NOTES

Unit 12: Electricity and Magnetism – Magnetism

OBJECTIVES:

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

Enduring Understanding 1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

Essential Knowledge 1.E.5: Matter has a property called magnetic permeability.

a. Free space has a constant value of the permeability that appears in physical relationships.

b. The permeability of matter has a value different from that of free space.

Essential Knowledge 1.E.6: Matter has a property called magnetic dipole moment.

a. Magnetic dipole moment is a fundamental source of magnetic behavior of matter and an intrinsic property of some fundamental particles such as the electron.

b. Permanent magnetism or induced magnetism of matter is a system property resulting from the alignment of magnetic dipole moments within the system.

Big Idea 2: Fields existing in space can be used to explain interactions.

Enduring Understanding 2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.

Essential Knowledge 2.A.1: A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.

a. Vector fields are represented by field vectors indicating direction and magnitude.

b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition.

c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.

Enduring Understanding 2.D: A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

Essential Knowledge 2.D.1: The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity, and the magnitude of the magnetic field. It also depends on the angle between the velocity and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles.

Learning Objective 2.D.1.1: The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field.

Essential Knowledge 2.D.2: The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.

a. The magnitude of the magnetic field is proportional to the magnitude of the current in a long straight wire.

b. The magnitude of the field varies inversely with distance from the wire, and the direction of the field can be determined by a right-hand rule.

> Learning Objective 2.D.2.1: The student is able to create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires.

Essential Knowledge 2.D.3: A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.

a. A simple magnetic dipole can be modeled by a current in a loop. The dipole is represented by a vector pointing through the loop in the direction of the field produced by the current as given by the right-hand rule.

b. A compass needle is a permanent magnetic dipole. Iron filings in a magnetic field become induced magnetic dipoles.

c. All magnets produce a magnetic field. Examples should include magnetic field pattern of a bar magnet as detected by iron filings or small compasses.

d. Earth has a magnetic field.

> Learning Objective 2.D.3.1: The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet.

Essential Knowledge 2.D.4: Ferromagnetic materials contain magnetic domains that are themselves magnets.

a. Magnetic domains can be aligned by external magnetic fields or can spontaneously align.

b. Each magnetic domain has its own internal magnetic field, so there is no beginning or end to the magnetic field — it is a continuous loop.

c. If a bar magnet is broken in half, both halves are magnetic dipoles in themselves; there is no magnetic north pole found isolated from a south pole.

> Learning Objective 2.D.4.1: The student is able to use the representation of magnetic domains to qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material.

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Big Idea 3: The interactions of an object with other objects can be described by forces.
Enduring Understanding 3.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

Essential Knowledge 3.C.3: A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.

a. Magnetic dipoles have north and south polarity.

b. The magnetic dipole moment of an object has the tail of the magnetic dipole moment vector at the south end of the object and the head of the vector at the north end of the object.

c. In the presence of an external magnetic field, the magnetic dipole moment vector will align with the external magnetic field.

d. The force exerted on a moving charged object is perpendicular to both the magnetic field and the velocity of the charge and is described by a right-hand rule.

Learning Objective 3.C.3.1: The student is able to use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current- carrying conductor.

Learning Objective 3.C.3.2: The student is able to plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion.

Big Idea 4: Interactions between systems can result in changes in those systems.
Enduring Understanding 4.E: The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

Essential Knowledge 4.E.1: The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.

a. Ferromagnetic materials can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles.

b. Paramagnetic materials interact weakly with an external magnetic field in that the magnetic dipole moments of the material do not remain aligned after the external field is removed.

c. All materials have the property of diamagnetism in that their electronic structure creates a (usually) weak alignment of the dipole moments of the material opposite to the external magnetic field.

Learning Objective 4.E.1.1: The student is able to use representations and models to qualitatively describe the magnetic properties of some materials that can be affected by magnetic properties of other objects in the system.

