EE 221L Circuits II Laboratory #2

DC Circuits

By

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Background

It is extremely important for an electrical engineer to be familiar with the fundamentals of DC circuits. All future topics build upon this knowledge. In this lab we will apply basic concepts learned in the circuits 1 class to real circuits in the lab. It is important to understand real world limitations of circuit elements and test equipment.

First let's begin with Ohm's law. In previous circuit courses you may have learned that Ohm's law is expressed as $V = IR$. This can be stated verbally as the voltage drop across a two terminal circuit element is equal to the product of the current flowing through it and its resistance. Instead of using the equation, let's look at Ohm's law graphically. Consider an ideal voltage source and what it looks like on a *current-voltage* or I-V plot. The I-V plot is a standard way to show how the current and voltage in any electronic device are related and is very important in understanding semiconductor devices and electronics in general.

An I-V plot with an ideal voltage source of 12V is shown in Fig. 1. The complete 4-quadrant I-V plot in Fig. 1 allows for plotting both positive and negative voltages and currents. For this lab and for most applications the I-V plot is restricted to the 2nd quadrant. An ideal 12 V source is a perfectly vertical line that fixes the voltage at 12 V and can supply any current. An ideal current source is plotted in Fig. 2 and is a perfectly horizontal line that can produce any voltage across its terminals to maintain its current flow. Neither ideal source actually exists in nature although many devices can approximate the ideal characteristics within bounds.

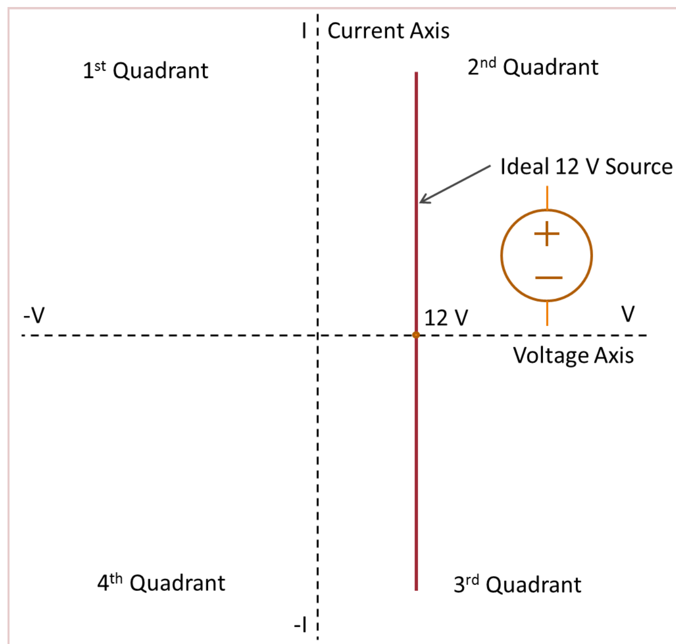


Figure 1. I-V plot of ideal 12 V source.

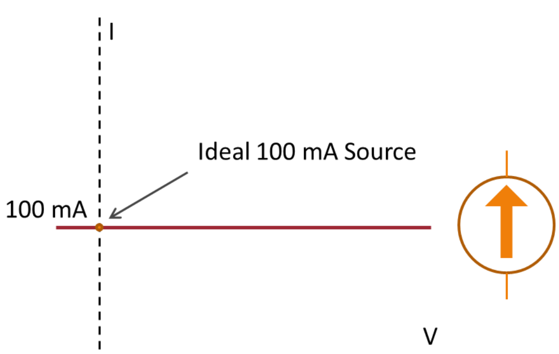


Figure 2. I-V plot of ideal 100 mA source.

Good to know...

To strictly follow the passive sign convention, sources would generally supply a negative current since they supply power. Historically, graphical analysis was very common and to do proper calculations the signs mattered. But for our lab, we will just concentrate on the magnitudes to illustrate the concepts. Currently, it is common to represent power sources such as solar cells on just the 2nd quadrant.

Resistors are represented in the I-V plot as shown in Fig. 3. The slope is the inverse of resistance or conductance. This may seem unintuitive but generally in the lab one controls the voltage and measures how the current changes, which is why voltage is the independent X-axis variable and current is the dependent Y-axis variable. A high resistance is plotted as a line with a low slope (conductance) and vice versa for a low resistance.

A non-ideal current source has a finite output resistance connected in parallel with its output and a non-ideal voltage source has a finite output resistance in series with its output. This is illustrated in Fig. 4 and Fig. 5 respectively. A current source has a high output resistance and a voltage source has a low output resistance. This is visible in the slope of their I-V curves. In this lab, we will try to prove basic circuit concepts using components which are not ideal and it is important to always remember the limitations.

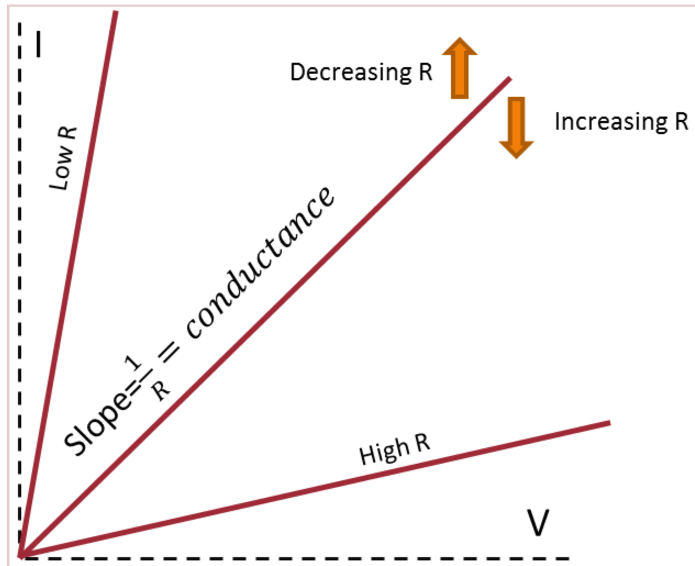


Figure 3. I-V plot of resistors.

