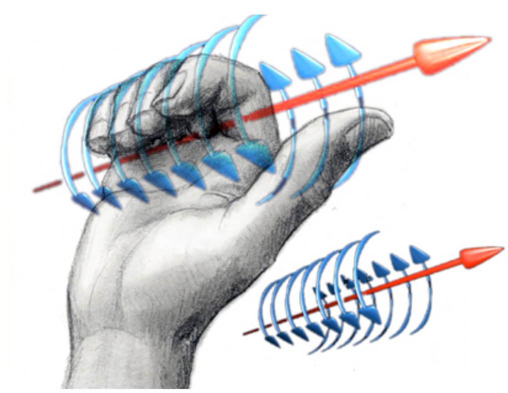
The Big Idea

For static electric charges, the electromagnetic force is manifested by the Coulomb electric force alone. If charges are moving, however, there is created an additional force, called magnetism. Our realization in the 19^{th} century that electricity and magnetism are aspects of the same force completely changed the world we live in. Moving charges – electric current – create magnetic fields. Varying magnetic fields create electric fields. Thus a loop of wire in a changing magnetic field will have current induced in it. This is called *electromagnetic induction.*

Key Concepts

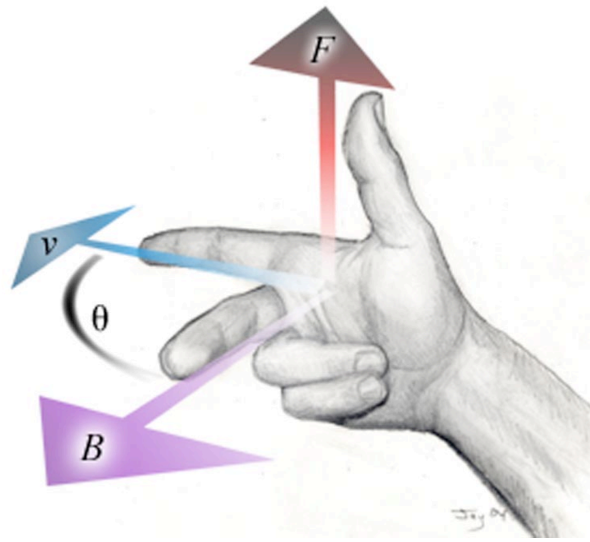
- Magnetic fields are generated by charged particles in motion.
- Magnetic fields exert magnetic forces on charged particles in motion.
- Permanent magnets (like refrigerator magnets) consist of atoms, such as iron, for which the magnetic moments (roughly electron spin) of the electrons are "lined up" all across the atom. This means that their magnetic fields add up, rather than canceling each other out. The net effect is noticeable because so many atoms have lined up.
- Changing magnetic fields passing through a loop of wire generate currents in that wire; this is how electric power generators work. Likewise, the changing amounts of current in a wire create a changing magnetic field; this is how speakers and electric motors work.
- Magnetic fields have a "3-D" property, obliging you to use special vector rules (called right hand rules) to figure out the directions of forces, fields, and currents.
    - **Right Hand Rule #1**

      A wire with electric current going through it produces a magnetic field going in circles around it. To find the direction of the magnetic field, point your thumb in the direction of the current. Then, curl your fingers around the wire. The direction your fingers curl tells you the direction that the magnetic field is pointing. Be sure to use your right hand!



- **Right Hand Rule #2**

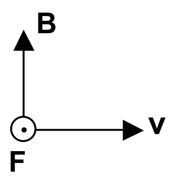
  Point your index finger along the direction of the particle's velocity or the direction of the current. Your middle finger goes in the direction of the magnetic field and your thumb tells you the direction of the force. NOTE: For negative charge reverse the direction of the force (or use your left hand)



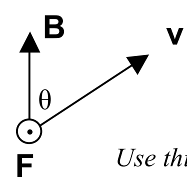
Key Equations and Applications

- $\mathbf{F}_B = q\mathbf{v}\times\mathbf{B} = qvB\sin(\theta)$

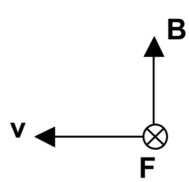
The force due to a magnetic field on a moving particle depends on the charge and speed of the particle. The direction is given by RHR #2. If **v** and **B** are not perpendicular, but instead separated by an angle θ, use the second formula.



