PHYS 1441 – Section 001 Lecture #15

Tuesday, June 29, 2016

Dr. Jaehoon Yu

- 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

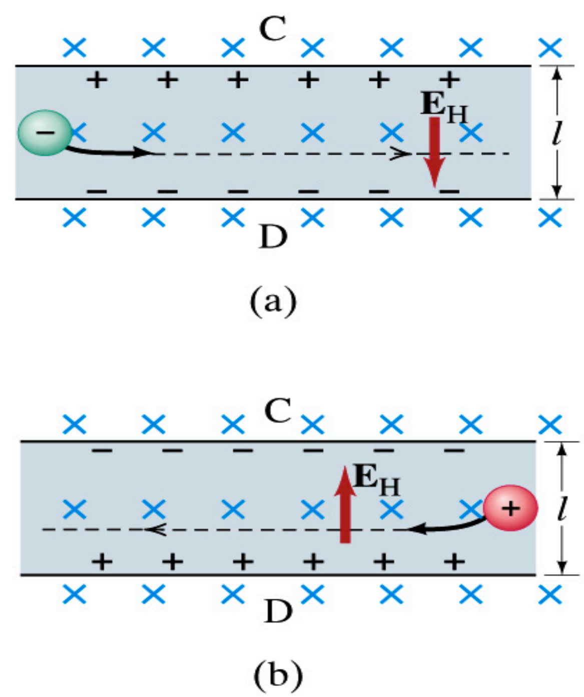
(a) the Ampere's law gives the same result as the simple long straight wire, $B=\mu_0 I/2\pi R$. (10 points)

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

- Must be your OWN work. No credit will be given for 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

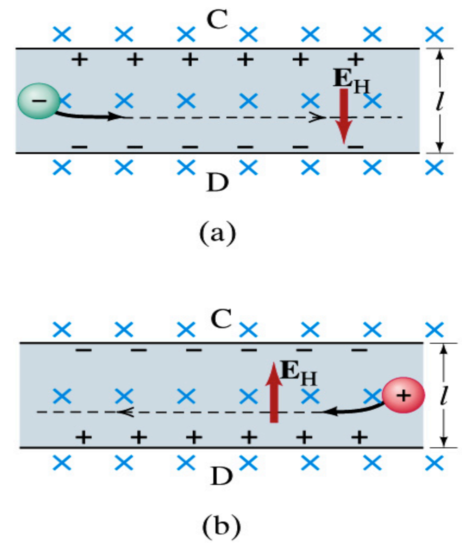
The Hall Effect

- 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?
    - $\vec{F}_B = -e\vec{v}_d \times \vec{B}$
  - 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, $\mathbf{E}_H$, and it points to the direction opposite to the magnetic force



The Hall Effect

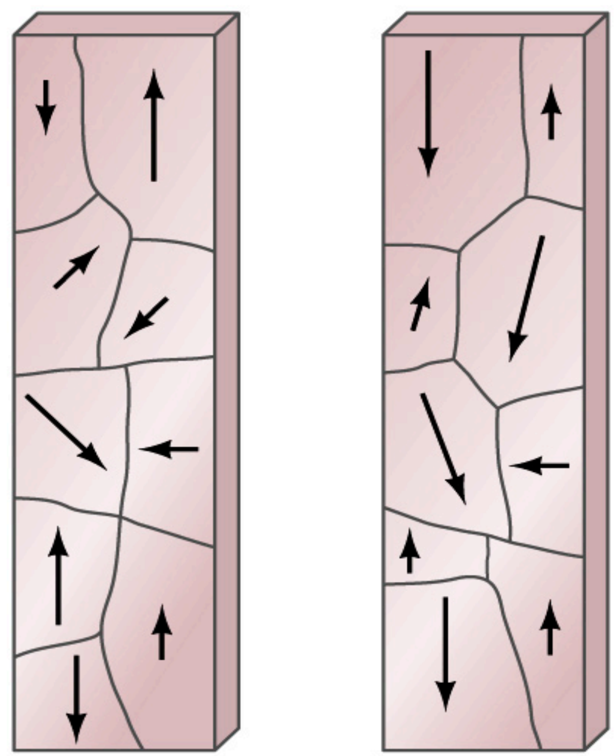
- In an equilibrium, the force due to Hall field is balanced by the magnetic force ev_dB, so we obtain



