

The Ring Fling Machine

Lenz's Law Demonstration Device



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Background

Faraday's law of induction states that a changing magnetic flux creates an induced electromotive force. In equation form, Faraday's law of induction is:

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

where the minus sign indicates that the direction of the induced electromotive force opposes the change of magnetic flux. This opposition becomes apparent in a closed, conductive circuit, where the induced electromotive force gives rise to an electric current whose magnetic field opposes the change of magnetic flux. This effect is stated as Lenz's Law: *An induced electromotive force always gives rise to a current whose magnetic field opposes the original change in magnetic flux.*¹ For example, if the magnetic flux within a certain region is increasing, an electric current will be established in such a way as to reduce the magnetic flux, assuming a closed, conductive path exists through which the induced current can flow.

Overview

Based on a description found on the Harvard University web site², this device consists of three main sections: the base, the coil and the core. The base needs to be constructed from a non-conductive material in order to prevent creating eddy currents within it. The coil was wound from approximately 76 meters (250 feet) of 18 gauge stranded hook-up wire around a core composed of 400 steel rods. The device runs on household alternating current (120 VAC, 60 Hz) and draws an average of 4.3 amps during steady state operation. **Never** operate this device with the core removed from the coil as the resulting current drawn by the device will be too high for standard household circuits.

Component List

- 18 gauge stranded hook-up wire (250 feet needed)
- PVC water pipe (28" long with an inside diameter of 1½" and outside diameter of 1.66")
- 30" long survey flags (400 needed)
- power switch (SPST, 15A)
- power cord (18 AWG, 3 conductor)
- fuse holder (1¼" × ¼" fuse, 20 amp capacity)
- 8 amp, 240 volt fast acting fuse (1¼" × ¼")
- 1 × 4 plank of white pine (roughly 4 feet needed)
- ¼" thick plywood (roughly 1 square foot needed)
- medium size wire nuts (2 needed)
- steel wool (grade #0 or #00)
- 3/16" diameter heat shrink (roughly 12 inches needed)
- 1" diameter heat shrink (3 32" long sections needed)
- copper ring (inside diameter of 1.70", outside diameter of 2.41" and .125" thick)
- aluminum ring (inside diameter of 1.70", outside diameter of 2.41" and .125" thick)
- split aluminum ring (inside diameter of 1.70", outside diameter of 2.41" and .125" thick)
- 1" long #6 wood screws (4 needed)
- 1½" long 4d finishing nails (roughly 12 needed)

- adhesive felt (roughly 6 inches needed)
- adhesive felt feet (4 needed)
- 5 minute epoxy (3 packets needed)
- wood glue
- duct tape



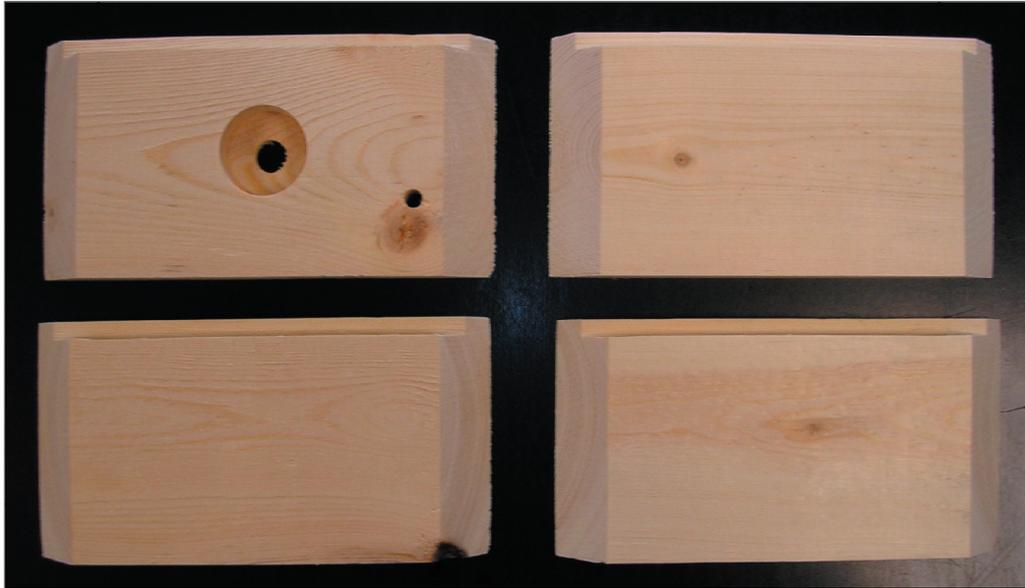
All of the components are gathered (the base has already been assembled).



