PHYS 1444 – Section 003
Lecture #18

Wednesday, Nov. 2, 2005

Dr. Jaehoon Yu

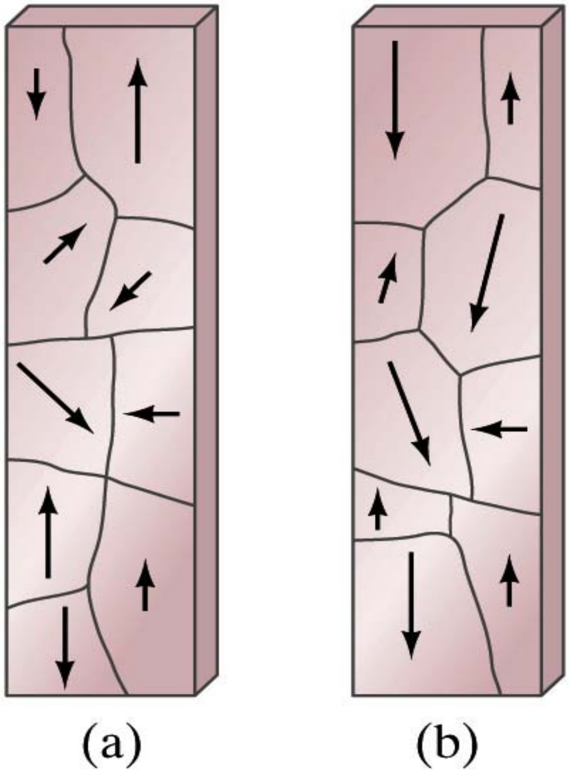
- Magnetic Materials – Ferromagnetism
- Magnetic Fields in Magnetic Materials; Hysteresis
- Induced EMF
- Faraday's Law of Induction
- Lenz's Law
- EMF Induced on a Moving Conductor

Announcements

- The 2nd term exam
  - Date: Monday, Nov. 7
  - Time: 1 – 2:20pm
  - Location: SH 103
  - Coverage: from CH 26 to CH29 – 3
- Your textbooks
  - UTA bookstore agreed to exchange your books with the ones that has complete chapters
    - You need to provide a proof of purchase
      - Receipts, copy of cancelled checks, credit card statement, etc.

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 consists 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 (fig. a)
- What if they are magnetized?
  - The domains aligned with the external magnetic field direction grows while domains not aligned reduce (fig. b)
  - This gives magnetization to the material
- How do we demagnetize a bar magnet?
  - Hit the magnet hard or heat it over the Curie temperature