- $eE_H = ev_d B$ and $E_H = v_d B$
- The Hall emf is then $\varepsilon_H = E_H l = v_d Bl$
  - 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 ➔ 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)

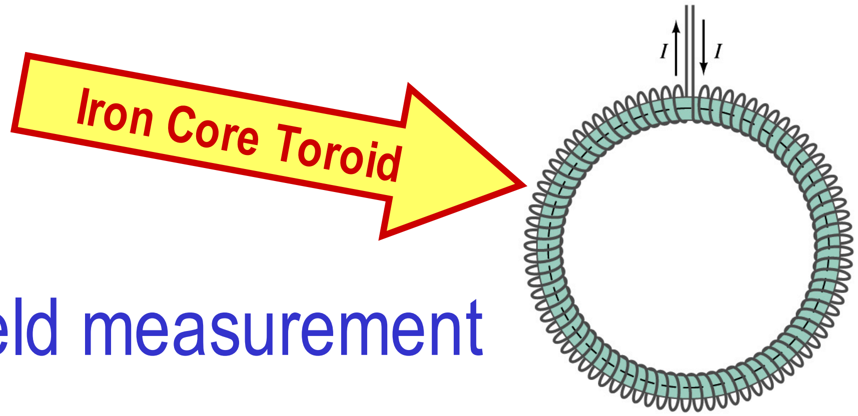
B in Magnetic Materials

- What is the magnetic field inside a solenoid?
- $$B_0 = \mu_0 n I$$
  - 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

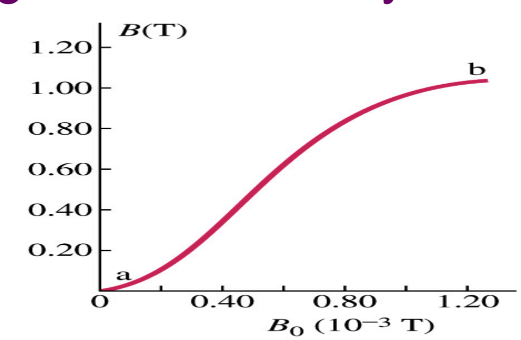
B in Magnetic Materials

- It is sometimes convenient to write the total field as the sum of two terms
- $$\vec{B} = \vec{B}_0 + \vec{B}_M$$
  - **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**>>**B_0**
- The total field in this case can be written by replacing μ_0 with another proportionality constant μ, the magnetic permeability of the material $B = \mu n I$
  - μ is a property of a magnetic material
  - μ is not a constant but varies with the external field

