ELECTRICAL ENGINEERING DEPARTMENT

EE143 California Polytechnic State University Lab #3

Resistance, Voltage & Current Measurements / Ohm's Law & Kirchhoff's Laws / & Accuracy and Precision / "Reverse Engineer" a PCB

VIDEOS:

Experiment #2 Playlist at
https://www.youtube.com/playlist?list=PLkooZoxYRwMg1b7MGKbXD4EiZxfy0sMHu

In addition, watch this video on breadboard basics
https://youtu.be/q_Q5s9AhCR0

PRELAB:

1. Determine nominal resistances and tolerances of the following resistors:

Label	Resistance Color Code	Nominal Resistance (ohms)	Tolerance(%)
R1	Red Violet Orange Gold		
R2	Brown Black Green Gold		
R3	Orange White Yellow Gold		
R4	Brown Red Brown Gold		
R5	Green Blue Black Brown Brown		
R6	Gray Red Black Orange Brown		

2. An ohmmeter measures the resistance of a single resistor in a circuit that has applied power. Why should the ohmmeter's displayed resistance not be trusted?

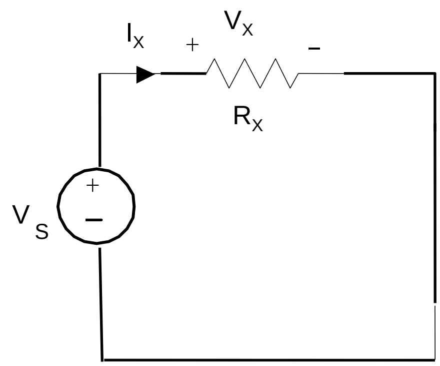
3. Differentiate between measurement precision and equipment precision.

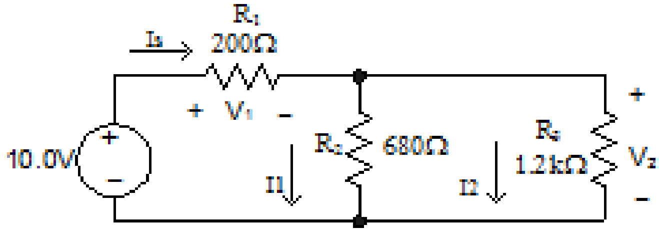
4. A 5 ½ digit multi-meter is used to measure resistance on the 10kΩ range. A resistance with a nominal value of 7.460kΩ is measured and the multi-meter displays 07.4132kΩ. What is the measurement accuracy if the nominal value is taken as the true value or "real value"? What is the maximum percent error if the multi-meter's equipment accuracy is 0.25% $\pm$1 count when set for the 10kΩ range?

5. A voltmeter is connected in ____________ with a circuit element and ideally has an internal resistance of _________ Ω thus preventing ____________ from diverting through the voltmeter.

6. An ammeter is connected in ____________ with a circuit element and ideally has an internal resistance of ________ Ω thus preventing ______________ from dropping across the ammeter.

7. In the circuit immediately below, if R_x = 100 ohms, ¼ W, what is the largest value of V_S such that the power rating of the resistor R_x is not exceeded?





8. In the circuit directly above, V_1 = 3.15 V. Solve for V_2, Is, I1 and I2.

9. If a short (0Ω path) is connected across (in parallel with) R_2 and R_3 will V_1 still equal 3.15V? If not, what is the new value of V_1? What are the values of V_2, Is, I1 and I2?

10. If an open (∞Ω = "break") is connected in series with R_2 will V_1 still equal 3.15V? If not, what is the new value of V_1? What are the values of V_2, Is, I1 and I2?

    Note: For problem 10 the short is no longer connected across R_2 and R_3.

ELECTRICAL ENGINEERING DEPARTMENT

EE143 California Polytechnic State University Lab #3

Resistance, Voltage & Current Measurements / Ohm's Law & Kirchhoff's Laws / & Accuracy and Precision / "Reverse Engineer" a PCB

PURPOSE:

- To learn to read resistance color codes.
- To learn to make resistance, voltage and current measurements.
- To understand and differentiate between the accuracy of and the resolution of measurements (or instruments).
- To verify Ohm's Law, KCL (Kirchhoff's Current Law) and KVL (Kirchhoff's Voltage Law).
- To understand the effect of short circuits and open circuits on circuit operation.
- To understand what a node is and demonstrate the ability to draw a schematic from a PCB.

This experiment relates to the following **course learning objectives**:

1. Ability to interconnect equipment and devices such as a multi-meter, and power supply to achieve required results.
2. Ability to relate practical laboratory results with lecture theory.
3. Ability to analyze and evaluate data.

