LABORATORY 2 – DC CIRCUITS

OUTLINE

SUMMARY

- Voltmeters measure the difference in voltage between two probes. Voltmeters should always be connected in parallel, as they have very high internal resistance.
- Ammeters measure the current flowing through a branch. Ammeters should always be connected in series (or else a fuse may blow), as they have very low internal resistance.
- Resistors must be disconnected from the circuit be-fore measuring their resistance with an ohmmeter to get the correct measurement.
- Any linear circuit that contains sources and resistors can be reduced to a circuit of only one voltage source V_T and resistance R_T . This is its Thévenin equivalent.
- LEDs (light-emitting diodes) only allow current to flow in one direction. LEDs typically have a non-zero threshold voltage.
- Potentiometers are three-terminal devices that act as two variable resistors sharing a common terminal.

1. BASIC MEASUREMENTS OF ELECTRIC CIRCUITS

Voltage Measurements

Recall that voltage is the difference of electric potentials between two nodes in a circuit, which we may denote ***node A*** and ***node B***. Correspondingly, a voltmeter has two terminals. One is called the ***probe*** and the other is called the ***reference***. The voltmeter measures the voltage difference between the probe terminal and the reference terminal. Figure 1 shows how to measure the voltage across a resistor.

$$V_{probe-minus-reference} = V_{AB} = V_A - V_B$$

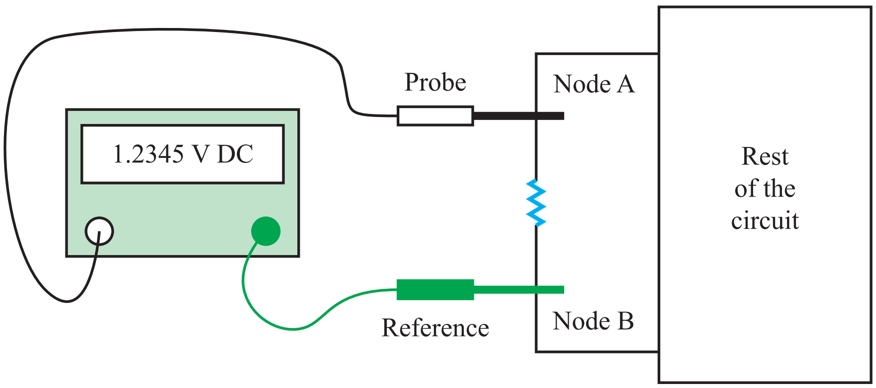


Figure 1: Voltmeter probe at Node A.

If we swap the connections of the cables to the circuit, as show in Figure 2, the voltmeter will measure

$$V_{BA} = V_B - V_A = -V_{AB}$$

Note the differences in the placement of the probe and reference terminals, and the opposite signs for the voltmeter reading. These figures also indicate the typical number of significant digits obtained in the lab measurements. When you do pre-lab calculations***, keep 4 or 5 significant digits to match the accuracy of lab measurements***.

The voltmeter has its own internal (input) resistance, which is usually very high. For an ideal voltmeter the input resistance is infinitely large. In real instruments, the input resistance usually exceeds 1 MΩ. When we measure voltage V_{AB}, the voltmeter's internal resistance (between its two terminals) is connected in parallel with all circuit components connected between these two terminals. In other words, the internal, or input resistance of the voltmeter is in parallel with the equivalent resistance R_{AB}. A good voltmeter, whose input resistance is very high, will not change the circuit when connected.

> ***You do not have to change anything in your circuit to measure voltages: just connect the voltmeter to the nodes of interest. Thus the voltage measurement is simple and noninvasive.***

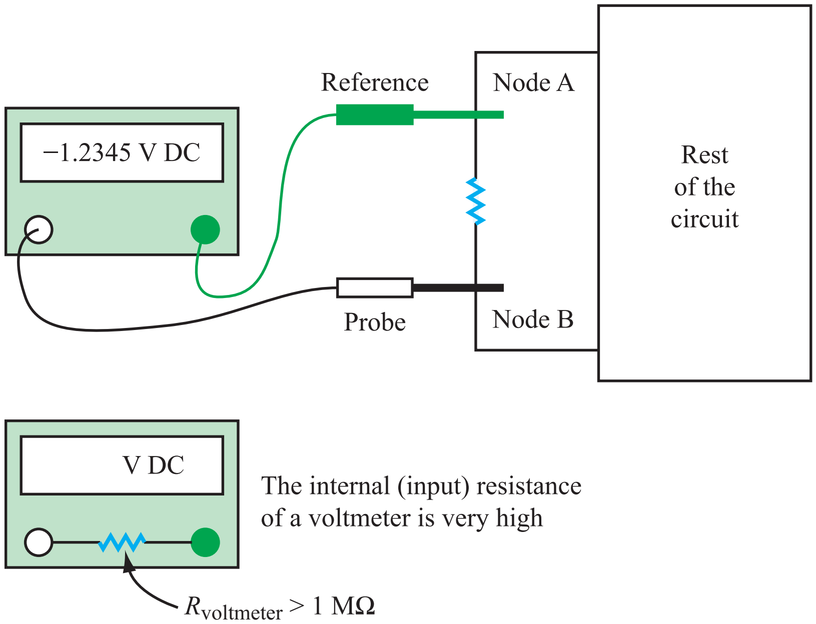


Figure 2: Voltmeter probe at Node B.

To measure voltage using an Agilent 34405A digital multimeter (DMM):

- Disconnect all cables from the terminals on its front panel if this was not done already.
- Turn on your multimeter.
- Make sure that your multimeter is in the Local mode, which means it responds to the front panel buttons, not to the commands sent remotely by the computer. Press the Local button and make sure that there is no Remote or Rmt displayed.
- By default, the DMM is ready to measure DC voltages right after it is turned on. To make sure, press the DC V button on the front panel. Since nothing is connected to the terminals, the displayed voltage should be around zero, fluctuating slightly due to electronic noise.
- Locate the two terminals for voltage measurement on the front panel of your DMM.
- Get two cables with banana plugs on both ends. Use different colors for the probe and reference cables.
- Plug the cables into the probe and reference terminals.

