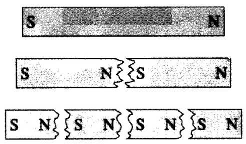
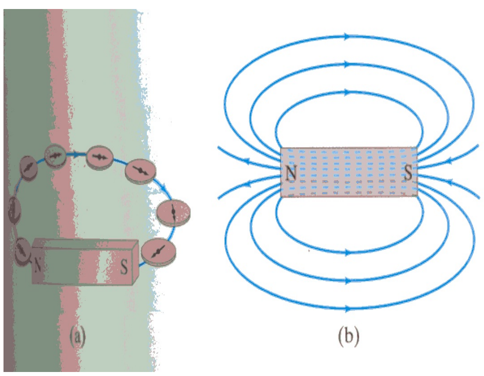
MAGNETISM

MAGNETS AND MAGNETIC FIELDS

FIGURE 20–2 If you break a magnet in half, you do not obtain isolated north and south poles; instead, two new magnets are produced, each with a north and a south pole.

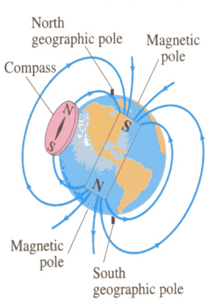


- **poles**--dipole; North and South
  - Suspend a magnet and the north seeking pole aligns with North--documented as a navigational tool since 11th century China
  - Opposites attract and likes repel--even without contact
- **NOT like electric charges** since a + or - charge can be isolated. You cannot isolate a pole
  - NO monopole has ever been isolated. When you break a magnet, you get pieces with new N and S poles
- **Fe, Co, Ni, Gd** show *strong* magnetic effects and are called ferromagnetic



- **magnetic field lines--**the force one magnet exerts on another can be described as the interaction between the magnet and the magnetic field of another magnet
  - direction of magnetic field is tangent to a line at any point
  - the number of lines per unit area is ∝ to the magnitude of the magnetic field
  - direction is the direction the N pole of a compass needle would point
  - draw these lines N → S

FIGURE 20–6 The Earth acts like a huge magnet but its magnetic poles are not at the geographic poles.



- **B--symbol for magnetic field**--magnitude is related to torque exerted on compass needle; greater torque, greater field strength
- Magnetic N is really S and 1300 km from Santa's home. Geographic N occurs at the "top" of the earth's rotational axis
  - Magnetic declination--angular difference between magnetic and geographic N poles. Value varies between 0° and 25°
- **uniform field**--hard to produce over a large area--fringes @ edges; much like the electric field lines do

ELECTRIC CURRENTS PRODUCE MAGNETISM

1820 Hans Christian Oersted found that a compass needle was deflected when placed near an electric wire ∴ an electric current produces a magnetic field

- A compass needle aligns itself so it is tangent to a circle drawn around the wire

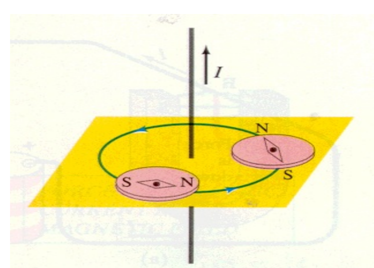


FIGURE 20–9 Deflection of a compass needle near a current-carrying wire, showing the presence and direction of the magnetic field.

- **Right hand rule**--one of them at least--this one is for a straight wire
  - grasp the wire with the right hand
  - point thumb in the direction of the POSITIVE current [thanks Ben!]
  - NOW, your fingers point in the direction of the magnetic field
- Loop of wire--right hand rule still applies and you can still use a compass to determine field as well

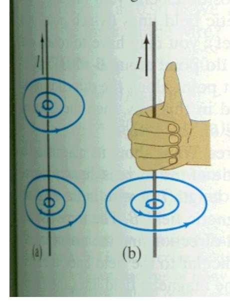


FIGURE 20-10 (a) Magnetic field lines around an electric current in a straight wire. (b) Right-hand rule for remembering the direction of the magnetic field: when the thumb points in the direction of the conventional current, the fingers wrapped around the wire point in the direction of the magnetic field.

FIGURE 20-11 Magnetic field due to a circular loop of wire.