STUDENT PROVIDED EQUIPMENT:

1 Arduino (only for use of 5V supply)
1 Digital Multi-meter (and its User's Guide)
1 Breadboard
1 Jumper Wire Set
1 LM311 IC
1 Red LED
1 1N4148 diode
1 20kΩ ¼ Watt Resistor
1 10kΩ ¼ Watt Resistor
1 2kΩ ¼ Watt Resistor
1 470Ω ¼ Watt Resistor
2 100Ω ¼ Watt Resistor

EXPERIMENTAL SECTIONS:

1) Accuracy and Precision (Resistance Measurements as an example)
2) Resistance Measurement [Body Resistance]
3) Reverse Engineer Continuity-Tester (Draw Schematic from PCB Layout)
4) Verification of Ohm's Law and Kirchhoff's Circuit Laws

BACKGROUND:

Resistors

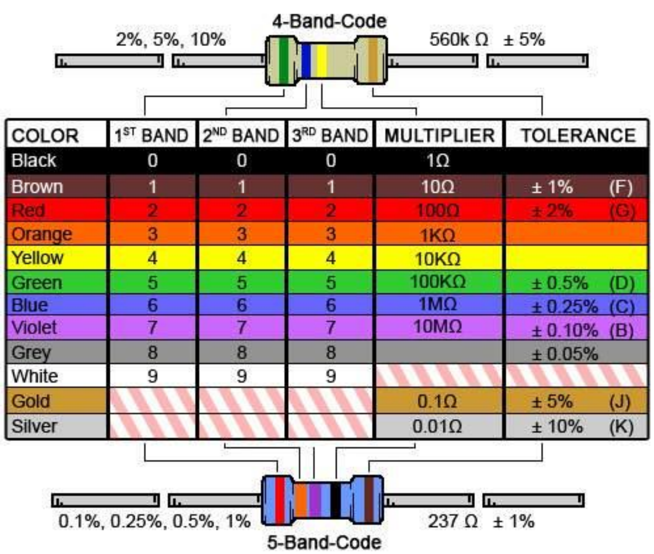
In electronic circuits, resistances serve to adjust voltage or current levels, or serve as "loads" for active devices. The load in this case is an element across which the output voltage appears and through which the output current flows. When designing circuits, the accuracy and power handling capabilities of any resistor used in the circuit must be considered.

A designer's specification of a resistor will include the required ohm value, the allowable tolerance of that value, and the power handling requirements of the element. The temperature range over which the resistance must remain within its specified tolerance will also be important. For example, many types of electronic equipment must operate over a wide range of ambient conditions. Also, components which are packed closely together in small packages can experience mutual heating effects which may alter the operation of the circuit.

The composition resistor is inexpensive and suffices for many applications. These resistors are made by imbedding particles of a resistive material such as carbon, along with suitable connecting leads, in a material that gives the completed resistor its mechanical characteristics. Since resistors are required to maintain their ohm values over a specified temperature range, they are designed to minimize temperature effects. The resistance of carbon decreases with increasing temperature, but when conductive particles are imbedded within the carbon, the temperature dependence and the resistance of the composite material can be modified.

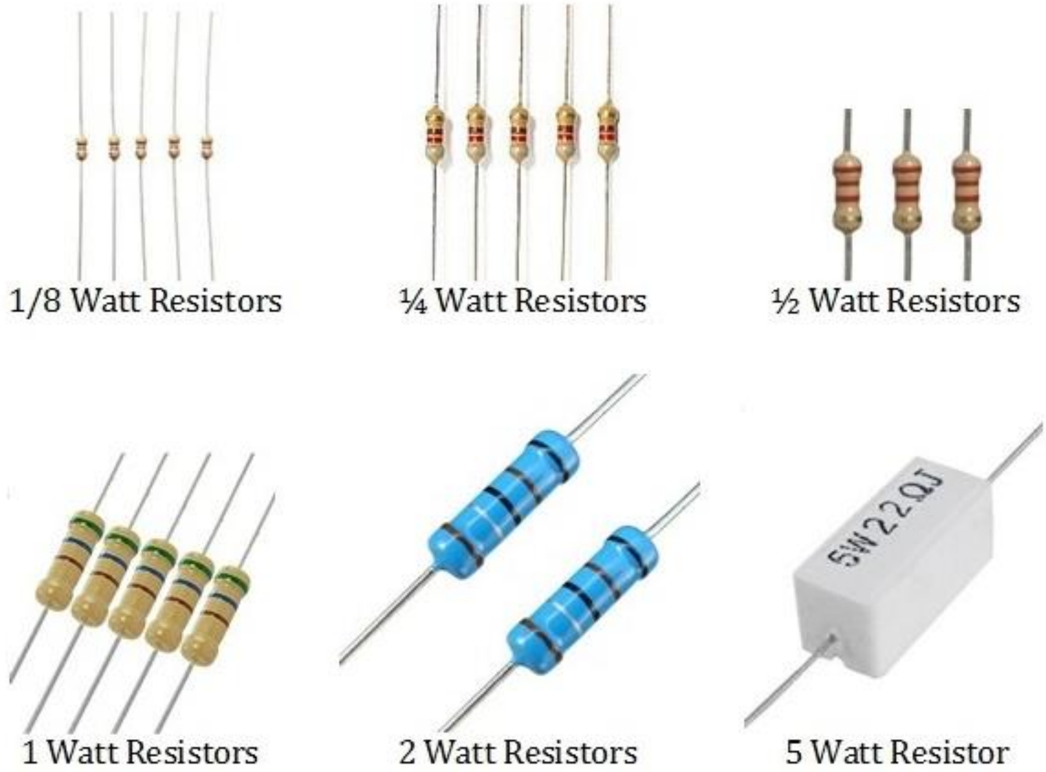
Commercial resistors come in a number of power ratings, a wide variety of ohm values, and several tolerances. Resistors are commonly available in the following ohm values: 1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, 9.1, and 10.0 multiplied by a power of ten value of ohms (1, 10, 100, … 1M). There are other ohm values available, but these are less common. The ohm tolerances for resistors are usually 10%, 5%, or sometimes even 1%. The smaller the tolerance, the more expensive the resistor; hence, a knowledge of the resistor requirements will potentially lower the cost of the circuit.

