PHYS 1441 – Section 001
Lecture #13

Monday, June 25, 2018

Dr. Jaehoon Yu

- Chapter26
  - EMFs in Series and Parallel
  - RC Circuits
- Chapter 27: Magnetism and Magnetic Field
  - Electric Current and Magnetism
  - Magnetic Forces on Electric Current
  - About Magnetic Field

Today's homework is homework #7, due 11pm, Friday, June 29!!

Announcements

- One-on-one mid-term grade discussion tomorrow Tuesday, June 24.
  - Class for the first 30min ➔ Quiz 3
  - In my office – CPB342.
  - Last names begin with
    - A – G: 11:05 – 11:35
    - H – M: 11:35 – 12:00
    - N – Z: 12 – 12:30
    - If you have schedule issue, please be sure to come in early for the discussion
- Quiz 3 tomorrow, Tuesday, June 26 in class
  - Covers CH25.6 – what we finish today
  - Bring your calculator but DO NOT input formula into it!
    - Cell phones or any types of computers cannot replace a calculator!
  - BYOF: You may bring a one 8.5x11.5 sheet (front and back) of **handwritten** formulae and values of constants
  - No derivations, word definitions or solutions of any kind!
  - No additional formulae or values of constants will be provided!
- Reading assignments: CH27.6 – CH27.9

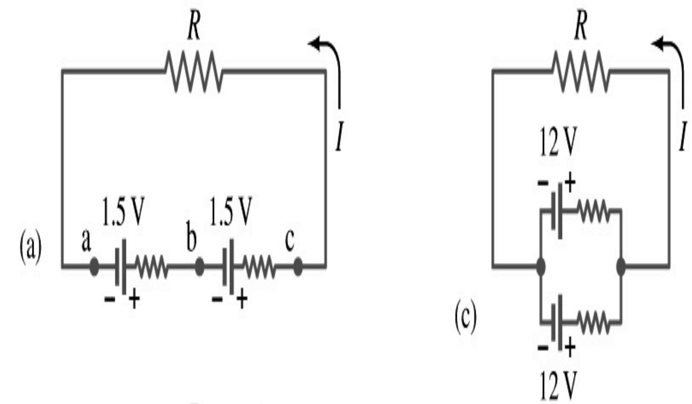
Reminder: Special Project #4

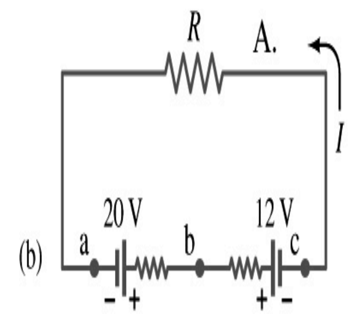
- Make a list of the power consumption and the resistance of all electric and electronic devices at your home and compile them in a table. (10 points total for the first 10 items and 0.5 points each additional item.)
- Estimate the cost of electricity for each of the items on the table using your own electric cost per kWh (if you don't find your own, use $0.12/kWh) and put them in the relevant column. (5 points total for the first 10 items and 0.2 points each additional items)
- Estimate the the total amount of energy in Joules and the total electricity cost per day, per month and per year for your home. (8 points)
- Due: Beginning of the class tomorrow Tuesday, June 24

Item Name	Rated power (W)	Number of devices	Number of Hours per day	Daily Power Consumption (kWh)	Energy Cost per kWh (cents)	Daily Energy Consumption (J).	Daily Energy Cost ($)	Monthly Energy Consumption (J)	Monthly Energy Cost ($)	Yearly Energy Consumption (J)	Yearly Energy Cost ($)
Light Bulbs	30	4									
	40	6									
	60	15									
Heaters	1000	2									
	1500	1									
	2000	1									
Fans											
Air Conditioners											
Fridgers, Freezers											
Computers (desktop, laptop, ipad)											
Game consoles											
Total				0		0	0	0	0	0	0

EMFs in Series and Parallel: Charging a Battery

- When two or more sources of emfs, such as batteries, are connected in series
  - The total voltage is the algebraic sum of their voltages, if their direction is the same
    - V_{ab}=1.5 + 1.5=3.0V in figure (a).
  - If the batteries are arranged in an opposite direction, the total voltage is the difference between them



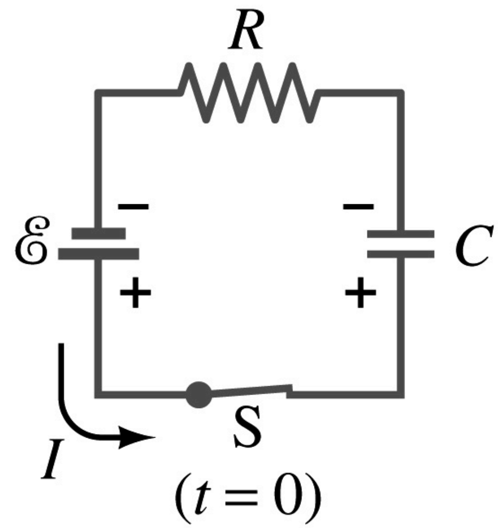


Parallel arrangements (c) are used only to increase currents. An example?