If a positively charged particle is moving to the right, and it enters a magnetic field pointing towards the top of your page, it feels a force going out of the page.



Use this figure to remember the geometry of the angle θ.



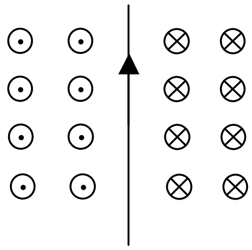
If a positively charged particle is moving to the left, and it enters a magnetic field pointing towards the top of your page, it feels a force going into the page.

- $\mathbf{F}_{wire} = \ell(\mathbf{I}\times\mathbf{B}) = \ell IB\sin(\theta)$

A current-carrying wire is made up of a whole bunch of individually moving charges. Thus this wire will feel a force. In this equation, ℓ refers to the length of the wire.

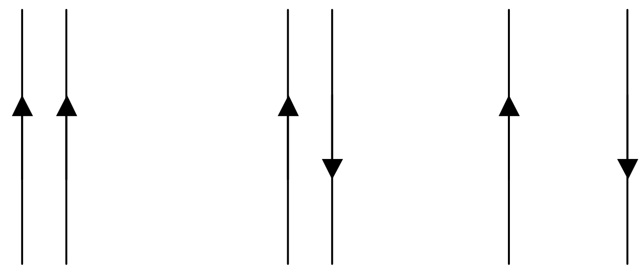
- $\mu_o = 4\pi\times10^{-7}$ T•m/A
- $\mathbf{B}_{wire} = \mu_o I / 2\pi r$

The magnetic field generated by a current-carrying wire depends on the strength of the current and the distance from the wire.



In the example to the left, a current is running along a wire towards the top of your page. The magnetic field is circling the wire in loops that are pierced through the center by the current. Where these loops intersect this piece of paper, we use the symbol $\odot$ *to represent where the magnetic field is coming "out of the page"and the symbol* $\otimes$ *to represent where the magnetic field is going "into the page." The distance r (for radius) is the distance from the wire.*

- Two current-carrying wires next to each other each exert magnetic fields and thereby forces on each other.



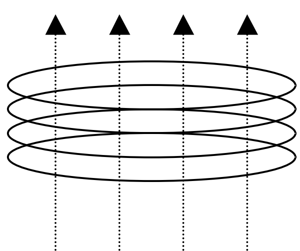
Currents in same direction: wires attracted to each other

Currents in opposite direction: wires repelled by each other

Greater distance d *means less force F*

- $\Phi = N\mathbf{B} \bullet \mathbf{A}$

If you have a closed, looped wire of area A (measured in m^2) and N loops, and you pass a magnetic field B through, the magnetic flux is Φ. The units of magnetic flux are $T \bullet m^2$, also known as a *Weber* (Wb).



In the example to the left, there are four loops of wire (N = 4) and each has area πr^2. The magnetic field is pointing toward the top of the page, at a right angle to the loops. Think of the magnetic flux as the "bundle" of magnetic field lines "held" by the loop. Why does it matter? See the next equation.

- $\varepsilon = -\Delta\Phi / \Delta t$

The direction of the induced current is determined as follows: the current will flow so as to generate a magnetic field that *opposes* the change in flux used in Faraday's Law. This is called Lenz's Law.

If you change the amount of magnetic flux that is passing through a loop of wire, electrons in the wire will feel a force, and this will generate a current. The equivalent *voltage* ε that they feel is equal to the change in flux $\Delta\Phi$ divided by the amount of time Δt it takes to change the flux by that amount. This is Faraday's Law of Induction.

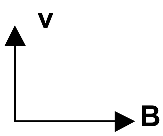
Magnetism Problem Set

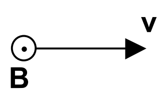
1. Can you set a resting electron into motion with a stationary magnetic field? With an electric field? Explain.

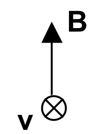
2. How is electrical energy produced in a dam using a hydroelectric generator? Explain in a short essay involving as many different ideas from physics as you need.

3. A speaker consists of a diaphragm (a flat plate), which is attached to a magnet. A coil of wire surrounds the magnet. How can an electrical current be transformed into sound? Why is a coil better than a single loop? If you want to make music, what should you do to the current?