Close-up of the rings on a one centimeter grid.

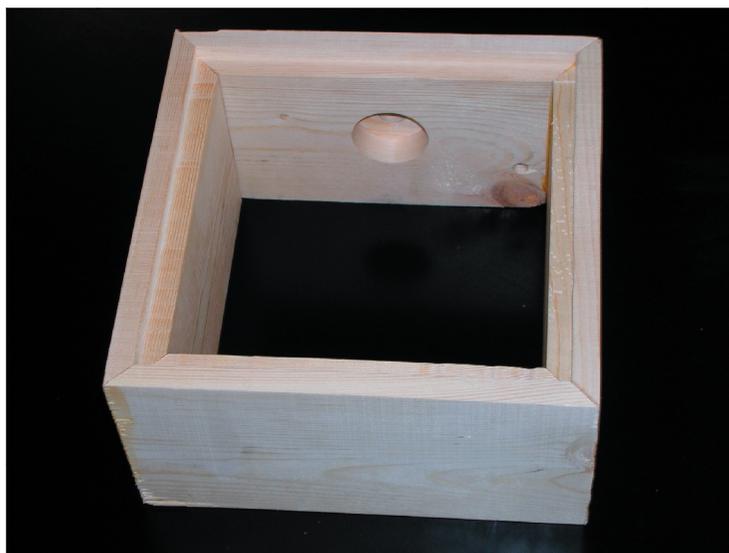
Base Construction

1. Cut four pieces from the 1 × 4 white pine board. Make each piece 6¾" long.
2. Miter cut both ends of each piece to a 45° angle.
3. Use a router to cut a ¼" × ¼" groove on the section of each piece that will eventually become the top, inside portion of the base.
4. Choose one of the four pieces as the one that will become the back of the base and drill two holes in it, one to accept the power cord and one to accept the power switch. Since our power switch was not designed to be used with a material as thick as the pine board, a Forstner bit was used to remove the excess wood.



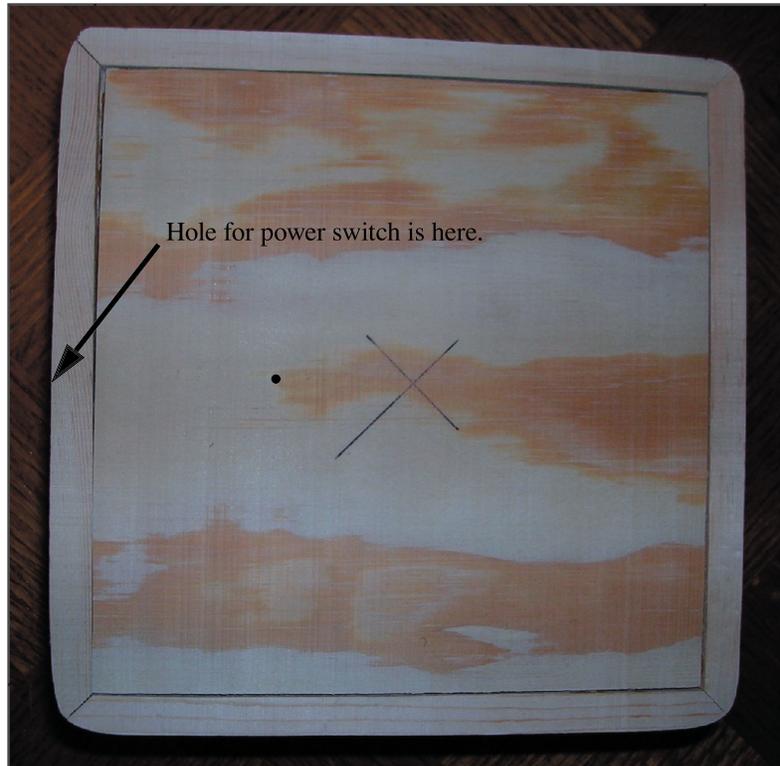
The four sections of white pine that will form the base.