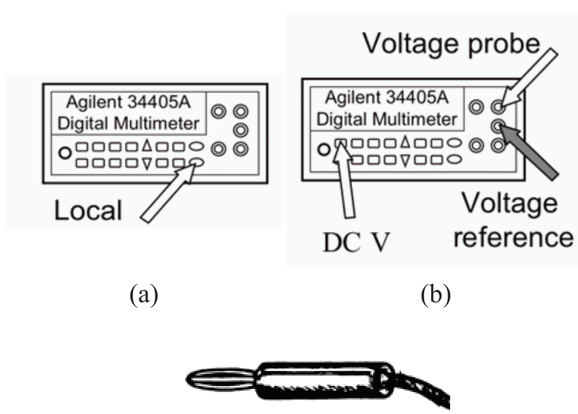


Figure 3: Multimeter dials.

Current Measurements

To measure the current that flows through a branch of a circuit, we should make this current flow through the ammeter. An ammeter has two terminals, one labeled ***Current In*** and ***Current Out***. Note that ***in order to measure the current, we have to interrupt the circuit***: the diagram in Figure 4 shows that instead of one node A, we work with two nodes: A1 and A2. These two nodes play distinct roles in our measurement: at node A1 the current leaves the circuit to the ammeter, and at node A2 the current is returned to the circuit. Since we make the current pass through the ammeter, the ammeter is connected in series with the resistor in the circuit, in contrast with a voltmeter, which involves a parallel connection.

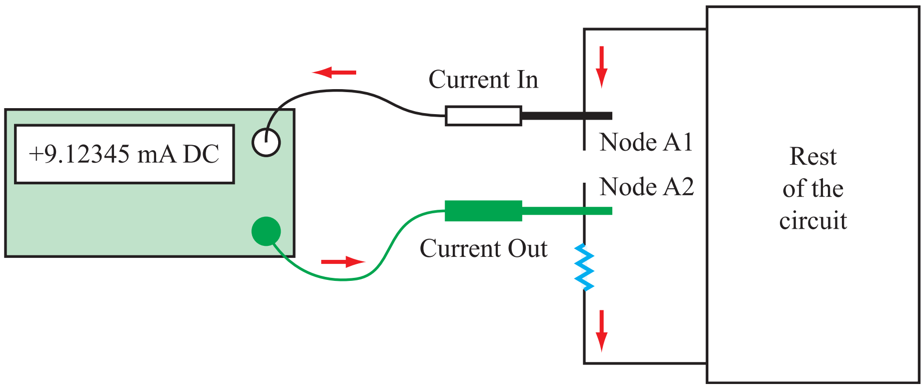


Figure 4: Ammeter "Current In" at Node A1.

If we swap the connection of the ammeter cables to the circuit, as shown in Figure 5, the current from the circuit will enter the Current Out terminal and the sign of the current measured by the ammeter will be reversed.

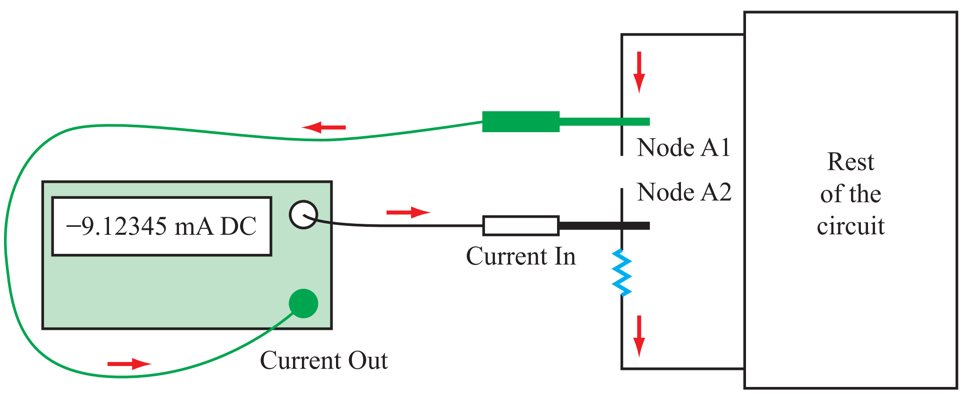


Figure 5: Reversing ammeter connections to the circuit.

Because an ammeter used to measure the current through a circuit component is connected in series with that component, it is important that the internal resistance of the ammeter be very small. Typically, $R_{AMMETER} \approx 1\ \Omega$ or less. An ideal ammeter is assumed to have zero internal resistance.

> ***You need to 'break the circuit' to measure currents: a series connection is required such that current flows through the ammeter.***

To Measure current using an Agilent 34405A DMM:

Compared with the measurement of voltage, the measurement of current with the Agilent 34405A digital multimeter (DMM) requires different connections of cables and different settings on the front panel.

- Note that 34405A has two ***Current In*** terminals, corresponding to different current levels.
- Press the DC I button to switch 34405A into the current measurement mode.
- Make sure that its display reads ***mA DC***.
- Connect the cables to the upper left ***Current In*** terminal and to the ***Current Out*** terminal.
- Measure all currents larger than 100 mA with the 10 A current terminal and set the range at the highest value. Use the 1 A current terminal for very small current levels.