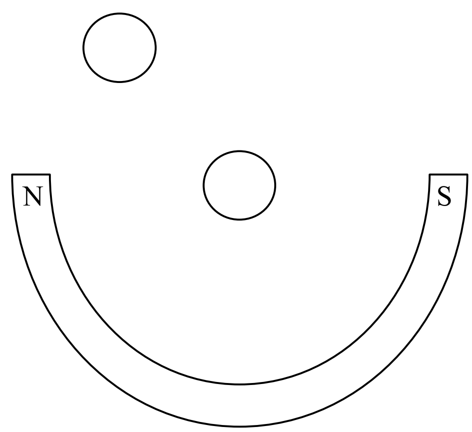
4. For each of the arrangements of velocity **v** and magnetic field **B** below, determine the direction of the force. Assume the moving particle has a positive charge.

a. 

b. 

c. 

5. Sketch the magnetic field lines for the horseshoe magnet shown here. Then, show the direction in which the two compasses (shown as circles) should point considering their positions. In other words, draw an arrow in the compass that represents North in relation to the compass magnet.



6. As an electron that is traveling in the positive x-direction encounters a magnetic field, it begins to turn in the upward direction (positive y-direction). What is the direction of the magnetic field?

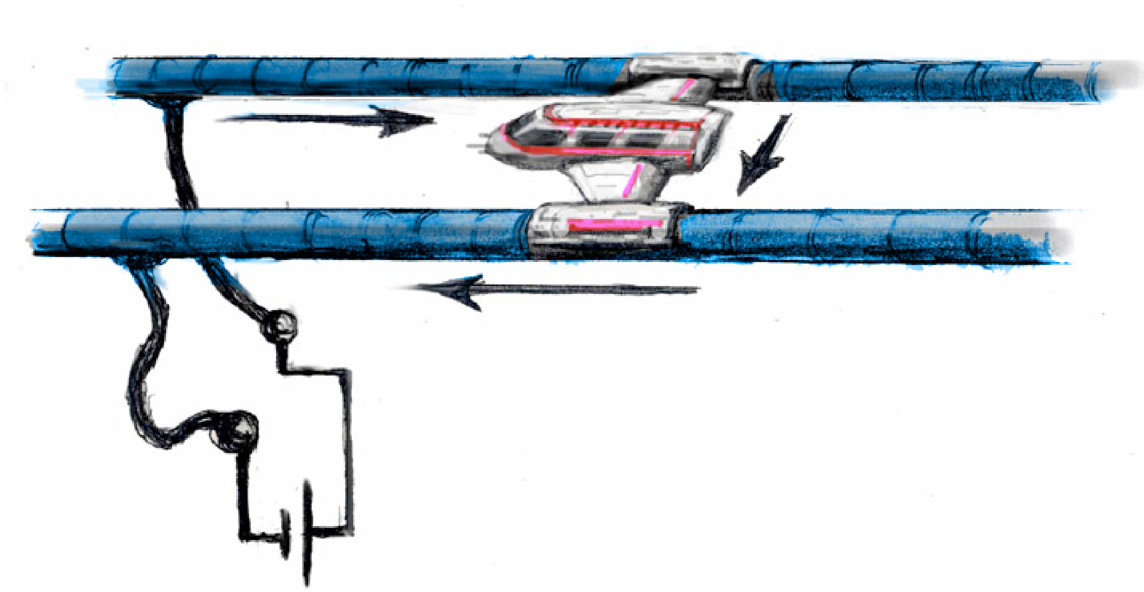
   a. -x-direction
   b. +y-direction (towards the top of the page)
   c. -z-direction (i.e. into the page)
   d. +z-direction (i.e. out of the page)
   e. none of the above

7. A positively charged hydrogen ion turns upward as it enters a magnetic field that points into the page. What direction was the ion going before it entered the field?

   a. -x-direction
   b. +x-direction
   c. -y-direction (towards the bottom of the page)
   d. +z-direction (i.e. out of the page)
   e. none of the above

8. An electron is moving to the east at a speed of 1.8×10^{6} m/s. It feels a force in the upward direction with a magnitude of 2.2×10^{-12} N. What is the magnitude and direction of the magnetic field this electron just passed through?

9. A vertical wire, with a current of 6.0 A going towards the ground, is immersed in a magnetic field of 5.0 T pointing to the right. What is the value and direction of the force on the wire? The length of the wire is 2.0 m.

