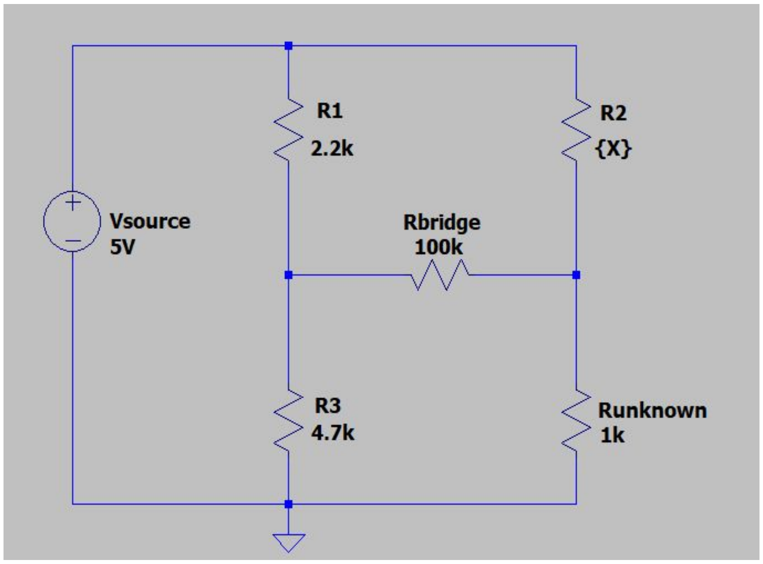
Proof of Concepts Alpha Lab 2: Jack Jiang, Vincent Lin, Saaif Ahmed

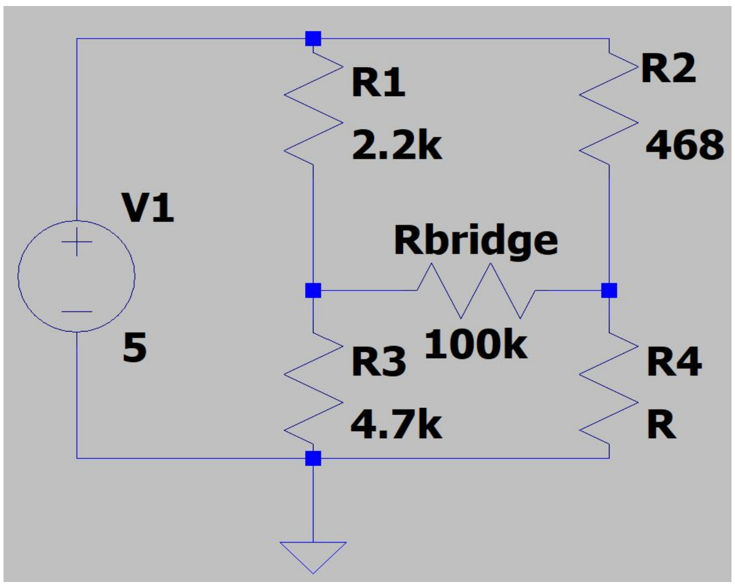
Part A: Prove the Concept of a Balance

Building Block:

Description: We have a Wheatstone circuit with a DC voltage source of 5V and R1=2.2k ohm, R3=4.7k ohm, R2 is the 10k ohm potentiometer, Rbridge is 100k ohm and Runknown selected to be 1k ohm.



Analysis:



The purpose of the Wheatstone bridge or the resistor Rbridge, in general, is to solve for an unknown resistor in the arrangement shown above in the circuit. In this case, our unknown resistor is in the lower right hand side.

How a Wheatstone bridge solves for a resistor is by using Rbridge's voltage. R1 and R3 serve to make a voltage divider and the same goes for R2 and R4. If the ratio of $\frac{R1}{R3} = \frac{R2}{R4}$ then the voltage between R1 & R3, and between R2 & R4 will be equal. Because Rbridge sits on the node between R1 & R3, and the node between R2 & R4, the voltage across Rbridge will be zero. That way we can solve for R4, by figuring out the resistor value that makes the voltage across Rbridge = 0.

$\frac{R1}{R3} = \frac{R2}{R4}$; $\frac{2200}{4700} = \frac{468}{R4}$; $R4 = 1000$.

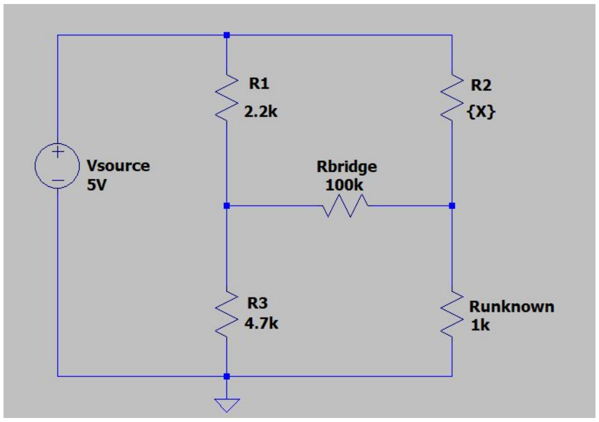
We used the ratio to solve for the unknown resistor R4, now we use voltage division to prove the voltage across Rbridge = 0.

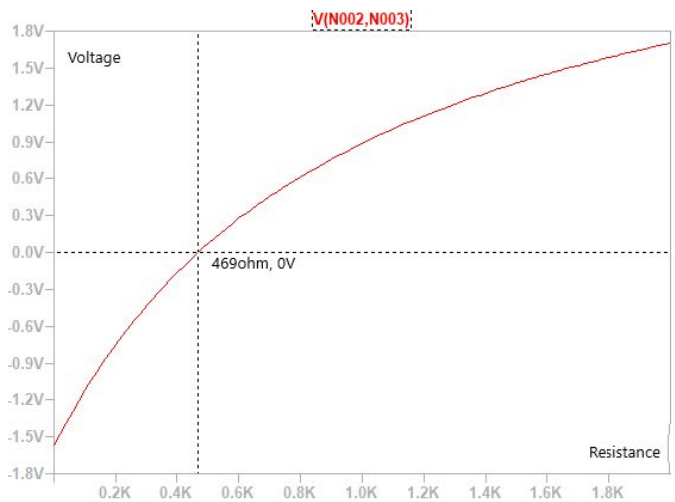
$$V_{between\ R1\&R3} = V1\,(R3)/(R1+R3) = 5(4700)/(2200+4700) = 3.4V$$
$$V_{between\ R2\&R4} = V1(R4)\,/\,(R2+R4) = 5(1000)/(1000+468) = 3.4V$$

$$V_{Rbridge} = V_{between\ R1\&R3} - V_{between\ R2\ \&\ R4} = 3.4V - 3.4V = 0V$$

Thus the concept of the Wheatstone bridge is proved.

