Laboratory 2:
Electrical Circuits and Measurements I

2.1 Introduction

This lab focuses on using virtual breadboards, variable voltage power supplies, multimeters, and circuit simulation tools. By the end of the lab, you should be able to virtually build a circuit as well as take resistance, voltage, and current measurements using a simulation system called Tinkercad. In the next lab we will explore another tool called MultiSim that uses schematics rather than virtual devices. We will also compare multimeter models in the packages.

2.2 Resources

The additional resources required for this assignment include:

- Book: Not required; outside of class, read Section 2.8.2 *Design of DC Meters*.
- Pratt Pundit Pages: `Tinkercad`, `Resistor Color Codes`

2.3 Equipment

This lab will all be done in a web browser. Later, you will be comparing the simulated results to actual measurements.

2.4 Tinkercad

Tinkercad (tinkercad.com) is a project from Autodesk that allows you to use computer aided design software to build and simulate a wide range of devices. For this course, there will be times that you will be modeling a circuit or a system mathematically, comparing your results to a simulation, and then comparing both to an actual circuit.

2.4.1 Account Setup

To get started, go to tinkercad.com and sign up for a free account. Click the "Join Now" button at the top right, then select "Create a personal account." We are *not* using the Tinkercad classrooms so the "In School?" options will not work. Choose whatever mechanism you want to save your account - just be sure to remember how you got there!

2.4.2 Circuits Tutorial

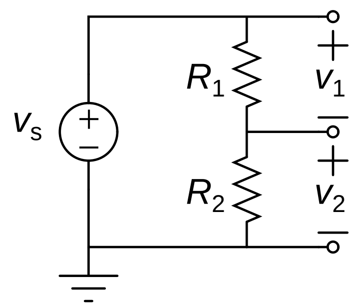
Once your account is set up, there should be a dashboard on the left side that shows Designs, Circuits, Codeblocks, and Lessons. Select Circuits and then Try Circuits. Tinkercad will now take you through four steps of designing and simulating circuits:

- Start Simulating
- Editing Components
- Wiring Components
- Adding Components

2.4.3 Building Your Circuit

For this lab, we are going to look at a voltage divider. To build this circuit in Tinkercad, you are going to place your components on a breadboard and use a virtual multimeter to take resistor, voltage, and current measurements. To begin, click the Tinkercad logo at top left to get back to the dashboard. Click on Circuits in the left column and then click the "Create new Circuit" button.

The schematic for the circuit you are building is:



where v_s will be set by the power supply and R_1 and R_2 will be a matched pair of resistors. Ideally, this voltage divider will split the voltage from the supply exactly in half. You will be measuring the voltage drop across the bottom resistor (v_2).

To start, on the right side of the Tinkercad window, set the Components drop down box to Basic. If you scroll through, you will see many basic circuit components are available. Drag a **Breadboard Small**, two **Resistor**, and two **Multimeter** from this list onto the design canvas. You will also want a power supply, which is not a part of the Basic components list. In the search box under the Components dropdown, type `Power Supply` and then drag a **Power Supply** onto the canvas. There is a picture on Pundit showing what your canvas might look like right now (Pic 1).

To take resistance measurements, you will want to connect the terminals of the multimeter to the terminals of the resistors with wires. This may be easier if the resistors are horizontal versus vertical; to rotate an element, select it and then press r to rotate clockwise or <shift> R to rotate counter-clockwise. Reposition the resistors so each one is under a different multimeter. Drag a wire from the terminal of one multimeter to one side of one of the resistors, then drag a wire from the other terminal of the same multimeter to the other wire. Do this for both multimeter-resistor pairs and start the simulation. You can make your connections as *realistic* as you want by having the wires bend or by changing the colors. Regardless, once you have made your connections, start the simulation. Since the meters are in voltmeter mode by default, both should be showing 0.00 V. To turn them into ohmmeters, click the **R** button on each meter. Your meters will now be showing the resistance value for each resistor, which will be 1.00 kΩ if you are using the default resistor. There is an image of this circuit on Pundit as well (Pic 2).