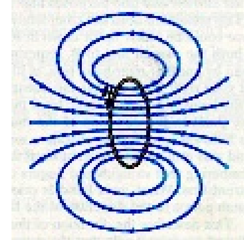


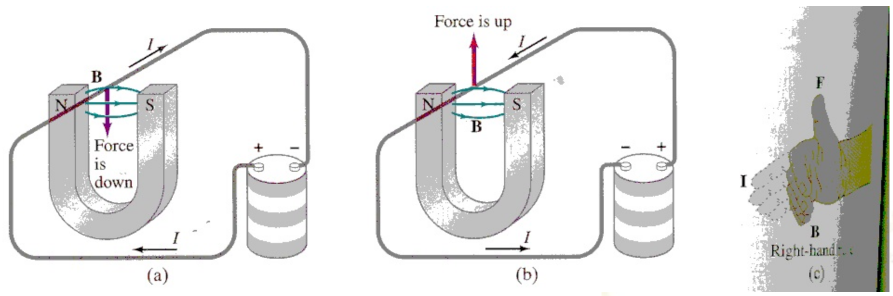
FIGURE 20-12 Right-hand rule for determining the direction of the magnetic field relative to the current.

FORCE ON AN ELECTRIC CURRENT IN A MAGNETIC FIELD; DEFINITION OF B

Oersted was a good Newtonian physics student and reasoned that if an electric current exerts a F on a magnet [the compass needle], then shouldn't a magnet exert a force on a current carrying wire according to Newton's 3rd Law? Yep.

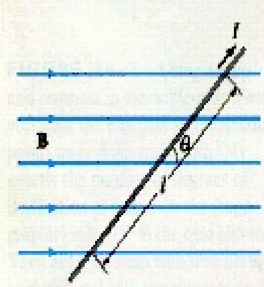
- A straight section of wire is placed between the two poles of a horseshoe magnet; when current flows, a F is exerted ⊥ to the magnetic field. Reverse the current, F reverses direction [same magnet with same amps coursing through it]. F is ⊥ to current flow and ⊥ to magnetic field.

FIGURE 20-13 (a) Force on a current-carrying wire placed in a magnetic field **B**; (b) same, but current reversed; (c) right-hand rule for setup in (b).



- **Right-hand Rule**--another one--this one lets you know the direction of the **force** exerted
  - point your right arm in the direction of the current flow
  - bend your fingers, about 90°, in the N → S direction
  - thumb points in the direction of the Force exerted
- **Magnitude of the F**--now that you can get the direction....
  - F ∝ I
  - F ∝ ℓ
  - F ∝ B
  - F ∝ sin θ where θ is the angle between current direction and magnetic field, B
    - When I is ⊥ to field lines, current is strongest!
    - When I is ∥ to field lines, NO FORCE EXISTS AT ALL!
  - Therefore,

Current-carrying wire in a magnetic field. Force on the wire is directed into the page.



Force exerted on a wire carrying current by a magnetic field:	**F ∝ B I ℓ sin θ**

- When is F_{max} = ZERO? When the current is parallel to the field, B.

- If current in the straight wire is ⊥ to the field [$\sin\theta = \sin 90° = 1$]
- $F_{max} = B I \ell$
- So....

$$B = \frac{F_{max}}{I\ell}$$

- The unit for B is the Tesla

$$1T = 1\frac{N}{A \bullet m} = \frac{Weber}{m^2}$$

- Also
  measured in a unit known as the Gauss (G); 1 G = 10^{-4} T
- Earth's Magnetic field @ the surface is about ½ G or 0.5 x 10^{-4} T

Example 1

A wire carrying a 30.0 A current has a length of 12 cm between the pole faces of a magnet at an angle of 60°. The magnetic field is approximately uniform at 0.90 T. We ignore the field beyond the pole pieces. What is the force on the wire? See figure on the previous page.

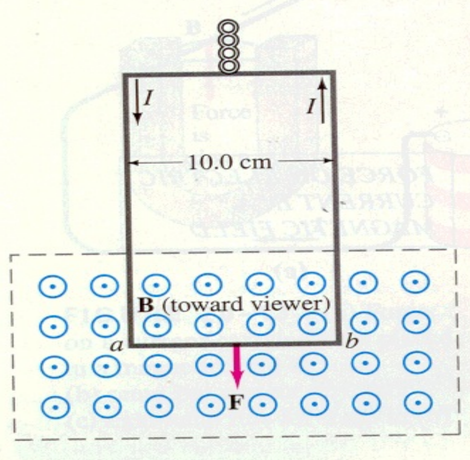


FIGURE 20–15 Measuring a magnetic field **B**. Example 20–2.