Essential Knowledge 4.E.2: Changing magnet flux induces an electric field that can establish an induced emf in a system.

a. Changing magnetic flux induces an emf in a system, with the magnitude of the induced emf equal to the rate of change in magnetic flux.

b. When the area of the surface being considered is constant, the induced emf is the area multiplied by the rate of change in the component of the magnetic field perpendicular to the surface.

c. When the magnetic field is constant, the induced emf is the magnetic field multiplied by the rate of change in area perpendicular to the magnetic field.

d. The conservation of energy determines the direction of the induced emf relative to the change in the magnetic flux.

Learning Objective 4.E.2.1: The student is able to construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area.

NOTES:

I. Magnetism Basics

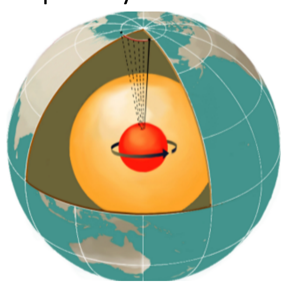
A. Magnets have two opposite poles (north and south.)

- Opposite poles attract; like poles repel.

B. Magnetic Dipole (part 1):

1. Moving charges create magnetic fields around themselves.

- The moving charges (current) in Earth's interior are the likely source of Earth's magnetic field. Our magnetic polar orientation is at an 11° angle compared to Earth's rotational axis, so our magnetic poles are offset from our geographical poles. Compass needles are magnets, and their north poles point to Earth's magnetic north pole. Speculate about the orientation of Earth's magnetic polarity.[1]

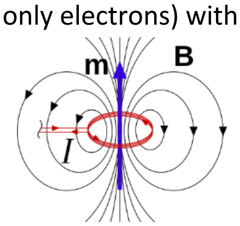


2. A loop of current carrying wire, therefore, has magnetic properties and is considered a magnetic dipole. We'll come back to this later (in Magnetic Dipole part 2.)

3. Magnetic dipoles are vectors represented with arrows pointing with their tails on the south pole and their heads on the north pole as shown below.

4. Electrons, which have angular momentum[2], behave magnetically like very small loops of current-carrying wire. They therefore create tiny magnetic fields around themselves based on their charge, mass, and angular momentum. This value is called the magnetic moment of the electron, and the electron, by virtue of its charge and motion, creates north and south magnetic poles around itself.

- All fundamental particles (not only electrons) with charge have magnetic dipole moments.[3,4]



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[1] Fun facts: Earth's magnetic field permanently magnetizes some of our rocks. The mineral magnetite is the most susceptible to this, and hunks of magnetized magnetite are called lodestones. Earth's polarity reverses itself periodically, around every 200,000-300,000 years, as shown in layers of lodestones in which different layers have different polarities. Currently our magnetic poles are migrating closer to the geographical poles by about 40 miles per year. This migratory rate is actually accelerating!

[2] An electron two types of angular momentum: Its own spin and its orbiting angular momentum.

[3] A dipole moment is, in essence, a measure of the overall polarity of the matter. (It has a formula related to charge and separation of charge.)

[4] The fact that the neutron has a magnetic dipole moment was evidence that it is not itself a fundamental particle but is, instead, made up of smaller, charged fundamental particles called quarks.

C. Magnetic domains and becoming a magnet, and magnetism is a system property.

1. Diamagnetic materials: In some materials, the electrons are paired, so their dipole moments mutually cancel. Hence there is no net dipole moment. When exposed to an external magnetic field, the materials can become very weakly magnetized, but the magnetism disappears when the field is gone. (*Teacher note: The temporary magnetism comes because one electron accelerates, while the paired electron that had the opposite spin slows down.*)

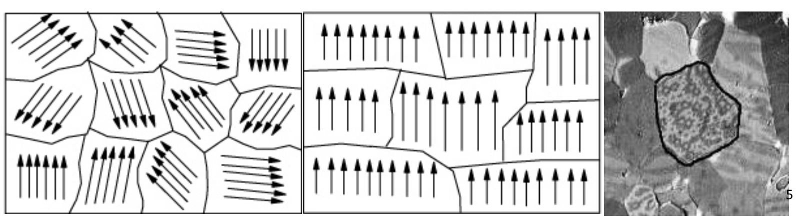
2. Paramagnetic materials: These materials have atoms that do have net dipole moments. When exposed to an external magnetic field these dipole moments can align making the material magnetic. However, this alignment only holds while the field is present, and to become magnetized again need to be induced by exposure to a magnetic field.

