

# ELECTRONICS LAB

Each person carefully record all measurements and observations in your lab notebook. As a group answer all the numbered questions. The report for this lab consists of your individual carbon pages from your notebook and the group's answers to the questions.

## Part I. OPERATIONAL AMPLIFIERS

**Introduction:** An op amp is designed to amplify the difference between the voltages applied to its two inputs with a very large amplification factor ( $A$ , open loop gain), typically  $10^5$  to  $10^8$ . In addition, it provides a very high input impedance and a low output impedance. Negative feedback is used in a variety of configurations to produce useful devices for manipulating analog signals. In this lab we will investigate a few of these op amp circuits.

Op amps come in several physical sizes and shapes. In this lab we will be using the LF 356 op amp in an 8-pin DIP (dual in-line package) which fits into the breadboard directly. The physical package looks like a piece of plastic with 8 metal legs, and the product number is usually stamped on the top of the chip. The DIP will have either a small dot/depression in one corner or a U-shaped depression in the center of one edge to aid in identifying pins. When the chip is oriented so that the dot or the U is at the top (see Fig. 1), pin 1 will be at the top left, and the pins are numbered consecutively down the left side, around the end and up the right side.

Fig. 1 shows a pin-out diagram for the LF 356 op amp. Mathematically the basic function of the op amp is given by  $E_{out} = A (E_{non-inverting} - E_{inverting})$ . The LF 356 will work with a wide range of power supply voltages from  $\pm 10$  to  $\pm 18$  V, but the positive and negative voltages must have about the same absolute value. We will use the  $\pm 15$  V supply on the breadboards to provide the power needed for the op amps (more details later). Theoretically, when both inputs of the op amp are grounded, the output should be 0 V. Due to non-idealities that result during manufacture, this is seldom the case. An external, variable resistor (trim pot) with the wiper connected to a power supply is used to balance the offset current to compensate for these non-idealities (more details later). In a schematic diagram of a circuit, the trimming circuitry and the connections to the power supply are often not shown. The schematics in this lab follow this convention. **Always assume that the op amp is connected to power and that a trimmer is in place and adjusted for zero offset.**

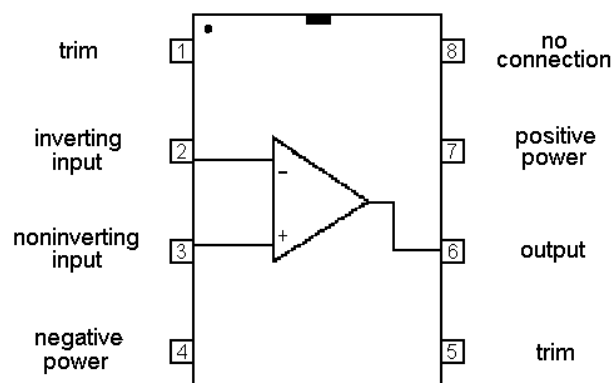


Fig. 1 LF 356 Op Amp Pin Out Diagram

**Introduction to the breadboard:** The POWERACE has two breadboards mounted together, each looks like a piece of plastic with several horizontal rows of holes. Focusing on one of those sections, note that the top two rows and bottom two rows are composed of sets of five holes separated by a short horizontal distance (analogous to a dashed line). Each of these "bus bars" has two HORIZONTAL segments of 25 holes (5 "dashes") that are electrically connected. In the center of each breadboard section there are two sets of five rows separated by a shallow trough. Here each VERTICAL set of five holes is electrically connected and there are NO electrical connections ACROSS the trough.

The pin spacing on DIP packages matches the hole spacing on the breadboard (0.1"). To build circuits based on DIP chips, insert the DIP so that it straddles the trough. Then insert jumper wires and other components into the appropriate holes of the breadboard to make the proper connections. DO NOT INSERT COMPONENTS WITH LEADS LARGER THAN 22 GA. WIRE. Power supply connections and a few other options are available at the pads on the sloping face of the PowerAce. Note that an inverted triangle represents ground in these connections.

#### Components List

PowerAce breadboard	LF 356 op amp	20 k $\Omega$ trim pot
Digital Voltmeter (DVM)	22 ga jumper wires	Voltage Reference Source (VRS)

**General Connections for All Op Amp Circuits in This Lab:** SUGGESTION - use a color code for the wires used to make connections on the breadboard and fold the wires down after inserting them into the breadboard. This makes it easier to trace connections and keeps the "forest" of wires from obstructing your access to the circuit components.

