Devices that Use Electromagnetism

Unit: Magnetism & Electromagnetism

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS2-5

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 12.2.B, 12.2.B.1, 12.2.B.2, 12.2.B.2.ii, 12.3.A.1, 12.3.A.1.i, 12.3.A.1.iii, 12.3.A.1.iv, 12.3.B.1, 12.3.B.1.ii

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

- Explain the basic design of solenoids, motors, generators, transformers and mass spectrometers.
- Calculate the voltage and power from a step-up or step-down transformer.

Success Criteria:

- Descriptions & explanations account for observed behavior.
- Calculations are set up and executed correctly.

Language Objectives:

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

Tier 2 Vocabulary: force, field

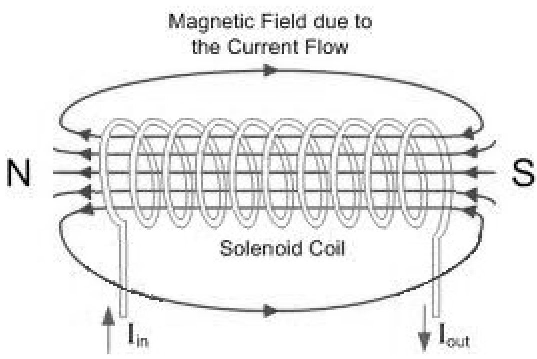
Labs, Activities & Demonstrations:

- build electromagnet
- build electric motor
- build speaker

Notes:

Solenoid

A solenoid is a coil made of fine wire. When a current is passed through the wire, it produces a magnetic field through the center of the coil.



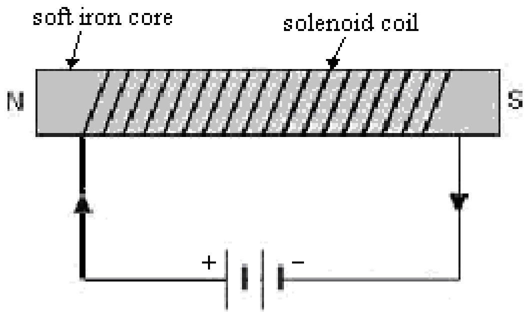
When a current is applied, a permanent magnet placed in the center of the solenoid will be attracted or repelled and will move.

One of the most common uses of a solenoid is for electric door locks.

Electromagnet

An electromagnet is a device that acts as magnet only when electric current is flowing through it.

An electromagnet is made by placing a soft iron core in the center of a solenoid. The high magnetic permeability of iron causes the resulting magnetic field to become thousands of times stronger:



Because the iron core is not a permanent magnet, the electromagnet only works when current is flowing through the circuit. When the current is switched off, the electromagnet stops acting like a magnet and releases whatever ferromagnetic objects might have been attracted to it.

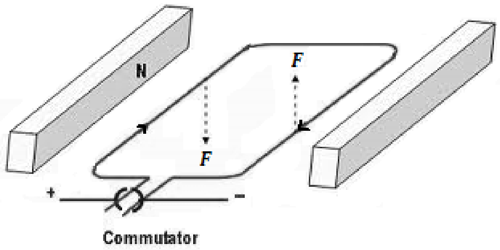
Of course, the above description is a simplification. Real ferromagnetic materials such as iron usually experience magnetic remanence, meaning that some of the electrons in the material remain aligned, and the material is weakly magnetized.

While magnetic remanence is undesirable in an electromagnet, it is the basis for magnetic computer storage media, such as audio and computer tapes and floppy and hard computer disks. To write information onto a disk, a disk head (an electromagnetic that can be moved radially) is pulsed in specific patterns as the disk spins. The patterns are encoded on the disk as locally magnetized regions.

When encoded information is read from the disk, the moving magnetic regions produce a changing electric field that causes an electric current in the disk head.