Simulation:





The plot of voltage across Rbridge over the resistance of R2

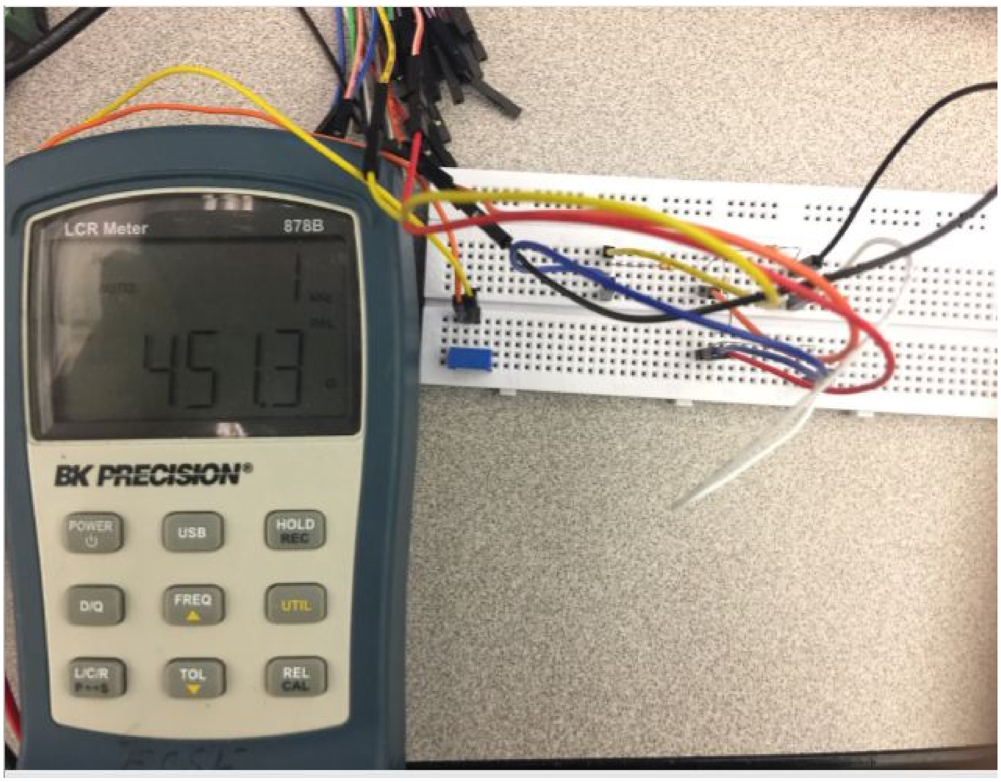
The simulation circuit has two known resistors(R1 = 2.2k ohm, R3 = 4.7k ohm), one potentiometer R2 resistance value range from 1 ohm to 2k ohm. With the plot of voltage across Rbridge over the resistance over R2, The resistance of R2 is 469 ohm when no voltage across the Rbridge. Runknown = R2*R3/R1 = 469*4.7k/2.2k = 1002 ohm, which is only 0.2% off from the set up of 1k ohm.

Measurement:

Measurement of Vbridge

	Channel 1
DC	-6 mV
True RMS	6 m$\tilde{V}$
AC RMS	2 m$\tilde{V}$

Measurement of the potentiometer



We build the Wheatstone Bridge with R1 =2.2k ohm, R2=?? potentiometer, R3=4.7k ohm, $R_{unknown}$ =1k ohm, and R_{bridge} =100k ohm as in the schematic. We used the ohmmeter and measured leg 1 and 2 of the 10k ohm potentiometer and got that the resistance of R2 to be 451.3 ohm.

At this resistance, we found the voltage across Rbridge to be rough 0V. We use the Wheatstone Bridge ratio to solve for a value of $R_{unknown}$.

$$\frac{R1}{R3} = \frac{R2}{R_{unknown}} \; ; \; \frac{2200}{4700} = \frac{451.3}{R_{unknown}} \; ; \; R_{unknown} = 964.14\,\Omega.$$

The percent difference from the theoretical measured is $\frac{|964.14-1000|}{1000} * 100 = 3.6\%$
This is within the tolerance of our resistors of 5% (gold band).

Discussion:

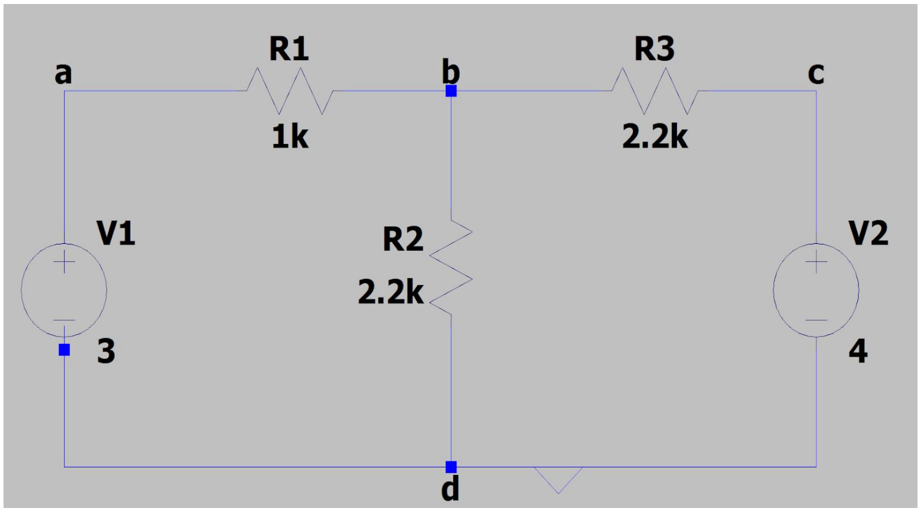
We used a Wheatstone Bridge to solve for the resistor $R_{unknown}$. How we did this was using R2 as a potentiometer and monitoring the voltage across Rbridge. When the voltage of $R_{bridge} \approx 0$ We used an Ohmmeter to measure what the potentiometer was set to. Our analysis calculation and our simulation calculation were very similar with only a 1 ohm difference. This can be attributed to LTSpice rounding our resistor value when observing the graph, as shown in the simulation.

From there we built the circuit using the analog discovery board and used a potentiometer to determine what ratio of R2 & R4 lead Rbridge to have 0V across it. We found that an R2 value of 451.3 ohms leads to this result. When using the Wheatstone Bridge ratio relationship we found that $R_{unknown}$ should be $964.14\ \Omega$. This was not that far off from what the actual value of $R_{unknown}$ was (1000 ohms). The percent difference between simulation/analysis and experiment was 3.6% which in the acceptable tolerance range of our resistors (gold band tolerance). Thus the results are as we expected.

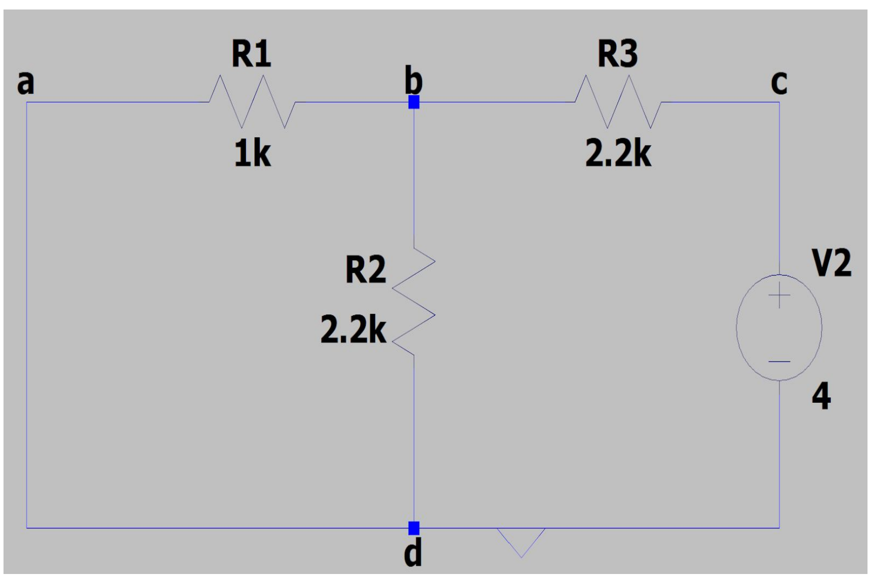
Part B: Prove the superposition concept

Building Block:

