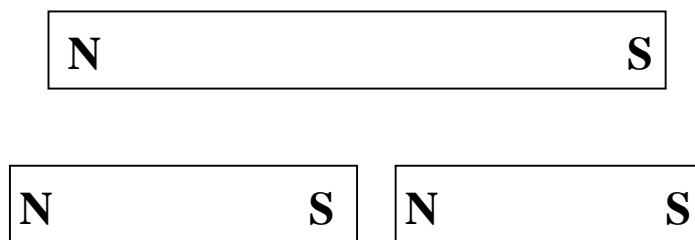


## Magnetic Poles

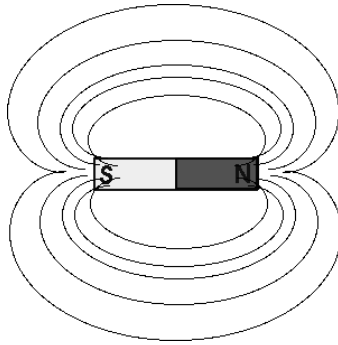
Magnetic forces are somewhat like electric forces. Magnets can both attract and repel one another. Magnets have **poles**. If a magnet is free to rotate on a string, one end will move around to point to the South and other end will point North because the earth acts like a magnet. We call these the North and South poles of the magnet. A compass is nothing but a small magnetized needle which is free to rotate.

When we talked about electricity, we discussed the idea of a dipole. This is an object that has positive charge on one side and negative charge on the other side. A very closely related idea to electricity is magnetism. The big difference is there are no 'magnetic charges'. All magnets are dipoles. With electricity we could think of cutting our dipole object in half and having a positively charged half object and a negatively charged half. Try this with a magnet and you end up with two complete (but weaker) magnets.



## Magnetic Fields

Magnets only come in **dipoles**. There are no free 'magnetic charges'. Actually, people have looked for 'magnet mono-poles' for years. No one has ever found one. The magnetic field around a bar magnet looks like the field lines around an electric dipole. As with electric fields, the **magnetic field lines** show us the direction of the force on a small magnet placed at some point.



What causes a magnetic field? Magnetic fields are caused by a current. Said another way, magnetic fields are caused by a moving charge. A current is just a bunch of electrons (tiny negatively charged particles) moving through a wire. The bar magnet does not have any current flowing through it so why is it a magnet? The electrons in atoms move around the nucleus. In most atoms, the electrons make the atom into tiny magnets because of the orbital motion. (The electron also has a property called spin. It is like a charged spinning ball. This spinning also adds to the magnetic field of the orbital motion). In most materials these spin and orbital motions are directed in all (random) directions so, on average, it cancels out. In a few materials, like iron, nickel, cobalt and some other metal alloys, the atoms are very strong little magnets. They have enough magnetic strength to line up in the same direction. Inside of the iron, there are small regions, called **magnetic domains** where the atom's magnetic fields are all aligned. When we impose an external magnetic field these magnetic domains all point along the magnetic field lines. This is what happens when you stick a refrigerator magnet on the steel refrigerator door. The magnet aligns the magnetic domains in the steel so that part of the door becomes a temporary magnet. If you place an un-magnetized piece of iron in a strong magnetic field, the iron will become permanently magnetized.

There are many kinds of permanent magnets. They range from the high tech to low tech. Refrigerator magnets are made of iron particles in rubber. The iron is made magnetic by placing it in a strong magnetic field. The magnetic strip on the back of your credit card is a magnet which is used to store information. Stereo speaker have fairly strong permanent magnets which interact with a changing electric current to produce the sound. Most small electric motors have magnets. The list is almost endless.

