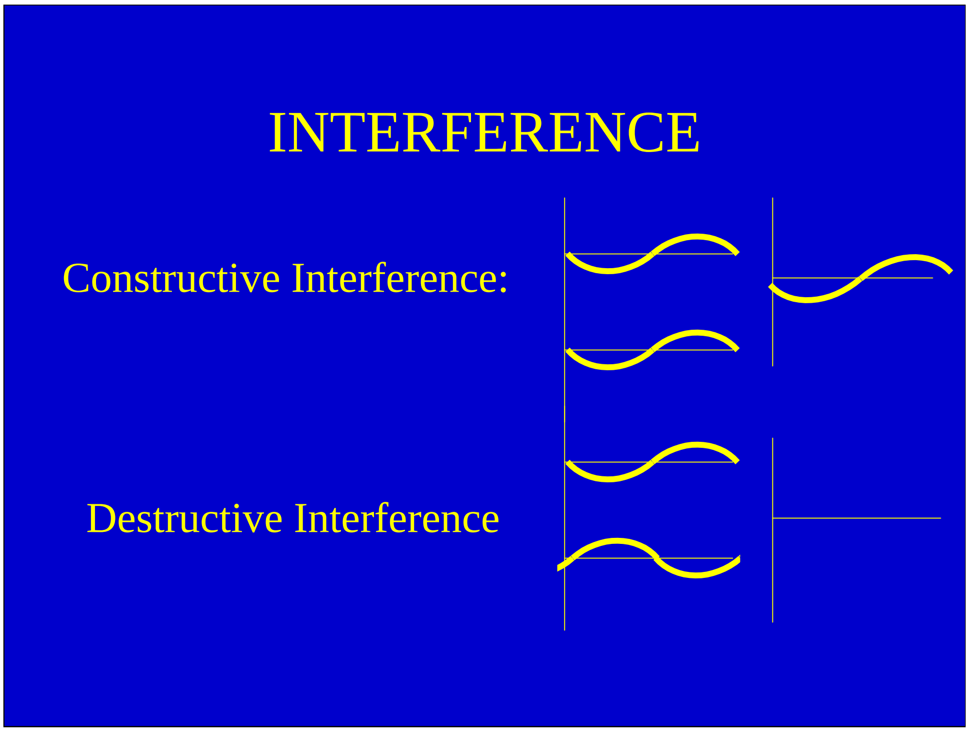


INTERFERENCE

Constructive Interference:

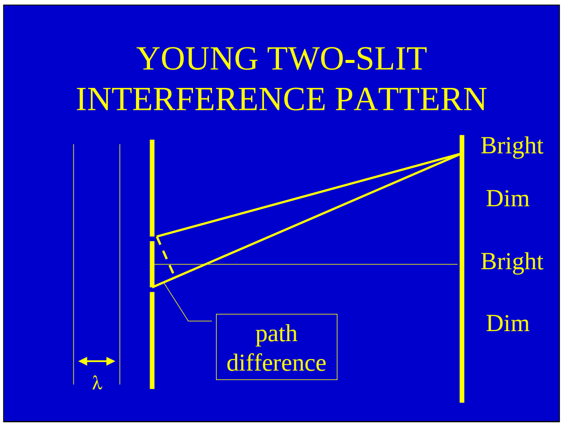
Destructive Interference

Interference refers to the superposition property of waves. If waves from two sources are brought together so the crest of one wave occurs at the same position as the crest of another, then the result is a larger amplitude wave. This is called constructive interference.

When two waves are brought together so the crest of one is at the same place as the trough of the other, then destructive interference occurs.

If light is a wave phenomenon, then it must exhibit interference. For different kinds of waves, we need to create special situations to make wave interference observable. Water waves, sound waves, and light waves each require different circumstances to bring out interference effects.

One way to do this with light is to separate a beam into two parts traveling different paths, then bring them back together again. If the two path lengths differ by ½ wavelength, the crests of one wave will line up with the troughs of the other, and we will see destructive interference. On the other hand, if the two paths differ by a multiple of a wavelength, then we will see constructive interference.



YOUNG TWO-SLIT
INTERFERENCE PATTERN

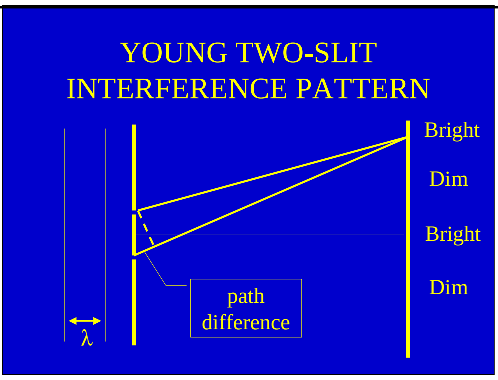
Thomas Young was a child prodigy. He began reading at age two and by 16 knew a dozen languages. He studied medicine and right away discovered how the eye focuses on objects at different distances. He explained that muscles around the lens in the eye contract or relax, making it more or less convex, and changing its focal length. For an object a certain distance away, a particular focal length is needed to produce a sharp image on the retina.

Young helped translate the Rosetta stone, found in Egypt by the French in 1799. It contains the same text in three languages, Greek, Egyptian demotic (used for books and deeds), and Egyptian hieroglyphics (with so many bird symbols).

Young knew the content of Newton's *Opticks* thoroughly. At one point he realized he could explain some of the experiments if he assumed that light was some kind of periodic wave, and that they obeyed the principle of superposition. Interpreting some of Newton's data in this way, he concluded that the wavelength of red light is 650 nm, and that of violet is 440 nm. Both numbers are close to modern values.

This is remarkable. It speaks very will for Newton's experimental skill and the accuracy of his descriptions of results he did not at the time understand.

So in the early 1800's Newton's particle theory and Young's wave theory of light coexisted. Newton's model could not account for the interference effects seen by Young, but his reputation was so strong that the particle model retained adherents for many years. As we have seen, in 1850, Foucault measured the speed of light in water and found it to be less than in air, so the wave theory triumphed. This still does not tell us, of course, what the wave consists of.



