From last time…

- Interference of waves
  - Constructive and 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
- Electric Charge
  - Intrinsic property of matter at the level of electrons and protons

Today: Electricity, magnetism, and electromagnetic waves

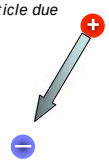
- Electric charge and electric forces
- Magnets and Magnetic forces
- Unification of electric and magnetic forces
- Electromagnetic waves

Force between charges

Opposite charges attract
Like charges repel.

- Other than the polarity, they interact much like masses interact gravitationally.
- Force is along the line joining the particles.

Force on positive particle due to negative particle



Charge on 1 electron or proton = 1.6×10^{-19} Coulomb

Electrostatic force: $F_E = k\, Q_1\, Q_2 \,/\, r^2$

$k = 9\text{x}10^9\ \text{Nm}^2/\text{C}^2$

Gravitational force: $F_G = GM_1M_2 / r^2$

$G = 6.7\text{x}10^{-11}\ \text{Nm}^2/\text{kg}^2$

Interactions between charges

Why did the electrons flow?

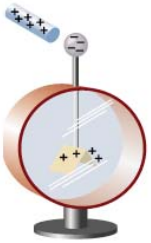
attractive force between positive and negative charges.

repulsive force between two positive or two negative charge

The positively charged rod attracts negative charges to the top of the electroscope.

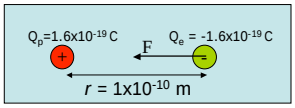
This leaves positive charges on the leaves.

The like-charges on the leaves repel each other.



Electrostatic force is strong

- Electrostatic force between proton and electron in a hydrogen atom



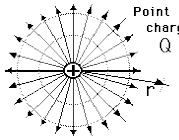
$F_E = (9\text{x}10^9)(1.6\text{x}10^{-19})(1.6\text{x}10^{-19}) / (10^{-10})^2 = 2.3\text{x}10^{-8}$ N

- Gravitational force between proton and electron

$F_G = (6.7\text{x}10^{-11})(1.7\text{x}10^{-27})(9.1\text{x}10^{-31}) / (10^{-10})^2 = 2.3\text{x}10^{-28}$ N

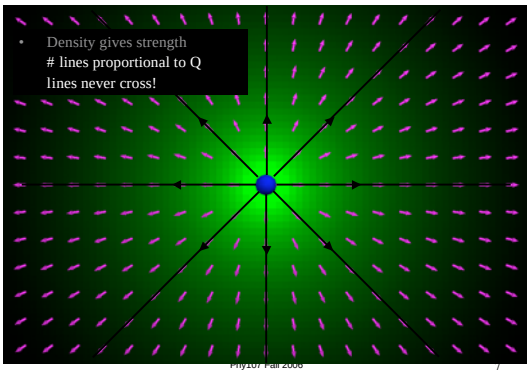
Electric field

- At any point, the electric force on a unit charge due to other fixed charges is called the electric field E.
- Faraday invented the idea of field lines following the force as a way to **visualize the electric field.**



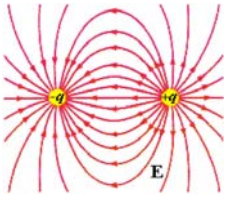
The field of a point charge is $E=F/q= kQ/r^2$

Electric Field Lines



Electric field lines

- **Electric field lines with two charges**



Field lines emanate from positive charge and terminate on negative charge.

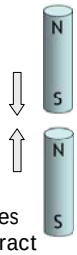
Local electric field is same direction as field lines.

Force is parallel or antiparallel to field lines.

Charged particle will move along these field lines.

Magnetism: Permanent magnets

- North Pole and South Pole
- This is the elementary magnetic particle
- Called magnetic dipole (North pole and south pole)
- There are no magnetic 'charges'

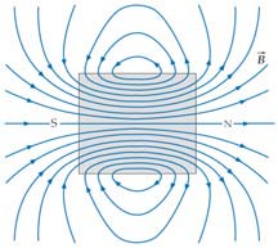


Likes attract

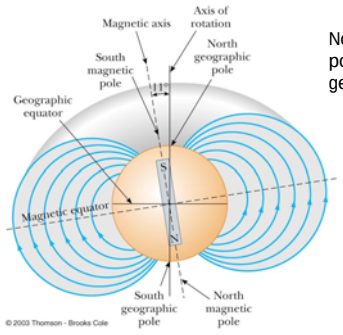
Unlikes repel

Field lines of a magnet

- As with electric charges a magnet produces a field. The magnetic field: B
- Field lines indicate direction of force
- Density indicates strength of force
- Similar to electrostatic force, but force is felt by magnetic dipole



The Earth is a Magnet!



North magnetic pole ~ at south geographic pole

A compass is a magnet

Compass needle aligns with local Earth field

Forces can do work

- Work = Force x Distance
- Coulomb force can do work on a charged particle in much the same way gravitational force does work on a mass.
- There is also an electrostatic and a magnetic potential energy in the same way that we had a gravitational potential energy.

