

Electric Train Experiment

Purpose

To build an “electric train,” utilizing uninsulated copper wire, a battery, and powerful magnets. The result is a fascinating and cheap experiment that displays the basic principles of electromagnetism and engineering. This experiment is guided towards STEM education and outreach, particularly for under funded schools. The end product is a train made of a battery and magnets that propels itself through a coil of wire using electromagnetic force. Figure 1 depicts the final product.

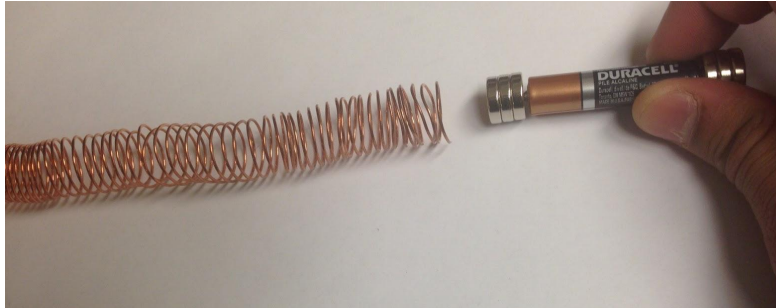


Figure 1: Finished Solenoid Track and Battery Train

Principles Of Operation

We will put two basic principles of electromagnetics and magnetism to work to create an electric train. The first is the magnetic field created by a solenoid. A solenoid is simply a coil of wire wrapped in a tightly packed helix shape as shown by the white lines in Figure 2.

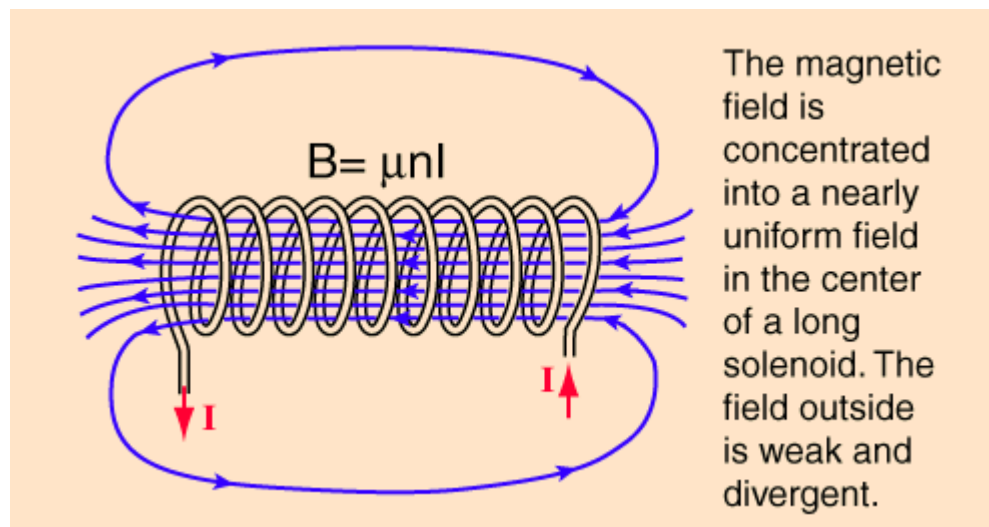


Figure 2: Solenoid and its Magnetic Field

(Source: <http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html>)

When the solenoid is connected to a voltage source, a current (I) is provided along the wire. The current, which is going through this circularly looped wire, results in a constant, (ideally) uniform magnetic field (B) through the center of the coil of wire. The resultant magnetic field

lines are shown by the blue lines in Figure 2. Thus, an electromagnet is created. The strength of the magnetic field ($B = \mu n I$) is proportional to both the number of turns of wire per unit length ($n = N/L$) and the strength of the current passing through.