YOUNG TWO-SLIT
INTERFERENCE PATTERN

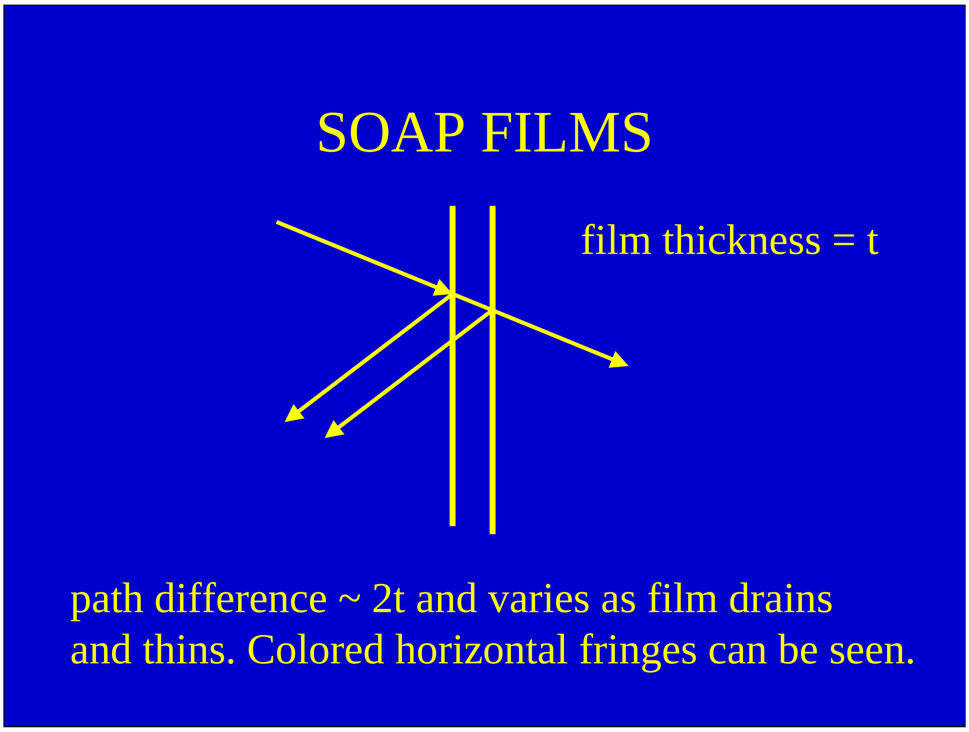
All during the 1700’s Newton’s particle model of light held sway. Huygens had proposed a wave model, but it was incomplete. There was no serious competition for Newton’s model until Thomas Young discovered interference of light in 1801.

The Young two-slit geometry is simple, easy to understand, and still one of the best demonstrations of light interference. Imagine two parallel slits cut into an opaque screen. Light of wavelength lambda from a distant source falls on the screen from the left as shown above. The only light to get past the screen comes through the two slits. The two slits act like sources of light that is “in phase”, i.e. the wave crests and troughs line up. If the slits are narrow enough, the light will spread. You can see this qualitatively by looking at a small bright object through the gap between two fingers at arms length, and squeezing the fingers until they nearly touch.

Behind the screen to the right is a white surface. What we want to observe is where on that surface light appears. Where does constructive interference from the two sources occur on the screen? First, it occurs in the center directly behind the two slits. The path lengths from the two slits are equal, and since the light waves were in phase as they came through the slits, they remain in phase after traveling equal distances. We see a bright stripe.

As we move upwards on the white surface, the path to the lower slit becomes longer than that to the upper slit. At some point this path difference becomes equal to ½ wavelength. Then destructive interference occurs: the wave crests from one slit line up with the troughs from the other. We see a dim stripe.

When the path difference equals one wavelength, we again see a bright stripe, and so on. A large number of bright and dim parallel stripes are seen. SHOW Single-slit and Young two-slit pattern.



SOAP FILMS

film thickness = t

path difference ~ 2t and varies as film drains and thins. Colored horizontal fringes can be seen.

If we create a soap film and view it in reflected white light, we see horizontal bands of color. Why does this occur?

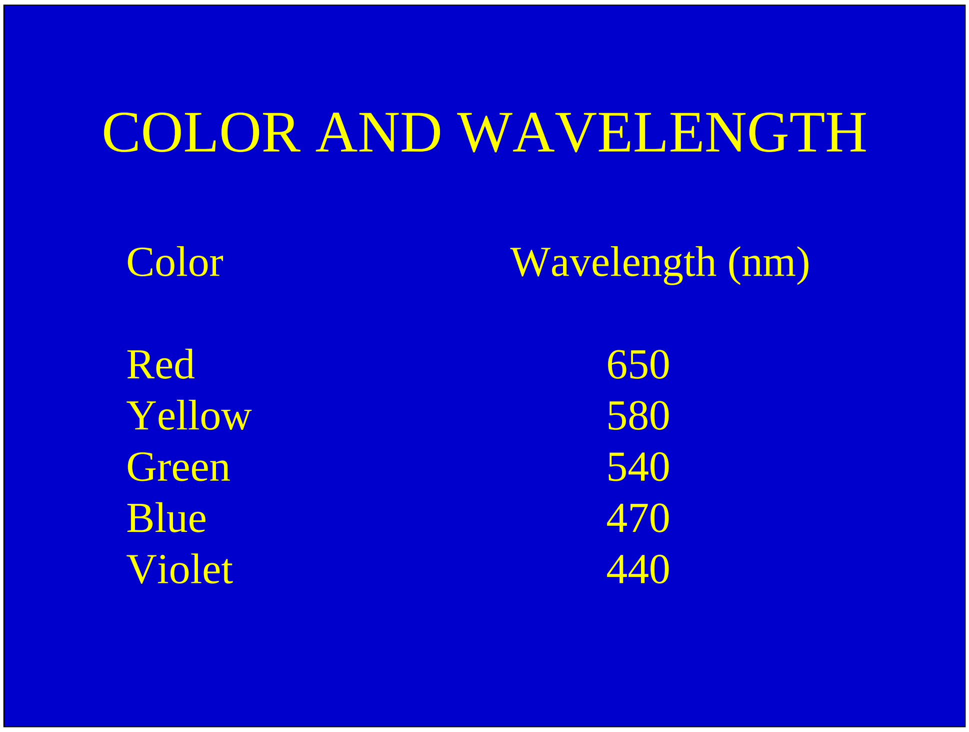
About 2% of the light beam is reflected at the air-water interface. So 98% continues on through, and 2% of this reflects from the back surface of the film. These two reflected beams emerge parallel to each other. They differ in distance traveled from the front surface by about twice the thickness of the film.

If this path difference equals a multiple of a wavelength of light, then we will see constructive interference. It will be destructive if the path difference is half a wavelength.

Different colors of light have different wavelengths. We started with white light, which, as Newton showed, contains all colors, hence all wavelengths.

The soap film thins with time by draining and evaporating. As water flows downward, the top becomes thin, and the film becomes slightly wedge-shaped. This is the reason for the horizontal bands of color. When the film thickness produces a path difference equal to a multiple of the wavelength of red light, we see red, and the same for other colors.

SHOW soap film in reflected light.



