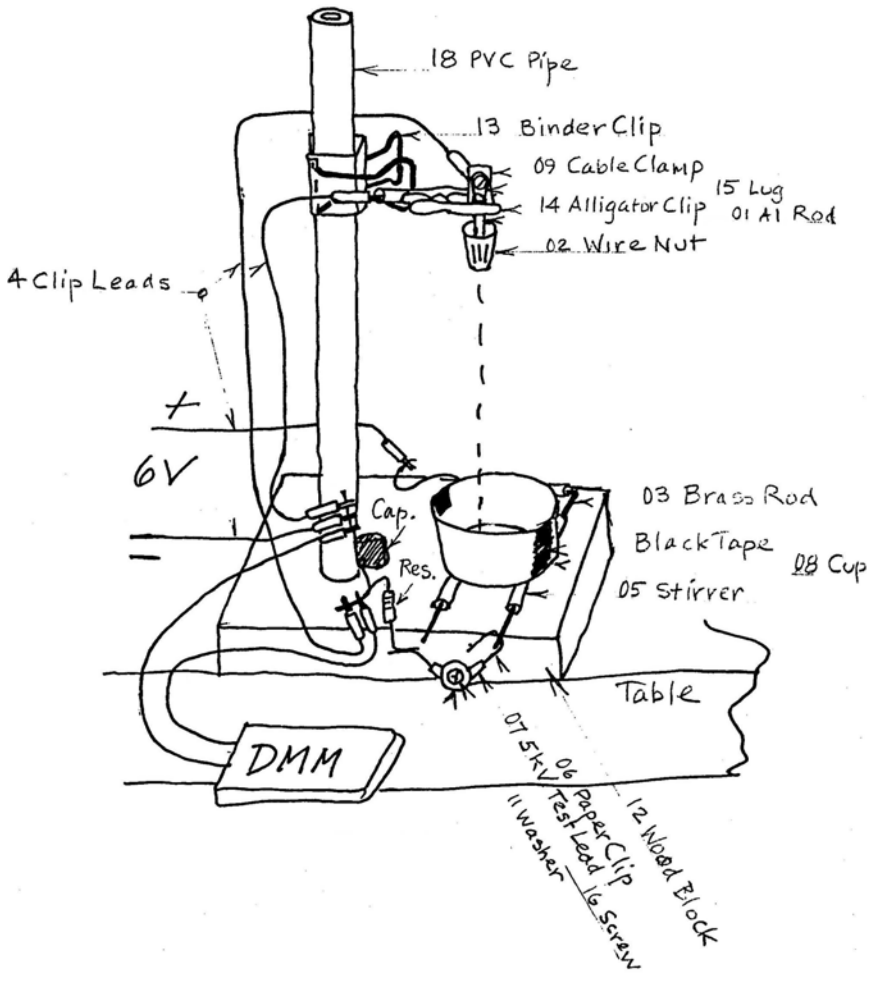
Mechanics Experiments from Kits



Peter Dourmashkin
John G. King

Mechanics Experiments from Kits

Peter Dourmashkin
Senior Lecturer in Physics
Massachusetts Institute of Technology

John King
Francis Freidman
Professor of Physics
Massachusetts Institute of Technology

This manuscript was supplied camera-ready by the authors:

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

KT Associates
19 Cottage Street, Cambridge, MA 02139

Table of Contents

About Experiments

1) Partners

Each of you should have one partner. During the first week, each partnership will receive a Red Box containing returnable parts used in the experiments, and parts kits for each experiment.

2) Tool Kits

Each student will buy a special Tool Kit designed for these experiments.

3) Red Boxes

Each pair of partners should have one Red Box to be returned at the end of the semester. Each experiment has its own plastic bag of parts in the Red Box. In addition, each experiment will make use of a selection of parts from the Red Box. Your instructions for the individual experiments will identify those items. Do not throw things away. Items that are used in one experiment may be re-used in a later experiment. We shall ask you to return the Red Box at the end of the semester, with all the major items present (of course this does not include obvious disposable items such as bits of wire).

4) Experiment Write-ups

Each experiment has a write-up that describes the experiment, apparatus, and measurements you will make. Carefully read these write-ups.

5) Safety

You will be working sometimes with sharp-edged tools and materials, soldering irons, and apparatus, which connects to the 120 Volt, 60 Hertz (60 cycles per second) line supply through a wall transformer. Use them carefully to avoid accidents. Always think about what you're doing and what would happen if the hand or the tool or the work slips, or if the soldering iron falls on flammable stuff, or if electrical things get wet. The items you will be using are fairly harmless, but be sure to tell us about any worries you or your friends have about safety.

Experiment ES Estimating a Second

Introduction: About Estimating

Before measuring and calculating comes estimation; a chance to exercise ingenuity. Often it's a matter of organizing your rough knowledge and experience in quantitative form, or making a simplified model so as to answer questions about numbers, such as: how many hairs are on your head? how much energy does an AA cell store? how many gallons of gasoline are burnt annually in the US? how many piano tuners are there in Chicago? etc. You might say: who wants such a rough answer, perhaps only good to an order of magnitude? Well if you aren't near a reliable reference source or able to measure, it's far better to have some estimate than nothing. A good estimate enables you to consider whether a new idea for an experiment or even a business is possible.

The question about piano tuners was an example from the physicist Enrico Fermi, and we often call these estimations "Fermi problems".

Consider the estimating of amounts, sizes and duration. These correspond to the physical quantities mass, length and time, the fundamental quantities of classical mechanics. One can develop a feel for some of these by using standards based on common objects (for instance a penny, dated 1982 and later has a mass about 2.5 g; earlier pennies have a mass about 3 g. A penny's diameter is about 2 cm. One's pulse, with a period of about 1 second, is a rather variable time standard that you always have around. But there is another way of estimating time which we'll explore here.

Estimating Time

Some people have a good idea of what time of day it is without looking at a watch, or can feel when an hour has passed; but how do they do it? It often turns out that the estimator has practiced this skill for many years. However, when its just a matter of estimating a few seconds, most people mark time by counting a word that takes one second to pronounce like: one one thousand , two one thousand, three one thousand , etc., or: one Mississippi, two Mississippi, three Mississippi, etc., To see how well this works we have developed a simple electrical timer which you and your partner can assemble and use to test how accurately you count seconds.

Parts

DPDT knife switch: This "double-pole double-throw" (DPDT) knife switch was chosen because it's obvious how it works and it's easy to connect to. Knife switches, so-called because the motion of the swinging arm is like that of a knife blade, are rarely used now but acronyms like

SPST, SPDT, DPST, DPDT (S for "single") still apply. The words "throw" and "pole" are old usages: "throw the switch", meaning to turn on of off, close or open the circuit, whose conducting wires are connected to the switch terminals, or "poles". See Fig.1 for the schematic of these switches.

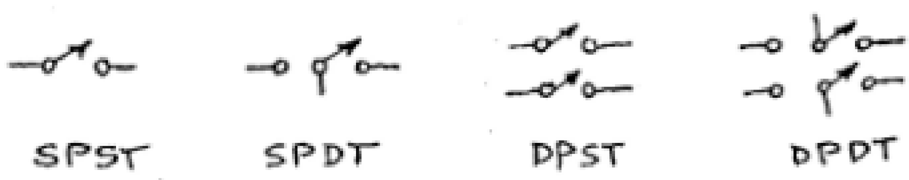


Figure 1: Various switches; SPST, SPDT, DPST, DPDT

Notice that in attaching leads to the screw terminals of the switch you should bend the lead clockwise around the screw so that it is drawn in as you tighten the conventional right-hand screw.

Two 10 megohm resistors, one 20 ohm resistor: Resistors are color coded by colored bands read from left to right when you hold them so that the gold band is on the right. Two of the three resistors in your kit have at the left a brown band meaning 1, for the first digit; a black band meaning 0, for the second digit; a blue band meaning 6 zeros-hence

$$1\text{-}0\text{-}000000 \text{ ohms } (\Omega) = 107\ \Omega = 10 \text{ megohm } (M\Omega).$$

The gold band on the right means that the resistor is within ±5% of the rated value. The third resistor is a $20\ \Omega$ resistor having at the left a red band meaning 2, for the first digit; a black band meaning 0, for the second digit; a black band meaning 0 zeros-hence 2-0- = $20\ \Omega$.

1.0 μF capacitor: The capacitor has a brown molded plastic case and the relevant part of the label is 105K. This is a code that has the following meaning. The “5” means place five zeros after the 10 and read the capacitance in picofarads (pF). A picofarad is 10^{-12} F. Thus

$$105 = 1-0-00000 \text{ picofarads} = 10^{6} \text{ pF} = 10^{-6} \text{ F} = 1\mu\text{F} = 1 \text{ microfarad}$$

The "K" means ±10%. Some capacitors have leads labelled plus or minus, but this one doesn’t.

AA cell and AA cell holder: The kit contains an AA cell and a holder with a red lead (plus,+) and a black lead (minus,-). These leads are insulated but you will need to remove more of the insulation so that about 1/2 inch , 12 mm, of bare wire are exposed at the end of each wire. Do this with the wire strippers in your toolkit, set so that they just grab a paper clip; too large and they won't cut the insulation or too small and they will cut the wire.

Three Wire Connectors: These hollow plastic cones containing conical springs are often called "wiring nuts" and are widely used in 120/240 volt wiring in buildings. They come in various sizes and what you have is about the smallest. Even so the leads are so small, (#22 and #25 AWG: American Wire Gauge) that you'll have to twist them together, bend them over and squeeze them with pliers before screwing on the wiring nut (see Fig, 2). In any case the leads should seem quite firmly connected when pulled or wiggled.

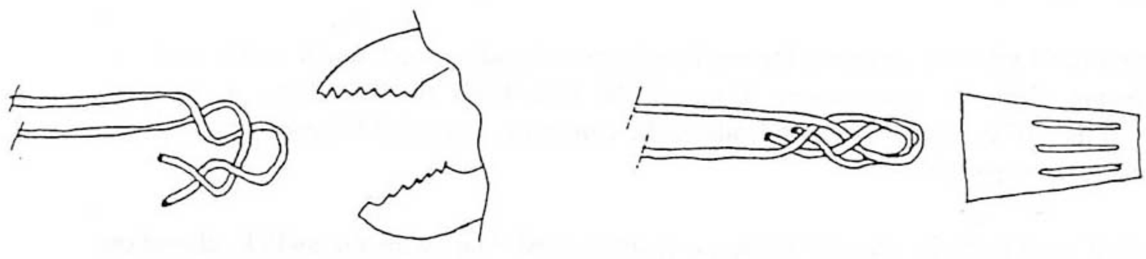
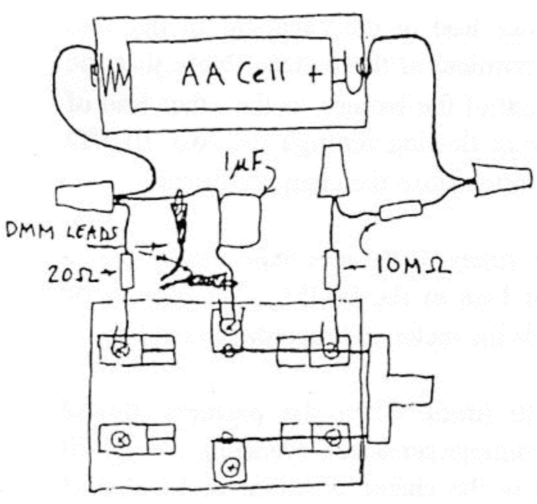


Figure 2: Wiring Nuts

Connections are made by attaching leads to screw terminals on the switch and using the wiring nuts to connect other leads. Alternatively you can use your soldering iron after tinning it. Assemble the circuit according to the sketch of the circuit, Fig. 3, and the circuit diagram, Fig. 4. For this experiment, a single-pole double-throw (SPDT) would do so , but the DPDT provides more mechanical stability when switching.



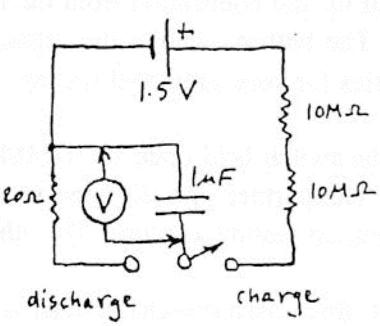


Figure 3: Sketch of circuit

Figure 4: Circuit diagram

Experiment

In this experiment you will estimate a second by closing a switch for about a second in a circuit that is charging a capacitor. A charged capacitor has a voltage difference between its two leads. Once you open the switch the charging stops and the voltage difference across the capacitor has a fixed value. The voltage difference is related to the charging time and for our device is nearly linearly proportional. After each trial the capacitor must be discharged until there is zero voltage difference across the leads so that a new trial can begin.

Operate the switch by grasping the small cylindrical handle; don't touch metal parts to avoid introducing electrical disturbances. Connect the two leads of the digital multimeter (DMM), set on the DCV range to the two leads of the capacitor. The DMM displays the voltage difference across the capacitor.

You first need to make sure the capacitor is discharged. Start with the switch, closed on the side that connects the $1\,\mu\text{F}$ capacitor to the $20\,\Omega$ resistor. This is the discharge side. Notice that the battery is not connected when the switch is in this position. The $1\,\mu\text{F}$ capacitor is discharged in a short time by current flowing through the $20\,\Omega$ resistor until the digital multimeter (DMM), reads zero. Once the capacitor is discharged you can put the switch in the open position.

We can now begin the charging. You will charge up the capacitor put throwing the switch to the other position for you consider to be one second and then opening the switch and reading the voltage difference across the capacitor.

When the switch is closed, you have connecting one lead of the capacitor to the two $10\text{ M}\Omega$ resistors, which are in turn connected to the positive terminal of the battery. Note that the circuit is closed by the connection from the negative terminal of the battery to the other lead of the capacitor. The battery charges the capacitor by a current flowing through the two $10\text{ M}\Omega$ resistors in series for your estimated second. Opening the switch stops the charging process.

With the switch held open the DMM displays the voltage difference across the leads of the capacitor. The partner operating the switch should not look at the DMM so as not to be influenced when estimating a second. The other partner reads the meter and records the reading.

Repeat this discharge-charge-read-voltage cycle 36 times. Then the partners should exchange tasks. These 72 readings (keep each partner's 36 readings separate), averaging around 70 millivolts ($1\text{ mV} = 10^{-3}\text{ V}$) are measures of the time the switch was closed in the charge position, and hence of your estimates of a second.

Data

Use your calculator or your favorite software program to compute the mean and standard deviation of the DMM readings corresponding to your estimate of one second.

Make a histogram of your data as follows. On a sheet of graph paper, draw a line along the long side about 1 inch from the bottom. Label every fifth space, starting at the left so as to accommodate the range of DMM readings you have made, say, from 40 to 100. Make an X in each space corresponding to each of your 36 values of DMM reading rounded off to the nearest integer. Count the number of Xs in each interval of 5 (eg. 45 through 49) and represent that number by a horizontal line above that interval. Connect the ends of these lines with vertical lines. You now have a bar graph (histogram) of your data.

Determining the Time Constant RC

To interpret the DMM readings in millivolts in terms of time it's necessary to determine the time constant, τ, of the resistance-capacitance combination.