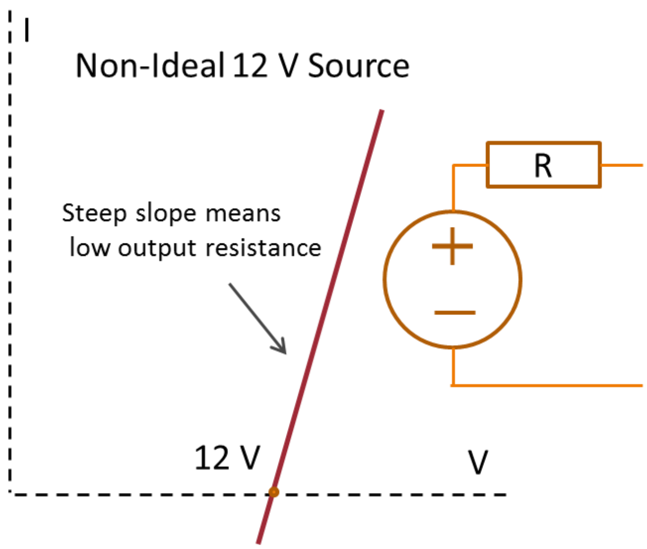


Figure 4. I-V plot of non-ideal voltage source.

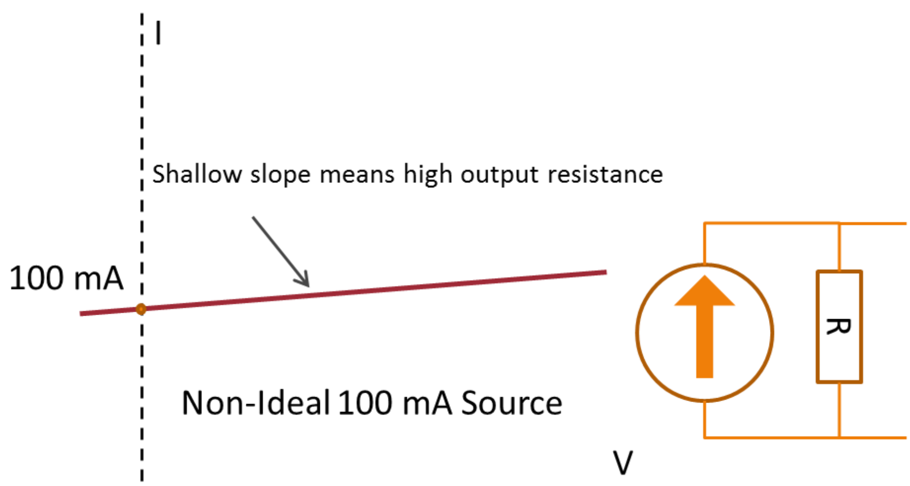
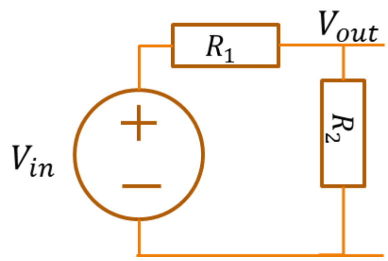


Figure 5. I-V plot of non-ideal current source.

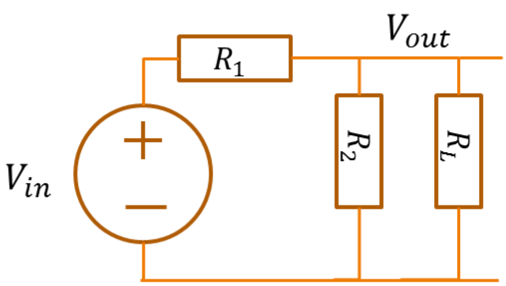
Next, let's examine voltage dividers and the loading effect. Fig. 6 shows a schematic of a basic voltage divider and the equation that describes it. However, the voltage is only valid when there is no load connected at the output. When a load is connected to the output as shown in Fig. 7, R2 is replaced by the parallel combination of R2 and RL. To make analysis easier for multiple loads, let's represent our voltage divider as a Thevenin equivalent circuit. The Thevenin equivalent is shown in Fig. 8a. Now the same voltage divider formula can be used when a load is connected to this Thevenin equivalent circuit as shown in Fig. 8b. Later, we will prove that both circuits are equivalent in the lab.



$$V_{out} = V_{in} * \frac{R_2}{R_1 + R_2}$$

Figure 6. Basic voltage divider.

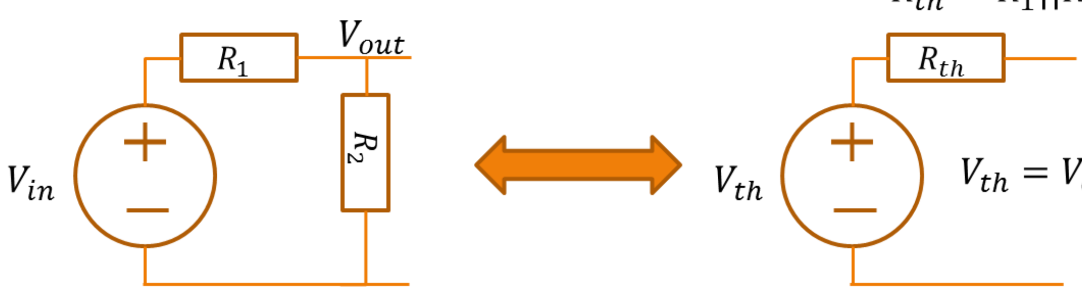
The loading effect describes how a load changes the output voltage from the ideal nominal value. For example a voltage divider designed to output 5V might drop to 4V once a load is connected. To keep the voltage within a specific tolerance the voltage divider has to be designed with a Thevenin equivalent resistance that is less than some acceptable fraction of the load resistance. For example, if a 10% drop is acceptable, then the Thevenin equivalent should be 1/10th of the load resistance.