COLOR AND WAVELENGTH

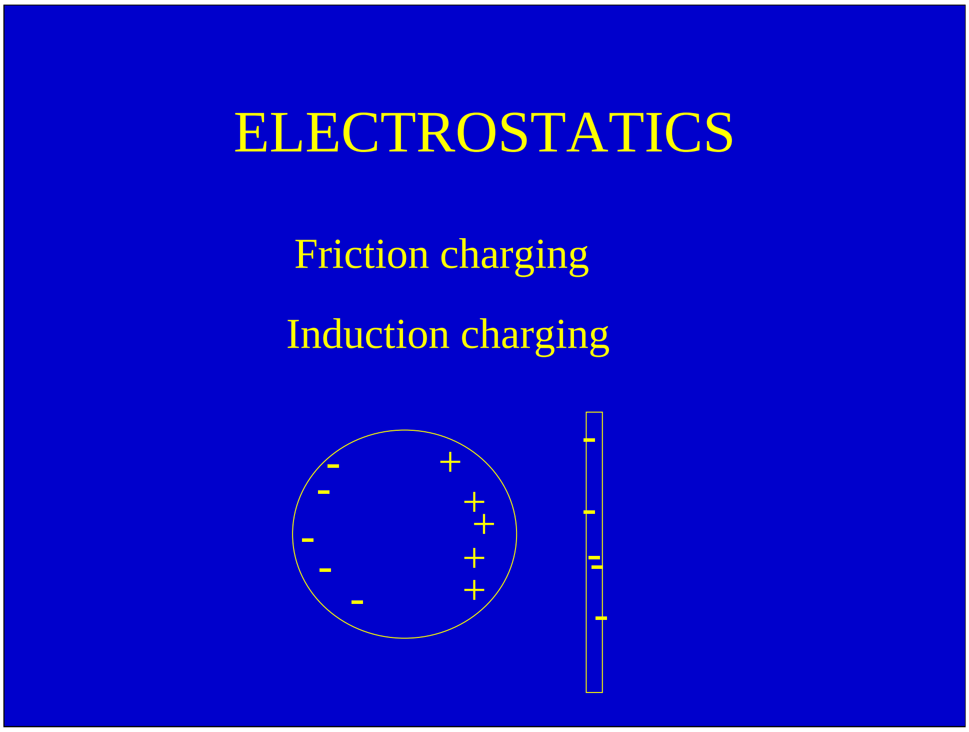
Color	Wavelength (nm)
Red	650
Yellow	580
Green	540
Blue	470
Violet	440

This table shows a rough correspondence between the colors of the rainbow or produced by a prism and the wavelength of light involved.

Colors used in decoration or by artists are more complex. What is called color above is referred to more generally as hue. A second color quality is called saturation. When we see green leaves on trees close up, they are pure green and close to the above wavelength in the spring. When seen from a distance however, scattering of the light between us and the trees adds a white haze to the green. The green is the same hue, but now less saturated.

When seen from even greater distances, a blue is added due to the blue light from the sky scattering into our eyes. This is how the Blue Ridge got its name.

So our perception of color is not just a simple matter of the wavelength of the light involved. Most outdoor colors are due to several contributions.



ELECTROSTATICS

Friction charging

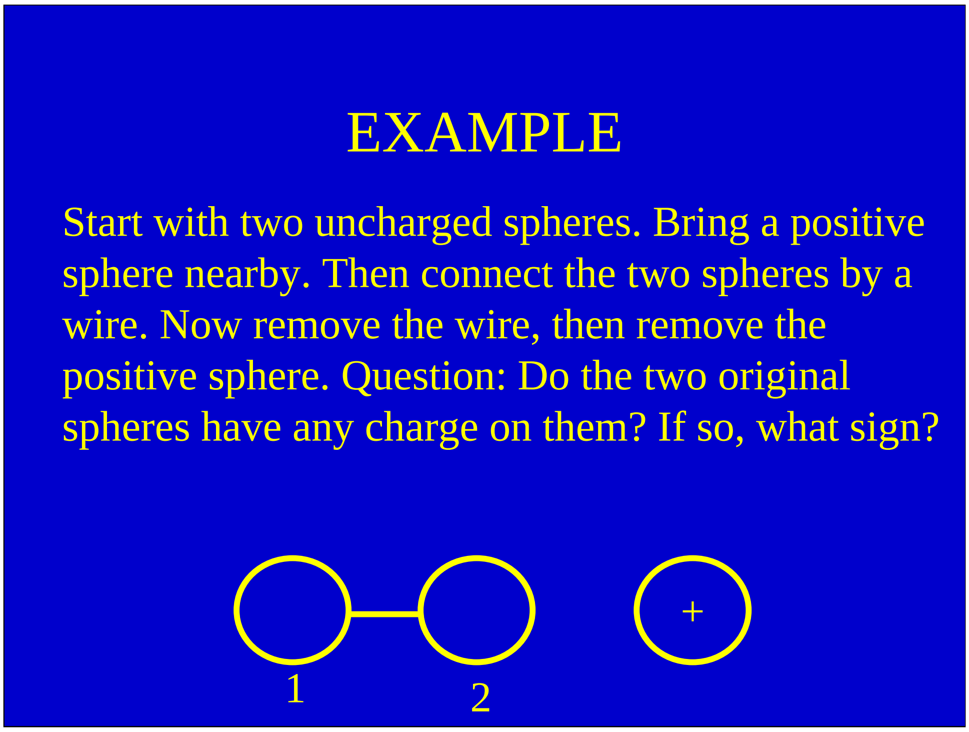
Induction charging

Now we know that light is a wave of some kind. But what is it that “waves” when we see a beam of light? To understand this, we need to take what might seem an unlikely turn. We study electrostatics. People have known for many centuries that on a dry day when you rub certain materials together, sparks can be generated. What is happening is this: All matter consists of huge amounts of positive charge (the nuclei of atoms) and negative charge (electrons on the atoms). Usually the two are exactly balanced and matter is neutral.

But if you rub a Teflon rod with silk, the teflon becomes negatively charged. It has taken a very small fraction of the electrons from the silk. This is called friction charging. SHOW charging pith balls. First they are attracted, then repelled. Like charges repel; Unlike charges attract each other. Pith balls are one way of detecting the presence of charge.

SHOW Braun electroscope. Electronic electroscope. SHOW 2x4 on watch glass.