Ampere's Right Hand Rule, shown in Figure 3, illustrates that a current carrying wire generates a magnetic field around the wire. Point the thumb of your right hand in the direction of current along a wire then curl your fingers inward. The direction of your curled fingers gives the direction of the magnetic field (red lines in Figure 3). The magnetic field radiates outward in a circle, with the magnetic field strength decreasing as you go farther from the current carrying wire. This information can be used to confirm the magnetic field lines for a solenoid depicted in Figure 2. Simply, follow along the curve of the solenoid with your thumb and confirm that the direction of the magnetic field will always be through the center of the solenoid.

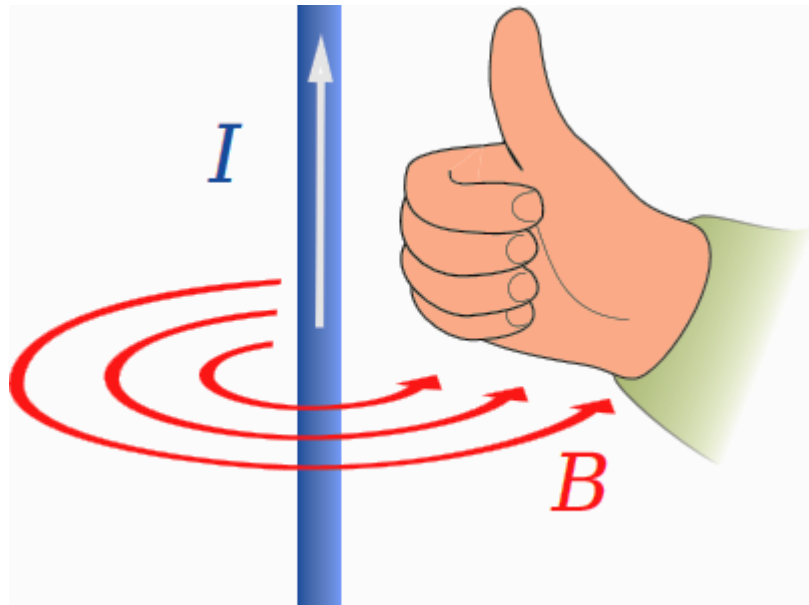


Figure 3: Ampere's Right Hand Rule
(Source: http://en.wikipedia.org/wiki/Right-hand_rule)

The second principle utilized is the premise of magnetic poles. A magnet always has a north and south pole. Figure 4 shows that if you break a magnet in half, the two halves will create new poles such that each magnet still has a North and South pole.

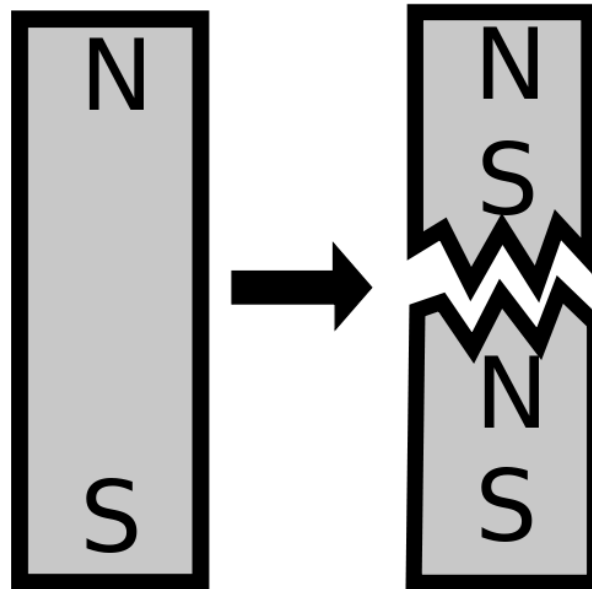


Figure 4: Magnetic Dipoles

The opposite North and South poles attract to each other and same poles (N-N and S-S) repel. A magnetic field can also interact with magnets and cause a force upon the magnet inside the magnetic field.