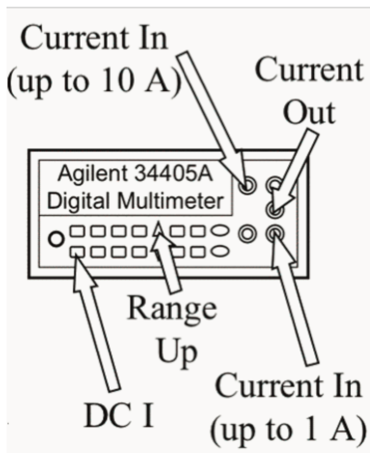


Figure 6: Ammeter dials

Resistance Measurements

To measure the resistance of a resistor, we simply connect it to the two terminals of an ohmmeter, labeled HI and LO, and then we read the resistance value from the display (Figure 7). Remember: You must disconnect the resistor from your circuit before measuring the resistance! Otherwise, you will NOT obtain the correct reading of resistance.

Here is why: The ohmmeter's internal circuitry includes a voltage source V_S (usually 1 V) and has a certain equivalent internal resistance R_S. The component whose resistance you wish to measure is connected to the two terminals labeled HI and LO on the equivalent circuit diagram as shown in Figure 7. From the voltage V_S and the current I that flows through terminals HI and LO (or the voltage drop between the terminals HI and LO), the instrument calculates the resistance R using the formula for voltage division and displays R in the units of ohms. Thus, the ohmmeter measures the combination of R and whatever other circuit connected in parallel with it.

A typical beginner's mistake is to hold the resistor between her/his fingers while measuring its resistance (Figure 8): some current I_2 will flow through the human skin and body. Although—in resistance measurements—such currents are not harmful (and barely noticeable), results of such resistance measurement will be worthless!

Another typical mistake is to keep the resistor, whose resistance you measure, connected to other parts of your circuit. Even if your circuit is not connected to a power supply, the current through terminals HI and LO will now depend not only on the resistance *R* but also on the other parts of the circuit.

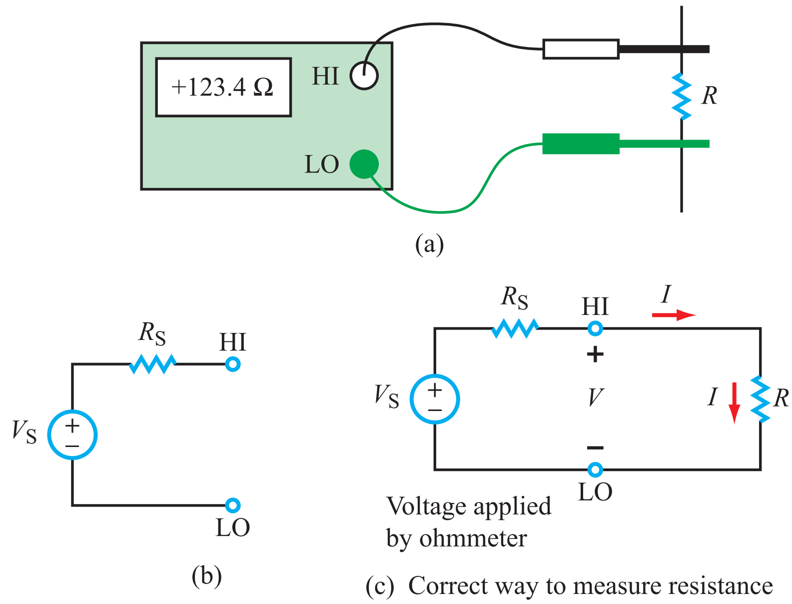


Figure 7: Ohmmeter measurement.

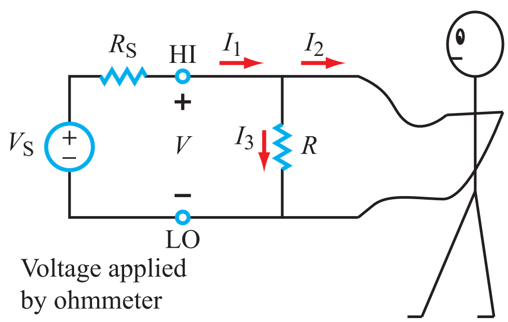


Figure 8: Wrong way to measure resistance.

To measure resistance with the Agilent 34405A digital multimeter (DMM):

- To activate the resistance measurement mode, press the button shown in Figure 9, and connect cables to the same terminals as for the voltage measurements
- Get two alligator clips and attach them to the cables.
- When the alligator clips are not touching each other and are not connected to anything, your display should read OVL.D MOHM indicating an open circuit.
- Grab one alligator clip with the other, creating a "short circuit" connection between the two terminals of the multimeter. The display should change from OVL.D MOHM to a reading less than 1 Ω. This proves that all connections are good.