3. Ferromagnetic materials hold the alignment when the field is removed and are permanent magnets. They are able to do so because they have the ability to form magnetic domains.

a. Magnetic domains: In some materials, the magnetic dipole moments can align in small systems called magnetic domains about 0.01-0.1mm wide. Each domain acts as a tiny magnet. However, if the domains aren't aligned with each other, the material is *capable* of becoming a magnet but isn't actually a magnet yet.

- Each magnetic domain has its own internal magnetic field, so there is no beginning or end to the magnetic field — it is a continuous loop. Therefore…
- If a magnet is broken into pieces, all pieces are magnetic dipoles in themselves; there is no magnetic north pole found isolated from a south pole.

b. Becoming a magnet: When a material is exposed to an external magnetic field, the domains (and therefore the magnetic dipole moments of the charged particles in the material) align, and the material becomes magnetized. (Sometimes magnetic domains may also spontaneously align, but most often alignment is due to exposure to an external field.)

 [5]

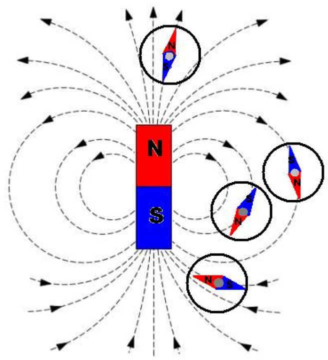
- http://commons.wikimedia.org/wiki/File:Moving_magnetic_domains_by_Zureks.gif
- The alignment of the material's dipole is always opposite the external field, since like poles repel, and opposite poles attract.
  - Jostling can knock domains back out of alignment. Some ferromagnetic materials are more resistant to this than others.
  - A compass needle is a permanent magnetic dipole.
- Iron filings in a magnetic field become induced magnetic dipoles.

[5] In the circled grain of a neodymium magnet, we see stripes. Each stripe is a magnetic domain. The fact that they are not all the same color shows that they are not oriented the same way. A special microscope took this image.

II. Magnetic Force on a Moving Charge and on Current-Carrying Wires

A. Magnetic fields:

1. Magnetic fields are vector fields that point from north to south;[6]



2. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

3. Iron filings becoming magnetized and orienting themselves in alignment with the magnetic field of a bar magnet show magnetic fields well.

B. Magnetic force:

1. A magnetic force results from the interaction of a moving charged object[7] or a magnet with other moving charged objects or another magnet. In other words, there is a magnetic force whenever a…

- Moving charged object & magnet interact.
- Moving charged object and another moving charged object interact.
- Magnet & another magnet interact.

2. The magnetic force is the result of a magnet or moving charge interacting with the other magnet's or moving charge's magnetic field: Because moving charges generate magnetic fields, when a charge travels in an external magnetic field, it experiences magnetic a force perpendicular[8] to the magnetic field provided that…

- the charge is moving, and
- its velocity has a component that is perpendicular to the field.
- Because the force is perpendicular to the particle's movement, magnetic force does NO WORK on a charged particle.[9]

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[6] This is the same direction a compass' north pole would point in the field. Therefore which magnetic pole is near Earth's geographical North Pole? ________________ ☺

[7] The moving charges include electrons in current-carrying wires.

[8] This is an experimental fact.

