Chapter 28: Sources of Magnetic Field
  - Magnetic Materials
  - Hysteresis

Chapter 29: EM Induction & Faraday’s Law
  - Induced EMF and EM Induction
  - Faraday’s Law of Induction
  - Lenz’s Law
Announcements

- Planetarium extra credit
  - Be sure to tape one end onto a sheet of paper with your name on it
  - Submit it at the beginning of the final exam
Reminder: Special Project #5

**B due to current** \( I \) **in a straight wire.** For the field near a long straight wire carrying a current \( I \), show that

(a) the Ampere’s law gives the same result as the simple long straight wire, \( B = \mu_0 \frac{I}{2\pi R} \). (10 points)

(b) That Biot-Savart law gives the same result as the simple long straight wire, \( B = \mu_0 \frac{I}{2\pi R} \). (10 points)

- Must be your OWN work. No credit will be given for copying straight out of the book, lecture notes or from your friends’ work.

- Due is at the beginning of the exam on Tuesday, July 5
The Hall Effect

- What do you think will happen to the electrons flowing through a conductor immersed in a magnetic field?
  - Magnetic force will push the electrons toward one side of the conductor. Then what happens?
    - $F_B = -ev_d \times B$
  - A potential difference will be created due to continued accumulation of electrons on one side. Till when? Forever?
  - Nope. Till the electric force inside the conductor is equal and opposite to the magnetic force

- This is called the **Hall Effect**
  - The potential difference produced is called
    - The Hall emf
  - The electric field due to the separation of charge is called the Hall field, $E_H$, and it points to the direction opposite to the magnetic force
The Hall Effect

- In an equilibrium, the force due to Hall field is balanced by the magnetic force $e v_d B$, so we obtain
- $eE_H = e v_d B$ and $E_H = v_d B$
- The Hall emf is then $\mathcal{E}_H = E_H l = v_d B l$
  - Where $l$ is the width of the conductor
- What do we use the Hall effect for?
  - The current of negative charge moving to right is equivalent to the positive charge moving to the left
  - The Hall effect can distinguish these since the direction of the Hall field or direction of the Hall emf is opposite
  - Since the magnitude of the Hall emf is proportional to the magnetic field strength $\Rightarrow$ can measure the $B$-field strength

- Hall probe
Magnetic Materials - Ferromagnetism

- Iron is a material that can turn into a strong magnet
  - This kind of material is called ferromagnetic material
- In microscopic sense, ferromagnetic materials consist of many tiny regions called domains
  - Domains are like little magnets usually smaller than 1mm in length or width
- What do you think the alignment of domains are like when they are not magnetized?
  - Randomly arranged
- What if they are magnetized?
  - The size of the domains aligned with the external magnetic field direction grows while those of the domains not aligned reduce
  - This gives magnetization to the material
- How do we demagnetize a bar magnet?
  - Hit the magnet hard or heat it over the Curie temperature
B in Magnetic Materials

- What is the magnetic field inside a solenoid?
  \[ B_0 = \mu_0 nI \]
  - Magnetic field in a long solenoid is directly proportional to the current.
  - This is valid only if air is inside the coil
- What do you think will happen to B if we have something other than the air inside the solenoid?
  - It will be increased dramatically, when the current flows
    - Especially if a ferromagnetic material such as an iron is put inside, the field could increase by several orders of magnitude
- Why?
  - Since the domains in the iron aligns permanently by the external field.
  - The resulting magnetic field is the sum of that due to current and due to the iron
**B in Magnetic Materials**

- It is sometimes convenient to write the total field as the sum of two terms
  
  \[ B = B_0 + B_M \]

  - \( B_0 \) is the field due only to the current in the wire, namely the external field
    - The field that would be present without a ferromagnetic material
  - \( B_M \) is the additional field due to the ferromagnetic material itself; often \( B_M \gg B_0 \)

- The total field in this case can be written by replacing \( \mu_0 \) with another proportionality constant \( \mu \), the magnetic permeability of the material
  
  \[ B = \mu n I \]

  - \( \mu \) is a property of a magnetic material
  - \( \mu \) is not a constant but varies with the external field
Hysteresis

• What is a toroid?
  – A solenoid bent into a shape

• Toroid can be used for magnetic field measurement
  – Why?
  – Since it does not leak magnetic field outside of itself, it fully contains all the magnetic field created within it.