Now you are going to build the voltage divider. Go ahead and stop the simulation, then delete the wires between the multimeters and the resistors. Start by moving your power supply so it is to the right of the breadboard - this is just to make it easier to connect the positive terminal to the + rail at the top of the breadboard and the negative terminal to the - rail. Connect a red wire from the positive terminal to the top + rail (later called top+) and a black wire from the negative terminal to the bottom - rail (later called bot-). Adjust the bends in the wires so the circuit looks nice by double-clicking in a wire to create a new adjustable location; you can get rid of these extra locations by selecting the wire, then selecting the circle indicating the adjustable location, then clicking delete. See Pundit for an example of what your schematic should look like at this point (Pic 3).

Next, build the divider:

- Put a horizontal resistor between i13 and i17
- Put a vertical resistor between f21 and d21
- Put a red wire between top+13 and j13; this will deliver the source voltage to the horizontal resistor
- Put a black wire between a21 and bot-21; this will ground the bottom of the vertical resistor

Drag the meters so the terminals are above the whole breadboard. We are going to be measuring the current through the circuit as well as the voltage drop across the vertical resistor. When measuring current, you measure *through* so the ammeter acts almost like a wire. Connect a gray wire from j17 to the left terminal of the right-hand multimeter, then connect a pink wire from the right terminal of the right-hand multimeter to j21. This means that the right side of the horizontal resistor is now electrically connected to the top of the vertical resistor. Finally, to measure the voltage drop across the vertical resistor, connect a purple wire from the right terminal of the left-hand multimeter to g21 and a brown wire from the left side of the left multimeter to bot-4. Start the simulation, then make sure the right meter is turned into a voltmeter and the left meter is turned into an ammeter. Your circuit should now be similar to that pictured on Pundit (Pic 4).

If there are any issues with circuit at this point, be sure to fix them before moving forward. Sometimes resistors do not fully attach to the breadboard. If you are getting no current through the circuit, first make sure your wires are in the right place. If they are, stop the simulation, then drag each resistor left and right or up and down and make sure it is affixing itself to a port on the breadboard (one of the resistor terminals will turn into a square if the resistor is going to connect to the breadboard).

2.4.4 Taking Data

Tinkercad does not have a great mechanism for loading and saving data, so you will need to type the values you are getting into a file. The easiest way to do this is to start Excel, Calc, Google Sheets, or some other spreadsheet program. Create a new sheet and add column headers of **R**, **V2**, and **I**. To take data, you will be manually changing both resistor values and then typing the resulting voltage and current into the appropriate row of your sheet. Start with 1 kΩ (1e3 Ω) resistors – you should have a 2.5 V voltage drop and -2.5 mA of current based on the direction of the ammeter. Increase both the resistors by a factor of 10 and type those measurements in the next row of the sheet. Keep increasing by powers of 10 until you get two 100 GΩ (1e11 Ω) resistors. This means you will have nine data points in your file. Note that eventually the measured current will go to 0; this is because the ammeters in Tinkercad can only measure down to 10 μA. The voltage across the bottom resistor will also change - more on that later.

2.4.5 Further Exploration

There are some other features of Tinkercad to explore. Notice on the power supply that there are two knobs - the top knob sets the desired voltage and the bottom knob sets the current *limit*. The supply will try to supply the required voltage, and if it can, you will see a green light to the top right of the voltage knob. To see what happens when this fails, go ahead and change both resistors to be 1 Ω. The current is now 2.50 A coming out of the supply and measured as -2.50 A by the ammeter. Slowly increase the voltage until you get almost to 10 V, then keep going - you will notice that the voltage cannot increase past 10 V and that the light goes off by the voltage knob and turns on near the current knob. The power supply is no longer able to deliver the current needed to get the voltage past 10 V. Next, roll the *current* knob counter-clockwise and notice that both the current and voltage decrease based on the new current limit. Once done with this exploration, go ahead and reset the current limit to its maximum value and set the voltage back to 5 V. Set the resistors back to 1 kΩ each, then take a screen shot of your simulated circuit. Be sure to include the meters in your picture.