Hysteresis

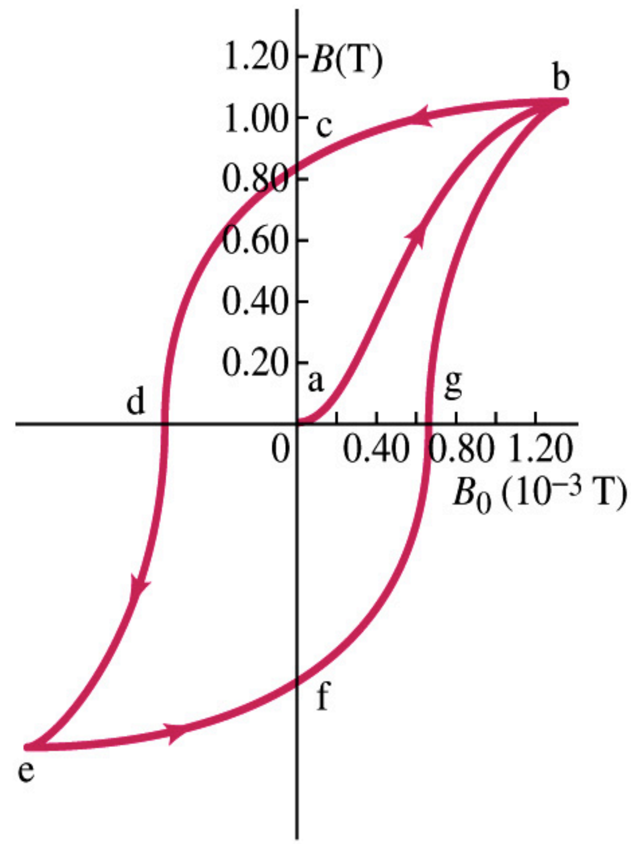


- What is a toroid?
  - A solenoid bent into a shape
- Toroid can be used for magnetic field measurement
  - Why?
  - Since it does not leak magnetic field outside of itself, it fully contains all the magnetic field created within it.
- Consider an un-magnetized iron core toroid, without any current 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



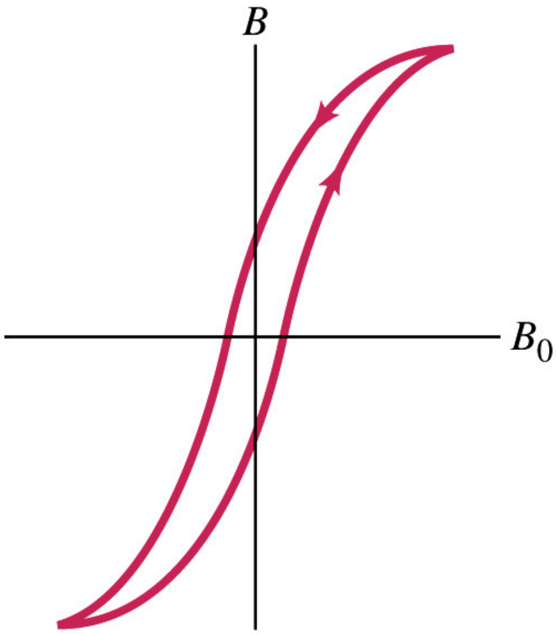
Hysteresis

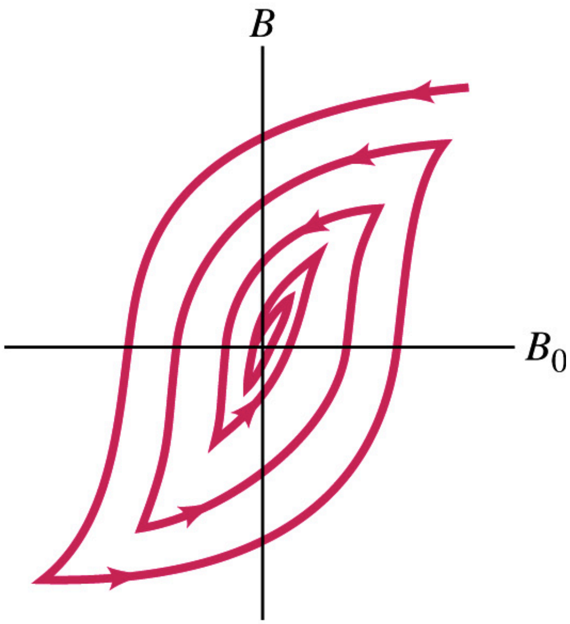
- What do you think will happen to B if the external field B_0 is reduced to 0 by decreasing the current in the coil?
  - ~~Of course it goes to 0!!~~
  - Wrong! Wrong! Wrong! They do not go to 0. Why not?
  - The domains do not completely return to random alignment state
- Now if the current direction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