If you purchase a through-hole resistor, its ohm value and tolerance will be specified by its color code (see chart below). A 4-band resistor of color Green, Blue, Yellow, Gold, will have an ohm value of 56*10K = 560Kohms with a tolerance of +/- 5%. A five-band resistor of color Red, Violet, Black, Black, Brown, will have an ohm value of 270*1 = 270 ohms with a tolerance of +/- 1%.



COLOR	1ST BAND	2ND BAND	3RD BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	± 0.5% (D)
Blue	6	6	6	1MΩ	± 0.25% (C)
Violet	7	7	7	10MΩ	± 0.10% (B)
Grey	8	8	8		± 0.05%
White	9	9	9		
Gold				0.1Ω	± 5% (J)
Silver				0.01Ω	± 10% (K)

The power rating of a resistor depends on its surface area, which determines how much heat it can transmit to its surroundings when a temperature differential exists between the resistor and its surroundings. If a resistor must operate in a hot environment, it must be "de-rated" for proper operation. The process of "derating the resistor" means to choose resistors with a power rating greater than the power that will ever be dissipated by the resistor. For example, if the power dissipated by a resistor would never be greater than 1W, derating the resistor by a factor of 2 would mean that a 2W resistor is required. The figure below shows the sizes of through-hole resistors with different power ratings.



Resistance, Voltage and Current Measurements
A DMM (Digital Multi-Meter) can be used to measure three important circuit quantities; resistance, voltage and current. Resistance measurements are made with the DMM selected as an ohmmeter. When measuring resistance with an ohmmeter, <u>**circuit power must be off**</u>. If a circuit is powered while using an ohmmeter, the ohmmeter readings will be inaccurate and even worse the ohmmeter could be severely damaged. Also, when measuring an individual resistance, the individual resistance must be disconnected from the rest of the circuit, otherwise, the total resistance (Req) is measured instead of the individual resistance. In addition, resistors are not polarized, meaning it does not matter how a resistor is oriented in a circuit, it will function the same electrically. Furthermore, since a resistor is not polarized, ohmmeter leads can be connected either way and the same resistance will be displayed.

A continuity-tester, like the one built in experiment 1, is a primitive ohmmeter as it will only indicate whether there's a connection (ideally 0Ω = "short") or not a connection (ideally ∞Ω = "open"). A continuity-tester does not display a finite value of resistance as an ohmmeter does. A DMM often includes a continuity-tester for quick checks of determining whether connections are good or not.

Voltage measurements are made with the DMM selected as a voltmeter. The circuit must be powered when measuring voltage; otherwise the voltmeter will display zero volts. A **voltmeter is connected in parallel** with a circuit element to measure its voltage. Ideally, a voltmeter has infinite resistance (an open circuit) thereby not taking any current away from the element being measured. A good practical digital voltmeter (DVM) has an internal resistance in the range of 10MΩ to 10GΩ (10,000,000Ω to 10,000,000,000Ω). Thus, a DVM draws relatively low current when connected across circuit elements. This high internal resistance enables the DVM to measure circuit voltages with negligible "loading" (drawn current). Loading (further discussed in experiment 3) is undesirable since it lowers voltage readings and hence introduces measurement error.

Current measurements are made with the DMM selected as an ammeter. The circuit must be powered when measuring current; otherwise the ammeter will display zero amps. **An ammeter is connected in series** with a circuit element to measure its current. Ideally, an ammeter has zero resistance (a short circuit) thereby not dropping any voltage, thus not introducing measurement error. A good practical ammeter has a small internal resistance (typically a few ohms) and therefore will decrease the current it's measuring a tiny amount.

Accuracy and Precision of Measurements and Instruments

It is important to realize there are limitations in the use of DMMs. Students often believe that the numbers shown on a DMM display are precisely accurate. This is never true and often the relative error can be quite high when measuring small values on the selected range.

Also, it is very important to distinguish between accuracy and resolution. As an example, a 3½ digit meter (½ digit refers to the digit which can only be "0" or "1") can count up to 2,000 when displaying the measured parameter, whether it is voltage, current, or resistance. The resolution for such a meter is one count or ± 1 part in 2,000. If DC voltage is measured on the 2V range, the meter will measure from 0.001V to 1.999V. The resolution is then one count or 0.001V.

In general, "measurement accuracy" is defined as the difference between the values obtained from measurement and the "real" value of a quantity. The "equipment accuracy" however is a different parameter. For a particular piece of equipment, it is the *worst-case* measurement accuracy obtainable from it. Accuracy for a digital meter is specified as a percentage of the reading plus or minus 1 or 2 counts of the least significant digit. For an analog meter, the accuracy is specified as a percentage of the full-scale value of the meter setting range. Therefore, digital instruments have an additional advantage; their accuracy is largely independent of the meter range. The accuracy is not completely independent of the range because of the 1 or 2 count uncertainty in the least significant digit. As an example, suppose 1.324V is measured on the 2V DC range of a digital meter with a DC accuracy of 0.25% ± 1 count. The maximum error is then

$$(0.0025)(1.324V) + 0.001V = 4.31mV$$

The percent error is

$$\frac{0.00431}{1.324} \times 100\% = 0.33\%$$

A second, more extreme example: Suppose 0.032V is measured on the same 2V DC range. The maximum error in this case is

$$(0.0025)(0.032V) + 0.001V = 1.08mV$$

The percent error is

$$\frac{0.00108}{0.032} \times 100\% = 3.38\%$$

This is less accurate than a good quality analog meter and much worse than the stated accuracy of the DMM. A solution to this problem is to switch to the next lowest scale, 200mV. The reading error would still be 0.25%, but the least significant digit uncertainty would be ± 0.1mV. Thus, the error for the 32mV reading is 0.56%. **The conclusion is that to obtain the <u>most accurate reading</u>, one should always choose the <u>lowest possible range</u>.**