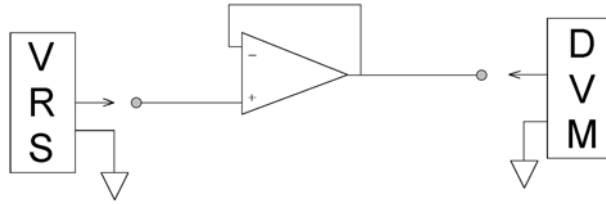
Always make sure that the power is turned off before configuring an op amp, otherwise you may burn it out. Insert the LF 356 op amp into the breadboard so that the pins straddle one of the troughs. Make sure the pins slide into the holes without bending over; insert carefully with gentle pressure. Connect a wire from +15V to pin 7 of the op amp. Connect another wire from -15V to pin 4 of the op amp. Insert a 20 k $\Omega$  trim pot into the breadboard; make sure that the pins are not shorted by the breadboard and that the adjusting screw is easily accessible for adjustment. Connect the wiper of the trim pot to +15V (see the note on variable resistors at the end of Appendix 2). Connect one end of the trim pot to pin 1 and the other end to pin 5.

The op amp does not have a specific connection for ground; it is referenced to the power supply ground. **Make sure that the grounds of ALL components are connected together in any circuit.**

Directions for adding additional components will be given in each section below. The op amp can be zeroed using either a follower or an inverter configuration; details are also given below.

#### **A. Voltage Follower** (pp. 62-63 in text)

The schematic of the follower configuration is given in Fig. 2. Starting with the basic configuration from above, add the following connections: Use a jumper wire to connect pin 2 to pin 6 (feedback from the output to the inverting input is called negative feedback). Connect a wire to pin 6 leaving the other end free for connection to the digital volt meter (DVM). Connect a wire to pin 3 leaving the other end free for connection to the voltage reference source (VRS). Connect the ground leads of the DVM and the VRS to the power supply ground on the breadboard. Now zero the op amp.



**Fig. 2 Voltage Follower**

**Zeroing the op amp:** Connect the pin 3 wire directly to ground (VRS disconnected from circuit). Connect the DVM to measure the output voltage (most sensitive scale eventually). Turn on the PowerAce and the DVM. If the output is more than  $\pm 10\text{V}$ , something is wrong with the circuit so check your wiring. When properly configured, the output will typically be less than  $\pm 200\text{ mV}$ . Now adjust the screw on the trim pot until the voltage is  $0.0\text{ mV}$ , then fine tune it further by adjusting it so that the negative sign on the DVM display just comes on or goes off when  $0.0$  is displayed).

With this setting of the trim pot the op amp will remain zeroed even when you change to another configuration. You can get a more sensitive zero adjustment if you use a configuration with gain. You will see this in Part B with the inverter configuration.

Now remove the ground wire from pin 3 and connect it to the VRS. Apply each of the voltages in Table 1 to pin 3 (input), and, using the DVM, measure and record the corresponding output voltage (pin 6), noting the polarity. You will have to use a voltage divider (Appendix 2, Fig. 6 and pp. 27-28 in text) with at least a  $15\text{ V}$  power supply to produce voltages greater than  $12\text{ V}$ . To answer question 1 below: Set the output of the divider to about  $12\text{ V}$ . While monitoring the output of the divider and the op amp (use two voltmeters), adjust the divider upwards until the divider and op amp voltages start to deviate. For the negative side, start at about  $-12\text{ V}$  and adjust downward (more negative).

Table 1. Test Voltages for the Voltage Follower Circuit.				
+ 0.1000V	+ 1.000V	+ 5.000V	+ 12.500V*	+ 15.000V*
- 0.1000V	- 1.000V	- 5.000V	- 12.500V*	- 15.000V*
*You may need to look at several steps between these voltages to answer Question 1 below.				