    - V_{ac}=20 – 12=8.0V in figure (b)
    - Connecting batteries in opposite direction is wasteful.
    - This, however, is the way a battery charger works.
    - Since the 20V battery is at a higher voltage, it forces charges into 12V battery
    - Some battery are rechargeable since their chemical reactions are reversible but most the batteries do not reverse their chemical reactions

RC Circuits

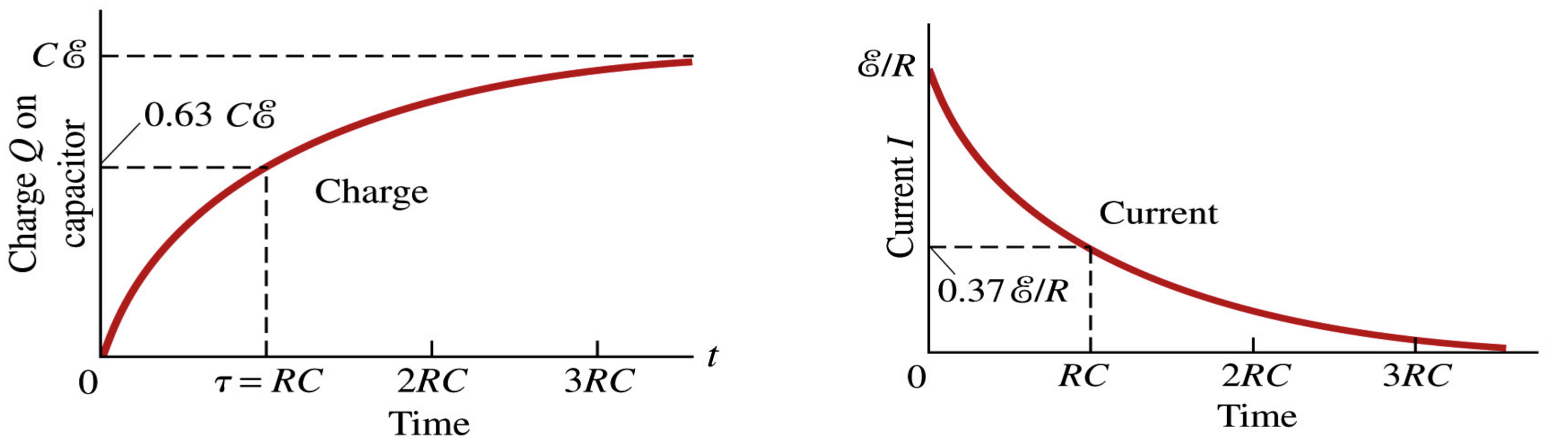
- Circuits containing both resisters and capacitors
  - RC circuits are used commonly in everyday life
    - Control windshield wiper
    - Timing of traffic light from red to green
    - Camera flashes and heart pacemakers
- How does an RC circuit look?
  - There should be a source of emf, capacitors and resisters



- What happens when the switch S is closed?
  - Current immediately starts flowing through the circuit.
  - Electrons flow out of negative terminal of the emf source, through the resister R and accumulates on the upper plate of the capacitor.
  - The electrons from the bottom plate of the capacitor will flow into the positive terminal of the battery, leaving only the positive charge on the bottom plate.
  - As the charge accumulates on the capacitor, the potential difference across it increases
  - The current reduces gradually to 0 till the voltage across the capacitor is the same as the emf.
  - The charge on the capacitor increases till it reaches to its maximum $C\mathcal{E}$.

RC Circuits

- How does all this look like in graphs?
  - The charge and the current on the capacitor as a function of time



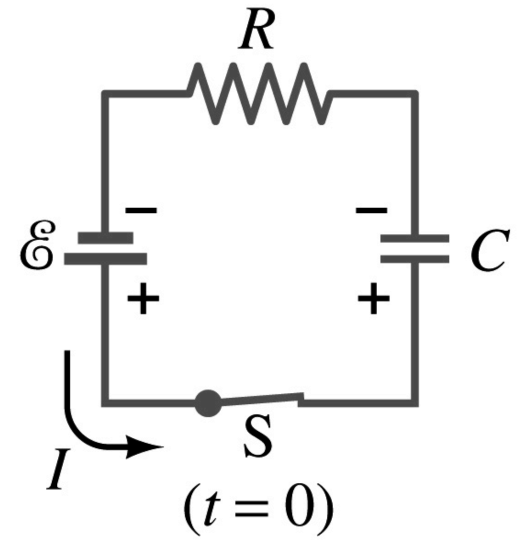
  - From energy conservation (Kirchhoff's 2nd rule), the emf $\mathscr{E}$ must be equal to the sum of voltage drop across the capacitor and the resister
    - $\mathscr{E}=IR+Q/C$
    - R includes all resistance in the circuit, including the internal resistance of the battery, I is the current in the circuit at any instance, and Q is the charge of the capacitor at that same instance.