Other hidden sources of error in DMMs are noise, variations in temperature, and errors due to lack of calibration. The most accurate measurements that can be made with a DMM are DC voltages. All other measurements are less accurate, with AC current being the least accurate. When a single accuracy figure is given for a meter, it is always for DC voltage. Always read the complete specifications listed in the DMM user guide if measurements other than DC voltage are to be taken.

Below is a glossary of important terms:

* **measurement accuracy**: how close the recorded value of a measurement is to the true physical value. One way this can be quantified is an *absolute error,*

  (absolute error) = (measured value) – (true value)

  — where the sign of the result is preserved. (Hence, there is no absolute value involved in computing an "absolute" error.) At times, it is also appropriate to express measurement accuracy as a *relative error,* the most common way being as percentage:

  $$\text{(relative error in percent)} = \frac{\text{(absolute error)}}{\text{(true value)}} \times 100\%$$

  — again, the sign being preserved. (An example of where relative error is usually not appropriate is when measuring an angle.)

* **measurement resolution** (sometimes referred to as "measurement precision"): how finely the measurement is recorded. For example, a voltage measurement might be recorded to the nearest 0.1 mV.

* **equipment accuracy:** the worst-case measurement error obtainable from the equipment output. This may be expressed as either an absolute error — e.g., "within ±5 μA" — or as a relative error (when appropriate) — e.g., "within ±3%".

* **equipment precision:** how much the equipment output varies from measurement to measurement, upon measuring the same physical quantity many times. Thus, the precision of an instrument quantifies how random its output is, and indicates how repeatable its readings are.

* **equipment resolution:** how finely the output is displayed. For a digital meter, its resolution is to the nearest least-significant digit. For an analog meter, the resolution is infinitely fine.

Lastly, are analog meters obsolete? Almost; their only advantage is that they can show trends. It is easier to see a needle move than it is to keep track of numbers changing on a display. To accommodate this feature, some digital instruments have an analog display in addition to the digital display. Analog meters find use in specialized measurement situations, such as high voltage, low current or high resistance.

Ohm's Law

Ohm's law is one of the most fundamental laws of circuits; this law shows the relation between current, voltage and resistance.

$$\boxed{i(flow) = \frac{V(pressure)}{R(oppositiontoflow)}}$$

An analogy often used in circuits is current is thought of as "flowing" like water (current is a continuous movement of electrical charge), voltage is like pressure (voltage is an indication of the amount of energy required to move the charge between two nodes) and resistance is like friction (opposition to the flow of current).

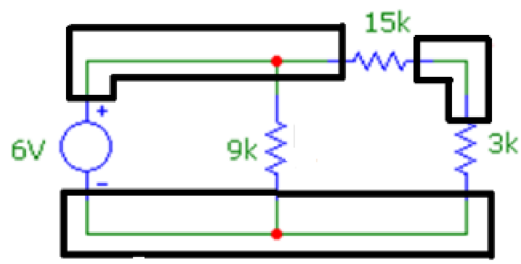
Kirchhoff's Circuit Laws

Kirchhoff's Current Law (KCL): The sum of currents entering a node must equal the sum of currents leaving the node. KCL is based on conservation of electrical charge. Electrical charge can neither be created nor destroyed. Since current is moving charge, if current into a node did not equal current out of a node, the conservation of electrical charge would be violated since the node would either be creating or destroying charge with cannot happen.

Kirchhoff's Voltage Law (KVL): The sum of voltage drops must equal the sum of voltage rises around any loop; a loop is a closed path. KVL is based on conservation of energy. As stated earlier, voltage is an indication of the amount of energy needed to force charge to move (current) between nodes. A voltage rise indicates an energy increase; a voltage drop indicates an energy decrease. If voltage rises did not equal voltage drops around a closed loop, the conservation of energy principle would be violated.

What is a node?

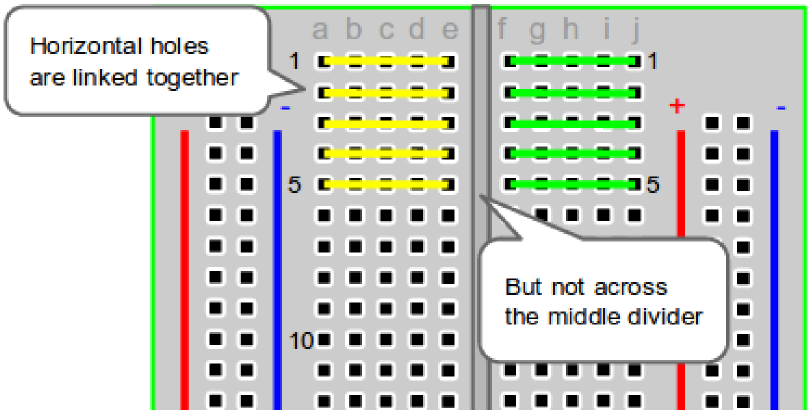
A node is simply a connection of two or more circuit elements. Every copper trace on a PCB is a node. A line on a schematic (circuit diagram) connecting circuit symbols is a node. Thus, each line on a schematic represents a copper trace on a PCB. On schematics often, rectangular boxes are drawn surrounding lines between symbols to indicate nodes, see below. Each of the three black rectangles encapsulates a node, each of the three rectangles represent a copper trace on a PCB.



