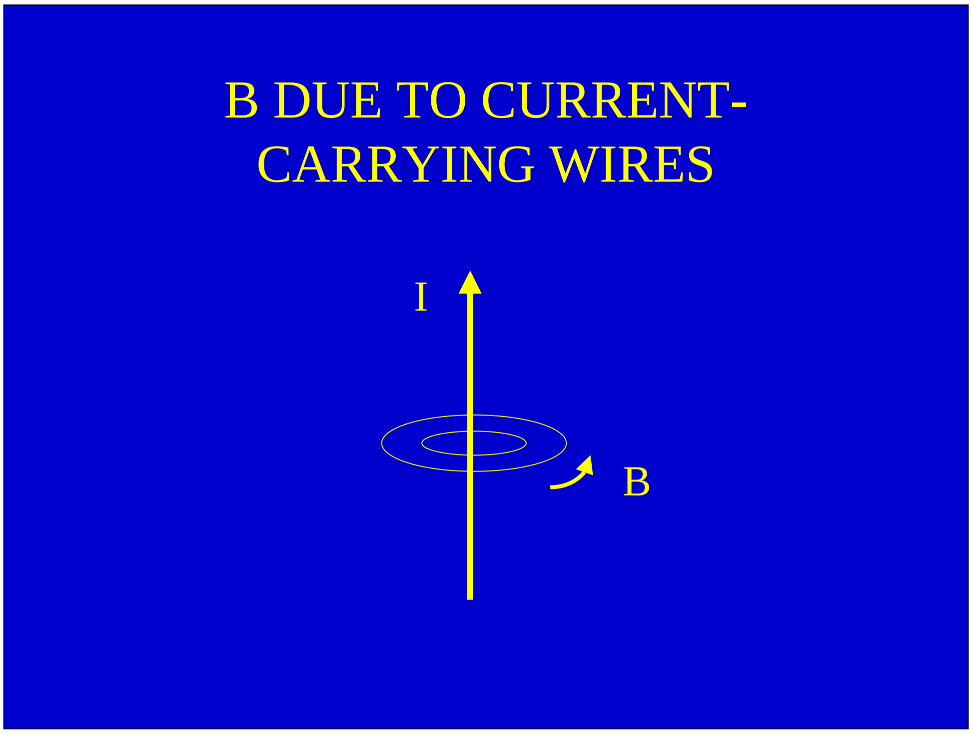
FORCE ON MOVING CHARGE

$F = qvB$
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 <u>sideways</u> 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.



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.