How do these two principals connect to create an electric train? The key is that the magnets are Neodymium. Neodymium magnets are man made magnets made up of a combination of iron, boron, and neodymium (these are all located on the periodic table of elements). These three materials are melted, combined, and then passed through a very strong electromagnetic field to magnetise them¹. This combination of conducting materials allows Neodymium magnets to conduct electricity. Most other magnets, such as ceramic magnets, are non-conducting. Ceramic magnets are also man made, made up of a combination of powders like iron oxide and strontium carbonate². Based on the materials that make them up, ceramic magnets do not conduct electricity. Thus, when the neodymium magnets are attached to either end of the battery and resting on the uninsulated copper wire, a local circuit is made along the length of the battery. The circuit is made from the positive terminal of the battery, into the magnets, through the copper wire of the solenoid and back into the magnets on the negative terminal of the battery. This local circuit provides the current to create the magnetic field within the solenoid. Next, the geometry of the battery is such that the magnets are on either end of the battery. This causes the magnetic poles of the magnets attached to the battery to simultaneously be pushed in and out of the local circuit (depending on which magnet you're looking at). This force causes the battery train to move. However, as the train moves it creates a new localized circuit that perpetuates the motion. Note: The magnets must be oriented such that the same pole is facing each other. This allows the forces to be in the same direction and to combine; otherwise, the forces will cancel out and the train will not move. If both magnets flip to have the other dipole facing out, the force will reverse direction as shown in figure 5.

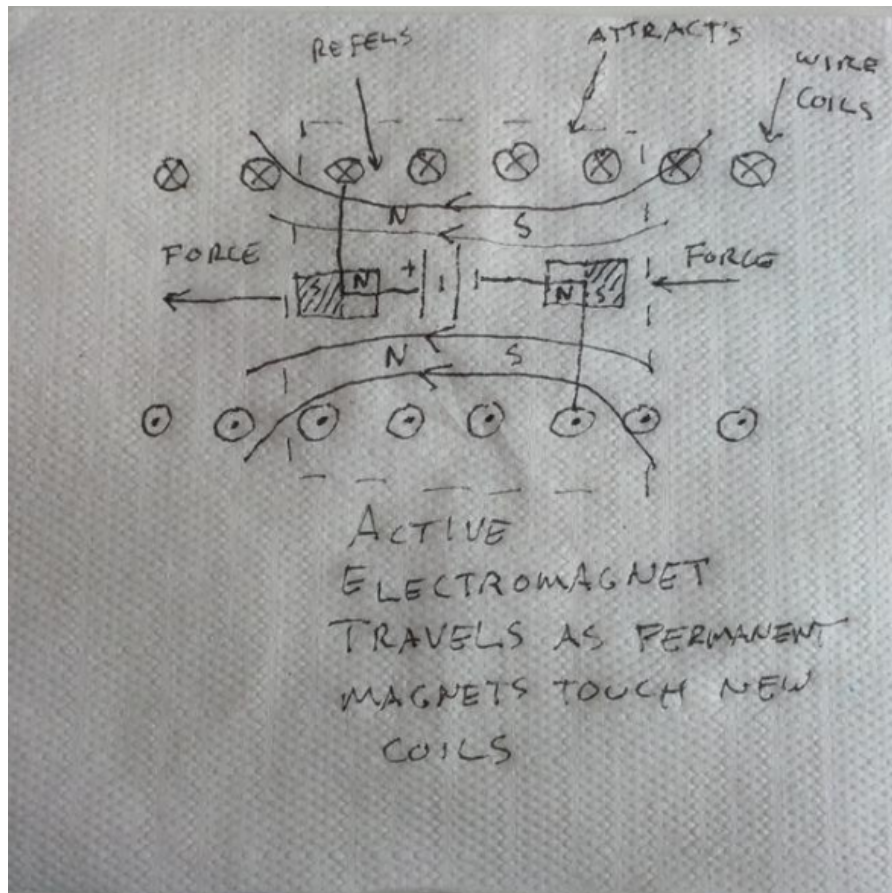


Figure 5: Depiction of Physics of Electric Train

(Source: Dan Zimmerman, <http://thekidshouldseethis.com/post/how-to-make-the-worlds-simplest-electric-toy-train>)