- ⊙ signifies a magnetic field line coming out of the page, toward you
- x signifies a magnetic field line going into the page, away from you
- Just imagine an archery arrow like this one ➵. If you look at the tip of the arrow head, you'd see a fine point [dot], rotate it 180° and you see the tail feathers as an x.

Example 2

A rectangular loop of wire hangs vertically as shown in this figure. A magnetic field B is directed horizonally, ⊥ to the wire, and points out of the page at all points represented by the symbol ⊙ . The magnetic field, B, is very nearly uniform along the horizontal portion of the wire, ab [length = 10.0 cm] which is near the center of a large magnet producing the field. The top portion of the loop is free of the field. The loop hangs from a balance which measures a downward force of $F = 3.48 \times 10^{-2}$ N when the wire has a current I = 0.245 A. What is the magnitude of the field, B, at the center of the magnet?

FORCE ON AN ELECTRIC CHARGE MOVING IN A MAGNETIC FIELD

- A current carrying wire experiences a F in a magnetic field.
- Free Moving electrons (not in a wire) also experience F in a magnetic field.
- I guess that means we need to know how to determine the F on a free moving e^- in a B
  - I = # q/t where t = time q travels ℓ in a magnetic field B
  - ℓ = vt where v = velocity of a particle
  - remember F = BI ℓ sin θ
    = B(#q/t)(vt) sin θ t's cancel and set # q equal to one

Force on an electric charge moving in a magnetic field: F = qvB sin θ

- When is F ZERO? When the particle moves parallel to the field lines since θ = zero
- F_{max} when the particle moves ⊥ to B so $F_{max} = qvB$
- The direction of F is ⊥ to B and ⊥ v
- **<u>Right-hand rule</u>**--to determine the direction of F
  - point arm along the motion of the POSITIVE particle
  - bend fingers in the direction of B
  - thumb points in the direction of the F

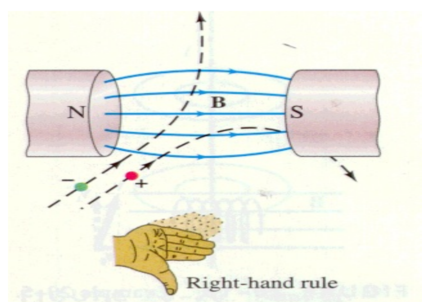


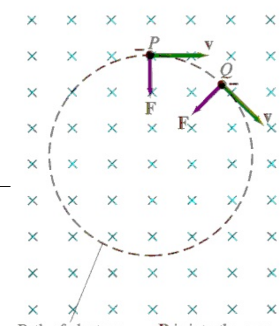
FIGURE 20–16 Force on charged particles due to a magnetic field is perpendicular to the magnetic field direction.

Example 3

A proton having a speed of 5.0×10^6 m/s in a magnetic field feels a F of 8.0×10^{-14} N toward the West when it moves vertically upward. When moving horizontally in a northerly direction, it feels zero force. What is the magnitue and direction of the magnetic field in this region? [$q = +e = 1.6 \times 10^{-19}$ C]

- Path of a charged particle moving in a plane ⊥ to a uniform B is a circle. Since F ⊥ v, magnitude of v doesn't change, BUT direction does and the particle moves in a circular path with centripetal acceleration. F is directed toward the center of a circle at all points. Note the electron moves clockwise. How about a proton?

FIGURE 20–17 Force exerted by a uniform magnetic field on a moving charged particle (in this case, an electron) produces a circular path.



Example 4

An electron travels at 2.0×10^7 m/s in a plane perpendicular to a 0.010-T magnetic field. Describe its path.

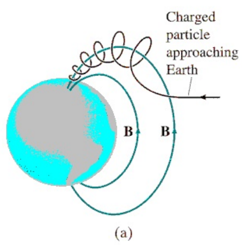
Example 5

What is the path of a charged particle if its velocity is NOT perpendicular to the magnetic field?