• Consider an un-magnetized iron core toroid, without any current flowing in the wire
  – What do you think will happen if the current slowly increases?
  – $B_0$ increases linearly with the current.
  – And $B$ increases also but follows the curved line shown in the graph
  – As $B_0$ increases, the domains become more aligned until nearly all are aligned (point b on the graph)
    • The iron is said to be approaching saturation
    • Point b is typically at 70% of the max
Hysteresis

- What do you think will happen to B if the external field $B_0$ is reduced to 0 by decreasing the current in the coil?
  - Of course it goes to 0!!
  - Wrong! Wrong! Wrong! They do not go to 0. Why not?
  - The domains do not completely return to random alignment state

- Now if the current direction is reversed, the external magnetic field direction is reversed, causing the total field $B$ pass 0, and the direction reverses to the opposite side
  - If the current is reversed again, the total field $B$ will increase but never goes through the origin

- This kind of curve whose path does not retrace themselves and does not go through the origin is called the **Hysteresis**.
Magnetically Soft Material

- In a hysteresis cycle, much energy is transformed to thermal energy. Why?
  - Due to the microscopic friction between domains as they change directions to align with the external field

- The energy dissipated in the hysteresis cycle is proportional to the area of the hysteresis loop

- Ferromagnetic material with a large hysteresis area is called magnetically hard while the small ones are called soft
  - Which one do you think are preferred in electromagnets or transformers?
    - Soft. Why?
      - Since the energy loss is small and much easier to switch off the field

- Then how do we demagnetize a ferromagnetic material?
  - Keep repeating the Hysteresis loop, reducing the range of $B_0$. 
Induced EMF

- It has been discovered by Oersted and company in early 19th century that
  - Magnetic field can be produced by the electric current
  - Magnetic field can exert force on the electric charge
- So if you were scientists at that time, what would you wonder?
  - Yes, you are absolutely right! You would wonder if the magnetic field can create the electric current.
  - An American scientist Joseph Henry and an English scientist Michael Faraday independently found that it was possible
    - Though, Faraday was given the credit since he published his work before Henry did
      - He also did a lot of detailed studies on magnetic induction
Electromagnetic Induction

- Faraday used an apparatus below to show that magnetic field can induce current.
- Despite his hope he did not see steady current induced on the other side when the switch is thrown.
- But he did see that the needle on the Galvanometer turns strongly when the switch is initially thrown and is opened.
  - When the magnetic field through coil Y changes, a current flows as if there were a source of emf.
- Thus he concluded that an induced emf is produced by a changing magnetic field. 

Electromagnetic Induction
Electromagnetic Induction

• Further studies on electromagnetic induction taught
  – If a magnet is moved quickly into a coil of wire, a current is induced in the wire.
  – If a magnet is removed from the coil, a current is induced in the wire in the opposite direction.
  – By the same token, the current can also be induced if the magnet stays put but the coil moves toward or away from the magnet.
  – Current is also induced if the coil rotates.

• In other words, it does not matter whether the magnet or the coil moves. It is the relative motion that counts.
Magnetic Flux

• So what do you think is the induced emf proportional to?
  – The rate of changes of the magnetic field?
    • the higher the changes the higher the induction
  – Not really, it rather depends on the rate of change of the magnetic flux, $\Phi_B$.
  – Magnetic flux is defined as (just like the electric flux)
    – $\Phi_B = B \perp A = BA \cos \theta = B \cdot A$
      • $\theta$ is the angle between $B$ and the area vector $A$ whose direction is perpendicular to the face of the loop based on the right-hand rule
  – What kind of quantity is the magnetic flux?
    • Scalar.
      • Unit?
        • $T \cdot m^2$ or weber
          $1Wb = 1T \cdot m^2$
  • If the area of the loop is not simple or $B$ is not uniform, the magnetic flux can be written as
    – $\Phi_B = \int B \cdot dA$