Parts List

Per group performing experiment:

- 4 or 6 Neodymium Magnets 1/2 x 1/8 inch Disc N48
- 6 yard spool of 20 gauge, uninsulated copper wire (5.5m, d=.032in = .812mm)
 - This must be
- 1 AAA battery
- 1 dowel rod (or other long cylinder) of 3/4 inch diameter

Non-essential items (For an improved experience)

- Scotch Tape
- Wire Cutters
- Small Pliers

Experimental Procedure

Before beginning, if you are interested in combining multiple solenoid “tracks” together, make sure to pay attention to Note 1 in the Advanced Procedure section when you start coiling the copper wire. You may wish to combine multiple “tracks” together to get the most out of the experiment, as this permits you to create a longer track, to experiment with how powerful the

train propulsion is, and how well the train will follow the track if you add in curves. Follow Note 2 in the Advanced Procedure section when you have completed the Experimental Procedure section and are ready to combine multiple solenoid “tracks.”

Creating the track is much easier if done with two people. To start creating a solenoid “track,” one person (person A) should take a strand of copper wire approximately 6 yards in length and another person (person B) should grab a single 6” dowel rod. While person B holds the rod, person A should uncoil 3-4 inches of copper wire from the 6 yard spool. Person A should then curl that amount of the wire over the top of the rod and then under and back towards himself. Then pull that tight and hold that part of the wire with your finger. Then curl the rest of the wire. Note: it is easiest to roll the dowel rod to curl the wire rather than trying to physically curl the wire around the rod. Be EXTREMELY careful to make a very tight, smooth loop around the rod with very little spaces in between the curls, and do not overlap the wire. If the solenoid doesn’t have smooth and well-rounded turns, the train won’t work as well.

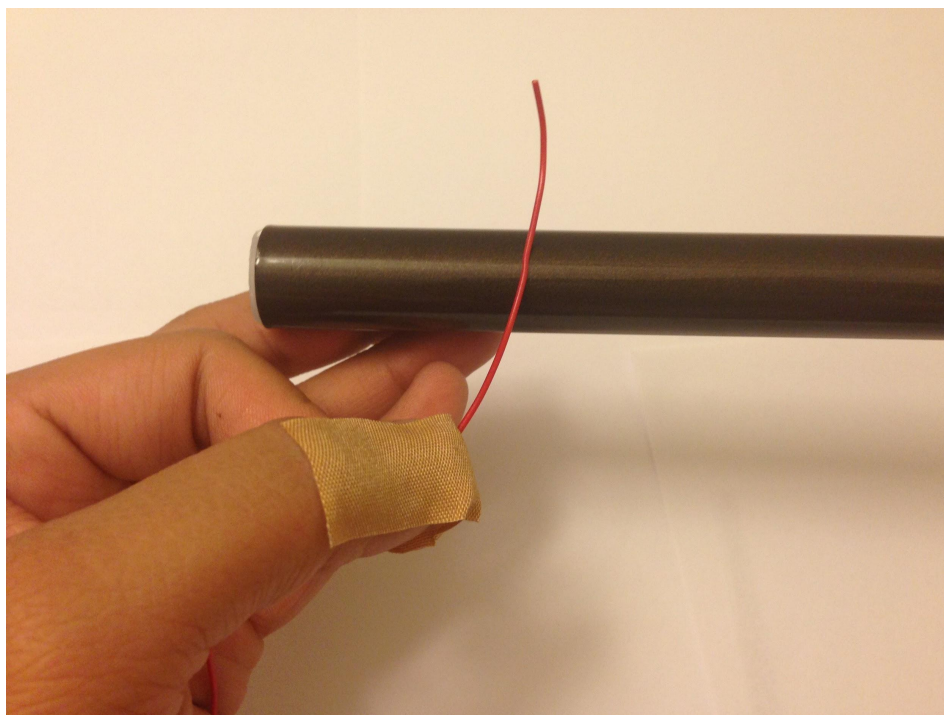


Figure 6a: Solenoid Curling (note photograph show insulated wire, but you should be using bare copper wire)

