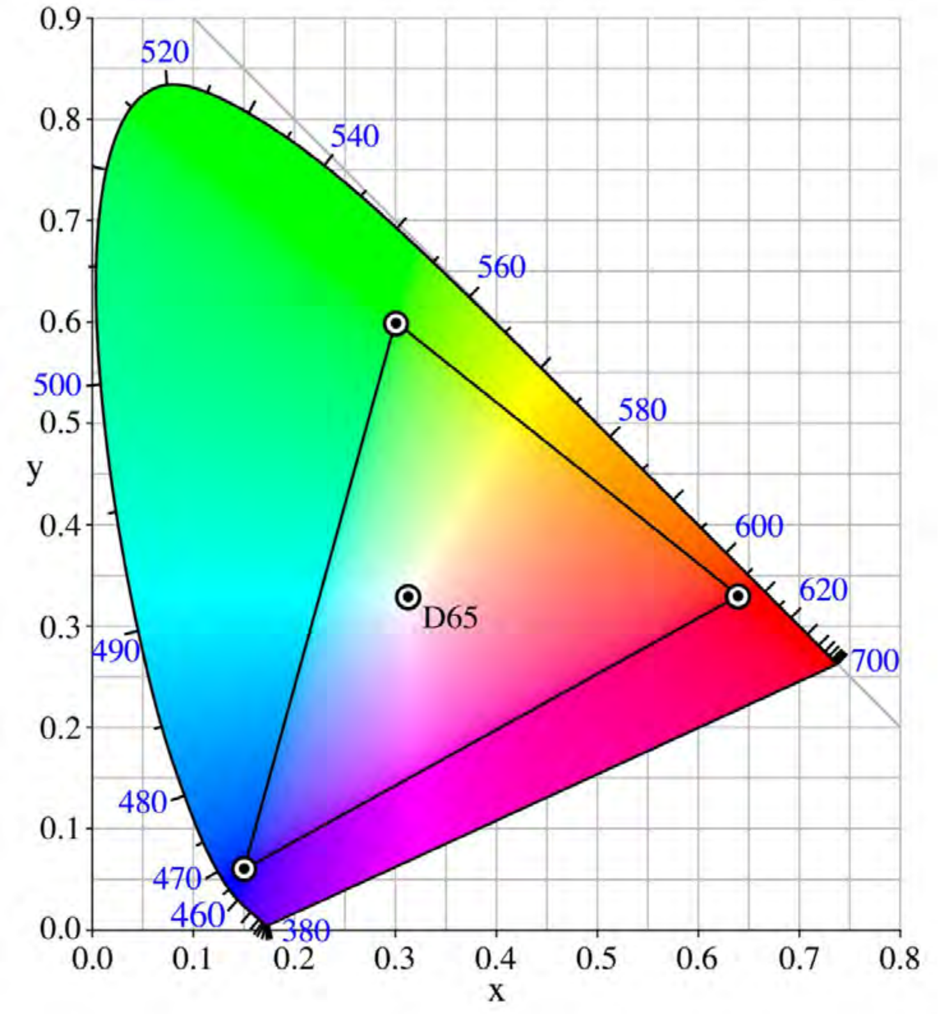
On the Limitations of Color Reproduction

Group 1

Siravid Chit-Arkhah, Rishi Mishra, Dominic Petruzzi, Colby Suppiger, Raymond Venneberg

Introduction

- Human eyes have three types of cone cells, each sensitive to their own range of wavelengths.
- When multiple wavelengths stimulate these cone cells, the brain blends them into a new color.
- It is possible to create the same color given two different combinations of light.
- Goals:
  - Explore this phenomenon and produce a color outside of the sRGB color space.
  - Utilize software to simulate and predict behavior of the human eye responses to different light combinations.