In the early 1900's Onnes discovered a curious property about some materials at very low temperatures. At a few Kelvin, some materials lose all resistance to the flow of electrical current. This is called **super-conductivity**. This property of super-conductivity has been exploited to make very strong magnets that require very little power to operate. They are in use today in many particle accelerators like Jefferson lab. One proposed use for super-conducting magnets is for 'maglev' (for magnetic levitation) trains. Super-conducting magnets exclude external magnetic fields. We will talk later about induction but the idea is that an external magnetic field would induce a current so large in the super-conductor which would cancel out the external magnetic field inside the super-conductor. This is called the **Meissner effect**. The force is so large from a super-conducting magnet that it can be used to 'float' a train above a track. This allows for very fast speeds since air resistance is the only retarding force. Super-conducting magnets are also used in MRI medical imaging

## Magnetic Forces

So how do we find the force produced by magnets? Magnets only come in dipoles. We can define a magnetic pole (in units of ampere-meter) and have a force law like gravity or Coulomb's law:

$$F = \frac{\mu_0 p_1 p_2}{4\pi r^2}$$

where  $\mu_0$  is the permeability of free space ( $4\pi \times 10^{-7}$  N/A<sup>2</sup>),  $r$  is the distance between the poles. The problem here is **there are no 'magnetic poles'**,  $p_1$  and  $p_2$ . In fact, we normally can define the torque on a dipole but not the force between 'magnetic poles' because they have never been found.

To illustrate the idea of the torque on a magnetic dipole, think of a compass needle. The magnetic forces on the compass due to the earth's magnetic field do not cause translational motion but cause the compass needle to rotate to align with the earth's magnetic field. While the book list ' $F = \mu B$ ', the proper relationship is:

$$\tau = \mu B$$

where  $\tau$  is the torque,  $\vec{B}$  is the magnetic field and  $\mu$  is the 'dipole moment'. We will see this in more detail when we discuss motors and generators.

## Electric Currents and Magnetic Fields

As we have discussed, magnetic fields are due to the motion of charge. Magnetic fields are routinely generated in motors and generator by having a current flow through a wire. The magnetic field depends on the geometry of the wire and the amount of current through the wire. A device that makes a magnet with an electric current is called an **electromagnet**.

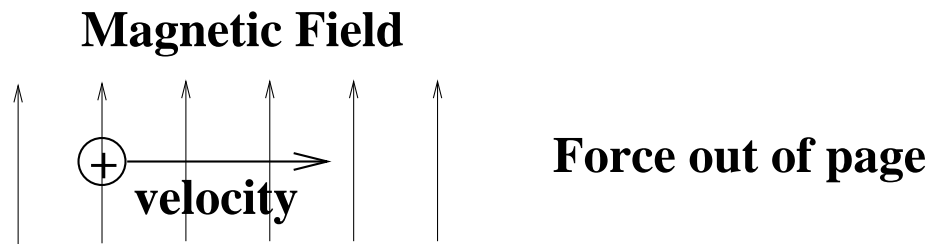
As an example of an magnetic field produced by a current, The magnetic field around a wire is given by the relationship:

$$B = \frac{\mu_0 I}{2\pi r}$$

Where B is the magnitude of the magnetic field in Tesla,  $\mu_0$  is the permeability of free space ( $4\pi \times 10^{-7} \text{ N/A}^2$ ), I is the current and r is the distance from the wire in meters.

## Magnetic Forces on Moving Charges

Place a charged particle at rest in a magnetic field and nothing happens. A charged particle at rest in a magnetic field experiences no force. If the charge is moving there is a force on the charge particle and the particles motion will be deflected.



For a positive charge moving to the right in a vertical magnetic field, the particle is deflected out of the page. The direction is determined by the 'right hand rule'. The magnitude of the force is given by:

$$\mathbf{F} = q\mathbf{v}\mathbf{B}$$

where F is the force in Newtons, q is the charge in Coulombs, v is the velocity in m/s and B is the magnetic field. Magnetic fields are measured in a unit called a **Tesla**. In terms of basic SI units the Tesla is  $\frac{\text{Newton}}{\text{ampere}\cdot\text{meter}}$ .

