ENGR 201 Laboratory Design Project (Individual)

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Contents

1 Introduction

1.1 Design Description

The design is a circuit that uses a photoresistor to measure light intensity as an input and three LEDs as an output. The three LEDs turn on sequentially as light intensity on the photoresistor increase. At the lowest threshold of light intensity the design is capable of measuring (dark environment), all LEDs are turned off. As light intensity increases, the first LED will turn on after a specific threshold. The second and third LEDs will turn on at their own respective thresholds with increasing values as determined by the circuit design. At the highest threshold of light intensity the design is capable of measuring (bright environment), all LEDs are turned on.

From darkest to brightest possible conditions, the resistance of the photoresistor ranges from about $5\,\mathrm{k\Omega}$ to $500\,\Omega$. This range in resistanace is the input parameter for the circuit. The output parameter of the circuit is the number of LEDs that are turned on. Each LED has two discrete states, on or off, and do not illuminate gradually.

1.2 Design Application

This design can be applied in situations in which light intensity at several exact locations need to be quickly measured and compared. The degree to which these light intensity differences can be compared may be increased with the number of LEDs in the design. The scope of light intensity may be adjusted with minor alterations to the design such as resistor values and LED specifications.

2 Circuit Design and Analysis

A circuit schematic of design was constructed using EveryCircuit and is shown in Figure 1.

The circuit analysis explains how the resistor values were calculated when designing the circuit. The goal of the design as well as the LED limitations were considered during this process.

The voltage V_{CC} supplied to the circuit by a power supply is $10\,\mathrm{V}$. The LEDs in the design are blue LEDs that range from $2.8\,\mathrm{V}$ to $3.2\,\mathrm{V}$ with a maximum current of $20\,\mathrm{mA}$. The design uses three LM2904P operational amplifiers to compare the input voltage (as determined by the photoresistor resistance) to three reference voltages.

The node voltage V_p between the photoresistor and $10\,\mathrm{k\Omega}$ resistor is a divided voltage determined by the photoresistor resistance R_p.

$$V_p = V_{CC}\left(\frac{10\,\mathrm{k\Omega}}{R_p + 10\,\mathrm{k\Omega}}\right)$$

In the darkest conditions ($R_p = 5\,\mathrm{k\Omega}$), V_p is about $6.67\,\mathrm{V}$.
In the brightest conditions ($R_p = 500\,\Omega$), V_p is about $9.52\,\mathrm{V}$.

The op-amps divide this input voltage into 4 distinct states, each having a different number of LEDs turned on. The op-amps act as comparators by taking three different reference voltage thresholds in the negative terminals. Based on the range of V_p, the reference voltage thresholds V_{n1}, V_{n2}, and V_{n3} were chosen to be $9\,\mathrm{V}$, $8\,\mathrm{V}$, and $7\,\mathrm{V}$ respectively. A voltage ladder uses V_{CC} and resistors to supply these reference voltages to the negative terminals of the three op-amps.

$$V_{n1} = 10\,\mathrm{V}\left(\frac{220\,\Omega + 220\,\Omega + 1540\,\Omega}{220\,\Omega + 220\,\Omega + 220\,\Omega + 1540\,\Omega}\right) = 9\,\mathrm{V}$$

$$V_{n2} = 10\,\mathrm{V}\left(\frac{220\,\Omega + 1540\,\Omega}{220\,\Omega + 220\,\Omega + 220\,\Omega + 1540\,\Omega}\right) = 8\,\mathrm{V}$$

$$V_{n3} = 10\,\mathrm{V}\left(\frac{1540\,\Omega}{220\,\Omega + 220\,\Omega + 220\,\Omega + 1540\,\Omega}\right) = 7\,\mathrm{V}$$

The circuit as described thus far turns the op-amp output voltages one-by-one from top to bottom as light intensity on the photoresistor increases. When $V_p > V_n$, there is a positive voltage drop across the terminals, causing an output voltage V_o. The output voltage of an op-amp cannot be greater than the input voltage supplied to the system. A maximum output voltage of $10\,\mathrm{V}$ is assigned to V_o in order to avoid underestimating the output current and potentially exceeding the