Initial Approach

We wanted to:

- Create an algorithm that took a desired wavelength as input and outputted LED intensities
- Create a device to measure our results
- Hook up a way to manipulate the brightness of our LEDs

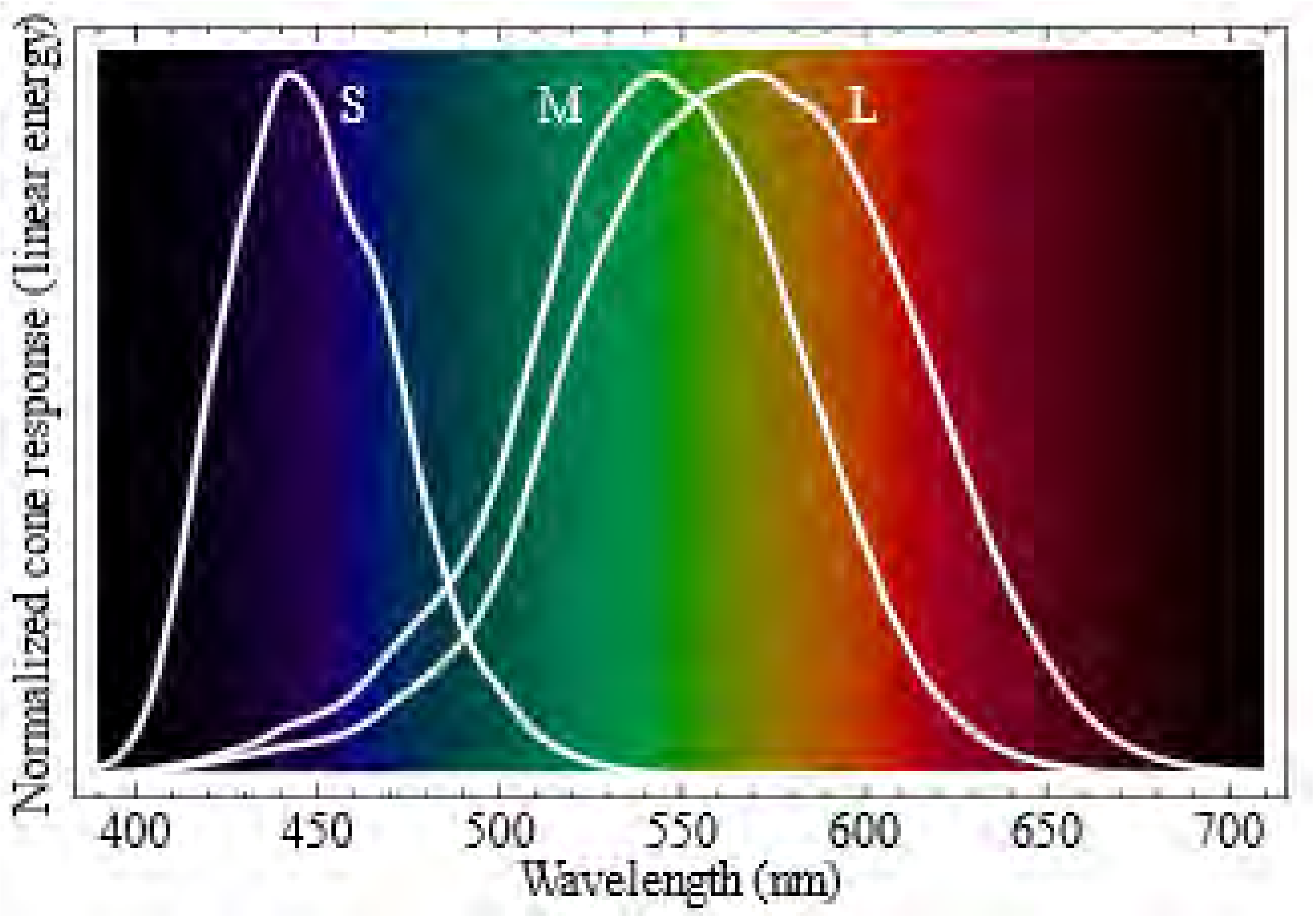
BACKGROUND

Definitions

- Color – The subjective experience that results from changing the responses of cone cells in a human eye.
- Color space – A specific organization of colors for the reproduction of color representations.
- Metamerism – The phenomenon of the same color arising from different spectral distributions.
- Metamers – The different spectral distributions giving the same color.