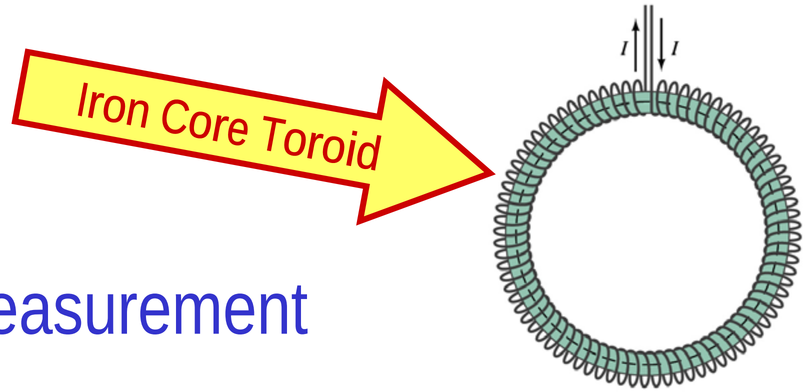
B in Magnetic Materials

- 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

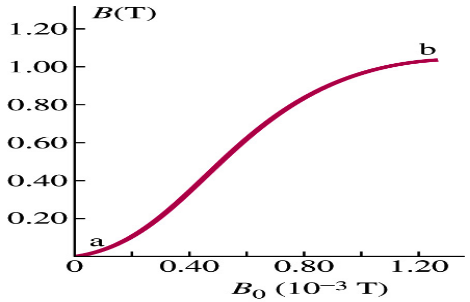
B in Magnetic Materials

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

Hysteresis

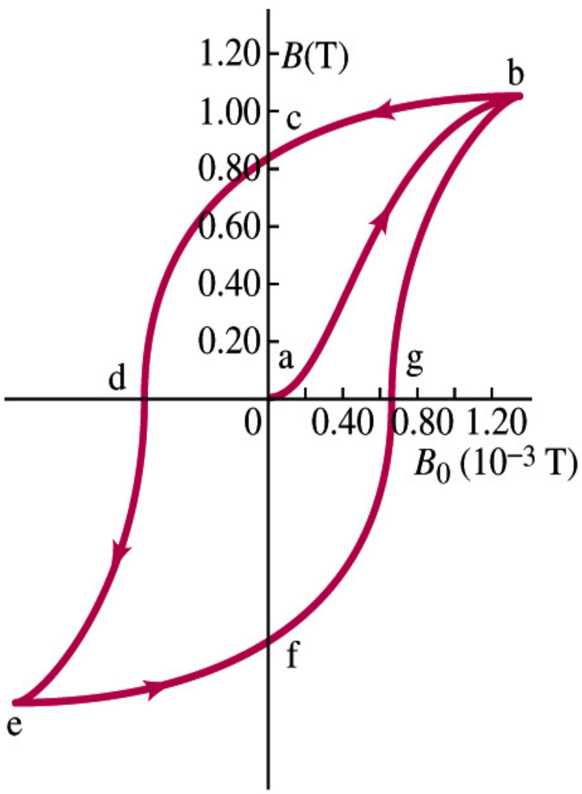


- What is a toroid?
  - A solenoid bent into a shape
- Toroid is used for magnetic field measurement
  - Why?
  - Since it does not leak magnetic field outside of itself, it fully contains all the magnetic field created within it.
- Consider an un-magnetized iron core toroid, without any current flowing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



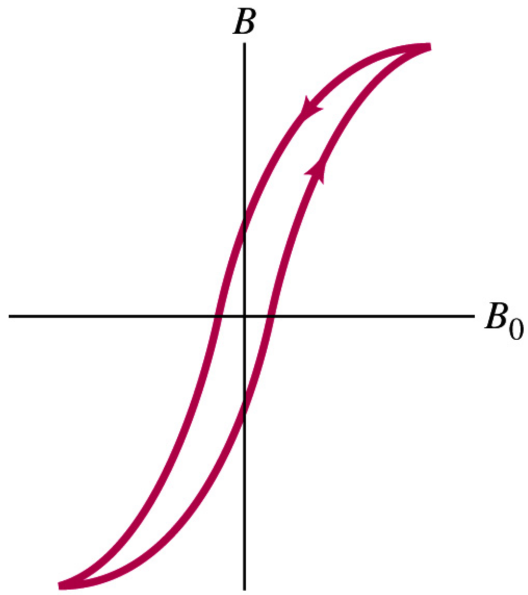
Hysteresis

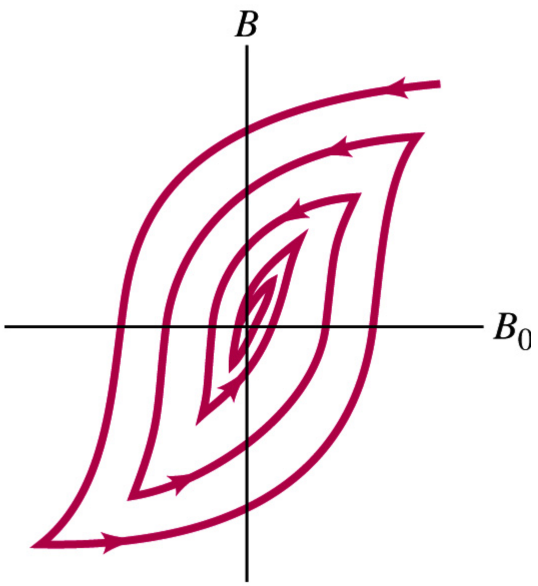
- What do you think will happen to B if the external field B_0 is reduced to 0 by decreasing the current in the coil?
  - ~~Of course it goes to 0!!~~
  - Wrong! Wrong! Wrong! They do not go to 0. Why not?
  - The domains do not completely return to random alignment state
- Now if the current direction 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 large hysteresis area is called magnetically hard while the small ones are called soft
  - Which ones 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.