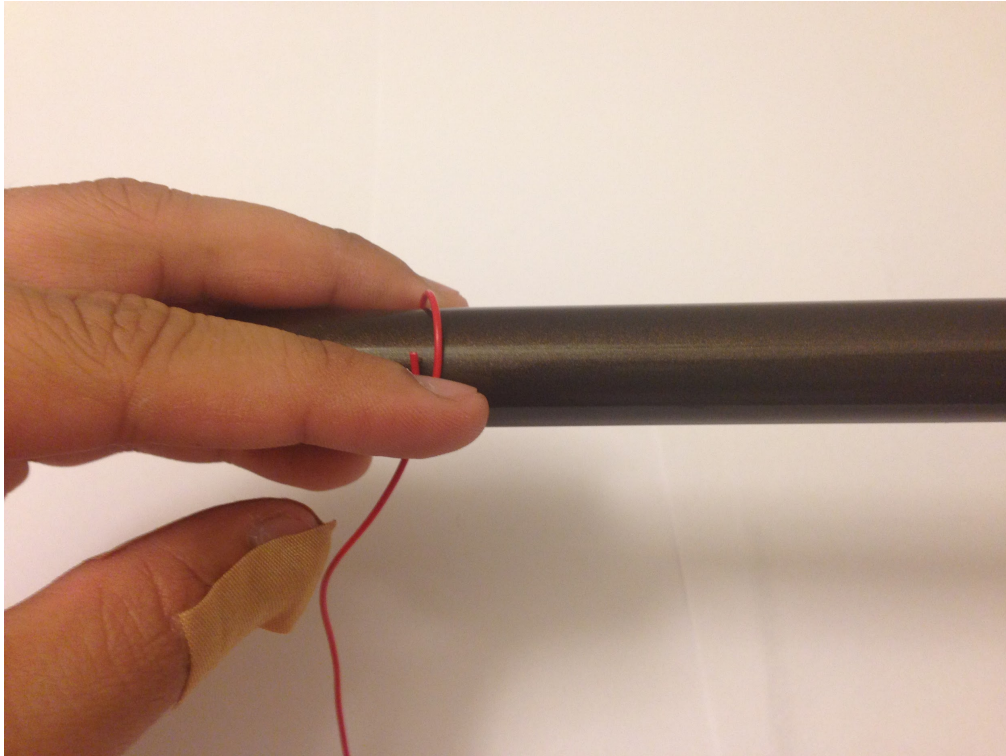


Figure 6b: Solenoid Curling

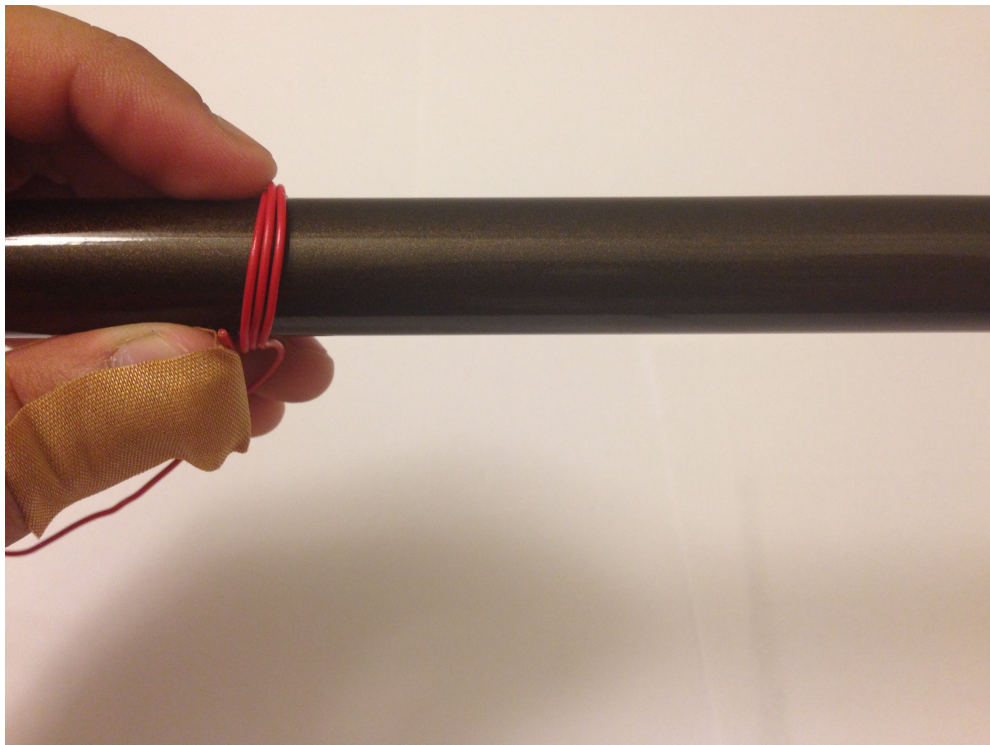


Figure 6c: Solenoid Curling

The wire cutters and small pliers are very handy here if you mess up and want to uncoil a section of wire or simply cut it off and try again for a smoother curve. Continue wrapping the

coil until you finish the spool of wire. This should create, roughly, a 6 inch long solenoid “track.” Carefully push the dowel rod out from within the coil by firmly holding the solenoid and pushing the dowel rod out with your finger. Be careful not to crush the solenoid. Once the solenoid is free of the dowel rod, put the solenoid aside.



Figure 7: Finished Solenoid

Next, take a stack of 2 or 3 magnets (half of what you have), and attach them together on one end of the battery (it does not matter which side you choose). Take the other stack of 2 or 3 magnets and carefully find the side that repels from the outward face of the magnet stack already attached to the battery. Attach the stack of magnets in your hand to the opposite side of the battery, with the repelling side facing out. This is in order to check the direction of the relative magnetic polarity between this stack and the stack already on the battery. For this to work, you must make sure that the same polarity is facing outwards (so either both N faces of the magnets face away from the battery or both S faces face out).

Put your newly created electric train inside the solenoid “track” and watch it go. If the battery repels out of the track instead of going through, simply turn the train around. If the train does not move at all, the orientation of the magnets may be incorrect. In this case, take off one stack of magnets, flip them around, reattach to the battery, and try again.