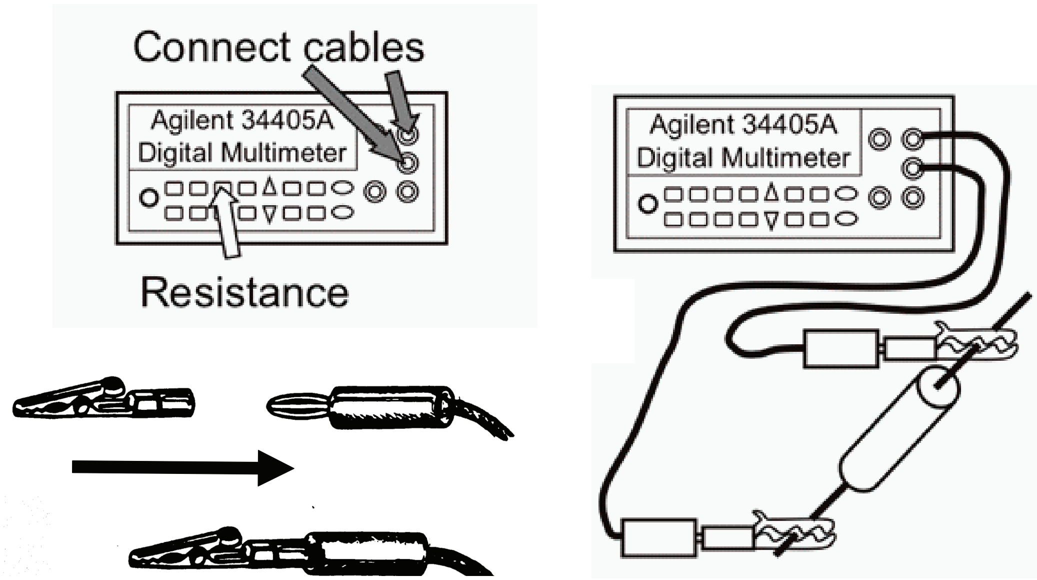


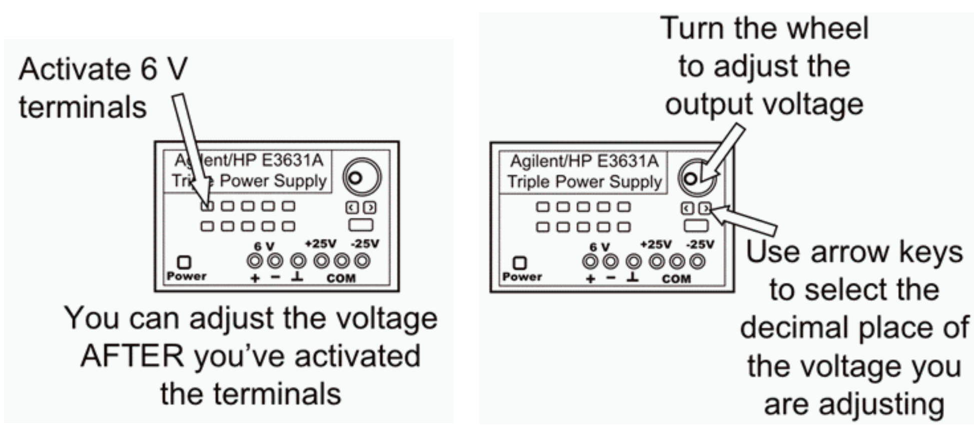
Figure 9: Measurement of resistance using DMM.

2. BACKGROUND FOR LABORATORY

The Agilent E3631A Power Supply

In addition to the Agilent DMM, you will commonly be using the Agilent E3631A Power Supply:

- Turn on the power supply by pressing the Power button
- Press the Local button to make sure that you are not remotely controlling the power supply.
- Activate the 6 V terminals by pressing the appropriate button shown in Figure 10.
- Note that the display of your power supply shows Output Off and +6 V.
- Output Off means that in this state practically no power is delivered to the output terminals.
- +6 V means that the power supply in the 6 V mode. The voltage can be adjusted to any value between 0 and +6 V.



(a) (b)

Figure 10: Adjusting power supply.

Thévenin Equivalent Circuit

Consider the independent voltage source shown in Figure 11. It is so called because it is expected to provide a voltage difference of V_S between its terminals, independently of anything else in the circuit, such as the resistance R_{eq} connected to it. According to this idealized circuit model, the current through the load is

$$I = \frac{V_S}{R_{eq}}$$

and the power absorbed by the load is

$$P = I^2 R_{eq} = \frac{{V_S}^2}{R_{eq}}$$

Thus, both the current and the power can grow infinitely high as the load resistance R_{eq} decreases to zero.

The fallacy with this voltage source model is the oversimplified representation of the voltage source. A more realistic model includes a source resistance as shown in Figure 12. Here the load R_L is connected to a combination of a source voltage V_T in series with a source resistance R_T. As you will observe in the pre-lab, this circuit model is free from absurd conclusions such as infinitely high current or power. The current in this circuit and the voltage across the load resistance are easy to calculate using the formulas for series connection of resistors, voltage division, etc.

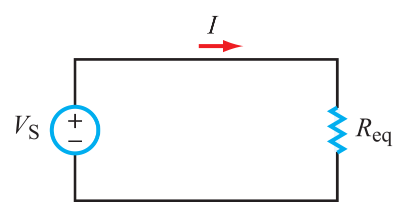


Figure 11: Equivalent circuit of power supply.

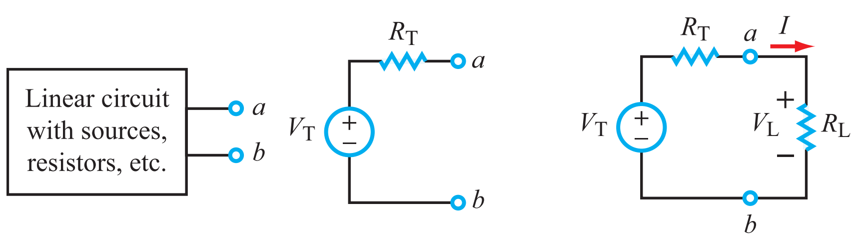


Figure 12: Voltage source connected to load.

According to the Thévenin equivalent circuit theorem, any linear circuit that contains sources and resistors can be reduced to its equivalent, which includes only one voltage source V_T along with its resistance R_T. This applies to a voltage source as well as to any linear circuit, no matter how complicated. The power that can be transferred from the circuit to the load reaches its maximum if the load resistance equals the resistance of the circuit. In this case, with $R_T = R_L$,

$$I = \frac{V_T}{R_T + R_L} = \frac{V_T}{2R_T}$$

$$P_{L,max} = I^2 R_L = \frac{{V_T}^2}{4R_T}$$

On the other hand, from the measured voltage V_L across the load and current I through it, you can calculate the equivalent voltage V_T and the equivalent resistance R_T, (of course, in order to calculate both parameters, you should do the measurements with at least 2 load resistances).

The equivalent resistance of a circuit is defined as the ratio of the voltage applied to the circuit to the current that flows through it; the entire circuit in Figure 13 can be represented by its equivalent resistance

$$R_{eq} = \frac{V_S}{I_{Total}}$$

This definition applies to simulations and measurements: in the pre-lab, you will simulate the circuit, determine V_S and I_{Total} and calculate R_{eq}; in the lab you will build the circuit and measure V_S and I_{Total}; in the post-lab you will compare the two values of R_{eq}.

