ¼ turn and the plane of the coil contains all of the magnetic field with the change occurring in the opposite direction.

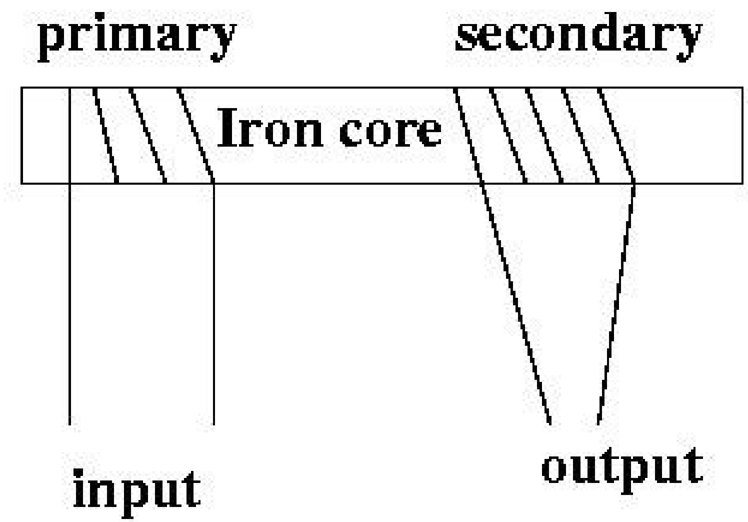


Hybrid Cars

When we discussed cars engines, I briefly mentioned hybrid cars. Part of the advantage of a hybrid car is that a gasoline engine is run at its most efficient speed to power a generator to charge batteries. Electric motors can then be used at speeds which are not efficient for the gasoline engine.

More relevant to our discussion of generators and induction is some more modern hybrids cars use the electric motors to re-charge the batteries when the car is braking (stopping). Since an electrical motor and a generator are basically the same thing, the motors are turned by the wheels when the car is stopping and induce a current which is used to re-charge the batteries. Of course, there are still brakes on the car.

Transformers



The major advantage to AC power (as Edison learned the hard way) is that AC power can easily transmitted long distances without serious losses. The key to this process is the transformer which only works with AC power.

A transformer consists of an iron 'core' and two coils of wire wrapped around the iron core. The number of turns of wire in each coil determine the properties of the transformer. The AC current in the primary produces a magnetic field which is (almost) completely contained by the iron core. The secondary coil 'sees' this changing magnetic field and a current is induced in the secondary coil. The voltage in the secondary coil is determined by the voltage of the primary and the number of coils in the primary and secondary coils.

Transformers

The secondary and primary voltages are related by:

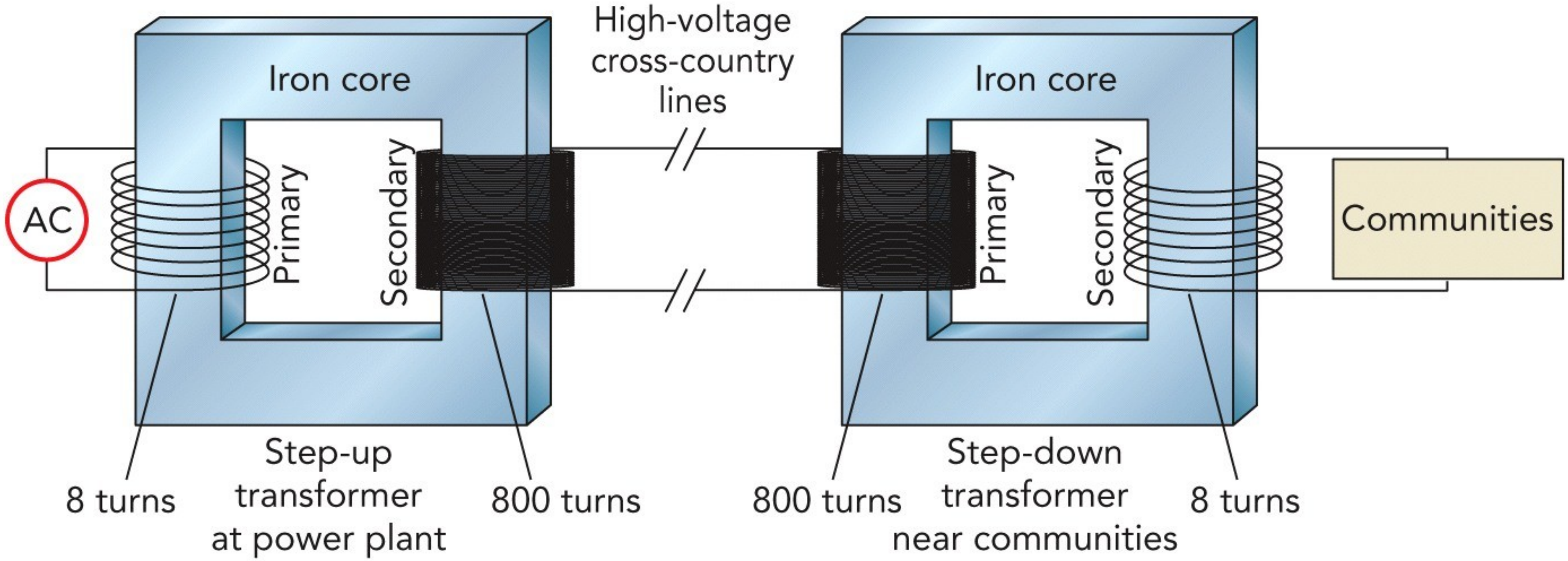
$$\frac{\text{Primary voltage}}{\text{Number of primary coils}} = \frac{\text{Secondary voltage}}{\text{Number of secondary coils}}$$

