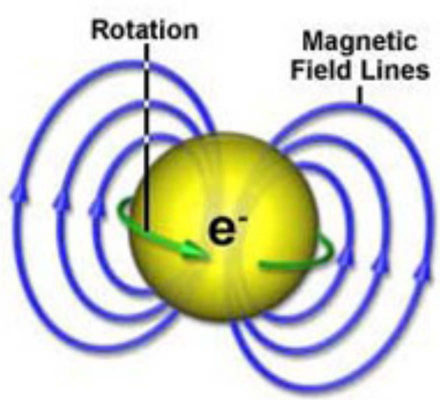
ELECTROMAGNETISM

I. CAUSES OF MAGNETISM

1. Moving electric fields (moving charges) cause magnetism. Yes, that current moving in electric circuits cause a magnetic field. More later!

2. Elementary nature of a material causes magnetism



Without diving too deeply here, electrons can be modeled like a spinning top. This causes a magnetic field. The electrons are like little bar magnets.

Materials with unpaired electrons, like iron, will sometimes have these little magnets lined up in one direction. When they do, the bulk material behaves like a magnet.

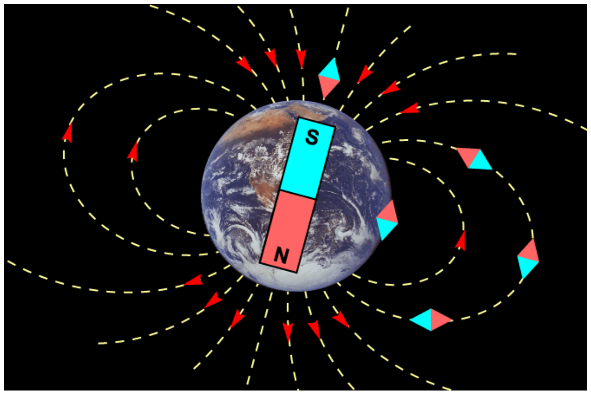
MAGNETIC DOMAINS in an object are areas that have an alignment of the magnetic fields of the each atom in the domain.

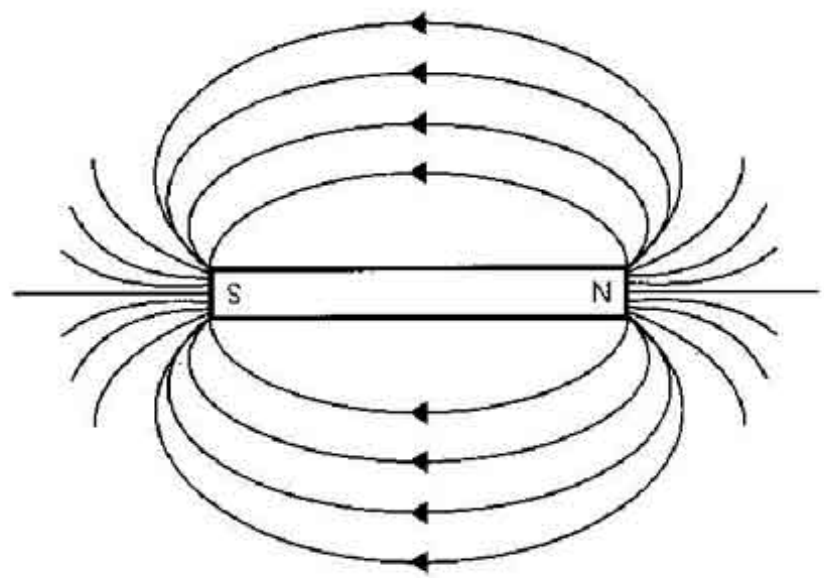
Domains Before Magnetization

Domains After Magnetization

arrows indicate direction of alignment of magnetic domains

II. MAGNETIC POLES AND FIELDS





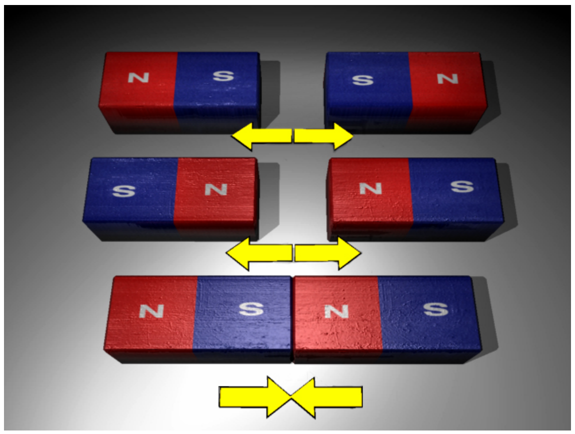
The Earth has a magnetic field.
It deflects charged cosmic particles, preventing them from entering Earth's atmosphere.

A bar magnet with imaginary lines of force. The lines reach from the N end of the magnet to the S end.