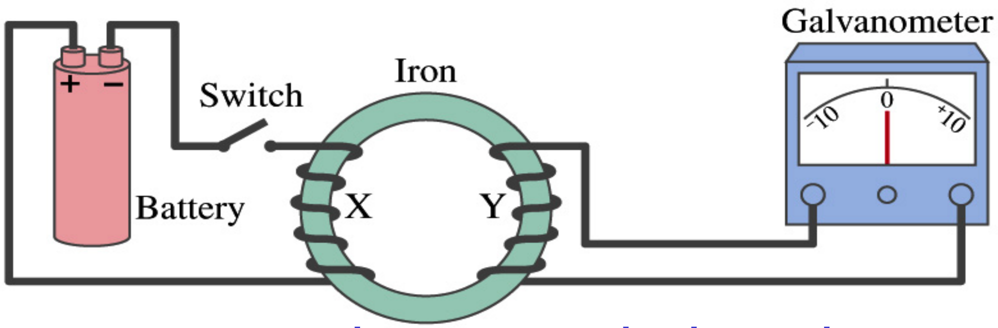


Induced EMF

- 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 electric charge
- So if you were scientists at that time, what would you wonder?
  - Yes, you are absolutely right. You would wonder if magnetic field can create 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

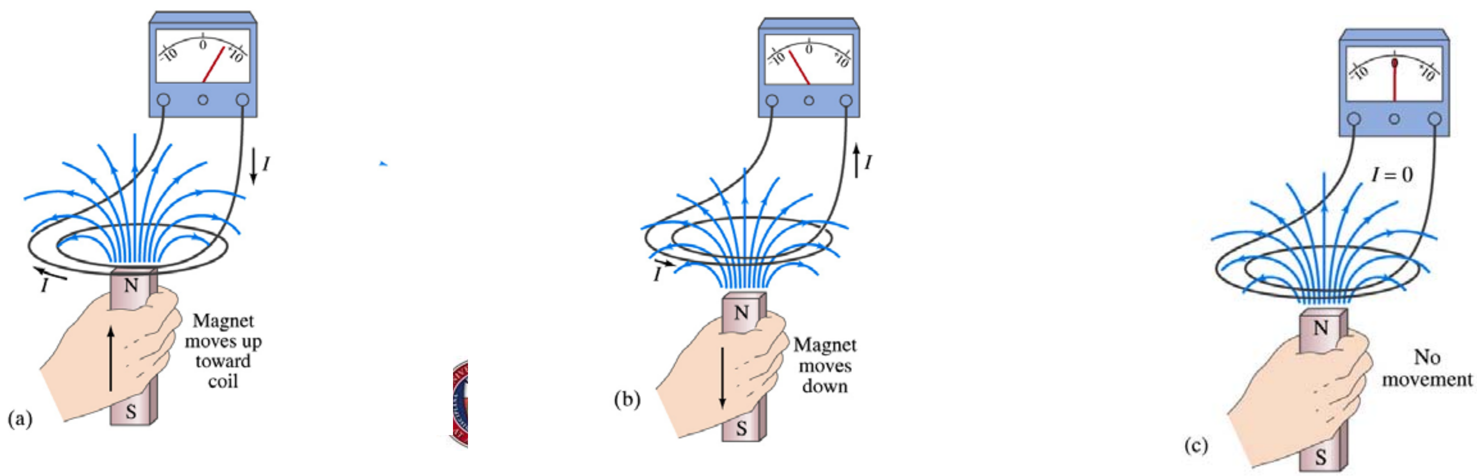
- Faraday used an apparatus below to show that magnetic field can induce current



- 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 <u>an induced emf is produced by a changing magnetic field</u> → <u>Electromagnetic Induction</u>

