Electromagnetism

Unit: Magnetism & Electromagnetism

MA Curriculum Frameworks (2016): HS-PS2-5

AP® Physics 2 Learning Objectives: 3.C.3.1, 3.C.3.2, 4.E.2.1

Mastery Objective(s): (Students will be able to…)

- Describe and explain ways that electric and magnetic fields affect each other.
- Calculate the voltage and current changes in a step-up or step-down transformer.

Success Criteria:

- Descriptions & explanations account for observed behavior.
- Voltage and current changes are described accurately.

Language Objectives:

- Explain how various devices work including solenoids, electromagnets and electric motors.

Tier 2 Vocabulary: force, field

Labs, Activities & Demonstrations:

- current-carrying wire in a magnetic field
- electromagnet
- two coils wired together and two rare earth magnets, one on a spring
- electric motor
- magnet through copper pipe (Lenz's Law)
- wire & galvanometer jump rope
- neodymium magnet & CRT screen

Notes:

A changing electric field produces a magnetic field, and a changing magnetic field produces an electric field. These actions can produce magnetic forces or electromagnetic forces (emf).

Use this space for summary and/or additional notes:

Magnetic Fields and Moving Charges

Like gravitational and electric fields, a magnetic field is a force field. (Recall that force fields are vector quantities, meaning that they have both magnitude and direction.) The strength of a magnetic field is measured in teslas (T), named after the Serbian-American physicist Nikola Tesla.

$$1\,\text{T} = 1\,\frac{\text{N}}{\text{A}\cdot\text{m}}$$

In the 1830s, physicists Michael Faraday and Joseph Henry each independently discovered that an electric current could be produced by moving a magnet through a coil of wire, or by moving a wire through a magnetic field. This process is called electromagnetic induction.

If we move a conductive rod or wire that has length L at a velocity v through a magnetic field of strength B, the magnetic forces send positive charges to one end of the rod and negative charges to the other. This creates a potential difference (emf) between the ends of the rod:

$$\varepsilon = vBL$$

If the rod or wire is part of a closed loop (circuit), then the induced ε produces a current around the closed loop. From Ohm's Law $\varepsilon = IR$, we get:

$$I = \frac{\varepsilon}{R} = \frac{vBL}{R}$$

Forces and Moving Charges

The force, $\vec{\boldsymbol{F}}$ on a charge q moving through a magnetic field $\vec{\boldsymbol{B}}$ with a velocity $\vec{\boldsymbol{v}}$ is given by the equation:

$$\vec{\boldsymbol{F}} = q(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}) \qquad \text{and} \qquad F = qvB\sin\theta$$

Recall that current is just a flow of charges, which means that an electric current moving through a magnetic field creates a force on the wire carrying the current.

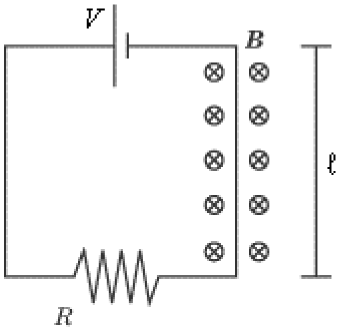
Recall that $\vec{\boldsymbol{I}} = \frac{\Delta Q}{t}$ and $\vec{\boldsymbol{v}} = \frac{\vec{\boldsymbol{d}}}{t} = \frac{\ell}{t}$, where ℓ is the length (distance) of the wire that passes through the magnetic field. This means that $q\vec{\boldsymbol{v}} = \ell\vec{\boldsymbol{I}}$, which we can use to create an equivalent equation:

$$\vec{\boldsymbol{F}} = \ell(\vec{\boldsymbol{I}} \times \vec{\boldsymbol{B}}) \qquad \text{and} \qquad F = \ell IB\sin\theta$$

Note that the direction of the cross products $\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}$ and $\vec{\boldsymbol{I}} \times \vec{\boldsymbol{B}}$ can be determined using the right-hand rule.

Use this space for summary and/or additional notes:

A current passing through a magnetic field would be represented like this:



In the above diagram, the battery has voltage *V*, the resistor has resistance *R*, and the length of wire passing through the magnetic field is ℓ.

The magnetic field strength is ***B***, and the field itself is denoted by the symbols ⊗ ⊗ ⊗ ⊗ ⊗ which denote a magnetic field going _into_ the page. (A field coming out of the page would be denoted by ⊙ ⊙ ⊙ ⊙ ⊙ instead. Think of the circle as an arrow inside a tube. The dot represents the tip of the arrow facing toward you, and the "X" represents the fletches (feathers) on the tail of the arrow facing away from you.)