[9] Review: What's another force that never does any work? **CENTRIPETAL**

C. Magnetic force on a moving charge

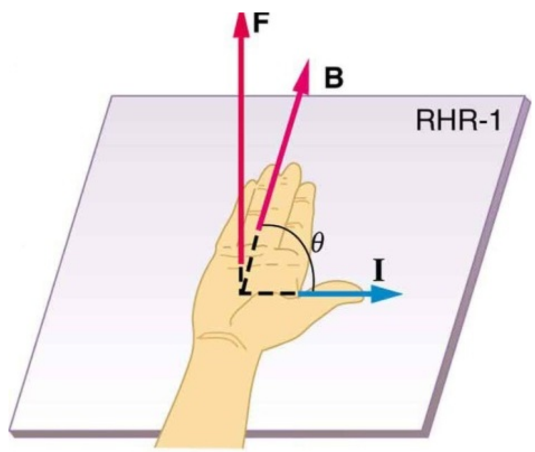
1. Formula:

or when the charge is moving at an angle relative to the field…

where…

- is the magnetic field measured in Teslas (T) where 1 T = 1
- is the magnitude of the magnetic force on a moving charge
- is the magnitude of the moving charge
- is the magnitude of the charge's velocity
- is the angle between the charge's velocity and the magnetic field[10]

2. The direction of magnetic force follows the "right-hand-rule."



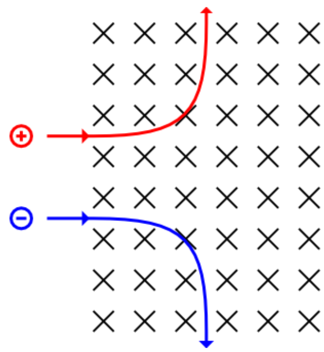
$F = I\ell B \sin\theta$

F $\perp$ plane of **I** and **B**

**where is the direction a POSITIVE charge moves. When dealing with a negative charge, it will experience a force in the opposite direction from the force on the positive charge.

[10] Therefore force is greatest when velocity is perpendicular to the field and disappears as the velocity becomes parallel to the field.

3. Paths of charged particles in magnetic fields will either be parabolas in the direction of the magnetic force. Prove this to yourself using the diagram below.



Rule of drawing magnetic field: Fields pointing into the page are marked with an X, and fields pointing out of the page toward you are marked with a dog.

Magnetic force, therefore, acts as a centripetal force, and the radius of the curved path can be found by:

so

You can derive this if you need it.

(Bringing back the idea that magnetic force does no work on a charged particle: Centripetal force does no work in the same way that magnetic force does no work.)

4. Examples:

a. <u>Example 1</u>: Magnetic force on a single charged particle: A proton in a particle accelerator has a speed of 5E6 m/s. The proton encounters a magnetic field whose magnitude is 0.40 T and whose direction makes an angle of 30^o with respect to the proton's velocity. The mass of a proton and of an electron are on your formula sheets. Find (a) the magnitude and direction of the magnetic force on the proton and (b) the acceleration of the proton. (c) What would be the force and acceleration if the particle were an electron instead of a proton?

b. <u>Example 2</u>: Two charged particles of equal charge move in a magnetic field. Particle 1 is moving perpendicular to the field. Particle 2 is moving at an angle but with a perpendicular component equal to the velocity of particle 1. Which experiences the greater force?

c. <u>Example 3</u>: An electron travels at 2.0E7 m/s in a plane perpendicular to a 0.010 T magnetic field. Describe its path.

d. Example 4: It is common for charged particles to travel in spirals in magnetic fields. How can this happen? *This is how the aurora borealis occurs from ions entering the atmosphere near the poles where the magnetic force is the strongest. The accelerating ions become energetic, causing electrons to emit light.*

e. Example 5: How could you make a charged particle move with a constant velocity in a magnetic field?

D. Magnetic force on current-carrying wires

1. Because moving charges generate magnetic fields, when a current-carrying wire is placed in an external magnetic field, it acts magnetic and therefore experiences magnetic force.