Consider the charging circuit in Experiment ES that is shown in figure 4. The DMM is measuring the voltage across the capacitor, V_{cap}. The rate of change of the voltage, dV_{cap}/dt, across the capacitor is proportional to two terms. The first is the voltage of the cell, V_{cell}. This is a constant factor. The second is the negative of the voltage, V_{cap}, that is already present across the capacitor.

$$\frac{dV_{cap}}{dt} = \frac{1}{\tau}(V_{\text{cell}} - V_{cap}) .$$

The constant of proportionality $1/\tau$ has the dimensions of inverse time. Hence τ is called the time constant. The rate of change of the voltage is inversely proportional to the resistance, R measured in ohms, in the circuit. The greater a resistance to the flow of current and hence charge, the slower the rate of change of the voltage across the capacitor. The rate of change is also inversely proportional to the amount of charge the capacitor is capable of storing. This property of the capacitor is called the capacitance and is denoted by C, measured in farads. So the rate of change of voltage across the capacitor is

$$\frac{dV_{cap}}{dt} = \frac{1}{RC}(V_{\text{cell}} - V_{cap}) .$$

Thus we can conclude that the time constant $\tau = RC$. For the charging circuit, $R = 20\ \text{M}\Omega$ and $C = 10^{-6}\ \text{F}$ so if the parts were ideal we would have for the charging process

$$\tau = RC = (20\ \text{M}\Omega)(10^{-6}\ \text{F}) = 20\ \text{s} .$$

To convert DMM readings to time, measure the AA cell voltage, V_{cell} and a particular DMM reading is $V_{cap}(t)$ corresponding to a time t. The voltage across the capacitor for a charging circuit is given by the relation

.

$$V_{cap}(t) = V_{\text{cell}}(1 - e^{-t/RC}).$$

The power series expansion for the exponential function is given by

$$e^x = \sum_{n=0}^{n=\infty} \frac{x^n}{n!} = 1 + x + \frac{1}{2}x^2 + \frac{1}{3!}x^3 + \cdots$$

In particular we have that

.

$$e^{-t/RC} = \sum_{n=0}^{n=\infty} \frac{(-t/RC)^n}{n!} = 1 - \frac{t}{RC} + \frac{1}{2}(\frac{t}{RC})^2 - \cdots .$$

Notice that when $t << RC$, we can ignore second order terms like $(t/RC)^2$ so the voltage across the capacitor grows linearly with time for $t << RC$.

$$V_{cap}(t) = V_{\text{cell}}(1 - e^{-t/RC}) \cong V_{\text{cell}}(1 - (1 - \frac{t}{RC})) = V_{\text{cell}} \frac{t}{RC} = V_{\text{cell}} \frac{t}{\tau}.$$

Therefore the time can be related to the voltage across the capacitor according to

$$t = \frac{V_{cap}(t)}{V_{\text{cell}}} \tau .$$

Example: Suppose $t << \tau = 20\text{ s}$, $V_{\text{cell}} = 1.645\text{ V}$, and $V_{cap}(t) = 80\text{ mV}$. So

$$t = \frac{V_{cap}(t)}{V_{\text{cell}}} \tau = \frac{(.08\text{ V})}{(1.645\text{ V})}(20\text{ s}) = (1.0\text{ s}).$$

Experiment ES: Parts

1	DPDT knife switch
1	AA cell
1	AA cell holder
3	wiring nuts
2	10 MΩ resistors
1	20 Ω resistor
1	1 μF capacitor

Making Clip Leads ---CLK--- About Soldering

You will solder together wires and electronic components to make an adjustable regulated direct current power supply and other devices. You will also use your magnetic multi-meter (MMM) to measure voltage, current and resistance.

Before you build the power supply and start doing the experiments, you and your partner will do three things involving soldering, namely: making two clip leads, putting alligator clips on the multimeter leads, and putting alligator clips on the wall transformer leads.

You will also use your MMM to measure the resistance of a resistor, the voltage difference across the terminals of a battery, and the current that flows in a simple circuit consisting of the battery and the resistor.

About Soldering:

This is a way of joining metals with solder, an alloy of 60% tin and 40% lead that melts at about 180 C (360 F). The hollow core of the wire solder in your tool kit contains a rosin flux that cuts through crud films on the surfaces of the metals so that the molten solder can wet and bond them.

Soldering Iron:

Your tool kit contains a 25 W (watt) soldering iron. Plug it in and after 2 to 3 minutes, rub its conical tip with solder to tin it; that means cover the tip with a film of molten solder.

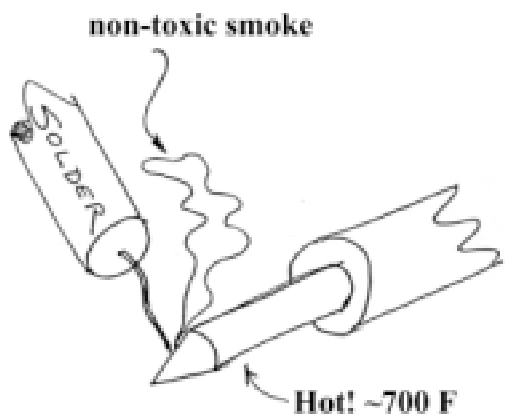


Figure 1: Tinning the soldering iron

The soldering iron in your toolkit requires some care. Once you have tinned the iron, you can clean the tip with a quick pass with a paper towel or emery cloth. It is important to keep your iron tinned otherwise crud will pile up on the tip of the iron and it will not properly conduct heat. You should not leave your soldering iron plugged in when not in regular use. Keep the soldering iron away from flammable materials. The tip of the iron gets very hot; be careful not to inadvertently touch it.

Soldering Wires:

To solder, put the iron up against the wires to be joined, letting the iron heat up the wires for a few seconds. Feed solder to the iron tip near the wires so that the molten solder can conduct heat to them and wet them. Smoke and vapors from this procedure are not harmful. Remove the iron and let the solder solidify before moving the wires. The resulting joint should not come apart except with a very strong pull.

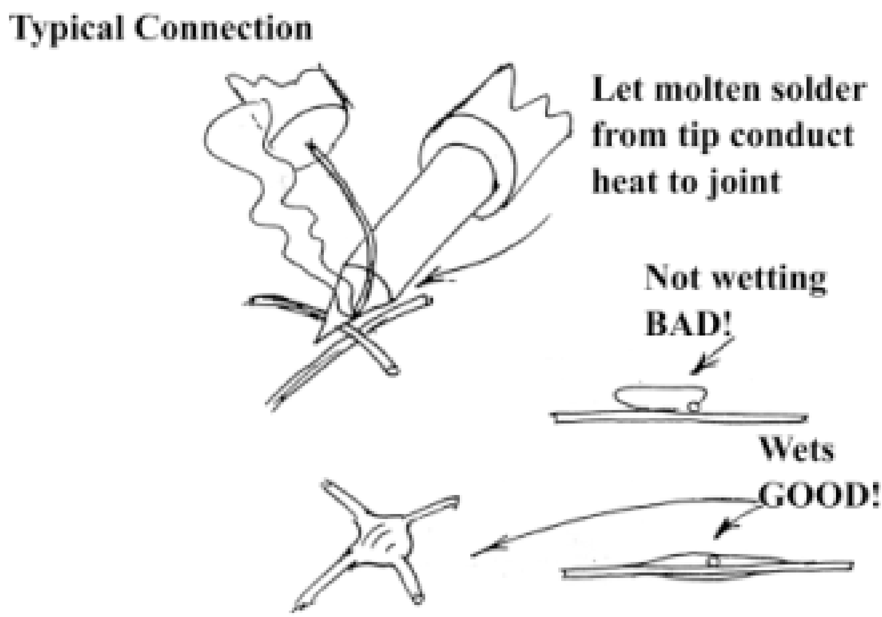


Figure 2: Soldering Connections

You should practice stripping (removing) the vinyl insulation from the ends of the stranded wire (in the clip lead kit—use the red as there's some extra), twisting the strands and tinning them with molten solder using your soldering iron. Then solder the two ends of the wires together. Try tugging them apart.

Making Clip Leads

Cut two pieces of vinyl-insulated stranded wire, about 250 mm (10 inch) long, one red, one black. You'll find wire in the Clip Lead kit. You can use the wire cutter part of the long-nose pliers, or the wire strippers or scissors. Loosen the adjusting nut of the stripper, and set it so that the notch in the jaws just allows a regular paper clip to slide through. Wire is most easily stripped of its insulation by holding the wire with pliers with the part to be stripped protruding and then levering the wire strippers against the plier jaws. Try not to cut any of the strands. Remove about 4 mm (1/4 inch) of insulation from each end of each of the wires, and twist the strands into a compact bundle.

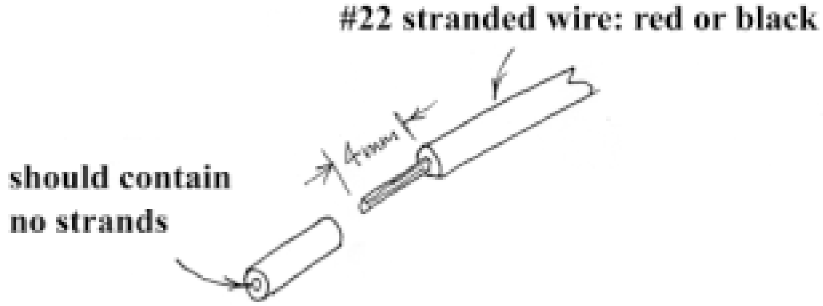


Figure 3: Stripping wires

Tin all the ends, which means put solder on them with your iron so that the strands are bound together. Put two sleeves of the same color as the wire insulation on the wires, large end facing the wire ends. Make a right angle bend in the middle of the tinned part and put that through the hole in the end of the alligator clip from above (the side where there is a round pad to put your thumb when opening the jaws of the clip).

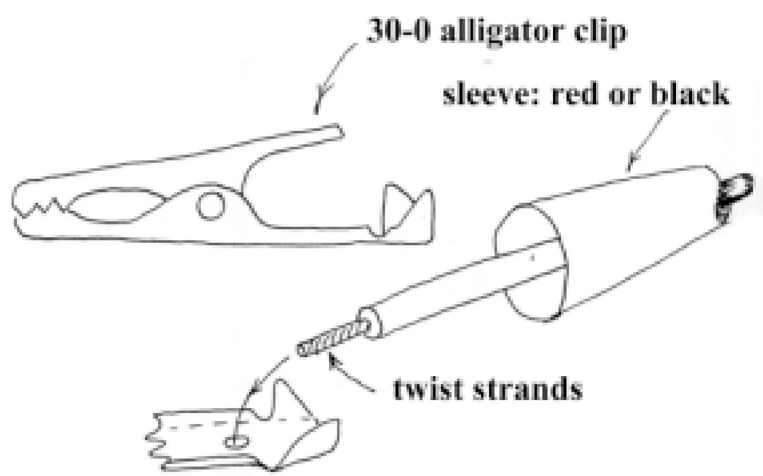


Figure 4: Alligator clip

Solder the tinned wire to the bottom side of the clip. You may find that it helps to hold the clip in your pliers using a rubber band around the handle of the pliers to give a firm grip. Let it all cool. Bend the insulated part back and crimp the end of the clip around it. Work the sleeve over the clip**. Repeat three more times to make two clip leads.**

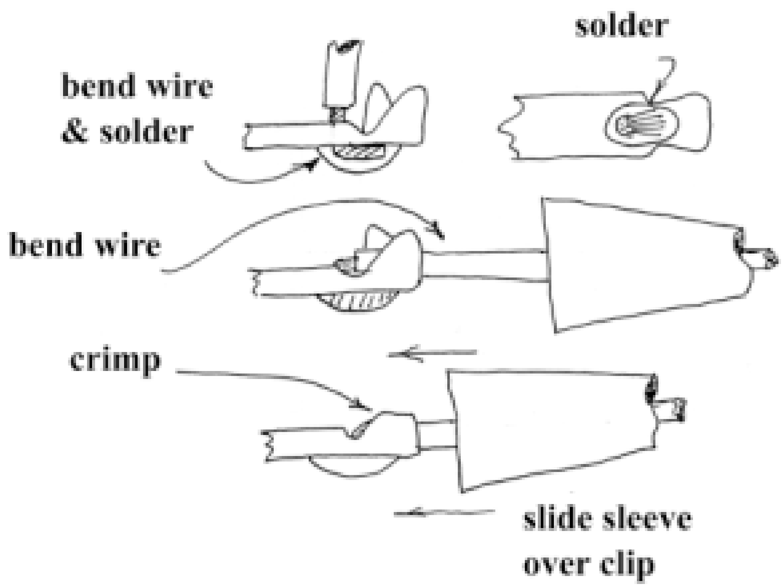


Figure 5: Soldering clip leads

Alligator Clips on Clip Leads: The analog or magnetic multimeter (MMM) come with test prods that have been removed. These prods would be useful in making quick measurements from point to point in some devices. They are not good for our purposes where we want to leave the meter connected for extended times. Put red and black sleeves on the appropriate leads. **Solder on alligator clips as you did for clip leads.**

Alligator Clips on Transformer Leads: In your Red Box you will find a black Class 2 Transformer, that reduces the input 120 V ac, 60 Hz (30 Watt) from the line to a safe and convenient 12 V ac 1000 mA output with only moderate loss of power (heating the transformer). It is IMPORTANT that the leads of the transformer should be of unequal length to reduce the likelihood of short circuits. If they are not, cut one of them so that it is about 50 mm (2 inches) shorter than the other. Put a black sleeve on each of the leads. Strip about 4 mm (1/4 inch) of insulation from each end of each of the leads. **Solder on alligator clips as before.**

Putting Alligator clips on the Multimeter Leads: Whenever you want to make a measurement, you will use the red and black test leads. Your analog multi-meter comes with test leads that have been removed. These leads would be useful in making quick measurements from point to point in some devices. They are not good for our purposes where we want to leave the meter connected for extended times. Put red and black sleeves on the appropriate leads. **Solder on alligator clips as you did for clip leads.**

Exercise MM—About the Multimeter

Introduction

Our world is filled with devices that contain electrical circuits in which various voltage sources cause currents to flow. Electrical currents generate heat, light, and magnetic fields, and produce chemical effects. Any of these phenomena can be used to measure current. One of the simplest ways is to let the current flow through a coil of wire that is in a magnetic field and to measure the resulting torque on the coil by observing the deflection of a torsion spring. This is how your multimeter works, which we call a magnetic multimeter (MMM), in contrast to the standard term `analog'. Look at the meter itself. You can see the copper colored coil and one of the two spiral torsion springs (the other is at the back; they also lead current in and out of the moving coil). The MMM is a current meter with a range selector switch, so that with appropriate resistors and other parts it can measure voltages and resistances.

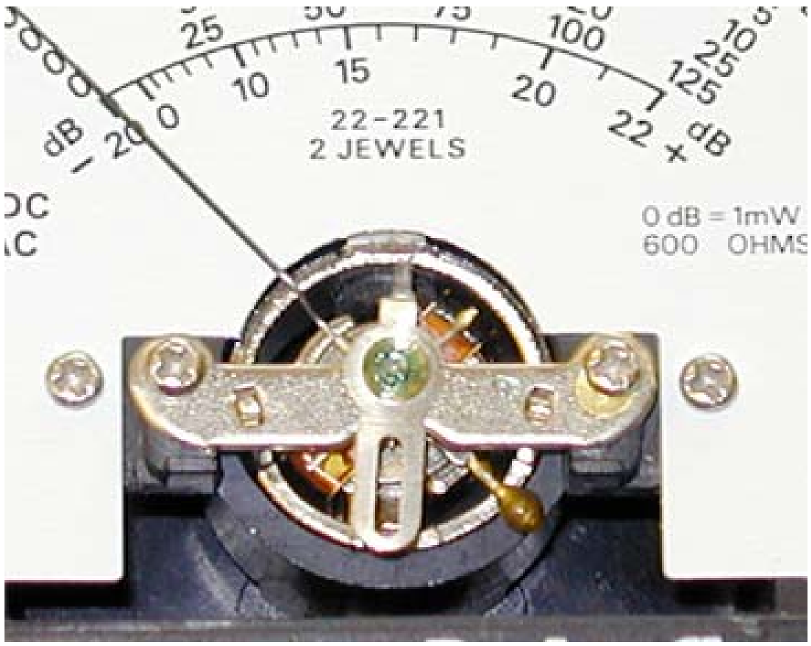


Figure 1: Coil and torsion spring

A meter has a needle that moves clockwise in proportion to the current flowing through the meter. The needle goes over various scales above a reflecting mirror intended to reduce parallax error—move your head so that you see the needle just above its reflection, and you'll be looking straight down onto the scale and be able to read the right number.

In this exercise you will use your MMM to measure the resistance of a resistor, the voltage difference between the terminals of a AA cell (battery), and the current that flows in a simple circuit consisting of the battery and a resistor.

The MM Kit contains one AA cell and one battery holder with a red lead (plus,+) and a black lead (minus,-). You may need to remove some of the insulation on the leads so that about $1/2\,in$, $12\,mm$, of bare wire is exposed. Do this with the wire strippers in your toolkit. The kit also contains two 20Ω resistors. You will also need one of the clip leads that you have just made.

There is a separate package in the top tray of the Red Box containing two AA cells, and four $500\,mA$ fuses. You should first open the back of the MMM and put in a $1.5V$ AA cell into the holder at the top of the MMM. Make sure the battery is placed with the + terminal connecting to the red wire. While the multimeter is open, notice that there is a fuse. If your multimeter is not working then there are two likely reasons. The first is that your test leads are broken or not making a good connection. The second reason is that the fuse may have blown. You have four spare fuses in your Red Box. The fuses may blow if you make a measurement with an inappropriate range selector setting, in particular the 250 DCA and Rx1 ranges.