For example, suppose we were given the following for the above diagram:

$$\vec{\boldsymbol{B}} = 4.0\times 10^{-5}\text{ T}$$
$$V = 30\text{ V}$$
$$R = 5\,\Omega$$
$$\ell = 2\text{ m}$$

Current (from Ohm's Law):

$$V = IR$$
$$30 = I(5)$$
$$I = 6\text{A}$$

Force on the wire:

$$\vec{\boldsymbol{F}} = \ell(\vec{\boldsymbol{I}}\times\vec{\boldsymbol{B}})$$
$$F = \ell IB\sin\theta$$
$$F = (2)(6)(4.0\times 10^{-5})\sin(90°)$$
$$F = (2)(6)(4.0\times 10^{-5})(1)$$
$$F = 4.8\times 10^{-4}\text{N}$$

If the current is going upward through the magnetic field, and the magnetic field is pointing into the paper, then the right-hand rule tells us that the force would be directed to the left.

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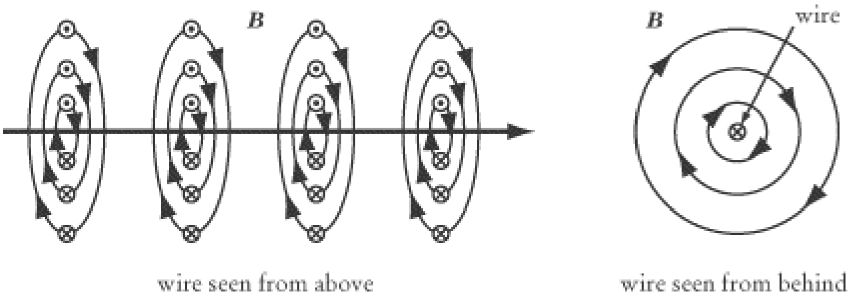
Magnetic Field Produced by Electric Current

An electric current moving through a wire also produces a magnetic field around the wire:



This time, we use the right-hand rule with our thumb pointing in the direction of the current, and our fingers curl in the direction of the magnetic field.

The strength of the magnetic field produced is given by the formula:

$$B = \frac{\mu_o}{2\pi} \frac{I}{r}$$

where B is the strength of the magnetic field, μ_o is the magnetic permeability of free space, I is the current, and r is the distance from the wire. (The variable r is used because the distance is in all directions, which means we would use polar or cylindrical coordinates.)

EMF Produced by Changing Magnetic Flux

A changing magnetic field produces an electromotive force (emf) in a loop of wire. This emf is given by the equation:

$$\varepsilon = -\frac{d\Phi}{dt} = -\frac{\Delta\Phi}{t}$$

(calculus) (algebraic)

If we replace the loop of wire with a coil that has n turns, the equation becomes:

$$\varepsilon = -n\frac{d\Phi}{dt} = -n\frac{\Delta\Phi}{t}$$

(calculus) (algebraic)

Use this space for summary and/or additional notes:

Combined Electric and Magnetic Fields

Recall that the force on a charged particle due to an electric field is:

$$\vec{\boldsymbol{F}}_e = q\vec{\boldsymbol{E}}$$

and that the force on a charged particle due to a magnetic field is:

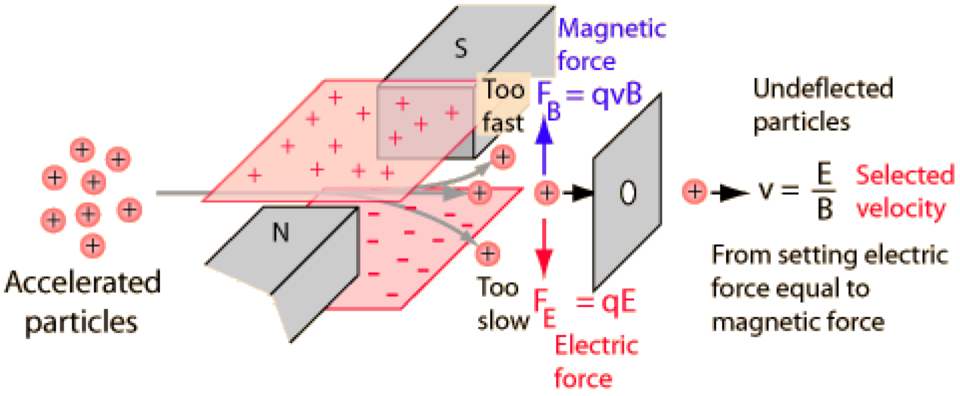
$$\vec{\boldsymbol{F}}_B = q(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$$

Therefore, the force on a charged particle that interacts simultaneously with an electric field and a magnetic field must be the sum of the two:

$$\vec{\boldsymbol{F}}_{EM} = q(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$$

An application of this combination is a particle sorter, which allows only particles with a given velocity to pass through.