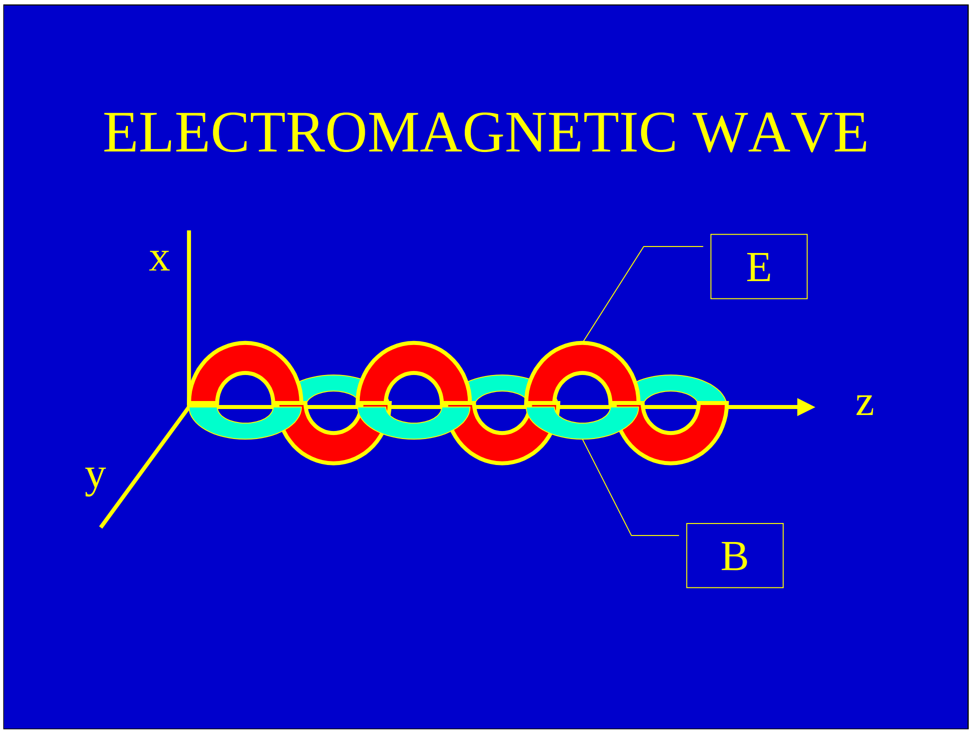
MAXWELL’S ANALOG TO FARADAY’S LAW

Faraday: Changing B $\rightarrow$ E

Maxwell: Changing E $\rightarrow$ 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.



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.

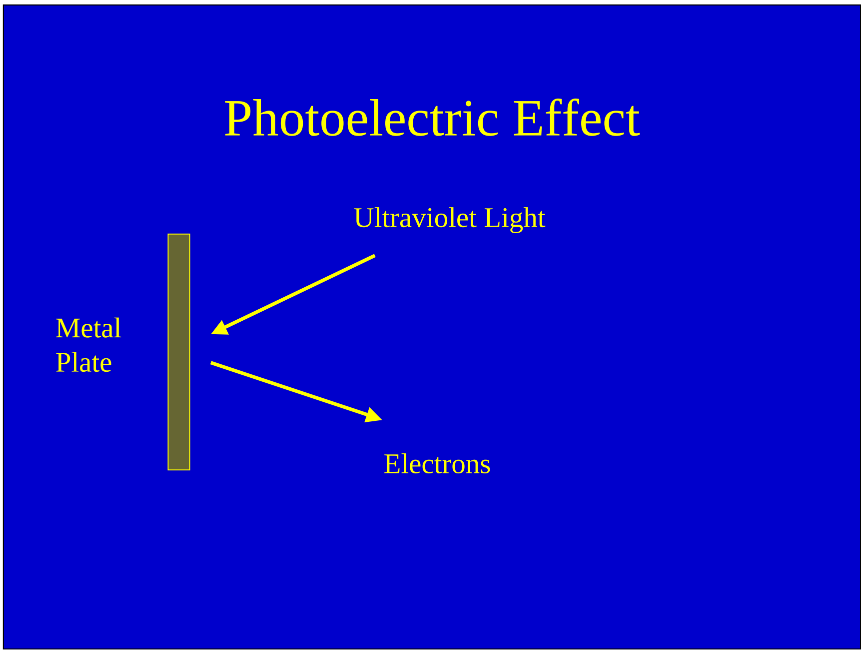
SHOW parallel wire transmission line. Here we have a standing wave confined to the two wires. It is generated from one end, travels out with the speed of light, and reflects off the other end. This is analogous to the spring we saw last week shaken at one end and fixed at the other.

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.



Einstein was awarded the Nobel Prize in 1922 for his interpretation of the photoelectric effect, not for special relativity! As the name implies, this effect involves both light and electricity. When UV light shines on a clean metal surface, electrons are emitted. What is unusual is the way they are emitted. They are emitted immediately, even in weak light. According to the wave interpretation of light, a time delay is needed for enough energy at a given spot to build up to release an electron. This time delay does not occur.

What seems to be happening is this. Electrons can exist inside a metal with a range of energies. When UV light is incident, electrons gain energy from it, and some of them can escape from the metal. There is a threshold wavelength of light to cause electrons to leave, and it varies from one metal to another. Shorter wavelengths cause electrons to leave the metal, and they have a maximum kinetic energy outside the metal. That maximum KE increases as the wavelength is reduced further.

LIGHT FREQUENCY

$$c = f\lambda$$

$$f = c/\lambda$$

$f \sim 10^{15}$ Hz for UV light

We know that for periodic waves, we have a definite relation between wave speed, frequency, and wavelength, as written above. For all EM waves, the speed is c, the speed of light, equal to $3*10^8$ m/s. For visible and near UV light, the wavelengths are very small, less than one millionth of a meter.

This means that the frequency, being a large quantity divided by a small one, is even larger. This makes frequency a somewhat unnatural value to think of as characterizing a beam of light. This large value did not bother Einstein, however, in 1905, so let’s go with him on this one.

What we just learned is that shorter wavelengths of light than a threshold value can release electrons from a metal surface. Instead of wavelength, let’s use frequency to characterize the light that releases electrons.

Electron KE_{max} vs f

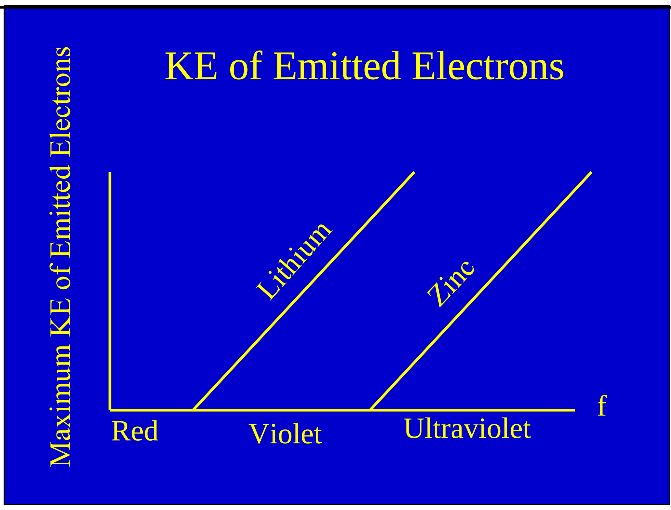
$$KE_{max} = hf - hf_T$$

In 1905 Einstein used data then available from this effect to propose that light consists of particles, later called photons. What he proposed is that the energy in a beam of light comes in bundles. It does not arrive continuously like a wave, but in bundles like particles. Einstein **predicted** that a graph of the maximum KE of the emitted electrons could be written as hf minus a threshold value (before the data were available). He supposed that each metal binds electrons by a certain energy, and that is the minimum energy needed to release electrons. If f is increased above this value, the maximum KE increases as well.

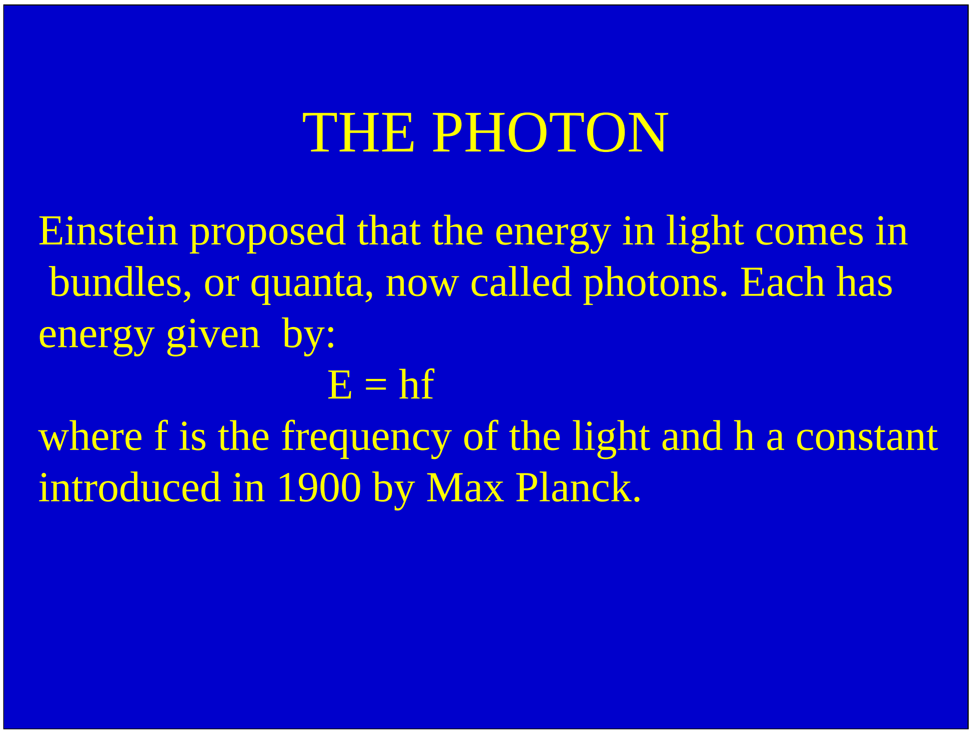
It is as though the light has energy proportional to its frequency. This is a radical idea, since Maxwell has just helped us decide that light is EM waves, whose energy is proportional to the strength of the E and B fields (actually to the square of them) and has nothing to do with the frequency f. Einstein was the kind of person who could handle radical ideas.