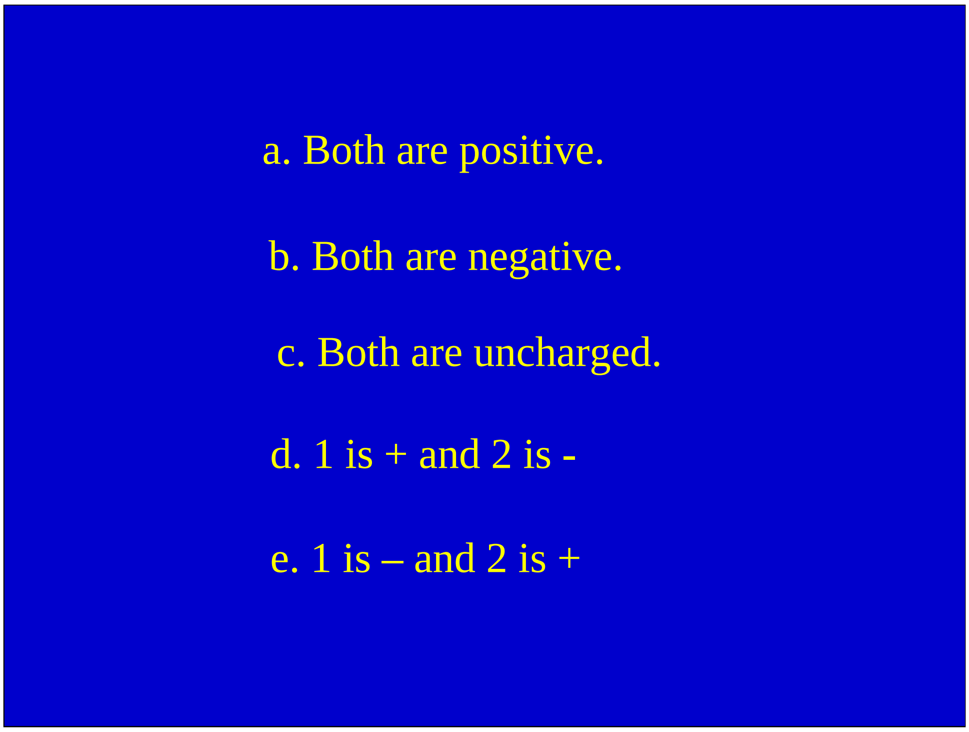
SHOW induction charging of mounted sphere. Induction charging results in the opposite sign of charge from the inducing rod. The negative Teflon rod attracts positive charges to the near side of the sphere, and repels negative charges to the other side as shown above. When the far side is then grounded, the negative charges leave, being able then to move even farther from the negative rod. Now the sphere has a net positive charge.



EXAMPLE

Start with two uncharged spheres. Bring a positive sphere nearby. Then connect the two spheres by a wire. Now remove the wire, then remove the positive sphere. Question: Do the two original spheres have any charge on them? If so, what sign?

Here is a question involving charge sharing between two spheres. They are momentarily connected by a wire which allows charge to flow between them.



a. Both are positive.

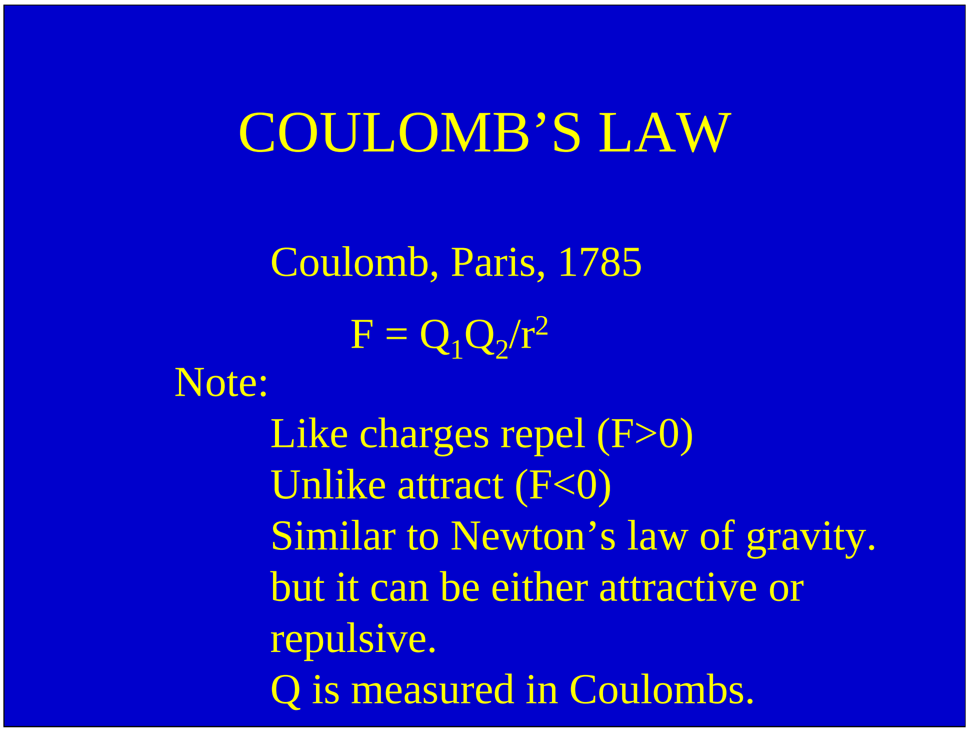
b. Both are negative.

c. Both are uncharged.

d. 1 is + and 2 is -

e. 1 is – and 2 is +

Here are the choices for the charges on the spheres. The correct answer is d. Positive charges are repelled from the third charged sphere. They flow through the wire when it is connected, and remain trapped on sphere 1 when the wire is removed. Similarly for the negative charges attracted to sphere 2.