Example 6

Charged ions approach the Earth from the Sun (the "solar wind") and are drawn toward the poles, sometimes causing a phenomenon called the aurora borealis or "northern lights" in northern latitudes. Why toward the poles?

FIGURE 20–19 (a) Diagram showing a charged particle approaching the Earth which is "captured" by the magnetic field of the Earth. Such particles follow the field lines toward the poles as shown. (b) Photo of aurora borealis.



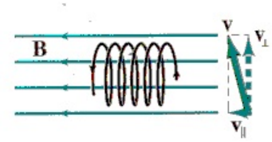


FIGURE 20–18 Example 20–5.

MAGNETIC FIELD DUE TO A STRAIGHT WIRE

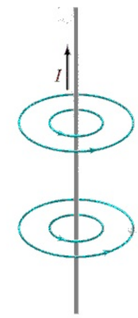


FIGURE 20–20 Same as Fig. 20–10a, magnetic field lines around a long straight wire carrying an electric current I.

- Remember field lines encircle a straight wire
- $B \propto \frac{I}{r}$
- Valid as long as r is MUCH LESS than ℓ

Magnetic Field due to current in a straight wire: $B = \frac{\mu_o}{2\pi}\frac{I}{r}$

- The value of μ_o is $4\pi \times 10^{-7}$ T •m/A and is called **the permeability of free space.**

Example 7

A vertical electric wire in the wall of a building carries a dc current of 25 A upward. What is the magnetic field at a point 10 cm due north of this wire?

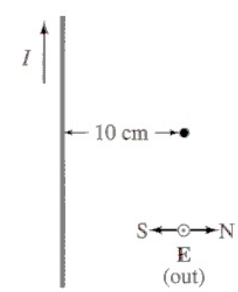


FIGURE 20–21 Example 20–7.

FORCE BETWEEN TWO PARALLEL WIRES

- A wire carrying current produces B AND feels force when placed in a magnetic field, therefore TWO current carrying wires would exert a F on each other!
- Consider 2 long ∥ wires separated by distance L. I_1 and I_2 each producing B_1 & B_2 at location of second conductor

$$B = \frac{\mu_o}{2\pi}\frac{I_1}{L}$$

figure only shown in this field

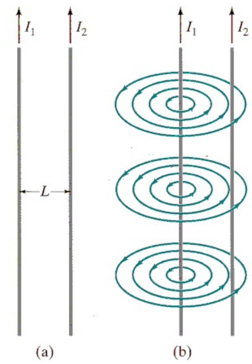


FIGURE 20–22 (a) Two parallel conductors carrying currents I_1 and I_2. (b) Magnetic field produced by I_1. (Field produced by I_2 is not shown.)

- The F/unit length on the conductor carrying current I_2 is

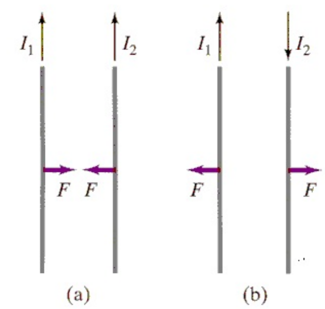
$$\frac{F}{\ell} = I_2 B_1$$

- Note that the force on I_2 is due only to field produced by I_1 ;I_2 also produces field but NOT a F on itself!
- Substitute in the above formula for B_1 and you get:

$$\frac{F}{\ell} = \frac{\mu_o}{2\pi}\frac{I_1 I_2}{L}$$

- **<u>Right-hand Rule:</u>**
  - You see that if the currents are in the SAME direction, the F's attract
  - OPPOSITE directions, the forces repel

FIGURE 20–23 (a) Parallel currents in the same direction exert attractive force on each other. (b) Antiparallel currents (in opposite directions) exert repulsive force on each other.



Example 8

The two wires of a 2.0 m long appliance cord are 3.0 mm apart and carry a current of 8.0 A dc. Calculate the force between the wires.

Example 9

A horizontal wire carries a current I_1 = 80 A dc. A second parallel wire 20 cm below it must carry how much current I_2 so that it doesn't fall due to gravity? The lower wire has a mass of 0.12 g per meter of length.