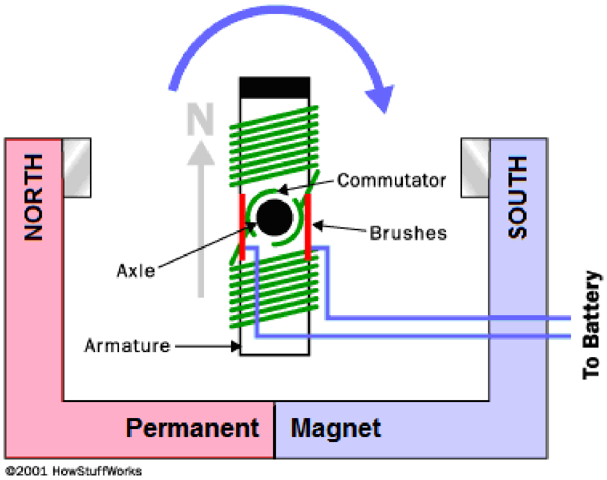
Motor

The force produced by a moving current in a magnetic field can be used to cause a loop of wire to spin:



A *commutator* is used to reverse the direction of the current as the loop turns, so that the combination of attraction and repulsion always applies force in the same direction.

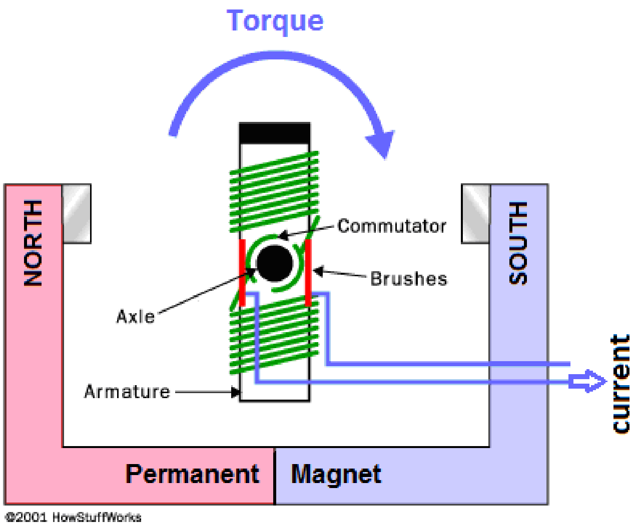
If we replace the loop of wire with an electromagnet (a coil of wire wrapped around a material such as iron that has both a high electrical conductivity and a high magnetic permeability), the electromagnet will spin with a strong force.



An electromagnet that spins because of its continuously switching attraction and repulsion to the magnetic field produced by a separate set of permanent magnets is called a *motor*. An electric motor turns electric current into rotational motion, which can be used to do work.

Generator

A *generator* uses the same components and operates under the same principle as a motor, except that a mechanical force is used to spin the coil. When the coil moves through the magnetic field, it produces an electric current. Thus, a generator is a device that turns rotational motion (work) into an electric current.



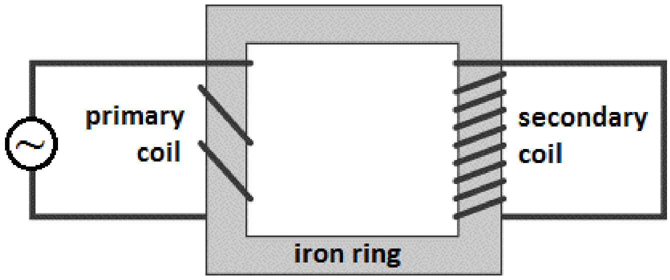
Recall from the previous section that Lenz's Law gives the emf produced by the generator. Because the coil is rotating through a uniform magnetic field, the magnetic flux through the coil is constantly changing, which means calculus is needed to calculate the emf produced.

$$\mathcal{E} = -n\frac{d\Phi_B}{dt}$$

Inductor (Transformer)

Because electric current produces a magnetic field, a ring made of a ferromagnetic material can be used to move an electric current. An inductor (transformer) is a device that takes advantage of this phenomenon in order to increase or decrease the voltage in an AC circuit.

The diagram below shows an inductor or transformer.



The current on the input side (primary) generates a magnetic field in the iron ring. The magnetic field in the ring generates a current on the output side (secondary).