COULOMB’S LAW

Coulomb, Paris, 1785

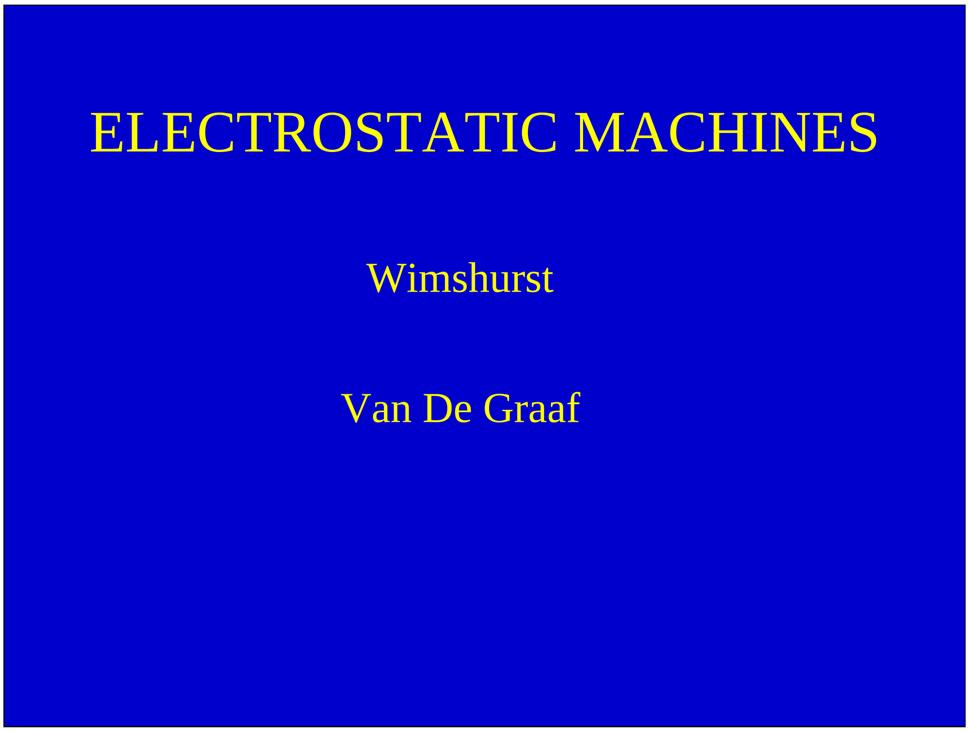
$F = Q_1Q_2/r^2$

Note:

Like charges repel ($F>0$)
Unlike attract ($F<0$)
Similar to Newton’s law of gravity.
but it can be either attractive or repulsive.
Q is measured in Coulombs.

In 1785 Coulomb showed how the electric force between two objects varies with the amount of charge and the distance apart. Henry Cavendish had discovered this result many years earlier, but had not published it. Coulomb had been a French military engineer who had worked on the fountains at Versailles, since there hadn’t been any wars. When he retired, he served on hospital commissions and other such things. He reinvented the torsion balance (being unaware, as the French are, of what had been going on in England), and used it to measure the force between two charged pussy willow catkins.

The unit of charge is named after Coulomb for this work.



ELECTROSTATIC MACHINES

Wimshurst

Van De Graaf

A Wimshurst machine is a very early device that generates charge by induction. The charging process is repeated over and over as the two disks rotate, allowing a sizeable charge and voltage to be generated. It takes about 30,000 volts to cause a spark in air one inch long.

A Van De Graaf machine can generate even higher voltage. It separates charges with a belt that is charged up as it passes by in the lower box. The charge is then carried to the sphere where it is deposited. SHOW pom pom, spinning pointer, jumping balls, …

ELECTRIC FIELD
AND POTENTIAL DIFFERENCE

The electric field, E, is defined as the electric force per unit charge in a region.

$E = F/q$ (Newtons/Coulomb)

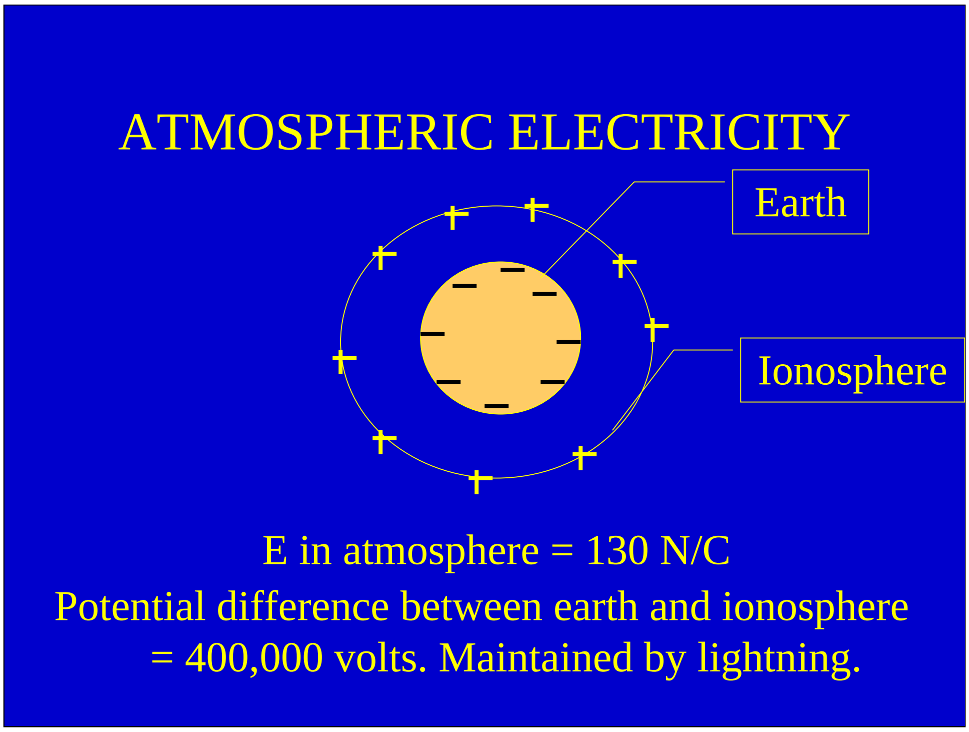
Electric potential difference is the work done per unit charge in bringing a charge to that location.

$V = W/q$ (Joules per Coulomb or Volts)

It is convenient to define the electric field as the force per unit charge in a region of space. E is caused by other charges in the area.

The SI unit of charge is the Coulomb. So electric field has units of Newtons per Coulomb.

Electric potential difference is the work done per unit charge on bringing a charge to its location. It is measured in volts, and can be either positive or negative. Whenever a potential difference exists between two points, there must be an electric field between them. When a charge is carried from one point to the other, work is done on the charge by the electric field, creating the potential difference.