$$V_{out} = V_{in} * \frac{R_2||R_L}{R_1 + R_2||R_L}$$

$$V_{out} = V_{in} * \frac{R_2}{R_1 + R_2}$$

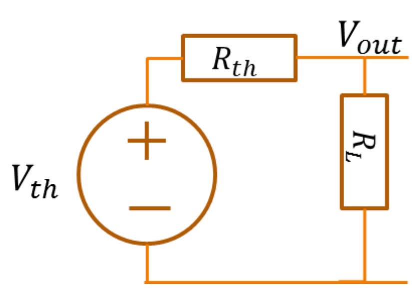
Figure 7. Basic voltage divider with loading.



$$R_{th} = R_1||R_2$$

$$V_{th} = V_{out}$$

Figure 8a. Thevenin equivalent of voltage divider.



$$V_{out} = V_{th} * \frac{R_L}{R_{th} + R_L}$$

Figure 8b. Thevenin equivalent of voltage divider.

The applications of these basic concepts will be illustrated by powering an LED and determining what is the best method for accuracy and repeatability. Although you may not have learned about LEDs in your classes, it is easy enough to use them without understanding the basic physics. The symbol for an LED and a picture of an LED is shown in Fig. 9. The anode is the positive terminal and the cathode is the negative terminal. When a positive voltage is applied that is equal to or greater than the forward voltage V_f, a current flows through the LED. If the terminals are reversed then no current flows except for a negligible leakage current. To identify an unknown LED, generally the longer lead is the anode for a standard thru-hole component. Some LEDs may not follow this convention and it is best to consult the datasheet.

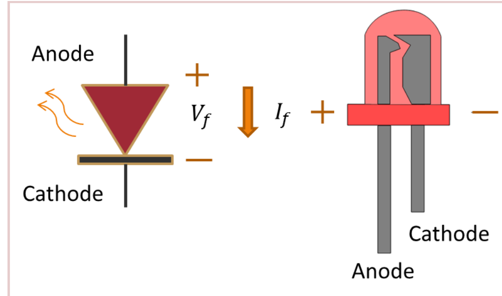


Figure 9. LED symbol and illustration.

The I-V characteristics are different from what has been depicted earlier. They are nonlinear and the current is an exponential function of the voltage. This is shown in Fig. 10. LEDs have a nominal current rating, which is recommended for continuous operation. The maximum current rating is the maximum current the LED can handle without being damaged. The amount of time that it can operate at this current depends on the way the manufacturer rated it. It is clear that a very small change in voltage can cause a large change in current as shown in Fig. 11. This leads to a problem if the LED is operated by attempting to set a constant voltage across its terminals. If the method of setting the voltage is not accurate, the current can significantly vary from the expected value and damage the LED. Furthermore, the forward voltage of an LED is highly temperature dependent. A better method of biasing an LED is by setting a constant current.

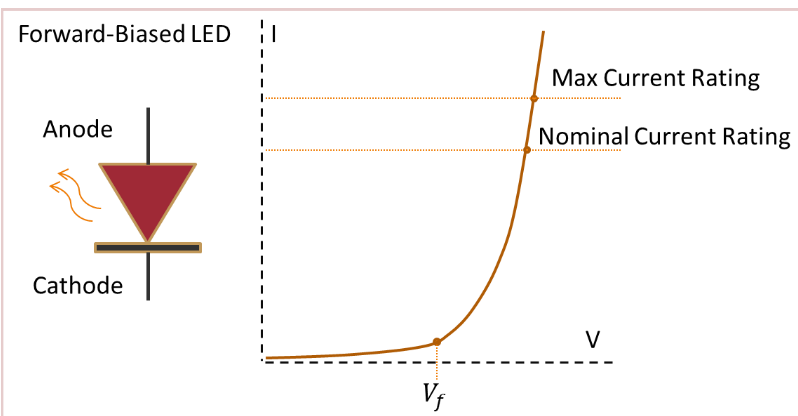


Figure 10. Forward-biased LED I-V curve.

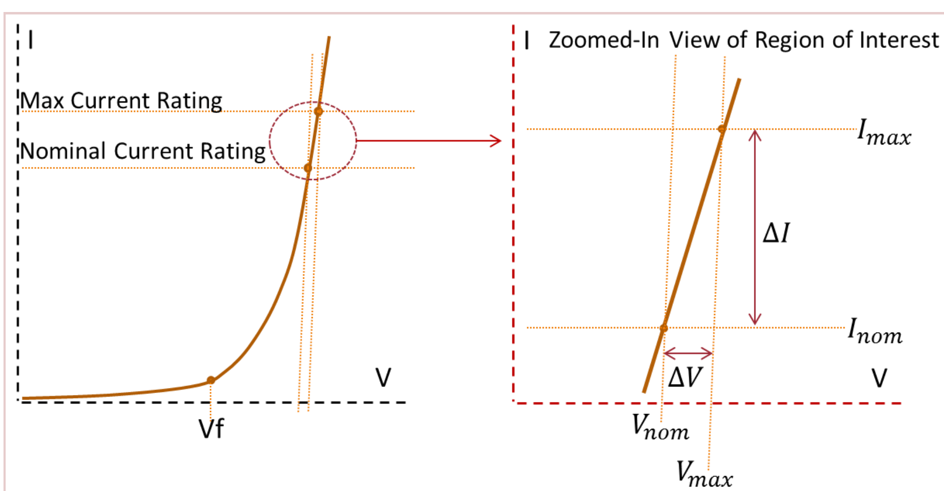


Figure 11. Zoomed-in LED I-V curve. Note the large change in current for a small change in voltage.

