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ECE2333

004

Laboratory No. 10: Night Light Resistive Sensor Design Part 2

Due Date: April 10, 2020

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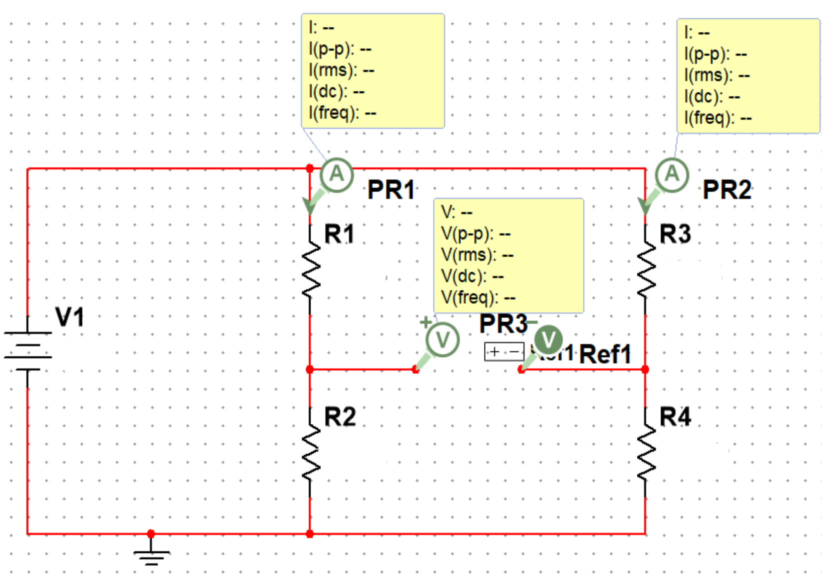
I. Objectives and Purpose

A nightlight design can be introductory circuit design that teaches students how to drive an LED without frying the diode. The circuit can be modelled around a Wheatstone Bridge powered by a 10V DC Voltage Source, using Four Resistors with one being a Photoresistor to measure light sensitivity. Since the photoresistor which has a range from $1k\Omega \; to \; 10k\Omega$, the voltage powering the LED will be dependent on three rules: 1) $Vout$ should equal $0V$ when the lights are on in the room, making photoresistor $1k\Omega$. 2) $Vout > 0V$ when the lights are turned off in the room, making the photoresistor $10k\Omega$. 3) $Vout$ should equal the calculated value using the derived equation when the lights are off. This project is important to Engineers because it demonstrates the ability to analyze and design circuits, it will use an operational amplifier to amplify current, and serves as an introduction to LEDs by tasking the designer with the obstacle of turning the LED on, without frying the component because of too much voltage or current, which should be taken into considering for any circuit design.

II. Design Procedure

Considering a typical Wheatstone Bridge set up below, the DC circuit can be transformed into a nightlight by determining the value of the resistors that should be chosen, and replacing the voltage across the open circuit ($Vout$) with an LED:



[Figure 1: Wheatstone Bridge no values]

Since $Vout$ is the difference across the voltage points Va (positive terminal) to Vb (negative terminal), and the required voltage source for this circuit is $10V$ DC, then KCL proves when splitting into the two parallel branches that $R1$ & $R2$ are in series, as $R3$ & $R4$ are also in series because they share the same current. Voltage division can then be applied to find the relationship between the resistor values, by solving algebraically for when $Vout = 0V$ (lights on). Therefore:

$$Vout = Va - Vb$$

$$Vout = Vs\left(\frac{R2}{R1 + R2}\right) - Vs\left(\frac{R4}{R3 + R4}\right)$$

$$0 = Vs\left(\frac{R2}{R1 + R2} - \frac{R4}{R3 + R4}\right)$$

$$\frac{0}{Vs} = \left(\frac{R2}{R1 + R2} - \frac{R4}{R3 + R4}\right)$$

$$\frac{R2}{R1 + R2} = \frac{R4}{R3 + R4}$$

$$R2(R3 + R4) = R4(R1 + R2) => R2R3 + R2R4 = R4R1 + R4R2$$

$$R2R3 = R1R4$$

$$\frac{R2}{R1} = \frac{R4}{R3}$$

Therefore, $R1 = R3$ and $R2 = R4$. This ratio also will satisfy when $Vout > 0, \frac{R2}{R1} > \frac{R4}{R3}$ which means to increase the voltage, either $R2$ or $R3$ must be a photoresistor. I decided to choose $R2$ as the photoresistor, from that I knew $R1 = R3$ so from examining the parts from our circuit kit, I knew that these resistors had to be chosen from a pair of resistors. From the kit the only values that I have two of are: $330\Omega, 1k\Omega, 10k\Omega,$ and $100k\Omega$:

99Y7506					
ECE2333	**Principles Electric Circuit**				
#	Item	Newark#	ECE Stock#	Qty	Alternative
1	100 ohm	58K5000	17	1	
2	330 ohm	58K5042	22	2	
3	680 ohm	58K5068	26	1	
4	1K ohm	58K5001	27	2	
5	1.2K ohm	59K8332	29	1	
6	1.5K ohm	58K5015	30	1	
7	2.2K ohm	58K5030	33	1	
8	3.3K ohm	58K5043	37	1	
9	10K ohm	58K5002	45	2	
10	100K ohm	58K5003	58	2	
11	LM741CN, Op-Amp	41K6294	119	2	
12	47000 pF (47 nF or 0.047 uF)	46P6681	178	1	
13	0.1 uF	46P6667	185	1	
14	1 uF	74AC1306	195	2	
15	Breadboard	71Y9233	n/a	1	56T0249
16	F-F Jumper Wire	31Y3511		1 PK 10	
17	M-F Jumper Wire	31Y3512		1 PK 10	
18	LED	09J9310	303	5	
19	TL072CP, Dual Op-Amp	60K6988	308	1	
20	Tactile switch	14H0928	349	4	
21	3.3 mH	32M9872	n/a	1	14AC4948/74R9996
22	M-M Jumper Wire	31Y3513		1 PK 10	99W1758, 88W2570
23	Photoresistor	54W2650		1	14J5050
24	Piezo buzzer	25R0888	n/a	1	
25	Speaker	18X4918		1	
26	Audio breadboard connector	75Y0814		1	
27	10K ohm Pot	62J2093		2	235/236, 05N1554

[Figure 2A: Circuit Parts kit]

Originally, in Lab 3 I settled on using two 330Ω resistors for $R1$ and $R2$, but because of a later stage in the circuit, these values were changed to $1k\Omega$ which I will discuss why, later in the report. The only resistor left to choose was $R4$ which could be any resistor within the range of the photoresistor, so I decided to pick a 1.5kΩ.