Advanced Procedure

The notes in this section guide you when trying to combine multiple solenoid “tracks” into one larger track.

Note 1: Be careful which way you are looping the coil around the dowel (over and under the dowel rod from left to right vs. under and over the dowel rod from left to right). This will only have an effect when separate solenoid “tracks” are combined. If two solenoid “tracks” are looped around in opposite directions they will generate magnetic fields in opposite directions. So, if the train goes one way through one of the “tracks,” as soon as it enters the other track it will be repelled the opposite way.

Note 2: To combine two solenoid tracks that are wrapped the same way, it is best to insert a dowel rod into the end of one track and the beginning of the other in order to overlap the ends of each "track." Then, tape the ends together to ensure the battery moves cleanly through both tracks. Be careful not to deform the circular area of the solenoid too much, or the train might not be able to pass through.

Sources:

<http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html>

<http://en.wikipedia.org/wiki/Solenoid>

http://en.wikipedia.org/wiki/Right-hand_rule

<http://thekidshouldseethis.com/post/how-to-make-the-worlds-simplest-electric-toy-train>

<https://www.kjmagnetics.com/neomaginfo.asp>

<http://www.rare-earth-magnets.com/types-of-permanent-magnets/>

Supplementary Reading:

<http://science.howstuffworks.com/magnet3.htm>

<http://science.howstuffworks.com/electromagnet1.htm>

<http://en.wikipedia.org/wiki/Electromagnet>