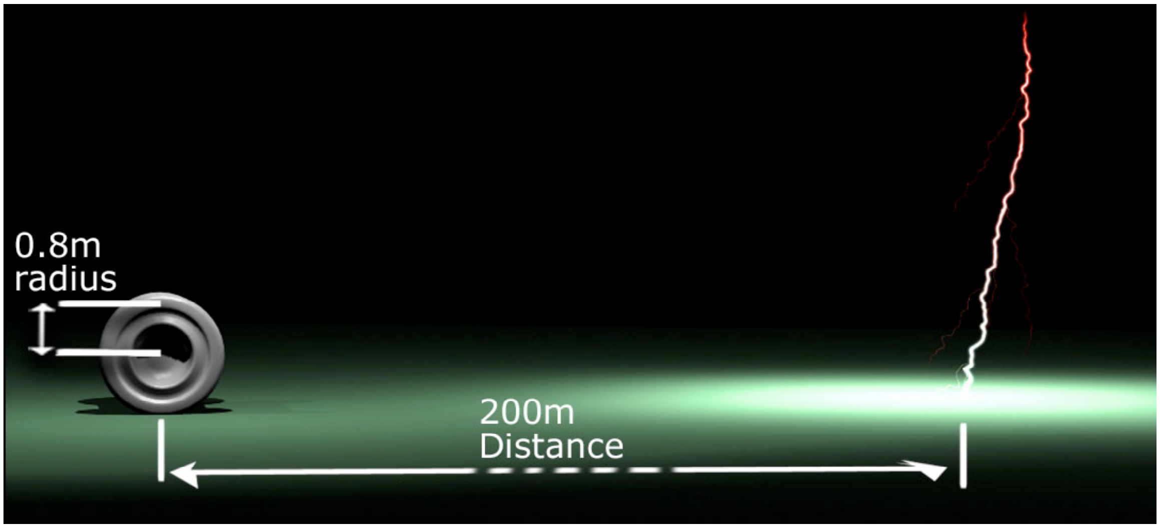


10. A futuristic magneto-car uses the interaction between current flowing across the magneto car and magnetic fields to propel itself forward. The device consists of two fixed metal tracks and a freely moving metal car (see illustration above). A magnetic field is pointing downward with respect to the car, and has the strength of 5.00 T. The car is 4.70 m wide and has 800 A of current flowing through it. The arrows indicate the direction of the current flow.

    a. Find the direction and magnitude of the force on the car.
    b. If the car has a mass of 2050 kg, what is its velocity after 10 s, assuming it starts at rest?
    c. If you want double the force for the same magnetic field, how should the current change?

11. A horizontal wire carries a current of 48 A towards the east. A second wire with mass 0.05 kg runs parallel to the first, but lies 15 cm below it. This second wire is held in suspension by the magnetic field of the first wire above it. If each wire has a length of half a meter, what is the magnitude and direction of the current in the lower wire?

12. Protons with momentum 5.1×10^{-20} kg·m/s are magnetically steered clockwise in a circular path. The path is 2.0 km in diameter. (This takes place at the Dann International Accelerator Laboratory, to be built in 2057 in San Francisco.) Find the magnitude and direction of the magnetic field acting on the protons.



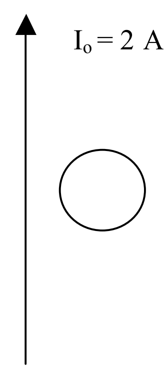
13. A bolt of lightening strikes the ground 200 m away from a 100-turn coil (see above). If the current in the lightening bolt falls from 6.0×10^{6} A to 0.0 A in 10 μs, what is the average *voltage*, ε, induced in the coil? What is the *direction* of the induced current in the coil? (Is it clockwise or counterclockwise?) Assume that the distance to the center of the coil determines the average magnetic induction at the coil's position. Treat the lightning bolt as a vertical wire with the current flowing toward the ground.

14. A coil of wire with 10 loops and a radius of 0.2 m is sitting on the lab bench with an electromagnet facing into the loop. For the purposes of your sketch, assume the magnetic field from the electromagnet is pointing out of the page. In 0.035 s, the magnetic field drops from 0.42 T to 0 T.

    a. What is the voltage induced in the coil of wire?
    b. Sketch the direction of the current flowing in the loop as the magnetic field is turned off. (Answer as if you are looking down at the loop).