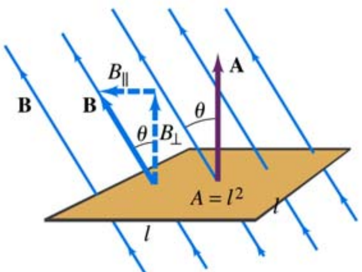
Electromagnetic Induction

- Further studies on electromagnetic induction taught
  - If magnet is moved quickly into a coil of wire, a current is induced in the wire.
  - If the magnet is removed from the coil, a current is induced in the wire in the opposite direction
  - By the same token, 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



  - 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

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

Faraday's Law of Induction

- In terms of magnetic flux, we can formulate Faraday's findings
  - The emf induced in a circuit is equal to the rate of change of magnetic flux through the circuit

$$\boxed{\varepsilon = -\frac{d\Phi_B}{dt}}$$

Faraday's Law of Induction

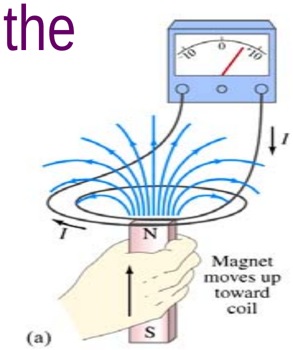
- If the circuit contains N closely wrapped loops, the total induced emf is the sum of emf induced in each loop

$$\boxed{\varepsilon = -N\frac{d\Phi_B}{dt}}$$

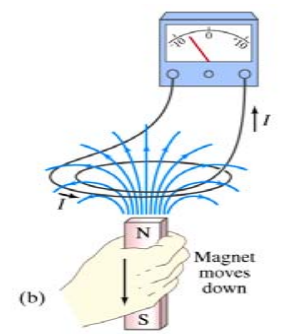
  - Why negative?
    - Has got a lot to do with the direction of induced emf…

Lenz's Law

- It is experimentally found that
  - An induced emf gives rise to a current whose magnetic field opposes the original change in flux ➔ This is known as **Lenz's Law**
  - In other words, an induced emf is always in a direction that opposes the original change in flux that caused it.
  - We can use Lenz's law to explain the following cases in the figures
    - First when the magnet is moving into the coil
      - The flux increases so the field inside the coil takes the opposite direction which then causes the current to flow clockwise
    - When the magnet is moving out
      - The flux decreases, so the field inside the coil takes the opposite direction to compensate causing the current to flow counter-clockwise



(a)

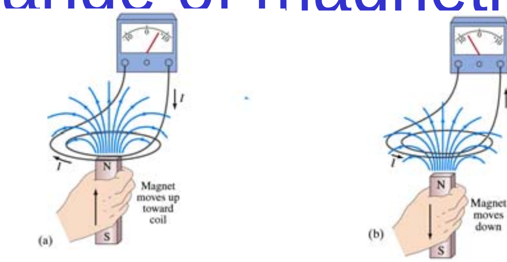


(b)

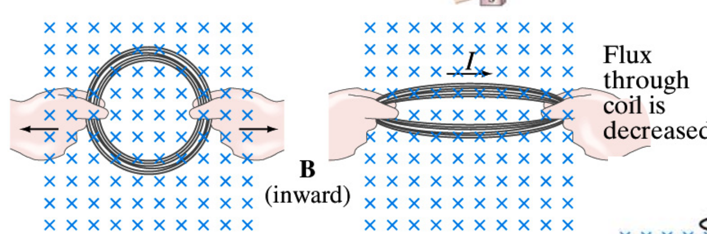
- Which law is Lenz's law result of?
  - Energy conservation. Why?

Induction of EMF

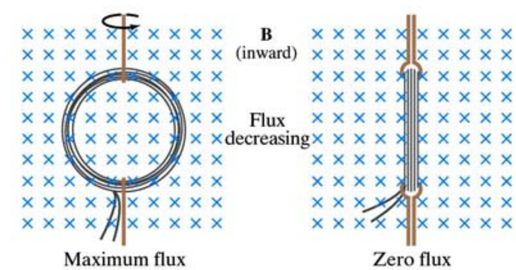
- How can we induce emf?
- Let's look at the formula for magnetic flux
- $$\Phi_B = \int \vec{B} \cdot d\vec{A} = \int B \cos\theta \, dA$$
- What do you see? What are the things that can change with time to result in change of magnetic flux?
  - Magnetic field