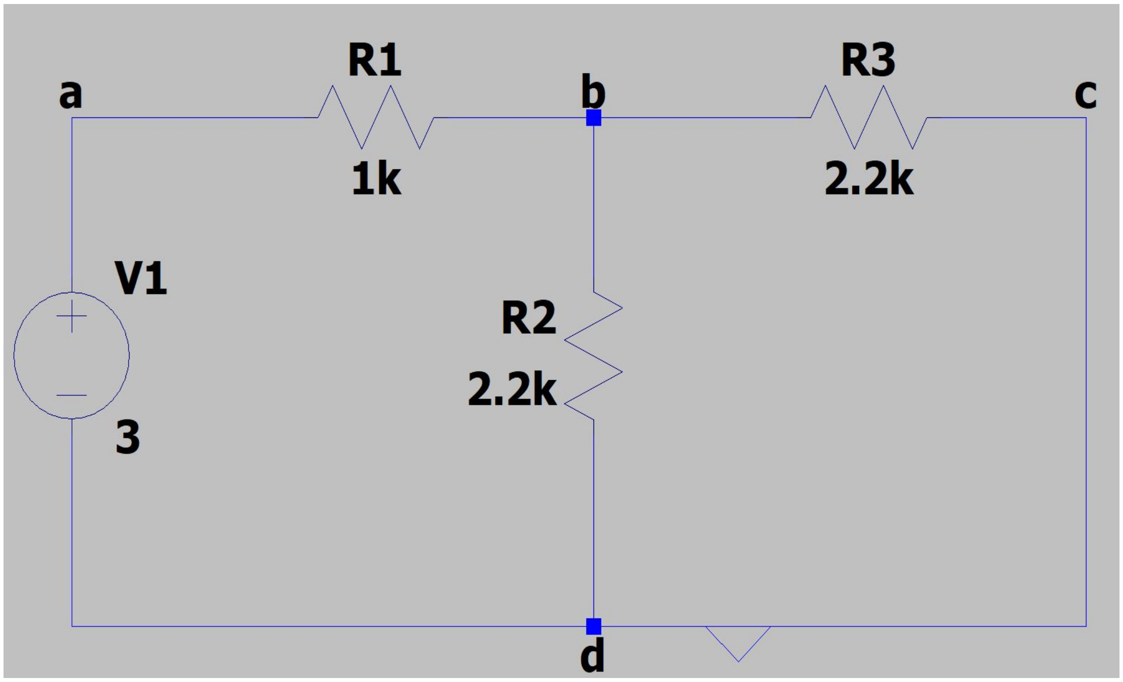
Description: We have two DC voltage sources with V1=3V and V2=4V and R1 = 1k ohm in series with V1, R3=2.2k ohm in series with VR2, and R2= 2.2k in between R1 and R3 parallel to both V1 and V2.



Analysis:



With V1 shorted, R1 and R2 are in parallel, thus the equivalent resistor $\frac{1}{R_{1/2}} = \frac{1}{1k} + \frac{1}{2.2k}$. $R_{1/2} = 687.5$ ohms. Then using the voltage divider equation $V_{R3} = 4 * \frac{2200}{2887.5}$ = 3.048 V.



With V2 shorted, R2 and R3 are in parallel, thus the equivalent resistor $\frac{1}{R_{2/3}}$ = $\frac{1}{2.2k}$ + $\frac{1}{2.2k}$. $R_{2/3} = 1100$ ohms. Then using the voltage divider equation $V_{R2/3}$ = 3 * $\frac{1100}{2100}$ = 1.571 V.

Since we know that LTSPICE assigns a newly created resistor object 's left to be the positive end

and the right side as the negative end, the voltage drop across R3 is the contribution of both V1 and V2 thus

VR3= -3.048 V (since its from the right end)+ 1.571 V (the left end)

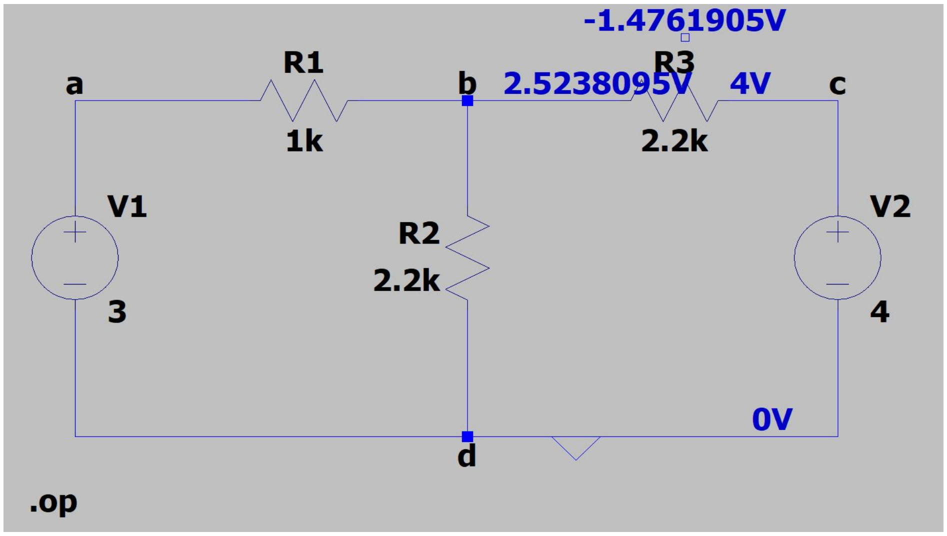
VR3= -1.477 V

Plugging the voltage divider results into the superposition formula VR3 = a(V1)+b(V2):

We get that VR3 = $3 * (\frac{1100}{2100}) - 4 * (\frac{2200}{2887.5})$

We find that the coefficient of a= 0.5238 and the coefficient of b= 0.7619

Simulation:



The simulation from LTSPICE shows that the voltage at node b is about 2.524 volt and the right end is 4 volt. The difference is about -1.476 V

Measurement:

Voltage source V1 = 3V, V2 = 4V

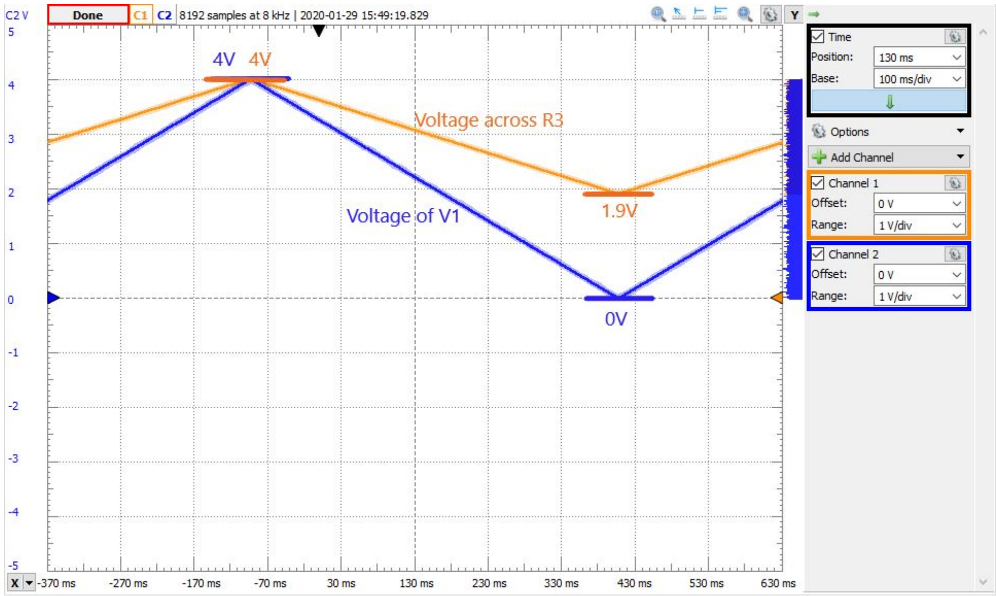
	Channel 1
DC	-1.475 V
True RMS	1.475 V
AC RMS	0 V