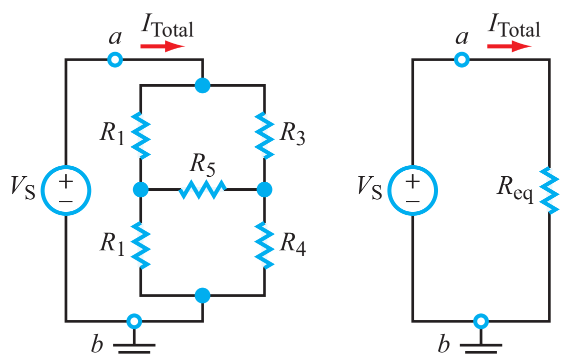


Figure 13: Example of equivalent resistance for a circuit.

Potentiometer

A ***potentiometer***, or ***pot*** in EE jargon, is basically a resistor with three terminals: in addition to the end terminals A and B in Figure 14, there is a movable tap C. The resistance between the potentiometer's ends is fixed: $R_{AB} = R_P$ (the potentiometer's resistance) while the resistance $R_X = R_{AC}$ between the end and the tap is variable. The resistance between the tap and terminal B is (R_P - R_X). Thus the potentiometer is equivalent to two resistors as shown in Figure 14. Potentiometers are used for user control, such as to control the sound volume of an audio system, and as variable resistors and voltage dividers. When a pot is used as a variable resistor, one of its end connectors is either left open or connected to the tap (Figure 14).

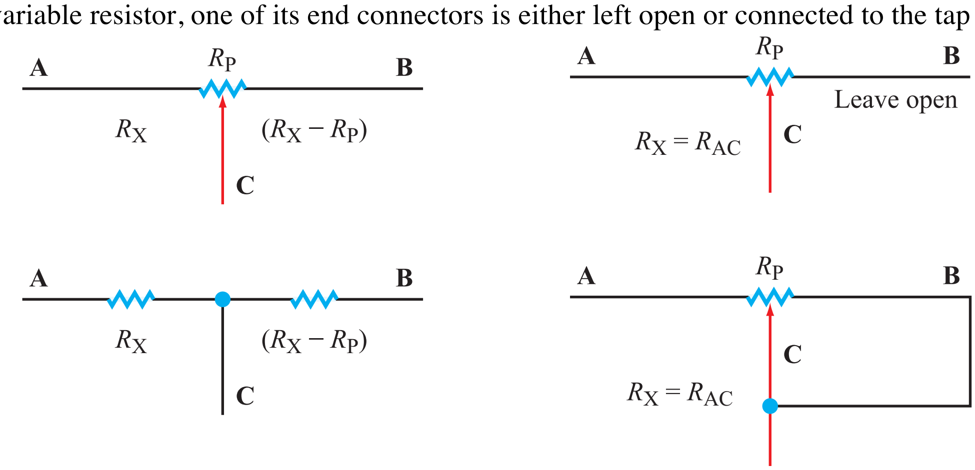
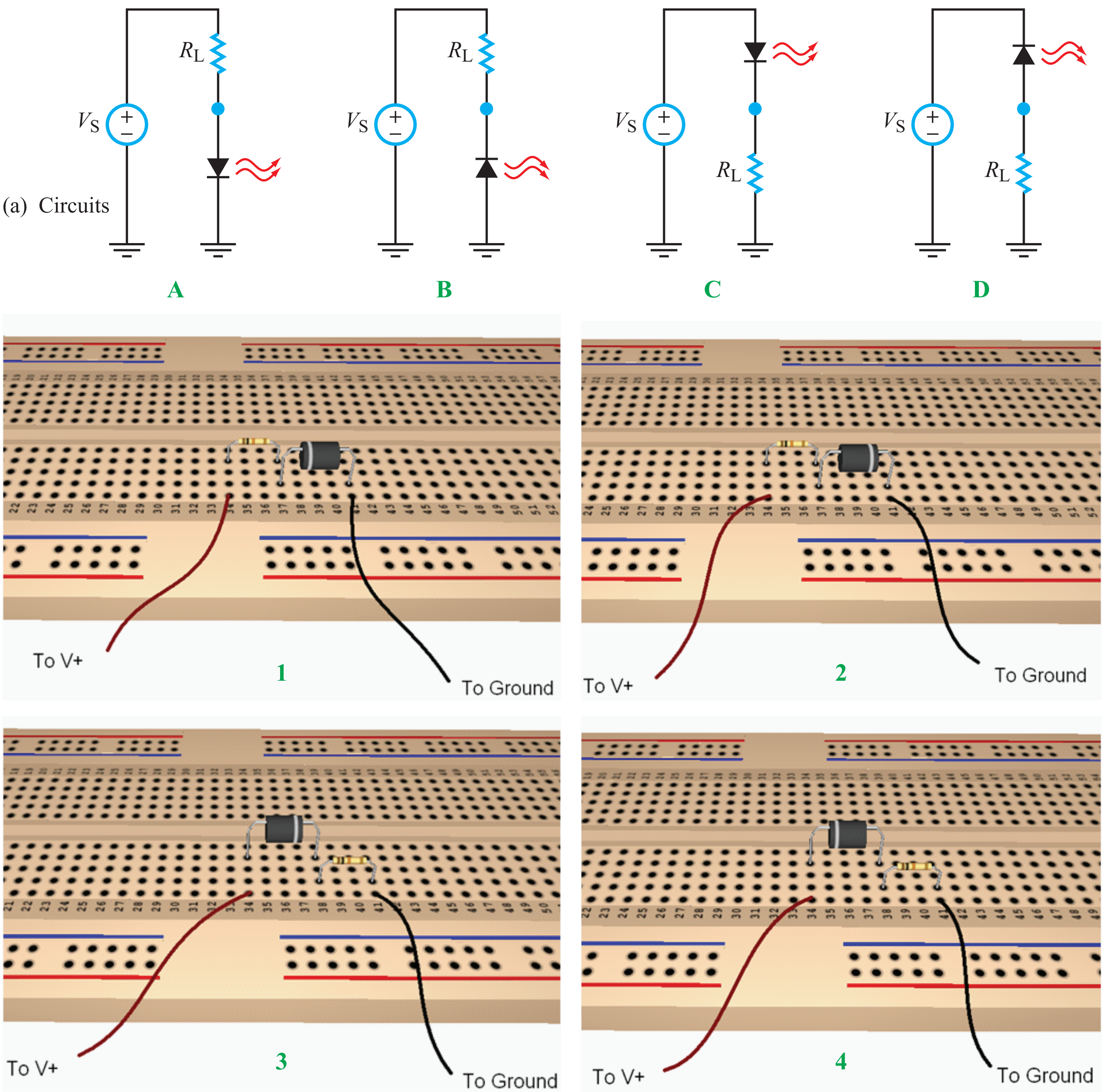