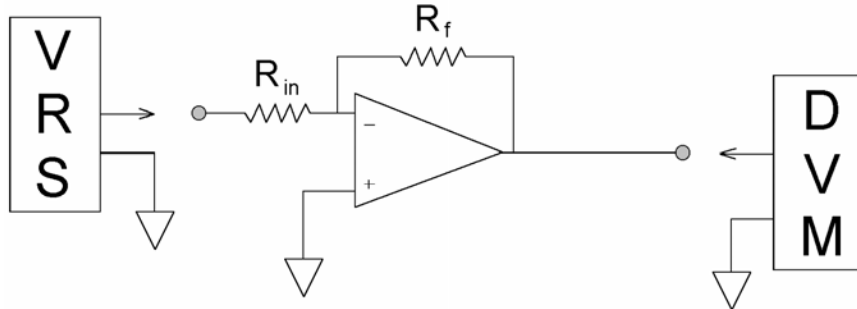
## **B. Inverting Amplifier** (p. 64 in text)

### Components List

Follower op amp circuit (Part A)	100 k $\Omega$ resistor	1 M $\Omega$ resistor
DVM	22 ga jumper wires	VRS

Turn off the PowerAce and reconfigure the op amp as an inverter amplifier as shown in Fig. 3: Connect pin 3 to ground. Replace the wire between pin 2 and pin 6 with a  $1\text{ M}\Omega$  resistor ( $R_f$ ). Connect one end of a  $100\text{ k}\Omega$  resistor to pin 2 ( $R_m$ ) and leave the other end free for connection to the VRS. Leave the other connections the same. A review of the color code for identifying resistors

is presented in Appendix 1. Use only 1% metal film precision resistors, the tolerance on the resistors determines how closely theory and practice agree on this part of the experiment. Turn on the power and check the zero.



**Fig. 3 Inverting Amplifier**

**Zeroing the op amp:** Connect the free end of  $R_{in}$  (at pin 2) to ground and measure the output at pin 6. DO NOT connect pin 2 directly to ground. Carefully adjust the trim pot to produce an output of 0.0 mV. This adjustment will be more touchy than before because the circuit has a gain of 10, so it may be difficult to attain exactly 0.0 mV. Get it as close as you can.

Remove the end of  $R_{in}$  from ground and connect it to the VRS. Apply each of the voltages in Table 2 and, using the DVM, measure and record the corresponding output voltage (pin 6), noting the polarity. To answer question 1 below: Set the output of the divider to about 1.25 V. While monitoring the output of the divider and the op amp (use two voltmeters), adjust the divider upwards until the divider and op amp voltages start to deviate. For the negative side, start at about -1.25 V and adjust downward (more negative).

Table 1. Test Voltages for the Inverter Circuit.				
+ 0.0100V	+ 0.1000V	+ 0.5000V	+ 1.250V*	+ 1.500V*
- 0.0100V	- 0.1000V	- 0.5000V	- 1.250V*	- 1.500V*
*You may need to look at several steps between these voltages to answer Question 1 below.				

From your data answer the following questions in your lab notebook:

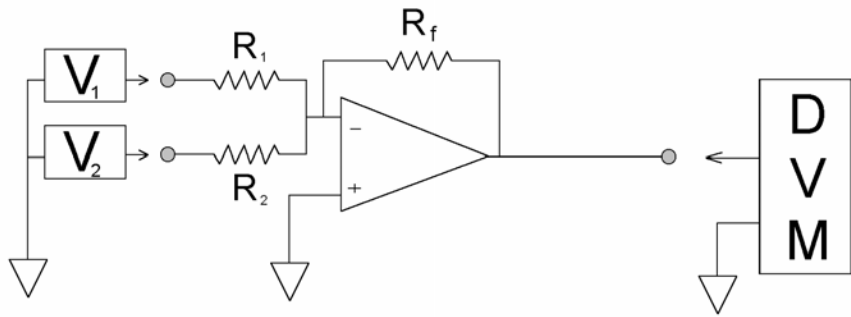
1. What are the approximate positive and negative **input** voltages where the **corresponding output** voltage begins to deviate from the theoretical output for: a) the voltage follower? b) the inverter?
2. The **output** voltages determined in question 1 a) and b) define the practical operating limits for the op amp. Do the operating limits depend significantly on op amp configuration?
3. Predict the output voltage of the inverter for each input. Show a sample calculation.

4. For output voltages within the operating limits of the op amp, does the measured output agree with your prediction within component tolerances for: a) the voltage follower? b) the inverter? If not, explain the discrepancy.

**C. Summing Amplifier** (p. 72 in text)

	Components List	
Zeroed Inverter op amp circuit (Part B)	100 kΩ resistor	1 MΩ resistor
DVM	Large variable resistor	22 ga jumper wires
	VRS	

A summing amplifier is just an inverter with two or more input resistors. Turn off the power to the breadboard. Using the resistors designated in the first row of Table 3, reconfigure the inverter op amp to a summing amp matching the schematic in Fig. 4. Use a voltage divider (Appendix 2, Fig. 6 and pp. 27-28 in text) to produce one of the voltages and the VRS for the other. Measure the output voltage for this set up and repeat for the other sets of conditions given in Table 3. Adding or changing the resistors will not affect the trimming significantly.



