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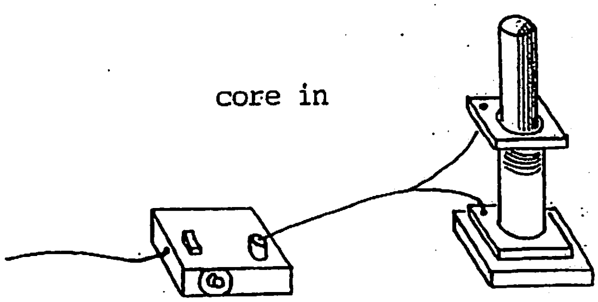
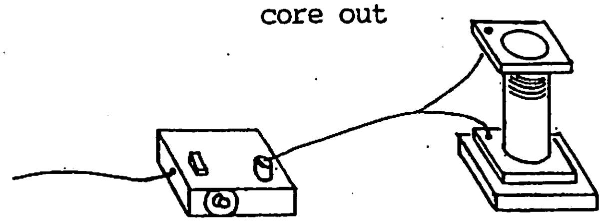
Self-inductance and mutual inductance - These important aspects of electromagnetic induction can be simply, but clearly, demonstrated with the use of the air core solenoid* described in "Electromagnetic Induction" and "The Ring Flinger"; these descriptions should be read first. They have most of the apparatus that you will need to perform these demonstrations.

Warning! This is a 120 V system. Observe all safety precautions. Keep unplugged until all adjustments are made; unplug when not in use. Tape over exposed terminals. This apparatus was designed for experienced teachers. You must add safety features for students' use, and you must supervise them.

(a) Self-inductance is a way to control current in a coil and/or circuit. It occurs in an operating coil of wire (a solenoid) when a current is changing (AC), thus, creating a moving magnetic field in each separate coil adjacent to another. One coil induces an opposite current in the other (Lenz's Law), a back EMF, that acts as a "resistance", really inductance or overall impedence. This "resistance" can be substantially increased by adding an iron core to the solenoid's core, greatly increasing the magnetic field strength involved and the induction in each coil of wire. With the iron core in the solenoid, the combination is commonly called a "choke coil".

Diagrams:





Begin the demonstration with the iron core all the way in the solenoid as in the left diagram. Using the switch box, turn on the circuit. With the "choke" (iron core) in, the self-inductance (impedence) is high enough to keep the current down (choked) to a level that the circuit can handle. Don't let this circuit operate for more than 30 sec.; 20 sec. might be enough because of coil heating. Turn off the circuit, and let the coil cool down, if warm, for a minute or two.

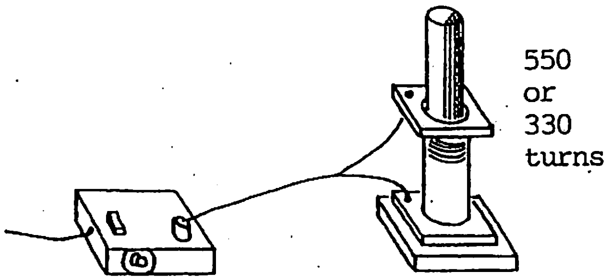
Now turn on the circuit with the "choke" (iron core) removed. With much less self-inductance (impedence) at work, the current in the circuit is much higher, so high that the circuit breaker is overloaded and pops. The current stops. Thus, the solenoid is protected from overheating and possibly "frying" the insulation, usually laquer on wire, that would ruin the coil. Because the breaker must heat up before it pops, it takes time to cool down before it can be reset (pushed back in). That's why you perform this part of the demo last, not first.

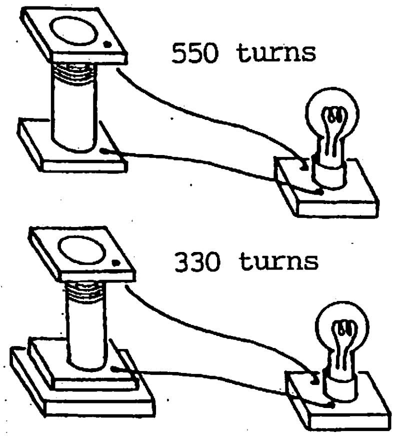
(b) Mutual inductance is an electromagnetic way of transferring energy without the wires from two separate coils ever touching each other. It occurs when an operating coil (solenoid) using AC induces an alternating current in another coil nearby. The inductance in the second coil is greatly enhanced if the two coils are "coupled" via one iron core shared by both. The iron core greatly increases the flexing magnetic field's strength, and the coupling brings the two solenoids into close proximity where the inducing field strength is greatest. The result is a much higher rate of efficiency in the transfer of electrical energy.

In reality, what we have here is a transformer, second only in importance to the generator in the mass distribution of electricity. It's a simple device with no moving parts that allows electrical energy to travel hundreds of miles to its users. It's also a kind of enclosed electromagnet system that controls voltages and currents in all kinds of electrical devices. Joseph Henry and Nikola Tesla are the "fathers" of the transformer.