This is confusing. Newton proposed a particle model for light, but it was rejected by Foucault's measurement of the speed of light in water. Maxwell then showed that light consists of electromagnetic waves. Now Einstein says we have to go back to particles again. Evidently light has both wave and particle properties.

In fact, all elementary particles such as electrons, pions, protons, photons, etc behave like this. They are both wave-like and particle-like. Matter on an atomic scale is strange, ethereal stuff. Of course there is no reason to expect our intuition, based on baseballs and planets, to give us valid guidance on the atomic scale. Nevertheless it is puzzling to see these seemingly contradictory properties combined in single objects.



The graph above shows Millikan’s data for the maximum KE of photoelectrons from two metals, plotted against the frequency of light used to emit them. Different metals have different threshold frequencies for emission, but the slope of the maximum KE vs f line is the same for all metals. The value of this slope is equal to a fundamental constant called h, Planck’s constant, as predicted by Einstein.



We think of Einstein primarily because of special relativity. In addition, his photon proposal had a profound impact on the development of quantum theory, and was, in fact, the reason cited for his Nobel Prize in 1922.

In 1900 Max Planck had successfully interpreted the shape of the radiation emitted by heated objects, usually called black body radiation, by introducing a new constant he called h. He could correctly understand the thermal radiation if he assumed that the radiation exchanged energy with the walls of its container only in units equal to hf.

What Einstein did in 1905 is to greatly extend this idea, saying that all electromagnetic radiation, in particular, ultraviolet radiation, consists of such bundles of energy. Quantum is just a latin way of saying bundle. This word characterizes the mechanics of atomic particles.

X-RAYS

Roentgen, Wurzburg, 1895

Fast electrons striking a solid produce a penetrating radiation.

Published picture of his wife's hand, wearing wedding ring.

Roentgen called them x-rays since he didn't know what they were.

von Laue, 1912, showed they exhibit interference: x-ray diffraction from crystals. They are short wavelength electromagnetic radiation.

In 1895 Wilhelm Roentgen accidentally discovered x-rays. He was experimenting with an electron beam in an evacuated glass vessel, and found that when the beam hit the wall of the vessel, it created a radiation that made phosphors glow and exposed photographic film, even after passing through cardboard or a book. His first publication showed a shadow of his wife's hand, showing that the flesh hardly absorbed x-rays at all, the bones did somewhat more, and her wedding ring stopped them altogether.

The nature of x-rays remained a mystery for some time. Roentgen tried to observe reflection and refraction, thinking they might be EM radiation, but could not observe these effects. We now know the reflectivity and refraction angles are both very small.

In 1912 Max von Laue and colleagues observed constructive and destructive interference of x-rays scattered from crystals. The atoms in the crystal each act as tiny sources of the scattered beam, so instead of a two-slit pattern, they saw a many-source pattern. X-rays are electromagnetic radiation with wavelengths about 5000 times smaller than those of visible light.