AMPERE'S LAW

Is there a general relationship between the current of a wire of whatever shape and the magnetic field around it?

$$\sum B_{parallel} \Delta \ell = \mu_o I$$

<u>solenoid</u>–long coil of wire with many loops

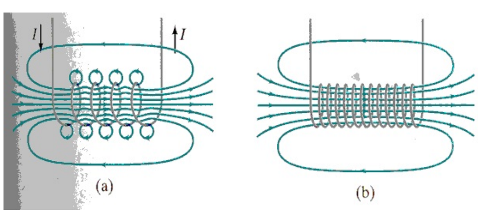


FIGURE 20–27 (a) Magnetic field due to several loops of a solenoid. (b) If the coils are closely spaced, the field is very nearly uniform.

$$B\ell = \mu_o NI$$

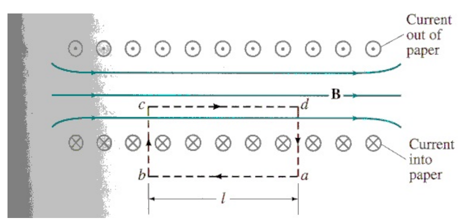


FIGURE 20–28 Magnetic field inside a solenoid is straight except at the ends. Dashed lines indicate the path chosen for use in Ampère's law.

let n = N/ℓ be the number of loops per unit length, then

$$B = \mu_o nI$$

B depends on the # loops per unit length n & I

Field does NOT depend on position within the solenoid, so B is uniform!

Example 10
A thin 10-cm long solenoid has a total of 400 turns of wire and carries a current of 2.0 A. Calculate the field inside near the center.

FERROMAGNETISM AND DOMAINS

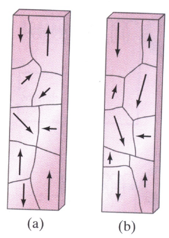


FIGURE 20–39 (a) An unmagnetized piece of iron is made up of domains that are randomly arranged. Each domain is like a tiny magnet; the arrows represent the magnetization direction, with the arrowhead being the N pole. (b) In a magnet, the domains are preferentially aligned in one direction, and may be altered in size by the magnetization process.

- **domains**–microscopic magnetic regions that atoms are grouped within; atoms are magnetically polarized parallel to a crystal axis. Not all pieces of iron behave as magnets since the domains may NOT be in line. Can be aligned in response to strong magnetic fields and become a permanent magnet
- **Curie point**–when a ferromagnetic material is heated above some certain critical value, it becomes more random with its domains and cannot retain its magnetism
- dropping a magnet or striking it may also randomize the domains

ELECTROMAGNETS AND SOLENOIDS

- Place a piece of iron inside a solenoid and magnetic field increases because the domains of iron are alighned by B produced by the current
- Reverse I and you reverse N & S
  - soft iron--loses magnetism
  - hard iron--holds magnetism

INDUCTION

- An electric current produces a magnetic field, B.
- A magnetic field exerts a F on an electric current OR moving charge.
- Is it possible that a magnetic field can produce an electric current? You betcha!
- 10 years after Oersted, American Joseph Henry and Brit Michael Faraday idependently found that was possible. Faraday published first!

INDUCED EMF

- Faraday used this device to produce an electric current from a magnetic field

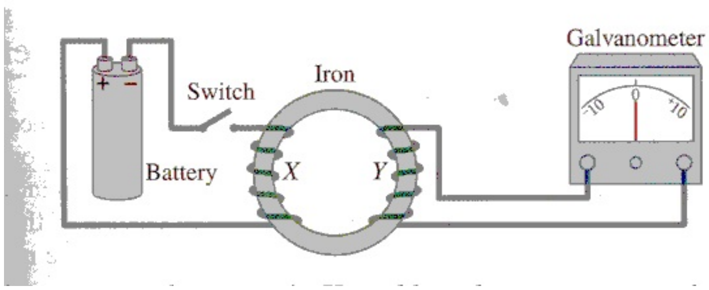


FIGURE 21–1 Faraday's experiment to induce an emf.