The electrostatic voltage

- Characterize the potential energy with Electrostatic potential *V*
  - *qV* = work required to bring charge *q* from infinitely far away to its present position = Pot. Energy
- Since *q*=Coulombs, and *W*=Joules *V* has units of Joules/Coulomb = Volts
- This is idea behind batteries and the voltage from a electric plug.

Force, Field, Work Potential

- Electric force and field from charges.

$$F = \frac{kq_1q_2}{r^2} \qquad E = \frac{kQ}{r^2}$$

- Work done by an electric force and potential energy.

$$W \rightarrow PE \qquad PE \rightarrow KE$$

- Electric work and potential. Bring a charge from ∞ to r.

$$W = \frac{kq_1q_2}{r} \qquad V = \frac{kQ}{r}$$

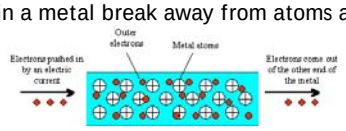
Moving Electric Charges and Magnets

- One of the most interesting behaviors is seen when you study moving electric charge or moving magnets.

1865: James Clerk Maxwell published mathematical theory relating electricity and magnetism

Electric Current

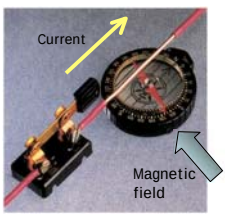
- Electrical current is the flow of charges.
- Electrons in a metal break away from atoms and flow.



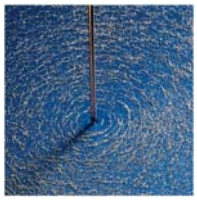
- Charge will flow from higher potential energy to lower potential energy position.
  - Higher voltage means more charge flow
- 1 A = 1 Coulomb per second
- Charge on electron = 1.6×10^{-19} C, so 1 A = 6.25×10^{19} electrons / second

What is the source of magnetic fields?

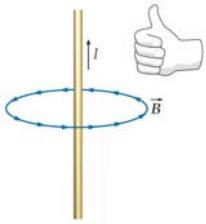
- Current in wire produces magnetic field.
- That magnetic field aligns compass needle



Magnetic field from a current

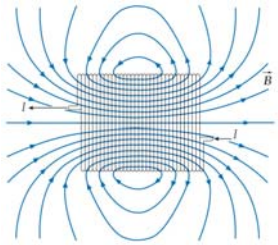


Iron filings align with magnetic field lines



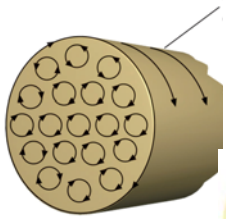
Field direction follows right-hand-rule

Solenoid electromagnet

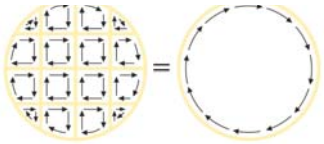


- Sequence of current loops can produce strong magnetic fields.
- This is an electromagnet

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 = evB
  - F perpendicular to both v and B

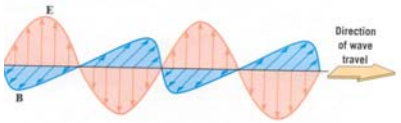
Faraday's law of induction and Lenz's Law

- 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!

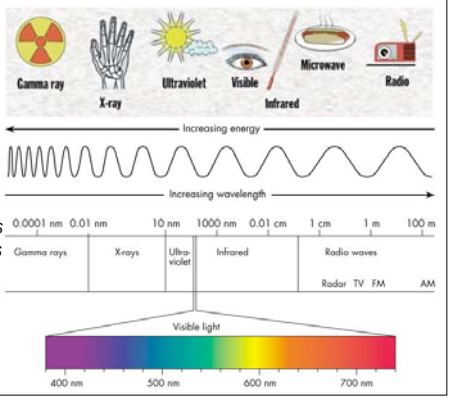
Properties of EM Waves



- 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

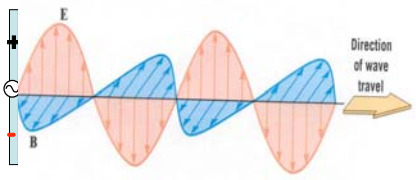
- Visible light has a typical wavelength of 500 nm = 500 x 10^{-9} m = 0.5 x 10^{-6} m = 0.5 microns (μm)
- A human hair is roughly 50 μm diameter
  - 100 wavelengths of visible light fit in human hair
- A typical AM radio wave has a wavelength of 300 meters!
- It's vibration frequency is $f = c / \lambda$ = 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

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

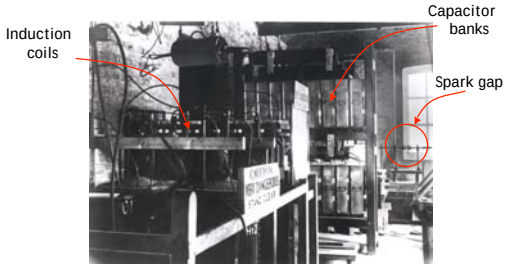
The balls and rods formed an electrically resonant circuit

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