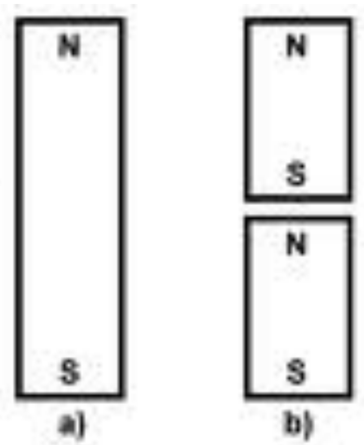
The magnetic field is detectable in the presence of other magnetic materials or when a moving charge passes through the field.

like the electric force or the gravity force, the magnetic force is an at a distance, non-contact force.

LIKE POLES REPEL. UNLIKE POLES ATTRACT.



in bulk, think of this as 1 magnetic dipole



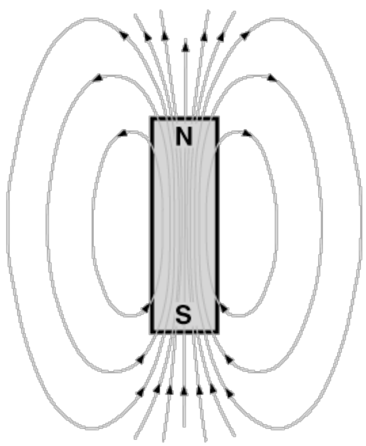
now we have 2 magnetic dipoles

Breaking a larger magnet results in smaller magnets with a N and S pole.

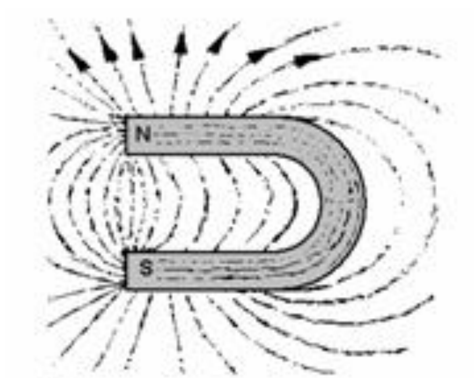
Key take-away from this page: There has never been an example of a magnetic monopole. Magnets are always dipoles, with magnetic field lines originating on the N end of the magnet and terminating on the S end of the magnet

Plots Magnetic Fields, B, for various magnet geometries

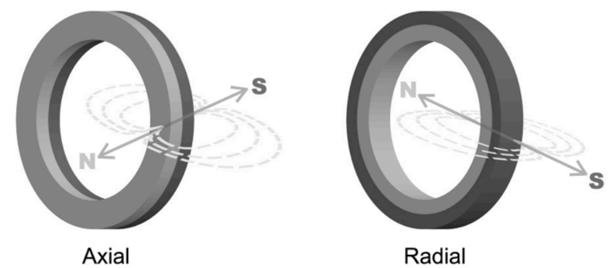
How the magnitude of vector B is calculated depends upon the geometry of the magnet that is the source of the magnetic field. The unit of magnetic field strength is the Tesla, T.



Bar magnet



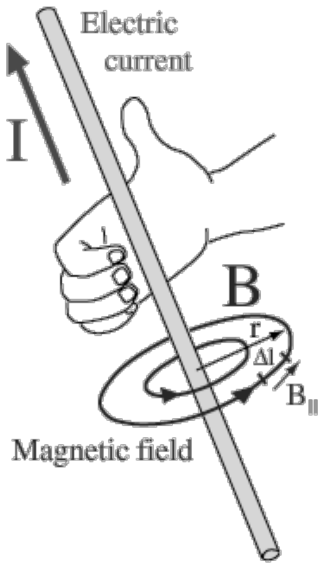
bent bar, horseshoe magnet



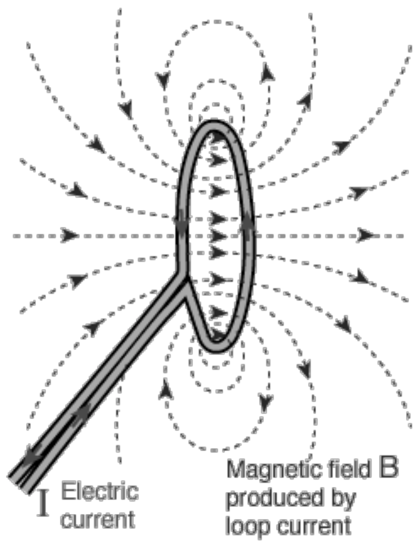
rings magnetized on different surfaces

Note that the magnetic field passes through the magnet itself, with the field line loops “closing” from S back to N

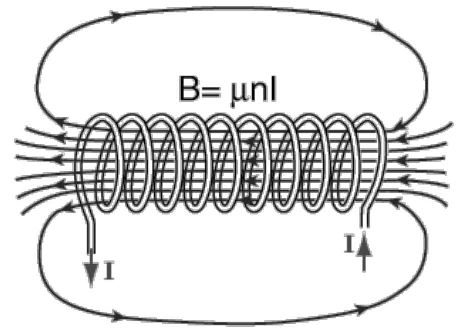
When a conductor is passing a current, I, a magnetic field is induced by the charge moving in a net direction



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



B field magnitude depends on whether you measure inside or outside the loop



The magnetic field is concentrated into a nearly uniform field in the center of a long solenoid. The field outside is weak and divergent.