Figure 14: Two equivalent circuit diagrams for a potentiometer and example of connections typically used in circuits. Node C is the movable tap.

3. PRE-LAB ASSIGNMENT

The Pre-Lab includes 6 problems. Make sure to complete them all before the lab.

1. Identify which circuit diagram in Figure 15(a) corresponds to each 3-D picture of the prototyping boards in Figure 15 (b).



(a) Circuits

(b) Prototyping boards

Figure 15: Four different circuit diagrams and four different protoboard arrangements.

2. Draw connections for the measurements of the voltage across and the current through a forward-biased LED (be careful with the polarity) as shown in Figure 16. In this circuit, no load resistor is needed. The power supply should be connected to the bus lines on the left and the LED should be connected to individual nodes on the right.

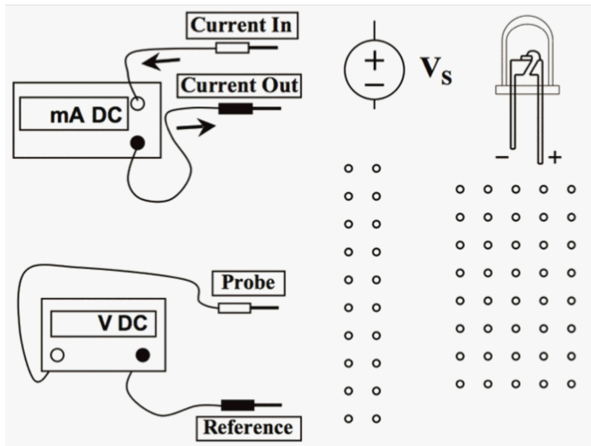


Figure 16: Connecting source and multimeter to circuit on protoboard.

3. Draw connections for a circuit with an LED and resistor as shown in Figure 17. The power supply should be connected to the bus lines on the left, the resistor and LED should be connected to the individual nodes on the right, and the voltmeter should measure the output voltage across the LED.

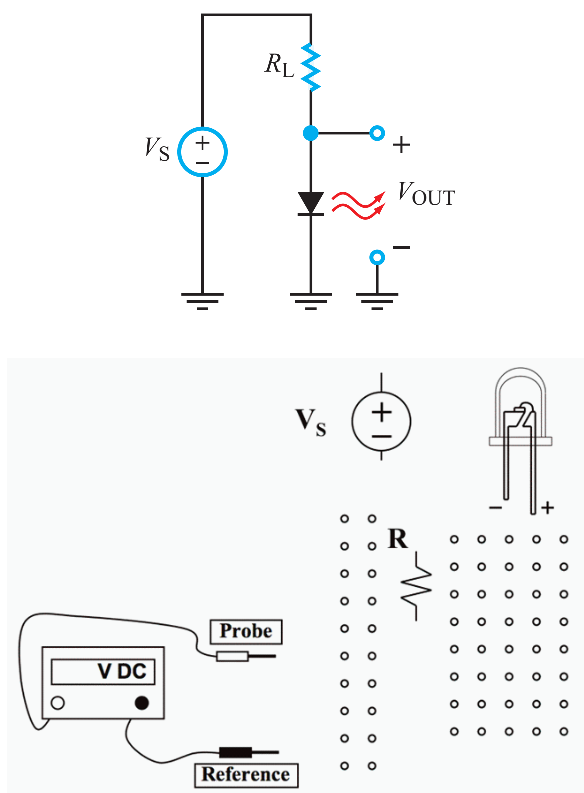


Figure 17: Implementation of resistor-LED circuit.

4. In the lab, you will build the circuit in Figure 18 and measure currents through resistors, node voltages, and the equivalent resistances. Assume $V_S = 6$ V and the following resistances:

   $R_1 = 51\ \Omega$
   $R_2 = 1000\ \Omega$
   $R_3 = 470\ \Omega$
   $R_4 = 150\ \Omega$
   $R_5 = 200\ \Omega$

   Calculate the following and record in the table below:

   - Node voltages V_c and V_d in volts
   - Total current I_{Total} and the current through each resistor.
   - The circuit's equivalent resistance in ohms between nodes a and b.

V_c	V_d	I_1	I_2	I_3	I_4	I_5	I_{Total}	R_{eq}

   Simulate the circuit in SPICE and verify that your values agree.

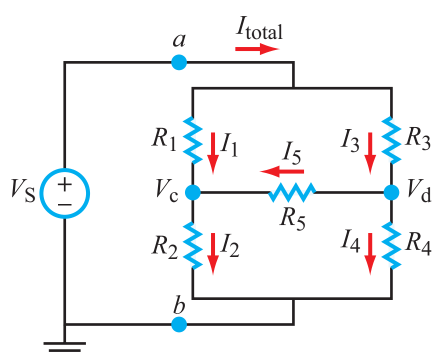


Figure 18: Resistor circuit for equivalent resistance.