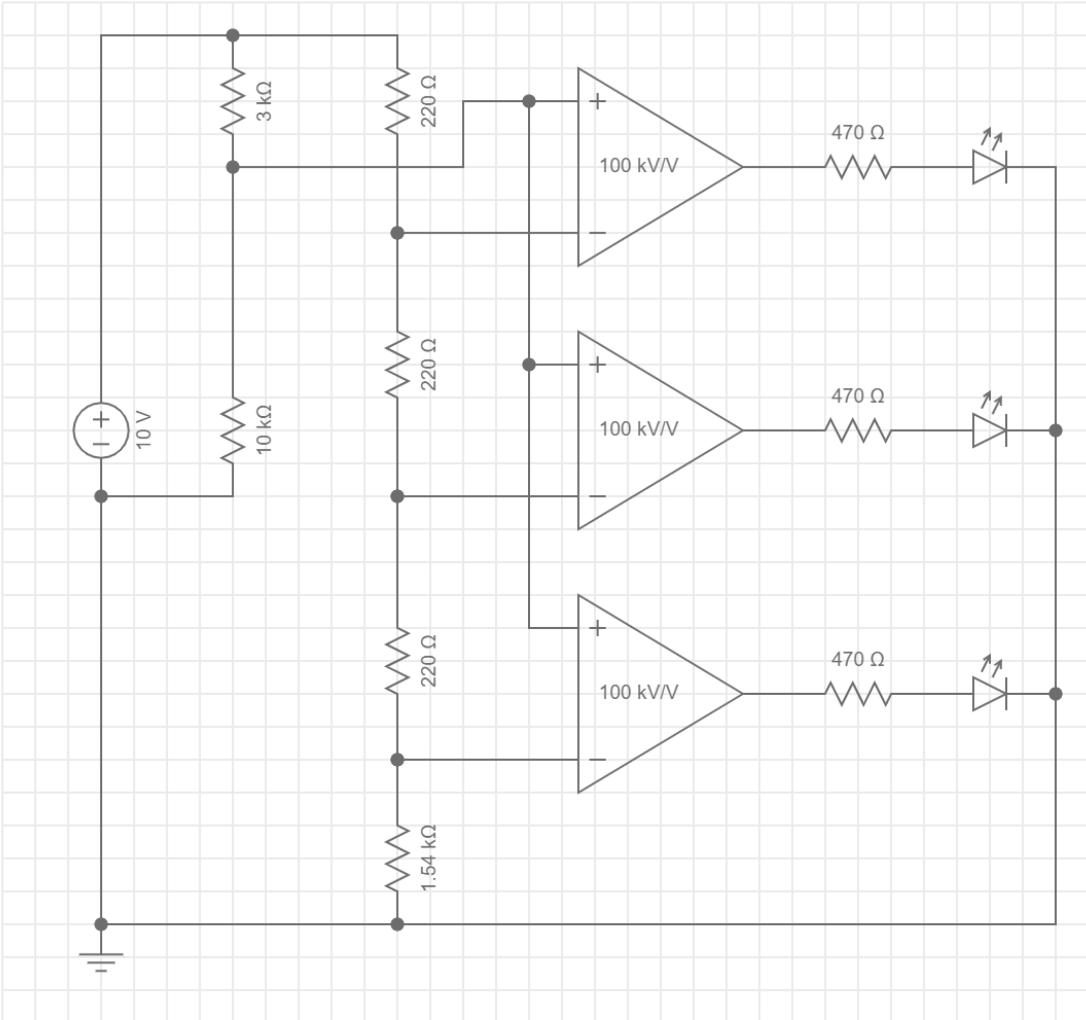

Figure 1: Circuit Schematic using EveryCircuit

LED's maximum current. This upper estimate does not have a significant impact on the accuracy of the design because the op-amps and LEDs only have two discrete states. When $V_p < V_n$, there is a negative voltage drop across the terminals, causing an output voltage V_o of 0 V.

About 3 V goes across the LED, so the series resistor R_s must have 7 V going across and limit the current to 15 mA to reduce the risk of exceeding the LED's maximum current of 20 mA. Ohm's Law determines the value of the series resistors.

$$R_s = \frac{7\,\mathrm{V}}{15\,\mathrm{mA}} = 467\,\Omega$$

This resistance was rounded up to 470 Ω in the implementation of the circuit.

3 Power Analysis

The power analysis calculates the remaining element currents and the power dissipated by each passive element. To simplify this analysis, the op-amps are assumed to be ideal with zero current flowing through the positive and negative terminals and an output voltage of 10 V matching the power supply when $V_p > V_n$.

The current i_1 flowing through the photoresistor and the 10 kΩ resistor can be found using their equivalent series resistance since there is no current flowing into the positive terminals of the ideal op-amps.

$$i_1 = \frac{10\,\mathrm{V}}{R_p + 10\,\mathrm{k\Omega}}$$

In the darkest conditions ($R_p = 5\,\mathrm{k\Omega}$), i_1 is about $0.667\,\mathrm{mA}$. The power P_p and $P_{10\,\mathrm{k\Omega}}$ dissipated by the photoresistor and the $10\,\mathrm{k\Omega}$ resistor is:

$$P_p = (i_1)^2 R_p = 2.22\,\mathrm{mW}$$

$$P_{10\,\mathrm{k\Omega}} = (i_1)^2 10\,\mathrm{k\Omega} = 4.44\,\mathrm{mW}$$

In the brightest conditions ($R_p = 500\,\Omega$), i_1 is about $0.952\,\mathrm{mW}$.

$$P_p = (i_1)^2 R_p = 0.453\,\mathrm{mW}$$

$$P_{10\,\mathrm{k\Omega}} = (i_1)^2 10\,\mathrm{k\Omega} = 9.06\,\mathrm{mW}$$

The current i_2 flowing through the voltage ladder can be found using their equivalent series resistance since there is no current flowing into the negative terminals of the ieal op-amps.

$$i_2 = \frac{10\,\mathrm{V}}{220\,\Omega + 220\,\Omega + 220\,\Omega + 1540\,\Omega} = 4.55\,\mathrm{mA}$$

The power $P_{220\,\Omega}$ and $P_{1540\,\Omega}$ dissipated by the resistors in the voltage ladder is:

$$P_{220\,\Omega} = (i_2)^2 220\,\Omega = 4.55\,\mathrm{mW}$$

$$P_{1540\,\Omega} = (i_2)^2 1540\,\Omega = 31.9\,\mathrm{mW}$$

The currents i_3, i_4, and i_5 flowing through each of the $470\,\Omega$ resistors when its respective op-amp is on are calculated under the assumption that the voltage across the resistor is $7\,\mathrm{V}$ as explained in the circuit analysis.

$$i_3 = i_4 = i_5 = \frac{7\,\mathrm{V}}{470\,\Omega} = 14.9\,\mathrm{mA}$$

The power $P_{470\,\Omega}$ dissipated by each of the $470\,\Omega$ resistors is:

$$P_{470\,\Omega} = (i_3)^2 470\,\Omega = 104\,\mathrm{mW}$$

The power P_{LED} dissipated by the LED when its respective op-amp is on is:

$$P_{LED} = i_3 3\,\mathrm{V} = 44.7\,\mathrm{mW}$$

A typical $9\,\mathrm{V}$ battery stores $600\,\mathrm{mAh}$ and has an energy capacity of $19.440\,\mathrm{kJ}$.[1] This design requires a $10\,\mathrm{V}$ supply, so this power analysis assumes that a theoretical $10\,\mathrm{V}$ battery with an energy capacity of $20.0\,\mathrm{kJ}$ is used to power the circuit.

In the darkest conditions, all three op-amps are off and the circuit would dissipate the least amount of power. The power P_{min} dissipated by the circuit would be:

$$P_{min} = P_p + P_{10\,\mathrm{k\Omega}} + 3P_{220\,\Omega} + P_{1540\,\Omega} = 52.2\,\mathrm{mW}$$

On the theoretical battery, the circuit in the darkest conditions would operate for the longest possible time t_{max}.

$$t_{max} = \frac{20.0\,\mathrm{kJ}}{52.2\,\mathrm{mW}} = 383\,068\,\mathrm{s} = 106\,\mathrm{h}$$

In the brightest conditions, all three op-amps are on and the circuit would dissipate the most amount of power. The power P_{max} dissipated by the circuit would be:

$$P_{max} = P_p + P_{10\,\mathrm{k\Omega}} + 3P_{220\,\Omega} + P_{1540\,\Omega} = 52.2\,\mathrm{mW} + 3P_{470\,\Omega} + 3P_{LED} = 501\,\mathrm{mW}$$

On the theoretical battery, the circuit in the brightest conditions would operate for the shortest possible time t_{min}.

$$t_{min} = \frac{20.0\,\mathrm{kJ}}{501\,\mathrm{mW}} = 39\,907\,\mathrm{s} = 11.1\,\mathrm{h}$$

[1] https://www.baldengineer.com/9v-battery-energy-density.html

4 Experimental Characterization

The design was constructed and simulated using EveryCircuit. The upper-left-most resistor represents the photoresistor, which ranges from 5 kΩ (darkest conditions) and 500 Ω (brightest conditions) and allows the circuit to operate in 4 discrete states, each with a different number of LEDs on indicating the light intensity on the photoresistor. The circuit was simulated with the photoresistor set to 5 kΩ, 3.5 kΩ, 2 kΩ, and 500 Ω to demonstrate the design at increasing levels of light intensity.

Figures 2, 3, 4, and 5 are the circuit simulations and show that the design functions as intended.

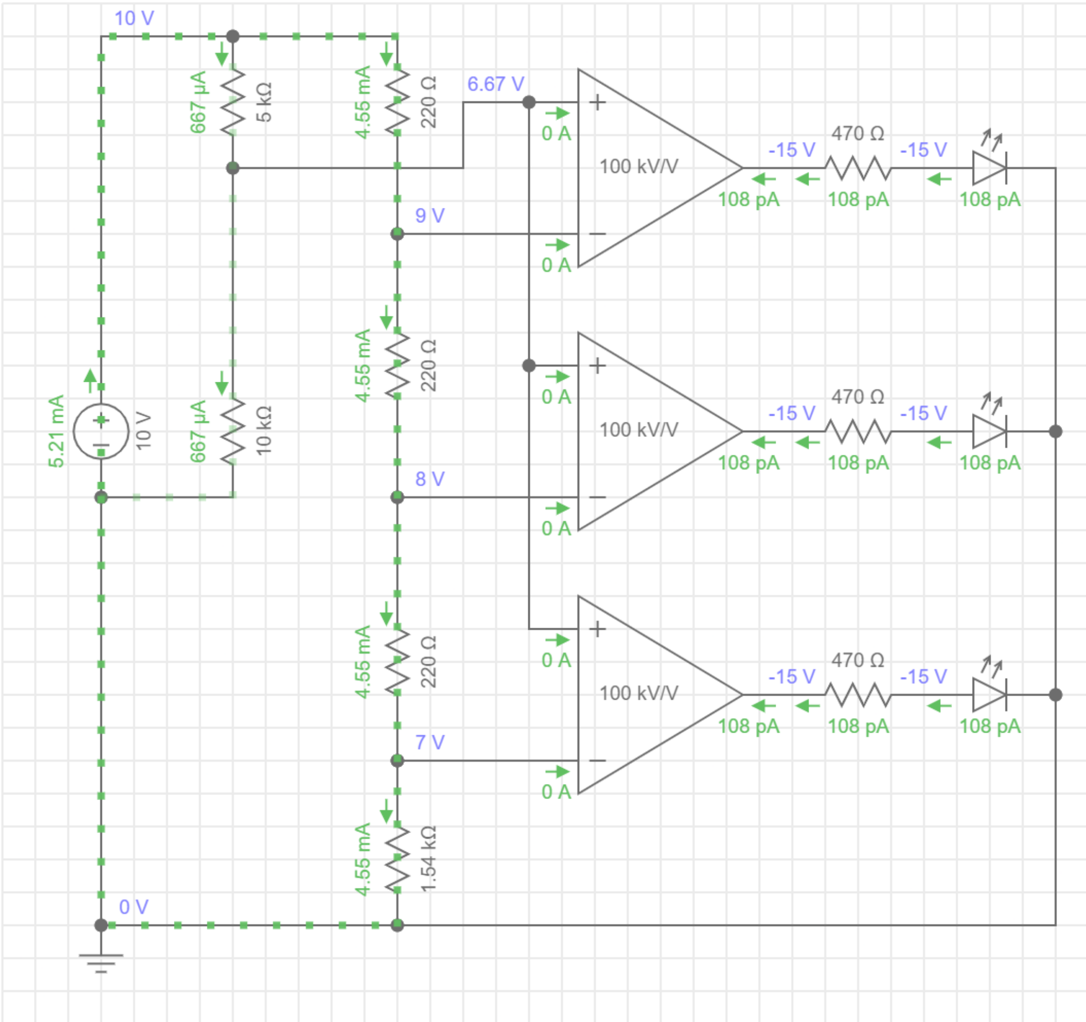

Figure 2: Circuit Simulation for darkest conditions

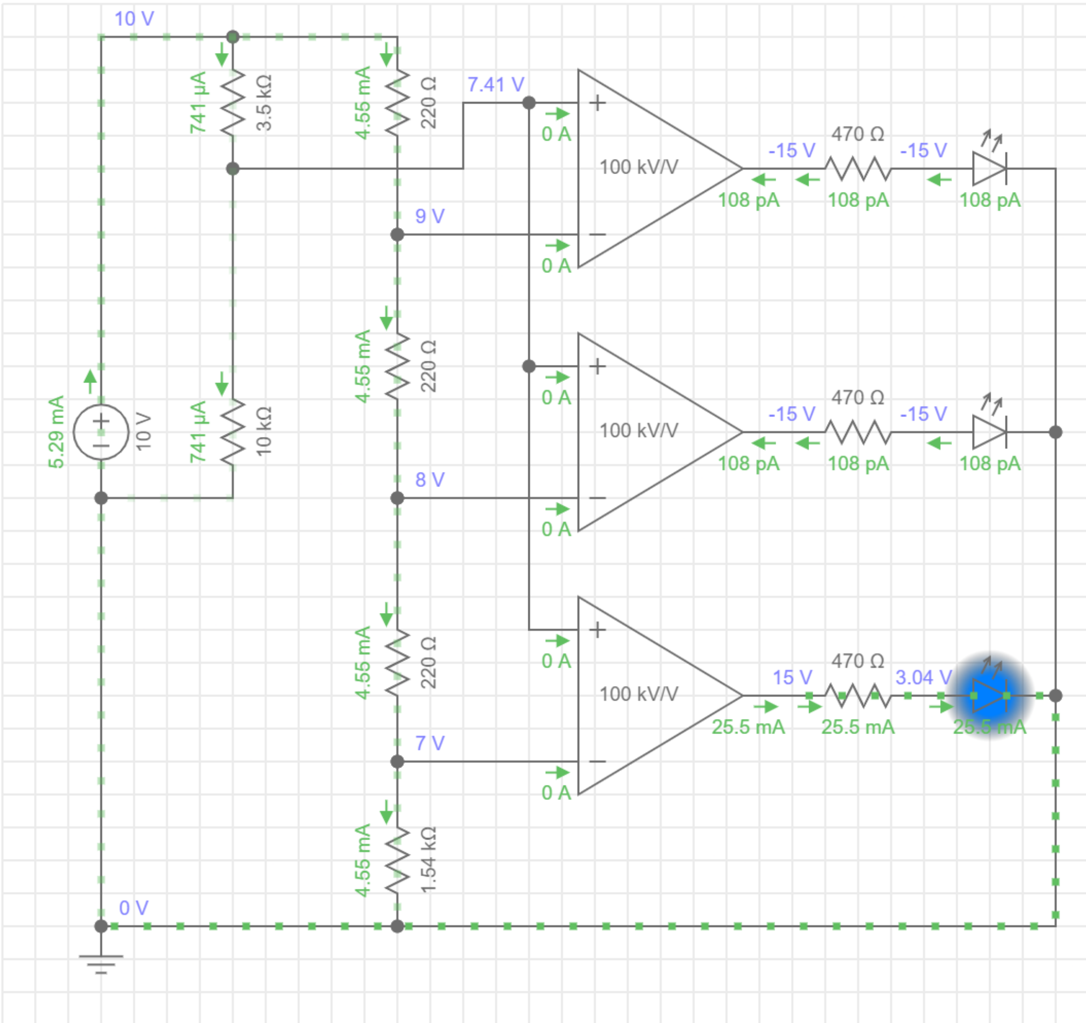

Figure 3: Circuit Simulation for low light intensity

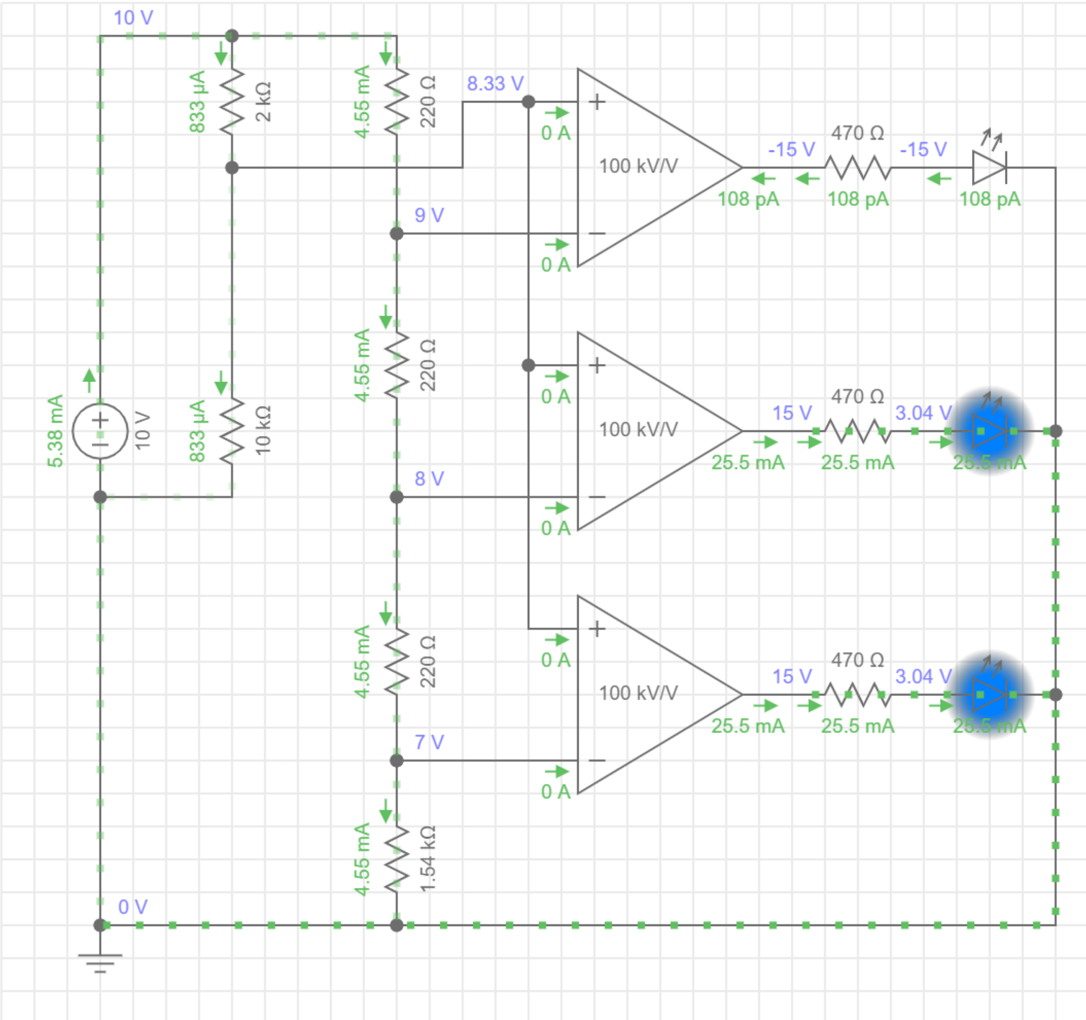

Figure 4: Circuit Simulation for medium light intensity

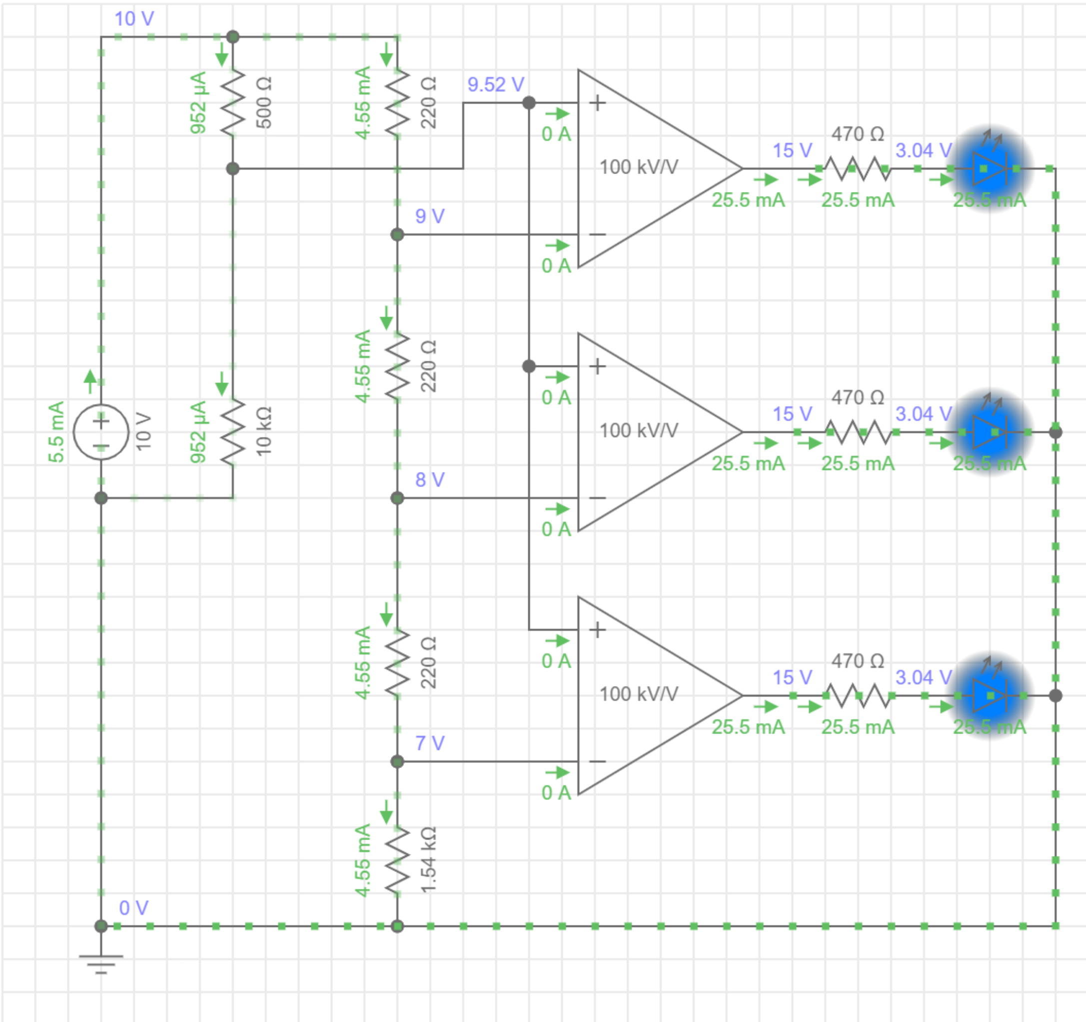

Figure 5: Circuit Simulation for brightest conditions

Figure 6 is the physical implementation of the design. The following YouTube link is a video demonstration of the physical implementation.

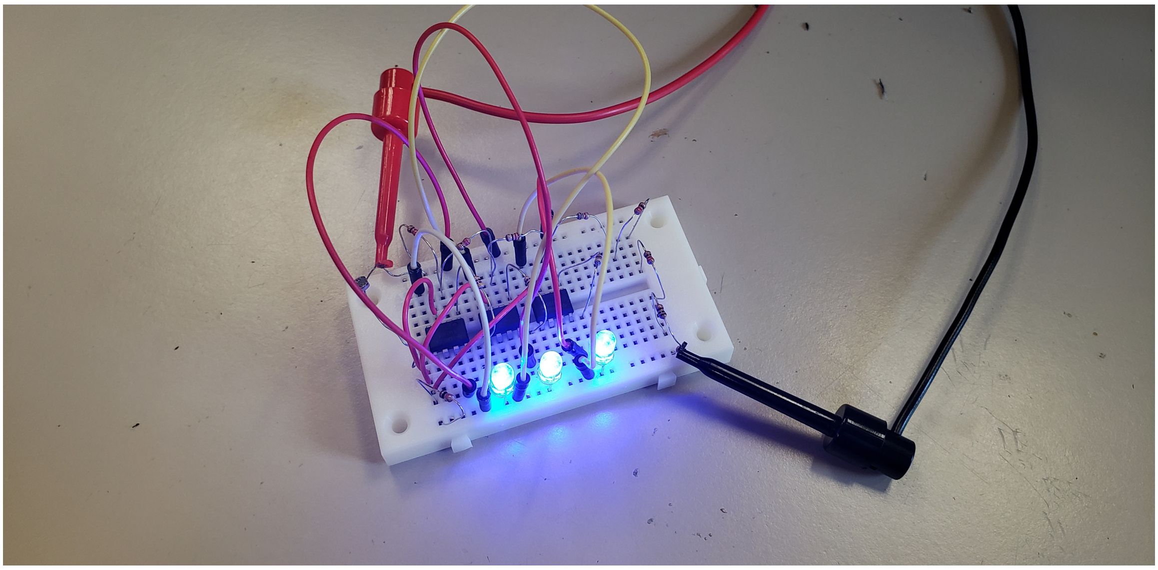

Figure 6: Design Implementation

https://youtu.be/Qji5QQdTQwg

5 Conclusion

The design could be improved by using a photoresistor with a greater range of resistance values for a greater range of light intensities. A greater range of resistance values would cause a greater range in voltages going into the positive terminal of the op-amps. This would allow the design to accurately measure light intensity in darker and brighter conditions than originally possible.

More LEDs with could be added to the design so that locations with smaller differences in light intensity can be compared to each other. This would be implemented by adding more rows of op-amps in parallel with different references voltages as determined by additional voltage ladder nodes. An increase in the voltage supply would be unnecessary as long as the op-amps are precise enough to work with a expanded range of reference voltages.