Analysis of RC Circuits

- In an RC circuit $Q = C\varepsilon\left(1 - e^{-t/RC}\right)$ and $V_C = \varepsilon\left(1 - e^{-t/RC}\right)$
- What can we see from the above equations?
  - Q and V_C increase from 0 at t=0 to maximum value $Q_{max}=C\mathscr{E}$ and $V_C=\mathscr{E}$.
- In how much time?
  - The quantity RC is called the **time constant** of the circuit, τ
    - τ=RC, What is the unit? Sec.
  - What is the physical meaning?
    - The time required for the capacitor to reach $(1 - e^{-1})=0.63$ or 63% of the full charge
- The current is $I = \frac{dQ}{dt} = \frac{\varepsilon}{R} e^{-t/RC}$

Example 26 – 12

RC circuit, with emf. The capacitance in the circuit of the figure is C=0.30μF, the total resistance is 20kΩ, and the battery emf is 12V. Determine (a) the time constant, (b) the maximum charge the capacitor could acquire, (c) the time it takes for the charge to reach 99% of this value, (d) the current I when the charge Q is half its maximum value, (e) the maximum current, and (f) the charge Q when, the current I is 0.20 its maximum value.



(a) Since $\tau = RC$ We obtain $\tau = 20\times10^{3}\cdot 0.30\times10^{-6} = 6.0\times10^{-3}\ \text{sec}$

(b) Maximum charge is $Q_{max} = C\varepsilon = 0.30\times10^{-6}\cdot 12 = 3.6\times10^{-6}\,C$

(c) Since $Q = C\varepsilon\left(1-e^{-t/RC}\right)$ For 99% we obtain $0.99C\varepsilon = C\varepsilon\left(1-e^{-t/RC}\right)$

$e^{-t/RC} = 0.01;\quad -t/RC = -2\ln 10;\quad t = RC\cdot 2\ln 10 = 4.6RC = 28\times10^{-3}\ \text{sec}$

(d) Since $\varepsilon = IR + Q/C$ We obtain $I = \left(\varepsilon - Q/C\right)/R$

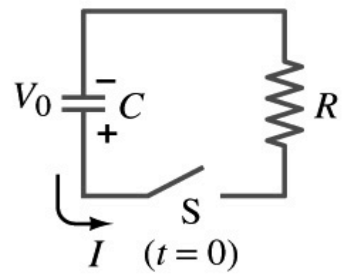
The current when Q is $0.5Q_{max}$ $I = \left(12 - 1.8\times10^{-6}/0.30\times10^{-6}\right)/20\times10^{3} = 3\times10^{-4}\,A$

(e) When is I maximum? when Q=0: $I = 12/20\times10^{3} = 6\times10^{-4}\,A$

(f) What is Q when I=120mA? $Q = C\left(\varepsilon - IR\right) =$

$= 0.30\times10^{-6}\left(12 - 1.2\times10^{-4}\cdot 2\times10^{4}\right) = 2.9\times10^{-6}\,C$

Discharging RC Circuits



(a)

- When a capacitor is already charged, it is allowed to discharge through a resistance R.
  - When the switch S is closed, the voltage across the resistor at any instant equals that across the capacitor. Thus IR=Q/C.
  - The rate at which the charge leaves the capacitor equals the negative the current flows through the resistor
    - I= - dQ/dt
    - Since the current is leaving the capacitor
  - Thus the voltage equation becomes a differential equation

$$-\frac{dQ}{dt}R = \frac{Q}{C} \quad \xrightarrow{\text{Rearrange terms}} \quad \frac{dQ}{Q} = -\frac{dt}{RC}$$

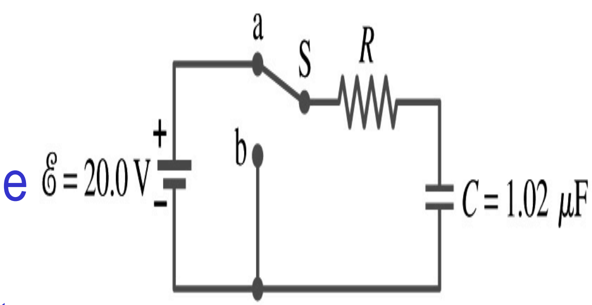
Discharging RC Circuits

- Now, let's integrate from t=0 when the charge is Q_0 to t when the charge is Q $\int_{Q_0}^{Q}\frac{dQ}{Q}=-\int_0^t\frac{dt}{RC}$
- The result is $\ln Q\Big|_{Q_0}^{Q}=\ln\frac{Q}{Q_0}=-\frac{t}{RC}$
- Thus, we obtain

$$Q(t)=Q_0e^{-t/RC}$$

- What does this tell you about the charge on the capacitor?
  - It decreases exponentially w/ time at the time constant RC
  - Just like the case of charging
- The current is: $I=-\frac{dQ}{dt}=\frac{Q_0}{RC}e^{-t/RC}$ (What is this?) $I(t)=I_0e^{-t/RC}$
  - The current also decreases exponentially w/ time w/ the time constant RC

Example 26 – 13



Discharging RC circuit. In the RC circuit shown in the figure the battery has fully charged the capacitor, so $Q_0 = C\mathcal{E}$. Then at t=0, the switch is thrown from position a to b. The battery emf is 20.0V, and the capacitance C=1.02μF. The current *I* is observed to decrease to 0.50 of its initial value in 40μs. (a) what is the value of R? (b) What is the value of Q, the charge on the capacitor, at t=0? (c) What is Q at t=60μs?