Calculating the voltage across by voltage division when the lights are on,

$$Vout = 10V\left(\frac{1.5\text{k}\Omega}{1\text{k}\Omega + 1.5\text{k}\Omega} - \frac{1.5\text{k}\Omega}{1\text{k}\Omega + 1.5\text{k}\Omega}\right) => 10V(0) => 0V$$

This satisfies the condition because $P = I * V$ so the LED will not turn on no matter how much current is feeding into it, because the voltage is $0V$.

Solving for when the lights are off, $R2$ changes from $1.5k\Omega$ to $10k\Omega$,

$$Vout = 10V\left(\frac{10\text{k}\Omega}{1\text{k}\Omega + 10\text{k}\Omega} - \frac{1.5\text{k}\Omega}{1\text{k}\Omega + 1.5\text{k}\Omega}\right) => 3.0909V$$

The Led given in the kit recommends a voltage of $2V$ and a current of $20mA$ thus giving a minimum power of $P = I * V => (2v) * (2 * 10^{-3}) = 40mW$, the voltage obtained by these components satisfies the voltage required to turn on the LED, however the current is never enough. I calculated the current by combining $R1\&R2$ and $R3\&R4$ since these pairs are in series, then combining these pairs in parallel creates an equivalent resistance for a simplified circuit with one resistor:

$$R1R2 = 1k\Omega + 10\Omega = 11k\Omega$$

($R2 = 10k\Omega$ because the I am finding the current when the LED is on)

$$R3R4 = 1k\Omega + 1.5k\Omega = 2.5k\Omega$$

$$Req = R1R2||R3R4 => \frac{11k\Omega * 2.5k\Omega}{11k\Omega + 2.5k\Omega} = 2.037k\Omega$$

From Ohm's Law, the current before the branches split is: $I = \frac{V}{R} => \frac{10V}{2.037k\Omega} = 4.9mA$

$I1$ and $I2$ can then be calculated through current division and KCL:

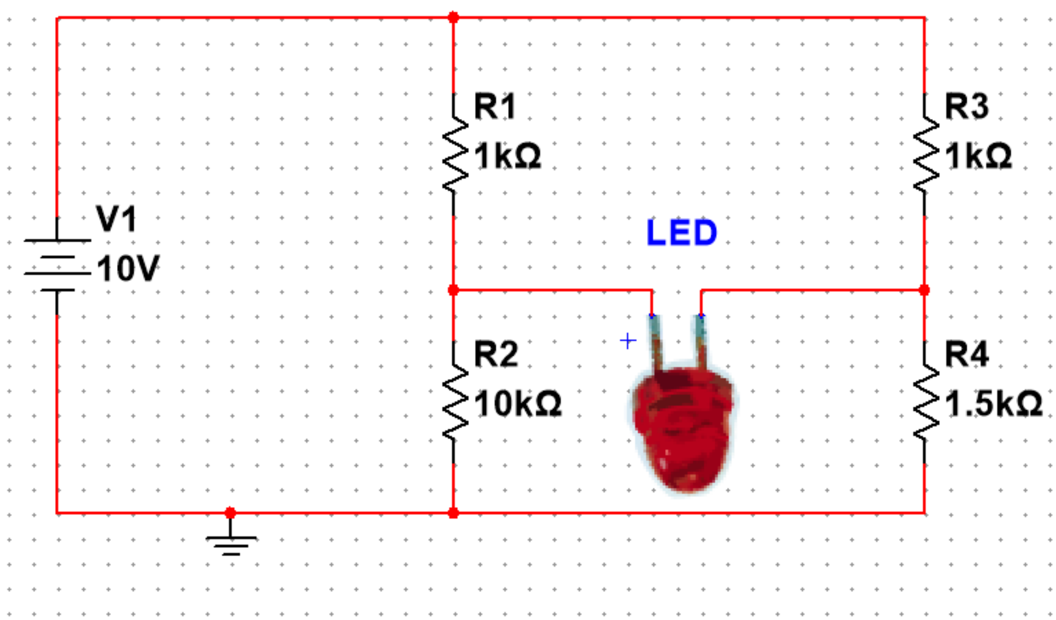
$$I1 = Is\left(\frac{R4R3}{R1R2 + R3R4}\right) => 4.9mA\left(\frac{2.5k\Omega}{11k\Omega + 2.5k\Omega}\right) = 909\mu A$$

$$I2 = Is - I1 => 4.9mA - 9.09pA = 4mA$$

The current before the split is never $20mV$ and even with $3.0909V$, the amount of current needed to power the LED would be $I = \frac{P}{V} = \frac{40mW}{3.0909V} = 12.9mA$. Even deriving the Thevenin Equivalent circuit proves that from $Rth = \frac{R1*R2}{R1+R2} + \frac{R3*R4}{R3+R4} = 1.5091k\Omega$

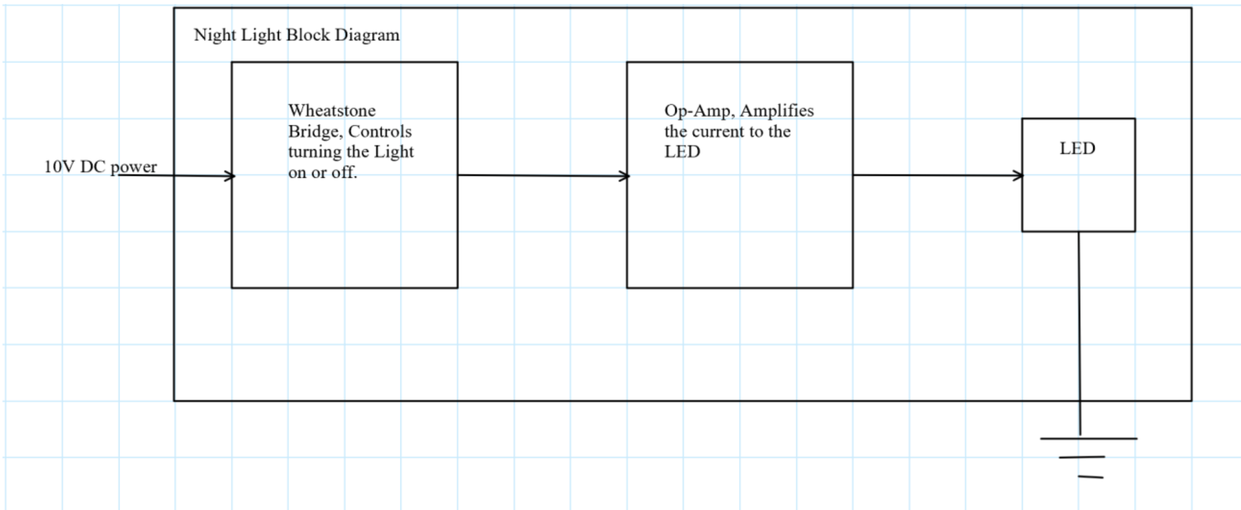
And gives a max power of, $P_L = \frac{Vth^2}{4RL} => \frac{Vout^2}{4Rth} = 1.6mW$

Since this circuit never generates enough power, this brings us to the amplification part of the circuit. Using an Op-Amp can add or subtract voltage/current, so given the circuit up until this point:



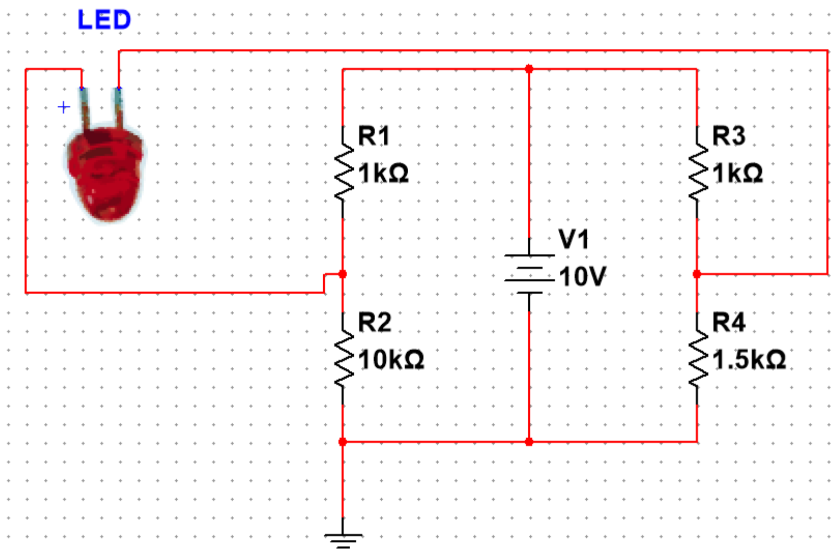
[Figure 1b: The Wheatstone Bridge, with Values, No Amplification]

An op-amp will be added to the after the wheatstone part of the circuit but before the LED, as shown below in the overall block Diagram:

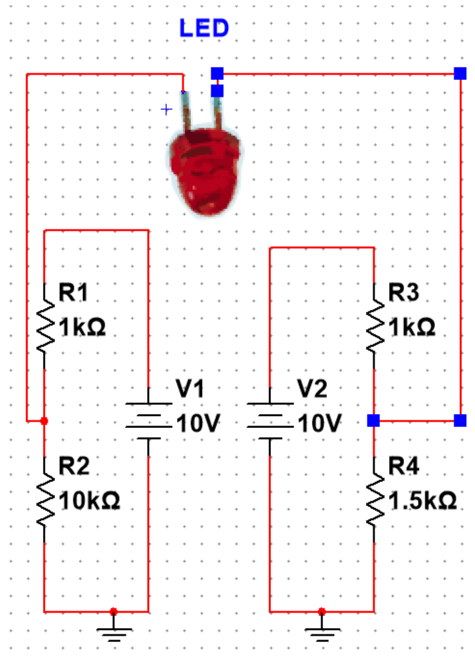


[Figure 2B: Block Diagram of entire circuit]

I knew that the op-amp needs to be placed after the current splits, because if it is placed before the split, then this could potentially provide too much voltage or current and fry the LED. Thinking about how I could redraw this circuit reminded me that $R1\&R2$ as well as $R3\&R4$ are in series, so this circuit could be redrawn in a series of multiple ways:

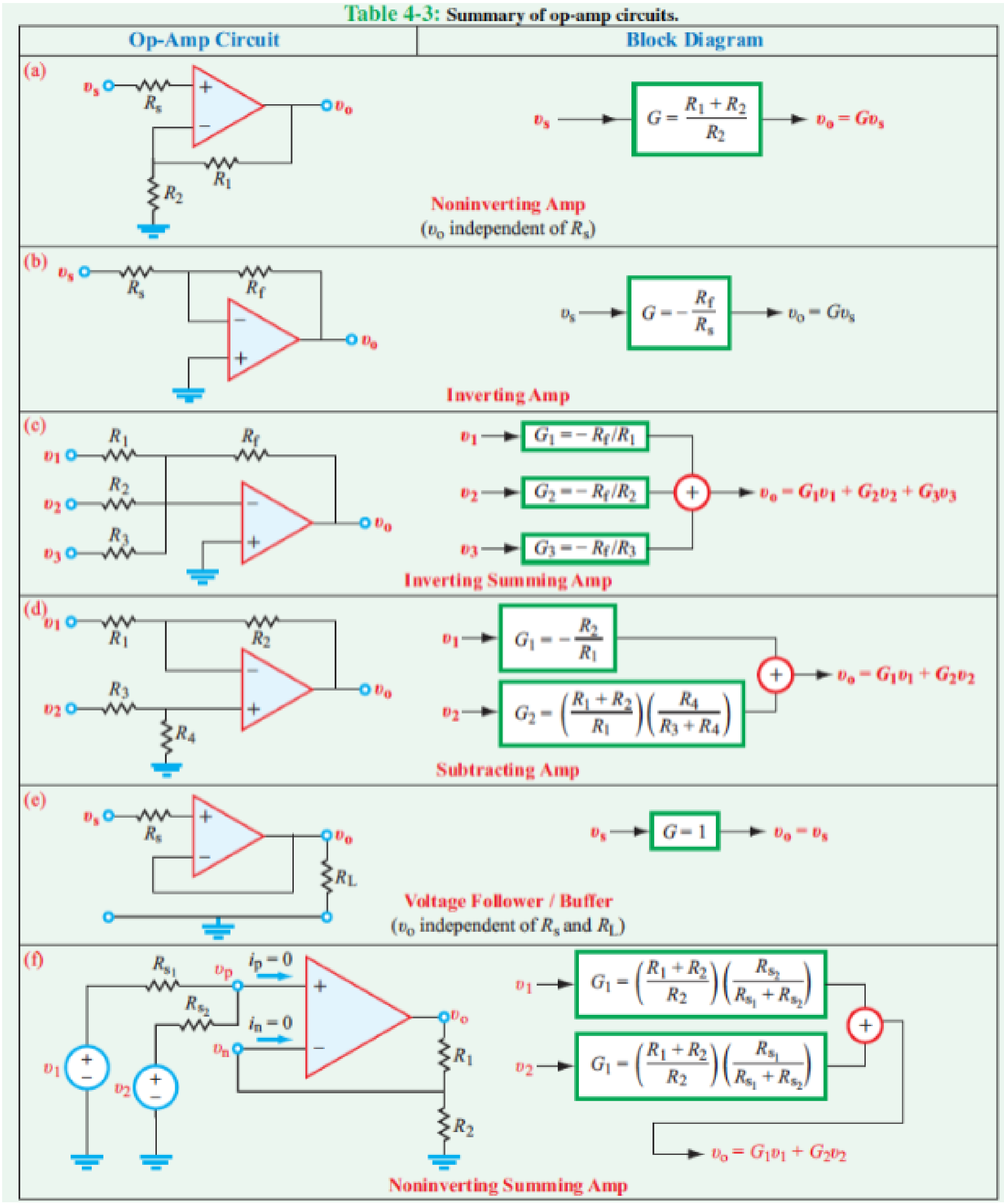


[Figure 1C: One equivalent drawing of the Wheatstone Bridge]



[Figure 1D: Another Equivalent Circuit]

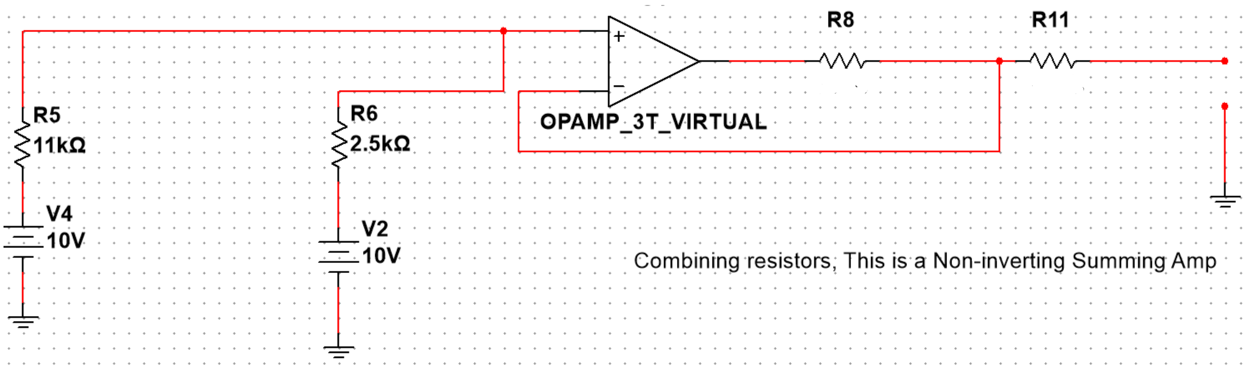
Ultimately, the circuit could be split into two separate circuits with resistors in series, as long as the nodes connecting to the LED remain the same. Knowing this information along with the idea that I can combine resistors, I referred to the Op-Amp configuration chart that we used throughout this class:



[Figure 2C: Table 4-3 From the Textbook]

Given the last transformation that the circuit can be divided into two separate circuits, a Non-inverting Summing Amp can be used to amplify the current and power the LED. To clean the circuit up into the format of the Non-inverting Summing Amp, Rs1 will equal the combined $R1\&R2$ and $Rs2$ will equal the combined $R3\&R4$ from their series calculations,

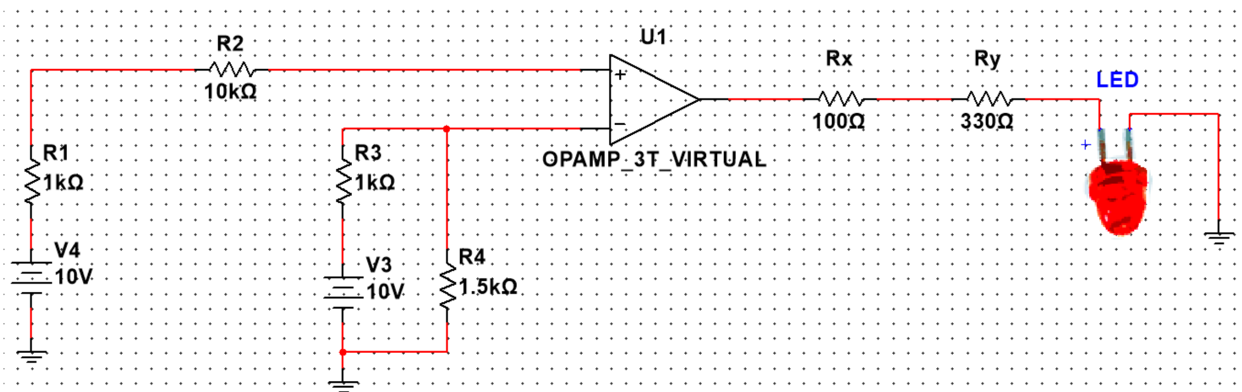
$$Rs1 = 11k\Omega \qquad Rs2 = 2.5k\Omega$$



[Figure 1E: Circuit Redrawn as a Non-Inverting Summing Amp without the LED. The resistors before the OP-Amp are combined by series calculations.]

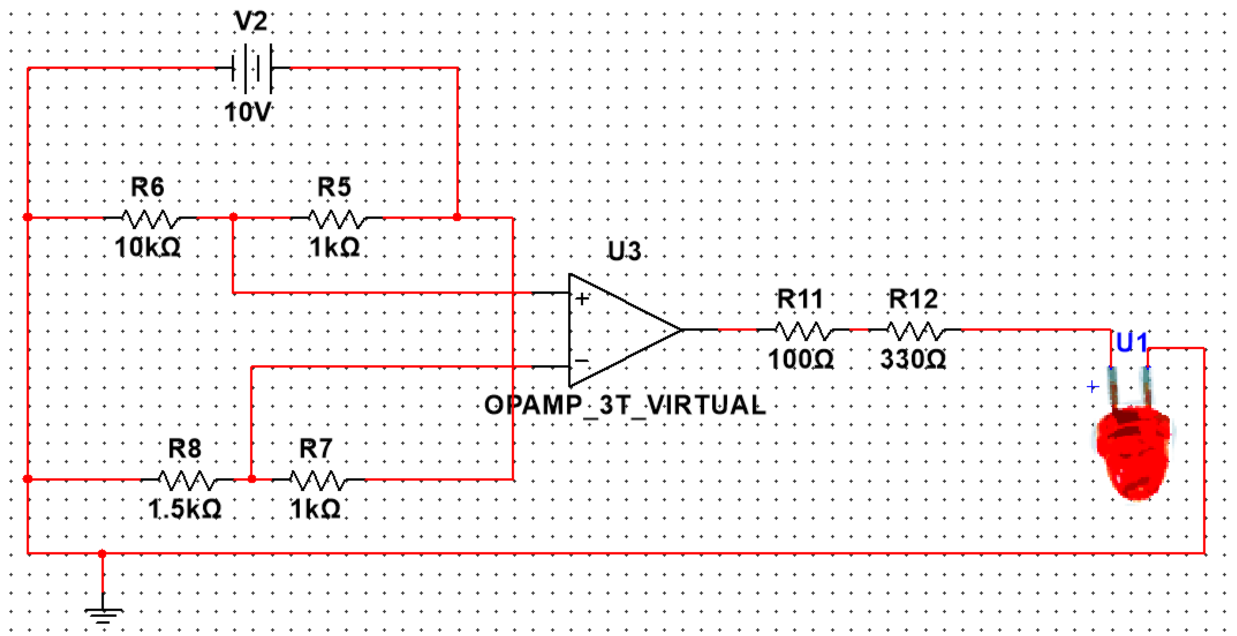
This is where I realized something though, because both resistor sections of the Wheatstone feed into the positive side of the op-amp, this is no longer technically a Wheatstone Bridge, in fact if I uncombined the resistors and set the circuit back up to look like a Wheatstone, the current feeding into the Op-Amp would be completely different to the original circuit design. This got me thinking about what defines the Wheatstone circuit which led to me discovering from this circuit, if I unwire the negative feedback loop and place the $2.5k\Omega$ resistor into the negative circuit, the circuit now becomes a Wheatstone Bridge that feeds into an Non-Inverting Op-Amp Comparator, that uses the resistors in the output to limit the current and power the LED.

From this, the circuit can be redrawn by uncombining the resistors and replacing them with the original circuit/kit resistors:



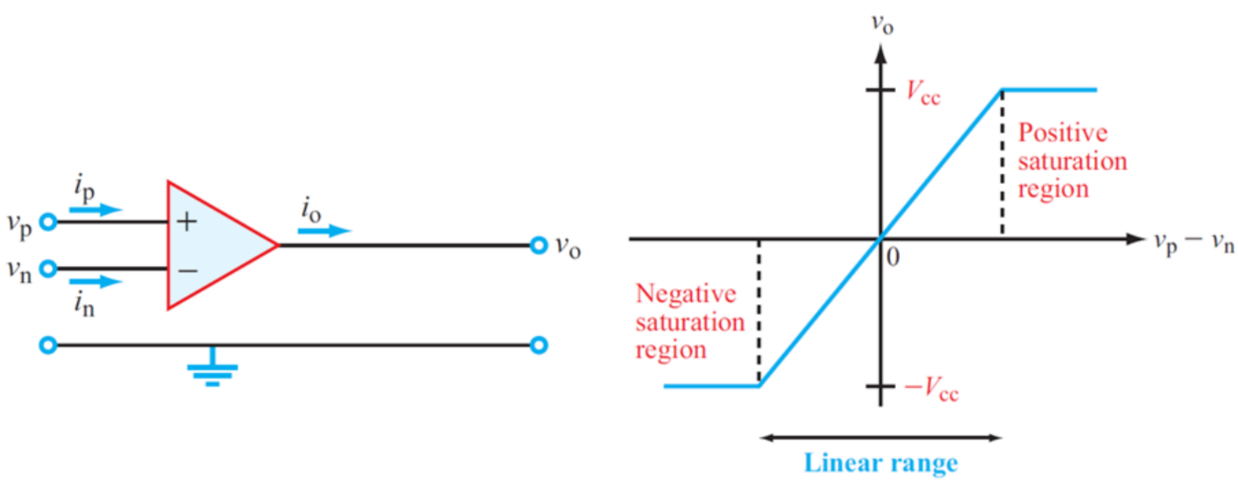
[Figure 1F: Redrawn Op-Amp Styled setup]

Finally, this circuit can be Redrawn back into a Wheatstone Bridge setup, with the op-amp configuration added:



[Figure 1G: Final Nightlight Circuit ready for simulation]

This setup is now an op-amp comparator. The $Vout$ coming out of the op amp can be derived from examining the behavior of an op-amp comparator:



[Figure 2D: Taken from Lab 4 manual]

If this circuit was actually built on a breadboard in a normal lab, Vcc would be what will power the op-amp which is done by connecting pin 7 of the LM741 to $+15V$ from the ELVIS board. To ensure the wheatstone section of the circuit still works, $-Vcc$ which is pin 4, will be wired to ground so when the Photoresistor goes to anything below $1.5k\Omega$, the voltage out of the op-amp will go to $0V$. The relationship is represented by a piecewise function:

$$Vout_{Op_{Amp}} = \begin{cases} Vcc, & Vp > Vn \\ -Vcc, & Vn > Vp \end{cases} == \begin{cases} Vcc, & 15V \\ -Vcc, & GND = 0V \end{cases}$$

From this the positive $15V$ can be treated like a voltage source and since the LED needs at least $2V$ to be powered on, Ohms' Law can be applied to determine what the limiter resistors will be:

$$RLED = \frac{V}{I} = \frac{2V}{20mA} = 100\Omega$$

Using KVL, the Voltage of the limiter resistor could be solved since the sum of all voltage must equal $0V$ and the voltage of the LED needs to be at least $2V$:

$$15V = V_{limit\ resistor} + 2V => 15V - 2V = 13V$$

Since the Voltage of the limit resistor is 13V and it is in series with the LED which needs to have a current of $20mA$, the limit resistor follows as: $R = \frac{V}{I} = \frac{13V}{20mA} = 650\Omega$, since the kit does not contain a 650Ω resistor, the closest that can be done is by combining a 100Ω and 330Ω in series to make 430Ω, this is why I originally changed my Wheatstone resistors to $1k\Omega$. From this more Ohm's Law can be developed to find the actual current, power, and voltage across the LED:

$$I = \frac{Vs}{R + RLED} = \frac{15V}{430\Omega + 530\Omega} = 28.3mA$$

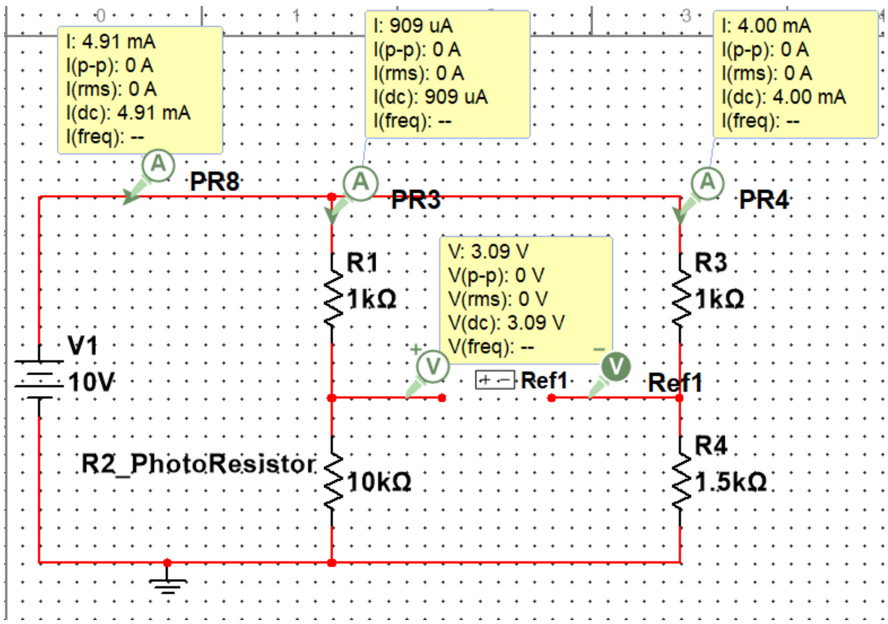
which is the current feeding into the LED because the LED is in series with the resistors, knowing the resistance of the LED:

$$V = IR = 28.3mA * 100\Omega\text{=2.83V}$$

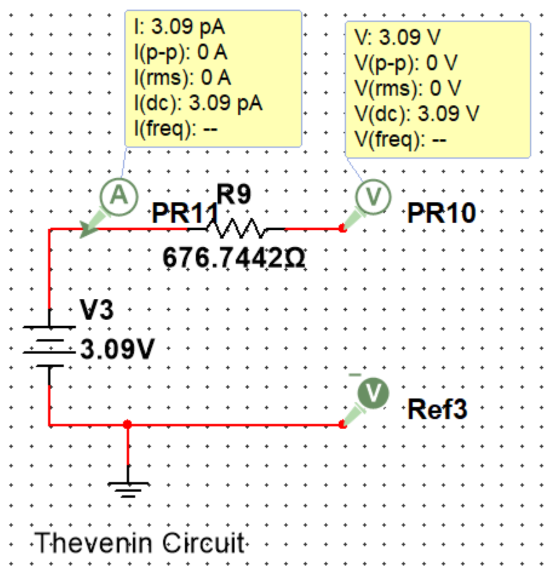
$$P = IV = 2.83V * 28.3mA = 80mW$$

As shown in the simulation however, this is with the op-amp being powered with $+15V$ as Vcc, the power can be decreased to approximately half the power by simply decreasing the voltage, to the op-amp which will then decrease the voltage to the LED, in the lab, I would do this by connecting Pin 7 of the Op-Amp LM741 to the Virtual Bench.

III. Simulation Results



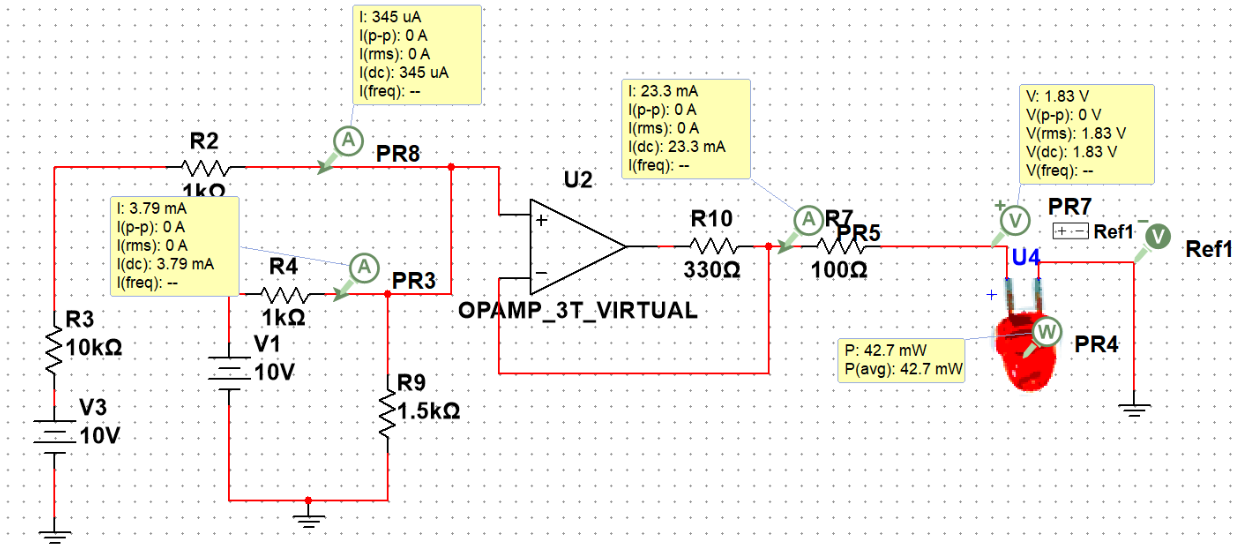
[Figure 3A: Wheatstone Bridge without Op-Amp simulation]



[Figure 3B: Thevenin Equivalent Circuit to the original Wheatstone Bridge simulation]

	Calculated	Simulated
Is	$4.9mA$	$4.91mA$
I1	$909\mu A$	$909\mu A$
I2	$4.00mA$	$4.00mA$
Vout	$3.0909V$	$3.09V$

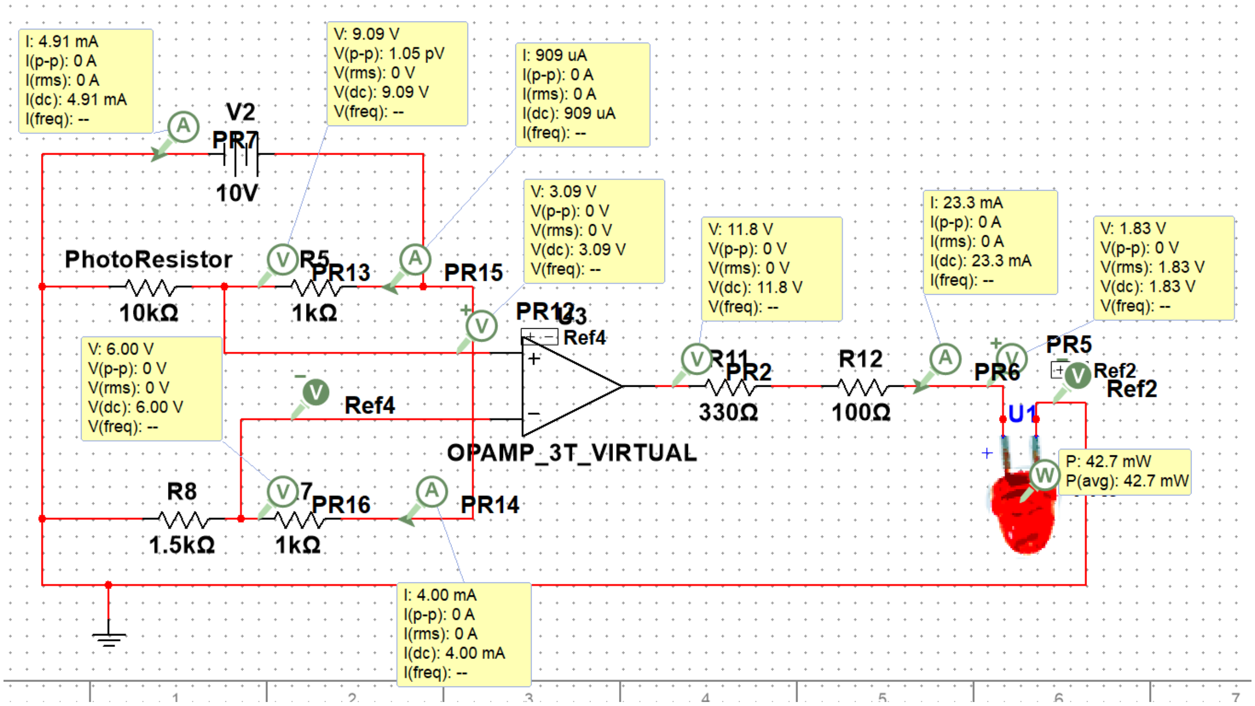
Power	$12.9mA$	$12.91mA$



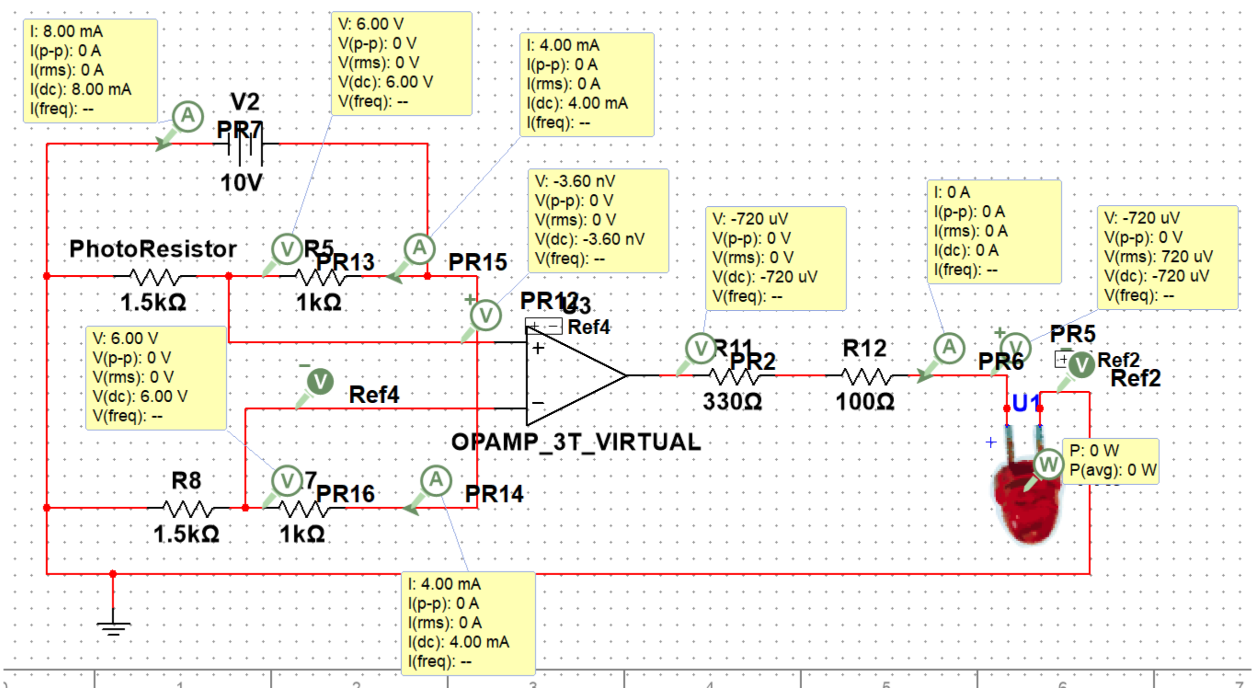
[Figure 3D: Simulation for Op-Amp with resistors from kit, Non-Inverting Summing Amp]

The problem between the calculated values and simulated values is that to my knowledge, I cannot set the Op-Amp's Vcc, so while my Calculation uses $15V$ because this is assumed the Op-Amp is setup to the ELVIS Board's $+15V$ supply. The simulation bases everything on the fact the simulated voltage is $11.8V$. To combat this, in the Lab, I would have disconnected the Op-Amp from the ELVIS supply and used the Virtual Bench instead, matching it to be approximately $12V$.

	Calculated	Simulated
I	$28.3mA$	$23.3mA$
Vout Op Amp	$15V$	$11.8V$
VLED	$2.83V$	$1.86V$
Power (LED)	$80mW$	$42.7mW$



[Figure 3E: Final Op-Amp Circuit with Wheatstone Bridge setup Simulation, LED ON]



[Figure 3E: Final Op-Amp Circuit with Wheatstone Bridge setup Simulation, LED OFF]

IV. Conclusion and Reflection

I believe as an Engineer that my abilities for designing a DC nightlight circuit were efficient enough to transform a Wheatstone Bridge circuit into a DC nightlight by using an Op-Amp. Designing the overall process however, I think my biggest weakness is not fully understanding the inner circuitry behind what exactly goes on within in an Op-Amp. I found myself often doing the hand calculations and simulation at the same time to try and grasp a better understanding of how I could amplify the circuit without frying the LED. Furthermore, one obstacle I fell victim of, was trying to properly identifying what kind of Op-Amp configuration I chose for this particular circuit, since even by combining resistors and breaking the circuit down to it's minimal point, I found that my circuit seems to look the closest like a Non-Inverting Summing Amp, however given that my two resistors at the end only have a wire connected from the negative end of the Op-Amp to the output side after the two resistors in series, which led me to researching more about the theory of Op-Amps and eventually settling on using a Comparator setup, and deriving the remaining part of the circuit by using the logic of the comparator. Since a comparator is based around how the Op-Amp is powered and since we use a fixed Op-Amp in multisim, this could explain any discrepancies within my calculations and simulations, and I probably would have been able to adjust my circuit within the lab by using the ELVIS board and Virtual Bench. Overall, the lab did teach me more about Op-Amps and I will further research the inner circuitry logic to strengthen myself as a design engineer.