Measuring Voltage, Resistance and Current with the Multimeter

Checking the MMM zero:

With the MMM lying flat on a table or desk and with nothing connected look down so as to line up the needle and its image in the scale mirror. The needle should bisect the 4 black zeros. Tap or swing the meter; the needle should still show zero. If not, your $5mm$ flat screw driver will just about fit the adjusting screw in the lower center of the meter. Turn carefully until the needle sits on zero.

Measure the resistance of the 20Ω resistor

There are 3 resistance ranges, RX1, RX10, and RX1K (1K=1000). The ohmmeter operation depends on the $1.5V$ AA cell that is inside the meter. Essentially, current flows through the meter in inverse proportion to the resistance in the circuit. This accounts for the markedly non-linear green scale at the top of the meter.

In order to zero the meter before measuring resistance, short the test leads by connecting them together. Then adjust the OHMS ADJUST knob (located to the left of center of the MMM) so that the meter reads 0 ohms; the needle is then at its maximum deflection. When the test leads are not connected, (an open circuit), no current flows and the needle sits on the infinite resistance mark ,∞, all the way on the left side of the scale.

Set the range selector switch on the MMM to the RX1 range. Connect the test leads to the resistor. Measure the resistance. You may want to make other resistance measurements. For example make a thick line with a lead pencil and measure the resistance of the mark. Grasp the clips firmly and see what your resistance is. Touch the clips to your tongue.

Measure the voltage of the AA cell

Set the range selector switch on the MMM to the 5 DCV range. Place the AA cell in the battery holder. Connect the test leads to the leads from the holder. Measure the voltage.

Measure the current in a simple circuit

First set the range selector switch on the MMM to the 250m DCA range. Make a simple circuit consisting of the 20Ω resistor, the AA cell, and the MMM. You can do this by connecting the red lead of the MMM to the red lead (plus, +) of the AA cell holder. Use a clip lead to connect the black lead (minus, -) of the AA cell holder to one end of the 20 Ω resistor. Connect the black lead of the MMM to the other end of the 20Ω resistor. Measure the current in the circuit. What effect do you think the MMM has on the circuit?

About the Magnetic Multimeter

Introduction

The MMM will be one of your most important tools in this course. Please read the following explanation of the MMM. You may not be completely familiar with all the terminology. As the course develops, you will learn all the physical principles necessary to understand the MMM. So please keep on referring to the reading below if you have any questions about your MMM.

Your analog multimeter (we call them MMM—magnetic multimeters) is a “moving coil meter” with a needle whose deflection shows and measures the torque on a current loop placed in a magnetic field. That torque is proportional to the current, and a device that measures current is called an *ammeter*.

The multimeter consists of a cylindrical magnet (magnetized across a diameter) arranged coaxially with a cylindrical magnetic return path as shown in Figure 2.

Figure 2: Multimeter Coil

In the gap is a pivoted rectangular coil; you can see the top of it if you look down into the meter. Spiral springs, top and bottom, lead current in and out of the coil and also provide a restoring torque. Jeweled bearings provide a low-friction mounting as in some watches.

Current in the coil interacts with the radial magnetic field to generate tangential forces, and hence torques about the axis of rotation. These turn the coil until the magnetic torque is balanced by the torque of the spiral springs. The meter has a pointer or needle, which moves clockwise in proportion to the current flowing through the meter. The needle goes over various scales above a reflecting mirror intended to reduce parallax error—move your head so that you see the needle just above its reflection, and you’ll be looking straight down onto the scale and be able to read the right number.

Any instrument that measure current will disturb the circuit under observation. (The coil itself has resistance.) There will be some voltage drop due to the resistance of the flow of current through the ammeter. An ideal ammeter has zero resistance, but a $0.1-0.2V$ drop is tolerable in our applications.

The range of an ammeter can be extended to measure higher currents by placing a resistor (called a shunt resistor) of resistance, R_s, generally lower than the coil resistance, *across* the meter coil. When connected in a circuit with flowing current I, the meter will read a fraction of that current say 0.1 I, with 0.9 I passing through the shunt. The meter scale can be calibrated so that it reads 10 times its original range.

To convert an ammeter into a voltmeter, a resistor (called a multiplier resistor) of resistance, R_m, generally higher than the coil resistance, is put in *series* with the meter coil. Suppose a current I through the meter coil produces a full-scale (FS) reading, that is FS deflection of the needle. The coil resistance is R_c, so the voltage across it, $V = I\,R_c$. Putting a multiplier resistor $R_m = 9R_c$ in series with the coil means that it will take $10\,V$ to produce a FS reading, so we now have another range and can calibrate and label the scale accordingly.

The ideal voltmeter should draw no current, corresponding to the zero voltage drop across the ideal ammeter. But in any moving coil meter currents produce torques which deflect springs and keep them deflected. Electrical power deflects the springs during the short time that the needle is moving and is also dissipated in the coil resistance as long as the needle is deflected.

Test Leads

The test leads are generally placed into the two pin jacks on the lower left of the MMM; black into –COM and red into +V-Ω-A. Note the warning label that the inputs for these cannot exceed the maximum values of 500V DC, 1000V AC, 250mA DC (Figure 8). When you want to measure DC voltages up to $1000\,V$, put the positive test lead into the pin jack labeled DC 1000V while leaving the black lead in –COM.

Range Selector Switch

The meter can measure current, dc voltage, resistance, or ac voltage depending on the setting of the range selector switch. There are four types of positions: DCA for dc current, DCV for dc voltage, OHMS for resistance, and ACV for ac voltage. Each position has several ranges; for example OHMS has three ranges: RX1, RX10, and RX 1K.

Figure 3: Pin Jacks

Figure 4: Range Selector Switch

Scales

There are four scales on the MMM. The top non-linear scale in green is used to measure resistance in ohms and ranges from ∞ to 0 reading left to right. Directly beneath the green scale is a red scale to measure AC. There are no markings on this scale. The black DC scale is divided into 10 large divisions over an angle of about 80 degrees; each large division is further divided into 5 small divisions. Alternate large divisions are labeled with 4 numbers. To the left, these are all zero. On the right are 5, 10, 25, 125; the voltage that produces full scale readings on the corresponding DCV range.

Figure 5: Scales

For example, if you set your range selector switch to 25 DCV then each large division corresponds to $2.5V$. When the needle points to full scale deflection, the voltage is $25V$. (Notice that there is no $10V$ full scale switch setting.) When the switch is set to the 500 & 1K setting, each large division corresponds to $50V$ or $100V$ depending on which pin jack the positive lead is inserted into. The non-linear bottom scale (also in black) measures decibels (dB), a logarithmic unit associated with sound level. This scale has the zero setting at $-20\,dB$ and then ranges from 0 to $22\,dB$ moving from left to right.

Current-Voltage Measurements

DC current Ranges (DCA)

First we'll consider the dc current ranges. DCA, ('DC' stands for direct current), 'A' stands for amperes so DCA means direct current amperage). There are two DCA current ranges, 250m and 50µ(250 mV). The more sensitive 50µ(250 mV) range can also be used to measure voltage. When the dial is set to 50µ(250 mV) the resistance of the meter is $5000\,\Omega$. If the needle deflects to full scale, then $50\,\mu A$ flows through the meter. This corresponds to a voltage difference

$$V = I\,R = (50\mu A)(5000\,\Omega) = 2.5\times10^{-1}\,V = 250\,mV\,.$$

So this setting can measure voltages between $0\,V$ and $250\,mV$.

Besides this most sensitive range, there is a $250\,mA$ range marked 250mDCA. This puts in a 1Ω shunt resistor in parallel across the $5000\,\Omega$ of the meter itself. Thus when current causes $250\,mV$ to appear across the shunt and the $5\,k\Omega$ meter resistance, a current of $250\,mA$ passes through the shunt while $50\,\mu A$ passes through the meter giving full-scale deflection. Many of the MMM's have a fuse to protect the meter from overload on this range, otherwise the 1Ω resistor will burn out inside the meter.

DC voltage Ranges (DCV)

There are 4 DCV range switch positions 5, 25, 125, and 500 & 1K, selected by turning the range selector switch. DC stands for direct current, so DCV means direct current voltage. Selecting the various DCV ranges introduces more resistance in series. The resistance of the meter on any DCV range is always the full scale reading in volts times 20,000 ohms/volt $[\Omega]/[V]$, a number that characterizes this meter as a dc voltmeter. For example, on the $25V$ setting, the resistance is

$$R_{25V} = (25V)(20{,}000\,\Omega/V) = 500k\,\Omega = 5.0\times10^{5}\,\Omega\,.$$

Table 1 shows the full scale value, the resistance of the meter on that range, and the power dissipated in watts through the meter for the DCV and DCA ranges.

Table One: resistance and power characteristics of DCV and DCA ranges on MMM

Range	Resistance in ohms $[\Omega]$	Power in milliwatts for full scale deflection $[mW]$
5V	$100\,k$	0.25
25V	$500\,k$	1.25
125V	$2.5\,M$	6.25
500V	$10\,M$	25.0
1000V	$20\,M$	50.0
250mV (50µA)	$5k$	0.0125
250mA	1	62.5

The DCV range 500 & 1K is one range selector setting. When the positive test lead is in the +V-Ω-A, the full scale deflection corresponds to $500\,V$. When the positive test lead is in the pin jack labeled DC 1000V, the full scale deflection corresponds to 1000V.

AC voltage ranges (ACV)

Suppose the ac input voltage is $V(t) = V_0 \sin(2\pi\, f\, t)$ where V_0 is the amplitude. A half-wave rectifier is inserted in series with the various resistors so that the ac has a dc component. The meter is insensitive to the fast variation of the output voltage across a load, so it will read the time averaged dc voltage $\langle V \rangle$. Each ac scale is then calibrated by various resistors to indicate the root-mean square value $V_{rms} = V_0 / \sqrt{2}$.

For non-sinusoidal waveforms, or for ac superimposed on dc (average in time not zero), the readings of the meter will most likely not be meaningful.

For ac you read the scales whose divisions and associated numbers are printed in red. Full-scale deflection corresponds to your choice of range for the root mean square voltage indicated on the rotary setting. At low voltages, the diode is not linear, (this is due to the small forward drop voltage) as can be seen from the small displacement of the red ac marks at the low end of the scale, from the corresponding black dc ones directly below.

The resistance of the meter on any ACV range is always the full scale reading in volts time 10,000 ohms/volt, a number that characterizes this meter as an ac voltmeter.

Resistance-Ranges (RX)

There are 3 resistance ranges, RX1, RX10, and RX1K. The ohmmeter operation depends on the $1.5V$ AA cell that is inside the meter case. Essentially, current flows through the meter in inverse proportion to the resistance in the circuit. This accounts for the markedly non-linear green scale at the top of the meter.

In order to zero the meter, short the test leads by connecting them together. Then adjust the OHMS ADJUST knob (located to the left of center of the MMM) so that the meter reads 0 ohms; the needle is then at its maximum deflection. When the test leads are not connected, an open circuit, no current flows and the needle sits on the infinite resistance mark ∞ all the way on the left side of the scale.

Half scale readings (that is with the needle pointing straight up parallel to the edge of the case) are: 24Ω, 240Ω and $24{,}000\Omega$ on the RX1, RX10, and RX1K ranges, respectively.

Note also that on the resistance ranges the meter puts substantial current through the resistor being measured. Maximum currents are $0.05A$, $5mA$, and $50\mu A$ on the RX1, RX10, and RX1000 ranges, respectively. You can check out some of this by making measurements of one meter with another.

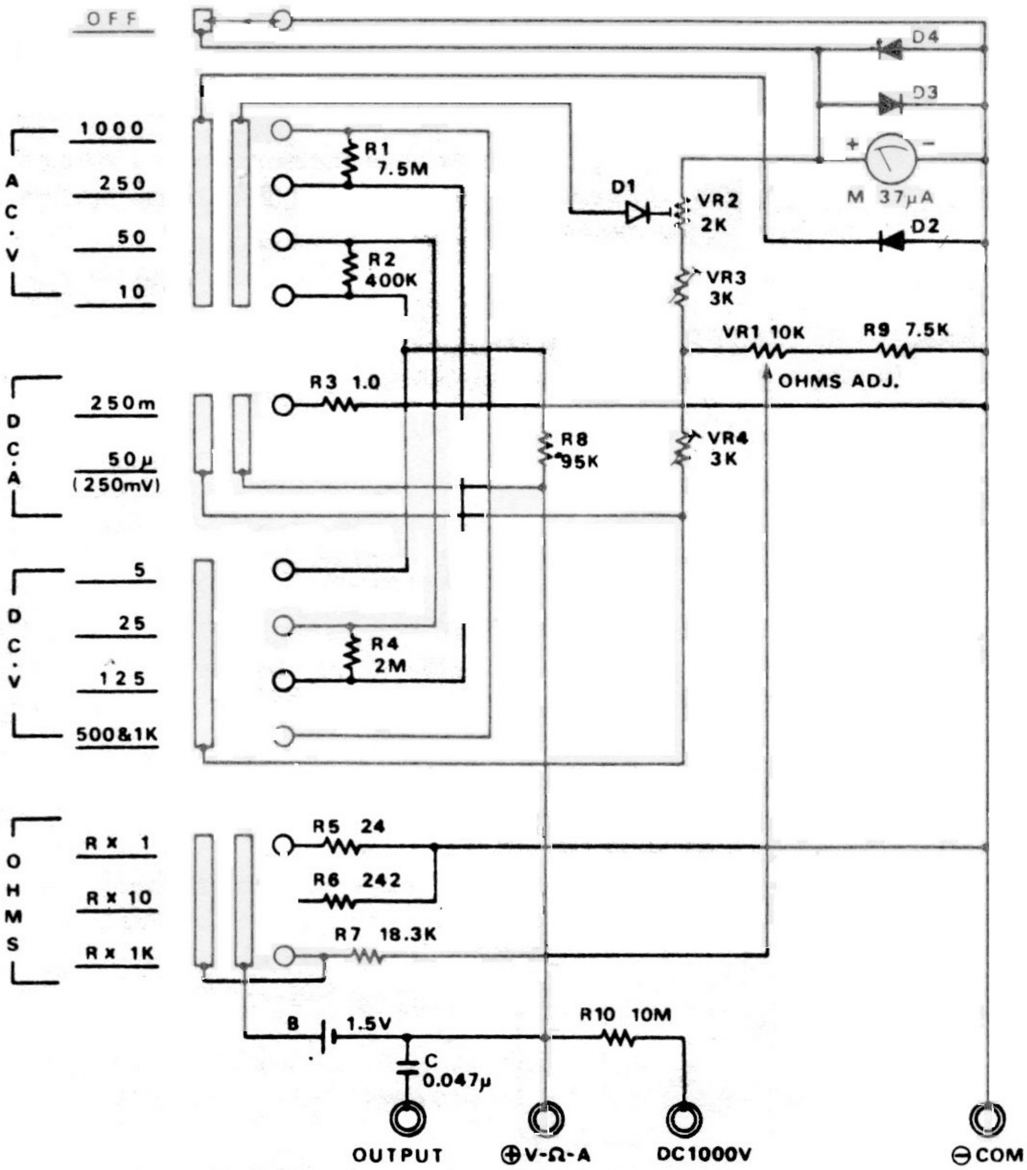
Meter Damage

Avoid dropping the meter. Keep its range switch on zero when it is not in use. This damps the motion of the coil and needle—you can see this by rotating the case back and forth in a horizontal plane and comparing the needle motion with the switch on a voltage scale and on OFF. Or: set the meter on the RX1K, connect the test leads and note the time that the needle takes to return to zero when the leads are disconnected. Compare that time with the time it takes the needle to return to zero when the leads stay connected but the range is switched from RX1K to OFF.

Besides the fuse, the moving coil is protected by resistors and a pair of back-to-back diodes across its windings. This means that it's hard to damage the meter coil except for the ranges with low resistance where resistors can be damaged by excessive currents (RX1 and 250mA ranges). However, it's good practice to start with high ranges, and not to measure the resistances of components that are wired into circuits, especially if power is on.

Figure 6 shows the circuit diagram for multimeter. Notice that when the meter range selected is 50µ(250 mV), it takes $50\mu A$ in the external circuit to produce full scale deflection, but only $37\mu A$ flows through the coil of the meter.

SCHEMATIC DIAGRAM



NOTE: (1) ALL RESISTANCE VALUES ARE INDICATED IN "OHM" (K = 10^3 OHM, M = 10^6 OHM)

(2) ALL CAPACITANCE VALUES ARE INDICATED IN "µF" (P = 10^{-6} µF).

