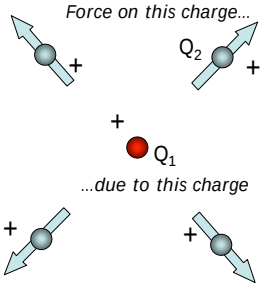
From Last Time…

- Charges and currents
- Electric and magnetic forces
- Work, potential energy and voltage

Today…

Electric fields, magnetic fields, and their unification and light

The electric force and field



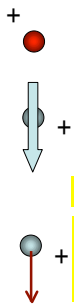
$$F = \frac{kq_1q_2}{r^2}$$

$$E = \frac{kQ}{r^2}$$

$$F = Eq$$

- Charge q_1 can exert a force on any number of charges. Would like to understand just the part from q_1.

Work and Voltage



$$W = \frac{kq_1q_2}{r}$$

$$V = \frac{kQ}{r}$$

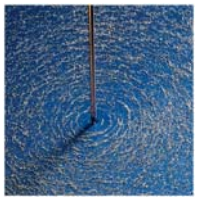
$$W \rightarrow PE \rightarrow KE$$

$$KE = \frac{1}{2}mv^2$$

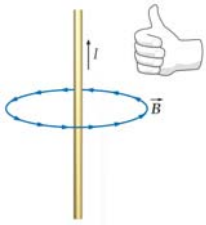
- The work we do to move charge q_2 from far away to near charge q_1 can converted to kinetic energy
  - We may want to do the same exercise with many charges. For instance a flow of charges that then go to your house to provide energy.

$$W = qV \rightarrow KE$$

Magnetic fields are from currents

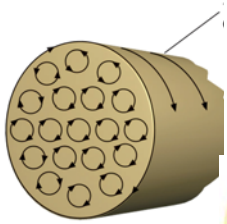


Iron filings align with magnetic field lines

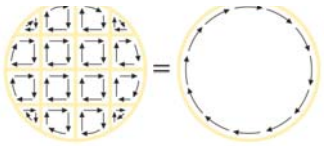


Field direction follows right-hand-rule

Currents in a permanent magnet



- Magnetic field from a permanent magnet arises from microscopic circulating currents.
- Primarily from **spinning** electrons

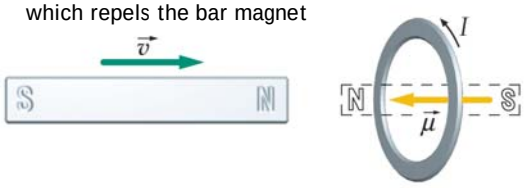


Magnetic Force

- What does the magnetic force act on?
  - Electric field is from a charge and exerts a force on other charges
  - Magnetic field is from a moving charge and exerts a force on other moving charges!
- Magnetic field B
- Magnetic force F = qvB
  - F perpendicular to both v and B

Faraday's law of induction and Lenz's Law

- A changing(moving) magnetic field causes a current in a metal. However, electric fields are what causes electrons to move in a metal
- Changing magnetic fields produce electric fields
- The current produces a magnetic field, which repels the bar magnet



Amperes Law and Light

- Finally: Changing electric fields cause magnetic fields!

- Electric fields are from charges
- Magnetic fields are from moving charges
- Changing Magnetic fields cause Electric fields
- Changing Electric fields cause Magnetic fields
- All this was expressed in Maxwell's equations

- Maxwell and others realized that a changing magnetic/electric field could cause a changing magnetic/ electric field. The condition for one to cause the other and vice-versa was for the two to change in a sin wave pattern and move at the velocity of light!

