Chapter 24: Magnetic Fields and Forces

Section 24.1: Magnetism

Things You Already Know

- Magnets can attract or repel: opposites attract/likes repel (surprise!)
- 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 $\boldsymbol{E}$ without the $\boldsymbol{B}$, but not the $\boldsymbol{B}$ without the $\boldsymbol{E}$
- It's all about charge, but there's more to figure out

Section 24.2: The Magnetic Field

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 $\boldsymbol{B}$ is totally connected to electric field $\boldsymbol{E}$ (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 south to north

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

The Earth's Magnetic Field

- North geographic pole = south magnetic pole
- Earth's rotational axis is not the sam as magnetic axis!
- Field is dynamic (not like a fridge magnet), generated by molten iron core spinning

Section 24.3: Electric Currents Also Create Magnetic Fields

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
- Congratulations! You've just made an electromagnet, whatever that is

Magnetic Field of a Straight Current-Carrying Wire

- Take it off the desktop and see it in 3 dimensions!
- Field lines form complete concentric circles around wire
- 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 $\boldsymbol{E}$ field, but electrons are actually moving the other way)
- Fingers curl the direction of the field lines
- $\boldsymbol{B}$ 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 $\boldsymbol{B}$ field (like charged parallel plates make a straight, uniform $\boldsymbol{E}$ field)

Section 24.4: Magnetic Fields Exert Forces on Moving Charges

Long Straight Wire

- Field strength $B = \frac{\mu_o I}{(2\pi r)}$
- I: more current, stronger field
- r: more distance, less field strength
- $\frac{\mu_o}{(2\pi)}$: proportionality constant

Magnetic Permeability

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

Magnetic Fields From More Than One Source

- Surprise! Superposition (no one is surprised)
- Field is a vector, so watch your signs and directions!

Current Loops

- Loops and coils are pretty useful
- Loop: $B = \frac{\mu_o I}{(2R)}$
- Coil with N loops: $B = \frac{\mu_o N I}{(2R)}$
- Stipulate that the coil is still a flat loop

Solenoids

- Make a loop with N coils, but now it's not flat, it's a cylindrical* coil with length L
- $B = \frac{\mu_o N I}{L}$
- *It doesn't have to be a circular coil

Section 24.5: Magnetic Fields Exert Forces on Moving Charges

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 or ions 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
- $F\ qvB \sin\alpha$
- 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!
- α: angle 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

Combine the E and the B to Control Motion and Measure Mass

- Perpendicular E and B_1 fields create 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 24.6: Magnetic Fields Exert Forces on Currents

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: $F = ILB \sin \alpha$
- I: Stronger current means more force
- L: Longer wire means more force
- B: Stronger magnet exerts more force
- α: The $\sin \alpha$ 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 on Each Wire

- Wire 1 creates B_1: $B_1 = \frac{\mu_0 I_1}{(2\pi r)}$, where r is the distance to Wire 2
- F on Wire 2 due to B_1: $F = I_2 L B_1 = I_2 L \left[\frac{\mu_0 I_1}{(2\pi r)}\right]$
- F on Wire 1 due to Wire 2 is equal and opposite (Newton! #! 3!)

Attract or Repel?

- Current in the same direction: wires attract
- Currents in opposite directions: wires repel
- Same rule for either straight wires or loops!

All Those Units!

- Force = Newtons (some things never change)
- Magnetic field: $T = \text{Tesla} = \frac{\text{N}}{\text{A·m}}$
- Earth's magnetic field: $B = 5 \times 10^{-5}\text{T}$
- Neodymium "supermagnets" about 1-1.3T

Section 24.7: Magnetic Fields Exert Torques on Dipoles

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 torque = force x 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 24.8: Magnets and Magnetic 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!