This coil of wire is called a solenoid. The B field equation is for the field inside the coil.

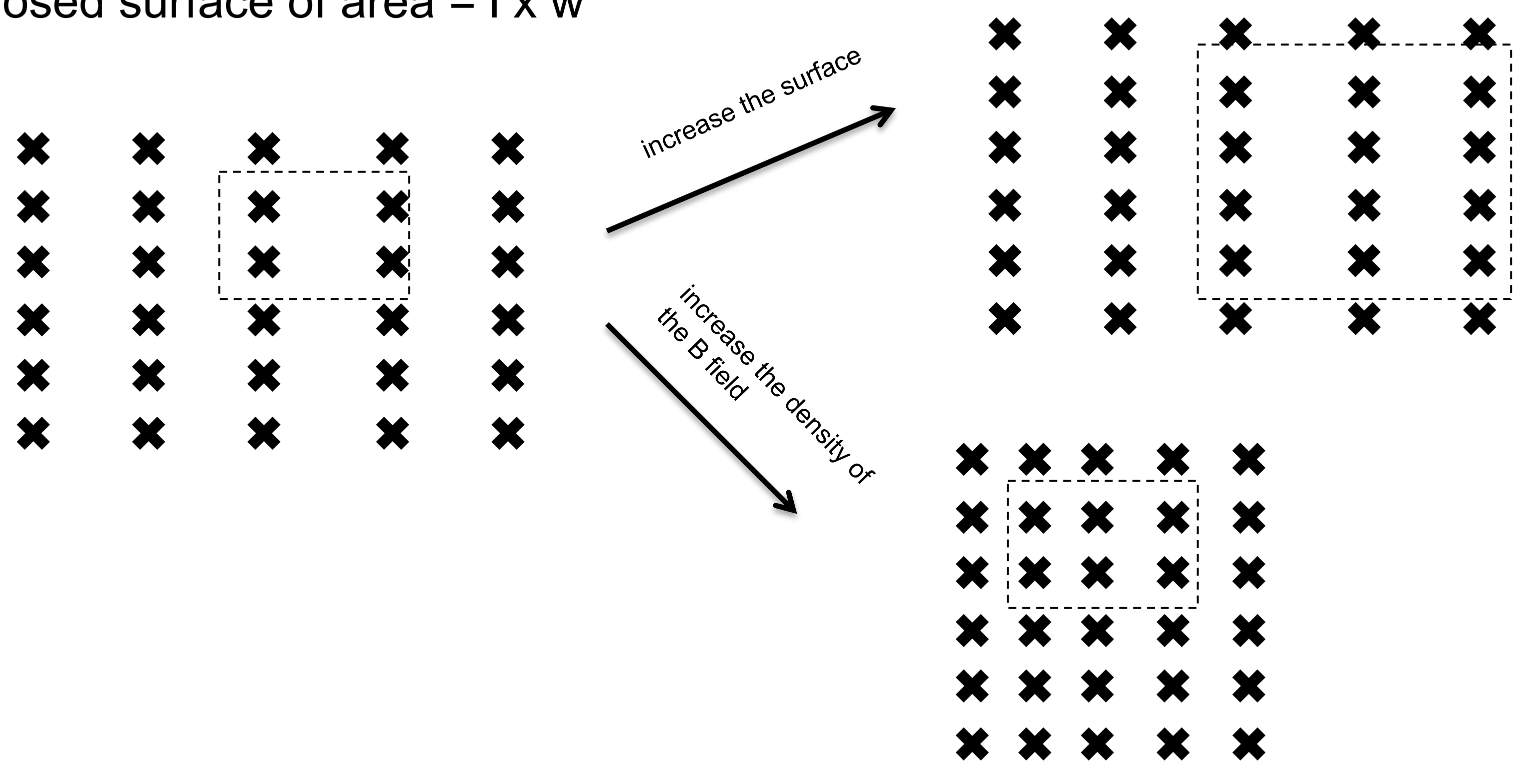
The B field magnitude is a function of the strength of the current and the geometry of the conducting path and the distance from the source. The field is weaker with increasing distance from the source.

What is Magnetic Flux?