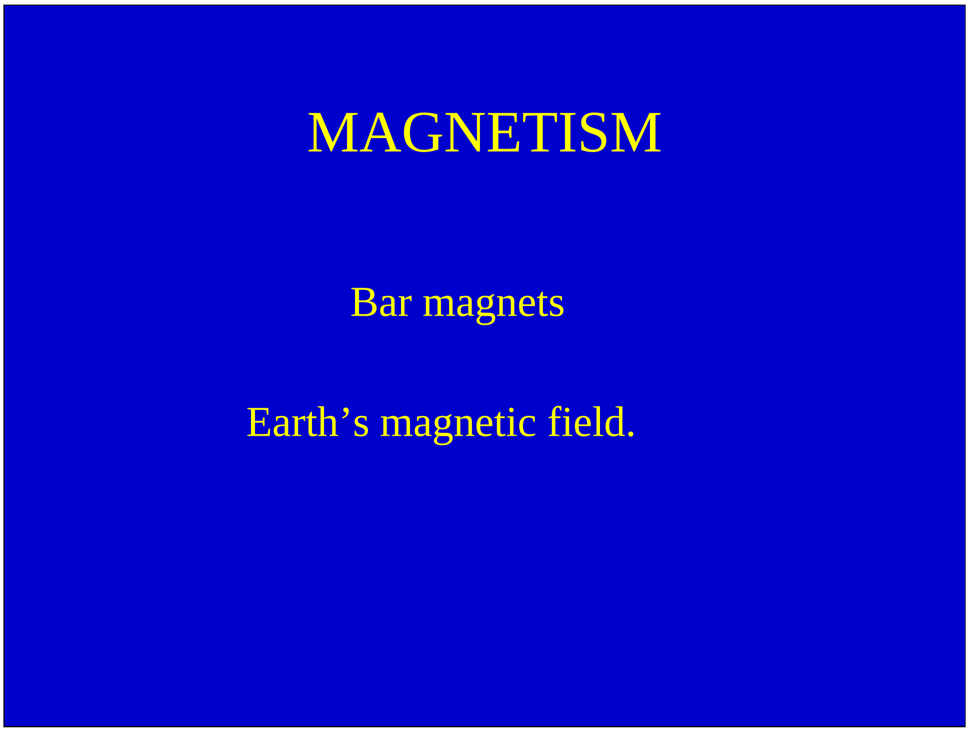
ATMOSPHERIC ELECTRICITY

E in atmosphere = 130 N/C

Potential difference between earth and ionosphere = 400,000 volts. Maintained by lightning.

On a clear day when you go outside, there is an electric field in the air of about 130 N/C pointing downward. The Earth is negatively charged and the ionosphere positively charged. The ionosphere is a layer of the upper atmosphere where the air is very thin and cosmic rays produce lots of ions.

Positive charges from the ionosphere slowly leak through the atmosphere to the earth, discharging it. The electric field would die out in a few minutes if nothing were maintaining it. What does the maintenance? The answer is lightning. A thunder cloud separates + and – charges by a mechanism still not understood. The result is the top of a thunderhead is + and the bottom -. So when lightning strikes the earth, it brings – charges down, and when it strikes upward into the ionosphere, it brings + charges up.



MAGNETISM

Bar magnets

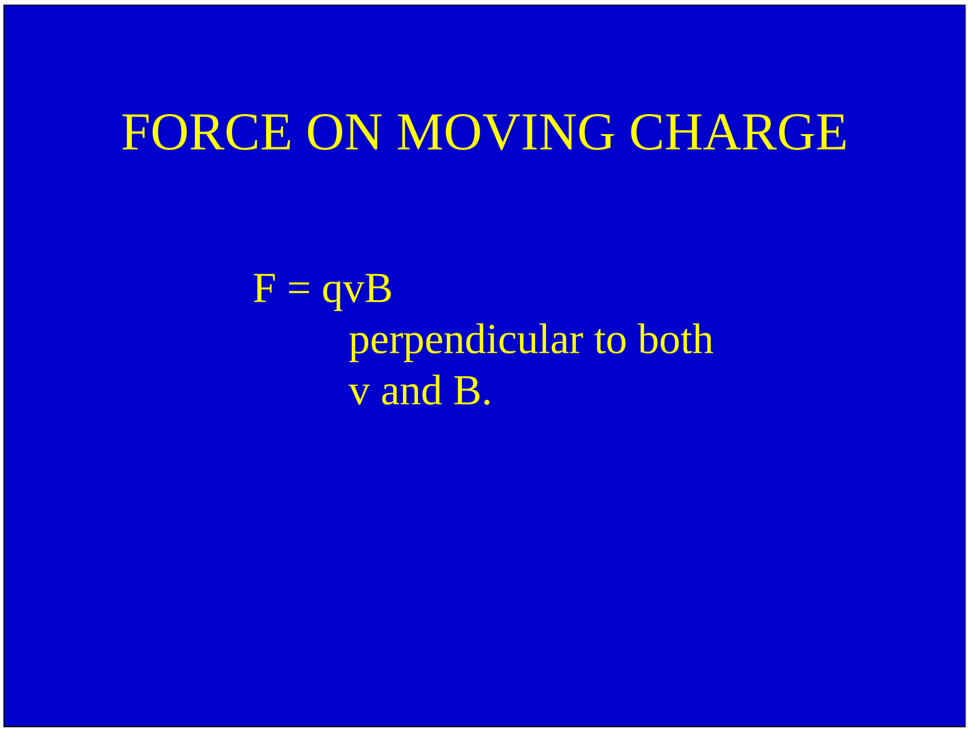
Earth’s magnetic field.

Magnetism has always had an air of mystery about it. We speak of animal magnetism. There is a new age idea popular today that having a magnet near your body helps it in some way.

We have all played with permanent magnets and felt the force between them. We ascribe the force to a magnetic field, B, produced by the magnets. We will see as we go along that all magnetism is due to electric currents. It is just Coulomb’s law when the charges are moving.

SHOW: Overhead projector view of B pattern around a bar magnet. SHOW compass needle array on overhead.

Deep within the earth is a core primarily made of molten iron. It produces a magnetic field by a mechanism having to do with the rotation of the earth, that is not well understood. One of its idiosyncrasies is that the direction of the field reverses sporadically about four times per one million years. We don’t know why it does this, but then we don’t know why it is there in the first place either.



