Science Lab

SEED

Engineering Challenge:

Make an Electromagnet

This SEED Engineering Challenge is to build the best electromagnet you can. Your electromagnet will be judged by how much weight it can lift so the "best" electromagnet is the one that lifts the heaviest object or objects.

As with any engineering problem, there are limitations and requirements you must meet.

Here are your guidelines:

1. You may use a maximum of 250cm of wire. There is no minimum.

2. The wire must be no less than 20 gauge. (The higher the gauge, the thinner the wire, so 20 gauge is the fattest wire you may use.

3. You may use anything for the core, or no core at all.

4. The electromagnet may be of any shape or size.

5. Your power source must be a single 1.5 volt battery, no larger than D size.

6. You may use any ferromagnetic material, such as iron, nickel or steel, as the weight you are lifting. You can try to lift a single object, or may small things such as paper clips or nails. It's the total weight that counts.

After you've built your electromagnet send us pictures and a description of what you did along with your results. We'll publish them here in the SEED Science Center.

Safety

1. Use only a single 1.5 volt battery, no larger than D size, as specified. Higher voltages can cause electric shock and a larger battery, even if it is only 1.5 volts, can cause dangerous overheating of some electromagnets.

2. Even with the precautions in 1, your electromagnet may get hot. If this happens, disconnect it immediately.

What Is an Electromagnet?

When electricity flows through a wire, a magnetic field is produced. Most electromagnets consist of wire that is coiled around a core made of iron or steel. Here's an example that we used in the Magnetic Relaxation Experiment.

The wire is wound around a straightened paper clip and is attached to one end of the battery. When the loose end of the wire is touched to the other end of the battery, electricity flows through the wire and the paper clip becomes magnetized.

This happens because the iron atoms in the paper clip are arranged in clusters known as domains. These are like little magnets, each with a north and a south pole. They are usually jumbled up and pointing every which way so their magnetic fields cancel each other out. When the domains are all lined up in the same direction the piece of metal is a magnet. When electricity flows through the wire that is coiled around the paper clip, the domains line up.

Another type of magnet is a permanent magnet, such as the ones you might stick on your refrigerator. A permanent magnet is made of iron or another ferromagnetic metal such as nickel or cobalt. The domains are lined up when the magnet is manufactured and stay that way.

How We Built and Tested Our Electromagnet

We held one end of the wire against the bolt, with a few centimeters hanging off to the side. The next step was to wind the wire onto the bolt in layers, going back and forth until the 250cm length was mostly used up, except for a few centimeters.

We twisted the two free ends together. Using a wire stripper, we removed about 2cm of insulation from each end of the wire. A knife will do in place of the wire stripper.

We could have used enamel-coated wire instead. The enamel is a kind of paint that insulates the wire in the same way as the plastic. The enamel can be removed from the ends of the wire with sandpaper.

To use the electromagnet we held the ends of the coil of wire against the battery and lifted some paper clips. This electromagnet lifted 21 paper clips. These were the same paperclips that we used for the Clay Boat challenge.

We weighed them then and determined that on average, each one weighed 0.52 grams. So, our electromagnet lifted 10.92g - not very impressive. No doubt you can do better.

Tips

There are many factors that affect the strength of an electromagnet. Here are some things to consider as you design and build yours:

- **The more turns of wire, the stronger the magnetic field.**
  You are limited to 250cm of wire. You should probably use all of it. The number of turns you can get out of a given length of wire is affected by how you wind it. Neatness counts.

- **The larger the diameter of the coil, the stronger the magnetic field.**
  But, since you are limited to a fixed length of wire, increasing the diameter of the coil will mean fewer turns.

- **The length of the coil affects the strength of the electromagnet.**
  If the length of the coil is equal to the radius, then increasing it further will reduce the strength of the electromagnet. The relationship between radius and length gets complicated. SEED Expert Ramon Hernandez gives this explanation of ***how radius and length of an electromagnet coil affect its strength****.

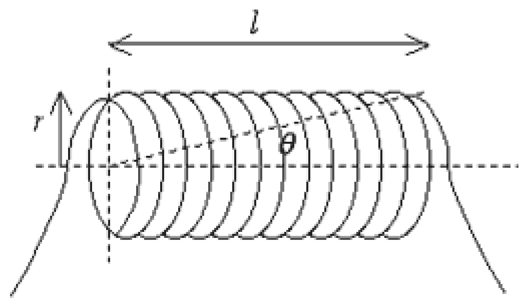
- **The more current the electromagnet draws, the stronger the magnetic field.**
  Since we have fixed the voltage at 1.5v, the resistance of the coil determines the amount of current it will draw. According to Ohm's Law: $I = V / R$
  where I is current, V is voltage and R is resistance. The thinner the wire, the higher its resistance.

- **The amount of current that the electromagnet draws may actually be less than what is determined by Ohm's Law.**
  The additional limitation is the power source, which has a maximum current that it can deliver. Not all 1.5v volt batteries are the same in this regard. A size D battery has a greater capacity than an AAA battery. Also, there are many different battery types of the same size. We used an alkaline battery. There are also inexpensive carbon and zinc batteries and a variety of rechargeable types including Nickel-Cadmium. Finally, a fresh battery has a higher capacity than one that has been used for a while.

*How radius and length of an electromagnet coil affect its strength

Coil size: radius
The magnetic induction at the center of one extreme of a long solenoid with jointing windings is:

$$B = \mu_0 \frac{NI}{l} \frac{\cos\theta}{2}$$



The force of the magnet will be proportional to the energy stored in the magnetic field:

$$W = \frac{1}{2} INB(\pi r^2) \approx \frac{1}{2} IN\mu_0 \frac{NI}{l}(\pi r^2) = \frac{1}{2}\mu_0 \frac{N^2 I^2}{l}(\pi r^2)$$

Note that the expressions on the right are only true for a solenoid with $l > r$.
From the equation above we see that the energy is proportional to the radius squared, indicating that the bigger the radius, the bigger the energy. But we have a given length of magnet wire and the larger the radius the smaller number of turns. Actually:

$$N \approx \frac{250cm}{2\pi r}$$

And replacing **N** in the energy equation:

$$W \approx \frac{1}{2}\mu_0 \frac{250cm I^2}{4\pi^2 r^2 l}(\pi r^2)$$

As we see, the radius squared in the numerator cancels out the radius squared in the denominator.

Conclusion: Given the limited length of magnet wire, the field energy, and hence the strength of the magnet, is fairly independent of the radius of the coil. A round shape is preferred because it gives the maximum cross section with the minimum perimeter.

Coil size: length

We see in the equation for the energy that the coil length is in the denominator and this can wrongly lead us to think that the shorter the coil the better. But remember the approximation that we made in the energy calculation about the coil being much longer than its diameter.

If we refer to the first part of the energy equation we see that it is proportional to the magnetic induction **B**. Therefore, we must size our coil to maximize **B**.

In the expression for **B** on the last page we see that the length **l** is in the denominator, but this length defines also the angle θ. For **l** very small and increasing, $\cos\theta$ will grow proportionally to **l**, canceling the effect of the coil length in the denominator. As θ goes above about 45 degrees, the cosine will increase more slowly, and **B** will decrease.

It is difficult to analytically evaluate these factors. Here is where magnetic design becomes and art. A finite element model will allow changing the length to radius ratio and observe where the maximum in energy is. As a rule of thumb I would suggest to try to pack the coil in a length about once to twice the radius and see what produces the higher strength. (At **l = r** the field intensity is still 70% of the maximum.) Packing the coil in more that one layer will increase the effective diameter of the coil, but will increase the turns per unit length.