From last time...

- Superposition of waves
- Interference of waves on a string
- Interference of sound waves
  - Constructive interference
  - Destructive interference
- Superposition of waves with different frequencies
  - Beat frequencies
- Doppler effect
  - Change in apparent frequency due to motion of source or observer

This lecture:
Electric and magnetic properties

- 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.

Origin of Charge

- Charge is an intrinsic property of matter
- Two types:
  - Positive Charge: Protons
  - Negative Charge: electrons
  - Opposites Attract! (likes repel)
- Atoms are neutral
  - Positively charged central nucleus \( r \sim 10^{-15} \) m
  - Negatively charged electrons orbit \( r \sim 10^{-10} \) m

Separating Charge

- Triboelectric
  - Charge is transferred by mechanical motion
- Conduction
  - charge transfers by contact

Measuring charge: electroscope

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.

'Mechanizing’ triboelectric effects

- The van de Graf machine continually transfers charge to the 'dome’ via a moving belt.
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

• Strong attractive/repulsive forces can tear electrons from air atoms
• Charged particles rapidly flow from one electrode to the other

Tesla coil

• Very large electric forces generated by time-varying charges

Coulomb’s Law

• Electrostatic force: \( F = \frac{kQ_1Q_2}{r^2} \)
  - Force between charges \( q_1 \) and \( q_2 \) separated by a distance \( r \).
  - Direction: Like charges repel unlike attract

Similar to gravitational force: \( F = \frac{GM_1M_2}{r^2} \)

Electrostatic force is strong

• Electrostatic force between proton and electron in a hydrogen atom
  \( F_e = \frac{(9 \times 10^9)(1.6 \times 10^{-19})(1.6 \times 10^{-19})}{(10^{-10})^2} = 2.3 \times 10^8 \text{ N} \)

• Gravitational force between proton and electron
  \( F_G = \frac{(6.7 \times 10^{-11})(1.7 \times 10^{-27})(9.1 \times 10^{-31})}{(10^{-10})^2} = 2.3 \times 10^{-8} \text{ N} \)

Electric field

• At any point, the electric force on a unit charge due to other fixed charges is called the electric field \( E \).
  \( E = \frac{F}{q} = \frac{kQ}{r^2} \)
1. Density gives strength
   E lines proportional to Q
   lines never cross!

2. Arrow gives direction
   Start on +, end on -

Electric Field Lines

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.

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 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

Electric Potential

- Electric Potential Energy/ Work
  - Uniform fields
  - Point charges

- Analogy with gravity
  - Uniform field
  - Motion of an object with mass in Earth’s gravity

Electric Potential

- Units Joules/Coulomb =Volts
  - Batteries
  - Power outlets
  - EKG

- Potential differences
  - Field lines point down hill
  - Charge will move along field lines just as mass falls in gravitational field.
**Electric Current**
- Electrical current is the flow of charges.
- Electrons in a metal break away from atoms and flow.
- Charged ions in a liquid can flow.
- Charge will flow from higher potential energy to lower potential energy position.
  - Higher voltage means more charge flow.
- $1 \text{ A} = 1 \text{ Coulomb per second}$
- Charge on electron $= 1.6 \times 10^{-19} \text{ C}$, so $1 \text{ A} = 6.25 \times 10^{19} \text{ electrons / second}$

**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'.

**Field lines of a magnet**
- 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.

**Magnetic field**
- Designated by $B$.
- Quantifies the strength of the magnetic force.

**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

**Magnetic field from a loop**
- One loop
- Many loops

**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 on currents**
- Currents (moving charges) produce magnetic fields
- A fixed external field can interact with this new magnetic field.
- Can think of this as a force from the fixed field on the moving particle.
- The magnetic force was first observed with current carrying wires. The force on a electron of speed \( v \) moving down a wire in a B field is \( F = evB \). For total current \( I = enAv \), the force per meter length is \( F = IB \).
- The electrons drag the wire with them.

**Faraday’s law of induction**
- Changing magnetic fields produce electric fields
- A time-varying magnetic flux induces a current in a conducting loop.
- The current produces a magnetic field, which repels the bar magnet
Induction: producing a current from a varying magnetic field

Lenz’s law
- The induced current is in a direction to oppose the change in flux.

Fields from time-varying currents
- Can also make a changing magnetic field from a time-varying current.
- This will induce currents in any conductor, sometimes with dramatic effect.

Generators