15. A wire has 2 A of current flowing in the upward direction.

    a. What is the value of the magnetic field 2 cm away from the wire?
    b. Sketch the direction of the magnetic field lines in the picture to the right.
    c. If we turn on a magnetic field of 1.4 T, pointing to the right, what is the value and direction of the force per meter acting on the wire of current?
    d. Instead of turning on a magnetic field, we decide to add a loop of wire (with radius 1 cm) with its center 2 cm from the original wire. If we then increase the current in the straight wire by 3 A per second, what is the direction of the induced current flow in the loop of wire?



16. An electron is accelerated from rest through a potential difference of 1.67 X 10^5 volts. It then enters a region traveling perpendicular to a magnetic field of 0.25 T.

    a. Calculate the velocity of the electron.
    b. Calculate the magnitude of the magnetic force on the electron.
    c. Calculate the radius of the circle of the electron's path in the region of the magnetic field

17. A beam of charged particles travel in a straight line through mutually perpendicular electric and magnetic fields. One of the particles has a charge, q; the magnetic field is B and the electric field is E. Find the velocity of the particle.

18. Two long thin wires are on the same plane but perpendicular to each other. The wire on the y-axis carries a current of 6.0 A in the –y direction. The wire on the x-axis carries a current of 2.0 A in the + x direction. Point, P has the co-ordinates of (2.0, 2,0) in meters. A charged particle moves in a direction of 45^o away from the origin at point, P, with a velocity of 1.0 X10^7 m/s.

    a. Find the magnitude and direction of the magnetic field at point, P.
    b. If there is a magnetic force of 1.0 X 10^{-6} N on the particle determine its charge.
    c. Determine the magnitude of an electric field that will cancel the magnetic force on the particle.

19. A rectangular loop of wire 8.0 m long and 1.0 m wide has a resistor of 5.0 Ω on the 1.0 side and moves out of a 0.40 T magnetic field at a speed of 2.0 m/s in the direction of the 8.0 m side.

    a. Determine the induced voltage in the loop.
    b. Determine the direction of current.
    c. What would be the net force needed to keep the loop at a steady velocity?
    d. What is the electric field across the .50 m long resistor?
    e. What is the power dissipated in the resistor?

20. A positron (same mass, opposite charge as an electron) is accelerated through 35,000 volts and enters the center of a 1.00 cm long and 1.00 mm wide capacitor, which is charged to 400 volts. A magnetic filed is applied to keep the positron in a straight line in the capacitor. The same field is applied to the region (region II) the positron enters after the capacitor.

    a. What is the speed of the positron as it enters the capacitor?
    b. Show all forces on the positron.
    c. Prove that the force of gravity can be safely ignored in this problem.
    d. Calculate the magnitude and direction of the magnetic field necessary.
    e. Show the path and calculate the radius of the positron in region II.
    f. Now the magnetic field is removed; calculate the acceleration of the positron away from the center.
    g. Calculate the angle away from the center with which it would enter region II if the magnetic field were to be removed.

21. A small rectangular loop of wire 2.00 m by 3.00 m moves with a velocity of 80.0 m/s in a non-uniform field that diminishes in the direction of motion uniformly by .0400 T/m. Calculate the induced emf in the loop. What would be the direction of current?

22. An electron is accelerated through 20,000 V and moves along the positive x-axis through a plate 1.00 cm wide and 2.00 cm long. A magnetic field of 0.020 T is applied in the -z direction.

    a. Calculate the velocity with which the electron enters the plate.
    b. Calculate the magnitude and direction of the magnetic force on the electron.
    c. Calculate the acceleration of the electron.
    d. Calculate the deviation in the y direction of the electron form the center.
    e. Calculate the electric field necessary to keep the electron on a straight path.
    f. Calculate the necessary voltage that must be applied to the plate.

23. A long straight wire is on the x-axis and has a current of 12 A in the –x direction. A point P, is located 2.0 m above the wire on the y-axis.

    a. What is the magnitude and direction of the magnetic field at P.
    b. If an electron moves through P in the-x direction at a speed of 8.0×10^7 m/s what is the magnitude and direction of the force on the electron?
    c. What would be the magnitude and direction of an electric field to be applied at P that would counteract the magnetic force on the electron?