Let's examine a few examples of good and bad LED biasing. Suppose we have a 5 V source and wish to light up a red LED with 20 mA of current. The forward voltage of a typical red LED is 1.6 V. Suppose that the I-V curves show that 20 mA flows when there is 1.65 V across the diode. The first thing that may come to mind is to use a voltage divider to create a voltage of 1.65 V and run the LED off that. This is a bad idea for three main reasons. The first reason is that it will be hard to set 1.65 V using standard 5% tolerance components in the lab. The second reason is that there are variations between individual LEDs due to manufacturing tolerances and each voltage divider would have to be tailored to each LED. The third reason is that the voltage divider will burn a lot of power. In order to maintain the voltage at 1.65 V the Thevenin equivalent combination of R1 and R2 should be much smaller (at least 1/10th) of the load resistance. The LED presents an 82.5 ohm load (1.65V/20mA). Designing a proper voltage divider will result in more power used in the voltage divider than actually delivered to the LED. This example is illustrated in Fig. 12A.

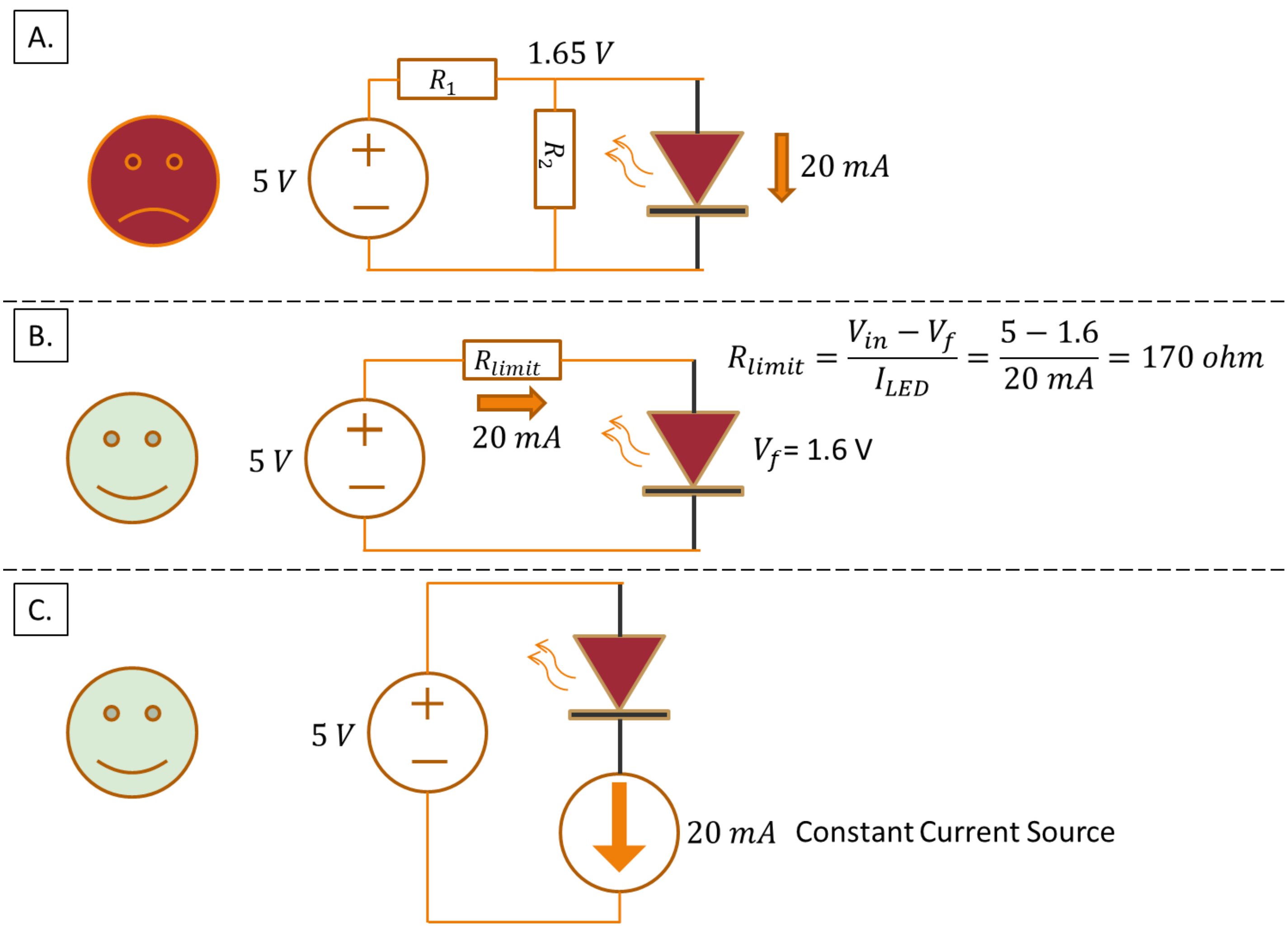


Figure 12. Three methods of LED biasing. A. voltage divider (bad). B. Series resistor (good). C. Constant current source (good).

The next method of LED biasing is the most commonly used. A current limiting resistor is used between the voltage source and the LED. The simple calculation is shown in Fig. 12B. This method allows the use of any voltage source higher than the forward voltage of the LED. For example, one could connect an LED to a much higher voltage such as 300V by using a properly sized limiting resistor. Of course in this example there will be significant power dissipation in the resistor and a properly rated resistor must be used. Natural variations in the LED's forward voltage do not cause a large change in current because the resistor reduces the "sharpness" of the exponential I-V curve seen in Fig. 11.