If the velocity and the magnetic field are not perpendicular, then we need to first find the component of the magnetic field perpendicular to the velocity. This adds a 'sin $\theta$ ' to the above equation i.e.,  $F = qvB\sin\theta$

A wire with a current is the same thing as a line of moving charges. If we put a magnetic field around a current carrying wire, the wire will be deflected by a magnetic field. In this case the force is given by:

$$\mathbf{F} = i\mathbf{L}\mathbf{B}$$

where  $i$  is the current and  $L$  is the length of the wire (inside the field).

## Direct Current Electric Motors

Small electric motors operate like this. Motors rotate instead of pushing only in one direction so a coil is used inside of a magnetic field. The current is supplied by a voltage source through the coil e.g, a battery. When the motor moves around  $\frac{1}{2}$  turn, the rotating contacts (commutator and brushes) switch the direction of the current which produces more torque in the same direction. Another  $\frac{1}{2}$  turn the same thing happens again and so on. Of course, real motors have more than one turn in the coil and more contacts.

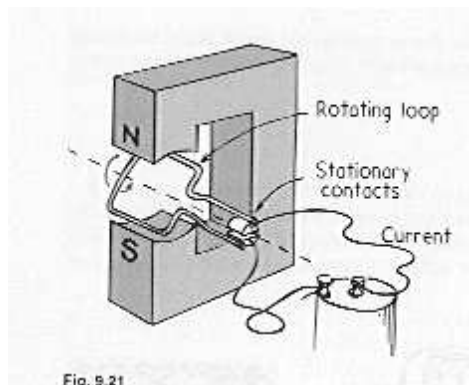


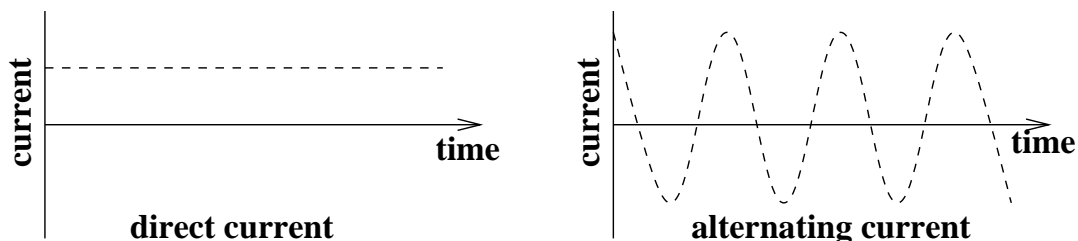
Fig. 9.21

In large motors, the permanent magnet is replaced by electromagnets (other coils). With modern electronics and sensor, the commutator and brushes can be replaced by electronic controls. This is done in 'brush-less' motors where electronic noise is important.

## Alternating current - AC

A current can be **direct current (DC)** or **alternating current (AC)**. A DC current is when the electrons always move in the same direction.

With an AC current the electrons move one way around the circuit and then reverse direction. Batteries like the one in your car provide a DC current. The components in your desk-top computer use DC but the power supply converts the AC to DC. However, most of our electric power comes from '110' power outlets which is AC.



Since the voltage is always changing with an AC power source, it is more difficult to define the voltage. A typical '110' outlet has voltage that goes from  $\approx 170$  volts to  $\approx -170$  and back to  $\approx 170$  sixty times a second (60 Hz). So why do we say '110' volts? The '110' volts is the average or 'root mean square (RMS)' of the magnitude of the voltage. Since Ohms law relates the current to the voltage by the resistance, the current also changes in time. The current in an AC circuit is also a 'RMS' (average) value. Use the RMS values for AC currents and voltages and the number work the same way as with DC i.e.  $V = IR$  and  $P=VI$ .

It is much easier to move AC currents without major losses (say from the power station to your house) than DC currents. Actually, when electricity was first introduced in the late 1800s, both AC and DC were used. AC won because of what we will see later about transmitting electrical power. Thomas Edison tried to use DC for the first electric system in New York but as the power system grew, the distances between the power plant and the users grew. Eventually, the AC system replaced the early DC power systems.