Breadboards

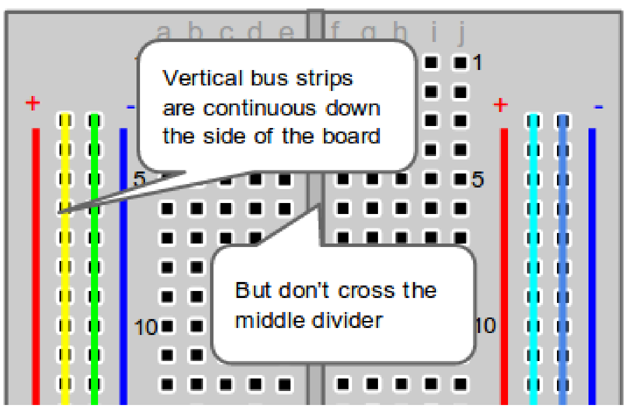
Breadboards are used to make experimental models of electric circuits. You can easily connect a variety of different circuit elements (resistors, capacitors, inductors, integrated circuits (ICs), power supplies, etc.) in your desired configuration.

Each row in a breadboard serves as a single node in your circuit diagram; however the middle divider electrically separates the two sides of the breadboards.

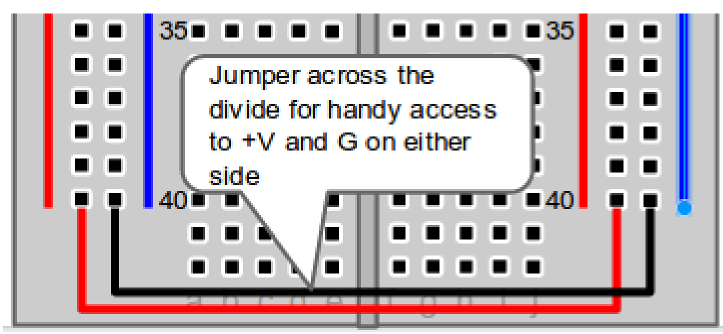


Many breadboards also have vertical bus strips down the sides of the boards. All of the holes next to the red line are electrically connected and all of the holes next to the blue line are electrically connected. These lines are typically used for connecting power (red line) and ground (blue line) to your board.

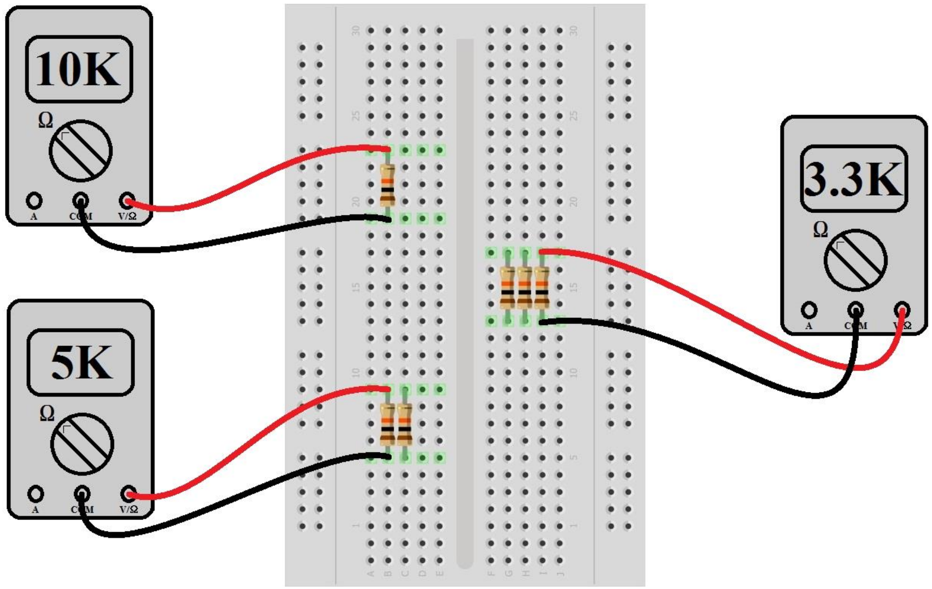
Note: There are some breadboards that have a break in the middle of the board for the power and ground bus. If unsure, check with an ohmmeter.