(a) Since the current reaches to 0.5 of its initial value in 40μs, we can obtain

$$I(t) = I_0 e^{-t/RC}$$

For $0.5I_0$

$$0.5I_0 = I_0 e^{-t/RC}$$

Rearrange terms

$$-t/RC = \ln 0.5 = -\ln 2$$

Solve for R

$$R = t/(C\ln 2) = 40\times10^{-6}/\left(1.02\times10^{-6}\cdot\ln 2\right) = 56.6\Omega$$

(b) The value of Q at t=0 is

$$Q_0 = Q_{\max} = C\varepsilon = 1.02\times10^{-6}\cdot 20.0 = 20.4\mu C$$

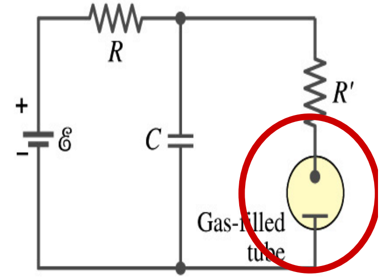
(c) What do we need to know first for the value of Q at t=60μs?

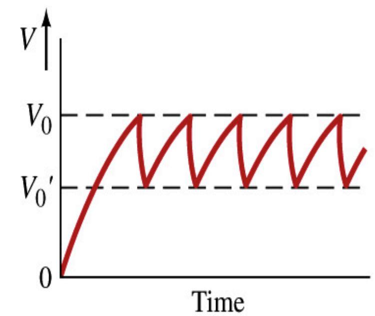
The RC time $\tau = RC = 56.6\cdot 1.02\times10^{-6} = 57.7\mu s$

Thus $Q(t = 60\mu s) = Q_0 e^{-t/RC} = 20.4\times10^{-6}\cdot e^{-60\mu s/57.7\mu s} = 7.2\mu C$

Application of RC Circuits

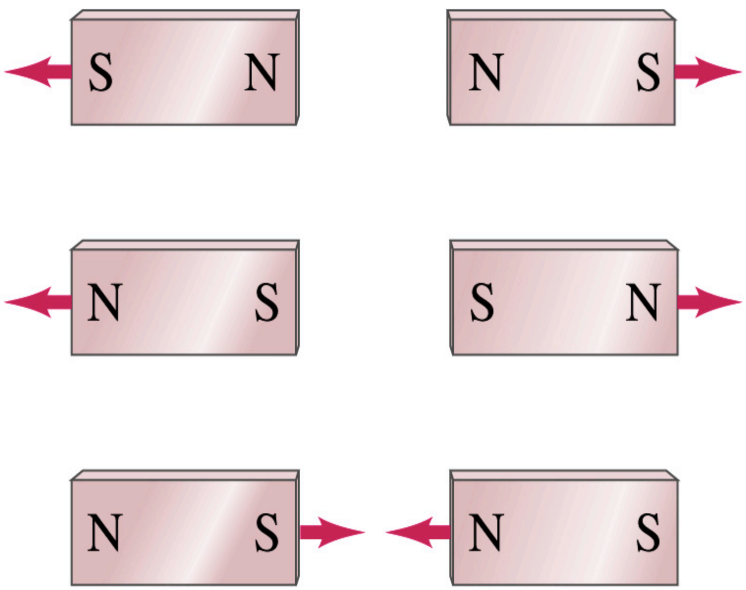
- What do you think the charging and discharging characteristics of RC circuits can be used for?
  - To produce voltage pulses at a regular frequency
  - How?
    - The capacitor charges up to a particular voltage and discharges
    - A simple way of doing this is to use breakdown of voltage in a gas filled tube
      - The discharge occurs when the voltage breaks down at V_0
      - After the completion of discharge, the tube no longer conducts
      - Then the voltage is at V_0' and it starts charging up
      - How do you think the voltage as a function of time look?
        - » A sawtooth shape
    - Pace maker, intermittent windshield wiper, etc





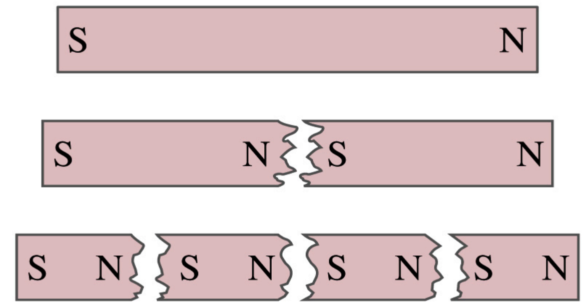
Magnetism

- What are magnets?
  - Objects with two poles, North and South poles
    - The pole that points to the geographical North is the North pole and the other is the South pole
      - Principle of compass
  - These are called the magnet due to the name of the region, Magnesia, where the rocks that attract each other were found
- What happens when two magnets are brought to each other?
  - They exert force onto each other
  - What kind?
  - Both repulsive and attractive forces depending on the configurations
    - Like poles repel each other while the unlike poles attract