Voltage measured across R3 = -1.475V

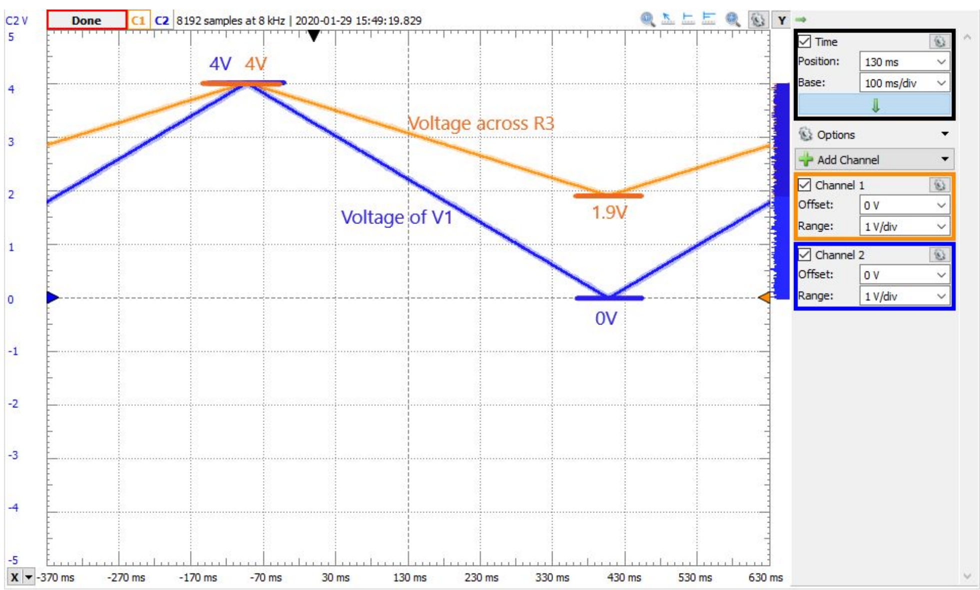
Discussion:

We built the circuit with two sources, one with 3V and one supplying 4V, and measured the voltage drop over R3 which is -1.475V. Doing the math find voltage drop over R3 by killing all sources except one, one at a time, we found the contribution of each source over R3. V1 contributed -3.048 V and V2 contributed 1.571 V. The sum of these two contributions is -1.477 V. The math value is very close to simulation and measurement value which are -1.476V and -1.475V respectively. The 0.001 V difference could be due to rounding errors in the analog discovery or due to resistor tolerance. Overall the values match our expectations and can be expressed in superposition equation of $3 * (0.5238) - 4 * (0.7619)$. Where the numbers in the parenthesis are the coefficients of the superposition equation and are found via the voltage divider equation. a= 0.5238 == $(\frac{1100}{2100})$ and b= $0.7619 == \frac{2200}{2887.5}$.

Question 2.2, 2.3

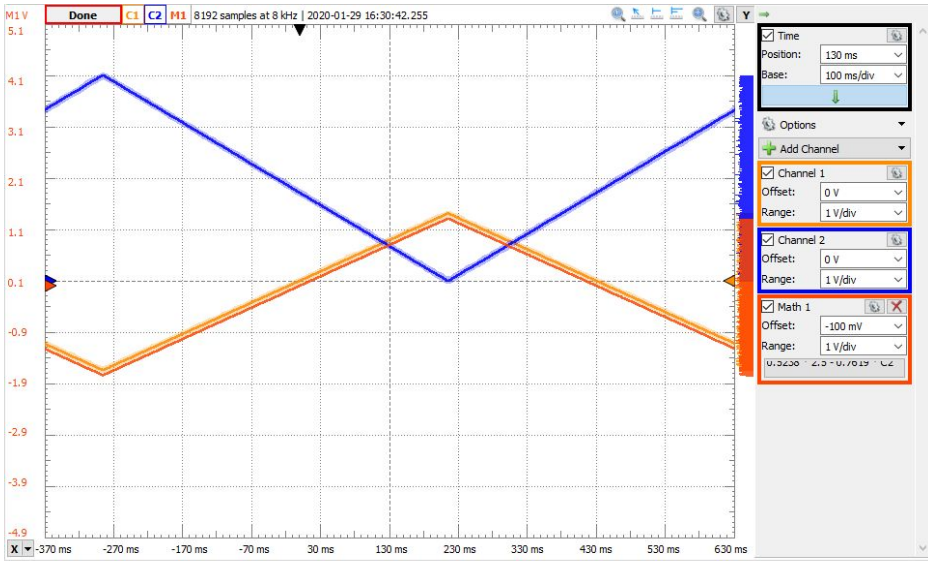


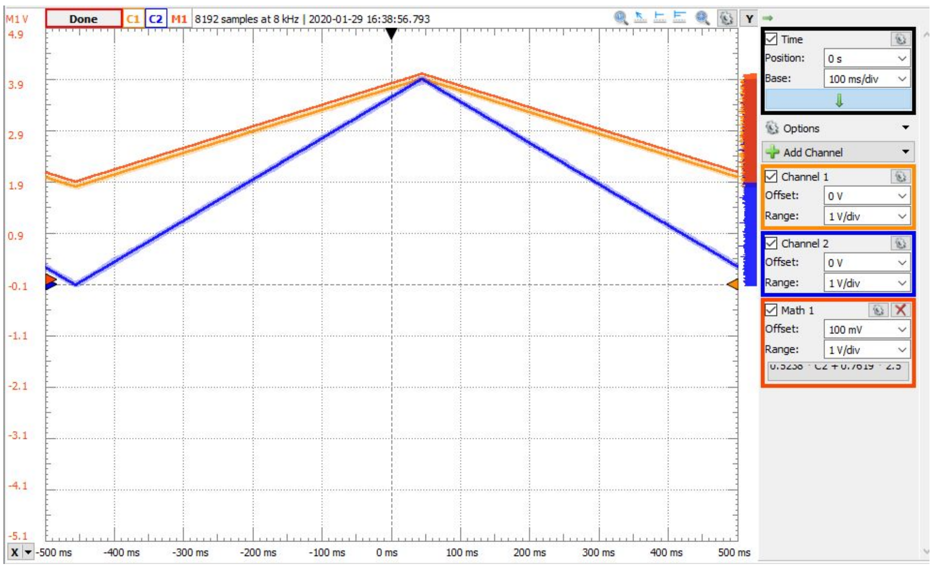
Plot of VR3 and V2 with V1 = 2.5V and 0V < V2 < 4V



Plot of VR3 and V1 with V2 = -2.5V and 0V < V1 < 4V

Question 2.4





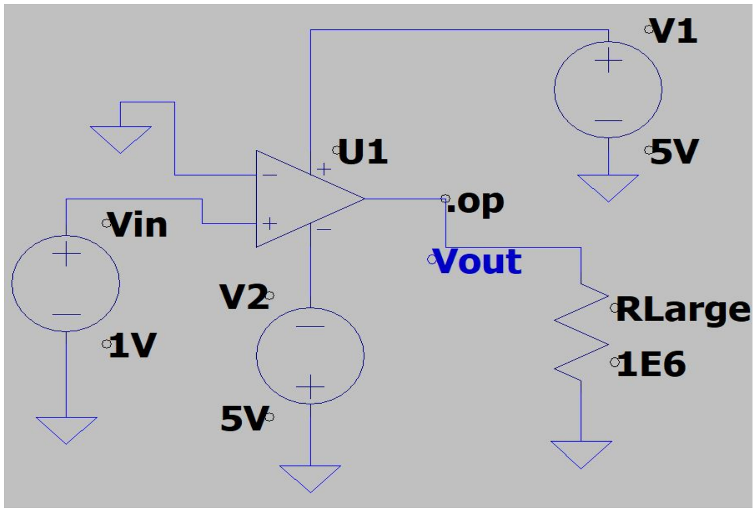
The plot of [a(V1) + b(V2)] and the output voltage across R3

Result of VR3 = $3 * (\frac{1100}{2100}) - 4 * (\frac{2200}{2887.5})$ derived value shown as red plots on the above pictures. It is shown that the result met the measurement of voltage across R3 which are the orange plots.