2.The formula for magnetic force on a current-carrying wire comes from the formula for the magnetic force on a single charge:

Multiply the whole thing by to get

where equals current () and equals displacement (length of wire,)

to get

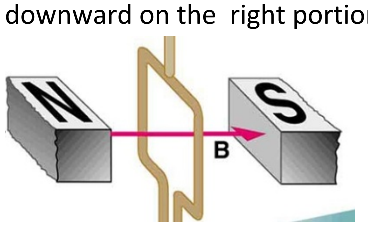
or when the wire is at an angle relative to the field…

3. The direction of the force follows the right-hand rule.

4. Example 6: A current travels to the right in a wire running horizontally in a uniform magnetic field of strength 1.42 T that points out of the page. The wire has a length of 10.0 cm, and the current in the wire is 0.245 A. What is the magnitude and direction of the magnetic force?

5. Current-carrying loops rotate in magnetic fields due to different directional forces on each side of the loop.

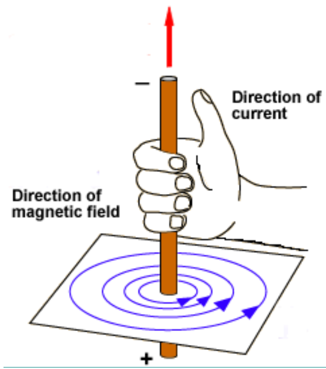
- Example 7: In the image below, the current runs upward on the left portion of the loop and downward on the right portion of the loop. Which way does the loop rotate?

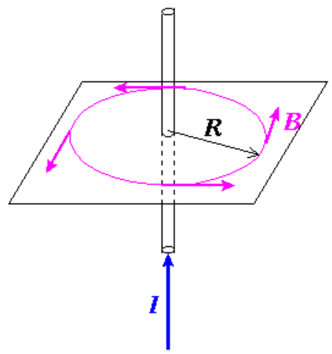


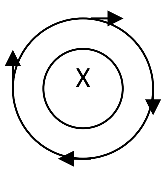
III. Magnetic Fields Created by Current-Carrying Wires

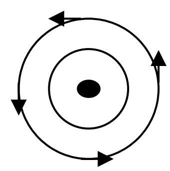
A. Since moving charges create magnetic fields, current-carrying wires create magnetic fields around themselves.

1. Fields created by wires form circles with the wire at the center. The magnetic field lines are tangent to the circle and follow the right-hand rule as follows.









Current into page:
Magnetic field is clockwise.

Current coming out of page:
Magnetic field is counterclockwise.

2. The magnetic force created by a long, straight wire can be found by

where…

- is the strength of the magnetic field.
- is the radial distance from the wire.
- is the current.
- is the vacuum permeability (the permeability of free space.)
  - Matter has a property called magnetic permeability.
  - Free space has a constant value of the permeability that appears in physical relationships.
  - The permeability of matter has a value different from that of free space.
  - = 4 x 10^{-7} Tm/A (Check this out on the front page of your formula sheet. It is not shown in this form, but you will use it this way.)

B. Superpositon: Two (or more) current-carrying wires create a combined effect on the region.

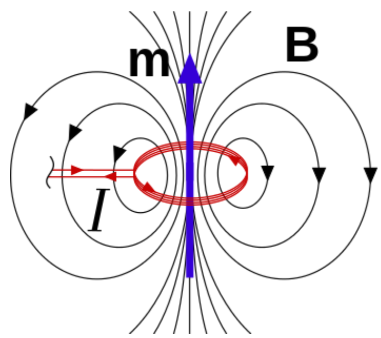
1. <u>Example 8</u>: The two wires of a 2.0m long appliance cord are 3.0mm apart and carry a current of 8.0 A. Calculate the force between these wires. (Assume the current is dc and that the current flows in opposite directions.)

2. Direction of the force:

a.) Parallel currents attract, because at the center, B_1 points opposite B_2.

b.) Anti-parallel currents repel, because at the center both magnetic fields point in the same direction and therefore repel.