Magnetic flux, ϕ, quantifies “how much” of a magnetic field passes through a given surface of area A

$\phi = B \bullet A = BA\cos\theta$ where θ is the angle between the magnetic field lines and the surface. When perpendicular to the surface, 0^{o} to the NORMAL of the surface, the maximum magnetic flux is observed since $\cos(0) = 1$ and $\phi = BA$

How increase magnetic flux: ✖ is the B field into the paper; dotted line is a closed surface of area = l x w



Lorentz Force Law

Both the electric field and magnetic field can be defined from the Lorentz force law:

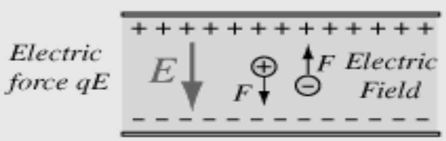
$$F_{total} = F_{elec} + F_B$$

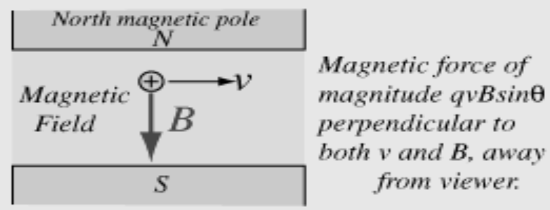
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Electric force — Magnetic force

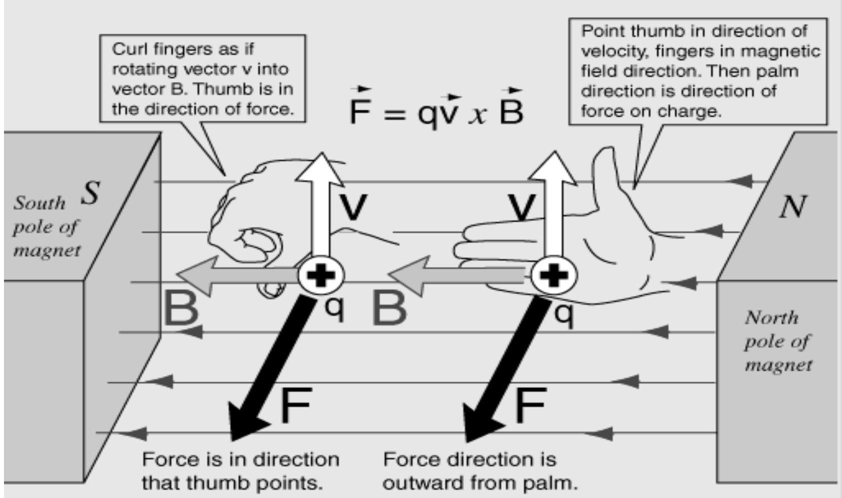
$F_{mag} = qvB\sin\theta$

The electric force is straightforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.





Right Hand Rule



what happens to the magnetic F when the particle is stationary?

Note too, that the magnetic force is always normal to the particle's velocity. *Hence, it can change the direction of the particle but WILL NOT do WORK on the particle and will not change its velocity.*

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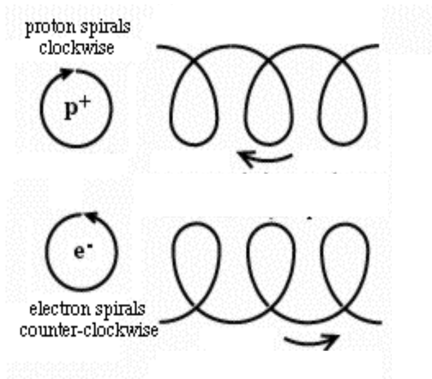
Charged particles and magnetic fields

If you remember Thomson's cathode ray experiment in Chemistry, then you recall that the path of an electron is bent by a magnetic field.

MOVING CHARGED PARTICLES generate their own magnetic field.
In the presence of an external magnetic field, their path can be pushed from linear.

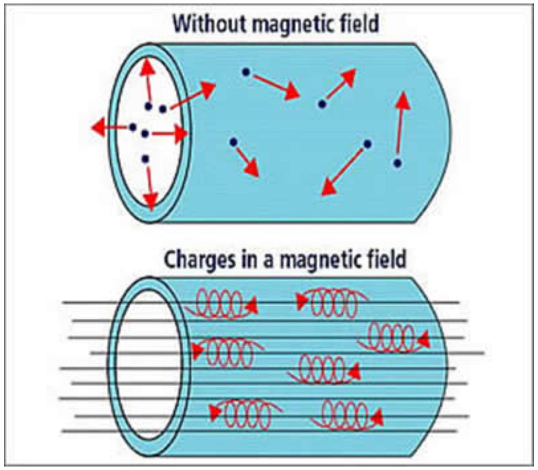
When charged particles cut across a magnetic field, their path is bent PERPENDICULAR to the field and the linear path of motion. - charges move in the opposite direction of + charges

If the particle is moving in the SAME direction as the magnetic field, no deflection is noted.