Part C1: Prove the function of a comparator op amp circuit (0V reference)

Building Block: WE USED 5V AS SUPPLY TO THE OMP-AMP

Description: The circuit is a comparator circuit using an op amp that outputs between 5V and -5V. The circuit determines whether the input is a positive or negative voltage.



Analysis:

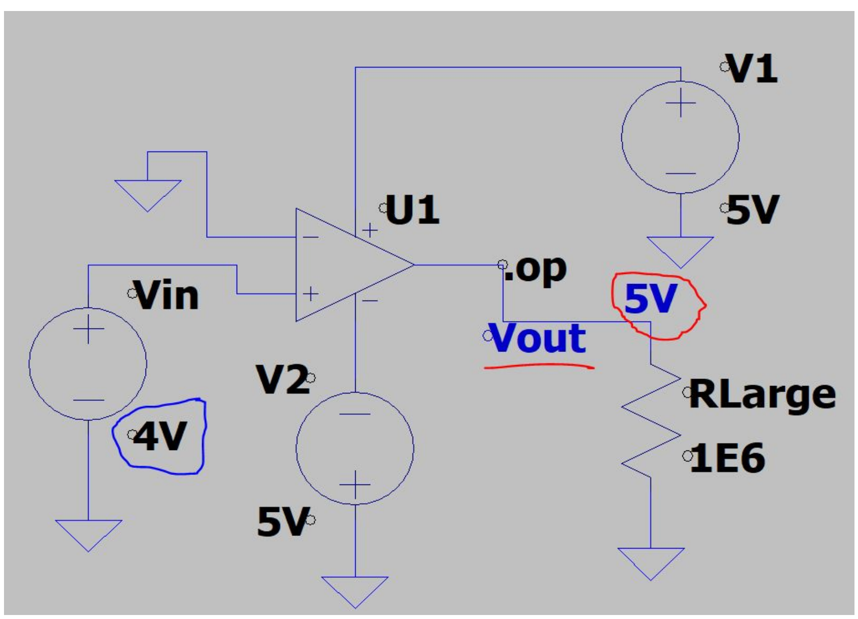
We expect the ideal op-amp to work as followed where x is the input voltage in V:

x<0V → Vout=-5V

x=0V → Vout=0V

x>0V → Vout=5V

Simulation:



Blue Circle is the input Voltage. Red Circle is Vout or the Output voltage of the comparator op-amp. We verify our conclusion from the analysis with the following table.

Vin[V]	Vout[V]
2	5
1	5
0	0
-1	-5
-2	-5

Measurement:

Vin[V]	Vout[V]
2	4.431
1	4.432
0	4.273
-1	-3.772
-2	-3.765

Discussion:

We built the comparator circuit using an op-amp with a 0V reference (to the negative input terminal of the op amp). Our simulation matched our analysis predictions, as expected because the simulation and analysis both used an ideal op-amp in their calculations.

Our measurements (experiment) did not use an ideal op-amp and it shows in the values produced. If we analyze the largest percent difference between simulation and experiment we see $(|4.432 - 5|/5) * 100 = 10\%$. This is an undesirable range away from the expected value. In addition, our value for 0V was truly off. There are a few reasons that we came up with as to why this is the case. #1 the op-amp is not ideal. There will be a voltage drop across the components of the op-amp and across the wires being used. This can account for the positive and negative input voltage differences. #2 the op-amp actually has a base voltage drop regardless. It takes the input voltage and subtracts 0.3 volts from the input. This could be why our 0V was off. #3, another reason why our 0V reading could be off is that the Analog Discovery board Ground output is not a true 0V. When using the scope to read the Ground Pin voltage was around -5mV. This would drastically alter our reading at low voltages.

However for voltages outside that small range, the circuit functions as predicted. If a Voltage less than the reference (0V) is inputted, the output will be the negative supply and if it is greater than the reference it will output the positive supply.

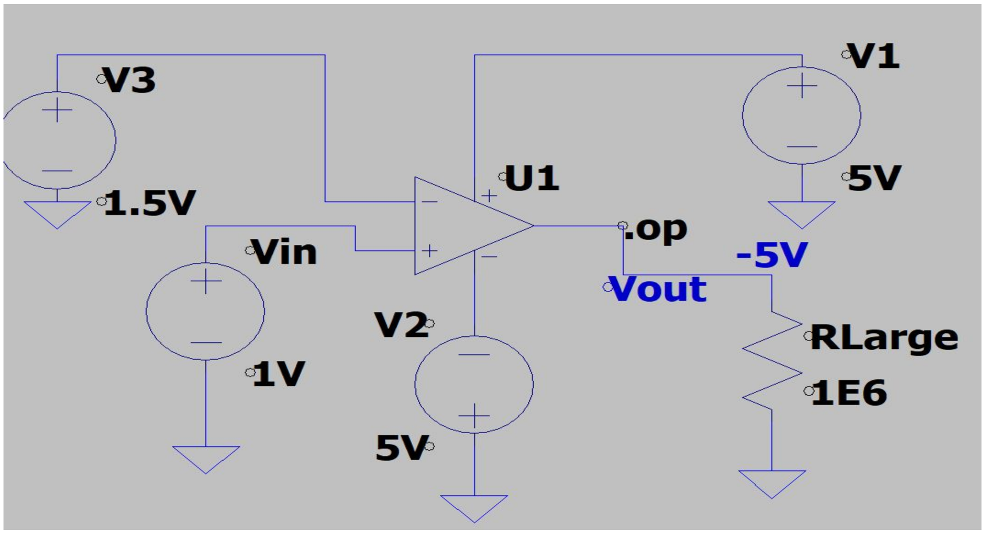
Questions from Lab:

At Vin = 0V we expected the output to be 0V. Simulation matched this result, but measurements did not. We explain why this may be above.

Part C2: Prove the function of a comparator op amp circuit (1.5V reference)

Building Block: WE USED 5V AS SUPPLY TO THE OMP-AMP

Description: The circuit is a comparator circuit using an op amp that outputs between 5V and -5V. The circuit determines whether the input is a positive or negative voltage based on the reference of 1.5V.



Analysis:

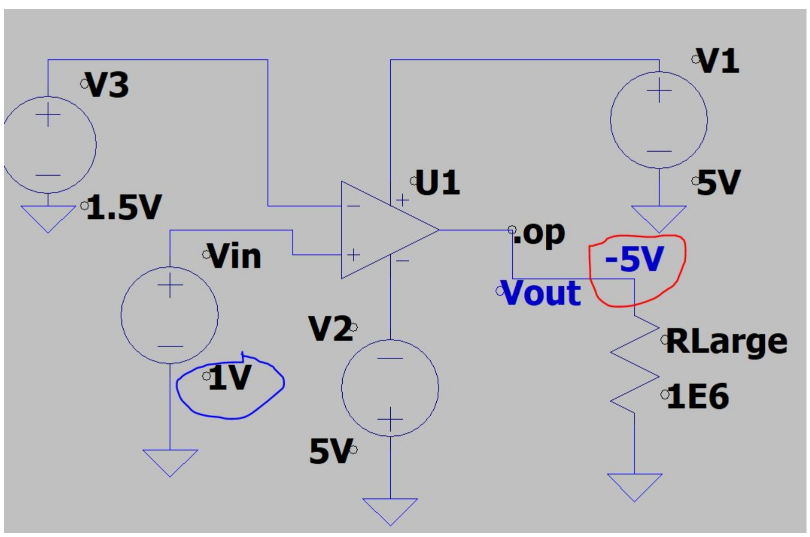
We expect the ideal op-amp to work as followed where x is the input voltage in V:

x<1.5V → Vout=-5V

x=1.5V → Vout=0V

x>1.5V → Vout=5V

Simulation:



Blue Circle is the input Voltage. Red Circle is Vout or the Output voltage of the comparator op-amp. We verify our conclusion from the analysis with the following table.