The final method of LED biasing is the constant current source. The schematic shown in Fig. 12C is an abstraction as the current source can be made up of a wide variety of components. Generally, a constant current source is an active circuit composed of transistors which tries to maintain a constant set current to the best of its ability. Within a set output voltage range, these devices very closely approximate an ideal current source and they are extremely important in almost all integrated circuits. Most commercial LED driver chips operate as a constant current source. This topic is outside the scope of this lab but we will use the power supply to approximate a current source.

Prelab Summary

You will simulate basic DC circuits and LED biasing in this prelab using .tran commands. You will also do simple PCB layouts.

Prelab Tasks

Prelab #1: PCB and Netlist Required

Prelab #2: PCB and Netlist Required

Prelab

This prelab will extensively use LTSpice. It is assumed that the student has some familiarity with LTSpice and will not go over basic functions. More complex functions will be detailed however. There are many LTSpice tutorial resources available on the web.

Prelab #1

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown below in Fig. 13. This is a voltage divider that outputs 5V from a 12V input. Find the power dissipated in each resistor. This is done by holding the "ALT" key and clicking over the element. (**Schematic, Input/Output Plot of Voltage, Powers in Resistors)**

2. Calculate the Thevenin equivalent circuit. **(Hand Calculation)**

3. Add a 1k load to the schematic in Fig. 13, resulting in Fig. 14. Plot the outputs and calculate the percentage change in the voltage output from 5V. (**Schematic, Output Voltage Plot, Hand Calculation)**

4. Draw the schematic of your Thevenin equivalent circuit and simulate with the 1k load. Verify that the output voltage is the same as (3). **(Schematic, Output Voltage Plot)**

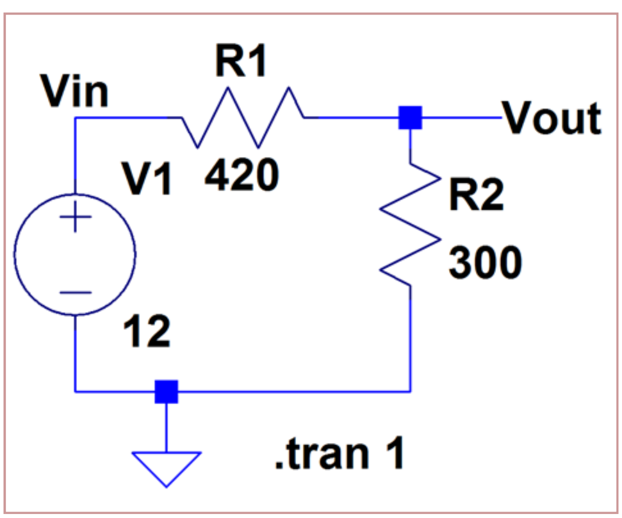


Figure 13. Voltage divider.

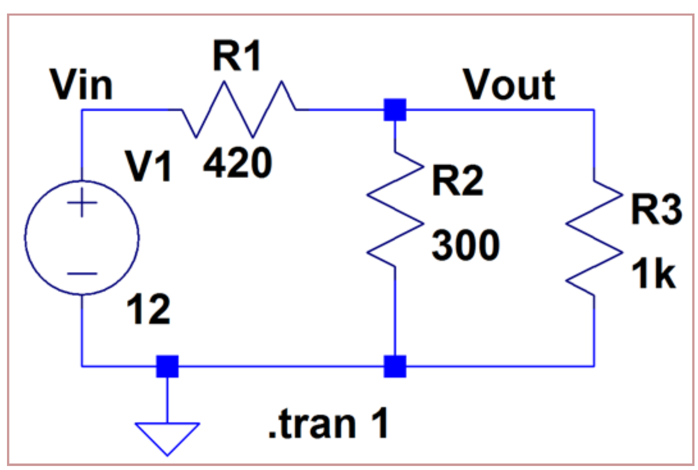


Figure 14. Voltage divider with load.

Prelab #2

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 15. Right click on the diode and select "NSCW100" as shown in Fig. 16. This is a white LED that was chosen for convenience since it was already in LTSpice. Plot the output voltage and all the currents and powers in the resistors and LED. Which device dissipates the most power and why is this bad? **(Schematic, Output Voltage, Currents and Powers)**
2. Draw the schematic as shown in Fig. 17. Calculate the value for the resistor using a forward voltage of 3.3V and a current of 20mA. Use the formula shown in Fig. 12B. Simulate the circuit and plot the output voltage, current and powers in the resistor and LED. **(Schematic, Output Voltage, Current, Powers)**
3. Simulate the schematic shown in Fig. 18. What is the voltage across the diode? **(Voltage Across Diode)**

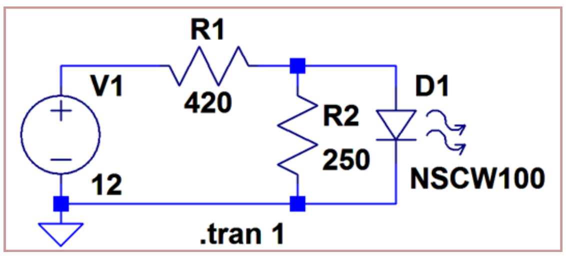


Figure 15. Voltage divider for LED.