5. Join the four sections together to form a box. Use wood glue and finishing nails to secure the joints.



The four sections are joined together.

- Cut two panels from the $\frac{1}{4}$ " plywood. One of the panels will form the top plate of the base while the other will form the bottom plate of the base. The exact dimensions depend on the size of your base. You can expect the top plate to be roughly $5\frac{3}{4}$ " \times $5\frac{3}{4}$ " and the bottom plate to be about $6\frac{3}{4}$ " \times $6\frac{3}{4}$ ".
- Use wood glue to attach the top plate to the base. Mark the center of the top base board and another point on the top base board $1\frac{1}{4}$ " away from the center towards the back of the base.



Two points are marked on the top base board.

- Cut three pieces from the 1×4 white pine board. Make each piece about 4" long. These pieces will be used to reinforce the top and bottom base boards as well as to secure the core to the base. Glue one of the pieces to the inside of the top base board and another to the inside of the bottom base board. Aim for the centers of both of the boards. The third piece will be used in a later step.



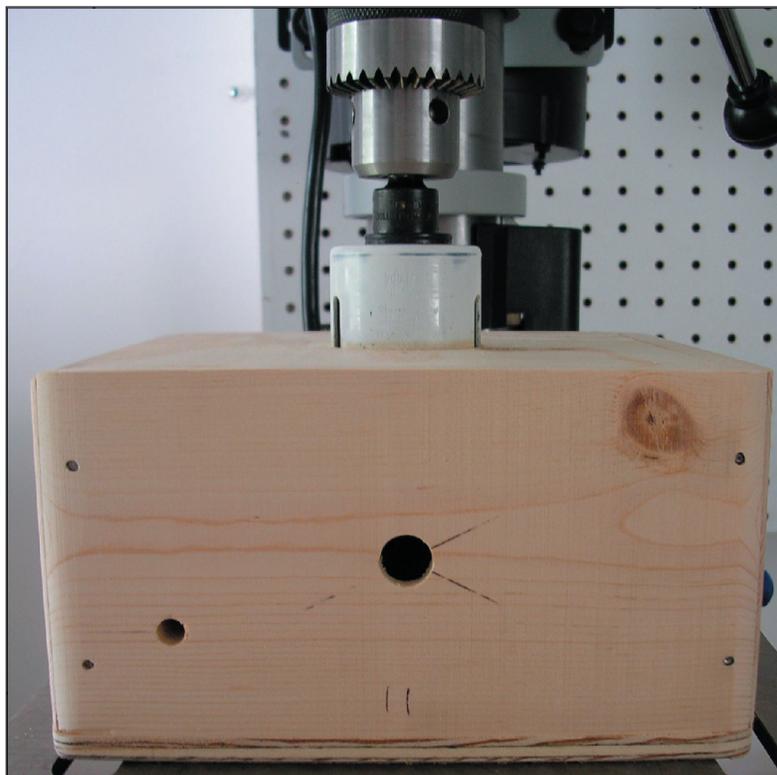
Reinforcement pieces are attached to the top and bottom base boards.

- Use a $1\frac{3}{4}$ " diameter hole saw to cut a hole through the center of the top base board as well as the reinforcement piece that is attached to it. This hole will eventually accept the core of the device.