Vin[V]	Vout[V]
2	5
1	-5
0	-5
-1	-5
-2	-5

Measurement:

Vin[V]	Vout[V]
2	4.431
1	-3.745
0	-3.776
-1	-3.762
-2	-3.764

Discussion:

We built the comparator circuit using an op-amp with a 1.5V reference (to the negative input terminal of the op amp). Our simulation matched our analysis predictions, as expected because the simulation and analysis both used an ideal op-amp in their calculations.

Our measurements (experiment) did not use an ideal op-amp and it shows in the values produced. If we analyze the largest percent difference between simulation and experiment we see $(|-3.745+5|/5) * 100 = 25\%$. This is an undesirable range away from the expected value. There are a few reasons that we came up with as to why this is the case. #1 the op-amp is not ideal. There will be a voltage drop across the components of the op-amp and across the wires being used. This can account for the positive and negative input voltage differences. #2 the op-amp actually has a base voltage drop regardless. It takes the input voltage and subtracts 0.3 volts from the input. This could be why our 0V was off.

However for voltages outside that small range, the circuit functions as predicted. If a Voltage less than the reference (1.5V) is inputted, the output will be the negative supply and if it is greater than the reference it will output the positive supply.

Questions from Lab:

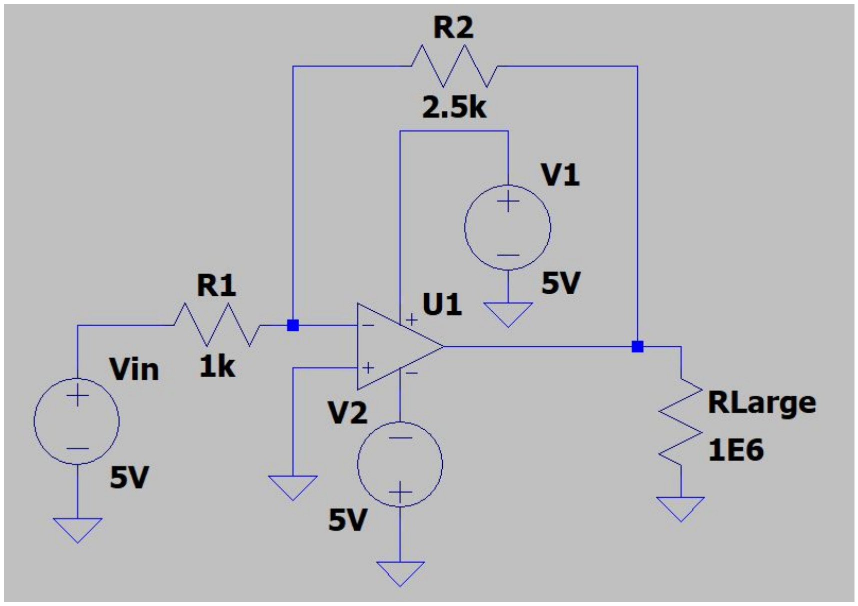
If we didn't use AWG2 for the 1.5 input, we could have used a voltage divider with the 5V supply as the source and used two resistors connected in a row starting from the column where the 5V supply is, which the top resistor being 7k and bottom being 3k and connecting the voltage drop over the 3k to the input negative input of the op amp which will be 1.5V.

At Vin = 0V we expected the output to be the negative supply. Simulation and Measurements matched this expectation.

Part C3: Prove the function of an inverting op amp circuit (gain -2.5)

Building Block: WE USED 5V AS SUPPLY TO THE OP-AMP

Description: The circuit is an inverting op amp circuit with a gain of -2.5 and output between 5V and -5V. The circuit output the voltage -2.5 times the input voltage within the range from 5V to -5V.



Analysis:

Doing KCL at the negative input node. Since there is negative feedback we know that in input voltage must be equal since V2 is tied to ground, at the negative input node, the voltage is 0V thus:

$$\frac{0-vin}{R1} + \frac{0-vout}{R2} = 0$$

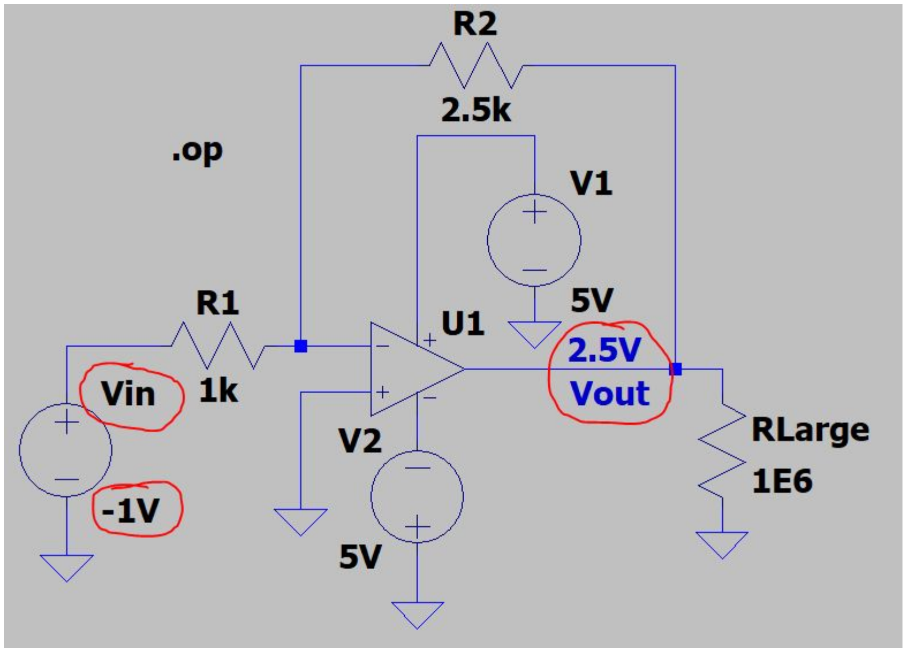
$$\frac{-vin}{R1} + \frac{-vout}{R2} = 0$$

$$\frac{-vin}{R1} = \frac{vout}{R2}$$

$$\frac{-R2*vin}{R1} = vout$$

Thus Vout will be the negative ratio (gain) of R2/R1 multiplied by Vin.
Eg if the Vin is 5V and R1=1k and R2=2.5k, Vout will be -12.5V but since the supplied are 5V to -5V, the output will saturate at -5V.

Simulation:



Vin[V]	Vout[V]
5	-4.969
3	-4.975
1	-2.500
0.5	-1.250
0.3	-0.750
0	0.000
-0.3	0.750
-0.5	-1.250
-1	-2.500
-3	4.975
-5	4.969

Measurement:

Vin[V]	Vout[V]
5	-3.186
3	-3.337
1	-2.500
0.5	-1.248
0.3	-0.746
0	0.005
-0.3	0.758
-0.5	1.264
-1	2.516
-3	3.822
-5	3.690

Discussion:

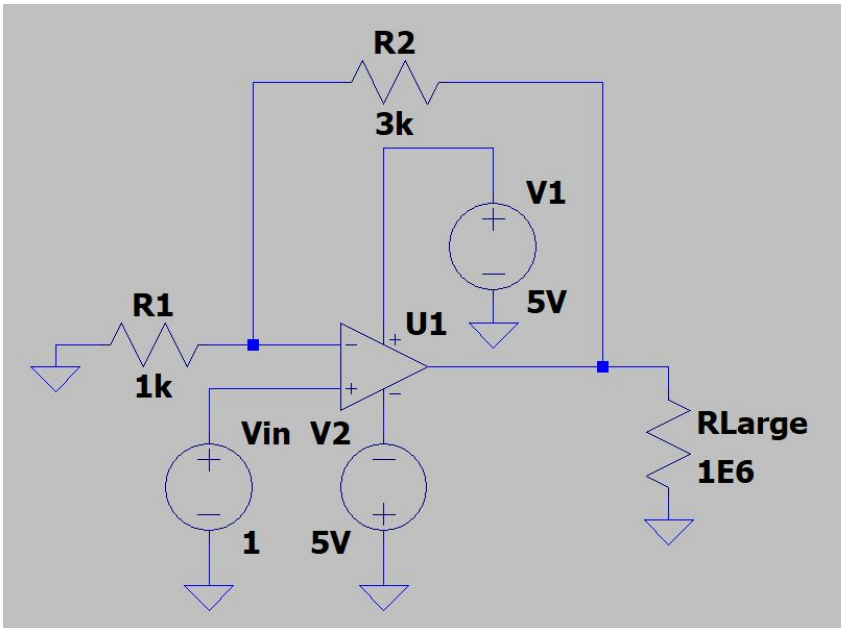
The simulation and measurement were done with the inverting op amp circuit with a gain of -2.5. The simulation result matches the analysis predictions, as expected because the simulation and analysis both used an ideal op amp in their calculations.