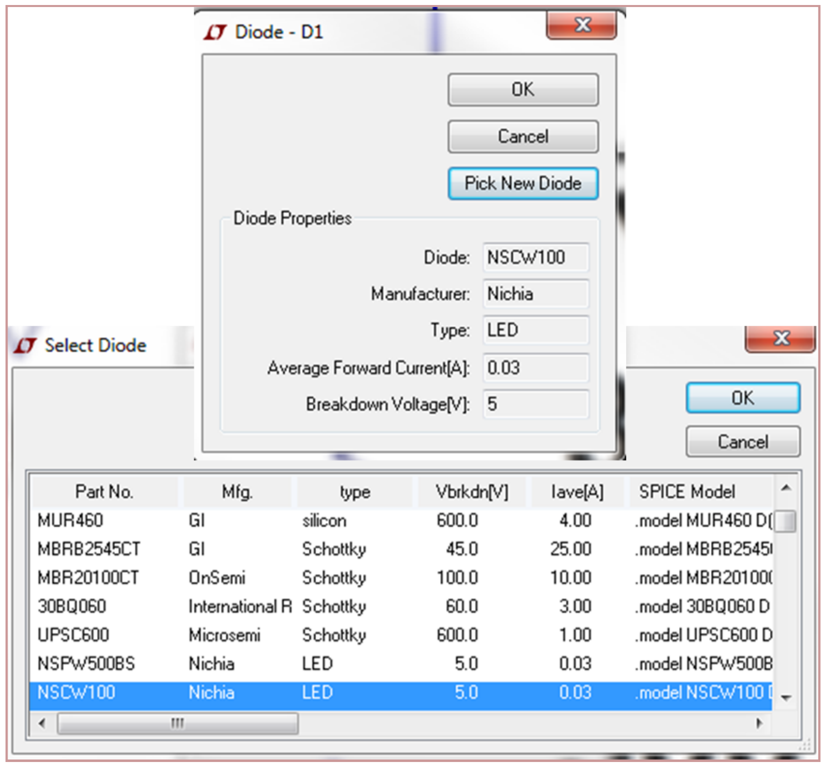


Figure 16. Selecting LED.

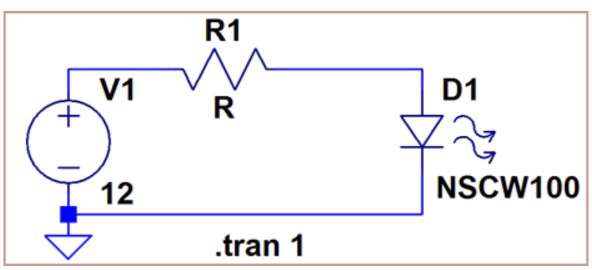
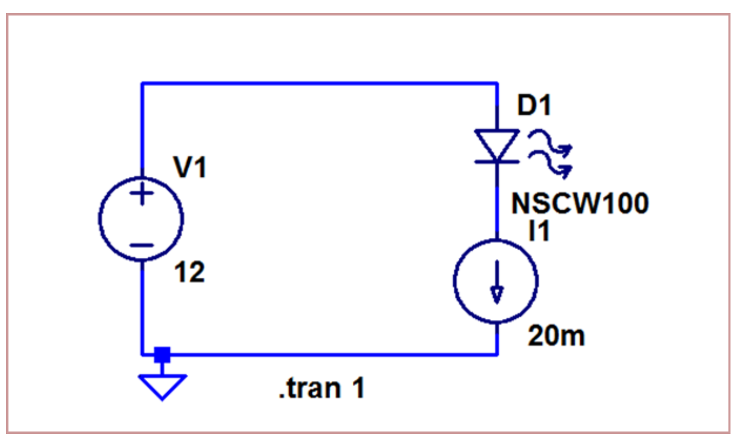


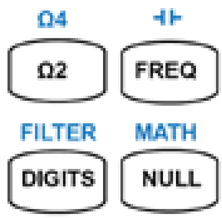
Figure 17. Series resistor for LED.

Figure 18. Constant current source biasing of LED.



Required Materials and Equipment

1. Power Supply
2. Multimeter
3. LEDS, Resistors, Wire
4. Breadboard
5. Banana Jack Cables
6. Multimeter Probe Cables



Postlab Tasks

Task 1: Power Supply Impedance

Task 2: Thevenin's Theorem

Task 3: LED Biasing

Measuring Equipment Basics

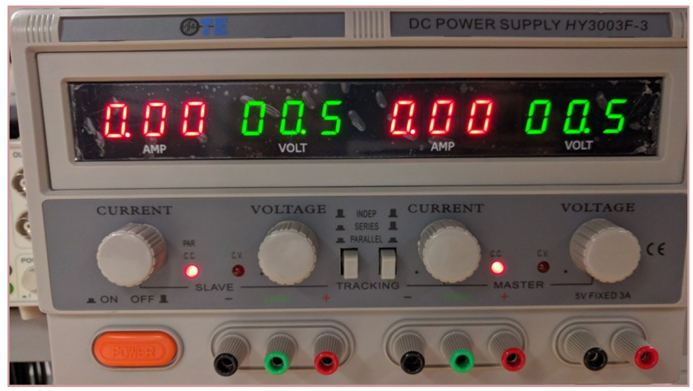


Figure 19. Power supply front panel.

In this lab, we will be using the power supply and multimeter. The power supply that is currently in the labs is the HY3003F-3 which has three voltage outputs, two of which are variable voltage and current and one which is fixed 5V. We will use one of the variable outputs. This is a very common power supply sold by multiple manufacturers. Although controls for power supplies are fairly standard, you should consult the manual if you are unfamiliar with any piece of test equipment. The multimeter currently in the labs is the Keithley 2110. This model has an extensive manual available online which needs to be consulted to use any of the more advanced features.