* air core solenoid #14825 - Science First (207) 701 - 8111 www.sciencefirst.com

Diagrams:





$$\frac{EMF_s}{EMF_p} = \frac{N_s}{N_p}$$

step down
or
step up

Presentation: (a) Set up the apparatus as in the diagram, the "primary" coil on the left with the iron core inserted and the "secondary" coil on the right with a 60 Watt incand. bulb or a 13 Watt CFL attached to make a circuit. Turn on the primary coil and bring the secondary coil close to it. Nothing happens. Now slip the secondary coil down over the iron core and watch the light intensity increase as the mutual inductance increases. Operate the primary coil briefly to protect the coil from overheating. Also, make sure the diameters of the two cores are exactly the same so the secondary coil will easily slip over the iron core. PVC pipe I.D.'s vary slightly and can fool you. Remind the students that no wires are connected between the two coils. You have a simple, but inefficient, transformer.

(b) Now the fun part, how inefficient? Simply measure the voltage over the primary coil and then over the secondary.

an example: $\frac{\text{secondary V}}{\text{primary V}} = \frac{53.4\ V}{121.0\ V} = 44.1\ \%$ "efficiency"

These solenoids have 550 turns (separate coils) or 5 layers of 110 turns each. If you can, purchase a third solenoid and carefully unwind two layers (220 turns) of wire from it, leaving a solenoid of 330 turns or 60 % of the original. Now you can demonstrate a step-down (in V) and a step-up transformer.

For the step-down transformer, replace the 550-turn secondary coil with the 330-turn coil. Measure the secondary V again, now down to 31.4 V. Doing the math,

53.4 V x 60 % = 32.0 V expected or only a difference of 0.6 V or $\frac{0.6\ V}{32.0\ V} = 1.9\ \%$ from the expected. Neat!

For the step-up transformer, mount the 330-turn coil, making it the primary coil and add the 550-turn coil as the secondary.

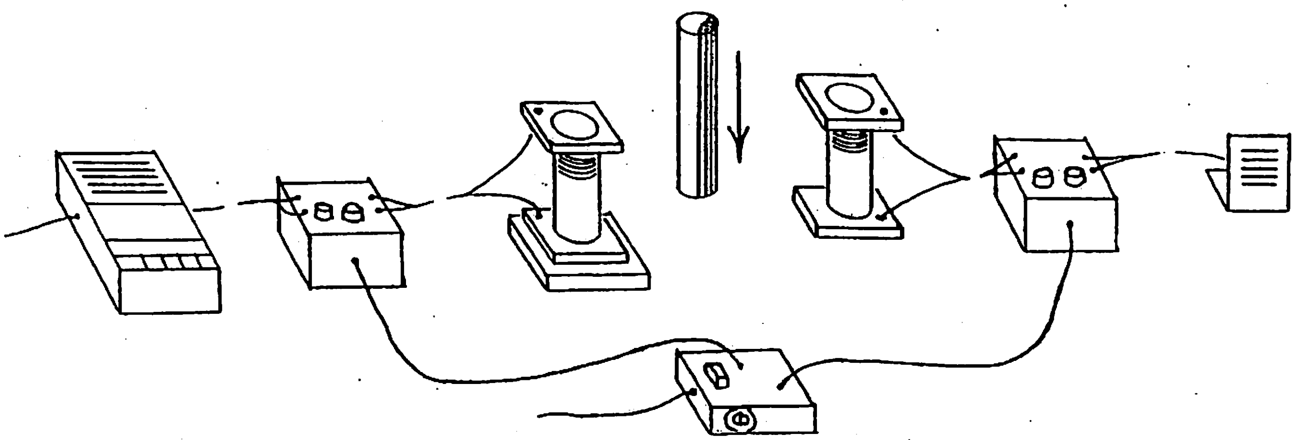
an example: primary V = 118.3 V secondary V = 88.2 V

118.3 V x 1.67 "turns" = 197.6 V x 44.1 % "efficiency" = 87.1 V expected

a difference of 1.1 V or $\frac{1.1\ V}{87.1\ V} = 1.3\ \%$ from the expected. Neat!

In conclusion, you can do a lot with three solenoids, qualitatively and quantitatively. Even if the voltmeter, the use of significant figures, etc. is off by a % or two, the results are excellent.

(c) Still employing the concept of mutual inductance but "expanding" the primary solenoid's flexing magnetic field farther out into space, set up the apparatus according to the diagram below.



Begin simply with a tape player and a patch cord from its earphone jack to the primary coil (the "broadcast antenna"). Leave out the amplifiers for the moment. From the secondary coil (the "receiving antenna"), patch a cord directly to the speaker. You are about to demonstrate "near-field" radio wave transmission in its simplest form. With the coils close together, side by side, play the tape and listen to the speaker; the sound should be very faint.

Add the iron core to the primary; the sound is still faint but slightly louder. Now add the amplifier to the primary coil; the sound grows louder. Add the second amplifier to the secondary coil; the sound grows even louder.

Now with enough volume, move the secondary coil away from the primary to notice the volume decrease with increased separation. Bring the secondary coil back up close, but rotate its orientation 90° from the original parallel position. What happens to the volume (reception)? Polarization is an important aspect of radio wave transmission.

Remind the students that the tape player's message has "jumped" through space to the speaker via the mutual inductance caused by the magnetic fields involved with the solenoids. The final step, of course, is to slip the secondary coil over the iron core. Be prepared to immediately turn down the amplifiers!

A great deal of good physics can be learned from this series of demonstrations with these very useful solenoids. And the demos are entertaining to boot!