A hole is cut through the top base board and its reinforcing piece.

- Attach and secure the bottom base board to the base using the four 1" long, #6 wood screws.
- Use the $1\frac{3}{4}$ " diameter hole saw to score the bottom base board's reinforcement piece by passing the hole saw through the hole in the top base board. You **are not** trying to drill a hole through the bottom base board or its reinforcement piece. You are just trying to mark its location for later use. A drill press makes this step much easier.



Scoring the bottom base board's reinforcement piece with a drill press by passing through the hole in the top base board.

12. Use the $1\frac{3}{4}$ " diameter hole saw to cut a hole through the center of the third piece of white pine that you made in step 8. (You didn't lose it, did you?)
13. Remove the bottom base board from the base. Glue the third piece of white pine to the reinforcing piece that is already attached to the bottom base board. Use the scoring mark you made in step 11 to align the pieces.



The bottom base board's reinforcement piece has been scored and the third piece of white pine has been cut through.



The third piece of white pine has been attached to and aligned with the bottom base board's reinforcement piece.

14. Drill a $\frac{1}{4}$ " diameter hole through the top base board and its reinforcing piece at the location you marked in step 7. The leads from the coil will eventually pass through this hole.
15. Sand and paint the base as desired.
16. Take five. You have finished building the base.

Coil Construction

1. Use the steel wool to smooth and polish the full length of PVC pipe.
2. Temporarily assemble the base and place the PVC pipe through the large hole in the top base board. Make certain the PVC pipe passes through the second alignment board and comes to rest on the bottom base board's reinforcement piece.
3. Make a mark on the PVC pipe about $\frac{1}{4}$ " above the top of the base. This is where the coil will start. Some space is needed between the coil and the base in order to accommodate the wires going to and from the coil.
4. Remove the PVC pipe from the base.
5. Use masking tape to secure the 18 gauge wire to the PVC pipe at the position you marked in step 3. You will need about a foot of wire in order to wire the coil to the rest of the circuit, so don't forget to give yourself some extra wire at the beginning of the coil. The extra wire can be tucked into the PVC pipe in order to keep it out of the way.
6. Wrap the wire around the PVC pipe for a total of 67 turns. The direction you wrap the wire is of no importance as long as you are consistent. If you start wrapping the coils in a clockwise fashion, **every** wrap on **every** layer must be done in a clockwise fashion. Alternating directions will only result in some of the wraps cancelling others. It is also important that the first layer be as neat and as tightly packed as possible. Any defects on the first layer will affect the layers above it.
7. Once you complete the first layer, secure both ends with masking tape. As there is no form to support the coil, the masking tape will help prevent this layer from shifting as other layers are placed on top of it.

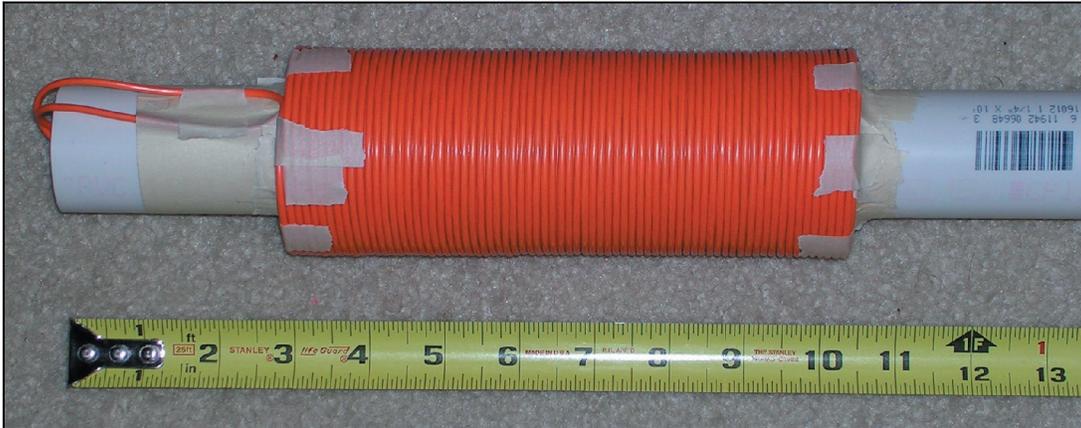


The first layer is complete and its ends are secured with masking tape.
Note the extra wire that is tucked into the left end of the PVC pipe.