**Fig. 4 Summing Amplifier**

Table 3. Summing Amplifier Configurations and Test Voltages.				
R1	R2	Rf	V1	V2
100k	100k	1M	+0.5V	+0.2V
100k	100k	1M	+0.5V	- 0.2V
100k	1M	1M	+0.5V	+0.2V
100k	1M	1M	+0.5V	- 0.2V

From your data answer the following questions in your lab notebook:

1. Calculate the predicted output voltage for each set of conditions. Show your work.
2. Does the measured output agree with your prediction within component tolerances? If not, explain the discrepancy.

## D. Integrator

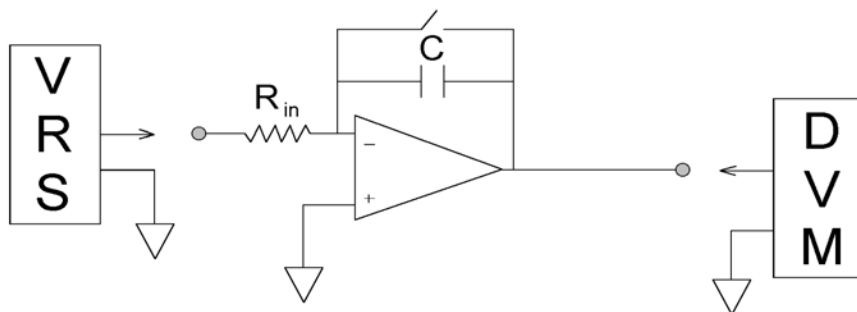
### Components List

Zeroed Inverter op amp circuit (Part B) stopwatch	1 $\mu\text{F}$ capacitor 22 ga jumper wires VRS	1 $\text{M}\Omega$ resistor DVM
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The op amp integrator is often used to obtain the area under curves from transient current or voltage signals (e.g. NMR), to average noise present with steady signals, and to provide various control functions.

Configure the op amp as a gain of 10 inverter as you did in part B (Fig. 3); remember to turn off power before configuring. Following the directions in Part B, **carefully** trim the op amp to **EXACTLY** 0.0 mV. Any untrimmed offset will have an affect on your observations in this part of the experiment (offset voltages get integrated too). Since the VRS often has an offset due to calibration drift, don't use the VRS set to 0.000 V as the ground for  $R_{in}$ . Connect  $R_{in}$  directly to ground (as indicated in Part B).

Now modify the circuit to that shown in Fig. 5: Replace the feedback resistor with a 1  $\mu\text{F}$  capacitor. Replace the input resistor with a 1  $\text{M}\Omega$  resistor (1%). Simulate the switch in the feedback loop by inserting and removing a wire into the breadboard. Capacitor tolerances are typically 20%, so measure the capacitance and use the measured value in your calculations.



**Fig. 5 Integrator**

Apply -100 mV (VRS) to the input and monitor the output with a DVM for several seconds. Then change the applied voltage to 0 V. With a 0 V input, the output should stop integrating and remain constant. If your observations are different than this, see the instructor. Sometimes miscalibration of the VRS results in a small voltage output when the display says 0.0 V. Disconnecting the input from the VRS and **CONNECTING IT TO GROUND** should halt the integration. If the VRS is miscalibrated, any applied voltages will also have an offset that may need to be accounted for in the calculations. The integrator behavior observed here is the basis of a sample and hold amplifier which we will not investigate further.

Now use your switch to short out the capacitor (discharge it); the output should go to zero. With the shorting switch closed, apply -100 mV to the input. Then open the switch and measure the time required for the output to rise from 0 to 1 V. Using the same procedure, measure the time (nearest second is sufficient) required for the output to rise from 0 to 3 V, 0 to 5 V and 0 to 8 V (three

separate measurements, short the capacitor between measurements). Use a wristwatch or stop watch to monitor the time while observing the output on the DVM.

From your data answer the following questions in your lab notebook:

1. Calculate the expected time to reach each output voltage. Show a sample calculation.
2. Do the measured times agree with your predictions within component tolerances? If not, explain the discrepancy.