Magnetic Field lines
perpendicular to the paper, upwards

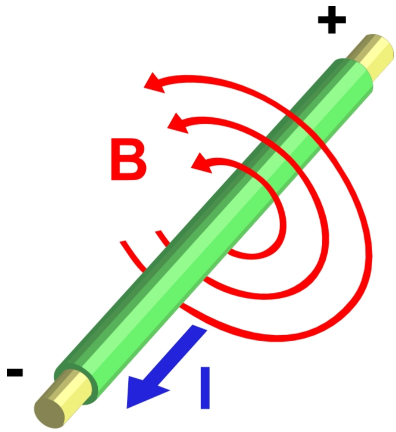
at the right speed, the particles will assume a circular motion in the magnetic field



Uncharged particles (moving or not) or STATIONARY charged particles are NOT affected by an external magnetic field

Magnetic field and current flow

An electric current in a wire contains particles (electrons) in motion. Therefore, there is a magnetic field surrounding a copper wire with a current in it. An amazing and important discovery was the fact that a wire carrying a current is deflected or pushed by an external magnetic field. The direction of the force can be reversed by reversing the direction of the current.

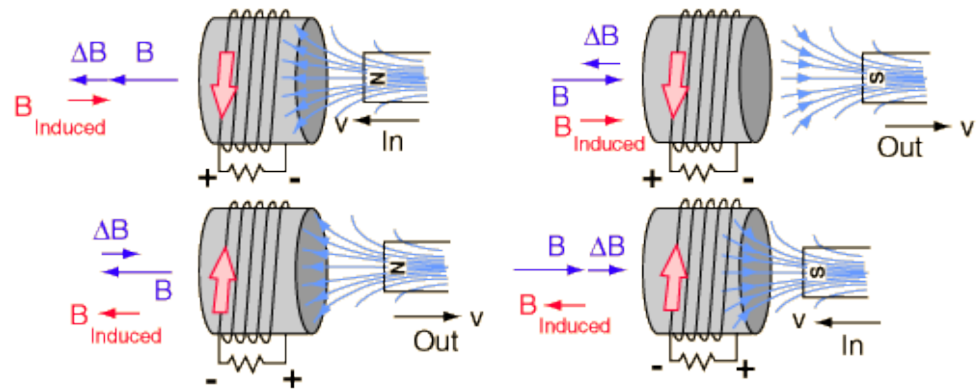


Point the thumb of your right right hand in the direction of the current. Wrap your fingers around the wire.

Your fingers point in the direction of the magnetic field.

This is one of the Right Hand Rules for determining the direction of current or magnetic field

NOTE: CURRENT DIRECTION IS CONVENTIONAL !!! ELECTRON FLOW IS THE OPPOSITE DIRECTION



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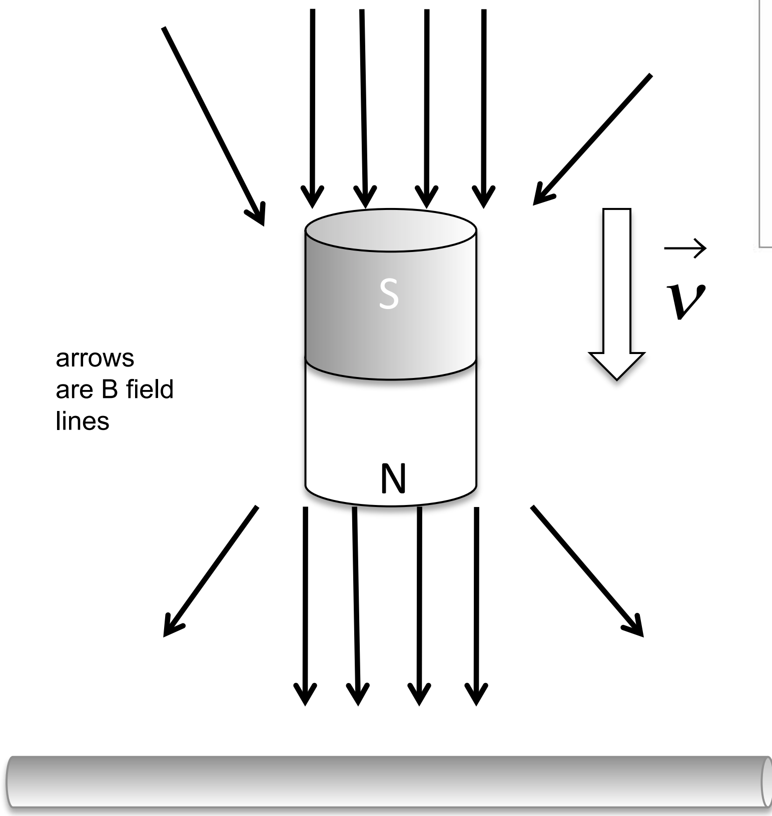
If an external magnetic is moved into a coil of wire, a current is produced. The current flows in the direction such that the magnetic field it produces OPPOSES the external magnetic field. You can think of this as another example of Newton's 3rd Law.

