Chapter 06: Electricity

Electric and magnetic fields interact and can produce forces. A thunderstorm produces an interesting display of electrical discharge. Each bolt can carry over 150,000 amperes of current with a voltage of 100 million volts.

Section 6.1: Concepts of Electricity

Electron Theory of Charge

- Amber Effect: Known since at least the time of the ancient Greeks, rubbing a piece of amber with a cloth would allow the amber to move around bits of paper, strands of hair
- Electron: From the Greek word for amber; these were not discovered until 1897!
- Electricity: Same Greek root, but you are not rubbing bits of amber to power up your laptop

Atoms

- Nucleus containing protons and neutrons
- Electrons in orbit around nucleus
- We are mostly concerned with these electrons, and how/why they move

Electric Charge

- Charge is a fundamental material property: all matter is made of atoms that are made of particles that carry charge
- Charge is a lot like like mass; you know it when you see it (or feel it...), but it defies easy description
- Two types of charge: negative (electrons) and positive (protons)

Mutual Attraction

- Opposite charges attract each other
- Negative attracts positive

Mutual Repulsion

- Like charges repel each other
- Negative repels negative
- Positive repels positive

Ions

- Most atoms are electrically neutral: Same number or (+) and (−) charges
- Ion: Add or subtract an electron (Only an electron! You are not pulling protons out of the nucleus!)
- Positive Ion: Remove one or more electrons
- Negative Ion: Add one more electrons

You Can Move It, But You Can't Lose It

- Possible (and relatively easy) to move charges around
- New charges cannot be created out of nothing
- Existing charges cannot be destroyed
- Moving charge means they go from somewhere to somehwere–they can't just appear or disappear into or out of nowhere
- Conservation of Charge is the direct result of Conservation of Matter!

Static Electricity

- Electrostatic Charge: Excess charge is stuck on an object (not flowing like a current)
- Scuffle across the carpet in your socks: You have used friction to scrape some electrons off the carpet, and onto your socks
- Touch the lightswitch: Ouch! That shock is the result of the extra charge you accumulated transferring to the metal switch plate

Polarization

- Redistribute the charges an object already possesses
- Rub a balloon on your head: friction causes some charges to leave your hair and accumulate on the balloon (it does have extra electrons)
- Balloon sticks to the wall, but the extra charges don't move from the balloon to the wall
- Charges on the balloon move (staying on the balloon), causing charges on the wall to move (staying on the wall)

Electrical Conductors and Insulators

- Surprise! Not everything is equally good at moving electrons from atom to atom
- Conductors allow electrons to move easily
- Insulators prevent electrons from moving easily

Metals Are Good Conductors

- Surprise! Not really, right?
- Metals have unfilled valence shells: Outermost electron shell has room to accept extra electrons
- Crystal structure: Once you pull an e^- off one atom, it's easy to transfer (the next atom over in any direction is predictable)

Insulators

- A material that does not easily permit the motion of charges is an insulator
- Valence electrons are tightly bound, shells are full: hard to pull an e- off, no place to put it when it gets to the next atom
- Amorphous non-metals are typically good insulators: glass, plastic, rubber, styrofoam

Measuring Electrical Charges

- The unit of charge is the Coulomb (C)
- Charge is quantized: Charge is carried in discrete amounts by discrete particles
- You can only have a whole number of e^- or p; you cannot have half an e^-
- q = ne: Possible for an object to carry -1.6×10^{-19}C (exactly one e^-), but not possible to have -2.4×10^{-19}C ($1.5e^-$)

Electrostatic Force: $F = k\frac{q_1 q_2}{r^2}$

- $k = 9 \times 10^9 \frac{\mathrm{N \cdot m^2}}{\mathrm{C^2}}$
- q_1, q_2: charges in Coulombs
- r: charge separation in meters
- This is for point charges only; charge distributions require you to integrate
- The form is an inverse-square law: force falls off rapidly with increased distance

Vector! Magnitude and direction!

- (+, -) or (-, +): force is mutually attractive
- (-, -) or (+, +): force is mutually repulsive

Force Field?

- Action at a distance: force still acts even when the objects are not in contact (gravitational, electrical, magnetic)
- "Sphere of influence"–an object that enters this sphere will be subject to a force that depends on the strength of the field created by the original object
- A field is a description (mathematical/graphical/visual) of what will happen to a test object that is subjected to that force

Electric Fields

- The more charge an object has, the greater its ability to exert force--the greater its field strength
- The farther away you are from this object, the less force it exerts--field strength diminishes with distance
- According to the inverse-square form of the force, the force does not go to zero until the distance reaches infinity
  This means that the sphere of influence is also infinite; field strength drops to zero at infinity
- Direction always defined by what happens to a (+) test charge

Electrical Potential

- Compare to gravity: objects with mass fall because the earth pulls them
  As an object falls toward earth, it speeds up: kinetic energy increases
- Objects with charge "fall" because other charges pull (or push) on them
  As a charge falls toward (away from) another charge, it speeds up: kinetic energy increases
- Where does this energy come from, in either case?
- Potential energy: energy stored by object, to be used or converted into kinetic energy (or another kind of potential energy) when required

Voltage

- Define electric potential or voltage
- voltage = potential energy per charge: $V = \frac{PE}{q}$
- Units are volts: Volt = Joule/Coulomb

Why Do We Need This?