COMPTON SCATTERING

Compton studied the scattering of x-rays by electrons.

He successfully interpreted the results in the same way we understand the collision of two billiard balls:

Conserve Energy: $E_i = E_f$
Conserve Momentum: $p_i = p_f$

$E_i = hf_i \qquad E_f = hf_f + 1/2mv^2$

$p_i = hf_i/c \qquad p_f = hf_f/c + mv$

Arthur Holly Compton studied the scattering of x-rays from electrons in a graphite target in 1923. He found that the wavelength of the scattered x-ray increased as the scattering angle measured from the forward direction increased. This puzzled him since according to electromagnetic wave ideas, the wavelength of the scattered wave should remain the same.

He then tried interpreting the results as though it were a collision between two “particles”, a photon, and an electron. The way to do this is to use two important conservation laws: Conservation of energy, and of momentum. No energy or momentum is added to the system of two particles from the outside, so both should remain constant during the collision.

Initially the energy is that of the x-ray since the electron is at rest. Afterward, the x-ray and electron share the total energy. It was known that the momentum of a light pulse was E/c. This means the momentum of an x-ray is hf/c, and that of an electron is mv.

The first equation explains why the wavelength of the scattered x-ray is longer: It has given up some of its energy to the electron, so has a smaller frequency f, and hence longer wavelength lambda = c/f. Compton was able to show that this pair of equations could quantitatively account for his data.

This experiment and its interpretation were very strong evidence for the reality of the photon. In scattering experiments we can think of it as a particle. But in interference experiments we must think of it as a wave. It has both properties.

This is not an easy set of results to live with, and is referred to as the “wave-particle duality”. Compton’s experiments convinced the world of the reality of the photon. When EM radiation propagates through space, it does so as a wave. When it interacts with matter, it does so as a particle.

ALBERT EINSTEIN

Slow start

Independent, proud

Patent office in Bern, 1902-1909

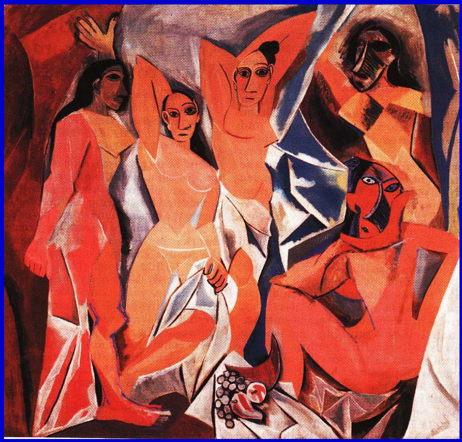
Miracle year, 1905

Director of Physics Institute, Berlin, 1914

Came to US, 1933

See toolkit file “Einstein.doc”

Les Demoiselles d'Avignon



Picasso's painting of 1907 said to be the first four dimensional painting. Einstein and Picasso became famous at about the same time, one for helping create modern physics, the other modern art. Did these two creations have something to do with each other? People have written and thought about this for decades, recently ranging from Steve Martin's "Picasso at le Lapin Agile", to Arthur Miller's "Einstein and Picasso".

During the early years of the 20th century, both men were trying to find themselves, and were doing so with the help of a small group of intimate friends, of which they were each the center. At that time, Henri Poincare, an influential French polymath had just written a book on possible geometries in our world. Einstein had read a German translation of it, and one of Picasso's group had read it and told the group about it. Poincare was particularly interested in a fourth spatial dimension, not a fourth time dimension as in H. G. Wells' "The Time Traveler" of 1895.

Ideas like these were in the air and discussed all over Europe by intense groups like those of Einstein and Picasso. Picasso may have put ideas like this into the above painting. If one can step into the fourth dimension, ("the Astral Plane") then one perhaps could see all three dimensions of ordinary objects at once instead of only two. The woman on the right above is perhaps Picasso's example of what this would look like.