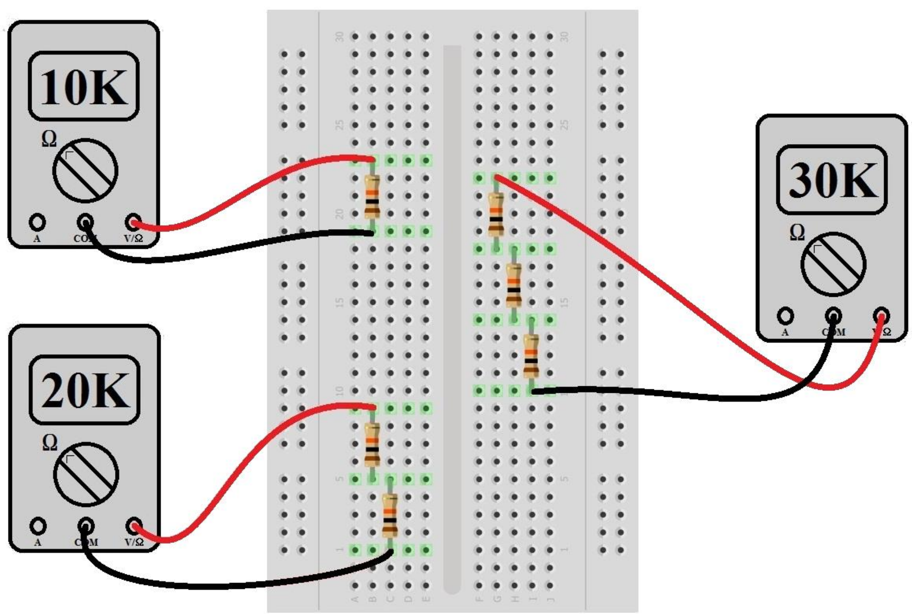
If you want to have the same power and ground connected to the left and right side of your board, you can add jumpers across the divide to connect the two red rails together and the two blue rails together.



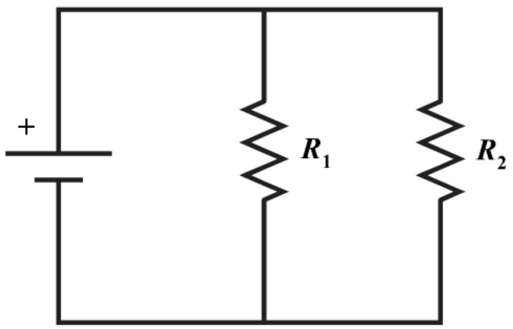
The image at the top of the next page shows how to connect resistors (or any two-terminal element) in parallel on a breadboard (the resistors depicted are all 10K ohms).

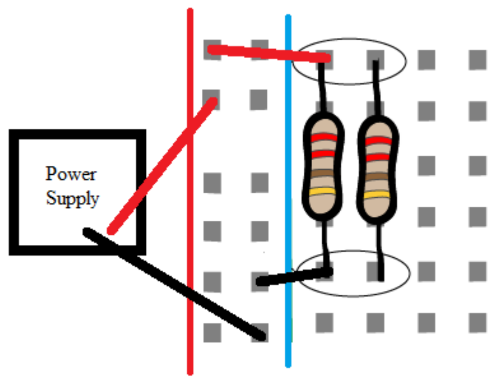


The image below shows how to connect resistors (or any two terminal element) in series on a breadboard (the resistors depicted are all 10K ohms).



The image at the top of the next page shows a circuit schematic and its realization on a breadboard (the red and black lines represent jumper cables).





PROCEDURE:

Section1) Accuracy and Precision (Resistance Measurements as an example)

a) Consult your multi-meter user guide for resistance ranges. For example, the Agilent 34401A Multi-meter has seven ranges; 100Ω, 1kΩ, 10kΩ, 100kΩ, 1MΩ, 10MΩ and 100MΩ. The range indicates the maximum resistance that can be measured; for example 1kΩ range can be used to measure resistance from 0 to 1,000Ω.

b) Measure 470Ω through-hole resistor with an ohmmeter set to manual range.

Note: If multi-meter only has an auto range setting, skip this step and proceed to step c)

- Observe (but don't record) the effect of changing the range; then, select the range that yields the <u>best precision</u> and record in the table below the complete readout (i.e., all the digits displayed).

Note: If range is less than measured resistance, OVLD (overload) or something similar is likely to be displayed.

Best Precision Range	Manual Readout (Ω)

Answer discussion question #1 before continuing to the next step.

c) Set the multi-meter to auto range, measure and record the range used and the resistance readout for the 470Ω resistance.

Note: If multi-meter only has a manual range setting, skip this step and proceed to step d)

Best Precision Range	Auto Range Readout (Ω)

d) Set ohmmeter to lowest resistance range, measure and record the resistance of the ohmmeter leads by connecting the leads together.

Leads Resistance _______________Ω.

Section2) Body Resistance Measurement

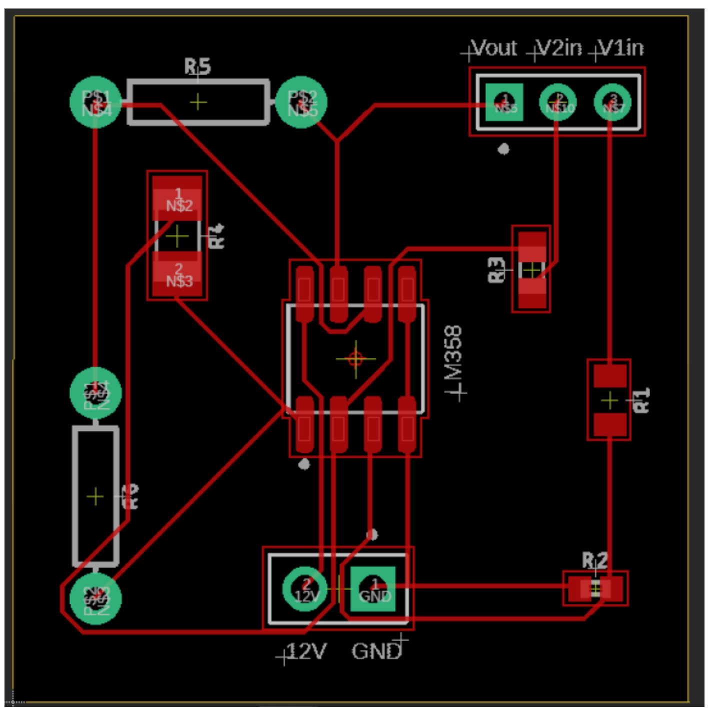
SAFETY ITEM: For steps a and b use a handheld multi-meter. Do NOT use multi-meter plugged into 120VAC.

a) Tightly hold the bare end of each meter probe between the thumb and forefinger of each hand. Measure and record your body resistance.

b) Moisten your thumb and forefinger of each hand with a damp cloth and repeat a).