- One good reason is that it makes sense: charge is quantized, so it is reasonable to think of energy per charge
- If we are moving electrons (current), then we are not dealing with a constant (static) amount of charge

Section 6.2: Electric Current

The Electric Circuit

- To make electrons flow (current), you have to give the a reason (a potential difference)
- This is still the work-energy theorem!
- Battery (voltage source) = pump!

The Nature of Current

- Time rate of change of charge: $I = \frac{\Delta q}{\Delta t}$
- Counting the number of charges per time, not how fast they are moving
- Unit: Ampere = Coulomb/second (A = C/s)

Sign Convention

- The convention for current is the direction of the motion of positive charge
- Electrons move from the negative to the positive (low to high) terminal of the voltage source (– charge falls up)
- Current flows from the positive to the negative (high to low) terminal of the voltage source (+ charge falls down)
- Why, oh why, must it be this way? Historical convention predates the discovery of the electron

Exactly What Are We Moving Here?

- In solid conductors: electrons are passed from atom to atom (disclaimers apply!)
- You are not pulling protons out of nuclei!
- In conducting fluids: positive ions are free to move (note that these are whole atoms which are missing an electron or two)

About Those Disclaimers...

- Direct current: electrons passed form atom to atom--locally! They do not pour out of one battery terminal, race around a circuit, then pour back into the other terminal!
- Drift velocity: electrons move significantly slower than the speed of light!
- Alternating current: electrons oscillate in place--they don't have to migrate at all!

Electrical Resistance

- Electrons encounter resistance as you try to move them through a potential difference
- Material makes a difference: typically metals have lower resistance
- Geometry makes a difference: longer wire makes more resistance; wider wire makes less resistance
- Temperature makes a difference: higher temperature, higher resistance

Current, Voltage, and Resistance

- The greater the resistance, the more work you have to do to move a given quantity of charge
- The greater the resistance, the less charge you can move by doing a given amount of work
- Ohm's Law: $V = IR$, or $R = \frac{V}{I}$
- Unit of resistance Ohm = Volt/Amp ($\Omega = \frac{\mathrm{V}}{\mathrm{A}}$)

Electrical Power and Electrical Work

- Remember V = energy/charge, or W/q so $W = qV$
- $P = \frac{qV}{t} = (\frac{q}{t})V = IV$
- Power = work/time
- $P = IV = (\frac{V}{R})V = \frac{V^2}{R}$
- $P = IV = I(IR) = I^2R$

Section 6.3: Magnetism

Only Some Things Are Magnetic

- Iron, nickel, cobalt: ferromagnetic materials
- Most everything else: Not so much
- The punch line is all about the electrons!

Magnetic Poles

- Analogy to electric charge: Instead of (+) and (–), use north (N) and south (S)
- Like repels like, opposites attract (just like charges)
- However, no particles are inherently N or S

Poles Always Come In Pairs

- Earth only spins in one direction
- If you look at it "top down," it appears to spin counterclockwise
- If you look at it "bottom up," it appears to spin clockwise
- The earth only spins in one direction, but it has two poles: North and South

- Same thing with magnets: an electron only spins in one direction, but has two poles

Magnetic Fields

- Magnetic force is an action-at-a-distance force
- Magnetic Field B: describe the behavior of a test magnet (like a compass) placed in the vicinity of a fixed magnet
- Field lines directed away from the North and toward the South pole of the fixed magnet

The Source of Magnetic Fields

- Electrostatic Force: force between charged particles at rest
  Exists because the charges themselves exist
- Magnetic Force: force between charged particles in motion
  Any time you move a charged particle, you will create a magnetic force
- Since both are directly because of charge, these forces are related—but not the same thing!

Oersted's Eureka

- Observation that a magnetic field exerts a force on a current carrying wire
- Observation that a current carrying wire creates its own magnetic field
- Any moving charge creates a magnetic field!

Permanent Magnets

- Your fridge magnets are not carrying currents!
- Other electron motions: orbit, spin (definitely Not the same as planets, but a useful visual image)
- Magnetic domain: region where electron spins are in alignment creates magnetic field

Not Every Piece of Iron Is a Magnet!

- Because the magnetic domains are randomly aligned, and cancel each other out
- Magnetic domain: localized region within the bulk matter where spins are aligned
- The greater the alignment, the stronger the magnetic field

Earth's Magnetic Field

- Not a permanent magnet: magnetic dynamo
- Field generated continuously by spinning the fluid iron-nickel outer core
- Field is offset: rotational axis ≠ magnetic axis!
- N and S poles have been known to reverse: who knows why?