Schematic subject to change without notice. For most accurate Schematic (and parts) contact Radio Shack. National Parts Dept. Fort Worth, TX 76101

In UK, contact Tandy Electronics, National Parts Dept., Bilston Road Wednesbury West Midlands WS10 7 JN

In Australia contact Tandy Australia Limited, National Parts Dept., 91 Kurrajong Avenue, Mount Druitt, N.S.W. 2770

Figure 6: Circuit diagram for MMM

Measuring Voltage, Resistance and Current with the Multimeter

- Measure the resistance of the 20Ω resistor
- Measure the voltage of the AA cell
- Measure the current in a simple circuit

Measure the resistance of the 20Ω resistor: In order to zero the meter, short the test leads by connecting them together. Then adjust the OHMS ADJUST knob (located to the left of center of the MMM) so that the meter reads 0 ohms; the needle is then at its maximum deflection. Set the range selector switch on the MMM to the RX1 range. Connect the test leads to the resistor. Measure the resistance. You may want to make other resistance measurements. For example make a thick line with a #2 pencil and measure the resistance of the mark.

Measure the voltage of the AA cell: Set the range selector switch on the MMM to the 5 DCV range. Place the AA cell in the battery holder. Connect the test leads to the leads from the holder. Measure the voltage.

Measure the current in a simple circuit: First set the range selector switch on the MMM to the 250mDCA range. Make a simple circuit consisting of the 20Ω resistor, the AA cell, and the MMM. You can do this by connecting the red lead of the MMM to the red lead (plus, +) of the AA cell holder. Use a clip lead to connect the black lead (minus, -) of the AA cell holder to one end of the 20Ω resistor. Connect the black lead of the MMM to the other end of the 20Ω resistor. Measure the current in the circuit. What effect do you think the MMM has on the circuit?

Building the LVPS—Low Voltage Power Supply

Introduction

Low voltage is one of those relative terms—up to 25 volts $[V]$ dc is low, and most people would call $1000V$ high. Power supplies provide energy from many different kinds of sources and at widely varying rates: gigawatts ($10^9 W$) from nuclear plants to microwatts ($10^{-6} W$) from watch batteries. Sources of energy for power supplies include nuclear fission, burning of coal, oil, gas or wood, chemicals reacting, and sunlight, wind and tides. Power is delivered in electrical form as alternating or direct current (ac or dc) and in many combinations of current and voltage. Electrical power supplies in a narrow sense are really converters from one voltage/current combination to another—with, one hopes, only small power losses.

Project LVPS

In this project, you'll build a power supply that takes power at $120V$, 60 hertz $[Hz]$ ac from a wall outlet and converts it to dc. The power supply is adjustable between $2V$ to $12V$ and can supply currents up to 1 ampere (A).

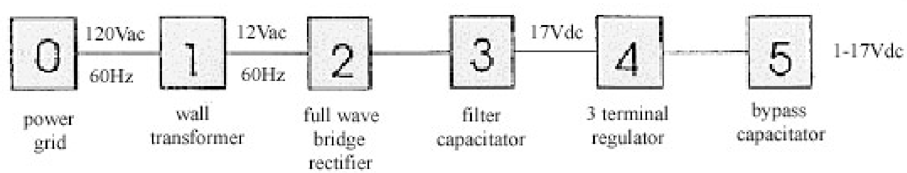


Figure 1: Block diagram of LVPS

Background

The circuit diagram for the LVPS looks like

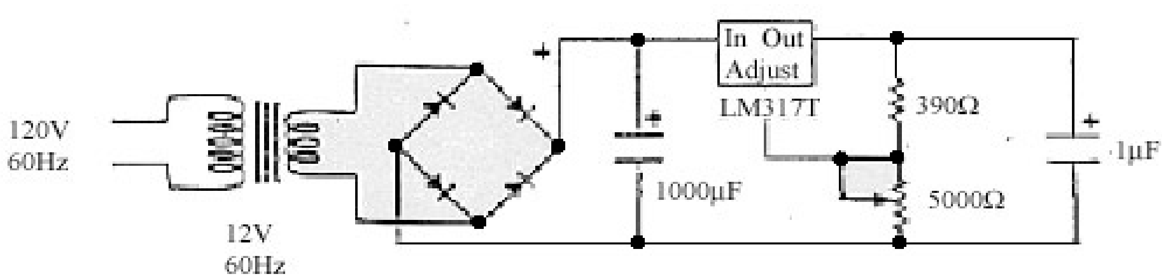


Figure 2: Circuit diagram for LVPS

Wall Transformer

The LVPS starts with your wall transformer, which reduces the $120\,V$ ac from the line to a safe and convenient nomuinal $12\,V$ ac sine wave voltage with only moderate loss of power (heating the transformer). A sine wave voltage varies in time and can be described mathematically by the function

$$V(t) = V_0\, sin(2\pi t / T + \phi) = V_0\, sin(2\pi f\, t + \phi)$$

where V_0 is called the *amplitude* (maximum value). The voltage varies between $V_0 = 17V$ and $-V_0 = -17V$ since a sine function varies between +1 and -1.

Figure 3: Wall transformer

The $12\,V$ ac refers to the root mean square (rms) amplitude defined by $V_{rms} = V_0 / \sqrt{2}$. The sine function is periodic in time. This means that the value of the voltage at time t will be exactly the same at a later time t′ = t + T where T is the *period*. The *frequency f* is defined to be $f = 1/T$. The units of frequency are inverse seconds [sec^{-1}] which are called hertz [Hz]. A graph of the sine wave voltage vs. time looks like

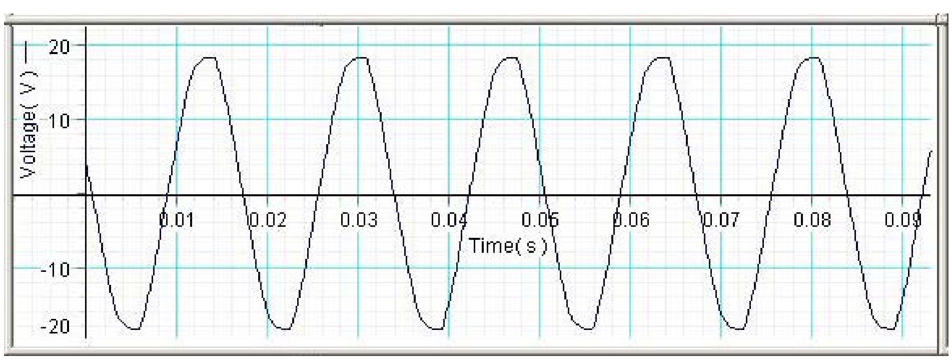


Figure 4: Wall transformer output voltage

Bridge Rectifier

Next comes a full-wave bridge rectifier consisting of four half-wave rectifiers that act as diodes. A half-wave rectifier allows current to flow through it in only one direction, as shown by the arrow in the symbol for it.

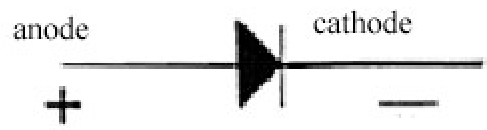


Figure 5: Half-wave rectifier

If an alternating sine-wave voltage is applied to a rectifier, it transmits only the positive half-waves as shown in the sketch below.

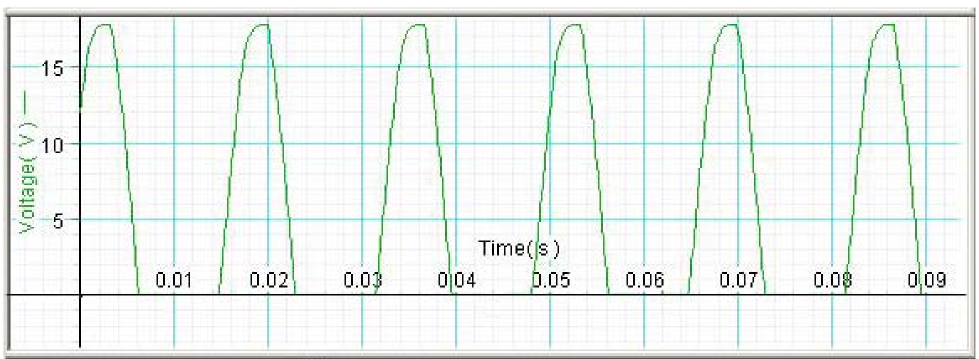
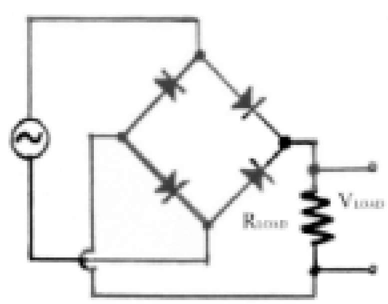


Figure 6: Rectifier sine wave after passing through half-wave rectifier

Four half-wave rectifiers connected as shown in Figure 7 form a bridge rectifier.



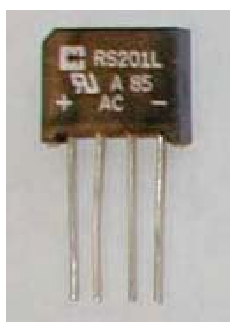


Figure 7: Bridge rectifier

In the next two sketches below, the four half-wave rectifiers act as switches that connect the upper or lower lead on the left, when either is positive, to the right-hand output lead, and to the left-hand output lead when either is negative (convince yourself of this).

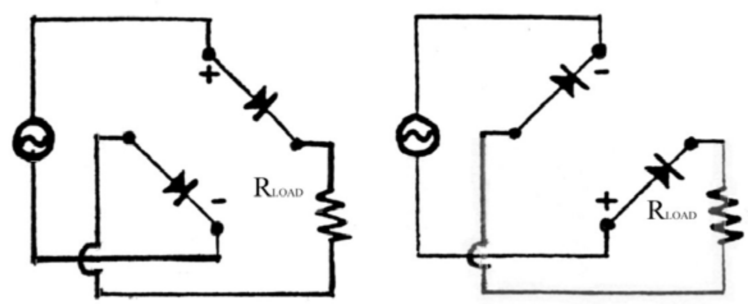


Figure 8: Bridge rectifier in action

In this way the wiggly ac is made to flow in only one direction—i.e., it is straightened out or rectified. This is shown in the next sketch.

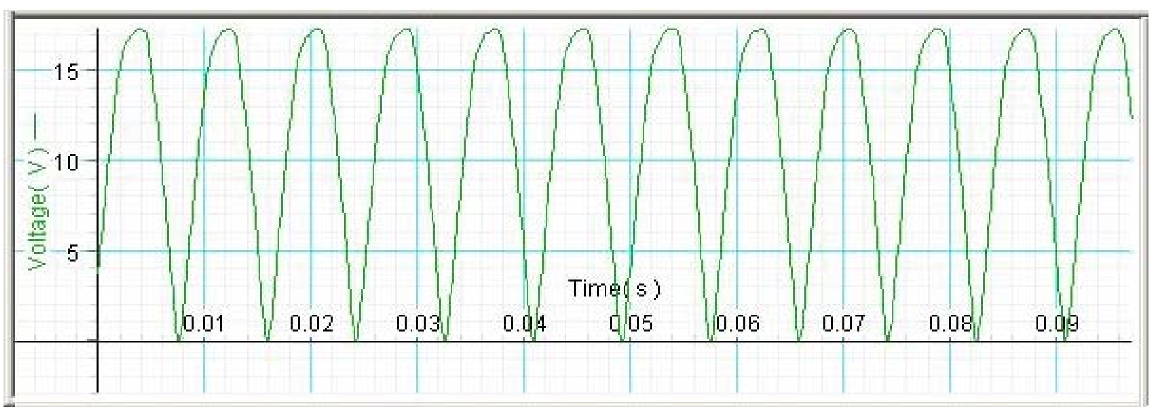


Figure 9: Voltage output from the bridge rectifier

Capacitors

Capacitors are circuit elements that store electric charge Q according to

$$Q = CV$$

where V is the voltage across the capacitor and C is the constant of proportionality called the capacitance. The unit of capacitance is the farad $[F]$ and is defined by $[1F] = [1C]/[1V]$.

Capacitors come in many shapes and sizes but the basic idea is two conductors separated by a spacing which may be filled with an insulating material (dielectric). One conductor has charge $+Q$ and the other conductor has charge $-Q$. The conductor with positive charge is at a higher voltage V than the conductor with negative charge. Most capacitors are in the picofarad [pF] to millifarad range, $1000\mu F$.

Capacitors can do many things in both ac circuits and dc circuits.

- Capacitors store energy
- Capacitors when coupled with resistors can delay voltage changes
- Capacitors can be used to filter unwanted frequency signals
- Capacitors are needed to make resonant circuits
- Capacitors and resistors can be combined to make frequency dependent and independent voltage dividers

We denote capacitors in circuits by the symbol

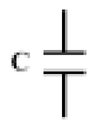


Figure 10: Capacitor symbol

Smoothing Out the Rectifier Output

A $1000\mu F$ capacitor then smoothes out the rectifier output.

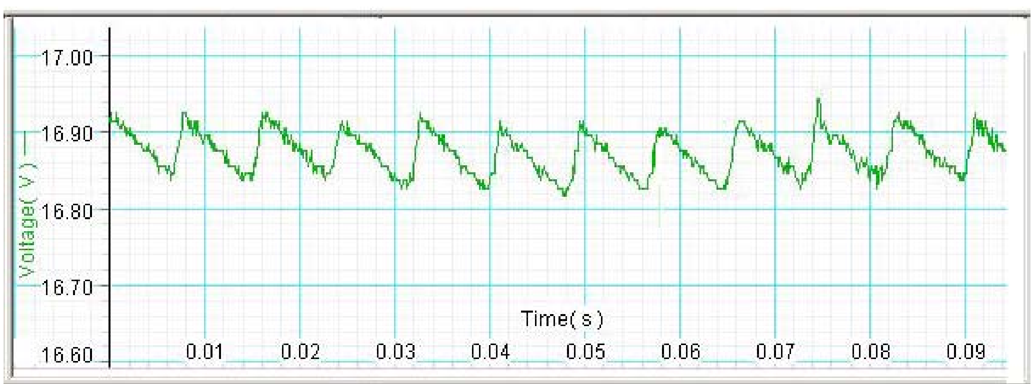


Figure 11: Smoothed out voltage due to $1000\mu F$

Voltage Regulator

Next comes the LM317T three-terminal integrated circuit (IC), containing 26 transistors and various resistors and capacitors. It keeps the output voltage constant with respect to an internal reference voltage, using feedback—i.e., it is a 'voltage regulator'. It also protects itself against overload (too much current) and is compensated for changes in temperature.

Figure 12: Heat sink, LM317T voltage regulator, and socket

Potentiometer

A resistor network—one variable resistor (a $5000\,\Omega$ potentiometer, or "$5k$ pot") and one fixed resistor ($390\,\Omega$, $1/2W$) serves to adjust the output voltage. Notice that the pot, here used as a variable resistance, has the slider and one end connected. This guarantees that some part of the pot resistance will be in the circuit, even if there is an uncertain contact inside the pot.

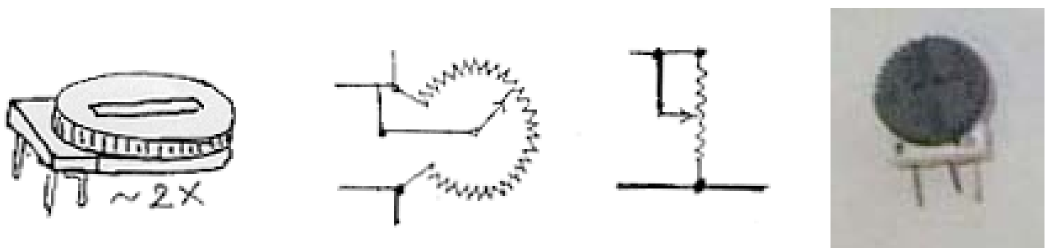


Figure 13: potentiometer and `pot' circuit diagram

High Frequency Filter

Finally, a $1\mu F$ capacitor across the output bypasses high-frequency disturbances from either direction—from the ac supply line or from the load.

Building the Low Voltage Power Supply

The circuit diagram for the LVPS tells us how the various parts are connected but we will place the parts on the perfboard in order to minimize the number of wires and solders. So in the following instructions try to understand the layout in terms of the circuit diagram. This will help you find any missed or incorrect connections.

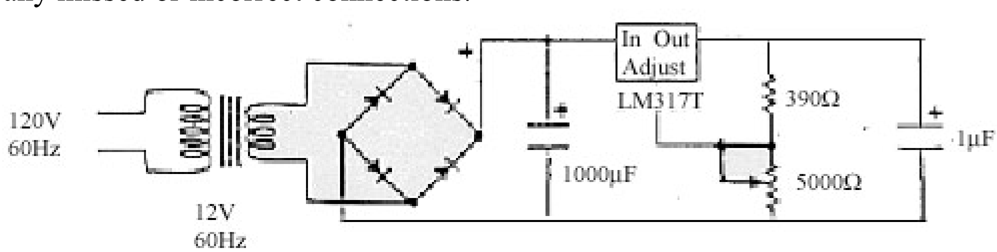


Figure 14: Circuit diagram for LVPS

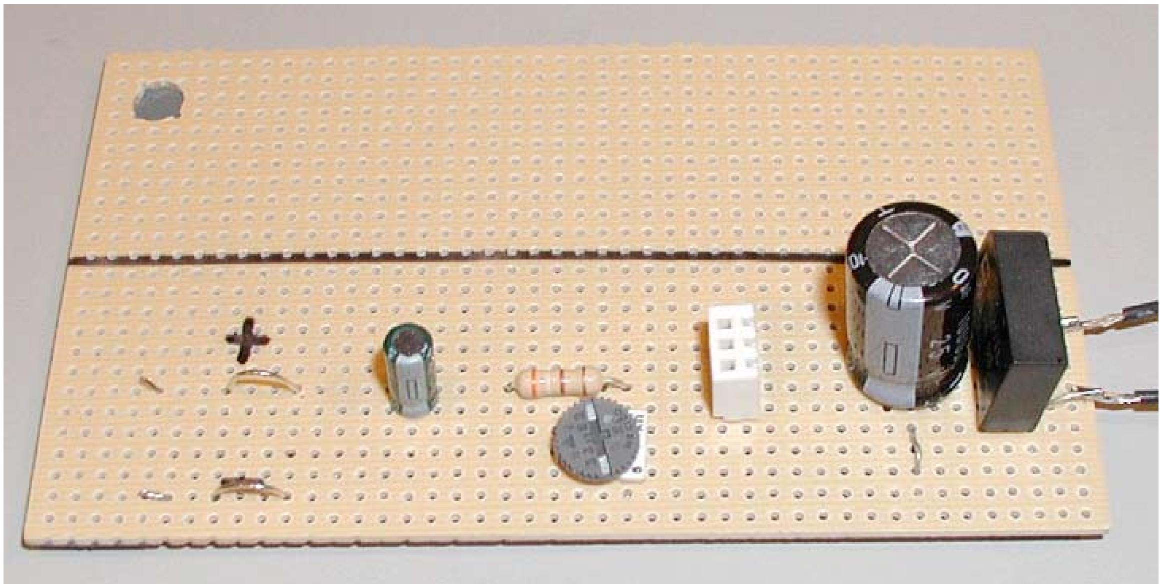


Figure 15: Top view of LVPS (transformer leads on right)

There are many ways to assemble the LVPS, but we will give you detailed step-by-step instructions to guarantee success. It takes up less than half the space on the perfboard, **leaving room to build other things later.** The top view of the LVPS will help in placing the parts.

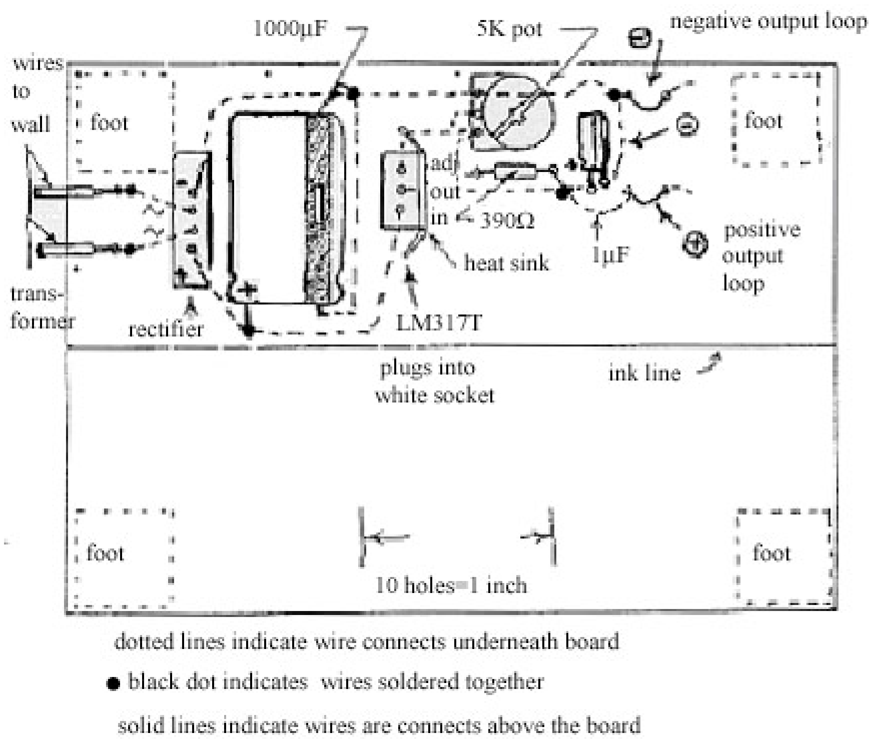


Figure 16 Top view of layout of LVPS (transformer leads on left)

Here is a template (top view) to help place the parts on the perfboard.

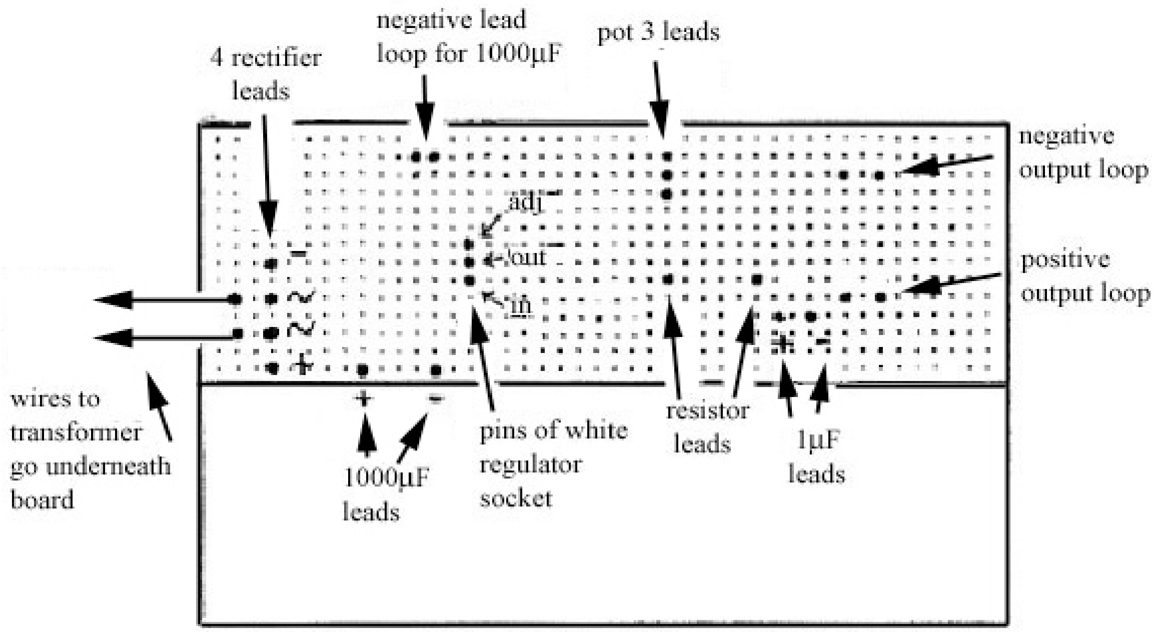


Figure 17 Template LVPS (top view)

The bottom view of the LVPS shows the wiring.

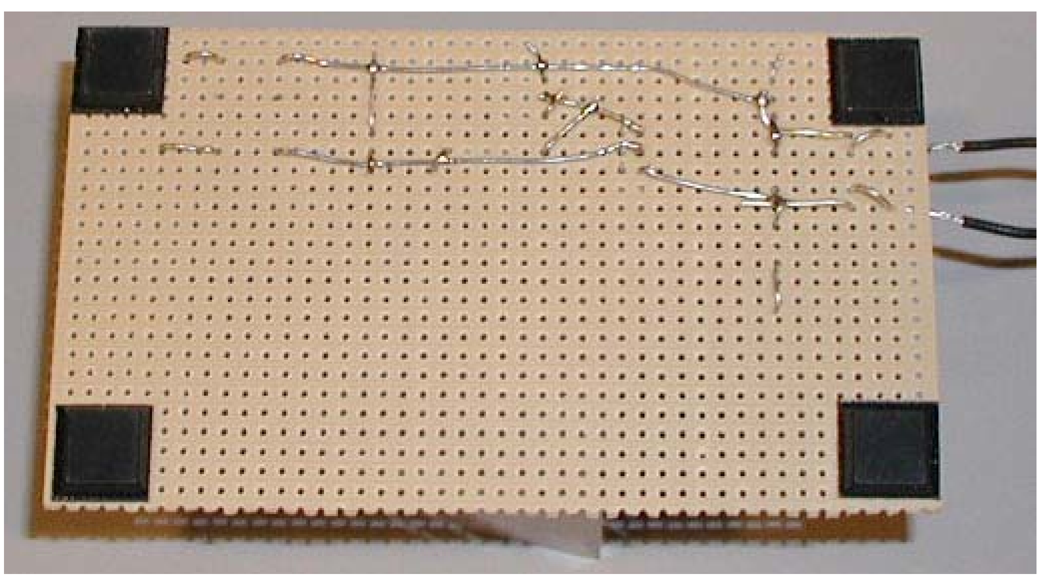


Figure 18: Bottom view of LVPS

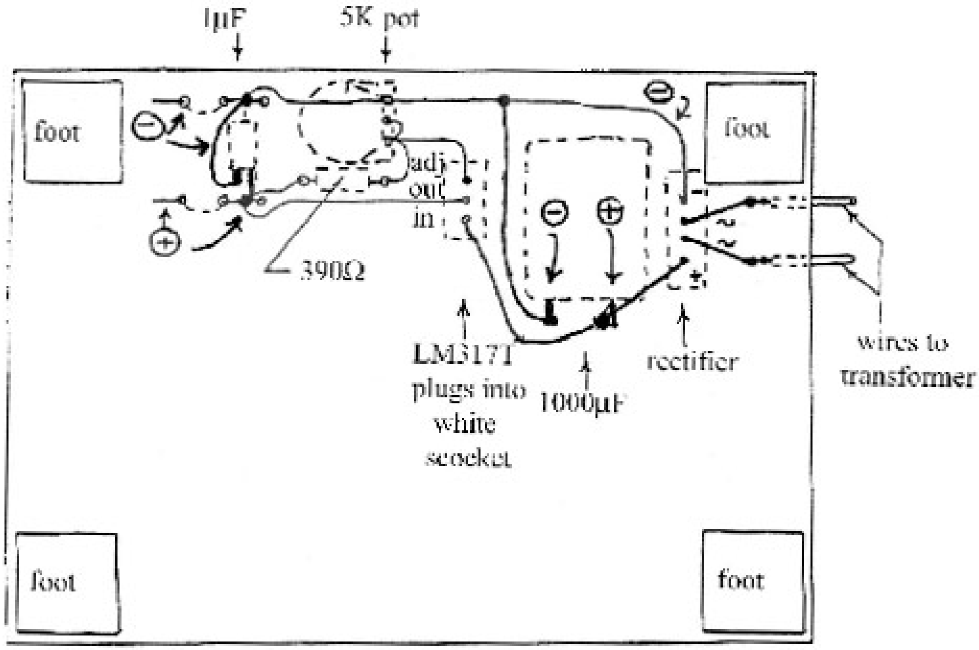


Figure 19: Wiring on bottom side of LVPS

Construction Steps

1. Find and identify parts in the plastic bag.

2. Draw a line with a pen lengthwise along the center of the perfboard.

3. Stick 4 feet on the corners of the bottom side as close to the edge as possible.

4. Place the parts according to the top view of perfboard. Bend the white socket's short leads carefully while installing. (The black regulator's three leads will fit into the socket. You will only solder the socket's leads so that the regulator can be easily removed). Identify on your perfboard which socket leads will correspond to the ADJ, OUT, and IN leads of the regulator.

5. Bend the leads of the rectifier, capacitors, and resistors as shown on the bottom view of perfboard.

6. Measure, cut, and solder a piece of the bare #22 wire to the minus lead (-) of the rectifier. Extend this wire across the board, and then form a loop on the top side. This will be the minus (-) output loop.

7. Loop the end of the minus lead (-) of the large capacitor (the band points to the minus lead) through the perfboard at the bare wire from step 6. (This will help hold the capacitor to the perfboard). Solder the minus lead (-) of the large capacitor to the bare wire from step 6.

8. Solder the pot lead nearest the edge of the perfboard to the bare wire of step 6. Be sure the pot is oriented as shown in the top view.

9. Solder the minus lead (-) of the small capacitor (the band points to the minus lead) the bare wire of step 6.

10. Solder the plus lead (+) of the rectifier to the plus lead (+) of the large capacitor.

11. Solder the plus lead (+) of the large capacitor to the IN lead of the socket. (See step 4).

12. Measure, cut, and solder another piece of the bare #22 wire to the OUT lead of the socket. Extend this wire across the perfboard, and then form a loop on the top side. This will be the plus (+) output loop.

13. Solder the plus lead (+) of the small capacitor to the bare wire of the previous step 12.

14. Solder one lead of the resistor to the bare wire of step 12.

15. Solder the other lead of the resistor to the two other leads of the pot, thus connecting those two leads of the pot together.

16. Measure, cut, and solder another piece of the bare #22 wire to the ADJ lead of the socket to either of the connected pot leads of the previous step 15.

17. Remove about $6\,mm$ of the insulation from two different lengths, $50\,mm$ and $100\,mm$ ($2\,in$ and $4\,in$) of black stranded wire. Tin all four ends and solder one length to each of the ac leads of the rectifier.

Trying out Your LVPS

Do not plug in the LM317T regulator. You should have already soldered alligator clips to your transformer leads, multimeter leads, and made clip leads. Clip one of the wall transformer leads to one of the LVPS leads of step 17.

Set the MMM to the 25DCV range. Connect the voltmeter across the $1000\,\mu F$ capacitor, red to the plus side and black to the minus side. Plug in the wall transformer. Now touch the second transformer lead to the other ac lead of the LVPS. There should be little or no spark and the meter should read about $17\,V - 18\,V$. Transfer the voltmeter leads to the output loops. Place the regulator in the heat sink with its metal back covered by the heat sink. **Now plug in the**

regulator into the socket with the number LM317T facing the large capacitor. Turn the pot and the output should vary from about $1.2V$ to $15V$ or more.

To make sure that your LVPS is working as it should, use the 1157 lamp (used as a rear brake light in a car) from the plastic bag labeled LVPST (***LVPS Test** Kit*) *as* a load on the LVPS. This lamp has two filaments (tail and stop light) with nominal ratings of 8 watts and 27 watts respectively at an applied voltage of $12.6V$.

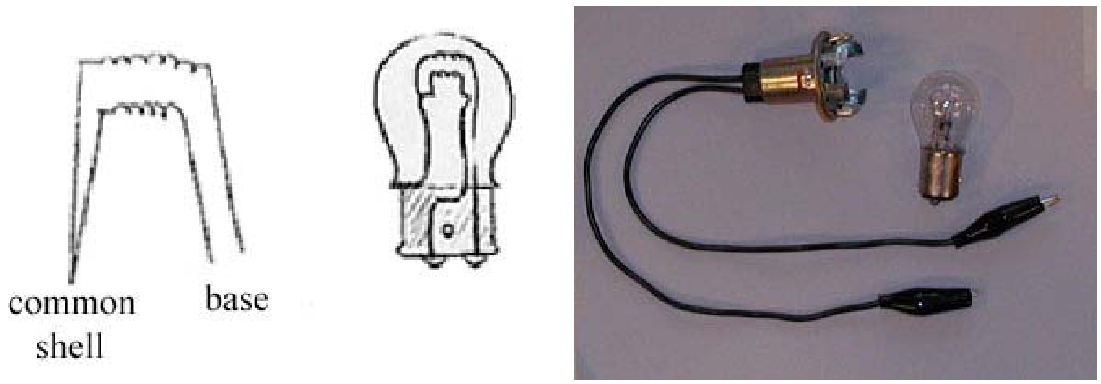


Figure 20: Lamp and socket

One lead to each filament is connected to the brass shell and the other lead is connected to one of the two terminals (soldered bumps) on the base of the lamp.

Plug the lamp into the socket provided in your Red Box. There are two black leads from the socket. In order to connect one of the filaments to the LVPS, use your clip lead to connect one of the black wires from the socket to one output of the LVPS. Use a second clip lead to connect the other output of the LVPS to anywhere on the socket. (This connects the LVPS to the brass shell of the lamp.) Identify the $8W$ filament (cold resistance about 2Ω), either with your MMM on the RX1 range or by lighting it with the LVPS---it's the upper filament in the lamp.

Parts List for LVPS

LVPS

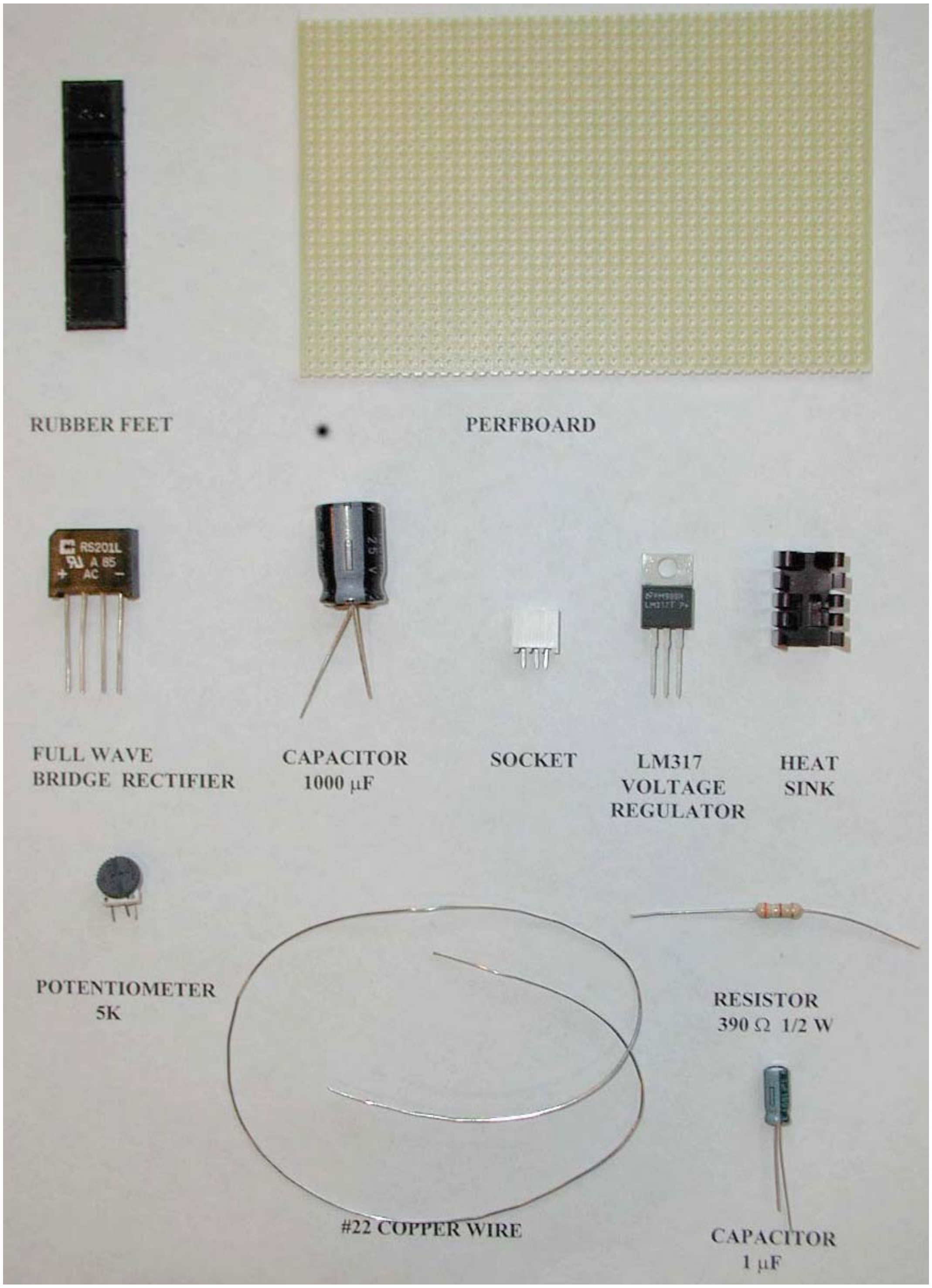
1	perfboard
4	rubber feet
1	full wave bridge rectifier
1	electrolytic capacitor, $1000\mu F$
1	socket for LM317T regulator
1	potentiometer, $5k\Omega$
1	electrolytic capacitor, $1\mu F$
1	resistor, 390Ω $1/2W$
1 *ft*	wire, #22 bare solid
1	voltage regulator LM317T
1	heat sink for LM317 regulator

LVPST

1 resistor, 2.4Ω $2W$
1 lamp #1157 automotive

RED BOX

1 socket for 1157 lamp


RUBBER FEET
PERFBOARD
FULL WAVE
BRIDGE RECTIFIER
CAPACITOR
1000 µF
SOCKET
LM317
VOLTAGE
REGULATOR
HEAT
SINK
POTENTIOMETER
5K
RESISTOR
390 Ω 1/2 W
#22 COPPER WIRE
CAPACITOR
1 µF

Testing the LVPS

Each of you has built a power supply that converts ac (alternating current) power at $120\,V$ (volt), at a frequency of $60\,Hz$ (hertz = cycles/sec) from the wall outlet into dc (direct current) power with a voltage range from $1.2\,V$ to about $17\,V$. When the output voltage without load (lamp) is set between $1.2\,V$ and about $12\,V$, the output voltage will not change appreciably if a load is then placed across it. You will find that range when you place the $8\,W$ (watt) filament of an 1157 lamp across the output of the LVPS. **See Building the LVPS: Trying out your LVPS.**

Measurements and Data

You can set your pot at ten different settings from lowest to highest output by turning the top of the pot either clockwise or counterclockwise (depending on how you wired the legs). Set the pot so the no load output voltage is minimium, $2\,V$, $4\,V$, $6\,V$, $8\,V$, $10\,V$, $12\,V$, $14\,V$, $16\,V$, and maximum. Use the accompanying table to record the results of your measurements. For each setting you will:

1. Measure the output voltage (no-load voltage) of the LVPS when the lamp is not connected;

2. Measure the output voltage (load voltage) of the LVPS when the lamp is connected across the output of the LVPS.

3. Then connect the lamp and measure the load voltage across the terminals of the LVPS.

Questions

1. What range of no-load output voltages remains unchanged after the lamp is connected across the LVPS output terminals?

2. Briefly describe how you distinguished between the $8\,W$ filament and the $27\,W$ filament?

3. What happens when you connect the outputs of the LVPS to the two black wires in the socket? Can you figure out the wiring diagram for the lamp?

Graph

Plot the output voltage of the LVPS without the lamp connected along the horizontal axis and the output voltage of the LVPS with the lamp connected along the vertical axis.

Data Table for LVPS

Pot Setting	V_{LVPS} (no load) [volts]	V_{LVPS} (load) [volts]
minimum		
	2	
	4	
	6	
	8	
	10	
	12	
	14	
	16	
maximum		

Experiment FO Falling Object

Introduction

We spend most of our time in the earth's gravitational field, so feeling the weight of objects and falling with constant acceleration are among our basic experiences.

The International Committee on Weights and Measures has adopted as a standard value for the acceleration of a body freely falling in a vacuum $g = 9.80665 \text{ m} \cdot \text{s}^{-2}$. The actual value of g varies as a function of elevation and latitude. If ϕ is the latitude and h the elevation in meters then the acceleration of gravity in SI units is

$$g = 9.80616 - 0.025928\cos(2\phi) + 0.000069\cos^2(\phi) - 3.086\times10^{-4}h \text{ m} \cdot \text{s}^{-2} \qquad (4.1.1)$$

This is known as Helmert's equation. The strength of the gravitational force on the standard kilogram at 42^o latitude is $9.80 \text{ N} \cdot \text{kg}^{-1}$, and the acceleration due to gravity at sea level is therefore $g = 9.80349 \text{ m} \cdot \text{s}^{-2}$ for all objects. At the equator, $g = 9.78 \text{ m} \cdot \text{s}^{-2}$, and at the poles $g = 9.83 \text{ m} \cdot \text{s}^{-2}$. (This is because the radius of the Earth is larger at the equator than it is at the poles by about 26.5 km, and because the Earth rotates at 2π radians per day introducing an apparent repulsive force that flattens the spherical shape). Both the magnitude and the direction of the gravitational force also show variations that depend on local features to an extent that's useful in prospecting for oil and navigating submerged nuclear submarines. Such variations in g can be measured with a sensitive spring balance. Local variations have been much studied over the past two decades in attempts to discover a proposed "fifth force" which would fall off faster than the gravitational force that falls off as the inverse square of the distance between the masses.

One can measure g by timing either a freely falling object or an object suspended from a support, oscillating as a pendulum.

Principle of the Method

In this experiment you'll time the free fall of a plastic wire nut by measuring the voltage across a capacitor in an RC charging circuit .The goal is to measure the time of fall of a wire nut as a function of the distance of fall. The distance is measured directly with a ruler. To measure the rather short time of fall, you will measure the voltage developed across a capacitor charged by an essentially constant current that flows only during the time the wire nut is falling.

The diagrams of Fig. 1 show the sequence of events:

- Initially both switches are closed, the upper switch shorts the capacitor and the voltage across it is zero.

- When the wire nut is released and during its fall the upper switch is open and the capacitor charges.

- When the wire nut hits the cup and opens the lower switch the charging current stops.

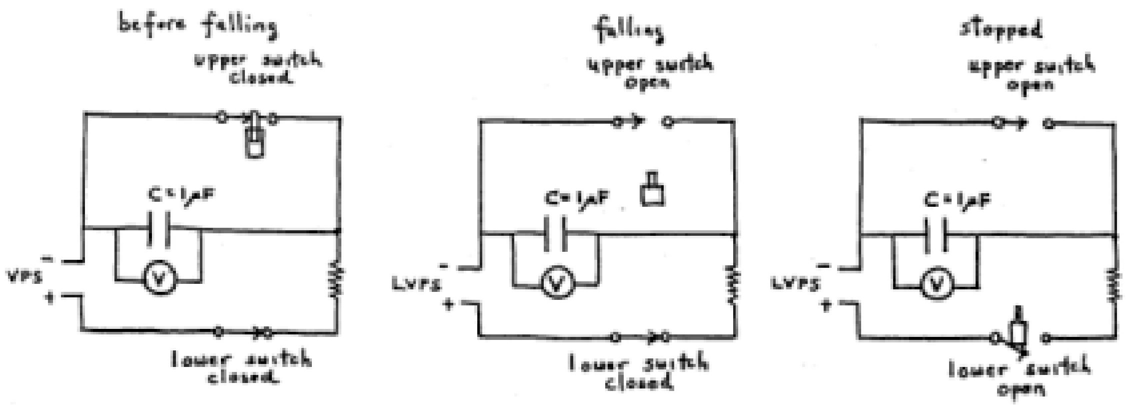


Figure 1: Circuit diagrams for falling object

Theory

The relation between height and time for free fall is given by

$$h = \frac{1}{2} g t^2 \tag{4.1.2}$$

The time of fall can be determined by measuring the voltage across a capacitor that is charging during the fall.

Let the voltage of the LVPS supply be V_0. The capacitor C is charged through the resistance R. When the capacitor is charging, the voltage across the capacitor varies in time according to

$$V(t) = V_0 (1 - e^{-\frac{t}{RC}}) \tag{4.1.3}$$

The voltage as a function of time is graphed in Figure 2.

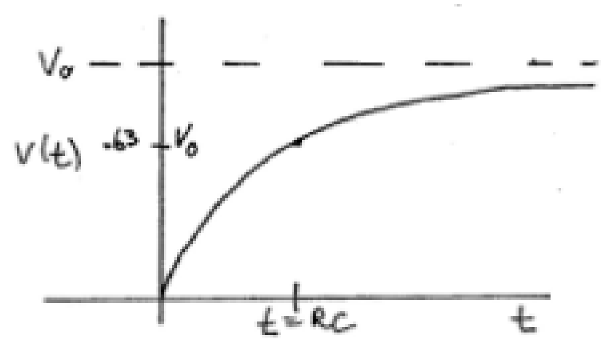


Figure 2: Graph of voltage as a function of time for charging capacitor

You will study capacitors in detail in 8.02X so for the moment we will use this charging voltage as a device to time how long the wire nut takes to fall a height h. wire nut hits the cup and opens the lower switch the charging current stops. You will then make a voltage measurement. So you will measure the quantities V, V_0, R and C.

The time of flight is experimentally much less than the product RC. This means that the exponential term in the expression for voltage, eq. (2), is approximately

$$e^{-\frac{t}{RC}} \approx 1 - \frac{t}{RC}.$$

Therefore the voltage is approximately

$$V(t) = V_0(1 - e^{-\frac{t}{RC}}) \cong V_0(1 - (1 - \frac{t}{RC})) = V_0 \frac{t}{RC}.$$

We can solve this equation for the time,

$$t \cong RC \frac{V(t)}{V_0} \qquad (4.1.4)$$

This equation tells us that our charging capacitor acts like a clock: the time elapsed is proportional to the voltage across the capacitor.

Now that we have measured the time of falling in terms of V, we can solve eq. (1) for the acceleration of gravity,

$$g = \frac{2h}{t^2} = \frac{2hV_0^2}{(RCV)^2} \tag{4.1.5}$$

The time constant, $\tau = RC$, of the 1.0 mF capacitor and the 10 MW resistor is given by the nominal value,

$$\tau = RC = (1.0 \times 10^7 \Omega)(1.0 \times 10^{-6} F) = 10s ,$$

that could be off by 10 % or more.

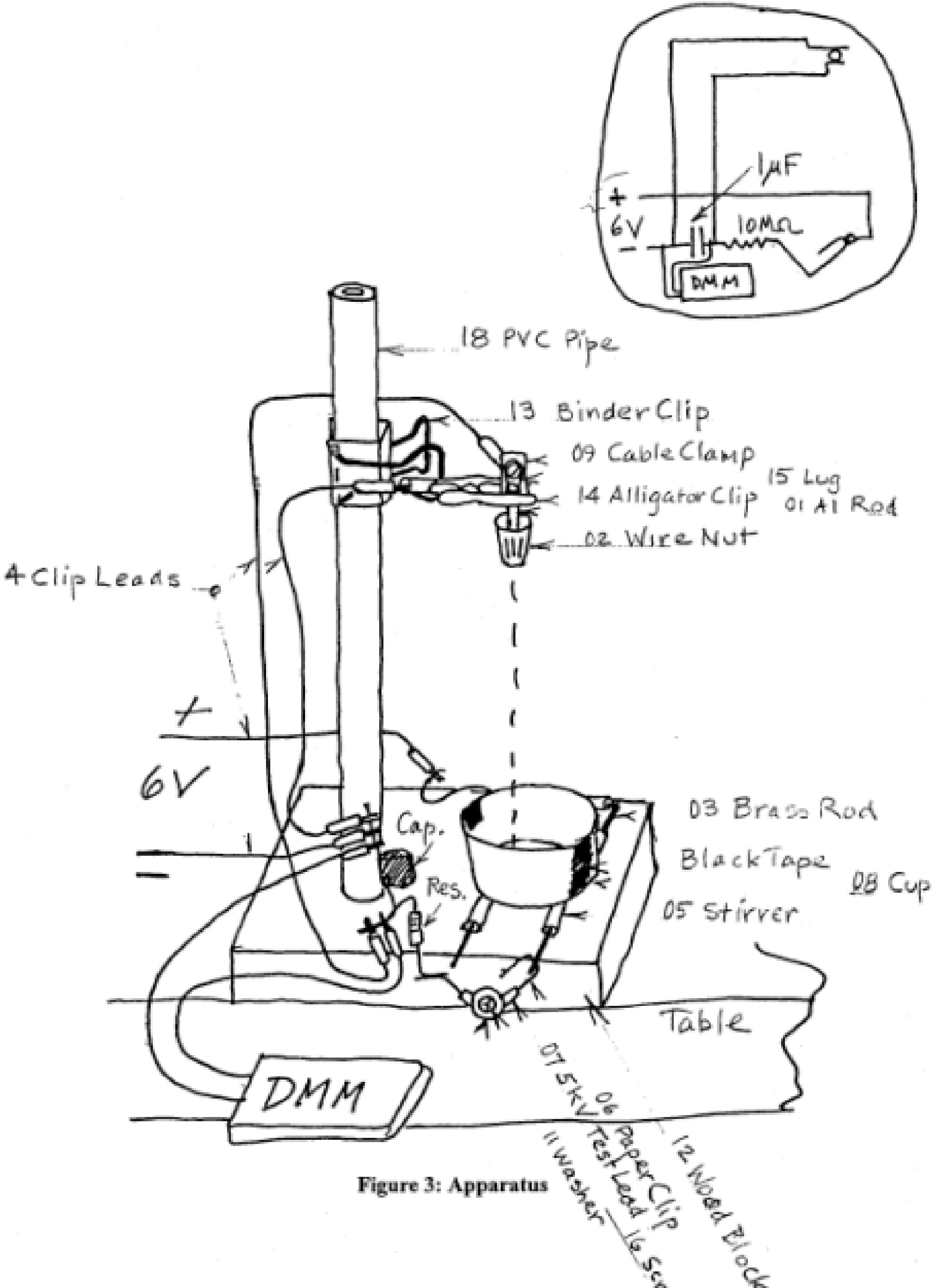


Figure 3: Apparatus

Apparatus

The apparatus is shown in figure 3. The wire nut has an aluminum rod screwed into it so that it can be held in the jaws of an alligator clip and released by squeezing the clip open. There is an insulated contact on one jaw of the clip; releasing the wire nut opens a circuit and allows the charging of the capacitor to begin. The binder clip that holds the alligator clip can be slid to various positions on the vertical piece of PVC pipe pressed into a wooden block clamped to your desk with a C-clamp.

On the wooden block is a switch made of a pivoted piece of bent brass rod, a paper clip and a cup to catch the wire nut. When the wire nut hits the cup, the switch opens and the charging current to the capacitor stops.

The apparatus is made of every-day stuff to illustrate what can be done without complicated, costly, specialized material. Just as describing a simple action like tying shoelaces in words can be lengthy, so are the instructions for assembling the 20 items into an apparatus that works properly and yields reasonably good data. **Assembly instructions and explanatory drawings are at the end of this hand-out.**

Experiment

After wiring up the circuit as shown in the diagrams, clamp the wire nut in the release switch, leaving the lower switch open. Set the LVPS to near 6 V and record the reading (and recheck it from time to time). Higher voltages up to 10 V may give better accuracy, but the automatic range-switching feature of the DMM between millivolt ranges and volt ranges, can give unreliable and unsteady readings.

Use your plastic ruler to measure the height (to the nearest millimeter) from the bottom of the suspended wire nut to the bottom of the cup in its lower position (lower switch open). Also measure the distance you have to raise the cup (just a few millimeters) to just close the lower switch from below—the position it has when it just opens. This distance has to be subtracted from the height

Close the lower switch.The DMM should read zero. Then release the wire nut by opening the alligator clip decisively but without shaking the whole works — squeeze it firmly between thumb and index finger — and **hold it open** until the wire nut has dropped into the cup and the DMM reading has reached a steady maximum value that you should record.

Put the wire nut back in the release switch; **then** close the lower switch. (This sequence avoids unnecessary charging of the capacitor.Then drop the wire nut again. Make 5 voltage measurements at each of 4 heights, eg. 0.2 m, 0.15 m, 0.1 m and 0.05 m.

Unsteady readings while holding the upper switch open arise from electrical leakage. Be sure that you are not touching anything besides the alligator clip. Leakage may be caused by high humidity, and a warm electric lamp nearby may help dry the apparatus out.

Analysis

For each height h, average the voltage measurements and using the formula in equation (3) for the time of a charging capacitor, calculate the time of fall.

Plot the square of the time (vertically) against h in m. There's also a point at the origin since it takes 0 time to fall 0 distance.

Fit the best straight line (by eye), and determine the slope. Since the relation between height and time for free fall is given by

$$h = \frac{1}{2} g t^2 ,$$

the slope of your graph can be used to calculate your average value for g,

$$g = \frac{2}{slope} .$$

Step-by-Step Assembly of Experiment FO Apparatus

Parts List

The parts are numbered as they appear in figures 4 and 5.

01	1”	1/8” Al rod
02	1	Wire Nut
03	8”	1/16” brass rod *
04	1’	#22 stranded wire
05	2	plastic stirrers
06	2	paper clips
07	2”	5kV test lead
08	1	paper cup *
09	2	cable clamps
10	2	#6 sheet metal screws
11	3	#6 steel washers
12	1	pre-drilled wood block * **(ALSO USED IN EXPT. FM)**
13	1	5/8” binder clip
14	1	alligator clip
15	1	solder lug
16	1	6-32 x 1/2" steel screw
17	1	6-32 steel nut
18	12”	1/2” PVC pipe *
19	1	10 MW resistor, 5%
20	1	1.0 mF 100-V capacitor, 10%,

The four items marked with an asterisk * are in the Redbox. The remainder are in a plastic bag.

Preliminary

1) Fig. 5a Hold the 1 inch long piece of 1/8 inch aluminum rod (01) with your slip-joint pliers and screw the wire nut (02) onto it so that they are firmly joined and the wire lies along the central axis of the nut. This is the “falling object”, and is shown in Fig. 5a.

2) Fig. 4a. Hold the 8 inch long piece of 1/16 inch brass rod (03) with your slip-joint pliers so that 4-3/4 inches sticks out sideways from the jaws of the pliers. Bend the rod to a right angle as in Fig. 4a.

3) Strip 1-1/2 inches of insulation off one end of the piece of #22 stranded wire (04). Don't twist up the strands. Cut the wire to 8 inches length and strip 1/4 inch off the other end and twist up the strands. Use the wire stripper, properly set for stripping the #22 wire. If in doubt, practice on the extra 4 inch piece.

4) Cut, with scissors, one of the plastic stirrers (05) into 3 pieces, one piece 1 inch long and two pieces 2 inches long.

5) Fig. 4i: Use long-nose pliers to straighten the smaller radius end of one of the paper clips (06) so that it becomes a hook. Hold the clip so that 1-1/2 inches sticks out sideways from the jaws of the pliers and bend it 90° into a V-shape as in Fig. 4i.

6) Cut a 1 inch long piece of 5 kV (kilovolt) test lead (07) with wire cutters. Use your long nose pliers to pull out the wire strands and wrapping thread from the rubber insulation, leaving in effect a piece of small-inside- diameter, thick-wall tubing.

7) Use scissors to cut around the paper cup (08) parallel to its rim 1-1/2 inches from the bottom so that the cup becomes smaller and less deep.

Assembly of the Lower Switch

8) Figs. 4a and 4b: Grasp the shorter bent part of the brass rod (03) and wrap the 1-1/2 inch stripped part of the stranded wire (04) about the rod, starting at the bend as shown in Fig. 4a. Slide the 1 inch length of plastic stirrer (05) over the rod and the wrapped wire, turning it as if to screw it on (Fig. 4b).

9) Fig. 4c: Hold the longer part of the brass rod (03) with your slip-joint pliers so that 3-1/4 inches sticks out sideways from the jaws of the pliers. Bend the rod to a right angle as in Fig. 4c so as to form a "U". Adjust the bends so that the arms of the U are parallel and in the same plane.

10) Fig. 4d: Bend the wire (04) back 180° so it's next to the stirrer and slip the plastic cable clamp (09) with its **flat side down** over the piece of stirrer and the wire as in Fig. 4d.

11) Fig. 4e: Use one of the sheet metal screws (10) and washers (11) to fasten the assembly of Fig. 4d to the wood block (12). Be sure that you use the pilot hole closer to the top of the block. The top side of the block is the one with the largest hole, 5/8 inch. A side view is shown, about 3 times full size, in Fig. 4e. Note: There should be enough friction so that the U-shaped piece barely falls under its own weight—this is to prevent it bouncing back when the falling object hits.

12) Fig. 4f: Slide onto the two arms of the U the two 2 inch pieces of stirrer, making sure that they don't extend beyond the edge of the block. Lift up the two arms and place a 6 inch length of black electrical tape, **adhesive side up**, on the wooden block with one end of the tape at the end nearest the 5/8 inch hole. See Fig. 4f. Press the arms of the U down so that the stirrer pieces stick to the tape.

13) Fig. 4g: Hold the cut-off cup (08) centered over the space between the two 2 inch pieces of stirrer (Fig. 4f) and pull up the tape on each side and down into the cup, as in Fig. 4g. Press the tape up so that it stretches and sticks to the bottom of the cup.

14) Fig. 4h: Screw a sheet metal screw (10) with a washer (11) part way into the wooden block (12) using the pilot hole closer to the bottom of the block.

15) Figs. 4h and 4i: Slip the piece of rubber insulation (07) over the right angle bend in the straightened paper clip (06) and attach it to the wooden block by tightening the screw and thus clamping the rubber insulated paper clip between the washer and the wooden block. See Figs. 4h and 4i. Note that the loop of the paper clip should be so positioned that the brass rod sits on it and can slip off easily. The straightened left end of the paper clip should be bent down as indicated by the dotted lines in Fig. 4h. To avoid electrical leakage, **no part** of the paper clip **should touch the wood block.**

Assembly of the Upper Switch

16) Fig. 5a: Clip the 5/8" binder clip (14) to the 12 inch long piece of 1/2 inch PVC pipe (18). Notice that by squeezing the clip levers slightly while keeping it pressed against the pipe you can slide it back and forth.

17) Figs. 5a: Take the alligator clip (14), remove the screw and put a #6 washer (11) on it. Replace the washer and screw with a few turns. Hook the screw and washer so the lever of the binder clip (13) is betwen the washer and the alligator clip as in Fig. 5a, and tighten the screw firmly.

18) Fig. 5b: Put the solder lug (15) on the 1/2 inch 6-32 machine screw (16), put the screw through the hole in a cable clamp from the flat side and screw on the 6-32 nut (17). With the small hole end of the lug lying on the flat side of the clamp tighten the nut moderately. See Fig. 5b. Use pliers to bend the small hole end of the lug so that it conforms to the curve of the clamp.

19) Fig. 5c: Loosen the nut (17) so that you can slip the clamp (09) over the stationary jaw of the alligator clip (14). Tighten the nut firmly. The lug is now sandwiched between the two jaws as shown in Fig. 5c.

Final Assembly

20) Fig. 6: Fit the PVC pipe into the 5/8 inch hole in the wood block with a careful rocking and/or twisting motion. A few taps with your slip-joint pliers may help seat the pipe firmly.

21) Fig. 6: With a well tinned soldering iron, tin the left end of the paper clip and solder one end of the 10 megohm resistor—no need to twist wires; simply hold them parallel and let the solder join them. Likewise, solder the 1 microfarad capacitor to the resistor, as shown in Fig. 6.

22) Clamp the apparatus to a desk or table. Use a C-clamp on the corner of the wood block furthest from the paper clip of the lower switch.

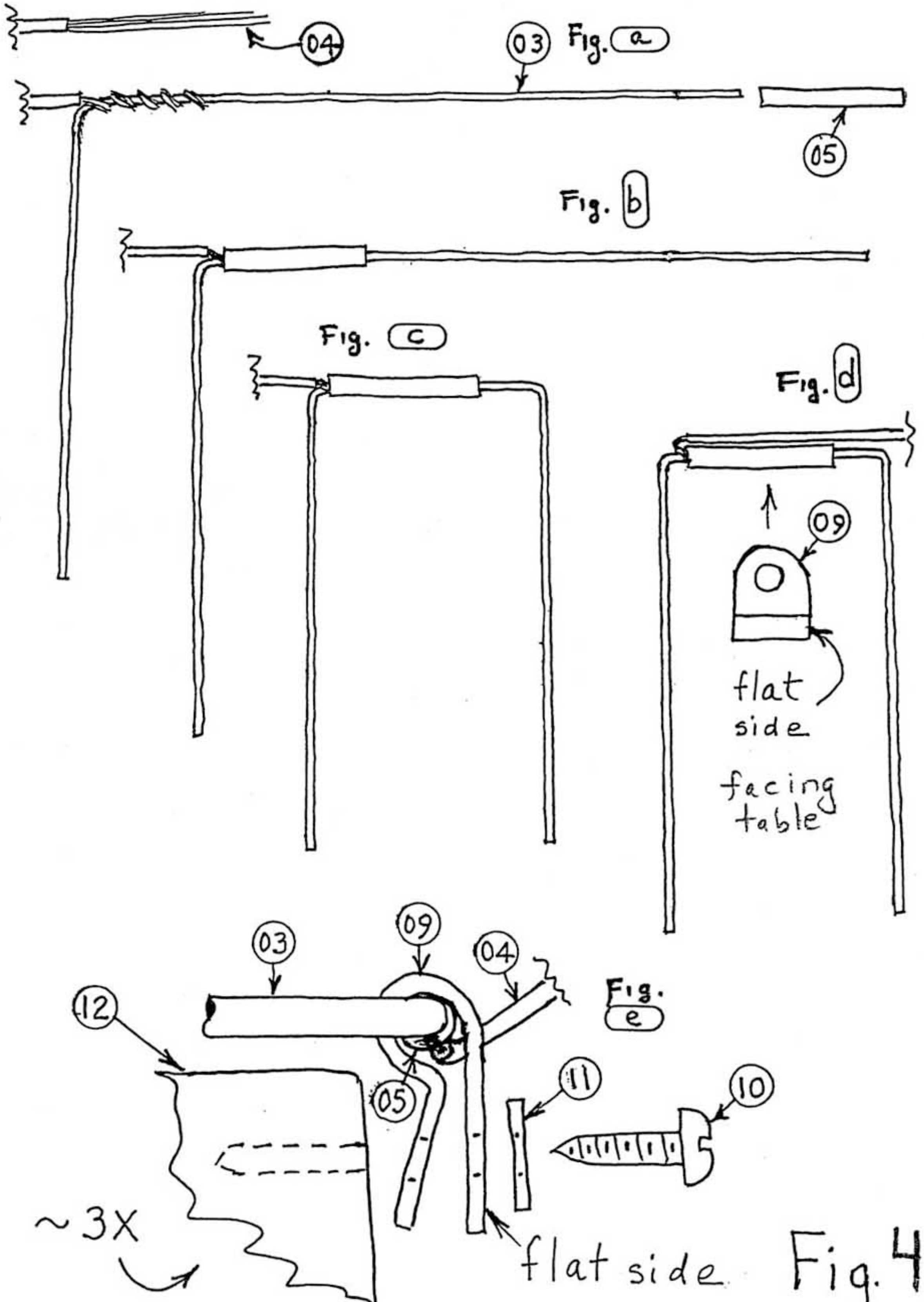
23) Connect the two switches, an LVPS, and a DMM to the resistor and capacitor with clip leads, as shown in Fig. 6.

Adjustment and Operation

24) Figs. 4h and Fig. 6: Slide the brass U sideways in its cable clamp hinge so that the right arm of the U rests on the U-shaped part of the paper clip as shown in Figs. 4h and Fig. 6. Hold the wire nut in your fingers and drop it into the cup from a height of ~2 inches—this should operate the switch and open the circuit.

25) Fig. 6: Slide the binder clip to the top of the PVC pipe with the jaws of the alligator clip approximately centered over the cup. Grab the aluminum rod of the falling object in the alligator clip, with the rod pointing straight down and with its end flush with the upper edges of the jaws. Again, see Fig. 6.

26) Try dropping the wiring nut and observe the action of the lower switch. It shouldn't bounce back up when the wire nut hits. Reclosing the circuit on bouncing will cause incorrect high readings. This was the reason for having some friction in the hinge. That friction can be increased by tightening the clamp screw or even by adding a straightened paper clip between the clamp and the piece of stirrer. If the switch doesn't open there's too much friction which can be reduced by loosening the clamp screw. Another way of preventing bouncing is to put a piece of electrical tape, adhesive side up, under the U of the lower switch so that the pieces of stirrer stick to it. Use three more pieces of tape to hold the first one to the wooden block.


04
03
Fig. a
05
Fig. b
Fig. c
Fig. d
09
flat side
facing table
03
09
04
12
Fig. e
05
11
10
~3X
flat side
Fig. 4

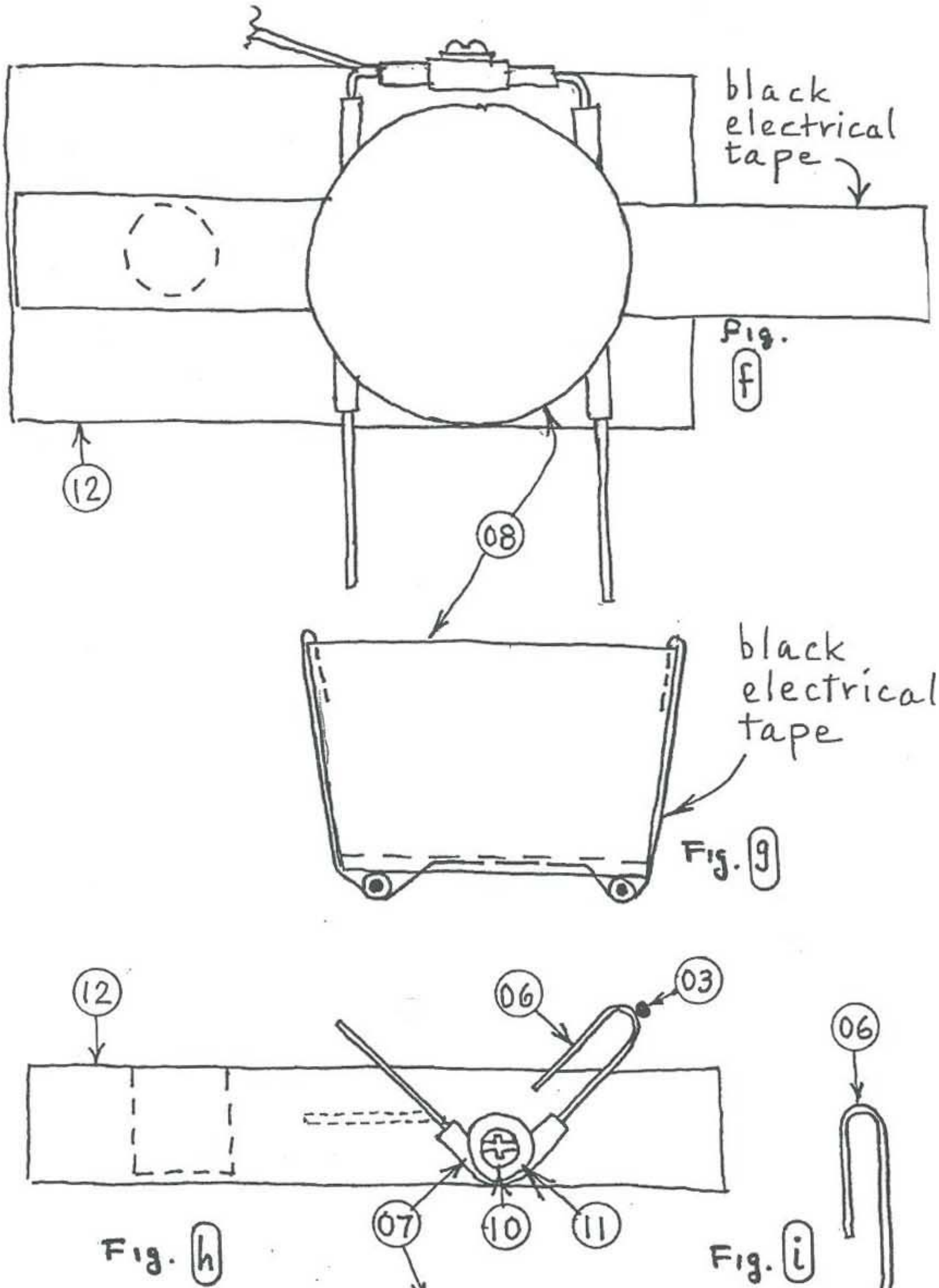


Fig. 4 (continued)

Fig. 5a

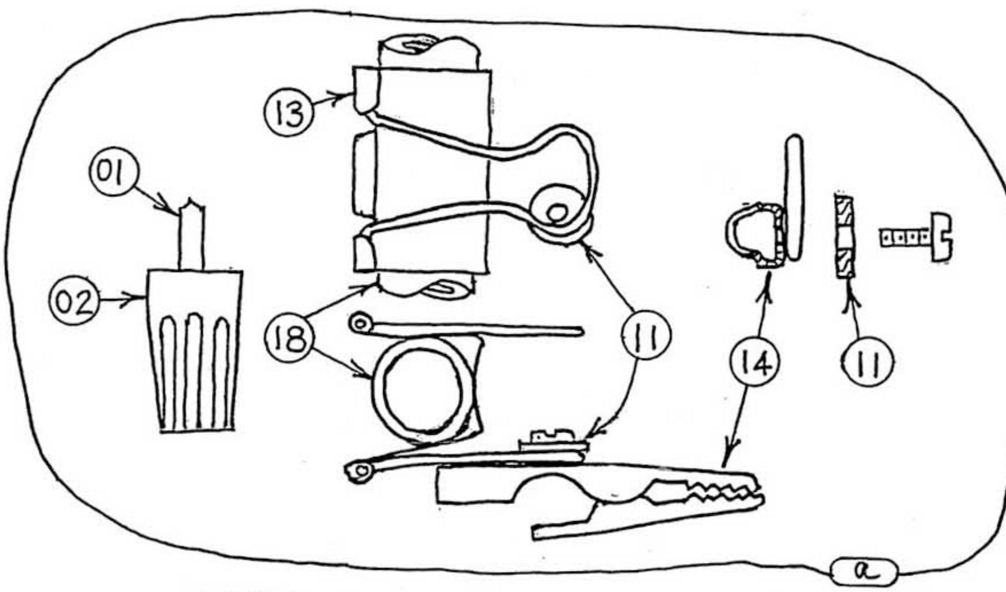


Fig. 5b

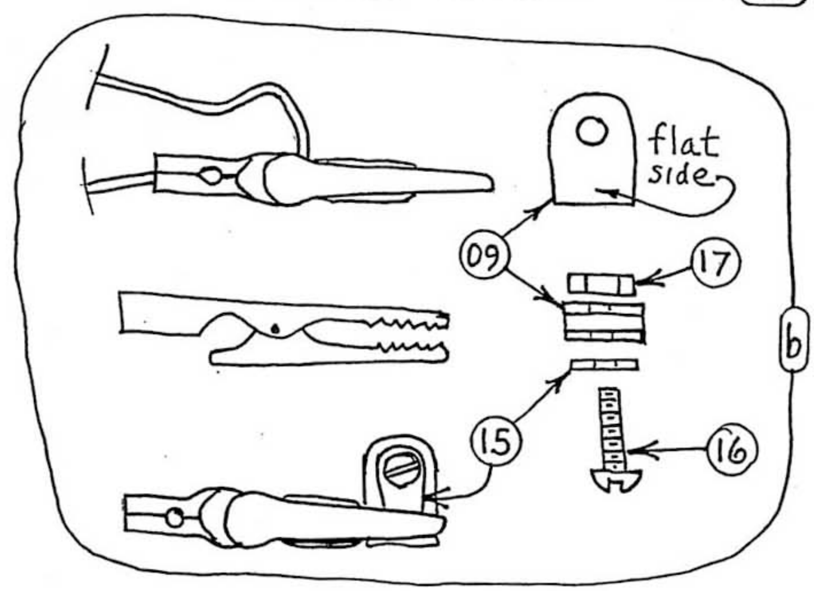


Fig. 5c

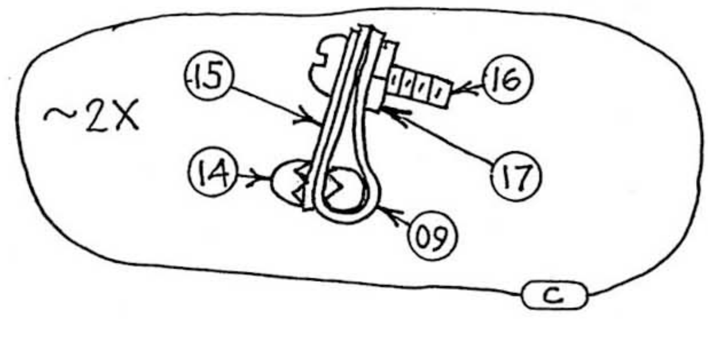


Fig. 5

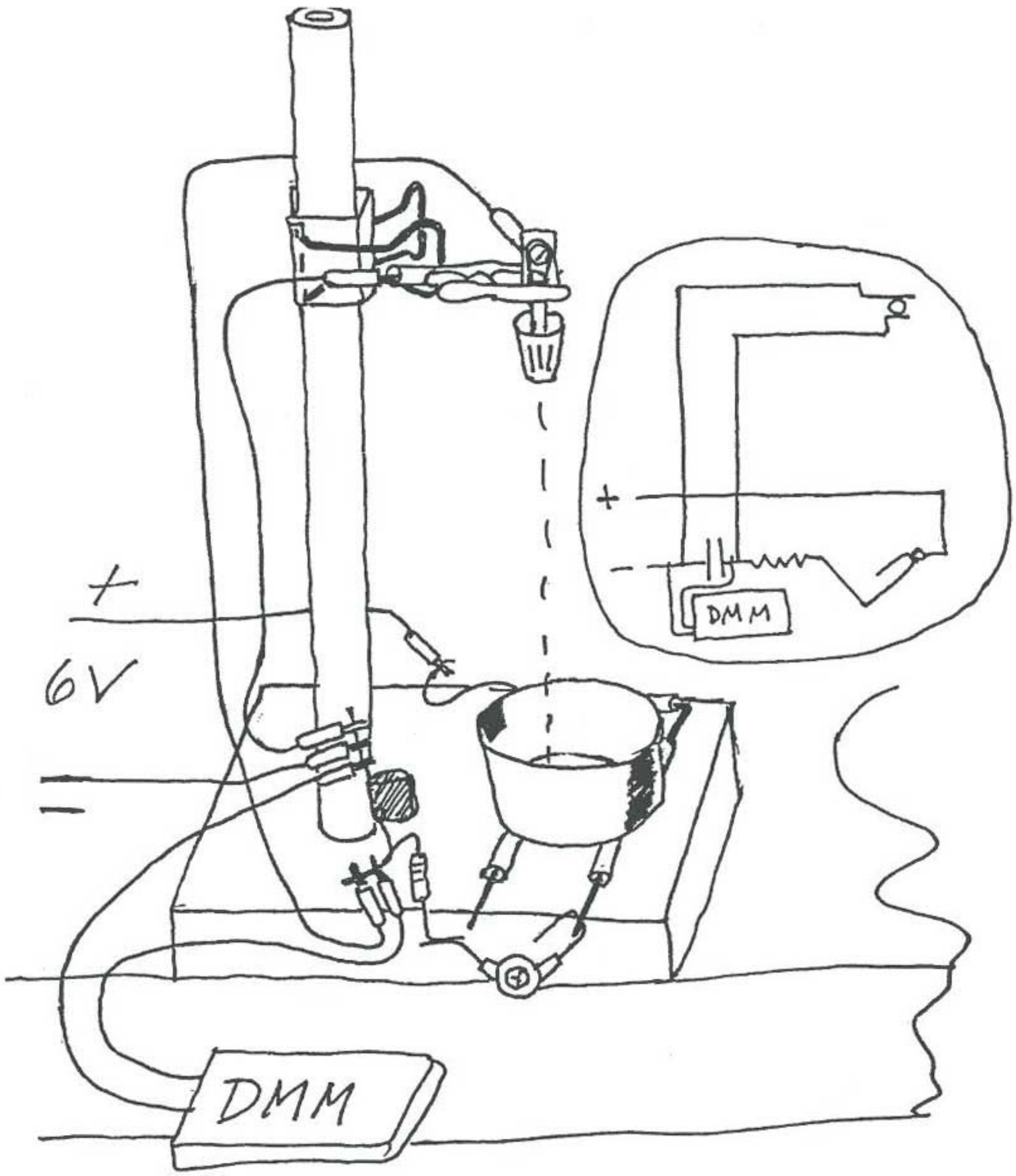


Figure 6

Experiment FM Force between Magnets

About Forces and Fields

There are forces that don't change appreciably from one instant to another, said to be constant in time, and forces that don't change appreciably from one point to another, said to be constant in space. The weight of a mass on the earth is an example, $\vec{\mathbf{F}}_{grav} = m\vec{\mathbf{g}}$.

There are forces that increase as you move away. When a mass is attached to one end of a spring and the spring is stretched a distance $|x|$, the spring force increases in strength proportional to the stretch, $|\vec{\mathbf{F}}| = k|x|$

There are forces that stay constant in magnitude but always point towards the center of a circle, for example when a ball is attached to a rope and spun in a circle, the tension force acting on the ball is directed towards the center of the circle. This type of attractive central force is called a centripetal force

There are forces that spread out in space such that their influence becomes less with distance. Common examples are the gravitation and electric forces. The gravitational force between two masses falls off as the inverse square of the distance separating the masses provided the masses are of a small dimension compared to the distance between them. More complicated arrangements of attracting and repelling things give rise to forces that fall of with other powers of r: constant, $1/r$, $1/r^2$, $1/r^3$, etc., Thus you might expect the force between 2 rectangular magnets to vary with distance in some not very obvious way—but calculable with time and patience.

In this experiment you'll measure the force F newtons (N) required to press two rectangular magnets together as a function of the distance between the centers of the magnets. One magnet will be fixed to a block and the other magnet will be suspended above. A cup is balanced on top of the upper magnet. Pennies will be added to the cup pressing the magnets together.

Assembling the Apparatus

- Press the aluminum wire into the hole in the wooden block. Don't bend the wire.
- Cut off a 100 mm length of the 7 mm OD plastic soda straw
- Make a hole (from below) in the center of the bottom of the Styrofoam cup with the Phillips screwdriver in your kit.
- Carefully enlarge the hole with the long-nose pliers so that the plastic soda straw fits tightly in the hole with one end flush with the bottom of the cup. NOTE: You can practice this first in the side of the cup if you like.

- Take the 140 mm length of number 22 wire and form a loop in the middle that will fit around the straw—just wrap it around. This is the centering wire.

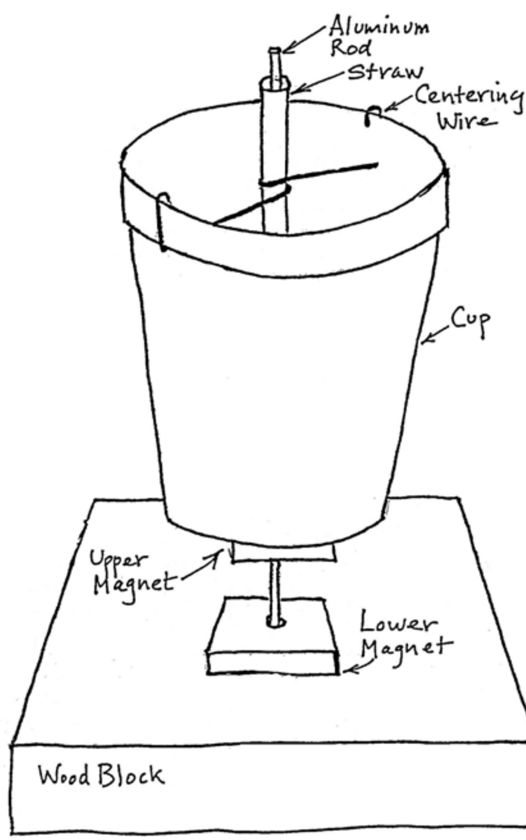
- Make two holes diametrically opposite in the side of the cup about 13 mm below the top edge, just below the reinforcing thicker part of the rim of the cup.

- Put the wire loop over the straw. Bend the straw first to one side and then to the other in order to put the ends of the wire through the two holes.

- Squeeze the cup a few millimeters out of round, until the straw is centered in the opening and bend up the wire on one side.

- Again squeeze the cup out of round, until the straw is centered in the opening and bend up the wire on the other side.

- Clamp the wooden block to your desk, put the two magnets over the aluminum wire in such a way that one repels the other and slide the cup with its central straw over the wire.



To make sure the apparatus is OK, press down on the cup with two fingers on a diameter until the magnets touch and release it—the cup should bounce up and down about 3 or 4