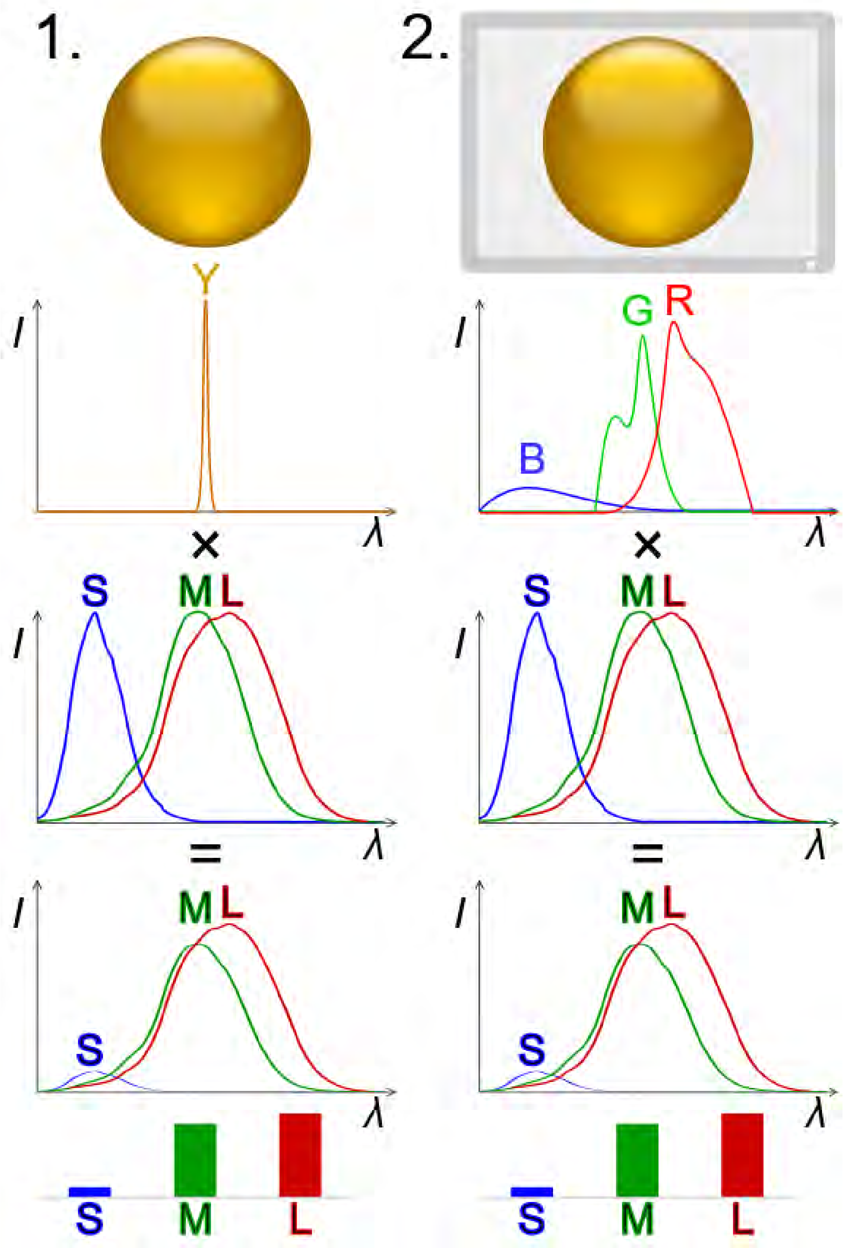
Human Color Perception

- Cones
  - 3 responses
  - Large overlap
- Rods
- Trichromatism



Color Metamerism

- Using 1 spectrum vs. 2+ spectra to make the same color –>
- Metamers are the sets of two or more spectra that create the same color.