Magnetism

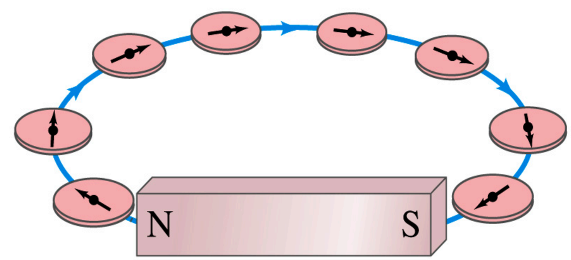
- So the magnetic poles are the same as the electric charge?
  - No. Why not?
  - While the electric charges (positive and negative) can be isolated, the magnetic poles cannot be isolated.
  - So what happens when a magnet is cut?
    - If a magnet is cut, two magnets are made.
    - The more they get cut, the more magnets are made

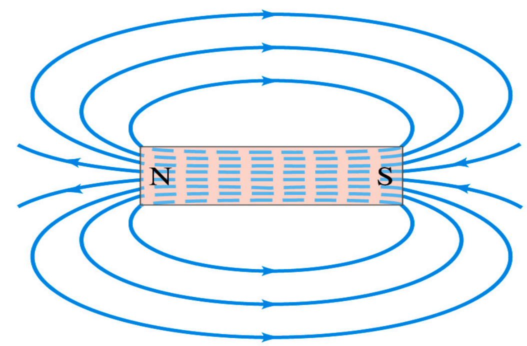


  - Single pole magnets are called the monopole but it has not been seen yet
- Ferromagnetic materials: Materials that show strong magnetic effects
  - Iron, cobalt, nickel, gadolinium and certain alloys
- Other materials show very weak magnetic effects

Magnetic Field

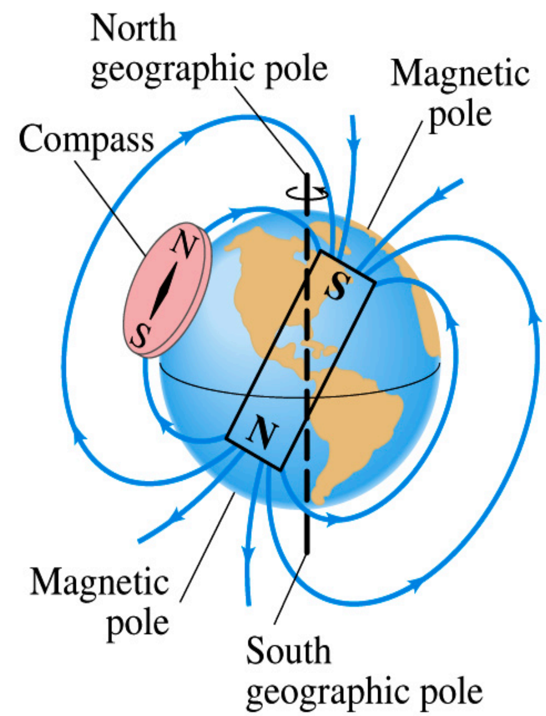
- Just like the electric field that surrounds electric charge, a magnetic field surrounds a magnet
- What does this mean?
  - Magnetic force is also a field force
  - The force one magnet exerts onto another can be viewed as the interaction between the magnet and the magnetic field produced by the other magnet
  - What kind of quantity is the magnetic field? Vector or Scalar? **Vector**
- So one can draw magnetic field lines, too.
  - The direction of the magnetic field is tangential to the field line at any point
  - The direction of the field is the direction the north pole of a compass would point to
  - The number of lines per unit area is proportional to the strength of the magnetic field
  - Magnetic field lines continue inside the magnet
  - Since magnets always have both the poles, magnetic field lines form closed loops unlike electric field lines





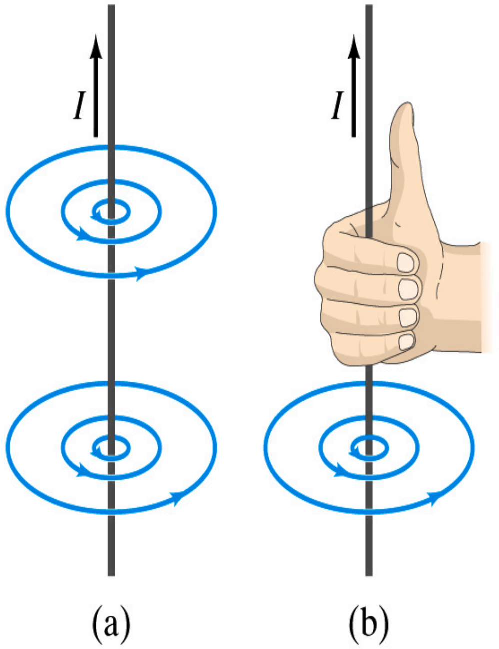
Earth's Magnetic Field

- What magnetic pole does the geographic North pole has to have?
  - Magnetic South pole. What? How do you know that?
  - Since the magnetic North pole points to the geographic North, the geographic north must have magnetic south pole
    - The pole in the North is still called geomagnetic North pole just because it is in the North
  - Similarly, South pole has magnetic North pole
- The Earth's magnetic poles do not coincide with the geographic poles ➔ magnetic declination
  - Geomagnetic North pole is in Northern Canada, some 900km off the true North pole
- Earth's magnetic field line is not tangent to the earth's surface at all points
  - The angle the Earth's field makes to the horizontal line is called the angle dip