## Part II. RC FILTERS

### A. Series RC Filter Circuits

	Components List	
Follower op amp circuit (Part A)	0.1 $\mu\text{F}$ capacitor	499 $\Omega$ resistor
5 k $\Omega$ resistor	50 k $\Omega$ resistor	22 ga jumper wires
Dual trace oscilloscope	Function generator	BNC connectors & cables

Filters, composed of various combinations of resistance, capacitance, and inductance, are used to attenuate or remove selected frequency bands from an electrical signal. In the lab, filters are usually used to decrease the amount of noise in a signal. In this part of the lab we will investigate one of the simplest of the filters, a series combination of resistance and capacitance which is called, strangely enough, a series RC filter.

**Series RC Filter Background Theory (pp. 32-42 in text, especially pp. 40-42):** For this discussion recall that a resistor restricts current flow in a circuit according to Ohm's Law,  $E=iR$ . Also recall that a capacitor stores charge; dc current will flow through the capacitor until the voltage across the capacitor is equal to the applied voltage in the circuit. For ac signals, the capacitor presents a resistance to current flow that is called impedance ( $\chi$ ) which is inversely proportional to the frequency of the signal,  $\chi=1/(2\pi f)$ . This series circuit then becomes a frequency dependent voltage divider.

Set up the circuit shown in Fig. 6 using a 0.1  $\mu\text{F}$  capacitor and 499  $\Omega$  resistor; remember to turn off power when you configure the op amp. Make sure the grounds from the power supply, signal generator, and oscilloscope are all connected to a common point. Connect the output of the function generator to channel A of the oscilloscope and to the input of the follower. Connect the output of the filter (junction of C and R) to channel B of the oscilloscope. Set channel A and B on the oscilloscope to the same frequency and voltage settings such that several cycles are displayed on the screen. Adjust the vertical offsets such that the two traces are superimposed. Channel A will display the unfiltered output of the function generator and channel B displays the filtered signal across the resistor at the output of this filter. See the instructor for directions on the operation and use of the signal generator and the oscilloscope.

**Effect of "loading a source" (pp.31-32 in text):** Distortion or attenuation of a signal because of loading is a primary concern in instrumentation design. It is important to recognize when it is present and what to do to eliminate it. To observe the effect of loading, set the function generator to output a 1 V SQUARE wave with a frequency of 2000-2500 Hz and apply it to the circuit just constructed. Adjust the time base of the oscilloscope to display two or three cycles. You should see

a square wave on channel A. Ignore channel B for now. Short out the voltage follower by inserting a jumper wire between pin 3 (input) and pin 6 (output) of the op amp, and note what happens to the output of the function generator displayed on channel A. Remove the jumper again and note the restoration of the square wave.

When the follower is shorted out, the filter circuit requires the function generator to supply more current than it is capable of supplying (loads the source). The function generator sees the impedance of the filter which draws more current than the function generator can supply, so the voltage output of the generator is attenuated to a level where the generator can produce the required current. When the voltage follower is in the circuit the generator "sees" only the high impedance input of the op amp and easily supplies the necessary current without affecting the voltage output of the generator. The low output impedance and relatively high current capability of the op amp supply the current necessary to feed the filter circuit without affecting the voltage, which eliminates the loading problem for this circuit. Placing a larger resistor in the filter will also reduce the loading, but that affects the functioning of the filter which may not be desirable.

**Filter Characteristics:** Remove the shorting jumper so the voltage follower is functioning. Set the function generator to output a 1 V peak-to-peak SINE wave. Now compare the output and input voltages for several frequencies between 10 Hz and 1 MHz, and determine the approximate frequency at which the signal begins to be attenuated. Also note which frequencies are attenuated, higher ones or lower ones.

Repeat using resistances of 5 k $\Omega$  and 50 k $\Omega$ .

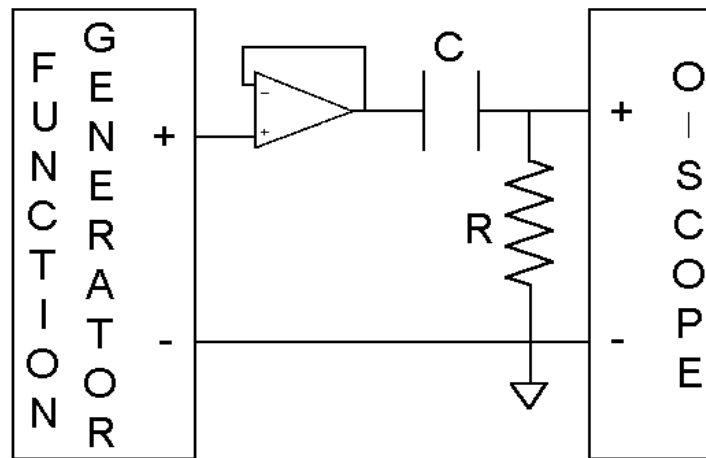


Fig. 6 Filters

From your data answer the following questions in your lab notebook:

1. Based on your measurements, is this circuit a high pass filter or a low pass filter? Briefly explain in qualitative terms how the theory predicts this behavior.
2. What effect does the time constant (RC) have on this filter?