C. Magnetic dipole (part 2): A simple magnetic dipole can be modeled by a current in a loop. The dipole is represented by a vector pointing through the loop in the direction of the field produced by the current as given by the right-hand rule. Adding many loops together multiplies this effect to create a strong magnetic field. The number of coils multiplied by the current and magnetic field gives a value called the magnetic dipole moment.



IV. Electromagnetism

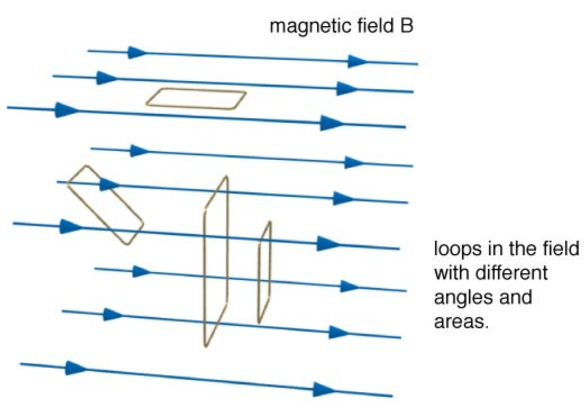
A. Magnetic flux refers conceptually to the quantity of magnetic field passing through a region.[11]

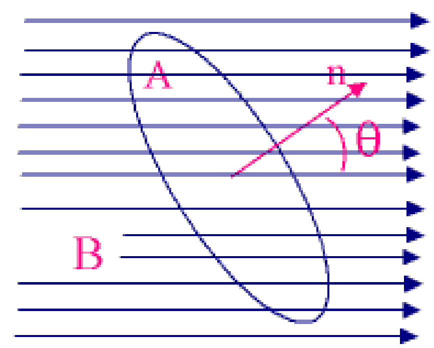
1. Conceptually: A stronger magnetic flux means the magnetic field is stronger in a region.[12]
2. Magnetic flux is proportional to the perpendicular components of the magnetic field lines passing through an area.[13]
3. Formula

or when the region is at an angle relative to the field…

where

- is the magnetic flux measured in webers (Wb) (1 Wb = 1Tm^2)
- is the angle between the direction of the magnetic flux and the normal to the area of the region





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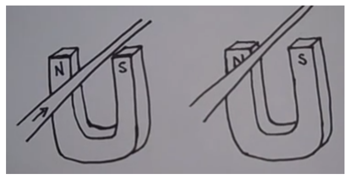
[11] All force fields have a flux: Electric flux, gravitational flux

[12] Think of it like sunshine through a window. The angle of the rays matters through the window matter, too, as we will see.

[13] The angle of sun rays through the window affect the strength of the sunshine, too.

B. Electromagnetic induction: Induced emf and induced current

1. When a wire with no current sits at rest in a magnetic field, nothing happens. However, we've seen that when we run current through a wire in a magnetic field, the wire can move (down in the example, left.) Likewise, if we move a magnet near a wire with no current, we can induce current in the wire. (Move the wire up (or the magnet down) in the example to the right, a magnetic force would cause current to flow into the page. (Think that if the wire moves up in the picture on the right, the velocity is up. Therefore the force is into the page.))



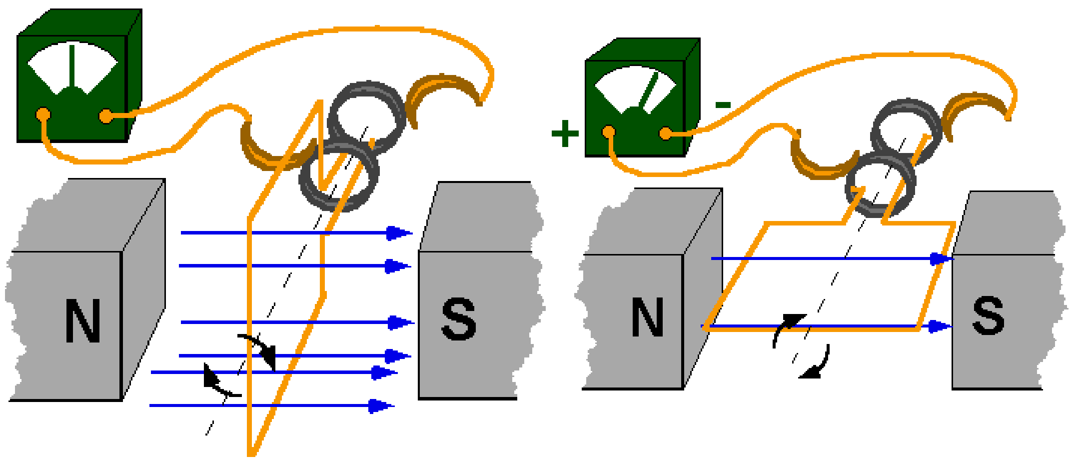
2. Induced emf: The "force" that moves electrons in a wire due to a temporary relative motion between the wire and an external magnetic field such that