8. Begin the second layer by wrapping the wire directly on top of the first layer. Again, it is helpful to secure the first couple of wraps with masking tape once they are in place. Try to make the face of the coil as flat as possible. While it is time consuming to achieve a flat face, it provides a much better surface for the copper and aluminum rings that will eventually be placed upon it. The ends of the coil should not have the same profile as the tip of a crayon. Although work will now progress towards the other end of the PVC pipe, the direction of the wraps (clockwise or counter-clockwise)

will remain the same.

9. Once the second layer is complete, secure the ends with masking tape and begin the third layer. Continue wrapping wire until you have completed 6 full layers. This should give you a coil containing about 400 wraps of wire and consuming about 230 feet of wire.
10. Once all six layers have been wrapped, cut the wire from the rest of the roll, leaving about a foot of wire at the end of the coil in order to allow for electrical connections. It is helpful if the two wire leads meet naturally in the same location on the pipe.



All six layers have been wrapped. Note that there are now two lengths of extra wire that have been tucked into the PVC pipe.

11. Very carefully remove the masking tape from the top face of the coil (the face without the two lead wires). A utility knife may be helpful. As this is mainly a cosmetic procedure, don't worry if you can't remove every single bit of tape, especially the pieces that are trapped between layers. Rather than completely removing the tape securing the outer layer, peel it away from the face of the coil like a banana peel. This will expose the face of the coil while still giving support to the body of the coil.
12. Open and mix a packet of 5 minute epoxy. Turn the coil upright and flood the top face with epoxy. Keep the coil upright until the epoxy cures.
13. Remove the masking tape from the bottom face of the coil just as you removed it from the top face. **Do not** remove the tape from the two lead wires. Keep them secured to the PVC pipe.
14. Open and mix a packed of 5 minute epoxy. Invert the coil and flood the bottom face with epoxy. Keep the coil inverted until the epoxy cures.
15. When you are certain that the coil is secure and won't self-destruct, remove any remaining masking tape and free the two lead wires. Make a single cord out of the two lead wires by braiding them together.
16. Relax. Go get some milk and cookies. That feeling of satisfaction you have means that you are done building the coil.

Core Construction

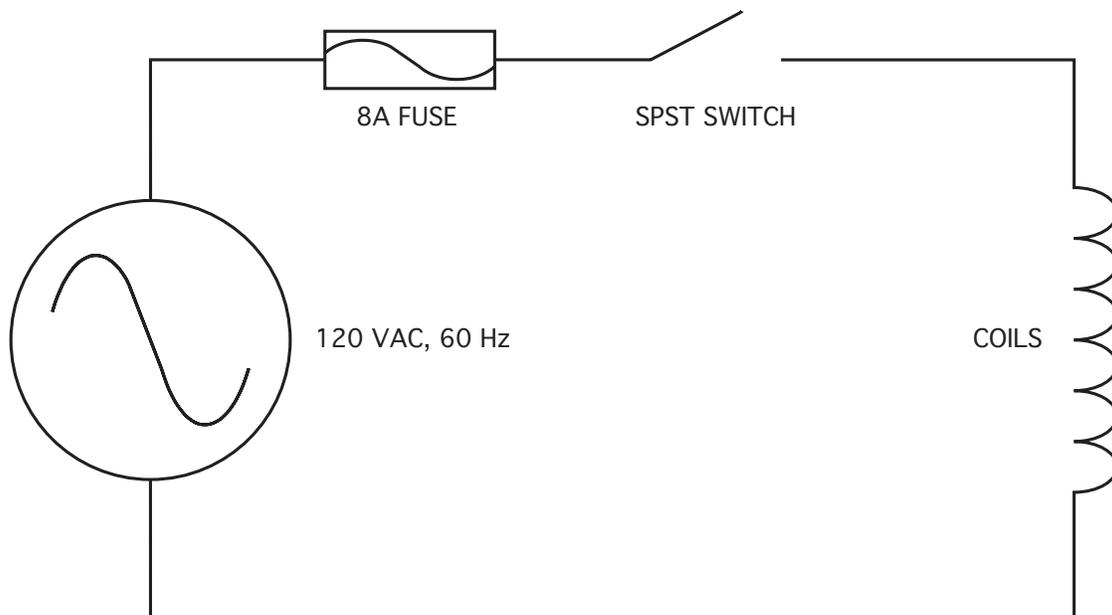
1. Use a utility knife to cut the plastic flag off of the end of one of the 400 surveying flags.
2. Repeat step 1 another 399 times.
3. As we are only interested in the steel rods, throw the plastic flags away³.