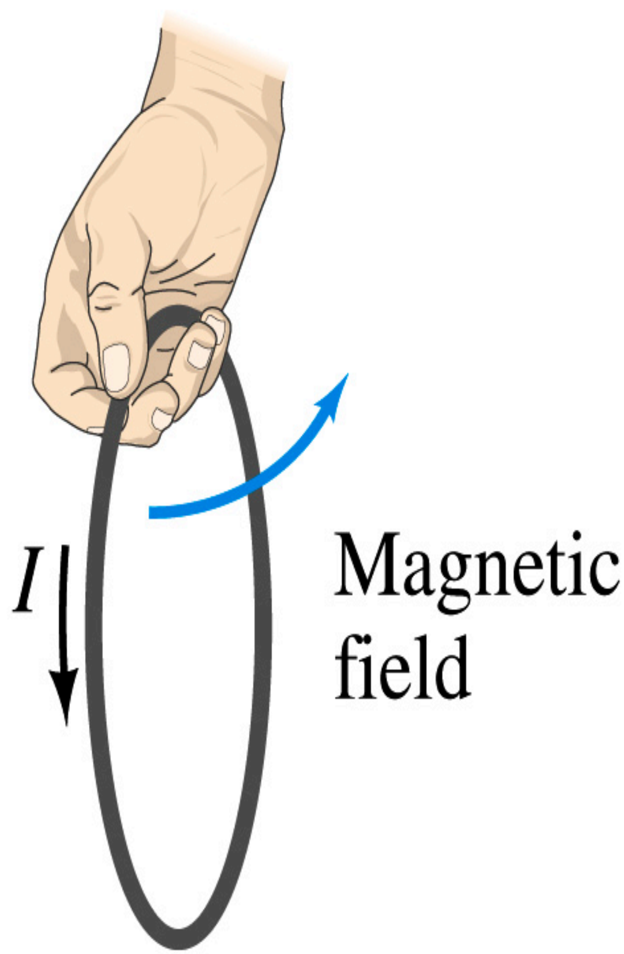
Electric Current and Magnetism

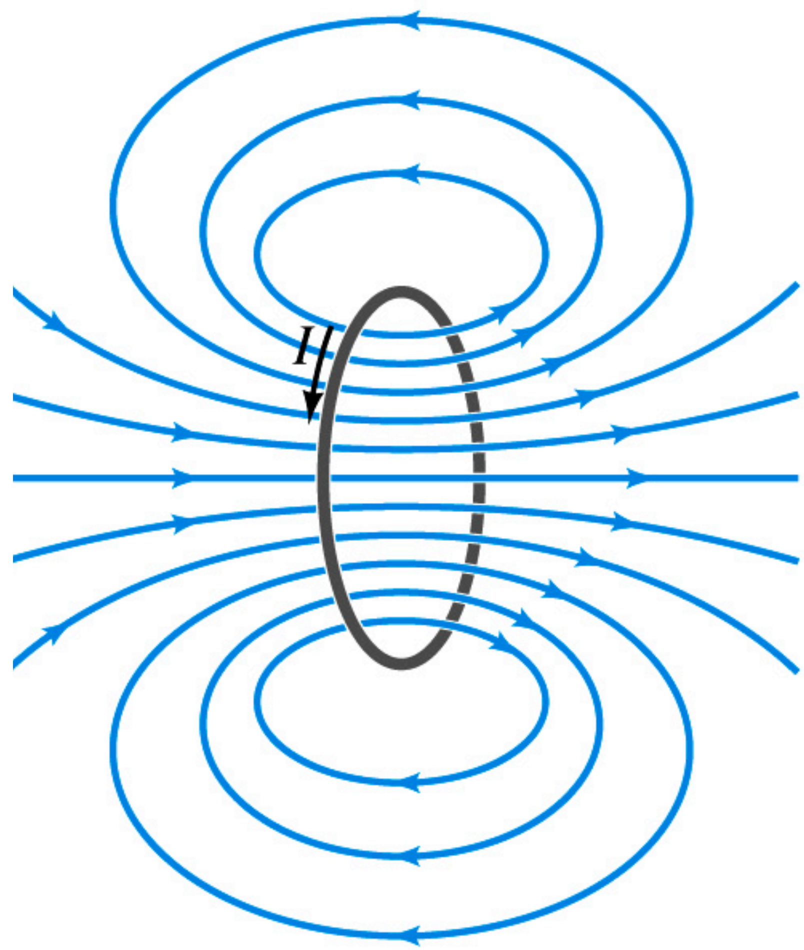
- In 1820, Oersted found that when a compass needle is placed near an electric wire, the needle deflects as soon as the wire is connected to a battery and the current flows
  - Electric current produces a magnetic field
    - The first indication that electricity and magnetism are of the same origin
  - What about a stationary electric charge and magnet?
    - They don't affect each other.
- The magnetic field lines produced by a current in a straight wire is in the form of circles following the "right-hand" rule
  - The field lines follow right-hand fingers wrapped around the wire when the thumb points to the direction of the electric current



Directions in a Circular Wire?