Now modify the configuration by physically interchanging C and R in the circuit so that one lead of C is grounded. Again determine which frequencies are attenuated and where the attenuation

begins using R's of 499Ω, 5 kΩ, and 50 kΩ. In this configuration you are monitoring the voltage across the capacitor. R and C had to be interchanged so that one lead of the capacitor was attached to ground because the oscilloscope does not have floating inputs; the ground lead of the oscilloscope must be attached to the ground of the circuit.

From your data answer the following questions in your lab manual.

1. Based on your measurements, is this circuit a high pass filter or a low pass filter? Briefly explain in qualitative terms how the theory predicts this behavior.
2. What effect does the time constant (RC) have on this filter?

## **B. Measuring Capacitance**

The charging curve for the capacitor in a series RC circuit can be used to measure the capacitance of the capacitor. Using a 0.1μF capacitor and a 499Ω 1% resistor, construct a series filter circuit as you did above with the output taken across the capacitor (Fig. 6 with R and C interchanged). Set the function generator to output a 1 V peak-to-peak SQUARE wave with a frequency between 2000 and 2500 Hz. Set the oscilloscope time base to display one or two cycles of the square wave. Channel A should show a square wave and channel B the charge and discharge curves for the capacitor.

The rate at which a capacitor charges (and discharges) depends on the resistance in the circuit such that  $E_C = E_{\text{applied}} (1 - e^{-t/RC})$ . The product RC is called the time constant for the circuit and has units of seconds (resistance in ohms \* capacitance in farads = seconds). When  $t = RC$ , the quantity in parentheses is equal to  $(1 - 1/e) = 0.63$ . Measure the time (x axis) it takes for the capacitor to charge to 63% of the maximum voltage (y axis) or the time it takes for it to discharge to 37% (1/e) of the maximum voltage (should get the same time for both). This is most easily done if the input trace and the output trace are superimposed on the oscilloscope display.

For comparison, measure the capacitance of the 0.1μF capacitor with the capacitance meter.

From your data answer the following questions in your lab notebook:

1. Calculate the capacitance from the RC time constant. Show your work.
2. Does the capacitance calculated from the charging curve agree with the nominal capacitance value within component tolerances? Does your calculated value agree more closely with the value measured by the meter? If not, explain the discrepancy.

## APPENDIX I. Resistor Color Code

0	black	5	green
1	brown	6	blue
2	red	7	violet
3	orange	8	gray
4	yellow	9	white

For the precision resistors we are using, the first three bands represent the number and the fourth band gives the multiplier. For example if the four bands of the resistor are all red, then the resistance is  $222 \times 10^2 \Omega$  or 22.2 k $\Omega$ . The tolerance on these resistors is  $\pm 1\%$ .

## APPENDIX 2. Voltage Divider

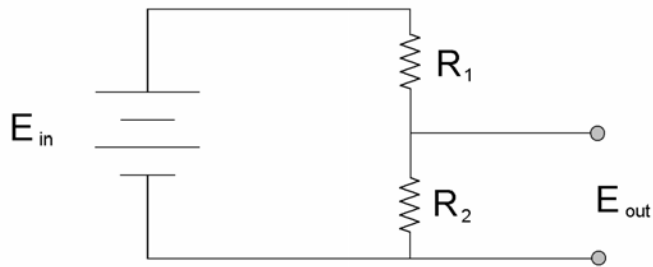


Fig. 7 Voltage Divider

$$E_{out} = \frac{R_2}{(R_1 + R_2)} E_{in}$$

If you use a variable resistor, look carefully case to see the at the location of the wiper. On some variable resistors like the trim pots we are using, it is the center connection. On others like the larger ones with the banana connections, the wiper is one of the end connections. If you are not sure, use an ohm meter between various pairs to see which vary resistance as the resistor is adjusted (wiper plus one end) and which do not vary with adjustment (two ends).