A wire with a current generates a magnetic field.

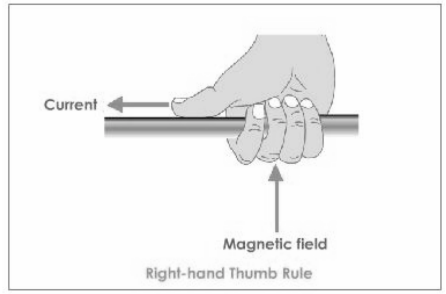
SIMPLE ILLUSTRATION OF LENZ'S LAW

"An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux."



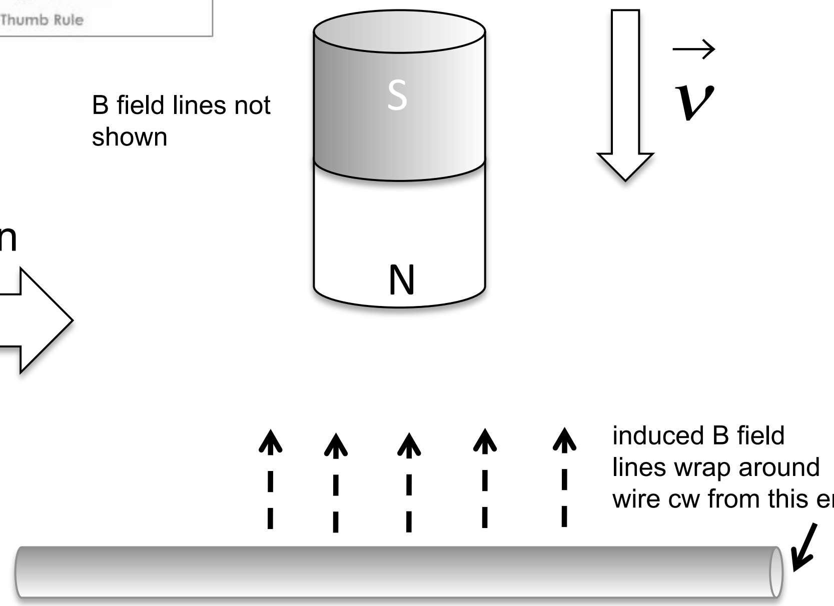
arrows are B field lines

no current initially



induction

B field lines not shown



induced B field lines wrap around wire cw from this end

← *i (conventional, positive current flow)*
e- go to the right

current must flow in such a way that the
induced magnetic field opposes the applied magnetic field

Questions:
What would happen if the S end of the magnet approached the wire?
What would happen if the N end of the magnet approached from the other side of the wire (from the bottom?)

III. Electromagnetic Induction

A voltage potential and hence a current can be INDUCED to flow in a conducting wire by passing a magnetic into and out of a loop of the wire.

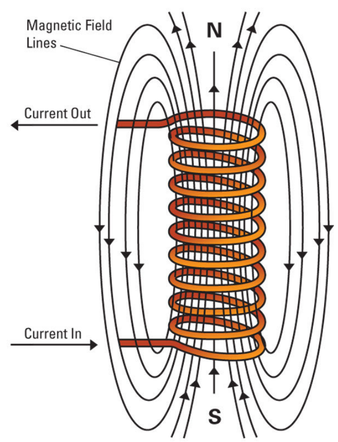
Or, a magnet can be held in place and a wire passed into and out of the magnetic field. This, too, will cause a current in the wire.

This important discovery is the basis for electromagnets and electricity production by ELECTROMAGNETIC INDUCTION

Faraday's Law allows us to predict the induced voltage from an electromagnet

$$\varepsilon = -N \frac{\Delta(BA)}{\Delta t}$$

BA represents "magnetic flux"



magnet passed back and forth through loops of wire gives an electric current

ε is the induced voltage or electromotive force
N is the number of wire loops
Δ(BA)/Δt is the rate of change of the magnetic field strength (B is the field strength and A is the surface area of the magnet or the perpendicular surface the magnetic field penetrates.)

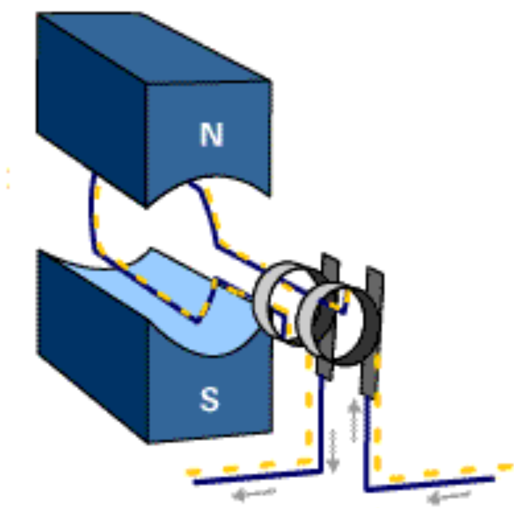
The (-) sign represents **Lenz's Law** which gives the direction of the electromotive force. "An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux." The induced voltage and the magnetic flux have opposite signs.

