Chapter 17: Magnetism

Section 17.1: The Magnetic Interaction

Things You Already Know
- Magnets can attract or repel
- Magnets stick to some things, but not all things
- Magnets are dipoles: north and south
- Labels are historic, because of magnetic compasses
- The earth itself has a magnetic field

The Magnetic Interaction Depends on Distance
- You probably already know this, as well
- You can stick one sheet of paper to the fridge, but you can't stick ten (using the same magnet)
- Force decreases as distance increases (this should not surprise you)

Magnetic and Electrical Interactions Are Different
- Pretty easy to demonstrate that these are related
- Also pretty easy to demonstrate that you can have the E without the B, but not the B without the E
- It's all about charge, but there's more to figure out

Section 17.2: Magnetic Fields

Why Would Magnets Have Fields?
- Action-at-a-distance: You already know that magnets don't have to touch for the force to be effective
- Gravity, electrostatic forces: same type of behavior
- Magnetic field $B$ is totally connected to electric field $E$ (thanks, Maxwell!), but not the same

Direction of the Magnetic Field
- Fields are vectors! Magnitude and direction!
- Magnitude = field strength (decreases with distance)
- Direction is from north to south

Representing Magnetic Field Lines
- Typical parlor-trick demo: Sprinkle iron filings around a magnet to reveal the pattern
- Field strength indicated by line spacing: closer lines, stronger field
- Lines begin (N) and end (S) at the poles of the magnet

Do Other Objects Produce Magnetic Fields?
- 1820: Oersted's Eureka Moment
- Make a circuit, but do not switch it on: A permanent magnet is unaffected
- Switch it on: Current flows, and a permanent magnet (compass needle) will respond
- Reverse the current: Compass needle deflects in the opposite direction
- You've just made an electromagnet, whatever that is

Field of a Long Straight Wire
- Take it off the desktop and see it in 3 dimensions!
- Field lines form complete concentric circles around wire
  \[ B = \mu_0 I / (2\pi r) \]
- Circles get farther apart, farther from the wire (surprise!)
Right Hand Rule
- All you lefties out there: sorry
- Thumb points the direction of current flow (recall that this matches the direction of the $E$ field, but electrons are actually moving the other way)
- Fingers curl the direction of the field lines
- $B$ is technically tangent to the circle

Loops and Solenoids
- Curl that straight wire into a circular loop: Now what?
- Take that straight wire and wind it into a coil consisting of multiple loops: Now what?
- Right-hand rule to the rescue: Fingers curl direction of current, thumb points $B$ field direction
- A solenoid is a great way to make a straight, uniform $B$ field (like charged parallel plates make a straight, uniform $E$ field)

Section 17.3: Magnetic Force Exerted By a Magnetic Field on a Current-Carrying Wire

If a Current Deflects a Magnet, Can a Magnet Deflect a Current?
- Short answer: Yes
- Place a straight wire in a uniform $B$ field; no current, no nothing
- Switch on the current: something happens, but only if the wire is not parallel to $B$
- A force is exerted on the wire, now to figure out how much and in what direction

Direction is the Easy Part
- Another right-hand rule (sorry, lefties)
- Hold your thumb (+x direction) out 90° to your fingers (+y direction)
- Let your fingers represent the $B$ field and your thumb the direction of current $I$
- The direction of the force on the wire is perpendicular to your palm (+z direction)
- Notice what happens if you change the direction of $B$ or $I$!

The Magnitude is More Complicated
- Short answer: $F = 2\pi LBI\sin(\theta)$
- $I$: Stronger current means more force
- $L$: Longer wire means more force
- $B$: Stronger magnet exerts more force
- $\theta$?? The $\sin(\theta)$ attaches to the $B$, and now you are thinking about only that component of the $B$ field which is perpendicular to the wire (parallel piece exerts no force)

Forces That Current-Carrying Wires Exert on Each Other
- If Wire 1 has current ($I_1$), it creates its own magnetic field ($B_1$)
- If Wire 2 also has current ($I_2$), it will experience a force due to $B_1$
- But Wire 2 has just created its own field ($B_2$)! It will exert a force on Wire 1!
- And don't forget about Newton Number Three!

Force Per Unit Length?
- Wire 1 creates $B_1$: $B_1 = (\mu_0 I_1)/(2\pi r)$, where $r$ is the distance between Wires 1 and 2
- $F$ on Wire 2 due to $B_1$: $F = I_2L_B_1 = I_2L[(\mu_0 I_1)/(2\pi r)]$
- $F$ on Wire 1 due to Wire 2 is equal and opposite (ΝΤerman)
- $F/L = (\mu_0 I_1I_2)/(2\pi r)$
Attract or Repel?
• Current in the same direction: Wires attract
• Currents in opposite directions: Wires repel

All Those Units!
• Force = Newtons (some things never change)
• Magnetic field = \( T = \text{Tesla} = \frac{\text{N}}{\text{A} \cdot \text{m}} \)
• Earth's magnetic field \( B_e = 5 \times 10^{-5} \text{T} \)
• Neodymium "supermagnets" about 1-1.3T

Force Leads to Torque
• Bend that straight wire into a square loop: You want sides that are parallel and perpendicular, not curved
• Examine loop in the plane of the \( B \) field, and at 90° to the plane of \( B \)
• Recall that \( \text{torque} = \text{force} \times \text{perpendicular distance} \)
• Now you've got to figure out how to keep it going!