Let's familiarize ourselves with the power supply. An image of the power supply is shown in Fig. 19. Each variable supply has two knobs, one for controlling voltage and one for controlling current. If you turn the voltage knob with nothing connected to the power supply terminals, the voltage will change. However if you turn the current knob nothing will happen. This is because there needs to be something connected for current to flow through. The two switches in the middle let you select from independent, series and parallel operation. For our labs we will only be using the independent mode. Series mode is used if one desires to turn the two 30V supplies into one 60V supply. Parallel mode is used if one needs to increase total output current to 6A instead of the 3A of the single supply. The two "C.C." and "C.V." LEDs are very important to look at. "C.C" stands for constant current and "C.V." stands for constant voltage. When "C.C." is lit, it means that the power supply has hit its set current limit. When all the knobs are set fully counterclockwise, it may be necessary to turn the current knob slightly clockwise until the LED changes to "C.V." in order to change the voltage. After setting the desired voltage, the current can be set by connecting a banana jack cable between the red and the black terminals. This shorts out the supply and the voltage should drop to zero. Now the current knob can be turned to the desired current.

It is a good idea to limit the current to a reasonable value if you are working with low power circuits. For example, if you are powering a few ICs it is good to limit the current to less than 500 mA. This allows for sufficient headroom if the circuit needs the power, but prevents components from exploding with high force if you make a mistake. When the power supply hits constant current mode, it does not actually behave like an actual current source. It doesn't change the voltage to maintain the set current. It simply prevents the current from going any higher and the voltage is kept within the set voltage limit.

The green terminal represents the earth ground connection. For most single supply circuits you should connect this to the black terminal and then run a cable to your breadboard. This provides a good ground for experiments where we use the function generator and oscilloscope. It is bad practice to ground the entire circuit through a scope probe's ground clip or through the function generator as it is not a low impedance path to ground. For some situations the ground will not be connected as parts of the circuit need to be floating. For those situations, this will be explicitly stated in the lab.

The multimeter is shown in Fig. 20. Take some time to familiarize yourself with the device. The multimeter has no ground connections on the front panel. This means it measures everything on a relative basis between its terminals. The red terminals are high impedance meaning that almost no current flows into them. They are used to measure voltage, resistance and capacitance. The "sense" terminals are used for precision 4-wire resistance measurements which we will not be doing in this lab. The white terminals are low-impedance terminals and allow current to flow through them in order to measure current. Never connect a voltage source or circuit in parallel with a white terminal and black terminal. This will simply short out the voltage source and cause a high current to flow into the multimeter and could burn out the internal fuses. The simplest way to remember whether your connection is correct is that if you are measuring a voltage, then the multimeter is connected in parallel with your circuit and if you are measuring a current, the multimeter is in series with your circuit. I have reproduced the front panel control functions from the manual at the end of this document for convenience.

Figure 20. Multimeter front panel.

Postlab #1: Output Impedance of Power Supply

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Set up the power supply to be current limited to 1A. The voltage setting is not critical, so a few volts should suffice.
2. Set the multimeter to measure DCV and connect the multimeter's red and black inputs in parallel to the outputs on the power supply.
3. Next short the power supply's terminals together and write down the current displayed on the power supply and the voltage measured by the multimeter. Once the measurement is completed, promptly remove the short circuit as it stresses the power supply.
4. Repeat this procedure for a current of 2A.
5. Using these two data points, calculate the output impedance of the power supply. (**Hand Calcs)**

Postlab #2: Verifying Thevenin's Theorem

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Set up the power supply for 12V and 100 mA current limit.
2. Design a voltage divider with a 5V output using standard resistors in the lab. Don't try to make precise values by combining resistors, just select the closest available values. Measure the output voltage. (**Hand Calcs, Measured Values)**
3. Connect a load to the voltage divider that is close to the Thevenin equivalent resistance and measure the output voltage. (**Hand Calcs, Measured Values)**
4. Measure the actual resistances of 10 of each resistor used to construct the voltage divider. For example if you used a 1k and 3.9k resistor to make your voltage divider, take 10 of each, measure their resistances and write them down. Next, average the values and determine the output voltage of a voltage divider made up of averaged resistor values. This will be your "design center value". Use the lowest measured value of one resistor and the highest measured value of the other resistor to determine the worst case voltage divider output. What is the percentage error between the highest mismatch value and the design center value? Please put the resistors back and straighten the leads out. **(Hand Calcs, Measured Values)**
5. Replace your voltage divider in step 2 with the Thevenin equivalent circuit. Remember to change your power supply voltage to a value close to the measured voltage divider output. Connect the same load from step 3, measure the output voltage and comment on how closely the voltages match. If there is an error comment on what you think caused the errors. **(Measured Values, Comments)**

Postlab #3: LED Biasing

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Look at Fig. 21, which provides measured I-V curves from red, green and yellow LEDs in the lab. Select a color.
2. Set the power supply to 12V and design a voltage divider that sets an output voltage equal to the nominal operating voltage given in the I-V curves for the color of your LED.
3. Determine the current flowing through the LED. The easiest way to do this is to measure the voltage across R2 in the circuit shown in Fig. 12A. Knowing the resistance, you can determine the current flowing in that branch. Then subtract this current from the current that is displayed on the power supply's meter. That will give you the LED current. The power supply meter is accurate to 1.5% which is good enough for this purpose. Comment on how well this biasing method worked. **(Hand Calcs, Measured Values, Comments)**
4. Next, set up the circuit in Fig. 12B. Use the formula to calculate the limiting resistor and use the nominal operating voltage from the I-V curves in place of the forward voltage. Note the current on the power supply. Measure the voltage drop across the resistor. Calculate the power dissipated in this resistor. **(Hand Calcs, Measured Values)**
5. Finally, use the current limiting on the power supply to approximate a constant current source. Set the power supply voltage to 5V, and use the procedure in Postlab #1 to limit the current to 20mA. Connect the LED across the power supply terminals and note the voltage. Search the internet for a constant current LED driver chip and write down the manufacturer, model number and describe it in two or three sentences. **(Measured Values, Comments)**