Hue, Chroma, and Luminance

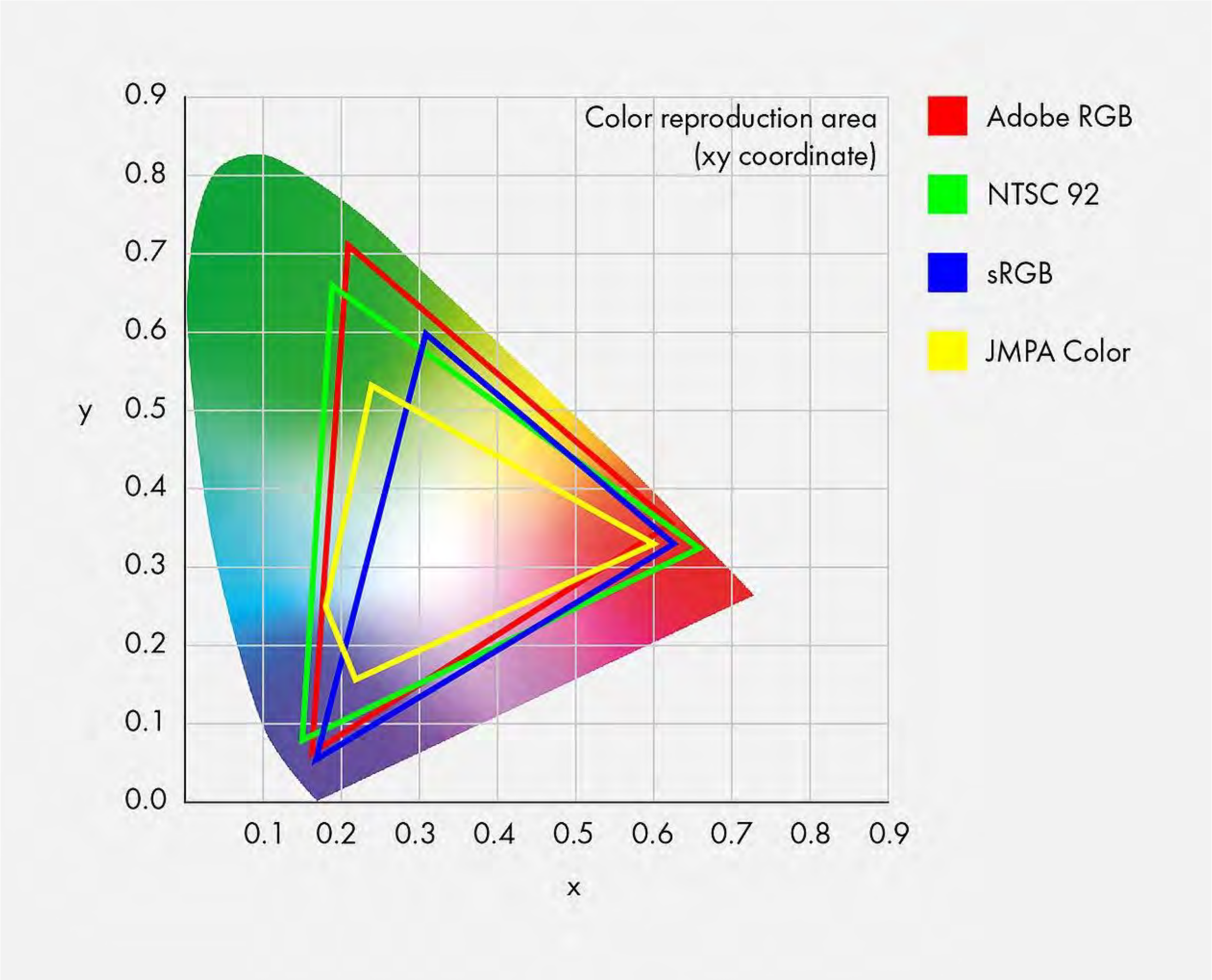
- Hue – Red, Orange, Blue, et cetera.