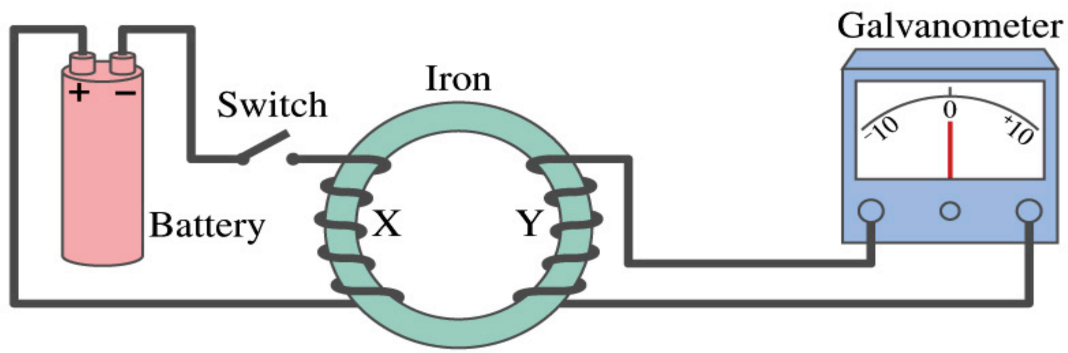


Induced EMF

- 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

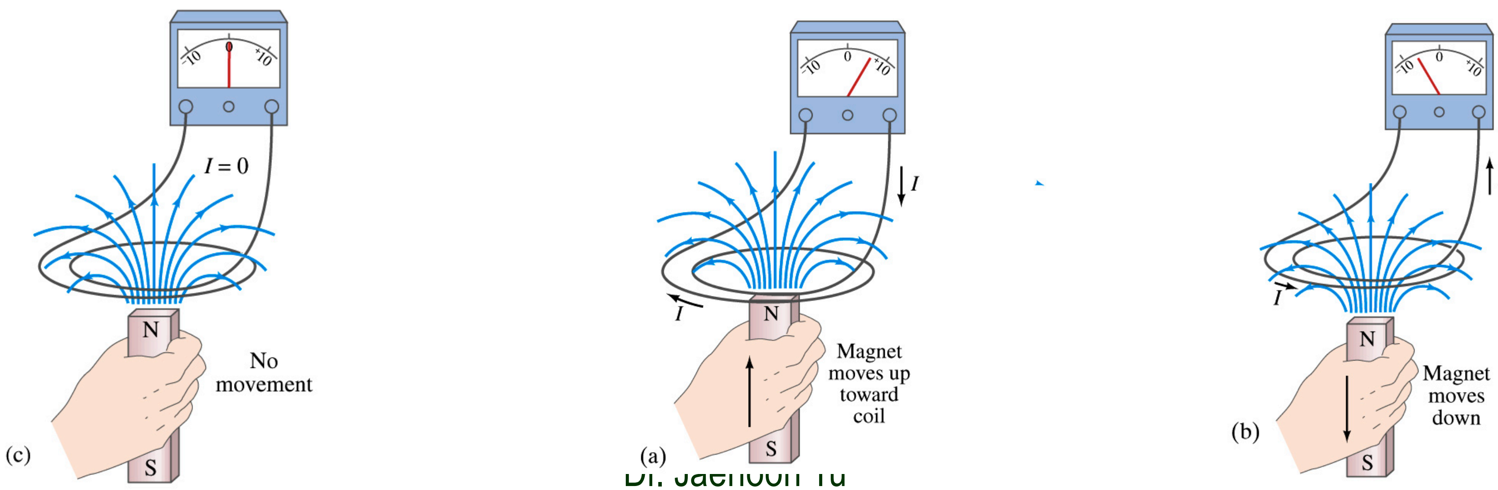
- Faraday used an apparatus below to show that magnetic field can induce current



- 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**

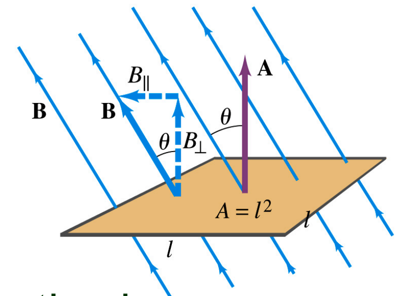
Electromagnetic Induction

- 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**, Φ_B.
  - Magnetic flux is defined as (just like the electric flux)
  - $$\Phi_B = B_\perp A = BA\cos\theta = \vec{B}\cdot\vec{A}$$
    - θ 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

$$\Phi_B = \int \vec{B}\cdot d\vec{A}$$