Note that a transformer can increase the voltage (step up) or lower the voltage (step down). With proper design of materials and geometry, a transformer can be very efficient (>98%). Power (energy) is conserved by the tranformer.

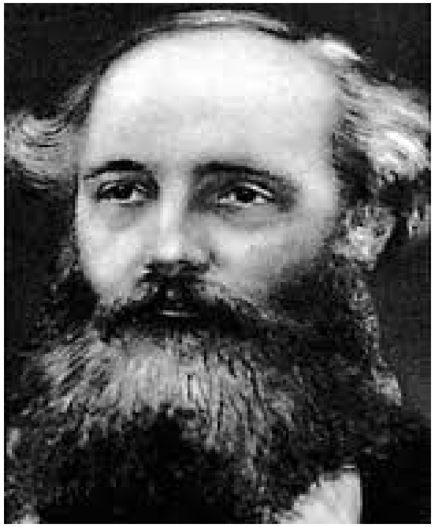
So why is this important. It goes back to Ohm's law (v=IR). From Ohm's law $P = V\ I = (IR)I = I^2R$. The resistance can only be changed by making a thicker (more expensive) wire. Transmit power at high voltage and low current ant the loses are much smaller.

Transformers

A generator produces AC power at some reasonable potential (440 V) and high current. A transformer steps up the voltage to a high voltage (750 kV) and > 10 amperes. This is then send across large distances (hundreds or thousands of miles). At the other end step down transformers convert the power back to lower voltages (110 V) and higher currents for distribution to homes and industry. Except for small loses the power (voltage x current) is the same at both ends.



Field Induction – Light!

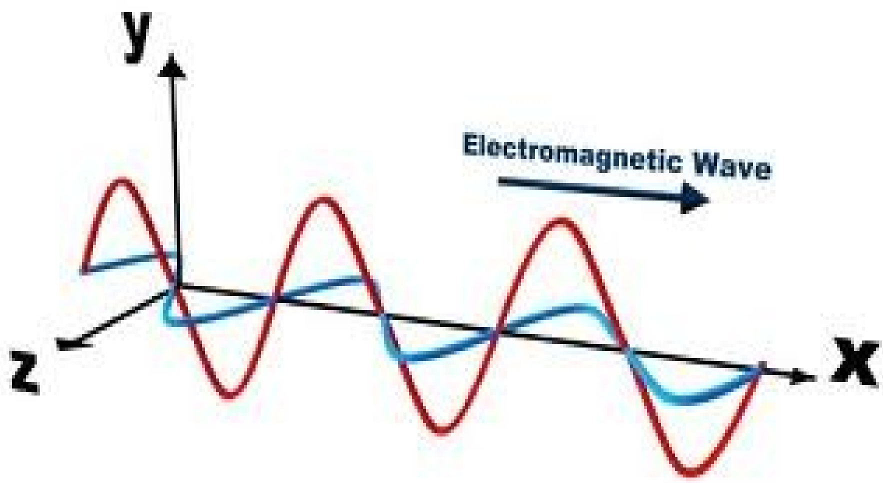


In the 1860's James Clerk Maxwell notices something about the laws of electricity and magnetism as they were then known. The equations were not symmetric. He proposed there as a term missing in one of the four equations. Purely by symmetry he propsed:

- A magnetic field is induced in a region of space where an electric field is changing in time. The magnitude of the induced magnetic field is proportional to the rate the electric field changes. The direction of the magnetic field is perpendicular to the direction of the changing electric field.

This looks a lot like Faraday's law: changing magnetic field producing an electric field. Maxwell says changing electric fields produce magnetic fields.

Field Induction – Light!



Maxwell's observation was actually an addition to one of the existing laws for electricity and magnetism (Ampere's law: how currents produce magnetic fields). With this addition (symmetry to the equations), Maxwell showed that light is an electromagnetic wave. Electromagnetic waves are just electric and magnetic fields regenerating one another as they propagate.

How do you make an EM wave? Accelerate (shake) a charge and you make EM waves. FM radio, WiFi, cell phone transmissions, even X-rays (quickly stopping an electron beam) and γ rays (protons jumping around in a nuclei)