- Coil X is connected to a battery and then wrapped around soft iron core to intensify the magnetic field in hopes that a current develops [is induced] in the Y coil
- Coil Y was attached to a galvanometer with detects faint electric currents [more sensitive than an ammeter]
- Faraday threw the switch and sent a steady dc current--failure! However, he did notice the needle was deflecting at the moment he threw the switch and again when he opened the switch....
- A CHANGING B produces and electromotive force, while a steady B does not!
- <u>**induced emf**</u>--produced by a changing B; move the magnet or move the coil, the emf is induced either way! emf is also symbolized by $\mathcal{E}$

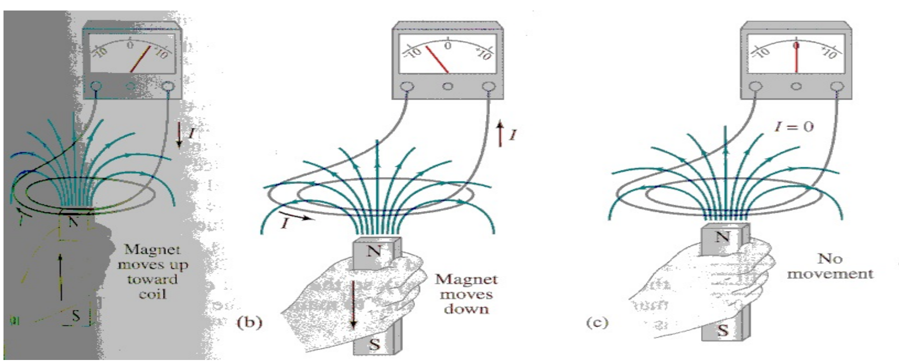


FIGURE 21–2 (a) A current is induced when a magnet is moved toward a coil. (b) The induced current is opposite when the magnet is moved away from the coil. Note that the galvanometer zero is at the center of the scale and the needle deflects left or right, depending on the direction of the current. In (c) no current is induced if the magnet does not move relative to the coil.

FARADAY'S LAW OF INDUCTION; LENZ'S LAW

Quantitative investigation by Faraday yielded

- Magnitude of $\mathcal{E}$ depends on time--more rapid change in B, the higher the $\mathcal{E}$
- <u>magnetic flux</u>--fluctuation in B; Φ_B ; $\mathcal{E}$ NOT simply proportional to chaning B, BUT rather changing B through a loop of area A
  - $\Phi_B = B_\perp A = BA\cos\theta$ [see the diagram!]
  - $B_\perp$ is the component of B perpendicular to the *face of coil*
  - θ is the angle between B and line drawn ⊥ to the face of coil

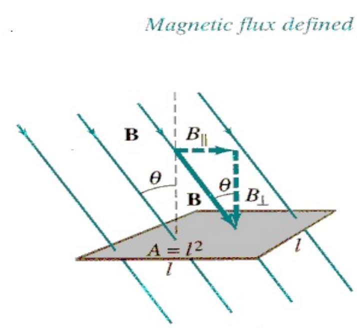
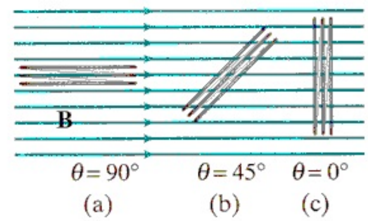


FIGURE 21–3 Determining the flux through a flat loop of wire. This loop is square, of side l and area $A = l^2$.

- square coil of side ℓ , so $A = \ell^2$

- When face of coil is parallel to B, $\theta = 90°$ and Φ_B = ZERO
- When B is perpendicular to coil, $\theta = 0°$ and $\Phi_B = BA$
- Φ_B is proportional to total # of lines passing through coil so when theta equals 90, no lines pass through the coil therefore the flux is ZERO
- When theta equals zero, the flus is at a MAXIMUM
- $\Phi_B = T \bullet m^2$ = Weber = 1 Wb = $1\ T \bullet m^2$

FIGURE 21–4 Magnetic flux Φ_B is proportional to the number of lines of **B** that pass through the loop.