- Chroma – Difference from a white or gray of the same brightness.
  - Colorfulness, Saturation, and Excitation Purity

- Luminance – How bright something is.

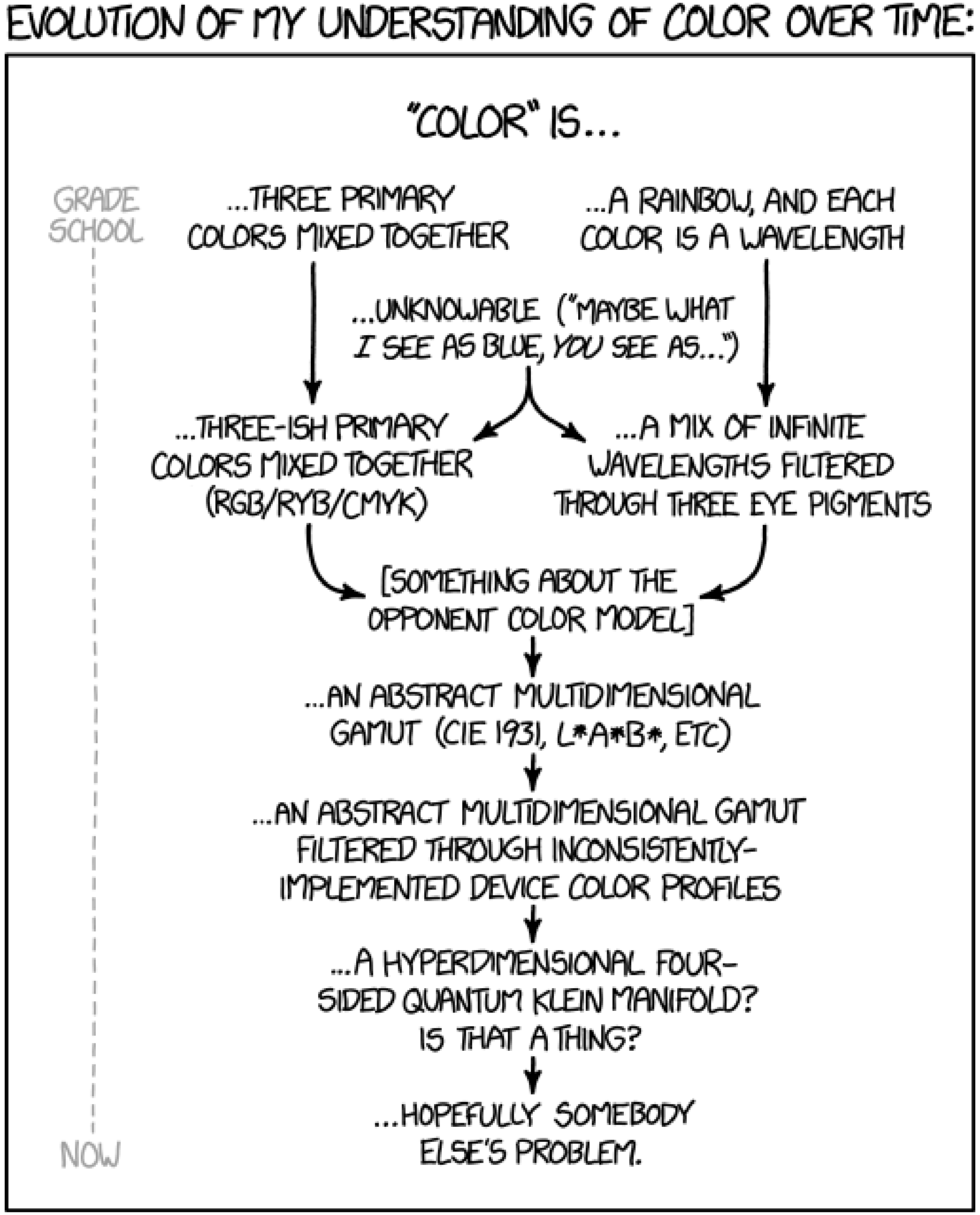
Color Spaces

- These are specific organizations of colors for the reproduction of color representations.
- Many are available and each exists for a purpose.