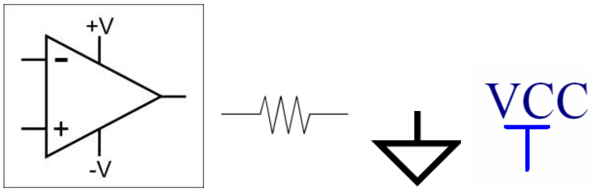
Name	Body Resistance Dry Fingers	Body Resistance Moist Fingers

Section3) Reverse Engineer a PCB layout.



a) Draw a schematic for the above PCB layout. The red lines represent copper traces on a PCB. Note that your schematic should have 2 op-amps, 6 Resistors, 2 inputs (V1in & V2in), 1 output (Vout), Power (VCC, same as 12V) and ground (GND). All components and pin numbers are to be labeled. In order to know the pin numbers of the 2 op-amps, see the datasheet for the 8-pin LM358 IC (just google LM358 datasheet).

Below are the circuit symbols to use in your schematic.

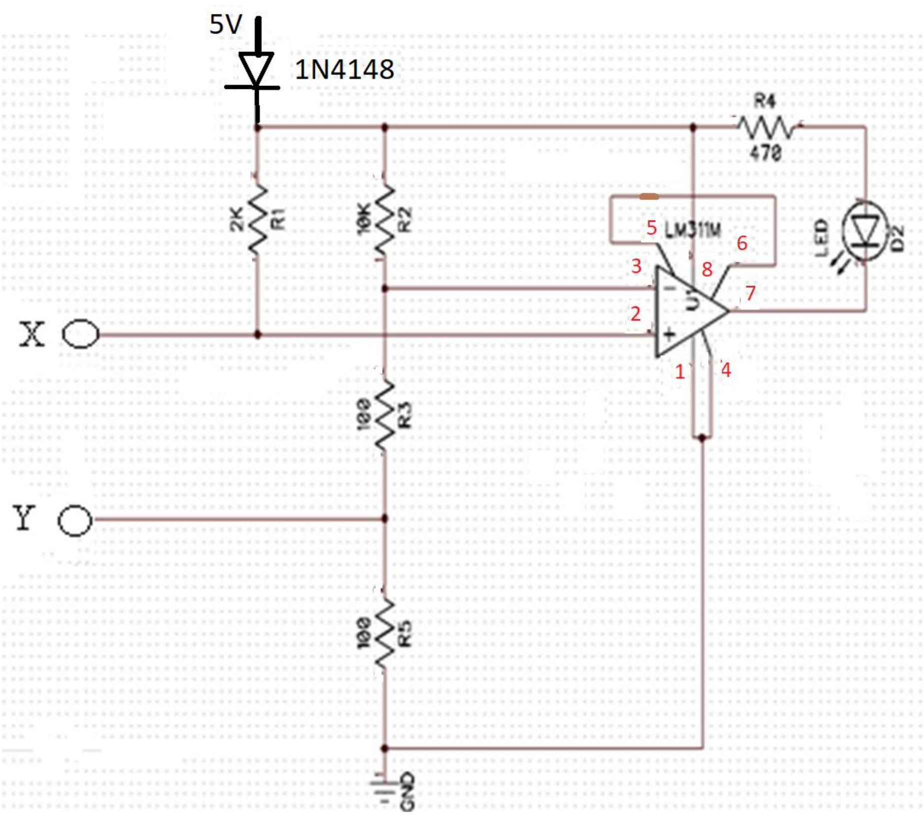


Op-amp. Resistor GND Power

Inputs, output, power and ground can be shown as pins on a connector symbol as shown below:

Section4) Verification of Kirchhoff's Circuits Laws

a) Build the continuity-tester circuit shown below on a breadboard. Red numbers are LM311 pin numbers; pins 5 and 6 are connected together, as well as, pins 1 and 4. Between nodes X and Y is where the test resistance is connected; i.e. the continuity being tested. When a wire is connected between X and Y the LED should light. When there is no connection (an open) between X and Y the LED should not light. The 5V is to be provided by the Arduino board.



b) Connect 5V and connect nodes X and Y ("short X and Y").
c) Use a voltmeter to verify KVL around each of the following loops:

NOTES: Recall from background discussion, a voltmeter is placed in parallel.
Also, if '+' voltmeter lead is connected to lower end of voltage difference, a minus sign is displayed.
All voltages measured in loops 1 and 2 are voltage drops except the 5V Arduino supply voltage.

Loop 1. There are 5 voltage measurements. Loop 1 contains the 5V source, diode (1N4148), 10KΩ (R2) and two 100Ω resistors (R3 & R5).

To measure the voltage across an element, place your voltmeter leads across the element leads.
Record your measurements in the table below.