Oh yes, before you think we get something for nothing with electromagnetic induction, remember work has to be done to move the coil or magnet in order to make the current. The electricity is not free.

IV. ALTERNATING CURRENT

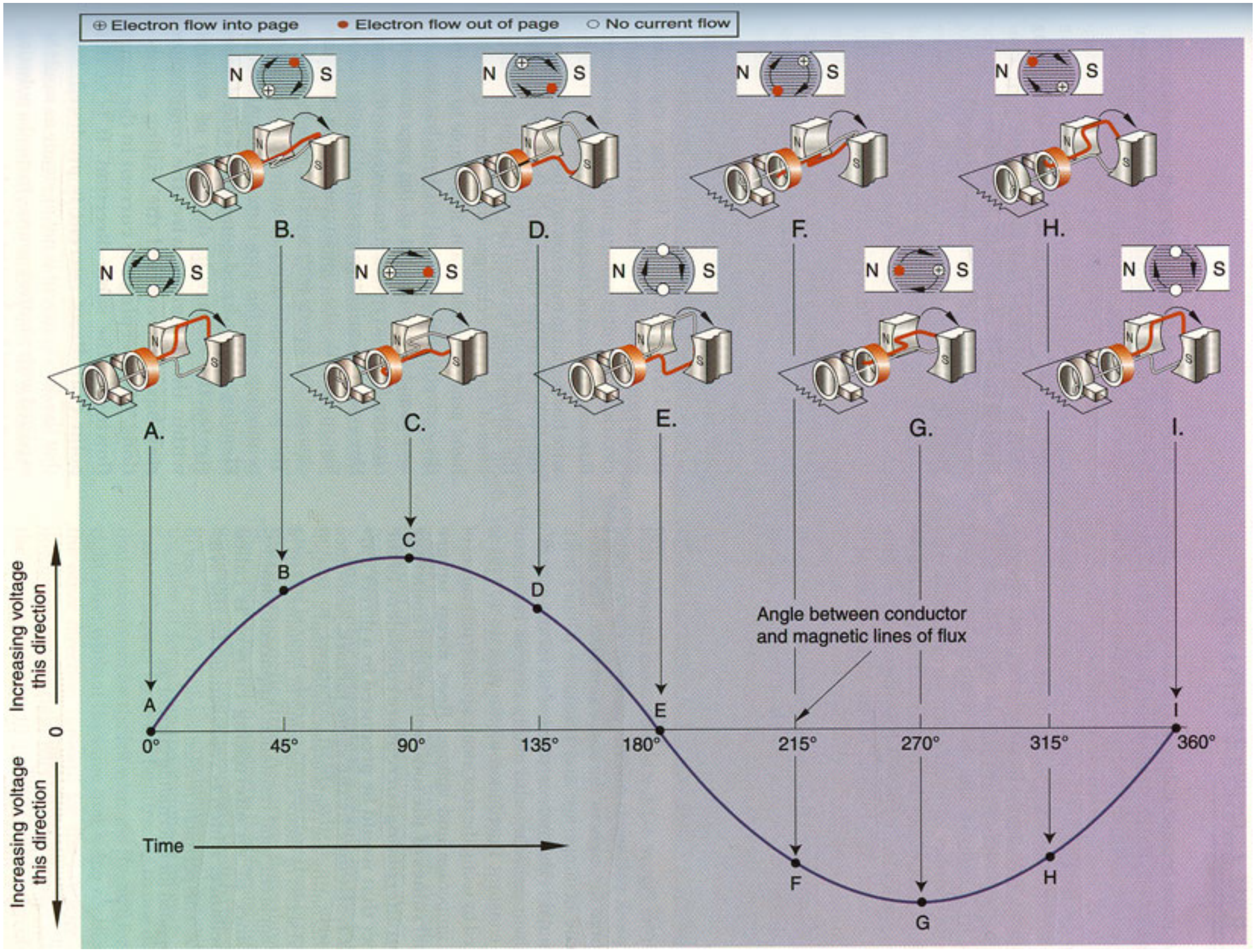
For producing current, it is more practical to have a loop of wire TURNING in a stationary magnetic field. This sort of device is called a GENERATOR.

The very act of TURNING the wire in the magnet causes the voltage to alternate, high to low, at a frequency depending upon how fast the wire loop turns. This alternating voltage occurs because a TURNING loop of wire breaks the magnetic field at different angles. At a certain point in the cycle, it doesn't break the field at all (it is parallel to it) and that point NO current is produced.