2.5 Assignment

For this assignment, you are going to present the data set you took from the voltage divider in Tinkercad and also use Tinkercad to solve for the voltages and currents in a different circuit. You will also be using the data set for the divider to estimate the internal resistance of Tinkercad's voltmeter. Later, you will compare values with actual measurement devices.

2.5.1 Tinkercad Voltage Divider

Fill out the following table with voltage divider voltage measurements using nominal resistor values:
Source voltage measurement: 5 V

Resistors	Calc. Voltage (V)	Sim. Voltage (V)	Sim. % Err. (%)
1 kΩ			
10 kΩ			
100 kΩ			
1 MΩ			
10 MΩ			
100 MΩ			
1 GΩ			
10 GΩ			
100 GΩ			

where percent error is given by:

$$\left|\frac{\text{simulated} - \text{calculated}}{\text{calculated}}\right| \times 100\%$$

Note: The above calculated voltages should assume a “perfect” voltmeter - that is a measurement device that does not change the measurement it is measuring.

2.5.2 Problem 2.35

Use Tinkercad to model the circuit given in Problem 2.35 on p. 69. Use a 20 V source instead of 200 V since Tinkercad's voltage source is limited to 30 V. Put an ammeter in series with the wire through which I_o is flowing (be sure to measure from left to right instead of right to left; when built correctly the current for this circuit will be positive) and put a voltmeter in parallel with the 5 Ω resistor. Once built and running, take a screen shot of the circuit being simulated showing the values of the current and the voltage. After documenting this circuit, go through and change all the resistors to be in MΩ instead of Ω and take a screen shot of the new values. *Note:* the current for the latter case will show as 0 A. Fill out the following table with voltage and current measurements using nominal resistor values
Source voltage measurement: 20 V

R Units	Calc. V (V)	Sim. V (V)	Sim. % Err. (%)	Calc. I (A)	Sim. I (A)	Sim. % Err. (%)
Ω						
MΩ					0 A	100

where once again percent error is given by:

$$\left|\frac{\text{simulated} - \text{calculated}}{\text{calculated}}\right| \times 100\%$$

2.5.3 Figures to include

Include a screen shot of your voltage divider with 1 kΩ resistors as well as the two screen shots from Problem 2.35. These can be in the body of your lab report or submitted as graphics files separately. The `includegraphics` command in LaTeX is capable of importing eps files as well as png and other types of graphics.

2.5.4 Questions, Calculations, and Conclusions

You will not be writing a full lab report but rather will be presenting your data sets, performing some calculations, and then answering some questions. Your report does not have to be in LaTeX but it does need to look professional. As noted above, the screen shots can either be a part of the document or apart from the document.

(1) What happened to the voltage drop measured across R_2 as the values of R_1 and R_2 changed in the voltage divider circuit? Why do you think that happened?

(2) What happened to the current and voltage drop in your second circuit as the magnitude of the resistors changed in the second circuit? Why do you think that happened?

(3) Given the various measurements you took in Tinkercad for the voltage divider, what do you think is the equivalent internal resistance of the Tinkercad voltmeter? Support your conclusions with calculations. Model the voltmeter as a resistor R_m and find an equation for R_m as a function of R_1, R_2, v_s, and v_2. Typeset this function into your lab report.

Next, use the spreadsheet to calculate the value of R_m for each of your nine R values; note that for the smaller values, your calculation will give ∞ but for the larger R values you will get finite values. Fill out the following table with multimeter internal resistance estimates using nominal resistor values:
Source voltage measurement: 5 V

Resistors	Sim. Voltage (V)	R_m Estimate (Ω)
1 kΩ		
10 kΩ		
100 kΩ		
1 MΩ		
10 MΩ		
100 MΩ		
1 GΩ		
10 GΩ		
100 GΩ		

Which value or values do you think are more accurate? Why do you think that?