The measurement also shows a trend that within a certain range the result also matches the analysis. It is expected that the voltage out equals to -2.5 times the voltage in while the voltage out cannot exceed the voltage supply. From the data above, when the voltage is between 1V and -1V there is an average of 0.8% off from the expected value. This data is acceptable since all the resistors used to contain 5% Torrance.

However, when the voltage out exceeds the range of supply voltage it would just act like a comparator op amp circuit. The result matches the performance in part A, which should consist of the same reason.

Part C4: Prove the function of a non-inverting op amp circuit (gain 4)
Building Block: WE USED 5V AS SUPPLY TO THE OMP-AMP

Description: The circuit is a non-inverting op amp circuit with a gain of 4 and output between 5V and -5V. The circuit output the voltage 4 times the input voltage within the range from 5V to -5V.



Analysis:

Doing KCL at the negative input node. Since there is negative feedback we know that in input voltage must be equal since V2 is tied to Vin, at the negative input node, the voltage is Vin Volts thus:

$\frac{vin-0}{R1} + \frac{vin-vout}{R2} = 0$

$\frac{vin}{R1} + \frac{vin-vout}{R2} = 0$

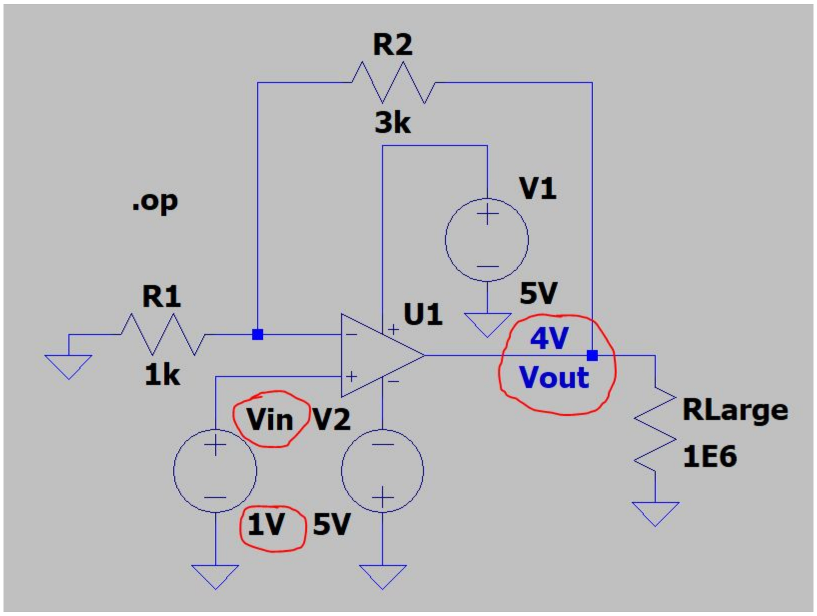
$\frac{vin}{R1} + \frac{vin}{R2} = \frac{vout}{R2}$

$(\frac{vin}{R1} + \frac{vin}{R2})R2 = Vout$

Eg if using the value from above: vin=1V, R1=1k, and R2=3k

$(\frac{1}{1000} + \frac{1}{3000})3000 = 4$ volts.

Simulation:



Vin[V]	Vout[V]
5	4.986
3	4.986
1	4.000
0.5	2.000
0.3	1.200
0	0.000
-0.3	-1.200
-0.5	-2.000
-1	-4.000
-3	-4.986
-5	-4.986

Measurement:

Vin[V]	Vout[V]
5	4.057

3	4.057
1	4.01
0.5	2.000
0.3	1.196
0	-0.016
-0.3	-1.221
-0.5	-2.027
-1	-3.495
-3	-3.561
-5	4.059

Discussion:

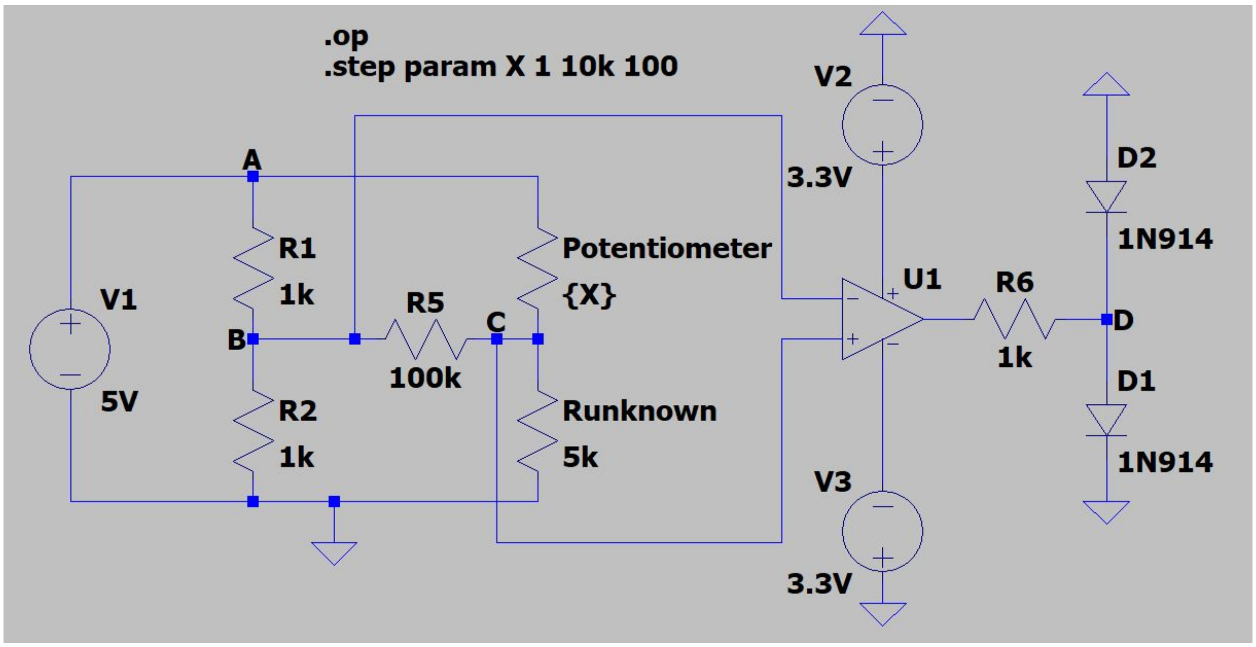
The simulation and measurement were done with the non-inverting op amp circuit with a gain of 4. The simulation result matches the analysis predictions, as expected because the simulation and analysis both used an ideal op amp in their calculations.

The measurement also shows a trend that within a certain range the result also matches the analysis. It is expected that the voltage out equals 4 times the voltage in while the voltage out cannot exceed the voltage supply. From the data above, when the voltage is between 1V and -0.5V there is an average of 1.1% off from the expected value. This data is acceptable since all the resistors used to contain 5% Torrance.