Here's a typical diagram of a simple generator. The loop of wire turns (possibly with a steam turbine) in the magnet. The AC voltage is used to push current along power lines to power society.

alternating current, continued



This diagram shows how the voltage alternates as the loop breaks the magnetic field at different angles as it turns

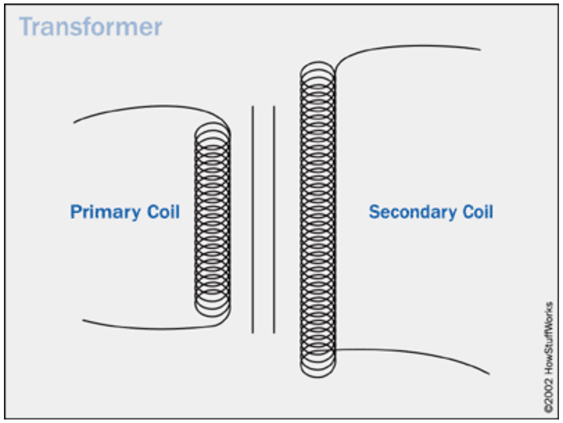
V. TRANSFORMERS

Transformers are devices that STEP UP or STEP DOWN AC voltage.

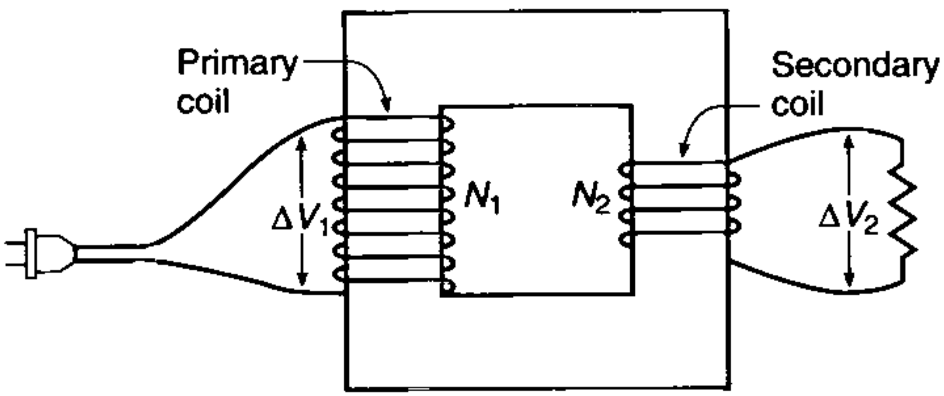
This is very practical since power lines push current with very high voltage potentials. Transformers step down the voltage for use in homes, etc. High voltage potentials are used to send low current down power lines. This is because HIGH current (not high voltage) causes a lot of heat over the long distance of a power line. The heat means large energy losses and inefficient electricity delivery.

A transformer is made of an iron core that is wrapped with a given number of colis of wire on one side of it. This is connected to a power source and these coils are called the PRIMARY COILS. The other side of the iron core is wrapped with a given number of coils of wire. In these coils a voltage is INDUCED. These are called the SECONDARY COILS and if their number is greater than the number of primary coils a HIGHER voltage is induced in the secondary coils. If the number of secondary coils is smaller, a lower induced voltage occurs in the secondary coils.

transformers, continued



If the primary coil were hooked to a battery, a voltage would be produced in the wire. The magnetic field generated would induce a voltage in the secondary coil, MOMENTARILY. If we unhook the battery, a brief change of voltage again occurs in the secondary coil but in the opposite direction.



An AC current serves to CONSTANTLY change (i.e. move) the magnetic field so that the voltage potential is sustained in the secondary coil. The voltage in the coils alternates because the current causing the magnetic field alternates.

Transformer equations:

$$\frac{\Delta V_1}{N_1} = \frac{\Delta V_2}{N_2}$$

since P = IV and P is constant,

$$\frac{I_1}{N_2} = \frac{I_2}{N_1}$$

VI. ELECTROMAGNETIC RADIATION, REVISITED

A **unifying** principle in physics is that ELECTRICITY, MAGNETISM, and LIGHT are different manifestations of the same thing:
THE ELECTROMAGNETIC FIELD

If you didn't learn it in the Waves Unit, by now you know from this unit that electric fields and magnetic fields are intimately related or tied together.

A moving electric field has a magnetic field perpendicular to it. A changing magnetic field generates a current (flowing charged particles) that has and electric field.

Maxwell discovered this about the NATURE of light. He was the first to realize that light (the whole electromagnetic spectrum) consists of energy with an oscillating electric field and an oscillating magnetic field perpendicular to the electric field. This energy is ultimately generated from a source consisting of oscillating (moving) charged particles (like the sun).

It always travels at the speed of light, no matter the wavelength or frequency

electromagnetic radiation is self-reinforcing. The oscillating electric field constantly generated an oscillating magnetic field and vice versa