FORCE ON MOVING CHARGE

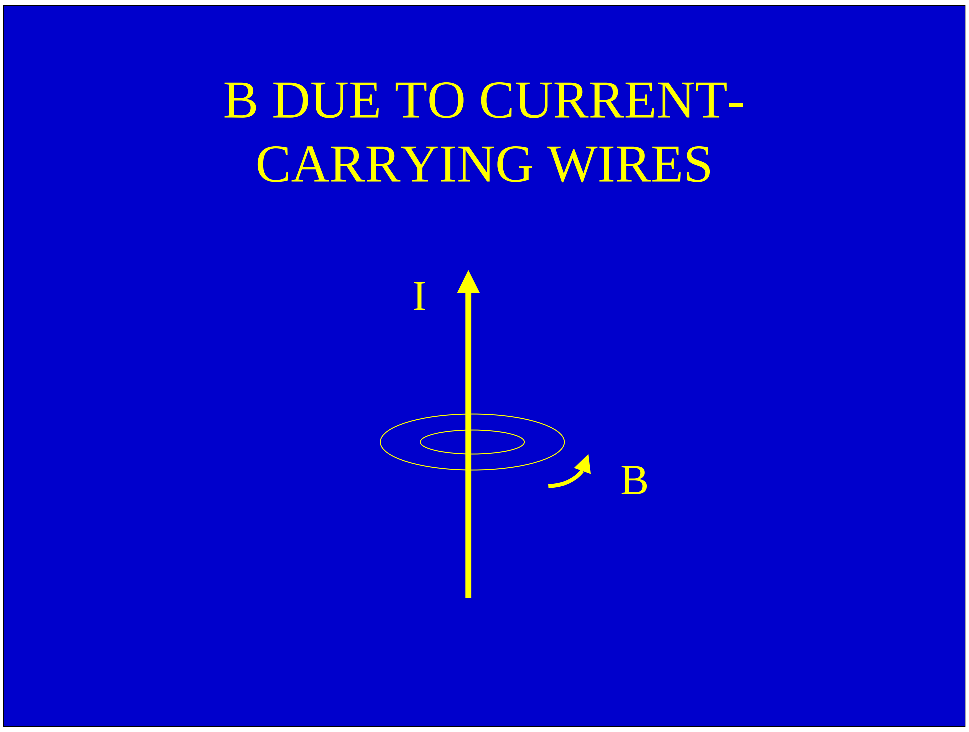
$F = qvB$

perpendicular to both
v and B.

An important advance was made when it was discovered that a B field exerts a force on a moving charged particle. This is an important clue. It takes us a step away from the murky business of permanent magnets and tells us that there is a direct connection between magnetism and moving charges.

A curious feature of the magnetic force is that it is exerted sideways both to the direction of B and the direction of the velocity of the moving charge. SHOW CRT e beam and B field.

This is the force used to steer the electron beam that paints a picture on the phosphor screen of a conventional TV set or computer monitor. This force can cause a moving electron or proton to move in a circle in a constant magnetic field. It provides a centripetal force similar to that caused by a string tied to a ball being whirled in a circle: acting always perpendicular to the velocity. Cyclotrons and other accelerators use this force, and in space near the Earth, charged particles from the sun are steered by this force caused by the Earth’s magnetic field.



B DUE TO CURRENT-CARRYING WIRES

If a moving charged particle experiences a force in a magnetic field, we can ask whether it creates a B field of its own. The easiest way to check this out is to use the moving charges in a current-carrying wire. SHOW overhead view of B near current-carrying wires.

So now we have gotten completely away from permanent magnets, the historical and mysterious origin of the study of magnetism. From this point forward it became possible to create magnetic fields using coils of wire. A much cleaner and more predictable way to do so.

Actually, all magnetic fields are created by electric currents, even in permanent magnets. The way this works is that electrons bound to atoms go around in circles about the nuclei, forming little current loops. When these current loops interact with each other so as to line up, we have a permanent magnet.

ELECTROMAGNETIC INDUCTION

Faraday’s Law:

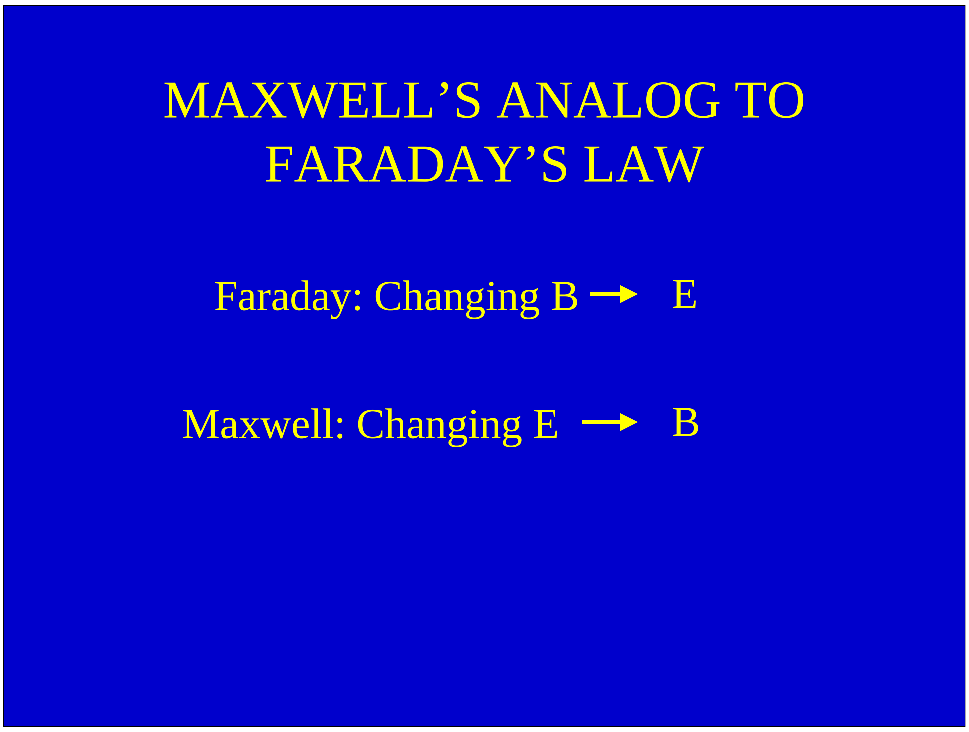
Voltage is induced in a coil proportional to the rate at which B is changing in the coil and the number of turns.

About 150 years ago Joseph Henry in the US and Michael Faraday in England were puzzling over the following paradox: A piece of iron placed in a coil becomes magnetized when a current passes through the coil. So one might think that the reverse should also occur: When a bar magnet is placed in a coil, does a voltage or current occur?

What they found was that a voltage does occur, but only as the bar magnet was entering or leaving the coil. SHOW induced induced voltage around coil when magnet enters or leaves. SHOW large coil with LEDs.

Here we have a second connection between magnetism and electricity. A magnetic field is caused by an electric current, and a voltage is induced by a changing magnetic field.

Lenz’s Law: The current induced in a coil is in such a direction to oppose the changing magnetic field that caused it. SHOW ring jumping from coil. SHOW magnet falling through copper tube.