- If the flux through N loops of wire changes by an amount $\Delta\ \Phi_B$ during a time Δt, the average emf during this time is

$$\mathscr{E} = -N\frac{\Phi_B}{\Delta t}$$

- <u>Lenz's law--</u>The negative sign shows direction. An induced emf ALWAYS gives rise to a current whose B *opposes* the original change in flux.
- English translation:
  - move a magnet thru a coil and an emf results therefore a current is produced
  - the current produces its own magnetic field
  - examine this diagram again:

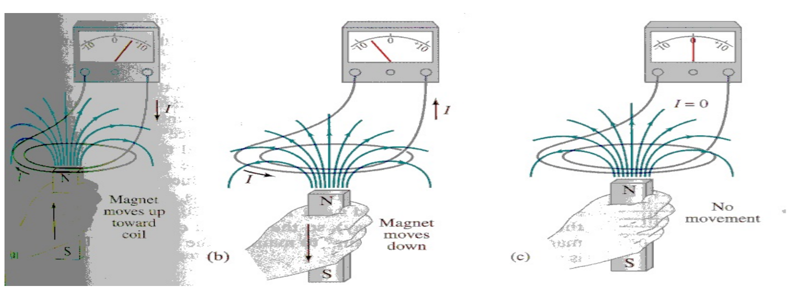


FIGURE 21–2 (a) A current is induced when a magnet is moved toward a coil. (b) The induced current is opposite when the magnet is moved away from the coil. Note that the galvanometer zero is at the center of the scale and the needle deflects left or right, depending on the direction of the current. In (c) no current is induced if the magnet does not move relative to the coil.

  - In a) the distance between the coil and the magnet decreases therefore B and flux through coil increases
  - The magnetic field points up while the magnetic field of the induced current points down; opposite to each other!
  - Lenz's Law tells us that the current moves as shown in b) [move the magnet down and the current reverses and travels up as indicated by the needle moving to the other side of zero]
  - The flux is decreases so the induced current produces and upward magnetic field that is "trying" to keep equilibrium
  - If Lenz's Law was NOT true: Induced emf produces Φ_B in the same direction and current would "grow" to infinity with a power of $P=I^2R$ and violate the first law of thermodynamics! Therefore Lenz's Law is consistent with the first law of thermodynamics

- emf is induced <u>whenever</u> there is a change in flux $\Phi_B = BA \cos\theta$
- emf is induced in THREE ways:
    - ΔB
    - ΔA of loop in field
    - Δ loops orientation with respect to field

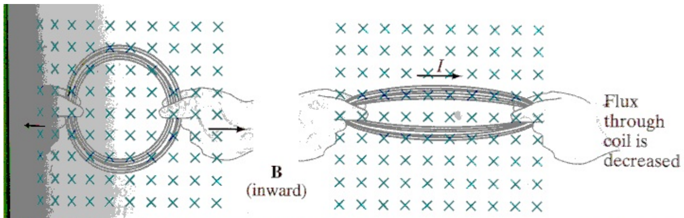


FIGURE 21–5 A current can be induced by changing the area of the coil. In both this case and that of Fig. 21–6, the flux through the coil is reduced. Here the brief induced current acts in the direction shown so as to try to maintain the original flux ($\Phi = BA$) by producing its own magnetic field into the page. That is, as the area A decreases, the current acts to increase B in the original (inward) direction.

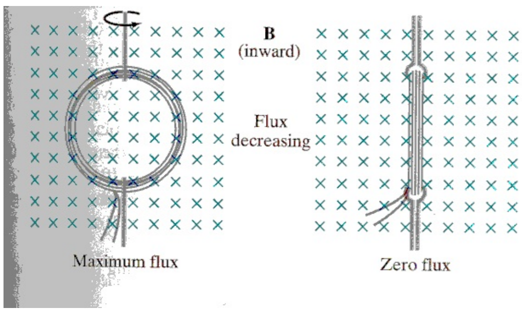


FIGURE 21–6 A current can be induced by rotating a coil in a magnetic field.

Example 1

Some modern stove burners are based on induction. That is, an ac current passes around a coil that is the “burner” [one that never gets hot]. Why will it heat a metal pan but not a glass container?

Example 2

In which dirction is the current induced in the coil for each situation in the following figure?