Leads to the DC Motor
• Motor: Electrical energy input, mechanical energy output
• DC: Direct current means you can only push through half a rotation
• Rotating split-ring commutator for the win!
• Yes, you can flip this: Mechanical in, electrical out = generator!

Coils in Magnetic Fields: Ammeters and Voltmeters
• That torques doesn't have to spin the ceiling fan
• Skip the commutator, and calibrate the rotation!
• You can calibrate for either current or voltage (thanks, Ohm!)

Section 17.4: Magnetic Force Exerted on a Single Moving Charge

Another Way to Manipulate Charges
• Charge in an \( E \) field: \( F = qE \)
• Charge in a \( B \) field? Is there an analogous force?
• Of course there is

Direction of the Magnetic Force on a Moving Charge
• Not talking about current any more; typically moving electrons around
• Same-ish right-hand rule as for a current-carrying wire, except the force shoots out the back of your palm (\(-z\)), not the front
• Thumb (\(+x\)) points the direction of motion of the charge, fingers (\(+y\)) still point the direction of \( B \)
• If you happen to be moving (+) charges, the force still shoots out of your palm (+\(z\)), same as before!

Magnitude of the Magnetic Force on a Charged Particle
• True derivation requires a vector cross-product
• \( F = qvB \sin(\theta) \)
• \( q \): More charge means more force. Use the absolute value; don't attach a negative to electrons
• \( v \): Faster speed means more force! Velocity is a vector! Pay attention to the direction!
• \( B \): Stronger field means more force. Magnetic field is also a vector!
• \( \theta \): Just like before, angle \( \theta \) between \( v \) and \( B \); resolves the \( B \) vector into its perpendicular component
Circular Motion in a Magnetic Field
- Doesn't matter where the force comes from; you know from Newton's Laws that if $F$ is perpendicular to $v$, the acceleration in centripetal
- You also already know that the centripetal acceleration results in circular motion

Cosmic Rays and Magnetic Deflection
- Particles come in from all directions; the ones heading in parallel to Earth's $B$ field won't be affected (and some of those are passing through your skull right now)
- The rest get sent into circular paths
- Recall that field strength increases as particles get closer to earth; radius gets smaller
- Result is a spiral towards the poles; particles enter the atmosphere, ionize the molecules, result is aurorae

Section 17.5: Magnetic Fields Produced by Electric Currents
Long Straight Wire
- We already mentioned that $B = (\mu_0 I)/(2\pi r)$
- $I$: More current, stronger field
- $r$: More distance, less field strength
- $\mu_0/(2\pi)$: Proportionality constant

Other Geometries
- Loops and coils are pretty useful
- Subtle difference between loop with $N$ turns and solenoid coil with $N$ turns

Magnetic Permeability
- $\mu_0$: Permeability of free space (vacuum) $\mu_0 = 4\pi \times 10^{-7} \text{T} \cdot \text{m/A}$
- $\mu$ of air is virtually identical to vacuum, and so is copper, teflon, hydrogen, wood, concrete (stuff that you can't really magnetize)
- $\mu$ of iron ranges (depending on purity, heat treatment, alloy, etc) from about $10^{-6}$ (almost vacuum) to 0.25 (200,000× vacuum)

Section 17.7: Mass Spectrometer
Combine the $E$ and the $B$ to Control Motion and Measure Mass
- Perpendicular $E$ and $B_1$ fields crate a velocity selector
- Shoot ions with a known velocity into a second region with a different field $B_2$
- Since $v$ is perpendicular to $B_2$, particle will have circular path
- You know the charge, can measure the radius; getting the mass is easy!

Section 17.8: Magnetic Properties of Materials
Why Isn't Everything a Magnet?
- Everything is made of atoms, atoms are loaded with moving electrons
- Shouldn't everything be a magnet?
- Individual atoms: Mostly the fields from individual electrons cancel
- Groups of atoms: Again, mostly cancel
Diamagnetic Materials
• Water, graphite
• Magnetic moments of individual atoms pretty much zero
• Place diamagnetic in an external $B$ field: Net $B$ of atom is tiny, but points opposite external $B$
• Diamagnetics are weakly repelled by magnetic fields

Paramagnetic Materials
• Aluminum, sodium
• Individual atoms may have weak magnetic moments
• Usually, one atom's moment cancels out another's
• Apply an external $B$ field: Induces the weak moments to align with the applied $B$

Ferromagnetic Materials
• Iron, nickel, cobalt
• Individual atoms have stronger magnetic moments than paramagnetics
• Domain: Localized region within material where moments have aligned
• Typically domains are random with respect to each other, and overall material not magnetic

Making Magnets
• Domains can be coaxed into alignment: Stroke a needle with a bar magnet, and you "pull" the domains into alignment
• Place material in a strong external $B$ field (perhaps the center of a solenoid?): Domains will align with it
• Electromagnet: Solenoid with a ferromagnetic core!