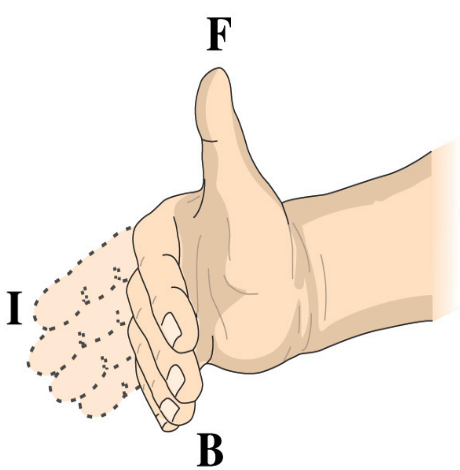
- OK, then what is the direction of the magnetic field generated by the current flowing through a circular loop?



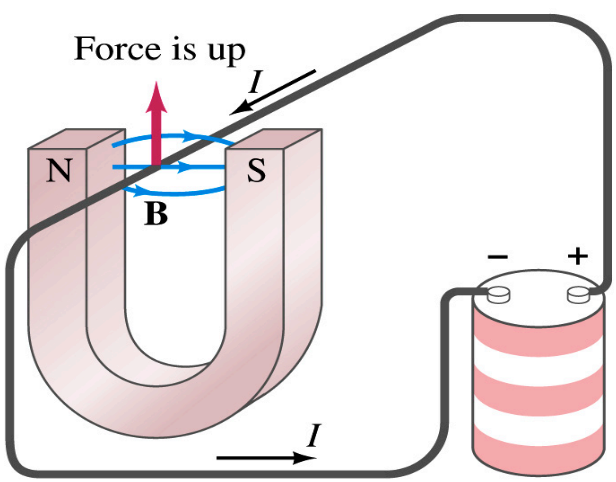


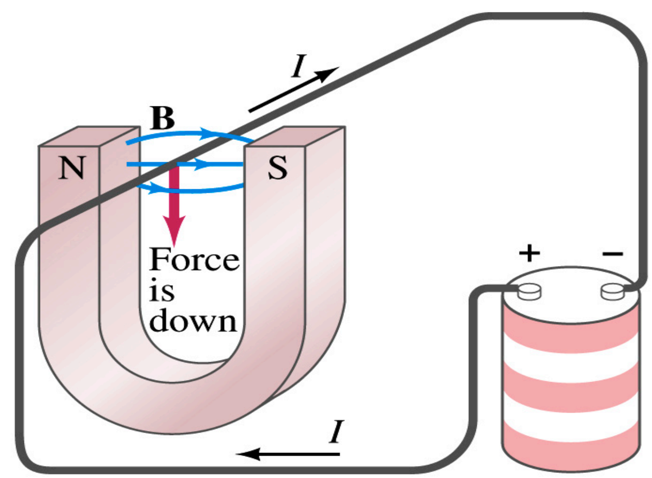
Magnetic Forces on Electric Current

- Since the electric current exerts force on a magnet, the magnet should also exert force on the electric current
  - Which law justifies this?
    - Newton's 3rd law
  - This was also discovered by Oersted
- Direction of the force is always
  - perpendicular to the direction of the current
  - perpendicular to the direction of the magnetic field, **B**
- Experimentally the direction of the force is given by another right-hand rule ➔ When the fingers of the right-hand points to the direction of the current and the finger tips bent to the direction of magnetic field B, the direction of thumb points to the direction of the force



Right-hand rule





Magnetic Forces on Electric Current

- OK, we are set for the direction but what about the magnitude?
- It is found that the magnitude of the force is directly proportional
  - To the current in the wire
  - To the length of the wire in the magnetic field (if the field is uniform)
  - To the strength of the magnetic field
- The force also depends on the angle θ between the directions of the current and the magnetic field
  - When the wire is perpendicular to the field, the force is the strongest
  - When the wire is parallel to the field, there is no force at all
- Thus the force on current I in the wire w/ length ℓ in a uniform field $\mathcal{B}$ is