Color is **HARD**

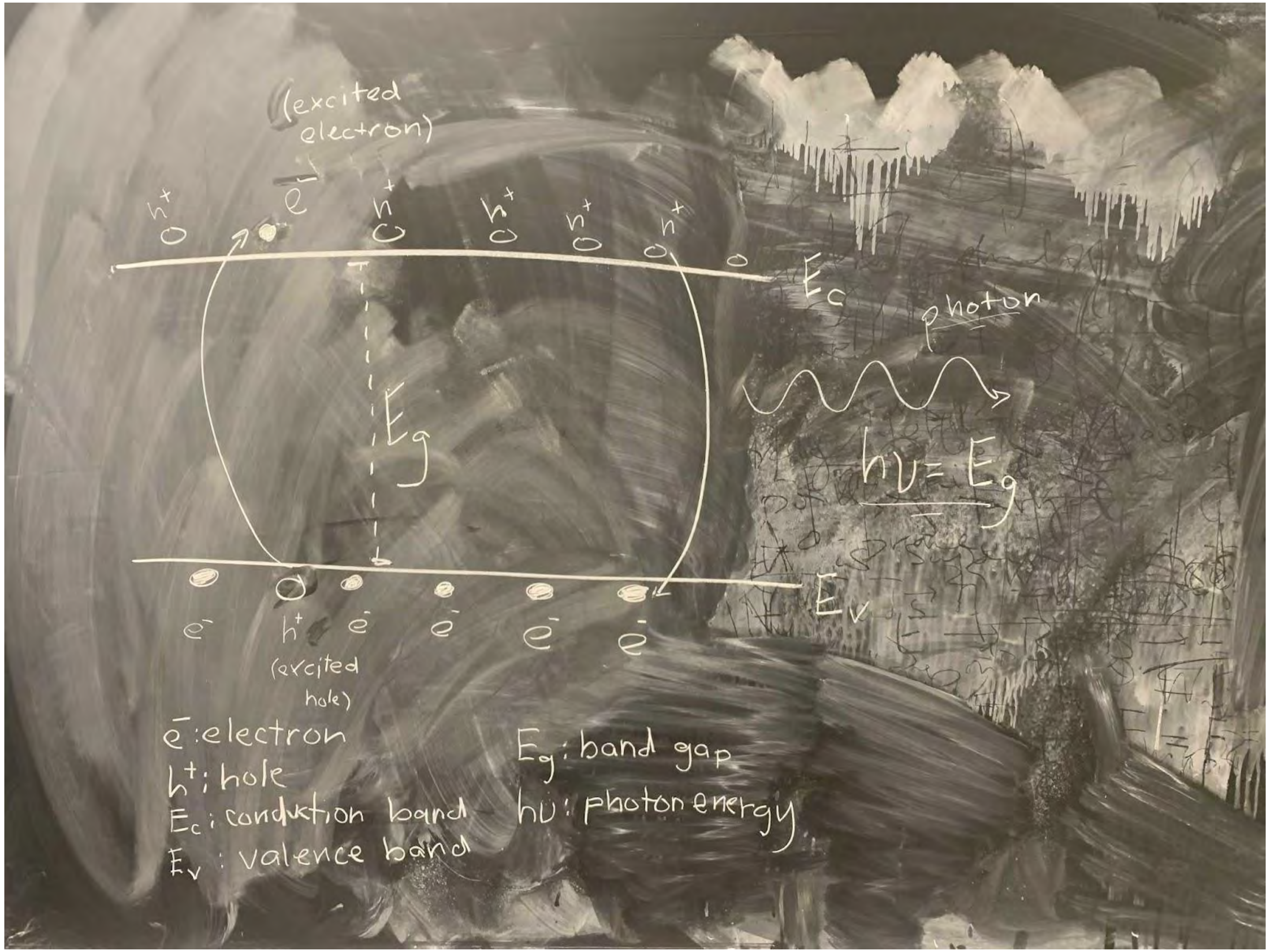
- There are MANY definitions.
- Our definition:
  - Qualia resulting from cone excitations.