V(5V source)	V(diode)	V(R2 = 10kΩ)	V(R3 = 100Ω)	V(R5 = 100Ω)

Using the measurements above, write an equation showing that KVL is satisfied.

Loop 2. There are 5 measurements. Loop 2 contains the 5V source, diode (1N4148), 470Ω (R4), LED and LM311N pin 7.

NOTE: When measuring pin 7 voltage, connect voltmeter between pin 7 (VOUT) and GND.

V(5V source)	V(diode)	V(R4 = 470Ω)	V(LED)	V(Pin7)

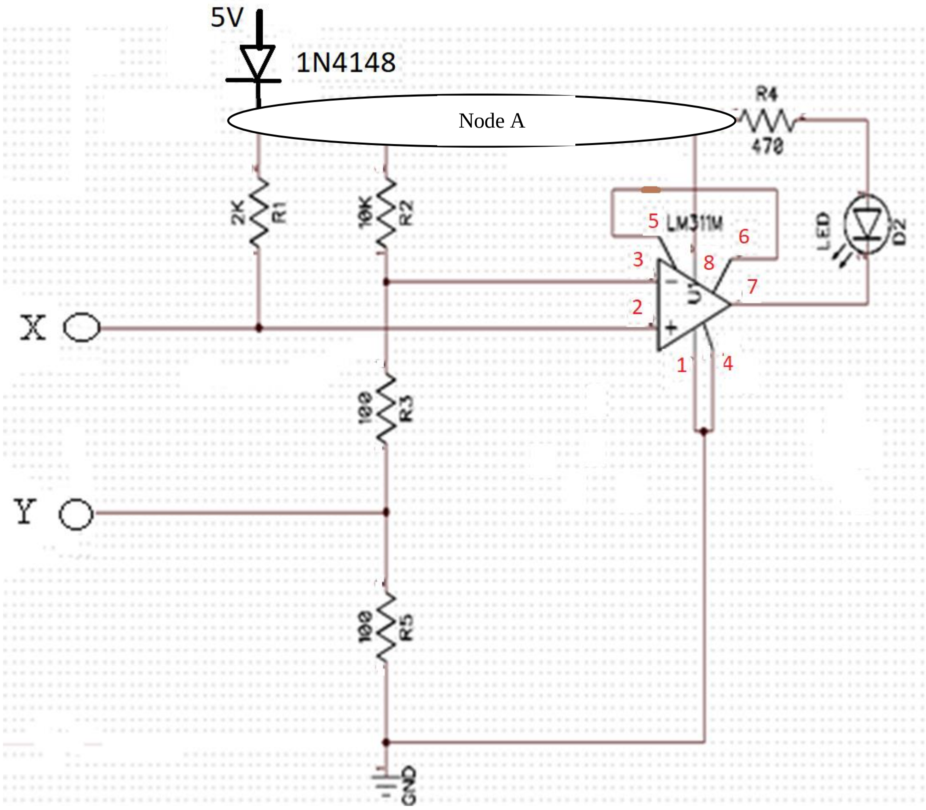
Using the measurements above, write an equation showing the KVL is satisfied.

d) Use an ammeter to verify KCL at the node A (shown below). Node A connects diode (1N4148), R1, R2, R4 and pin 8 of IC. Verify KCL when there is an open X and Y and for when there is a short X and Y. Record currents below.

NOTE: Recall from background discussion, an ammeter is placed in series.
Easy method to connect ammeter in series is to first break a connection on one side of the element and then insert ammeter between break. Ideally an ammeter has an internal resistance of 0Ω, so placing an ammeter in between a break makes a connection.

If ammeter is placed in a circuit so that current flows from '+' input to '-' input, display will not show a minus sign. The only current flowing into node A is the diode current.

SAFETY: When making a change in a circuit; for example, breaking a connection and then placing ammeter in series, disconnect 5V supply. After change is made reconnect 5V supply to make measurement.



X and Y	I(diode)	I(R1 = 2kΩ)	I(R2 = 10kΩ)	I(R4 = 470Ω)	I(pin8)
disconnected					
connected					

Using the measurements above, write equations showing that KCL is satisfied (both when the leads are open and when they are shorted).

e) Replace the 470Ω resistor with a 20kΩ resistor. You should observe a change in LED brightness.

DISCUSSION:

Section 1

1) Generally, which multi-meter range yields the best precision?

Section 2

2) Contrast your body resistance with dry fingertips compared to your body resistance with damp fingertips. For a given amount of voltage, when are you more susceptible to serious injury due to electricity? Use Ohm's Law to support your answer.

Note: For discussion #2, the more current; the more lethal. Current as small as 6 milli-amps can cause painful shock and a current of greater than 50 milli-amps can be fatal.

Section 3

3) Draw a box / rectangle around each of the nodes on your schematic. Insert a picture of schematic here.

4) How many nodes are there in the schematic?

Section 4

5) Explain the difference in diode current when there's an open between the continuity-tester leads and when there's a short between the leads.

6) Write the KVL equation for the loop containing the 5V source, diode and 2kΩ resistor when there is an <u>open</u> between the continuity leads. What is the voltage across the open?

7) Using data from procedure steps c) and d), how much power is expended by the LED when lit? Recall that P=IV

8) In step e), did the LED glow brighter or dimmer after the 470Ω resistor was replaced with a 20kΩ resistor? Explain with your knowledge of Ohm's Law.
   Hint: When lit, LEDs have, for all practical purposes, a constant voltage across their leads.