   where…
   - is the electromotiveforce
   - is the velocity of the relative motion
   - is the magnetic field
   - is the length of the conductive material (e.g., rod or wire)

3. Induced current: Current that results from the creation of an induced emf. (Important: Relative motion must be occurring, or the emf reduces to zero again, halting current.)
4. Electromagnetic induction: The process of creating an induced emf.

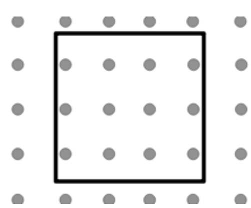
C. Faraday's Law: When we create a loop of wire and create relative motion by rotating the loop in a magnetic field (or by moving the magnetic field with respect to the loop,) the flux changes as changes or as changes. This creates an emf according to the formula:

so that the strength of the flux and how little time it takes to change the flux (faster loop rotation) creates more emf.

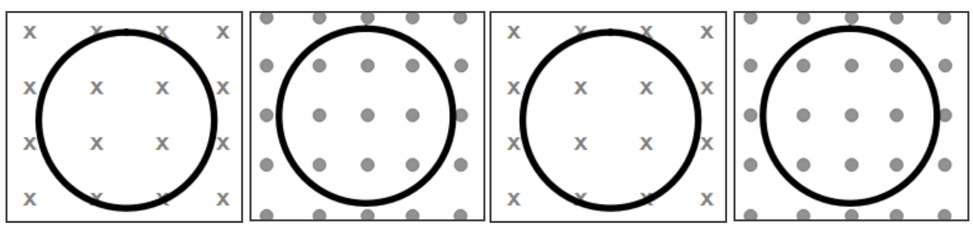


This is how generators create electromotive force.

- Example 9: A 0.1m x 0.1m loop is rotated so that it makes a full turn every 0.04s in a magnetic field of 2T. What is the emf produced? (Hint: To go from phi equals 0^o to phi equals 90^o takes ¼ of the time.)



D. Lenz's law
   1. Lenz's law explains the direction of the current and explains the negative sign in Faraday's Law.
   2. The direction of the induced current will be to minimize the change in magnetic flux. Conducting loops resist changes to magnetic flux inside of them by creating their own flux to minimize the change.
      - Analogy: Mass resists changes in velocity as conducting loops resist changes in the flux inside of their loops.
      - Counter-analogy-type thing: If the loop DIDN'T do this and instead created current that enhanced the field emf would grow as B grew on and on infinitely. This is impossible by the conservation of energy.
   3. <u>Example 10</u>:
      a. Which way will current flow in a loop if a magnetic field is flowing into the page and is increasing in strength?
      b. Which way will current flow in a loop if a magnetic field is flowing out of the page and is increasing in strength?
      c. Which way will current flow in a loop if a magnetic field is flowing into the page and is decreasing in strength?
      d. Which way will current flow in a loop if a magnetic field is flowing out of the page and is decreasing in strength?



Increasing Increasing Decreasing Decreasing

4. <u>Homework</u>: Construct an explanation of the function of a microphone using the image below. The incoming air molecules push on the diaphragm to create the sound wave.