From last time...

- Interference of waves
  - Constructive interference
  - Destructive interference
- Doppler effect
  - Change in apparent frequency due to motion of source or observer
- Resonance
  - Natural frequency of oscillation
  - Object will tend to oscillate at that frequency
  - Other frequencies (wavelengths) cancelled by destructive interference reflections

Today: Electromagnetic waves, electricity and magnetism

- Electromagnetic waves
- Electric charge and electric forces
- Magnetic forces
- Unification of electric and magnetic forces
  - Lorenz force on moving charged particle
  - Faraday induction of currents by changing magnetic field.

Electromagnetic (EM) waves

1865: James Clerk Maxwell published mathematical theory relating electricity and magnetism
1887: Heinrich Hertz produced and measured electromagnetic waves in the laboratory.

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!)

Sizes of EM waves

- Visible light has a typical wavelength of $500 \text{ nm} = 500 \times 10^{-9} \text{ m} = 0.5 \times 10^{-6} \text{ m} = 0.5$ microns ($\mu$m)
- A human hair is roughly 50 $\mu$m 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 $f = c / \lambda$
    - $3 \times 10^8$ 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

**Electric and magnetic fields**

- But what are electric, magnetic fields?  
- To understand electric and magnetic fields, need to take a few steps back.  
- Probably familiar with electrostatic shocks  
- This comes from electric charge  
- We now know that there are two varieties of electric charge, positive and negative.

**Electrical Charge**

- Only the negative charge moves around. These are the electrons.  
- The positive charges are protons. Protons and electrons form a ‘planetary’ atom.  
- Electrons orbit around a nucleus containing the protons. Compare planets orbiting around a sun.  
- Atoms are bound together, forming solid materials. Electrons can be torn from atoms, transferred to other materials.

**Pos and neg charges can be separated**

- Triboelectric  
  - Charge is transferred as a result of mechanical (frictional) action  
- Conduction  
  - charge transfer by contact (spark)

**Electrical charge**

- Electrons carry electrical charge, and can be moved from one material to another.  
- The electrons have a negative charge.  
- The unit of electric charge is the Coulomb  
- One electron carries only a tiny amount of charge

Charge on 1 electron = 1.6 x 10^-19 Coulomb

Transferring 1 Coulomb of charge means that 6,250,000,000,000,000,000 electrons have moved!

**Separating charge**

- Positively charged rod can then be used to transfer electrons from other objects.

Rod becomes positively charged after rubbing with fur. Electrons (negative charges) have been transferred from rod to fur.
Interactions between charges

Why did the electrons flow?
- attractive force between positive and negative charges.
- repulsive force between two positive or two negative charges.

The positively charged rod attracts negative charges to the top of the electroscope.
- This leaves positive charges on the leaves.
- The like-charges on the leaves repel each other.

Electrostatic force is strong
- Electrostatic force between proton and electron in a hydrogen atom
  \[ F_e = k \frac{Q_1 Q_2}{r^2} = 9 \times 10^9 \frac{1.6 \times 10^{-19} \cdot 1.6 \times 10^{-19}}{(10^{-10})^2} = 2.3 \times 10^{-8} \text{ N} \]

- Gravitational force between proton and electron
  \[ F_g = \frac{G M_1 M_2}{r^2} = 6.7 \times 10^{-11} \frac{1.6 \times 10^{-19} \cdot 1.6 \times 10^{-19}}{(10^{-10})^2} = 2.3 \times 10^{-28} \text{ N} \]
Charge transfer and forces

- Ben Franklin’s ‘door bell’.
- Announced presence of lightning so knew to go out and do his experiments!

The van de Graf machine

- The van de Graf machine continually transfers charge to the ‘dome’ via a moving belt.
- Charge on the dome can be transferred to other objects.

Van de Graaf

The sphere gives the girl a large negative charge. Each strand of hair is trying to:

A. Get away from the charged sphere.
B. Get away from the ground.
C. Get away from the other strands of hair.

Like charges attached to the hair strands repel, causing them to get away from each other.

Sparks

- If we separate enough charge, strong attractive/repulsive forces can tear electrons from air atoms
- Charged particles flow from one electrode to the other
- This flow of charged particles is an electric current.

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.
But still haven’t said what electric/magnetic fields are
Resonators again!

Transmitter
The balls and rods formed an electrically resonant circuit
Spark initiated oscillations at resonant frequency ~ 1 MHz

Receiver
Resonantly tuned to pick up the transmitted signal

Eventually transatlantic signals!

Guglielmo Marconi’s transatlantic transmitter

The idea of electric fields
- EM wave made up of oscillating electric and magnetic fields.
- But what is an electric field?
- Electric field is a way to describe the force on a charged particle due to other charges around it.
- Force = charge × electric field
- The direction of the force is the direction of the electric field.

Why bother?
- Why invent fields - why not just use forces?
- Think of the EM wave. A spark is an accelerating current flow, producing the wave.
- The wave continues to propagate even when the spark is gone.
- No charges anywhere, but oscillating fields are still present.
- This is an extension of the basic idea of fields.

Electric field lines
- Faraday invented the idea of field lines following the force to visualize the electric field.
- Field lines emanate from positive charge and terminate on negative charge.
- Local electric field is same direction as field lines.
- Force is parallel or antiparallel to field lines.
- Charged particle will move along these field lines.