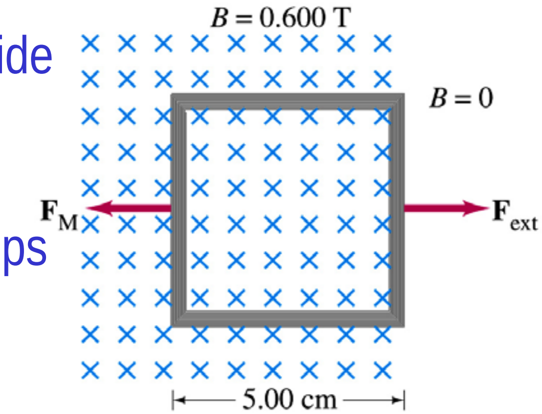
  - The area of the loop



  - The angle θ between the field and the area vector



Example 29 – 2



Pulling a coil from a magnetic field. A square coil of wire with side 5.00cm contains 100 loops and is positioned perpendicular to a uniform 0.600-T magnetic field. It is quickly and uniformly pulled from the field (moving perpendicular to B) to a region where B drops abruptly to zero. At t=0, the right edge of the coil is at the edge of the field. It takes 0.100s for the whole coil to reach the field-free region. Find (a) the rate of change in flux through the coil, (b) the emf and current induced, and (c) how much energy is dissipated in the coil if its resistance is 100Ω. (d) what was the average force required?

What should be computed first? The initial flux at t=0.

The flux at t=0 is $\Phi_B = \vec{B}\cdot\vec{A} = BA = 0.600T\cdot\left(5\times10^{-2}m\right)^2 = 1.50\times10^{-3}Wb$

The change of flux is $\Delta\Phi_B = 0 - 1.50\times10^{-3}Wb = -1.50\times10^{-3}Wb$

Thus the rate of change of the flux is

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{-1.50\times10^{-3}Wb}{0.100s} = -1.50\times10^{-2}\,Wb/s$$

Example 29 – 2, cnt'd

Thus the total emf induced in this period is

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -100\cdot\left(-1.50\times10^{-2}\,Wb/s\right) = 1.5V$$

The induced current in this period is

$$I = \frac{\varepsilon}{R} = \frac{1.5V}{100\Omega} = 1.50\times10^{-2}\,A = 15.0mA$$

Which direction would the induced current flow? Clockwise

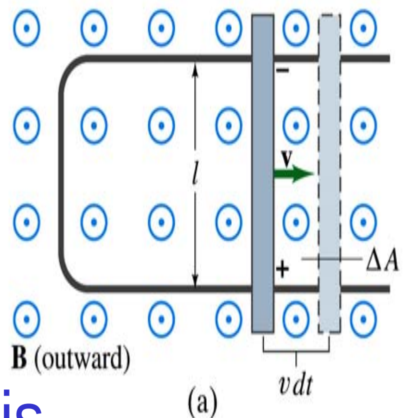
The total energy dissipated is

$$E = Pt = I^2Rt = \left(1.50\times10^{-2}\,A\right)^2\cdot100\Omega\cdot0.100s = 2.25\times10^{-3}\,J$$

Force for each coil is $\vec{F} = I\vec{l}\times\vec{B}$ Force for N coil is $\vec{F} = NI\vec{l}\times\vec{B}$

$$\left|F\right| = NIlB = 100\cdot\left(1.50\times10^{-2}\,A\right)\cdot\left(4\times5\times10^{-2}\right)\cdot0.600T = 0.045N$$

EMF Induced on a Moving Conductor



- Another way of inducing emf is using a U shaped conductor with a movable rod resting on it.
- As the rod moves at a speed v, it travels $v$dt in time dt, changing the area of the loop by dA=lvdt.
- Using Faraday's law, the induced emf for this loop is

$$|\varepsilon| = \frac{d\Phi_B}{dt} = \frac{BdA}{dt} = \frac{Blvdt}{dt} = Blv$$

  – This equation is valid as long as B, l and v are perpendicular to each other. What do we do if not?
    - Use the scalar product of vector quantities
- An emf induced on a conductor moving in a magnetic field is called a **motional emf**