Section 6.4: Electric Currents and Magnetism

Long, Straight Wire

- Does a current carrying wire create a magnetic field? YES
- More current, stronger field
- Field strength decreases with distance: note that this is a linear decrease (no inverse square here)
- Right Hand Rule: thumb points current, fingers curl in direction of B field created

Current Loops

- Start with a current-carrying wire
- Field lines are perpendicular to the loop
- Make a coil with multiple loops: Make field even stronger

How Do You Make an Electromagnet?

- The name pretty much says it all
- Any current-carrying wire is actually an electromagnet: more current, stronger field
- Wind that coil around an iron core, and you can make an even stronger magnet by inducing the domains in the iron to align

How Strong Can You Make Your Electromagnet?

- Strength is limited by wire: maximum amount of current Remember that resistance increases with temperature, so wire can carry less current
- Strength is limited by core: you can only magnetize the iron to the point where all of the domains are aligned; beyond that, more current won't make the iron more magnetic

Applications of Electromagnets

- Magnet pushes current carrying wire: Link to mechanical work!
- If v is perpendicular to B, maximum force
- If v is parallel to B, force = zero

Electric Meters

- Galvanometer uses proportionality: bigger current = bigger push
- Calibrate your dial to measure current, resistance, or voltage! Easy!

Electromagnetic Switches

- Thermostat! Uses both thermal expansion and electromagnets!

Electric Motors

- Energy conversion: Electrical in, mechanical out
- Use electrical input to control magnetic fields to push-pull
- Ceiling fan; blow dryer; stand mixer; blender; coffee grinder; drill; circular saw

Section 6.5: Electromagnetic Inductions

Faraday and Henry Induce Current

- 1831: Faraday and Henry perform same experiment independently of one another
- Pretty much exactly what we will do in lab: move a permanent magnet through a coil of wire

How Does the Induced Current Depend on the Magnet?

- A stronger magnet will induce a greater current
- A weaker magnet will induce a smaller current

How Does the Induced Current Depend on the Wire?

- The more coils, the greater the induced current
- The fewer coils, the less current induced
- For the same magnet, twice as many coils means twice as much current

How Does the Induced Current Depend on Motion?

- You can move the magnet, keeping the loop stationary
- You can move the loop and keep the magnet stationary
- Either way works just as well; you can even move both at the same time

How Does the Induced Current Depend on the Speed?

- Whether you move the magnet or the loop, the faster the motion, the more current induced
- If you move very slowly, you will induce no current at all

Generators

- Precisely the same idea as an electric motor
- Mechanical energy (spin) in, electrical energy (current) out

Transformers

- Two coils wrapped around an iron core
- Primary coil: input alternating current creates time-varying magnetic flux
- Closed iron core loop: concentrates the flux because it's iron–ferromagnetic
- Secondary coil: flux created by primary induces emf in secondary coil
- Ratio p/s: $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

Step Up or Step Down

- Step-Up: secondary voltage is higher than primary
  If $V_s > V_p$ then $N_s > N_p$
- Step-Down: secondary voltage is lower than primary
  If $V_s < V_p$ then $N_s < N_p$

Section 6.6: Circuit Connections

Voltage Sources In Circuits

- AC: Alternating current drives devices that you plug in to the wall
- DC: Direct current drives battery-operated devices

Series Circuit

- Devices are added along the same path: there is one and only one path for electrons to follow
- Every electron must pass through every device in the circuit: cut one device, entire circuit goes out
- Same current through every device (current is common)
- Different voltage across each resistor: depends on resistance of device (use Ohm's law)
- Add more devices, makes it harder for the electrons to get around the circuit: more devices, more resistance
- $V = I(R_1 + R_2 + \cdots + R_n)$
- $V = V_1 + V_2 + \cdots + V_n$

Parallel Circuit

- Each device is added to the circuit on its own path: many possible paths for electrons to follow
- Each path is independent of the other pathways: cut one device, others are unaffected
- Any electron cannot pass through every device: can only travel one pathway
- Same voltage across every device (voltage is common): every path starts and ends at same points
- Different current through each path: amount of current depends on resistance of device (use Ohm's Law)
- Add more devices, opens more pathways: can pull more electrons through the circuit–more devices, less resistance
- $I = I_1 + I_2 + \cdots + I_n$
- $I = \frac{V}{R_1} + \frac{V}{R_2} + \cdots + \frac{V}{R_n}$
- $I = \frac{V}{(R_1 + R_2 + \cdots + R_n)}$

Household Circuits

- Series or parallel? What makes sense here?
- Multiple separate parallel circuits, protected by fuses/circuit breakers
- Old-timey fuses: Tin strip melts if it gets too hot, breaking the circuit
- Modern breakers: See thermostat above! Exactly the same kind of switch!

Plug Protection

- Polarized plug: Makes sure that current-carrying wire gets disconnected if circuit breaker is tripped
- Three-prong plug: Third prong is ground, so excess current id diverted and you don't get shocked (or worse)
- GFCI: Ground-fault circuit interrupter (notice that red button the outlets in the kitchen or bathroom)