5. The circuit shown in Figure 19 is built with the same resistors as the circuit shown in Figure 18, except for the addition of the variable resistor R_X. Determine the value of R_X such that the current I_5 vanishes.

   Your result: R_X = ________________ Ω

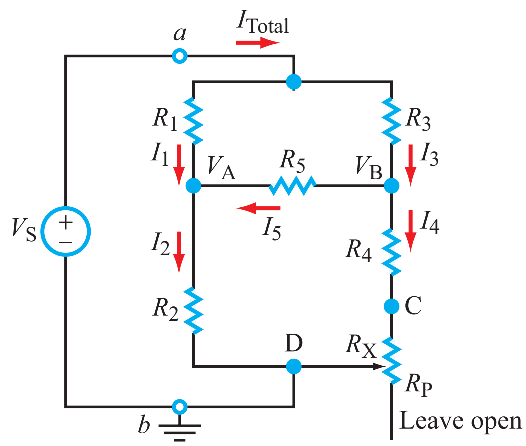


Figure 19: Resistor circuit including a variable resistor.

6. Circuit 3 is also known as a ***Wheatstone Bridge***, which is an effective circuit for measuring changes such as light intensity, strain, and pressure when used with a sensor. A variable resistor (potentiometer) is used to "balance" the bridge at a nominal value, where small changes from the nominal value will produce a voltage output. For the circuit below, derive the value of V_{out} in terms of V_S, R_1, R_2, R_3, and R_4.

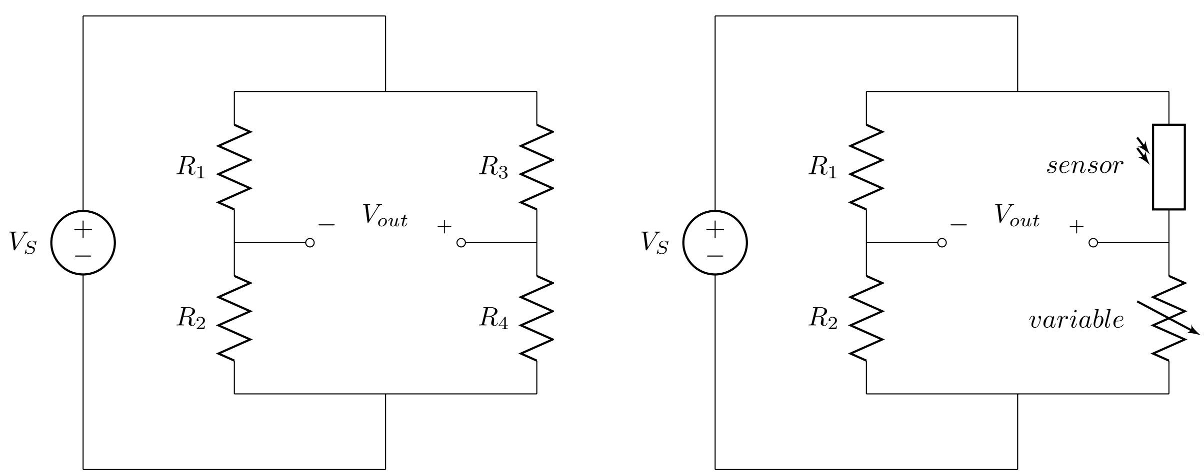


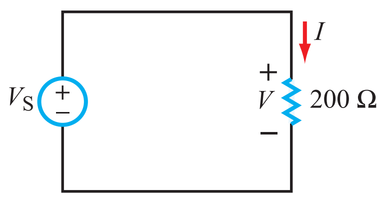
Figure 20: Wheatstone Bridge and example application as a light detector.

4. IN-LAB WORK

Resistor

1. Build the circuit shown in Figure 21 and connect the voltage source V_S.
2. Adjust V_S so that V across the resistor is 1 V, then 2 V, then 3 V.
3. Measure the corresponding currents.
4. Fill in the table below, and calculate the resistances
5. Write a brief conclusion on whether or not Ohm's Law applies to the resistor. Include the tables in your lab report.

Note: For current measurements, be sure to use the most sensitive scale you can on the DMM. Be careful not to put the DMM ammeter into a condition where it is effectively a short circuit (this will blow the protection fuse). If the ammeter appears to not be working properly, consult with your lab instructor and replace the fuse.

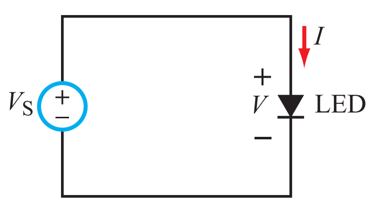


Voltage (V)	1.00 V	2.00 V	3.00 V
Current (mA)			
Resistance from V/I (Ω)			

Figure 21: In-Lab Circuit.

LED

1. Replace the resistor with an LED, as shown in Figure 22. Be sure to insert the LED in the forward biased orientation.
2. Fill in the table below, and calculate the resistances
3. Write a brief conclusion on whether or not Ohm's Law applies to the LED. Include the tables in your lab report.



Voltage (V)	1.00 V	2.00 V	3.00 V
Current (mA)			
Resistance from V/I (Ω)			

Figure 22: In-Lab Circuit with LED.

Thévenin Equivalents

1. Obtain the following resistors: 2 separate 100 Ω and 1 each of 20, 51, 200, 470 Ω and 1 kΩ
2. Use the DMM to accurately measure each resistor value and record your numbers in the table below. We will call one of the 100 Ω resistors "R_s," so be sure you know which is which
3. Build the circuit shown in Figure 23. Set the power supply voltage to $V_s = 6$ V.
4. For each value of R_L, measure V_L and record your data in the table.