## **Electromagnetic Induction**

Currents in a wire produce a magnetic field. Faraday and Henry discovered in the first half of the 19<sup>th</sup> century that a **changing magnetic field** can produce a current in a closed loop of wire. It depends on how fast the magnetic field is changing and how many loops there are. This is called **Faraday's Law**:

- **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**

Of course, the current can be found by Ohm's law if we know the resistance of the loop. You should also note that it only depends on the relative motion. Moving the coil to the magnet is the same as moving the magnet to the coil. Either way, we are changing the magnetic field inside the coil.

## **Energy Stored in a Magnetic Field**

A magnetic field has energy. When you put a current through a wire or coil of wire, a magnetic field is created around that wire or coil of wire. Energy is stored in the region (or volume) of space.

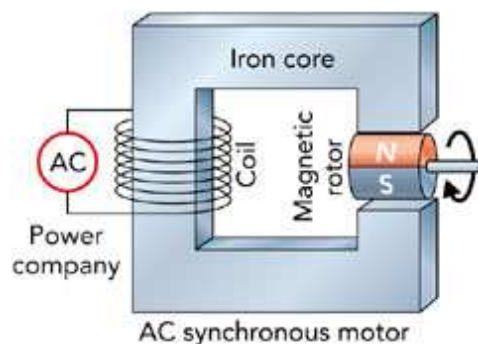
If you turn off the current the magnetic field will collapse and induce a current in the wire (or any other coil in the region). The energy stored in a magnetic field is given by:

$$U = \frac{B^2 \cdot V}{2 \cdot \mu_o}$$

where  $U$  is the stored magnetic energy,  $B$  is the magnetic field in Tesla,  $V$  is the volume of the region in  $\text{m}^3$  and  $\mu_o$  is the permeability of free space.

## AC Motors

Electric motors can be made to operate using AC current. One of the simplest types of AC motor is the AC synchronous motor. With this type of motor, AC current is used to make an alternating magnetic field. The permanent magnets 'flip' each time the AC current changes the magnetic field.

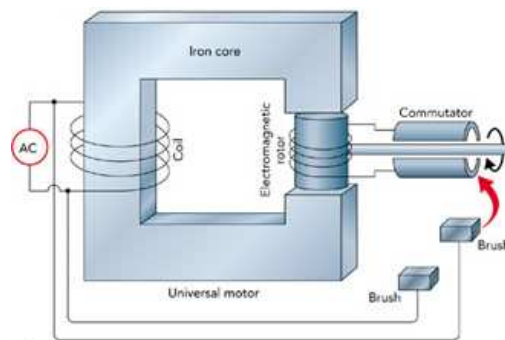


The motor turns at a speed equal the the frequency of the AC current (60 Hz). Before electronic clocks, synchronous ac motors were used for reasonably accurate clocks

Motors can be made to work on both AC and DC. In a universal motor, the permanent magnets which produce the stationary magnetic field are replaced by an electromagnet connected directly to the power supply.

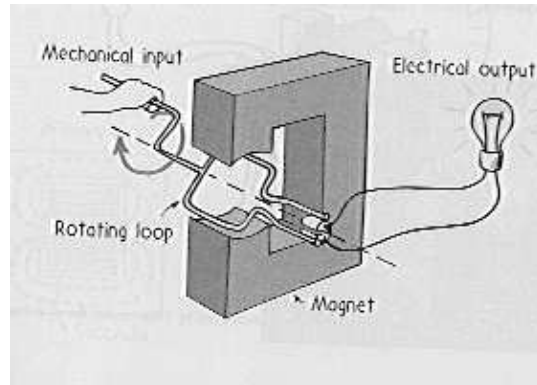
For DC input the magnet works as a normal DC motor with the except that the motor only turns one way. For an AC input the magnetic field from the electromagnet flips with each AC cycle. Since the current flips each turn for the rotor, each half turn the motor continues rotate in the proper direction.