4. Separate the steel rods into four groups of 100.
5. Place one group of 100 steel rods into one of the 32" long pieces of 1" diameter heat shrink. Use a heat gun to shrink the heat shrink tubing and remove any overhanging heat shrink with a utility knife. Repeat this procedure for two more sets of 100 steel rods, leaving the fourth set of 100 loose.
6. Eat any leftover cookies and finish the milk because you are done preparing the core.

Assembly

1. Remove the bottom base board from the base.
2. The diameter of the large hole that was drilled through the top base board is too large to hold the PVC pipe firmly. Line the inside of this hole with the strip of adhesive felt to help improve the fit.
3. Feed the coil's lead wires through the small hole in the top base board and fit the PVC pipe through the large hole. Flip the base over so that you can access its interior.
4. Install the power switch.
5. Feed the power cord through its hole in the back of the base. You may wish to knot the power cord in order to prevent it from being accidentally pulled out of the base.

The circuit for this device is very simple as the coil is essentially connected directly to the household power supply. The circuit provides a switch to conveniently turn the device on and off and a fuse to guard against accidental overloading. Once again, **this device should never be used if the iron core has been removed from the coil.** The circuit starts at the hot side of the AC power line, passes through the fuse, then through the switch, then through the coil and ends at the neutral side of the AC power line:



If your power cord follows the standard color coding scheme, the **black** wire is the **hot** lead, the **white** wire is the **neutral** lead and the **green** wire is **ground**. If your cord is coded differently, you can use a multimeter to identify which leads are which. If you are looking directly at a standard three prong plug, the upper left blade is hot, the upper right blade is neutral and the lower blade is ground. Set your multimeter to measure resistance and, **with the cord unplugged from the wall**, attach one end of the multimeter to one of the blades and touch the other end of the multimeter to each of the cord's leads in turn. When you find the lead that makes the resistance drop to zero (or nearly zero), you have found the lead that corresponds to that blade. You can identify all of the leads in this fashion.