$$F \propto IlB \sin\theta$$

Magnetic Forces on Electric Current

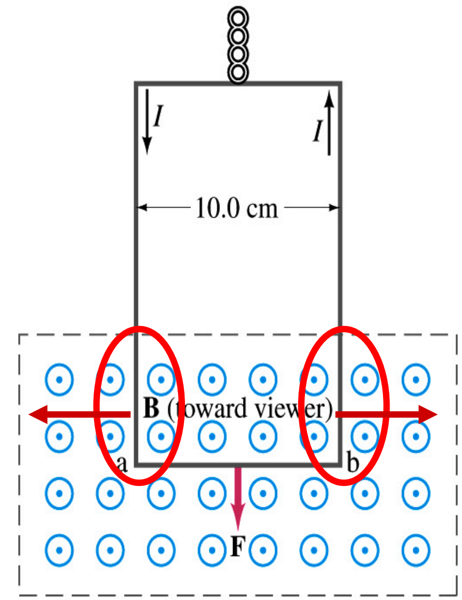
- Magnetic field strength B can be defined using the previous proportionality relationship w/ the constant 1: $F = IlB\sin\theta$
- if θ=90º, $F_{\max} = IlB$ and if θ=0º $F_{\min} = 0$
- So the magnitude of the magnetic field B can be defined as
  - $B = F_{\max}/Il$ where F_{max} is the magnitude of the force on a straight length ℓ of the wire carrying the current I when the wire is perpendicular to **B**
- The relationship between F, B and I can be written in a vector formula: $\vec{F} = I\vec{l} \times \vec{B}$
  - ℓ is the vector whose magnitude is the length of the wire and its direction is along the wire in the direction of the conventional current
  - This formula works if **B** is uniform.
- If B is not uniform or ℓ does not form the same angle with B everywhere, the infinitesimal force acting on a differential length dℓ is $d\vec{F} = Id\vec{l} \times \vec{B}$

Fundamentals on the Magnetic Field, B

- The magnetic field is a vector quantity
- The SI unit for B is tesla (T)
  - What is the definition of 1 Tesla in terms of other known units?
  - 1T=1N/Am
  - In older names, tesla is the same as weber per meter-squared
    - $1Wb/m^2=1T$
- The cgs unit for B is gauss (G)
  - How many T is one G?
    - $1G=10^{-4}$ T
  - For computation, one MUST convert G to T at all times
- Magnetic field on the Earth's surface is about $0.5G=0.5x10^{-4}T$
- On a diagram, $\odot$ for field coming out and $\otimes$ for going in.

Example 27 – 2

Measuring a magnetic field. A rectangular loop of wire hangs vertically as shown in the figure. A magnetic field **B** is directed horizontally perpendicular to the wire, and points out of the page. The magnetic field **B** is very nearly uniform along the horizontal portion of wire ab (length l=10.0cm) which is near the center of a large magnet producing the field. The top portion of the wire loop is free of the field. The loop hangs from a balance which measures a downward force (in addition to the gravitational force) of F=3.48x10^{-2}N when the wire carries a current I=0.245A. What is the magnitude of the magnetic field B at the center of the magnet?



Magnetic force exerted on the wire due to the uniform field is $\vec{F} = I\vec{l} \times \vec{B}$

Since $\vec{B} \perp \vec{l}$ Magnitude of the force is $F = IlB$

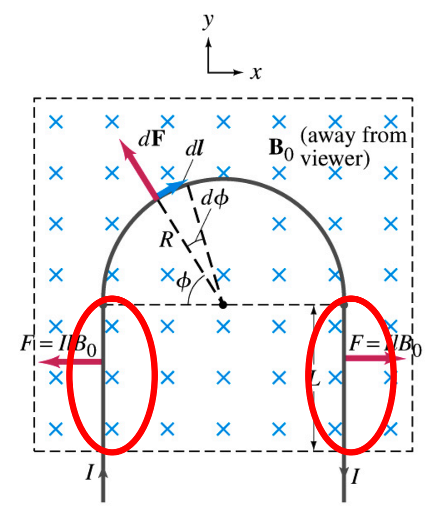
Solving for B $B = \frac{F}{Il} = \frac{3.48 \times 10^{-2}\,N}{0.245A \cdot 0.10m} = 1.42T$

Something is not right! What happened to the forces on the loop on the side?

The two forces cancel out since they are in opposite direction with the same magnitude.

Example 27 – 3

Magnetic force on a semi-circular wire. A rigid wire, carrying the current I, consists of a semicircle of radius R and two straight portions as shown in the figure. The wire lies in a plane perpendicular to the uniform magnetic field $\mathbf{B_0}$. The straight portions each have length ℓ within the field. Determine the net force on the wire due to the magnetic field $\mathbf{B_0}$.



As in the previous example, the forces on the straight sections of the wire is equal and in opposite direction. Thus they cancel.

What do we use to figure out the net force on the semicircle? $d\vec{F} = Id\vec{l} \times \vec{B}$

We divide the semicircle into infinitesimal straight sections. $dl = Rd\phi$

What is the net x component of the force exerting on the circular section? 0 **Why?**

Because the forces on left and the right-hand sides of the semicircle balance.

Since $\vec{B}_0 \perp d\vec{l}$ Y-component of the force dF is $dF_y = d\left(F\sin\phi\right) = IRB_0 d\phi$

Integrating over φ=0 - π

$$F = \int_0^\pi d\left(F\sin\phi\right) = IB_0R\int_0^\pi \sin\phi d\phi = -IB_0R\left[\cos\phi\right]_0^\pi = 2RIB_0$$

Which direction?

Vertically upward direction. The wire will be pulled deeper into the field.