In this particular transformer, the coil wraps around the output side more times than the input. This means that each time the current goes through the coil, the magnetic field adds to the electromotive force (voltage). This means the voltage will increase in proportion to the increased number of coils on the output side. However, the magnetic field on the output side will produce less current with each turn, which means the current will decrease in the same proportion:

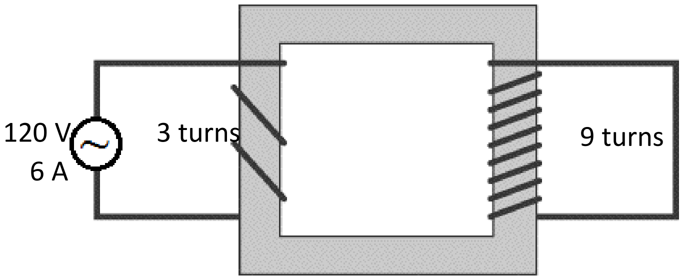
$$\frac{\#turns_{in}}{\#turns_{out}} = \frac{V_{in}}{V_{out}} = \frac{I_{out}}{I_{in}}$$

$$P_{in} = P_{out}$$

A transformer like this one, which produces an increase in voltage, is called a ***step-up transformer***; a transformer that produces a decrease in voltage is called a ***step-down transformer***.

Sample Problem:

If the input voltage to the following transformer is 120 V, and the input current is 6 A, what are the output voltage and current?



The voltage on either side of a transformer is proportional to the number of turns in the coil on that side. In the above transformer, the primary has 3 turns, and the secondary coil has 9 turns. This means the voltage on the right side will be $\frac{9}{3}=3$ times as much as the voltage on the left, or 360 V. The current will be $\frac{3}{9}=\frac{1}{3}$ as much, or 2 A.

We can also use:

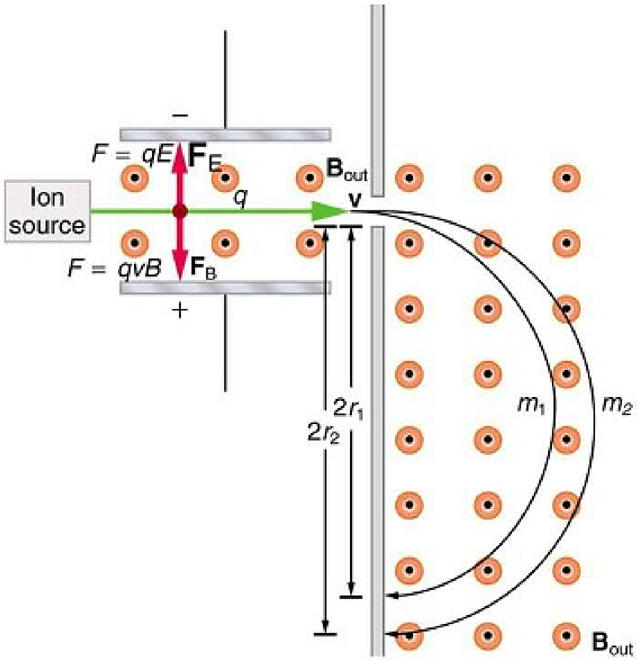
$$\frac{\#turns_{in}}{\#turns_{out}}=\frac{V_{in}}{V_{out}}$$
$$\frac{3}{9}=\frac{120\text{ V}}{V_{out}}$$
$$V_{out}=360\text{ V}$$

$$\frac{\#turns_{in}}{\#turns_{out}}=\frac{I_{out}}{I_{in}}$$
$$\frac{3}{9}=\frac{I_{out}}{6\text{ A}}$$
$$I_{out}=2\text{ A}$$

Mass Spectrometer

A mass spectrometer is a device that uses the path of a charged particle in a magnetic field to determine its mass.

The particle is first selected for the desired velocity, as described on page 292. Then the particle enters a region where the only force on it is from the applied magnetic field. (In the example below, the magnetic field is directed out of the page.)



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The magnetic field applies a force on the particle perpendicular to its path. As the particle's direction changes, the direction of the applied force changes with it, causing the particle to move in a circular path.

The path of the particle is the path for which the centripetal force (which you may recall from physics 1) is equal to the magnetic force:

$$F_B = F_c$$

$$qvB = \frac{mv^2}{r}$$

$$r = \frac{mv^{\cancel{2}}}{q\cancel{v}B} = \frac{mv}{qB}$$

Thus if the particles are all ions with the same charge and are selected for having the same speed, the radius of the path will be directly proportional to the mass of the particle.