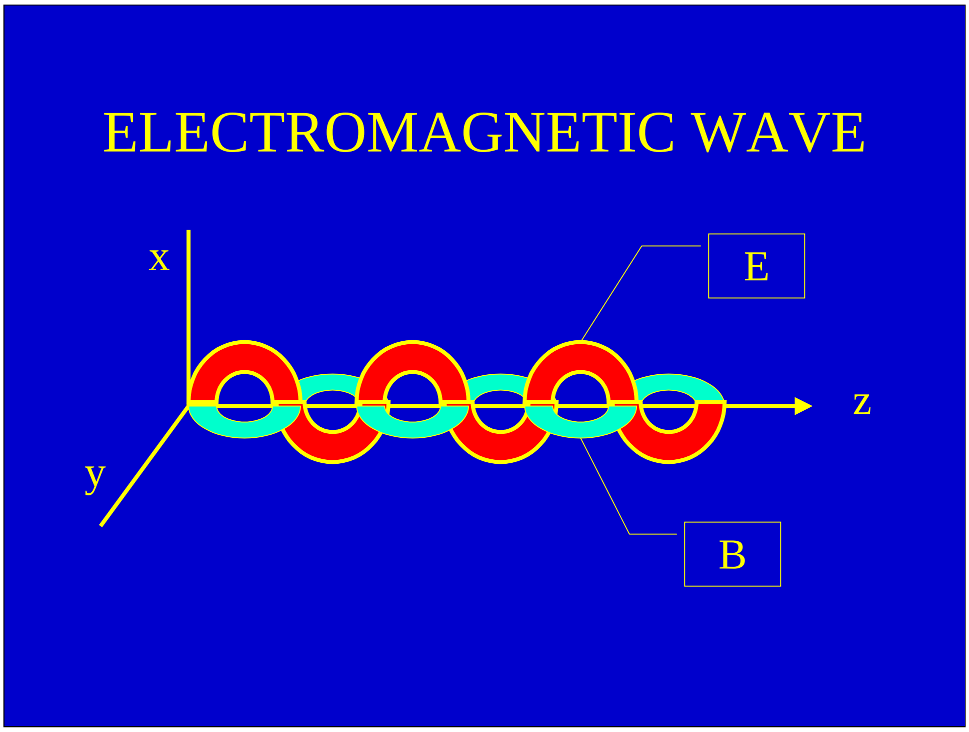
MAXWELL’S ANALOG TO FARADAY’S LAW

Faraday: Changing B → E

Maxwell: Changing E → B

In the 1860’s in England, James Clerk Maxwell was the leading physicist of his generation. One day in 1864 he wondered about the above possibility. If a changing B field produces an E field, as Faraday and Henry had demonstrated, could the reverse also occur?

He tried the idea out, and showed that these two effects together predicted that the electric and magnetic fields together would make waves that propagate through space. The changing B field creates an E field, which creates a B field, and so on. The two fields together regenerate each other.

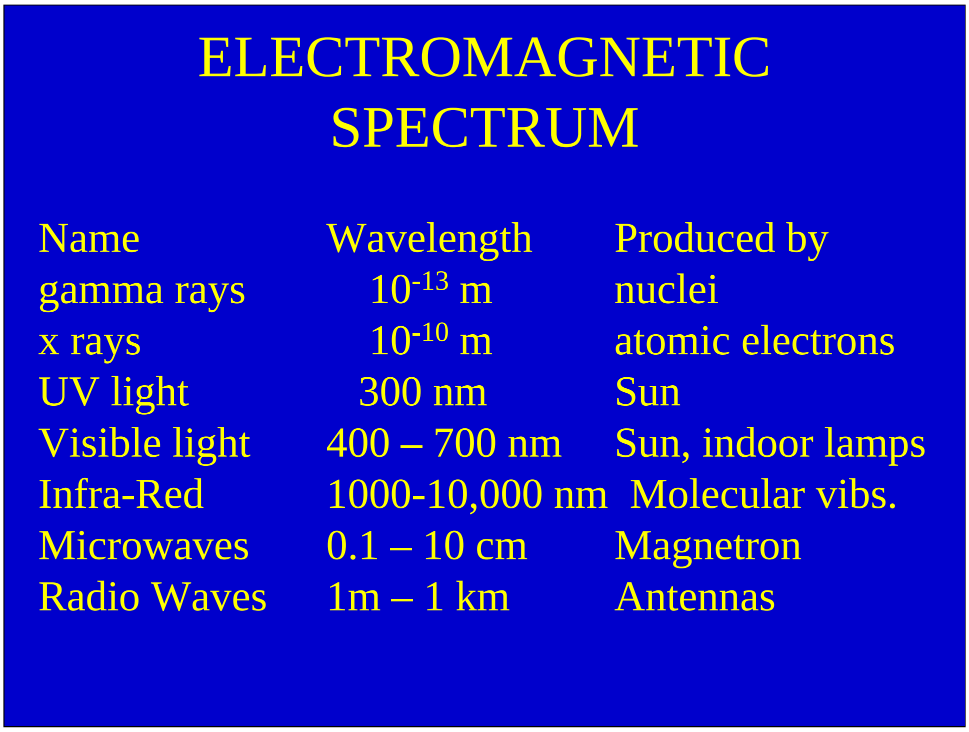


ELECTROMAGNETIC WAVE

A traveling electromagnetic wave can look like this schematic picture. Here we see a wave traveling in the z direction. The electric and magnetic fields of which it is composed are oriented in the x and y directions respectively in the plane perpendicular to the direction of propagation. The wave sketched above is polarized in the x direction. The orientation of the electric field specifies the axis of polarization. Another wave could be sketched with the electric field in the y direction and the magnetic field in the –x direction.

When Maxwell solved his equations for the wave speed, given in terms of coefficients in the equations describing electric and magnetic field behavior, he found it was equal to the speed of light (within experimental errors). He was astonished. The problem of the nature of light had been around for millennia. By making this one conjecture and combining it with Faraday’s law, Maxwell had found the answer.

SHOW parallel wire transmission line. Here we have a standing wave confined to the two wires. It is generated from one end, travels out with the speed of light, and reflects off the other end. This is analogous to the spring we saw last week shaken at one end and fixed at the other.



ELECTROMAGNETIC SPECTRUM

Name	Wavelength	Produced by
gamma rays	10^{-13} m	nuclei
x rays	10^{-10} m	atomic electrons
UV light	300 nm	Sun
Visible light	400 – 700 nm	Sun, indoor lamps
Infra-Red	1000-10,000 nm	Molecular vibs.
Microwaves	0.1 – 10 cm	Magnetron
Radio Waves	1m – 1 km	Antennas

The propagation speed, and transverse nature of electromagnetic waves is specified by Maxwell’s equations. What is left completely free is the wavelength of the waves. Maxwell’s equations describe all of the above examples, ranging from AM radio waves to gamma rays. All that changes on this list is the wavelength. The processes that produce the waves, and the ways we humans use them are completely different. Before Maxwell, people had no idea that UV light and Infra-Red were just the same thing with different wavelengths. And most of the other examples above had not yet been observed at that time.

So Maxwell’s results not only unified electric and magnetic phenomena, they also unified all of the above examples under a single theoretical description. Today in theoretical physics, people are trying to emulate what Maxwell did: To devise theories that bring together, or unify, seemingly different forces. The ultimate goal is to create a theory that unifies gravity, electromagnetism, and the strong and weak nuclear forces. Of these, gravity is the hardest nut to crack.