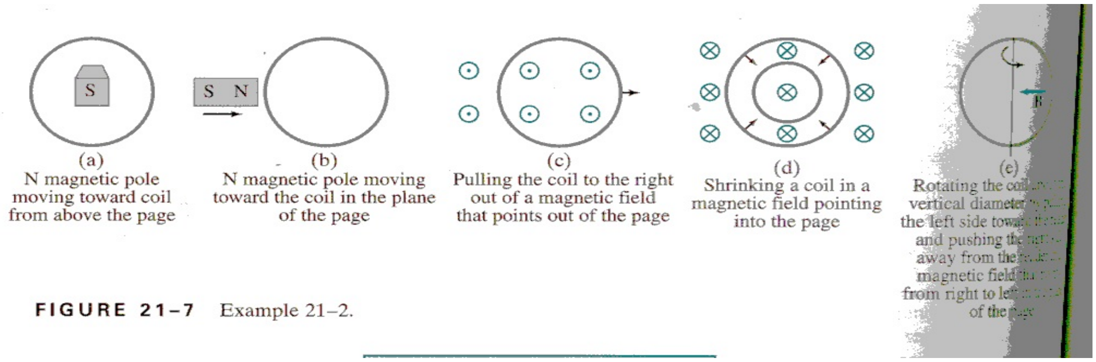


FIGURE 21–7 Example 21–2.

Example 3

A square coil of sides 5.0 cm contains 100 loops and is positioned perpendicular to a uniform 0.60 T magnetic field. It is quickly and uniformly pulled from the field [moving perpindicular to B] to a region where B drops abruptly to zero. IT takes 0.10 s for the whole coil to reach the field-free region.

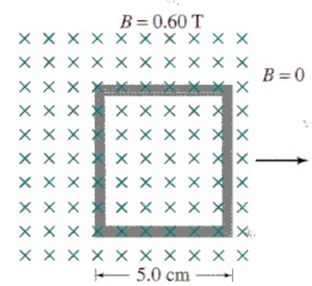


FIGURE 21–8 Example 21–3. The square coil in a magnetic field $B = 0.60$ T is pulled abruptly to the right to a region where $B = 0$.

a) Find change in flux through the coil

b) Find the emf and current induced

c) Find how much energy is dissipated in the coil if its resistance is 100Ω

d) what was the force required?

EMF IN A MOVING CONDUCTOR

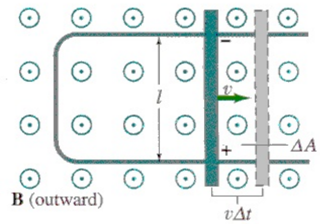


FIGURE 21–9 A conducting rod is moved to the right on a U-shaped conductor in a uniform magnetic field **B** that points out of the paper.

Assume a uniform B is ⊥to area bounded by the U-shaped conductor and the movable rod resting on it.

- rod moves at a speed v
- travels a distance $\Delta x = v\Delta t$ in a time Δt
- Area of loop increases by an amount $\Delta A = \ell\Delta x = \ell v\Delta t$, so....
- $$emf = \frac{\Delta\Phi_B}{\Delta t} = \frac{B\Delta A}{\Delta t} = \frac{B\ell v\Delta t}{\Delta t} = B\ell v$$
- as long as B, ℓ, and v are mutually perpendicular!!!
- IF not mutually perpendicular, simply use the perpendicular components

Alternate derivation:
Start with F = qvB

- when rod moves right with speed v, the electrons move with v also, therfore EACH feels F = qvB which acts upward (rt-hand rule)
- IF rod were not in contact with conductor, electrons would collect at upper end leaving lower end positive therefore, induced emf
- IF rod makes contact with the U-shaped conductor then electrons transfer to it, therefore clockwise I in loop
- $W = Fd = qvB\ell$

$$emf = \frac{W}{q} = \frac{qvB\ell}{q} = B\ell v$$

Example 4
An airplane travels 1000 km/h in a region where the Earth's field is 5.09×10^{-5} T and is nearly vertical. What is the potential difference induced between the wing tips that are 70 m apart?

CHANGING MAGNETIC FLUX PRODUCES AN ELECTRIC FIELD

- Electrons in a moving conductor feel a force therefore there is an electric field in a conductor

$$E = \frac{F}{q} = \frac{qvB}{q} = vB$$

- Move conductor or move magnetic field–you get an emf either way.
- An electric field will be produced anywhere in space there is a changing magnetic field!

Example 5

The rate of blood flow can be measured using the apparatus shown since blood contains charged ions. Suppose that the blood vessel is 2.0 mm in diameter, the magnetic field is 0.080 T, and the measured emf is 0.10 mV. What is the flow velocity of the blood?

FIGURE 21–11 Measurement of blood velocity from the induced emf.