Particles that enter a mass spectrometer must have the correct velocity in order for the mass spectrometer to be able to separate the particles properly. Before the particles enter the mass spectrometer, they first pass through a particle sorter, which applies opposing electric and magnetic forces to the particle:



If the particles are moving too quickly, the magnetic force is stronger and the particles are deflected upwards. If the particles are moving too slowly, the electric force is stronger and the particles are deflected downwards. Particles with the desired velocity experience no net force and are not deflected.

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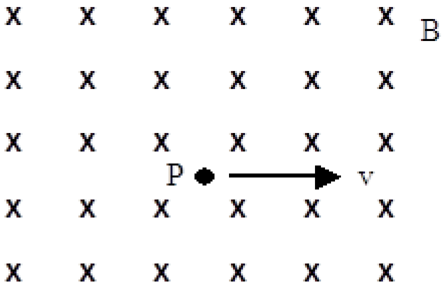
Sample Problem:

Q: A proton has a velocity of $1\times10^{5}\,\frac{\text{m}}{\text{s}}$ to the right when it is at point *P* in a uniform magnetic field of 0.1 T that is directed into the page. Calculate the force (magnitude and direction) on the proton, and sketch its path.



A: The force on the proton is given by:

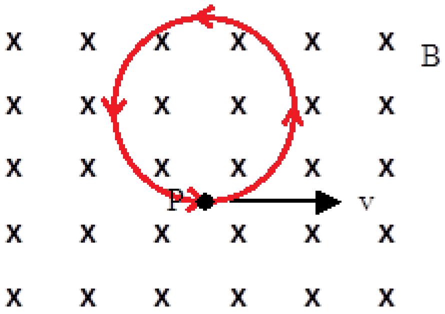
$$\vec{F}_B = q(\vec{v}\times\vec{B}) = qvB\sin\theta$$

Because the velocity of the particle and the direction of the magnetic field are perpendicular, $\sin\theta = \sin(90°) = 1$ and therefore the magnitude of $F_B = qvB$.

$$F_B = qvB$$
$$F_B = (1.6\times10^{-19})(1\times10^{5})(0.1)$$
$$F_B = 1.6\times10^{-15}\,\text{N}$$

The direction is given by the right-hand rule. Start with the fingers of your right hand pointing straight in the direction of velocity (to the right) and rotate your right hand until you can bend your fingers toward the magnetic field (into the page). Your thumb will be pointing upwards, which means that the force on a positively charged particle moving to the right is upwards. (Note that if the particle had been negatively charged, it would have moved in the opposite direction.)

However, note that the action of the force causes a change in the direction of the proton's velocity, and the change in the direction of the proton's velocity changes the direction of the force. This feedback loop results in the proton moving in a continuous circle.



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Homework Problems

1. **(M)** A wire 1 m long carries a current of 5 A. The wire is at right angles to a uniform magnetic field. The force on the wire is 0.2 N. What is the strength of the magnetic field?

   Answer: 0.04 T

2. **(S)** A wire 0.75 m long carries a current of 3 A. The wire is at an angle of 30° to a uniform magnetic field. The force on the wire is 0.5 N. What is the strength of the magnetic field?

   Answer: $0.\overline{4}$ T

3. **(M)** Two currents (one of 2 A and the other of 4 A) are arranged parallel to each other, with the currents flowing in the same direction. The wires are 3 m long and are separated by 8 cm (0.08 m). What is the net magnetic field at the midpoint between the two wires?

   Answer: 1×10^{-5} T

Use this space for summary and/or additional notes:

4. **(M)** A wire 2 m long moves perpendicularly through a 0.08 T field at a speed of $7\,\frac{\text{m}}{\text{s}}$.

   a. What emf is induced?

   Answer: 1.12 V

   b. If the wire has a resistance of 0.50 Ω, use Ohm's Law to find the current that flows through the wire.

   Answer: 2.24 A

Use this space for summary and/or additional notes: