EE70L – Introduction to circuits lab

I. General comments

You need to know several things before even starting the first experiment in this class. Good lab practices are the key to safe and successful experiments. This chapter contains many important suggestions for you. You may not be able to understand everything at first, as some of the suggestions are given in a context you will encounter later on. Nevertheless, you should read the chapter carefully in its entirety now, so that when the situation arises you will be aware of this material. You should then come back to this chapter and reread as appropriate.

1. Safety

It is imperative to minimize the dangers of receiving an electric shock by following certain safety procedures. The effects of electric shock are determined by the value of the current that passes through the body, the frequency, the path followed by the current, the time the current persists, and so on. The effects of an electric current can vary from a startling reaction (with unpredictable results) to involuntary muscle contraction (resulting in the "can't let go" effect) to pain, burns, fainting, heart failure, respiratory paralysis, and death.

The amount of current that passes through the body is determined by the voltage applied to it and by the resistance through which the current flows. The resistance can become especially small if there are cuts, if the skin is wet or moist, and if the contact area is large (e.g., through a metallic object such as a watch or a bracelet). Furthermore, the resistance decreases once a current begins to pass. When the body resistance is small, even moderate amounts of voltage can cause a harmful amount of current. It is therefore wise to consider any voltage as dangerous and to take precautions to limit the chances of receiving an electric shock, as well as to be familiar with what to do in case one of your colleagues receives a shock.

- Before starting to work in the lab, familiarize yourself with the location of the circuit breakers and know where to call for help and what to do in case one of your colleagues is injured. Consult appropriate posters or leaflets. If in doubt, ask your instructor.
- Never work in the lab alone.
- Use equipment with three-wire power cords and with a properly grounded case (see the following chapter on ground connections).
- Inspect all cords, plugs, and equipment for possible damage, and notify your instructor if you see any such damage. Also notify your instructor if you see any other sign of trouble, such as loose wall sockets or sparks, or if you receive an electric shock, however small.
- Be careful when inserting or removing a plug. Do not remove plugs by pulling on the cord.
- While making connections, keep the power off.
- Do not touch bare wires and parts. If you have to do so, turn off all power first and unplug the equipment. Even then, be aware that capacitors can store electric charges and can give you an electric shock, especially if their capacitance is large and they are charged to a large voltage.
- Do not work when your skin is wet. Wear shoes while working, and be sure they are dry.
- Do not wear metallic objects such as bracelets, necklaces, rings, or chains while working.
- Do not lean against metal surfaces, such as the case of a piece of equipment, pipes, or the frame of your lab bench.
- Do not leave lose metal parts, including wires, on your bench.
- Do not place drinks or food on your bench.
• If somebody else in the lab receives an electric shock, immediately turn off the power and/or remove the victim from the source of electricity without coming into electrical contact yourself (e.g., use a dry piece of wood, a dry piece of cloth, or a nonmetallic belt). Follow appropriate procedures for calling for help, providing artificial respiration and/or cardiopulmonary resuscitation, and otherwise providing aid until medical help arrives.

Possibilities for hazards other than electric shock also exist in an electronics laboratory. Do not exceed the voltage and/or power rating of electronic components. Be very careful to observe the polarity of electrolytic capacitors, which can explode if connected in the wrong way. Be aware of the fact that electronic components can overheat. Be careful with sharp objects, such as wire ends, component terminals, and integrated circuit pins. Be careful with soldering irons; they can cause burns or fires. Long hair and loose clothing can cause hazards when tangled with circuit boards, equipment, soldering irons, or machinery with moving parts.

Additional considerations and rules may apply in your situation and environment. If in doubt, consult your instructor.

2. Wiring your circuit

There are several ways in which you can build an experimental circuit (as opposed to a permanent one, meant for repeated use). A common way to conveniently assemble a circuit without having to solder is to use a plastic "proto" board. This section has been written for the use of such boards, but many of the wiring suggestions given here apply to other types of boards as well.

A plastic proto board has sets of holes into which wires can be inserted. Inside each hole, invisible to you, is a metallic socket appropriate for snugly receiving a wire pushed into the hole. Sets of sockets, arranged in rows and columns, are connected together internally. An example of part of a proto board is shown in Fig. 1.

The holes as they appear externally are shown in (a); the internal connections under the surface are revealed in (b). Each set of holes connected together as shown can form a single node in a circuit. Most sets contain five or six holes and are used for internal nodes in the circuit. Other sets, such as the ones shown vertically in (b), are used for power supply and ground connections. On some boards, some of these sets may be broken into separate parts, as indicated in the second vertical line in (b). There are several variations of proto boards, more or less based on this general scheme. Your instructor can explain the internal connections of the particular board you will be using (or you can find them out yourself by using an ohmmeter as a continuity tester, as explained in Experiment 2; you can attach small pieces of wires to the ohmmeter's probes and insert those into the holes). Proto boards are appropriate for low-frequency work (up to a few MHz). At higher frequencies, the large capacitance between adjacent rows of connector holes can interfere with proper operation.

To make connections to a proto board, use pieces of insulated solid (not stranded) wire of an appropriate diameter (usually #22 to #24 AWG), the insulation of which has been removed on both ends, exposing about
12 mm (or about 0.5 inches) of bare wire. Several different lengths of such wires may be appropriate for a given circuit. Sets of connecting wires are commercially available in various lengths and colors. To insert a connecting wire, make sure its bare ends are straight and push each end vertically all the way into a hole. A pair of long-nosed pliers can help in this task. Electronic components such as resistors, capacitors, or integrated circuits can also be plugged directly into a proto board. In the case of resistors, common Vi W ones have lead diameters that are well suited for this purpose. Resistors with a larger power rating may have leads that are too thick, which can damage the connections in the board.

It is very important to get into the habit of wiring a circuit neatly right from the beginning. A neatly built circuit is less likely to contain mistakes, it is easier to debug, and it is easier for a colleague or for your instructor to understand. Figure 2(a) shows a neatly wired circuit, whereas Figure 2(b) shows a messy one. In principle, both wirings implement the same circuit; but if your wiring habits are like those in Figure 2(b) you will soon run into trouble. Several hints to help you form good wiring habits follow. You can interpret several of them by referring to Figures 2(a) and 2(b).

![Fig.2](https://example.com/fig2.png)

- Keep the power off while you are wiring your circuit, as well as while you are changing anything in it.
- Always start with a carefully drawn schematic of the circuit you want to build, properly labeled with component types or values and pin numbers for integrated circuits. Do not try to do things directly from memory.
- Mark all completed connections on your diagram as you go, for example, by using a color marker.
- Use connections as short as possible. Long wires contribute to messiness and can cause interference through undesirable capacitive, inductive, or electromagnetic interaction with other parts of the circuit. (This suggestion does not imply that you need to cut each wire exactly to size; for this lab, it will be sufficient to choose the right length among several pre-cut wires commonly found in a wire kit.)
- Keep wires down, close to the board's surface.
- As a rule, if you can connect components such as resistors or capacitors directly (without extra wires connected to them), do so.
- Plug in chips so that they straddle the troughs on the proto board. In this way, each pin is connected to a different hole set, as shown in Fig. 3(a). Fig. 3(b) shows a common mistake (for a six-hole set proto board).

![Fig.3](https://example.com/fig3.png)
Why is this practice wrong? You can answer this question by considering how the holes are connected together internally [Fig. 1(b)]. You can also see why the practice shown in Fig. 3(c) for a two-trough board is most likely inappropriate when working with more than one chip.

• Do not pass wires over components (or over other wires, if you can avoid doing so without significantly lengthening a connection). This makes the circuit difficult to figure out, and it makes it difficult to remove a component if you have to replace it.

• Use the longer strings of holes as power and ground "buses." For example, use one such string for the connections to the power supply pins of your chips and other components, and wire that string to your power supply.

• Be sure that bare wires or component terminals are clear of each other so that they cannot become accidentally shorted together if something is moved.

• Do not use more wires than you have to. The more connections, the more likely it is that something can go wrong (e.g., a wiring error can occur, or a connection in the proto board can be loose).

• Use color coding for your wire connections (e.g., red for all wires connected to the positive power supply and black for all wires connected to "ground"). This makes it easier to inspect and debug the circuit.

• If convenient, locate components associated with a circuit with a well-defined function, close to each other in one group. For example, if your circuit includes a preamplifier, all components that are part of the preamplifier should be physically located close to each other, in an easily identifiable block. This can help later during the debugging process (see below).

• Before plugging ICs (integrated circuits) into a proto board, be sure that their pins are straight. The tips of the two rows of pins on the ICs you will be using in this lab should be 0.3" apart. Sometimes you will find some ICs with their pins bent; in that case, straighten them before plugging in the ICs. A pair of long-nosed pliers can make this task easy, as then each row of pins can be straightened at one time.

• Be aware of the fact that ICs, especially those made with MOS technology, can be instantly damaged by static electricity, such as that accumulated by your body. You should make sure you are "discharged" before handling them, by momentarily touching the metal case of a properly grounded instrument.

• Be sure to use resistors with a sufficiently high power rating (Vi W resistors are fine in almost all circuits in this lab) and capacitors with a sufficiently high voltage rating. Observe the polarity on electrolytic capacitors - they can explode if connected in the wrong way.

• Be sure capacitors are discharged before plugging them into a circuit. If in doubt, short their leads (in critical cases you may have to do so at least twice, as a capacitor can have residual charges even after you have discharged it once).

• Unplug ICs very carefully to avoid bending the pins. You may want to try an IC extractor if one is available in your lab.

• For points that must be connected to external instruments such as power supplies and function generators, connect a wire from an appropriate hole on your proto board to a sturdy post (such as a banana or coaxial socket, often available on the larger test board on which a proto board may be mounted). Then, use an appropriate cable to connect that post to the instrument. This helps make your connections mechanically stable.

• For the inputs of measuring instruments, such as voltmeters and oscilloscopes, you should normally follow the same practice as above. An exception to this rule occurs when you want to probe several different points in your circuit by moving the instrument probe from point to point or when the connection to the instrument probe must be as short as possible. If you have to connect an instrument probe to a hole on your proto
board, you can do so through a short piece of wire; be sure the connection of this wire to the probe is not loose and does not touch any other connections.

- The coaxial connector of oscilloscope probes (Experiment 3) should only be connected to the input of the oscilloscope. It should never be connected to the function generator, to other instruments, or to your test board.

- Be especially careful of ground connections. Read carefully the chapter on ground connections.

- When finished wiring a circuit, inspect all connections to make sure you have made no mistakes. Only when you are happy with the result should you turn on the circuit.

- If you have connected a signal source (such as the output of a function generator), do not turn it on until after you have turned on the power supplies, if any are used in your circuit. Some ICs can be damaged if you do otherwise. If you later want to turn off the power, turn off the signal source first. In short, never have a signal connected to a circuit with power supplies unless those supplies are on.

3. Debugging

It is very likely, despite the care with which you may have wired your circuit, that it will not work when you first turn it on, perhaps because of a defective component or a wrongly designed circuit; often, however, this is due to a missing or wrongly connected wire, a loose connection, bent IC pins that have not been properly inserted into holes on the board, an unintended short between two bare wires or terminals, and so on. You will then need to debug, or troubleshoot, your circuit. Trying to do so for a large circuit can be a very difficult task (made easier with experience). Following are some tips to help you debug your circuit.

- Turn off your circuit and visually inspect it for wrong connections or accidental shorts.

- Be sure that you know the correct underlying connection pattern of your proto board and that you have not made any mistakes in this respect. Beware of breaks in some power supply or ground buses on some boards [see Fig. 1(b)]. Beware of mistakes such as those shown in Figs. 3(b) and 3(c).

- If you suspect that a connection is not made as intended, you can use an ohmmeter as a continuity tester (see Experiment 2), but first make sure that all power to the circuit has been turned off.

- A malfunctioning circuit may have overheated components. Be careful with them. On the other hand, a hot component may be a clue to the problem.

- If your power supplies have a current meter, observe it. If the current is zero, it may be a sign of a missing connection. If it is excessive, it may be a sign of a short or other problem.

- In some power supplies you can set a current limit. You may want to limit the current accordingly, to protect your components in case of circuit errors. On the other hand, if this limit has been set too low (lower than the expected total current for the circuit), it may be the very reason the circuit does not work properly.

- Use a voltmeter to test whether the power supply voltage reaches an intended point in the circuit, attaching one of its terminals to ground and the other to that point. Test all such points if necessary. A zero voltage may indicate a broken connection or a short to ground. If a voltage is correct at some point, move your probe to the next point where this voltage, or part of it, is supposed to appear, and remeasure. It is usually better to do this type of testing with only the power supplies on and any signal sources off.

- If the proceeding procedure does not reveal the problem and if your circuit contains a signal source, turn it on and do some further sleuthing with the oscilloscope: Is the signal present at the output of the signal source? If so, is it present at the input of your test board? If not, you may have a bad cable or a short to ground. If there is a signal at the input of the board, is it also present at the next logical point (e.g., at an IC pin to which the board input is supposed to be connected)? The idea is to eliminate possible problems one by one until you hit the points that are causing the trouble.
• Unless the circuit is very simple, do not try to check its behavior all at once. Rather, do some sleuthing to find out where the problem lies. If the circuit can be broken down (physically or mentally) into two independent parts, check each part separately (e.g., the preamplifier and the power amplifier of the sound system in Experiment 4). To do this, you may need to power the part being tested separately from the rest of the circuit, apply to it an appropriate signal (e.g., obtained from the function generator), and check its output accordingly (e.g., using an oscilloscope). The use of the function generator and oscilloscope is described later.

• You can carry the above hint one step further: When wiring a large circuit, you can first wire a part of it and test it by itself to make sure it is correct before proceeding to wire the rest. For this approach to work, of course, you need to be sure that the part you are testing is independent of the rest and is supposed to work correctly by itself.

• If you must try to find out what the problem is by changing things on your test board, change them one at a time, observing the result in each case. If you change more than one thing at once, not only may you be unable to isolate the cause of the problem, but also the second change may undo the result of a first, correct change, and you will have missed your chance to make the circuit work.

• In some cases problems can be caused by external interference (from a TV station, from lighting or other equipment in the room, etc.). Such interference can be picked up by long wires connected to your circuit (e.g., those carrying power to your setup), which can act as antennas. In such cases, you may be seeing a signal at the output of your circuit, even though no signal is being applied at its input.

• If all else fails, and only as a last resort, you may have to disassemble your circuit and start from scratch, especially if sloppy wiring in your first version prevents you from identifying the problem. This time, it is hoped, you will be more careful and neat with your wiring.

• This last solution should not be overused. You should stick with your original circuit and persist in looking for the problem. You can learn a lot not only from properly working circuits but also from knowing what went wrong in bad ones.

4. Lab Reports

There are many types of lab reports, which vary according to the kind of information that has to be reported, the level of informality, and so on. Your instructor will let you know what type of report he or she expects. Unless your instructor indicates otherwise, it is wise to adopt the following practices.

• Use a pad of quad graph paper (with squares V** on a side). The squares will make it easier for you to construct tables and plots and to draw schematics.

• Be sure your report is orderly and neat. Conciseness is appropriate for some styles of reporting, but sloppiness isn't. Even you may find it hard to follow your own sloppy report a few weeks after you have written it.

• Include a careful schematic for each circuit you have built, labeled with component values, types and pin numbers of ICs, and other pertinent information. This is needed for anyone (including your instructor, your colleagues, or even yourself at a later time) to be able to interpret what you have done. In some cases, you may even want to include a board-level layout of your components and connections, corresponding to their physical location on your proto board.

• When preparing plots, label your axes appropriately, including tics and values along them; the quantity being plotted along each axis; and the corresponding units.

• Show experimentally obtained points as dots or small circles on plots. Be sure to take a sufficient number of points to appropriately show the behavior you are investigating, especially in regions where rapid variations are observed. Points that are far apart may completely bypass such regions.

• Pass a best-fit line through the points on your plot. Do not simply join them with straight-line segments.
• When asked to plot a variable y versus a variable x without further specification, consider what ranges and values are appropriate. When asked to plot current versus voltage for a resistor, for example, it is appropriate to use both positive and negative voltage values unless instructed otherwise.

5. Preparation

Always study the experiment you are going to do before coming to the lab. Read each instruction carefully, trying to imagine your experimental setup. Try to anticipate the probable results of your measurements, as well as what to watch out for and what problems are likely to arise. Take notes as appropriate. Being fully prepared is necessary for you to be able to finish an experiment in the time allowed and to be able to benefit from it as much as possible. The experiments in this book are based on the assumption that you will have fully prepared yourself before doing each one. You also owe it to your lab partner to be fully prepared, so that you can contribute to the experiment.

6. Running an experiment

• Always read each step in its entirety before acting. Do not stop in the middle of a step and start wiring or measuring, as the rest of the step may contain information relevant to those tasks, which can save you time or trouble.

• Try to guess the likely result of each step before you perform it. This will enhance your understanding and will prepare you to catch a possible problem, saving time.

• Do not put off plotting or other tasks until the end of the experiment. Do plots when asked to. This is because some plots reveal information that can be useful in interpreting your results and identifying potential problems before time is wasted on a possibly malfunctioning circuit. Plots can also tell you whether you need to measure more points before going further, while you still have your circuit connected for doing so. Finally, they can give you intuition and information that will help you in the subsequent steps. Again, completing each task when asked to in each experiment can save time and trouble.

• Measurements are never exact. Keep this in mind, but otherwise try to obtain measurements as accurately as possible. Think about the sources of measurement error in each case, and interpret your results accordingly.

• Use an appropriate range on measuring instruments to obtain enough significant digits. On the other hand, you should not overdo this. It is not appropriate to give the impression of precision by keeping more digits than makes sense in a given situation. Also, with some instruments (such as some ammeters; see Experiment 1), the range chosen can affect the degree to which the instrument affects the circuit under measurement.

• Be very careful if you need to obtain a small quantity by subtracting two much larger quantities. For example, 1.344 - 1.336 = 0.008, but if the two numbers had been measured with three significant digits, you would have gotten 1.34-1.34 = 0.

• Become very familiar with your test instruments. Do not arbitrarily push buttons until you get something; know which buttons to push.

• If you are doing an experiment with a lab partner, make sure you both contribute equally. If you do not contribute, you are not only being unfair to your partner but also not really learning. Passive observation cannot replace doing. If, instead, you are the type that takes over and would rather do the lab by yourself, you are hurting your partner's learning process. Be sure both of you have a chance to do each type of task. For example, if you wire and your partner takes measurements, the next time around your partner should do the wiring and you should measure.

• REMEMBER: Above all, resist the temptation to just blindly follow the procedures. If you just do so, take all the measurements correctly, and write your report, you will have wasted several hours. Observe, think, act, and discover. Many of the "why" questions in this book are meant to just make you think. But do not stop
there. Ask yourself, as often as you can, why something is done in a certain way, why it works or doesn’t, or what would happen if something were done differently. This is a very important part of your education. Discuss such questions with your lab partner. If you have ideas that you want to try, first make sure they are safe; if in doubt, ask your instructor.

7. Ground connections

The issue of ground connections is one that will concern you again and again, in this and in other labs. Read this chapter carefully, and try to understand it as much as possible. Not everything in it may make perfect sense in the beginning; some of this material will become clearer as you gain laboratory experience. Nevertheless, it pays to have a preliminary understanding at this point. As you attempt to connect various instruments in future experiments, you may need to return to this chapter for advice.

a) Producing positive or negative supply voltages with respect to ground

Lab instruments have terminals so that you can connect them to the circuits you are working with. For example, a "floating" power supply has plus (+) and minus (-) terminals. The voltage between them is a well-defined quantity, which you can set at will. However, the voltage between one of these terminals and a third point, such as the instrument's metal case (if it has one) or the case of another instrument, may not be well defined and may depend, in fact, on instrument construction and parasitic effects that are not under your control. Parasitic voltages can interfere with proper operation of the circuits you are working with, or can even damage them. Worse, in some cases they can cause an electric shock. To avoid such situations, the instruments have an additional terminal called the ground, often labeled GND or indicated by one of the symbols shown in Fig. 1;

![Fig. 1](image1)

the use of this terminal will be explained shortly. The ground terminal may be connected to the internal chassis of the instrument (it is some-times referred to as the chassis ground); to the instrument's metal case; and if the power cord of the instrument has three wires, to the ground lead of the cord's plug. When you plug in the instrument, this lead comes in contact with the ground terminal of the power outlet on your bench, which is connected to earth potential for safety and other reasons. In fact, other instruments on your bench, on other benches, or even elsewhere in the building may have their grounds connected to that same point, through the third wire of their power cords.

When you use a power supply with the output floating (i.e., with neither of the output terminals connected to ground), you get the situation shown in Fig. 2. The little circles indicate terminals for making connections to the instrument's output or ground. In the following discussion, \( v_\text{X} \) will denote the voltage from a point \( X \) to a point \( Y \). In Fig. 2, \( v_{AB} \) is the power supply's output voltage \( V \), and it is well-defined. However, \( v_{AG} \) and \( v_{BG} \) are not well defined and can cause the problems already mentioned. To avoid this, you should strap one of the two output terminals to the ground terminal, as shown, for example, in Fig. 3(a). Now all voltages are well defined: \( v_{AB} = V, v_{BG} = 0 \), and \( v_{AG} = v_{AB} + v_{BG} = V + 0 = V \). If we assume that \( V \) is a positive quantity, the connection in Fig. 3(a) develops a positive voltage at terminal \( A \) with respect to ground. If you happen to need a negative voltage with respect to ground instead, you would use the connection in Fig. 3(b). Here terminal \( B \) has a potential of \(-V\) with respect to ground. In some power supplies, ground connections as shown in Fig. 3 are permanent, and you do not have access to them. In other power supplies, it is up to you to make such connections.
b) Connecting one instrument to another

When more than one instrument or circuit with ground connections are used, one should think carefully. Consider the situation in Fig. 4, where it is attempted to connect the output of one instrument to the input of another. For example, instrument I can be a function generator, discussed in Experiment 3. Instrument 2 can represent an oscilloscope, or an oscilloscope probe, also discussed in Experiment 3. At first sight, the connections shown seem to be correct. However, there is a big problem. Although not apparent from Fig. 4, the ground terminals are connected not only to the instrument cases but also to the common ground of the power outlet on the bench (through the ground pin on the power plug, as explained earlier). Making these connections explicit, we have the situation shown in Fig. 5. It is now clear that the second instrument's ground connections short the first instrument's output across CD (i.e., they place a short circuit across it; you can trace this short circuit along the path CIHGED). Not only will this prevent a voltage from being developed at that output, but also it can damage the instrument. The problem is solved if the connection between the two instruments is modified, so that instrument ground is connected to instrument ground, as shown in Fig. 6.

At this point, one may wonder what the connection marked x is needed for in Fig. 6, given that the two ground terminals are connected together anyway through the power cables, as shown by the heavy lines. The answer is that there may not always be a ground terminal on the power plug, and even if there is one, it may not be reliable; although ideally all ground terminals on power receptacles should be at the same potential, they sometimes are not. In addition, the long ground wires (IH and GH in Fig. 6) may act as antennas, picking up interference. To be safe, then, use a short connection such as x between the ground terminals of the two instruments.

A final word of caution: Since an instrument's case is in contact with ground connections, you need to be sure that cables and devices do not accidentally come into contact with it. If this happens, malfunction or damage can occur.

These guidelines will be sufficient for the purposes of this lab. Grounding is actually a complicated issue, and you should not expect the simple practice discussed above to be adequate in all situations. As you gain experience, you will obtain a better feel for grounding practices.
II. Instruments Basics

1. The Power Supply (PS) and the Digital Multimeter (DMM) (Experiment 1)

The PS will be used to power the circuits you will be building. The DMM is one of the most important instruments in the EE laboratory, and it is one of the simplest to understand and to operate. You will find a PS and a DMM on your bench. Simple user's manuals for both instruments may be made available by your instructor. In this experiment, we will use the DMM to measure DC voltage and current. Study the face of the PS and the DMM, and try to guess the function of each control before proceeding.

The following instructions have been written for a generic DMM. The particular type you will be using may have to be operated somewhat differently. Your instructor will tell you if additional settings, considerations, and precautions apply to the particular DMM type you will be using.

a) Voltage measurements

1. Set up the DMM as a voltmeter. This will involve both pushing the appropriate buttons and connecting the DMM's leads (one of which is red, and the other black) at the appropriate DMM terminals. In some DMMs, the terminal to which the red lead should be connected is red itself or is labeled HI, or V; the terminal where the black lead should be connected is black itself, or is labeled LO or COM. If you do not see these markings, ask your instructor for help. If there is a DC/AC button on the voltmeter, set it to DC since only DC (constant with respect to time) voltages and currents will be measured in this experiment.

If the DMM is properly set up as a voltmeter, it will behave approximately as an open circuit. Make sure you do not set it up as an ammeter (current meter), in which case it will act as a short circuit and, if improperly used, can cause damage.

To measure a voltage between two points, a voltmeter must be connected across the two points so that it can sense the potential difference between them. If you want the potential of point K with respect to point L, you need to connect the red terminal of the voltmeter at K, and the black terminal at L. You should not disconnect anything in the circuit under measurement in order to measure a voltage in it.

2. Connect the - terminal of the PS to the PS's ground terminal. Turn on the power supply (PS). Connect the black DMM lead to the - terminal of the power supply, and the red lead to the + terminal. Measure the voltage of the PS for various settings of its voltage knob. For a reliable measurement, you should set the voltmeter to an appropriate measurement range. The range must be one for which the maximum measurable voltage is higher than the voltage you are trying to measure. Also, the range should be such that a sufficient number of decimal places are shown in the voltmeter display; for our purposes, two decimal places are enough. Experiment with various range settings of the voltmeter, and try to fully understand their purpose and function. What will the problem be if the range on the DMM is too small for the voltage being measured? If it is unnecessarily large? Compare the reading of the DMM to that of the PS's own volt-meter, if there is one. Be sure you interpret the units on the instruments correctly (e.g., mV means 0.001 V).

3. Set the PS voltage at a certain value, and record the reading of the DMM. Then, without changing the PS and DMM settings, interchange the connections of the DMM's leads at the PS and record the new reading. How are the two readings related? Why?

4. Set up the circuit shown by the solid lines in Fig. 1. Although many devices can in principle be used as element X in the figure, for our purposes this element will be a resistor with a value of several kΩ which will be provided to you. The switch shown is not part of the PS; you should use a stand-alone switch provided to you. Set the PS voltage at a few volts. Now attach the voltmeter, as shown by the broken line, and measure the voltage of point K with respect to point L, with the switch open and
with the switch closed. Now measure the voltage of point L with respect to point K. Relate this reading to the previous one and explain. 

![Fig. 1](image1.png)

**Fig. 1**

![Fig. 2](image2.png)

**Fig. 2**

**b) Current measurements**

5. You will now prepare for measuring, in step 6 below, the current through element X. First, disconnect the DMM from the preceding circuit, leaving the rest of the circuit connected. Configure the DMM as an ammeter (current meter). This will involve both button pushing and selecting the appropriate DMM terminals for connecting the red and black leads. In some DMMs, these terminals may be the same as those used for voltage measurements; in others, the red lead may have to be connected to a separate terminal, which may be labeled A.

To measure a current at a given point in a circuit, you need to break the connection at that point and insert the ammeter there. To measure the current in a given reference direction, you need to make the current enter the ammeter at the red lead, go through the ammeter, and exit from the black lead.

If a DMM is properly set as an ammeter, it will appear approximately as a short circuit (or "short," for short :-) between the two leads. So, when the ammeter is inserted in a circuit, it does not disturb the circuit; it acts approximately as a wire. In many ammeters, the extent to which they act as shorts depends on the measurement range set on them. In general, the larger the range selected, the more the ammeter acts like a short (i.e., the lower the resistance between its two terminals). In ammeters with only a few display digits, it is better to select the range as large as possible, while still allowing for a sufficient number of significant digits to be displayed. For our present purposes, displaying two or three significant digits will be adequate. When interpreting the ammeter reading below, make sure you take into account unit prefixes, if any are present (e.g., mA means 0.001 A).

6. Consider again the circuit shown in solid lines in Fig. 1. Suppose you need to measure the current in the wire that connects the switch to the upper terminal of element X, in the direction from left to right. To do so, break that connection, and insert the ammeter (A) in series with the element, as shown in Fig. 2 (think about where the red and black leads should be connected). Ideally, since the ammeter acts as a short circuit, it is just a piece of wire as far as the circuit is concerned and does not influence the circuit's operation. Nevertheless, the current of element X now goes through it, and can be measured. Measure the current 11 indicated in the figure. Keep the PS and the circuit switch in the off position until you are ready to do this measurement, and then switch them on. When finished with this step, return the switch to the off position.

**c) Resistance measurements**

1. Configure the DMM as an ohmmeter. In this configuration, the instrument passes its own current through a resistor to be measured, measures the voltage across it, and calculates and displays the resistance value \( R = V/I \). Measure the resistance of the resistor you used in step 3, using the ohmmeter as shown in Fig. 3. **Note:** Be sure that nothing else is connected to the resistor you are attempting to measure and no power is supplied to the resistor to be measured.
2. Potentiometer R: (Fig. 6) A potentiometer is a voltage divider with a variable division ratio. The symbol for this element is shown in Fig. 6. The total resistance between terminals D and E is constant. The resistance between F and D is \( R_1 \), and that between F and E is \( R_2 \). The arrow represents a slider, which can slide up and down the length of the potentiometer. (Many practical potentiometers have the resistance laid out over part of a circle, and the slider must be rotated rather than moved up and down.) Thus, the values \( R_1 \) and \( R_2 \) can be varied, while their total resistance, \( R_1 + R_2 \) stays fixed. In this way, a variable voltage divider can be implemented. Use the ohmmeter to study the potentiometer provided to you. Do not connect anything else to the potentiometer in this step. Identify the terminals D, E, and F, and determine the minimum and maximum values of \( R_1 \), \( R_2 \), and \( R_1 + R_2 \). NOTE: It is good practice to shorten an unused potentiometer terminal to one of the other terminals to avoid ‘floating inputs’.

![Fig. 3](image1)

![Fig. 6](image2)

d) Effect of instruments on circuit being measured

One should be aware that no quantity that can take values in a continuous range can be measured exactly. No measuring instrument is perfect. For example, a real voltmeter is not a perfect open circuit, so a small current can flow through it. Also, a real ammeter is not a perfect short circuit, so a small voltage can develop across it. There are situations in which these small quantities can affect the currents and voltages in the circuit. In such cases, the measuring instruments will be influencing the quantities to be measured. The instrument's indications, then, will have to be properly interpreted, based on knowledge of the instrument's characteristics. We will have a chance to see instances of this in future experiments (e.g., in Experiment 1, we will see how a voltmeter's input resistance can affect a measurement and how we can take this effect into account and correct for it). In most cases in this lab, though, the circuits and element values used are such that the voltmeters and ammeters do not affect the circuits appreciably; they can then be assumed to be ideal, that is, perfect open circuits and perfect short circuits, respectively.

2. The Oscilloscope (Experiment 3)

1. The oscilloscope (or, simply, "scope") is used to display and measure time-varying signals (waveforms). If you are interested in viewing and measuring a voltage waveform, you can connect a scope to it, just as you connected a voltmeter to a DC voltage in previous experiments. In fact, the first voltage we will display on the scope will be a DC voltage (which is a special case of a waveform).

We will first need to set a number of controls, the function of which will become clear later in this experiment; for now, do not worry if you do not yet understand what they are. Depending on the oscilloscope you have, the following settings may be appropriate:

- **Vertical mode:** channel I
- **Channel I settings:** position control at midpoint
- **sensitivity:** 1 V/division
- **DC input coupling**
Horizontal mode: position control at midpoint
sweep rate 0.2 s/division
Trigger: source: channel 1
DC coupling
positive slope
auto mode
level at midpoint

All continuously variable controls that have a "calibrated" or "CAL" position should be set to that position. All magnifiers (X 10), if any are present, should be deactivated. If some of these settings do not make sense for the type of oscilloscope you have, set the controls as specified by your instructor.

2. Turn on the oscilloscope. The display should show a spot, moving from left to right; depending on the type of oscilloscope, this spot may or may not leave a trace behind it. In either case, we will call the result "the trace." If there is an intensity or brightness control, use it to keep the brightness of the trace low; otherwise, the screen can be damaged in some scopes. If there is a focus control, use it to make the trace sharp. Use the channel 1 vertical position control to bring the height of the trace to the midpoint of the screen. Adjust the horizontal position control so that the trace starts at the left end of the graticule. Verify that the time it takes for the spot to be swept across the screen is consistent with your setting of 0.2 s/division (a division, or "div," is the distance between two major graticule lines).

3. You will now prepare to connect an external voltage to the input of the scope's channel 1. The outer shield of the scope's input connector is grounded to the metal enclosure of the instrument and to the ground of the electrical installation in the building. A voltage to be measured must be connected between the inner conductor of the input terminal and the outer, grounded conductor. You will be making connections to the scope's input through a X I probe (where X I means that the probe does not attenuate, or reduce the signal; if your probe has a X I/X 10 selector, set it to X 1). See Fig. 1. The cable of the probe is coaxial, consisting of an inner conductor and an outer shield. The outer shield is connected to the ground and protects the inner conductor from external interference, for example, from a radio station (if two separate wires were used instead, they might have acted as antennas, picking up the radio station's signal; this would have interfered with proper measurements).

Connect a X I probe to the input of channel 1. Of the two leads of the probe, the flexible one (usually supplied with an alligator clip) is the ground terminal (Fig. 1). If the voltage source to be measured
has one terminal grounded, make sure that the ground of the probe is connected to the ground of the voltage source and not vice versa; otherwise, the source will be shorted and may be damaged. See the chapter on ground connections in the first part of this book, especially the section entitled "Connecting One Grounded Instrument to Another."

4. To create a voltage source with one terminal grounded and with a positive voltage with respect to ground, first connect the PS’s negative terminal to the PS’s ground. Now connect the scope’s probe to the output of the power supply, making sure you follow the practice outlined in the previous step. Turn the supply on, and set its voltage to 2 or 3 volts. Observe its effect on the vertical position of the trace. Vary the setting of the power supply somewhat, and again observe the effect on the vertical position of the trace. Disconnect the probe from the PS. Then, create a voltage source with a negative voltage with respect to ground, and again display it on the scope (again, be careful with grounds). What difference do you see?

5. To prepare for measuring the DC voltage with the scope, you need to do two things. First, you need to set the sensitivity of the scope to an appropriate value. This is like setting the range on a voltmeter. For this measurement, set the sensitivity to 1 V/division. Second, you need to establish your zero-voltage reference. Disconnect the probe from the PS, and short together the probe’s input terminals to make sure that the scope input voltage is zero (this can be done more conveniently with an appropriate button on the scope’s face, as we will see below; for now, though, follow the procedure just described). Use the vertical position control to adjust the height of the trace to the mid-point of the screen. This position will be your zero-voltage reference; nonzero voltages will be measured with respect to this level. Now unshort the probe’s input terminals.

6. Again connect the PS to the probe’s input. Set the PS voltage at 2 or 3 volts, positive with respect to ground. Measure the PS voltage by observing the vertical displacement of the trace from the zero-reference level:

\[
\text{Voltage (in V)} = [\text{displacement (in major divisions)}] \times [\text{sensitivity (in V/division)}]
\]

Note that displacement upward is taken as positive, whereas displacement downward is taken as negative. Confirm your measurement by using a voltmeter (the one on the power supply, or the DMM). Change the voltage of the power supply and the vertical sensitivity setting to other values, and repeat the measurement. Be sure it all makes sense to you; at the end of this step, you should feel comfortable with using the scope as a DC voltmeter.

![Fig. 2](image)

We emphasize here that, since one end of the probe is ground, it can only be connected to the ground in the circuit to be measured. Thus only voltages with respect to ground can be directly measured by using a probe in the way described above. For example, the connection shown in Fig. 2(a) is appropriate since both the probe’s alligator clip and the bottom terminal of device Fare connected to ground. However, the connection shown in Fig. 2(b) is not allowed since the bottom clip of the probe connects point B to point G’; the latter, being ground, is electrically the same as
point G. Thus, device Y is shorted out by the two grounds at its top and at its bottom. The operation of the circuit is disturbed, and even damage can be caused by the short.

7. If your probe has a XI/XIO selector, set it to X 10 and observe the effect on the screen. (If your probe has no such setting, use a separate X 10 probe.) What does this setting do to the overall sensitivity of the probe-scope combination? In this setting, the probe’s "loading effect" on the circuit being measured is smaller (i.e., the probe draws less current from it and is less likely to disturb its operation). This setting is used for measuring certain sensitive circuits, and its proper use includes a probe adjustment (tuning), which will not be used here.

In this experiment, the X 10 setting will not be used further. Before proceeding, return the probe to the X 1 setting (or, if you had connected a separate X 10 probe, disconnect that and reconnect the X 1 probe to the scope’s input).

8. To prepare for this step, be sure the vertical sensitivity is at 1 V/div, and the sweep time at 0.2 s/div. You will now observe how a time-varying voltage is displayed on the scope. To manually produce such a voltage, grab the voltage control knob on the PS and move it quickly back and forth. The combination of the spot’s horizontal movement and the voltage’s changes up and down should result in a display that has, very roughly, a sinusoidal shape. As you continue varying the voltage quickly up and down, experiment with both vertical sensitivity and sweep time settings. Make sure that what you see makes qualitative sense. When finished, turn off the power supply and disconnect it from the scope.

3. The function generator (Experiment 3)

9. A sinusoidal voltage can be produced accurately and predictably by an instrument known as a function generator, which you see on your bench. The function generator produces time-varying voltages (waveforms), just as the PS produces DC voltages. Just as there is a voltage control on the PS to set the magnitude of its DC voltage, there are controls on the function generator to set the amplitude of the voltage variations of the waveforms that this instrument produces. Sometimes this is done with two controls: one is continuous, and is often marked "amplitude"; the other is discrete (e.g., with three possible settings), and is often marked "attenuator." The amplitude of the variations of the waveforms is a function of the setting of both of these controls. There are other controls that determine how fast the variations of the waveform will be. There are also controls that determine the shape of the waveform, plus a few other controls, the function of which will become clear later on.

To prepare for use of the function generator, you will first need to set its controls as follows:

- **Frequency:** 1 Hz (in some generators, this may necessitate setting both a dial and a multiplier button)
- **Amplitude:** 1 V (this may necessitate setting both an amplitude and an attenuator control; if the generator does not give an indication of its amplitude, you may simply turn down the amplitude and set it after you have connected the generator to the scope below)
- **Function type:** sinusoidal
- **DC offset:** off
- **Sweep and modulation:** off (not all function generators have these features)

If some of these settings do not make sense for the type of generator available to you, set up the generator as specified by your lab instructor. The scope’s vertical sensitivity should be set to 1 V/div, and the scope’s sweep rate should be set to 0.2 s/div.
IMPORTANT NOTE: When you turn on the HP33120A function generator in the lab, it is by default set to match a 50Ω load. This means that any amplitude you dial in is the amplitude that WOULD be dropped across a 50Ω load resistor. If your load differs from 50Ω, the value on the display is DIFFERENT from the actual voltage across your load. You can think of the function generator in this setting as an ideal voltage source (whose voltage is twice the displayed value) in series with a 50Ω internal resistor and your load resistance. If your load has a much higher resistance than 50Ω you will drop twice the displayed voltage across it (why?). If this setting confuses you, you can change it by going to the ‘SYS’ menu. Choose option ‘1:Out term’, and select ‘High Z’. Then the function generator will assume an infinite load resistance.

10. Connect the output of the function generator to channel 1 of the scope. You can do this in any one of several ways, depending on the type of output connector on your generator. If that connector is coaxial, you can use a cable with a coaxial connector on each side; correct connection of grounds is then guaranteed. If the output is instead provided with "banana" receptacles, you need to use an appropriate cable or a combination of a cable and an adapter; in this case, you need to be careful with grounds, as explained in the chapter on ground connections. Be sure that, of the two banana plugs, the one connected (through the cable) to the ground of the scope goes to the ground of the generator. (Another way to connect the scope to the generator is to use a probe again; use the X 1 scope probe; if your probe has a X1/X10 selector, set it to X1. The coaxial connector of the probe should be connected to the scope's, the clips of the probe should be connected to the function generator. In this case, you may need to attach a short piece of wire to the nongrounded output connector of the generator so that you can clip the nongrounded tip of the probe to it.)

If you have made the connections correctly, the spot on the scope's display should be moving qualitatively as in step 8, except that now the voltage takes both positive and negative values. Vary the amplitude controls on the function generator and the sensitivity control on the scope, in a coordinated fashion. Observe the effect on the trace. Be sure you understand the function of these controls. Note that although the effect of the these controls on the scope's trace is qualitatively similar, controlling the function generator's amplitude determines how large a signal this instrument gives', in contrast, controlling the sensitivity of the scope determines how large the displacement of the trace will be per volt of the signal connected to the scope's input.

11. Vary the frequency controls on the function generator and the sweep rate control on the scope, in a coordinated fashion, so that each time you can see a few cycles of the waveform on the screen. Observe the effect on the trace. If necessary, adjust the intensity of the trace to obtain a convenient display. Continue experimenting, until you fully understand the function of these controls. To prepare for the next few steps, set the generator frequency at 1 kHz, and set the sweep time on the scope so that you can observe several cycles on the screen.

12. (This step is to be done if your function generator has an attenuation control. If it does not, proceed to step 13.) You will now experiment with the attenuator of the function generator. This control functions like a voltage divider inside the instrument, dividing the amplitude of the waveform produced by a specified attenuation factor, which we will denote by a. For example, there may be a setting of this control corresponding to a = 1; this means that the entire signal appears at the output. There may be another setting corresponding to a = 10; this means that the amplitude of the signal appearing at the output is one-tenth of what it was at the a = 1 setting; and so on. Often, though, rather than marking the attenuation factor value a directly, what is marked is the corresponding value in decibels, or dB. You will find a discussion of decibels in Appendix C. Try different settings for the attenuator, and verify that the attenuator markings make sense.

13. In preparation for the following step, disconnect the scope's input from the function generator. Connect a short across the scope's input. Using the scope's vertical position control, set the zero-reference level of the trace at the midpoint (see step 5). Now disconnect the short, and again
connect the function generator to the scope's input. Do not touch the scope's vertical position control, for the rest of this step and for the following step. Set the "trigger coupling" to AC.

Turn on the DC offset control on the function generator. Vary its setting, and observe its effect on the trace. Why is this control called DC offset?

14. You will now experiment with the input coupling control on the scope (this control may or may not be marked explicitly as such). This control has settings marked DC, AC, and GND. CAUTION: There are also other controls that may be similarly marked; make sure that you have identified the one in the "channel I" group of controls. The name of these settings may be confusing at first. Note that the names "DC" and "AC" do not refer to the type of voltage observed; that voltage is generated by the function generator, so only controls on that instrument can affect it. To find out what these names on the scope's face really mean, set the DC offset on the function generator to a nonzero value, and move the scope's channel I coupling control between the DC and AC settings. What do you observe? Repeat for a different offset value. Think of how the scope treats the DC offset of the observed waveform when the scope's coupling is set to AC. What do you believe is the function of the AC setting? In contrast, what is the function of the DC setting?

15. Change the scope's coupling control between the AC (or DC) and GND settings. Observe the effect on the scope trace. The GND setting shorts the scope's input internally to ground (without shorting the external connection), which has the same effect on the trace as if zero V had been connected across the input. This is a convenient feature, which allows you to set your zero-reference vertical level without having to go through the entire procedure outlined in step 5. Before proceeding, turn the DC offset on the function generator off, and set the trigger coupling on the scope to DC.

16. Play the following educational game: Ask a lab partner to set the generator to a given amplitude and frequency, covering the generator's front panel so that you cannot see the settings. Determine the function generator settings by observing the waveform with the scope. You will need the values of both the vertical sensitivity and sweep time on the scope to do this. You can set these values as needed to obtain a convenient trace. Then, exchange roles with your lab partner and repeat. Before proceeding, make sure you understand the function of all of the controls discussed so far.

17. You will now find out what the scope's trigger function does. (You should be warned right away that this function can be tricky, so you may not be able to understand it completely the first time you are using it. Further understanding will come with experience, as you use the scope in other experiments.) Use a 1 V peak, 1 kHz sinusoidal signal for this part. Set the trigger mode to normal (as opposed to auto). Choose an appropriate sweep rate so that you can observe a few cycles on the screen. Experiment with the trigger level and slope settings. You should observe that the level control determines the value of the voltage waveform at which the trace is triggered; that is, starts its left-to-right movement. The slope control determines whether the value chosen by the level control will be on an up-going or down-going part of the waveform (i.e., with a positive or negative slope, respectively).

Note that at the normal trigger setting, the trace is triggered only if the signal has a level and slope compatible with the level and slope settings. In contrast, at the auto setting, there is always a trace; when no appropriate triggering can be achieved, the trace automatically switches to a free-running mode. Verify this.

Triggering can also be activated by an external signal, connected to the external trigger input of the scope, by setting the trigger control to "external." It can also be activated at the frequency of the voltage on the electric power lines by setting the trigger control to "line." We will not be using these modes in this lab.

When you are finished with this part, return the trigger controls on the scope to the settings specified in step 1.
At this point, you have been acquainted with the main controls of the oscilloscope and the function generator. There are some other controls and features, depending on the models of the instrument. You do not need to worry about these for now; they are best studied after you have practiced, and feel comfortable with, the basic features you have just studied. More information can be found in the user's manuals for the instruments.

### 3. Amplifier chips (Experiment 4) and op amps (Experiment 5)

The following is an introductory description of op amps and op amp chips. While op amps are used specifically in lab 5, this section is also useful for lab 4 when an audio amplifier chip in a similar package is used.

The op amp is an active element that needs to be supplied with power to operate. A common way to supply this power is shown in Fig. 2(a). Two power supply voltages are used, with equal values denoted by \( V_{CC} \) (often in the range of 5V to 15 V). Notice the polarity of each supply voltage. The common node between the supplies is the ground node. The op amp's output voltage is taken between the output terminal and the ground node. The remaining two terminals are the input of the op amp.

![Fig. 2](image)

We will follow common practice and draw the circuit of Fig. 2(a) as shown in Fig. 2(b). Here, the power supply voltages are understood to be connected at the appropriate terminals, although the supply voltage sources are not explicitly shown. Sometimes, even the supply connections shown in Fig. 2(b) are omitted from circuit diagrams, but they are always understood to be there. Remember: Whether the power supply connections are explicitly shown or not, power must be properly connected to an op amp before it can operate.

In lab 5, we will use a popular op amp type known as the 741. It comes in a package, with metal pins that can be pushed into a prototyping board such as the one you will be using for this experiment (for a more permanent connection, the pins can be soldered to a printed circuit board). A widely used package for this op amp, when viewed from above, is shown in Fig. 3(a).
With the package viewed from above and positioned as shown (mark at the top), the pin numbering is understood to be as indicated. The pins that correspond to the input, output, and power supply connections are indicated. It is often convenient to transfer the pin numbers onto circuit diagrams, as shown, for example, in Fig. 3(b). If, for the 741 chips you will be using, the package (and associated pin numbering) is different from that shown in Fig. 3(a), you will be supplied with information for that package. When the op amp is connected to other elements, extremely small currents flow at its input terminals. For our purposes, these currents can be assumed to be zero.