A more sophisticated AC motor is the induction motor. Here the rotor is a closed circuit coil. The magnetic field is made to rotate. Since the rotating magnetic field induces a current in the closed circuit rotor, the induced current causes rotor to turn at nearly the same speed as the rotating magnetic field. It takes a fair amount of engineering to make the magnetic field rotate in a uniform manner. These motors are normally used in industry and not in household applications.

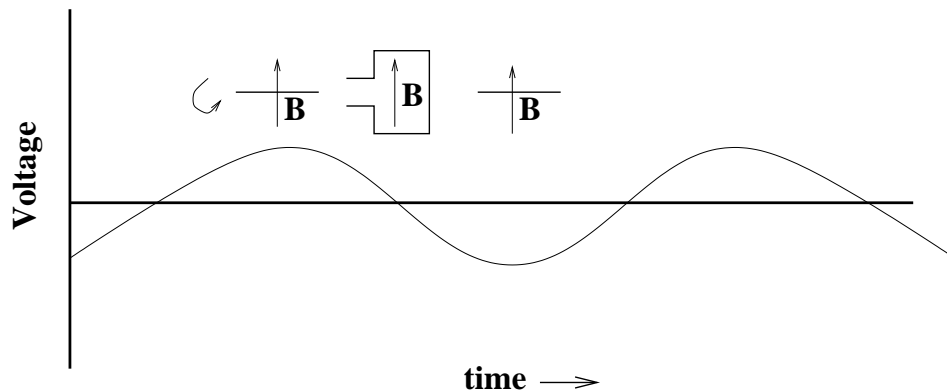


## Generators

If you remove the battery and turn an dc electrical motor, you are changing the magnetic field through the coil as you rotate it through  $90^\circ$ . This produces a voltage where the battery would be connected. Such a device is called a **generator**. Remember, it is the relative motion that counts so we can move the magnetic field or the coil. It is easier to move the coil than the magnets.



As the coil rotates, from its viewpoint, field alternately fills the coil (when the plan of the coil is perpendicular to the magnetic field) and is removed when the plane of the coil is in the same direction as the field. The results in the sinusoidal variation of the induced voltage. The frequency of the variation in the voltage is same as the frequency of turning of the coil.

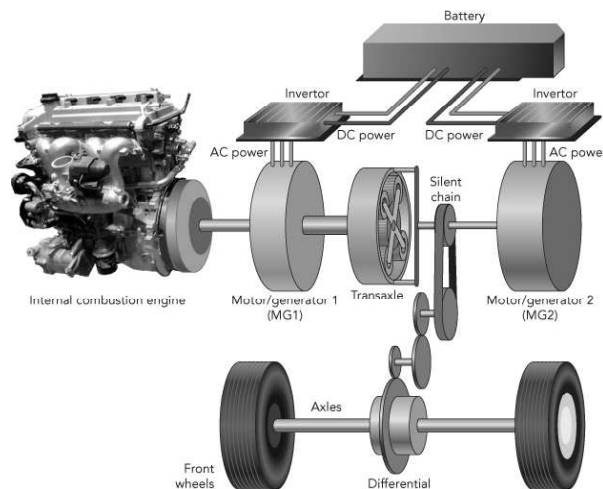


In a power station, a turbine is turned by high pressure steam. The steam can come from burning coal, natural gas, oil or nuclear fission. There have been experiments with using solar heat to generate the steam. The turbine turns a coil in a magnetic field. The induced voltage in the coil is sent out over power lines to power home, offices etc. The rotation of the coil in the magnetic field produces the AC currents we all use in our daily lives.

# Hybrid Cars

Hybrid cars use both an electric motor/generator and an internal combustion engine. The efficiency is greatly improved ( $\approx$  factor 1.5-2.0) by using this approach. This advantage is due to two different factors.

An internal combustion engine does not produce power efficiently at all speeds and loads. At low speeds, the engine is not as efficient as at high speeds. By charging a battery with the electric motor generator, the internal combustion engine can run at a more efficient power output. The electric motor can then be used in situation like starting when the internal combustion engine is not so efficient.