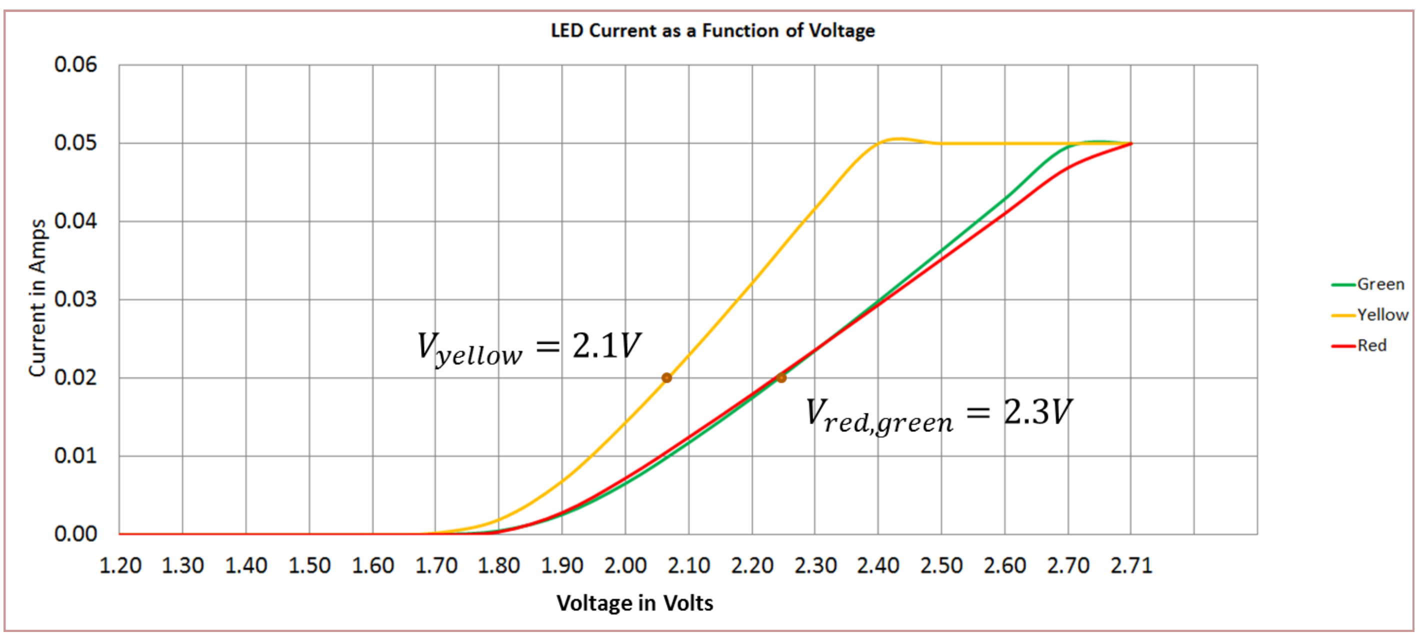
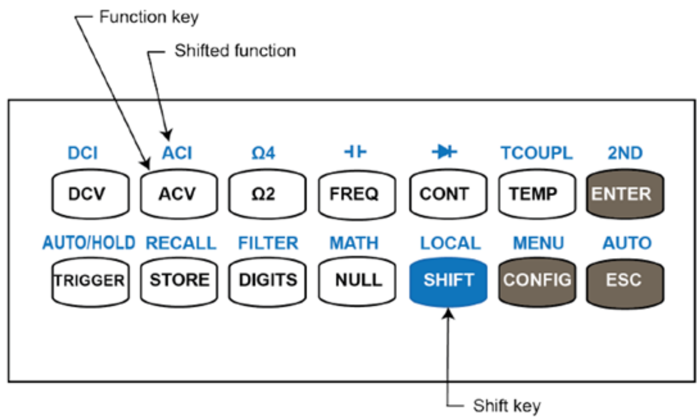


Figure 21. Measured LED I-V curves.

Front Panel Button Summary for Keithley 2110 Multimeter



Key Function
DCV Selects DC voltage measurement.
ACV Selects AC voltage measurement.
Ω2 Selects 2-wire resistance measurement.
FREQ Selects frequency measurement.
CONT Selects the continuity test.
TEMP Selects RTD temperature measurement.
ENTER Accepts selection, moving to next choice or back to measurement display.
DCI Selects DC current measurement.
ACI Selects AC current measurement.
Ω4 Selects 4-wire resistance measurement.
Selects capacitance measurement.
Selects diode test.
TCOUPL Selects thermocouple temperature measurement.
2ND Sets secondary measurement.
TRIGGER Sets the external trigger mode. When the TRIG indicator is lit, you can trigger the instrument by pulsing the EXT TRIG input or by pushing the TRIGGER button to generate manual triggers.
STORE Stores a specified number of subsequent readings.
DIGITS Changes display resolution. Note that changing the display resolution also changes the integration time. If you change the digits to 4½, the integration time is set to 0.02 PLC. If digits are set to 5½, the integration time is set to 1 PLC.
NULL Activates the null function in order to offset the measurement error due to the test leads.
SHIFT Used to access shifted-functions printed in blue over each key.
CONFIG Configures the settings of selected measurement function. Refer to the topics in Basic measurement functions (on page 3-1) for configuration details.
ESC Cancels selection, moving back to measurement display.
AUTO/HOLD Enables or disables the reading hold function.
RECALL Displays stored readings.
FILTER Enables or disables averaging digital filter.
MATH Enables or disables mathematical operations/tests, including PERCENT, AVERAGE, NULL, LIMITS, mX+b, dB, and dBm.
LOCAL Switches the instrument to the local mode from the USB or GPIB remote mode.
MENU Offers system-wide settings, trigger settings, and interface configurations. Refer to (7) Menu overview (on page 2-10) for information about menus.
AUTO Enables or disables autorange.