Maxwell's unification

- Intimate connection between electricity and magnetism
- Time-varying magnetic field induces an electric field (Faraday's Law)
- Time-varying electric field generates a magnetic field

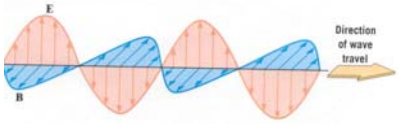
In vacuum:

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

This is the basis of Maxwell's unification of electricity and magnetism into *Electromagnetism*

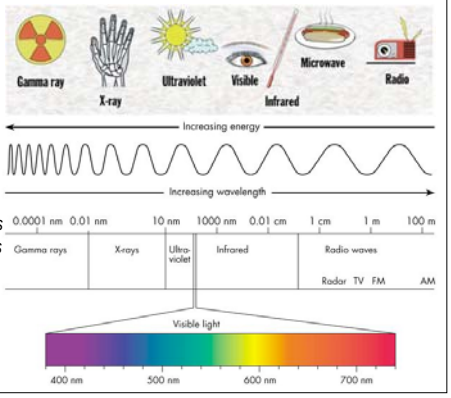
Properties of EM Waves



- Has all properties of a wave: wavelength, frequency, speed
- At a fixed location, electric and magnetic fields oscillate in time.
- Electric and magnetic fields in the wave propagate in empty space at the wave speed.
- Electric and magnetic fields are perpendicular to propagation direction: a transverse wave.
- Propagation speed $c = 3 \times 10^8$ m/s (186,000 miles/second!)

We are familiar with many different wavelengths of EM waves

All are the same phenomena



Sizes of EM waves

- Visible light has a typical wavelength of 500 nm = 500 x 10^{-9} m = 0.5 x 10^{-6} m = 0.5 microns (μm)
- A human hair is roughly 50 μm diameter
  - 100 wavelengths of visible light fit in human hair

- A typical AM radio wave has a wavelength of 300 meters!
- It's vibration frequency is $f = c / \lambda$ = 3x10^8 m/s / 300 m = 1,000,000 cycles/s = 1 MHz
- AM 1310, your badger radio network, has a vibration frequency of 1310 KHz = 1.31 MHz

Question

AM 1310, your badger radio network, has a vibration frequency of 1310 KHz = 1310 x 10^3 Hz = 1.31 x 10^6 Hz

It travels at 3 x 10^8 m / s.

What is it's wavelength?

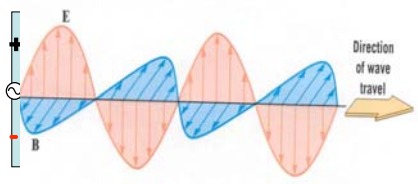
A. 230 meters
B. 2.3 meters
C. 0.0043 meters
D. 4.3 meters

Producing EM Waves

Accelerating electrical current generates a wave that travels through space.

Lightning / spark produces electromagnetic wave.

Wave consists of oscillating electric and magnetic fields.



Resonators

Transmitter

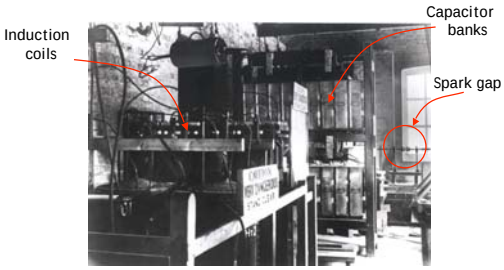
The balls and rods formed an electrically resonant circuit

Spark initiated oscillations at resonant freuquency ~ 1 MHz

Receiver

Resonantly tuned to pick up the transmitted signal

Eventually transatlantic signals!



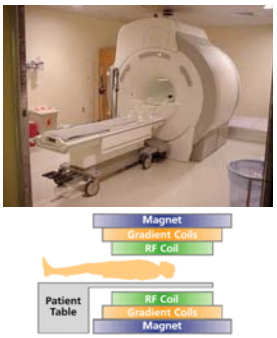
Gulgielmo Marconi's transatlantic transmitter

But wait… there's more

- Energy can be stored in the field.
- Energy density proportional to
  (Electric field)^2
  (Magnetic field)^2
- Makes sense since light clearly has some energy in it. Light can heat things up. Also using a solar sail(sail to catch all the light that hits it) you can be sped up by absorbing the momentum of the light.
- Finally electromagnetism propagates at the speed of light. Light seems to be what causes electric and magnetic fields!

Applications: Magnets for MRI

- **M**agnetic **R**esonance **I**maging typically done at 1.5 T
- Superconducting magnet to provides static magnetic field
- Detects a small magnetic field from Hydrogen atoms in water that align with the field.