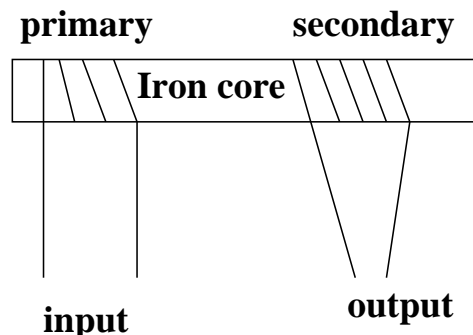
More relevant to our discussion of generators, the generator can be used as a brake when stopping the car. When the car is braking, the kinetic energy of the car is converted by the generator into current which charges the battery.

The main issue with a hybrid are the extra expense and complexity of having two propulsion systems.

# Transformers

One of the big advantages of AC is that it can be transformed from one voltage to another fairly easily without substantial losses. With a current, the power ( $P = I \cdot V$ ) lost to resistance is voltage times current. From Ohm's law,  $V = IR$  so power lost to resistance is  $I^2R$ . Since the resistance of a transmitting wire is fixed, we lower the losses if we transmit the power at **high** voltage and low current. This is why long distance power lines use high voltages (100,000 Volts or more) and low current (only a few amperes).

How do you get a high voltage to start with and, when you get it where you want, turn it back into something useful for the average house or office. Since the current is constantly changing, a transformer is just two coils of wire (called a primary and a secondary) connected magnetically. Normally an iron core is used since the iron couples the two coils together very well magnetically. The changing magnetic field produced by the primary induces a current in the secondary coil. The voltage of the output is determined by the number of input and output coils and the input voltage.



The relationship between the primary voltage, secondary voltage and the number of coils in the primary and secondary is given by:

$$\frac{\text{Primary Voltage}}{\text{Number of Primary turns}} = \frac{\text{Secondary Voltage}}{\text{Number of Secondary turns}}$$

With proper design of the materials and geometry of the iron core, transformers are efficient ( $\approx 99\%$ ). Because the losses are so low and since power is voltage time current, we can write:

$$\text{Power into Primary} = \text{Power out of Secondary}$$
$$(\text{Voltage} \times \text{current})_{\text{primary}} = (\text{Voltage} \times \text{current})_{\text{secondary}}$$

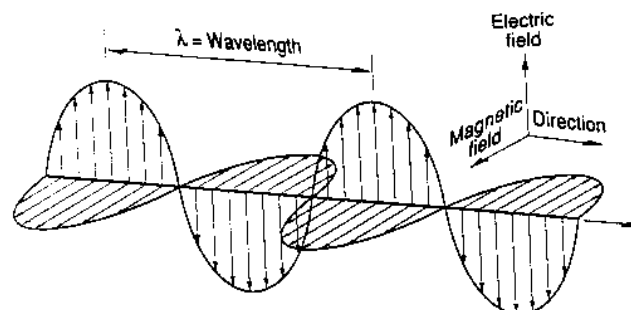
## Field Induction

In the 1860s, James Maxwell looked at what was known about electricity and magnetism. Purely by symmetry of the equation, he proposed that:

- A magnetic field is induced in regions of space in which an electric field is changing in time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the direction of the changing electric field.

This looks a lot like Faraday's law. Maxwell's counterpart is about changing electric fields producing magnetic fields. Faraday's law tells us a changing magnetic field produces an electric field.

With this observation (actually a change to an existing law) Maxwell explained **electromagnetic radiation** like light and radio-waves. Light is just magnetic and electric fields regenerating one another as they propagate.



How do you make an electromagnetic wave. You simply 'shake' (accelerate) a charge. To make radio or TV waves, a current is sent oscillating back and forth in the antenna. For FM and TV this is done at 100 MHz to several hundred MHz. For AM radio it is done at about 1 MHz.