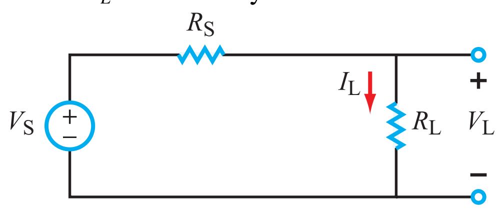


Figure 23: In-Lab load circuit.

Component	Nominal Value (Ω)	Measured (Ω)	Measured V_L (V)	$I_L = V_{L,meas}/R_{L,meas}$ (mA)
R_S	100			
R_{L1}	20			
R_{L2}	51			
R_{L3}	100			
R_{L4}	200			
R_{L5}	470			
R_{L6}	1 k			

Equivalent Resistance

Now let us analyze the more complicated multi-resistor circuit shown in Figure 24, using the nominal resistor values listed in the prelab.

1. Measure the equivalent resistance between nodes *a* and *b* using the DMM ohmmeter before you connect the voltage source.
2. Connect the voltage source and set $V_s = 6$.
3. Use the DMM voltmeter to measure V_s, V_c and V_d . Record your values.
4. Use the DMM ammeter to measure I_{total} and I_5. Record your values.
5. Compare your results with your pre-lab calculations. If the results differ by more than 5%, something is wrong. Check for errors in the circuit or calculations.

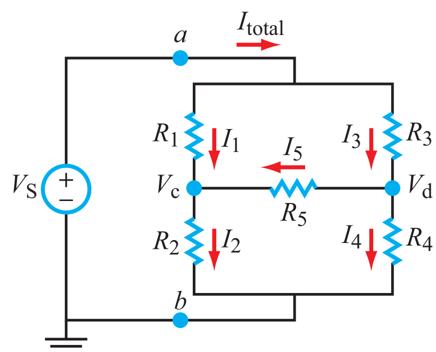


Figure 24: In-Lab multiple resistor circuit.

Quantity	Nominal or Theoretical	Measurement
R_{eq}		
V_s	6 V	
V_c		
V_d		
I_{total}		
I_5		

Wheatstone Bridge Balancing

1. Build the circuit shown in Figure 25 using the same resistors, but now add a potentiometer R_X with maximum resistance of 10 kΩ.
2. Use the DMM ammeter to measure I_5.
3. Adjust the potentiometer so that I_5 = -0.2 mA, -0.1 mA, 0 mA, and the most positive current you can obtain. At each current, taking care not to disturb the setting of the pot, disconnect R_X from the circuit and measure its value using the DMM in ohmmeter mode. Then reconnect and move to the next indicated value of I_5.

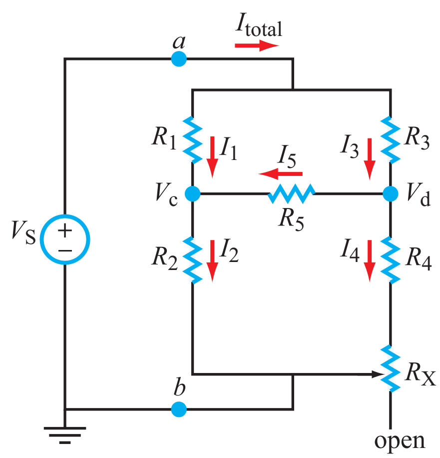


Figure 25: Bridge circuit.

Nominal I_5 (mA)	R_X measured (Ω)	I_5 measured (mA)
-0.2		
-0.1		
0 (balanced)		
Largest possible		

Light Sensor

Now that you know the basics, use a photoresistor to design/build/measure a light detecting circuit based on the concept of a Wheatstone Bridge. (This is a "real" circuit, so do not expect it "ideal"/textbook behavior!)

1. Build a circuit similar to Figure 20 for light detection, where V_{out} will vary with light intensity. Draw a schematic of your circuit, and indicate final values chosen for voltage supply, resistors, potentiometer, etc. (It will be useful to first measure resistance of photoresistor to aid in design)
2. The circuit should be balanced under ambient lighting of the lab (V_{out}=0), and then V_{out} will vary when light is increased or decreased from the ambient level.
3. Collect data on photo resistor resistance and circuit output voltage V_{out} for variable light intensity (approximately ten data points). Record light intensity in terms of lux, where you can measure using a lux meter or an app on your smartphone. You can vary lux by shadowing room lighting and/or adding light sources such as a smartphone light.

5. POST-LAB ASSIGNMENT

Thévenin Equivalent

1. Calculate I_L using Ohm's law and the values of R_L and V_L measured in the lab.
2. Using MATLAB, plot I_L versus V_L (6 data points).
3. From this plot, find the Thévenin voltage and equivalent resistance (V_T, R_T). Compare this result with your measured value of R_S and the power supply setting. Comment on any differences you observe between (V_S, R_S) and (V_T, R_T).

Light Sensor

1. Construct the following plots:
   a. Photoresistor resistance versus light intensity
   b. Circuit output voltage versus light intensity
   c. Circuit output voltage versus Photoresistor resistance
2. Calculate the ***sensitivity (S)*** of your photoresistor and circuit, defined as the $S = \frac{\Delta R}{\Delta lux}$ and $S = \frac{\Delta V_{out}}{\Delta lux}$, respectively.
3. Simulate your circuit using SPICE, doing a parameter sweep for the light sensor over a range of resistance that is ± 20% of the nominal value under the room lighting in the lab.
   a. Define the light sensor as a resistor with a resistance value that is a variable by typing in
   `{Resistance}`
   b. To sweep, issue the SPICE directive
   `.step param Resistance <start_value> <end_value> <increment>.`
4. Compare the plot of circuit output voltage versus resistance obtained from measured data in the lab to the simulated data from SPICE.
5. Comment on the sensitivity, linearity, and accuracy of your circuit.
6. Describe an application where you might use your light sensor circuit to report information or control another object. Be sure to comment on how the sensitivity, linearity, and accuracy of the circuit would impact the proposed application, comparing measured values to what you would expect requirements to be.