6. Cut a $\frac{3}{4}$ " length of $\frac{3}{16}$ " heat shrink and slip it onto the power cord's hot lead. Use a wire stripper to expose about $\frac{1}{2}$ " of the hot lead's copper wiring.
7. Use a wire stripper to expose about $\frac{1}{2}$ " of one of the fuse holder's lead's copper wiring.
8. Join and solder the hot lead to the fuse holder's lead. Make certain that the heat shrink is far enough away so that the heat from the soldering operation doesn't accidentally shrink it.
9. Once the joint has cooled, slip the heat shrink over the exposed wire and shrink it with a heat gun.
10. Follow the same general procedure to solder the other end of the fuse holder to one of the power switch's terminals.
11. Obtain a 6" length of 18 gauge hook-up wire and use a wire stripper to expose about $\frac{1}{2}$ " of copper wiring from each end. Solder and heat shrink one end of this wire to the power switch's other terminal.
12. Use a wire stripper to expose about $\frac{1}{2}$ " of copper wiring from both of the coil's leads. You may need to undo some of the braiding in order to get reasonable lengths of wire with which to work.
13. Take the free end of the wire that you attached to the power switch in step 11 and place it beside one of the coil's leads. Hold the wires so that their exposed ends are even with and parallel to each other. Place a wire nut over the exposed ends and twist it to join the wires.
14. In a similar fashion, use a wire nut to join the coil's other lead to the power cord's neutral lead.
15. The power cord's ground lead is not used in this device. To prevent it from accidentally shorting part of the circuit to ground, fold the ground lead back upon itself and cover it completely with heat shrink.
16. Place the 8 amp, fast acting fuse in the fuse holder.
17. Since the large hole on the bottom base board is too large to securely hold the PVC pipe, reduce the hole's diameter by taping small strips of duct tape around it in a starburst pattern. A strip of duct tape can also be wrapped around the end of the PVC pipe in order to increase its diameter.



The wiring is complete. The switch is located at the top of the photo. Duct tape has been wrapped around the PVC pipe in order to secure it to the hole in the bottom base board. This particular device has already had its iron core installed.

18. Install the bottom base board, making certain that the PVC pipe is fully seated. Secure the bottom base board to the rest of the base with the four #6 wood screws.
19. Attach the four adhesive felt feet to the bottom of the base and set the device upright.
20. Insert the three bundled sets of steel rods into the PVC pipe. Use the remaining 100 steel rods to fill in the gaps between the bundled sets. It may take some doing, but you should be able to fit all of the iron rods into the PVC pipe.
21. Once the core is in place, take a step back and marvel at your greatness, for you are done.

Operation

1. **MAKE CERTAIN THAT THE IRON CORE IS IN PLACE!**
2. With the power switch in the 'OFF' position, plug the device in.
3. Turn the power switch on. You may hear a faint buzzing.
4. Take the copper ring, place it over the PVC pipe and let it go. It should hover about half way up the pipe.
5. Turn the power off and the copper ring will come to rest on the coil. Turn the power back on and the copper ring will leap off the device. Beware of low ceilings.

Things to Note

1. Due to the resistance within the rings, the induced current flowing through them will cause them to heat up. A ring held near the coil quickly becomes too hot to hold. A ring clamped near the coil will become hot enough to boil water or melt the PVC pipe.
2. The core was segmented and wrapped in heat shrink in an attempt to reduce the induced currents formed within the core itself. Ideally, every iron rod would be insulated from every other iron rod.
3. Wire nuts were used to connect the coil to the rest of the circuit in order to make it easily removable. You can easily experiment with different coils using the same base.
4. A metal hose clamp was not used to secure the PVC pipe to the base because the currents induced within the hose clamp would quickly melt the PVC pipe.
5. While the same size as the copper ring, the aluminum ring is less dense and, therefore, less massive. Its internal resistance, however, is higher than the copper ring's. Will it jump higher or lower than the copper ring?
6. Why doesn't the split aluminum ring jump at all? Why doesn't it get hot when it is held near the coil?

Typical Performance Data

	Copper Ring	Aluminum Ring	Copper Annulus ⁴
Hover Height (room temperature)	25 cm	33 cm	26 cm
Jump Height (room temperature)	120 cm	150 cm	90 cm
Jump Height (LN ₂ cooled)	240 cm	310 cm	370 cm

All heights are measured with respect to the top of the coil.

Footnotes

¹ Douglas C. Giancoli, Physics for Scientists and Engineers, Second Edition, p676

² <http://www.fas.harvard.edu/~scdiroff/Ids/ElectricityMagnetism/RingFlinger/RingFlinger.html>

³ If anyone knows of a use for these flags, or knows of a way to get the survey flag poles without the flags, please contact me through Jefferson Lab's Science Education web site.

⁴ This ring has an ID of 1.980 inches, an OD of 2.440 inches and thickness of .08 inches.