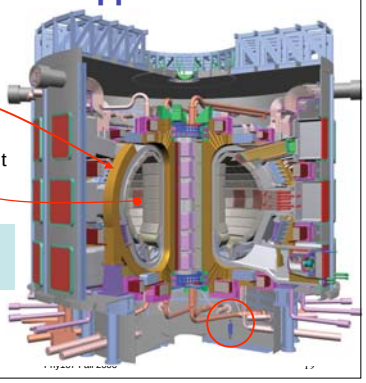


Large scale applications

Superconducting magnet

Plasma confinement torus

Proposed ITER fusion test reactor



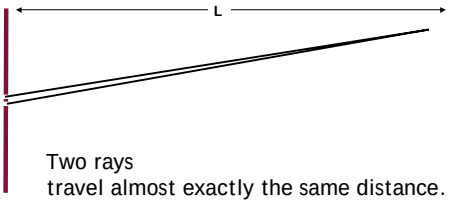
Wave effects in EM radiation

- Same properties as sound waves: common to all waves.
- **Doppler shift**: change in light frequency due to motion of source or observer
- **Interference**: superposition of light waves can result in either increase or decrease in brightness.

EM version of Doppler shift: the red shift

- If a star is moving away from us, the light from that star will be shifted to lower frequencies - the Red Shift.
- All astronomical objects are found to be retreating from each other - the Universe is expanding.
- Extrapolating back in time, the Universe must have begun from a single point in space and time - the Big Bang.

Interference: Key Idea



Two rays travel almost exactly the same distance.

Bottom ray travels a little further.

Key for interference is this small extra distance.

Interference Requirements

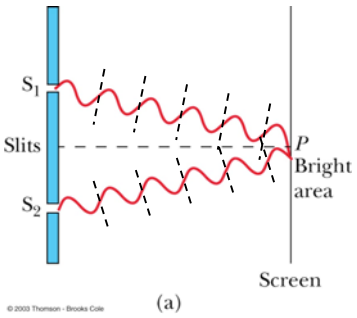
- Two (or more) waves
- Same Frequency
- Coherent (waves must have definite phase relation)

These are usually satisfied if the light arises from the same source.

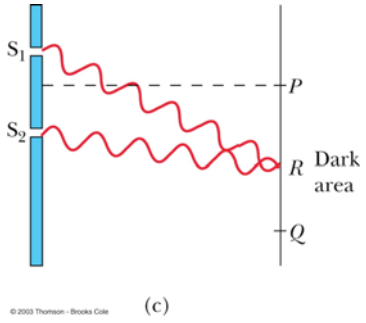
Such as shining a single light through two adjacent slits.

Interference of light waves

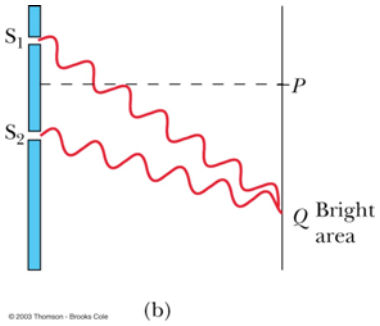
- Coherent beams from two slits
- *Constructive interference:* waves in phase at screen



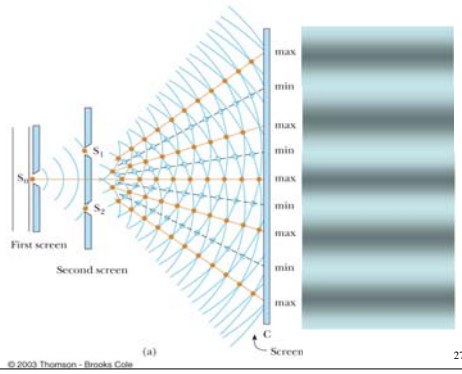
Destructive interference



Interference: secondary maxima



Resulting diffraction pattern



Hertz's measurement: the speed of electromagnetic waves

- Hertz measured the speed of the waves from the transmitter
  - He used the waves to form an interference pattern and calculated the wavelength
  - From $v = f \lambda$, v was found
  - v was very close to 3×10^8 m/s, the known speed of light
- This provided evidence in support of Maxwell's theory
- This idea still used today measure wavelengths when studying stars