However, when the voltage out exceeds the range of supply voltage it would just act like a comparator op amp circuit. There shows an inconsistency range that positive voltage tends to have a larger range. When the voltage is -1V it should expect a -4V out but result in -3.495V which is 12.6% off. That value is larger than 5% which exceeds the range of tolerance of the resistor. Also from the result of -3V input, we could conclude that with the limit of supply voltage the voltage on the negative side of this circuit is limit around -3.5V.

Part D: Prove that your individual design blocks with your given input resulted in the correct output for the next stage of your design
Building Block:

Description: A potentiometer tunes a Wheatstone bridge to generate a voltage across R5 or our Bridge Resistor. If the voltage across R5, as seen by the OP amp, is positive then the LED or Diode D1 turns on. Otherwise, if the voltage across R5 is negative then the Diode D2 turns on. If the voltage across R5 is 0V then neither LED will turn on.



Analysis:

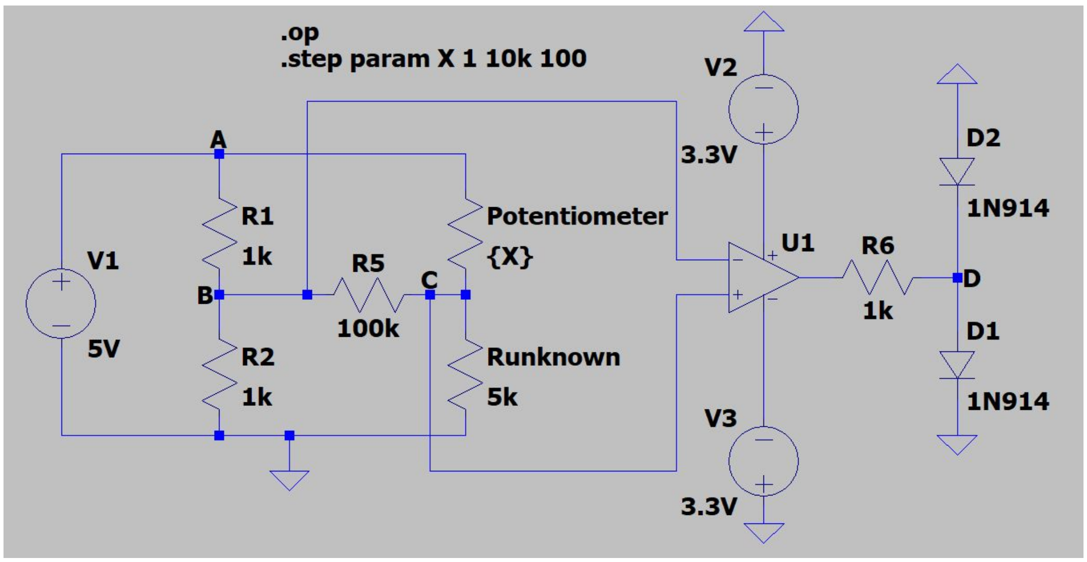
For the input stage we have a potentiometer connected to a Wheatstone bridge:
Since B is tied to the negative input of the comparator, the reference voltage is $5(\frac{1000}{2000})$ = 2.5V
When the bridge R5 is balanced, Vb is equal to Vc. In this case, Vb equals to Vc when:
$5(\frac{1000}{2000}) = 5(\frac{5000}{x+5000})$. We can divide out the 5
$(\frac{1000}{2000}) = (\frac{5000}{x+5000})$
1000(x+5000)=10000000
x+5000=10000
x=5000 ohms
When the potentiometer is at 5000 ohms, the bridge is balanced and no voltage drop happens across nodes B and C. When both the negative and positive input of the comparator is 0V. The output is 0V. Since the output of the comparator is 0V, at node D there is 0V so there is no voltage supplied to the diodes thus no diode is turned on.

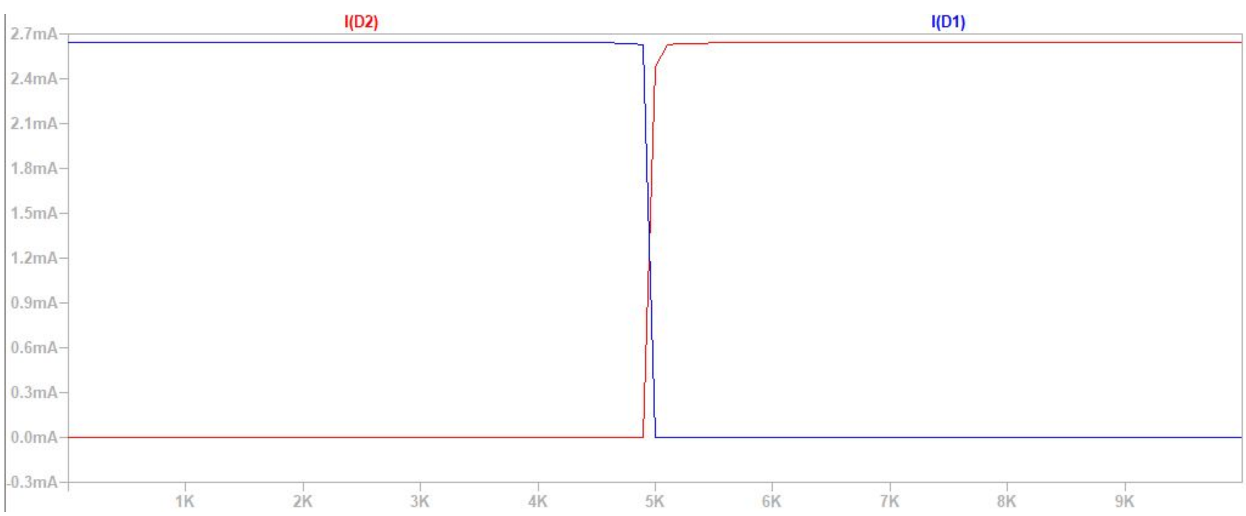
When the potentiometer is over 5000 ohms:
$5(\frac{1000}{2000})$ =2.5V into the negative input of the comparator
$5(\frac{5000}{x+5000}) > 5(\frac{1000}{2000})$

$\frac{5000}{x+5000} > \frac{1000}{2000}$. We can divide out the 5
10,000,000>1000x+5,000,000
5,000,000>1000x
5000ohms>x
When the potentiometer is less than 5000 ohms, the input to the positive terminal is greater than the negative terminal of 2.5V, which means the output is positive supply voltage which means at node D there is a positive voltage. Since diodes are direction sensitive, the positive voltage will turn on D1.

And thus, doing the reverse analysis, when x<5000 ohms the input to the positive terminal is less than the negative terminal of 2.5V, which means the output is negative supply voltage and D2 will turn on.

Simulation:





X-axis: Resistance of Potentiometer.
Y-axis: Current through Diodes
Current of D2: Red line
Current of D1: Blue line

Measurement:
No measurement for part D as we do not build the circuit.

Discussion:
We built a circuit that allows a user to determine which LED turns on based on the way the user tunes the potentiometer. We compare Analysis and Simulation as we do not build the circuit. The idea of the circuit was to use a potentiometer in a wheatstone bridge where tuning the potentiometer generates a voltage difference across the bridge resistor, which we use to sense the "direction" the user decided. Based on analysis we determined that if the potentiometer resistance (X) is less than 5000 ohms then Diode 1 turns on and when X>5000 ohms Diode 2 turns on. From our graphs in the simulation we can see that we were correct in the analysis.

Questions from Lab:
Our circuit did work exactly as planned, both in analysis and simulation. However we did not build the circuit so it is not determined whether it will work with non-ideal op-amps. We reason that it should still work as expected within a given margin of error of the breadboard components. Because we are not dealing with low voltages and operating in an essentially on/off region, non-ideal components should still work.