HARDWARE

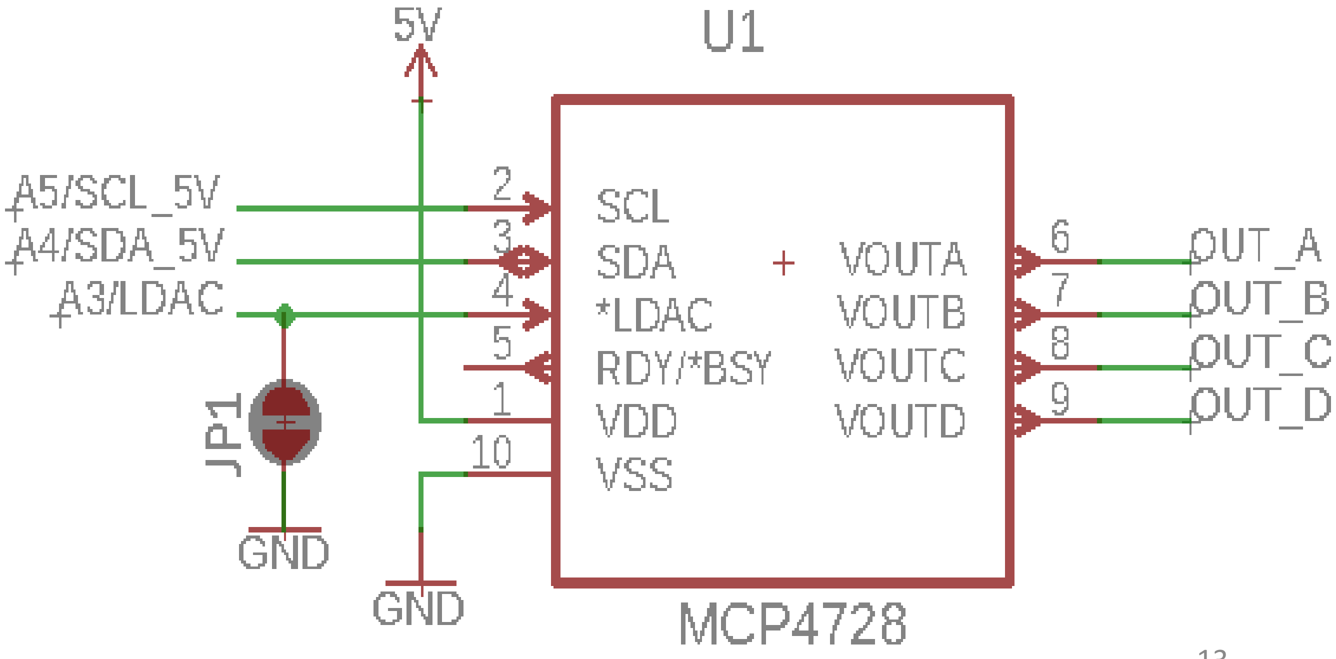
Light Emitting Diodes (LEDs)

- What are diodes?
- Conduction bands & valence bands
    - •Band gap –> photon energy
- Colors:
    - Red, Green, Blue
    - Yellow
    - Violet (not used)
- LEDs emit a spectrum of wavelengths.
- Determined wavelengths using the AS7262 color sensor.
- "built-in electric field"



MCP4728 DAC

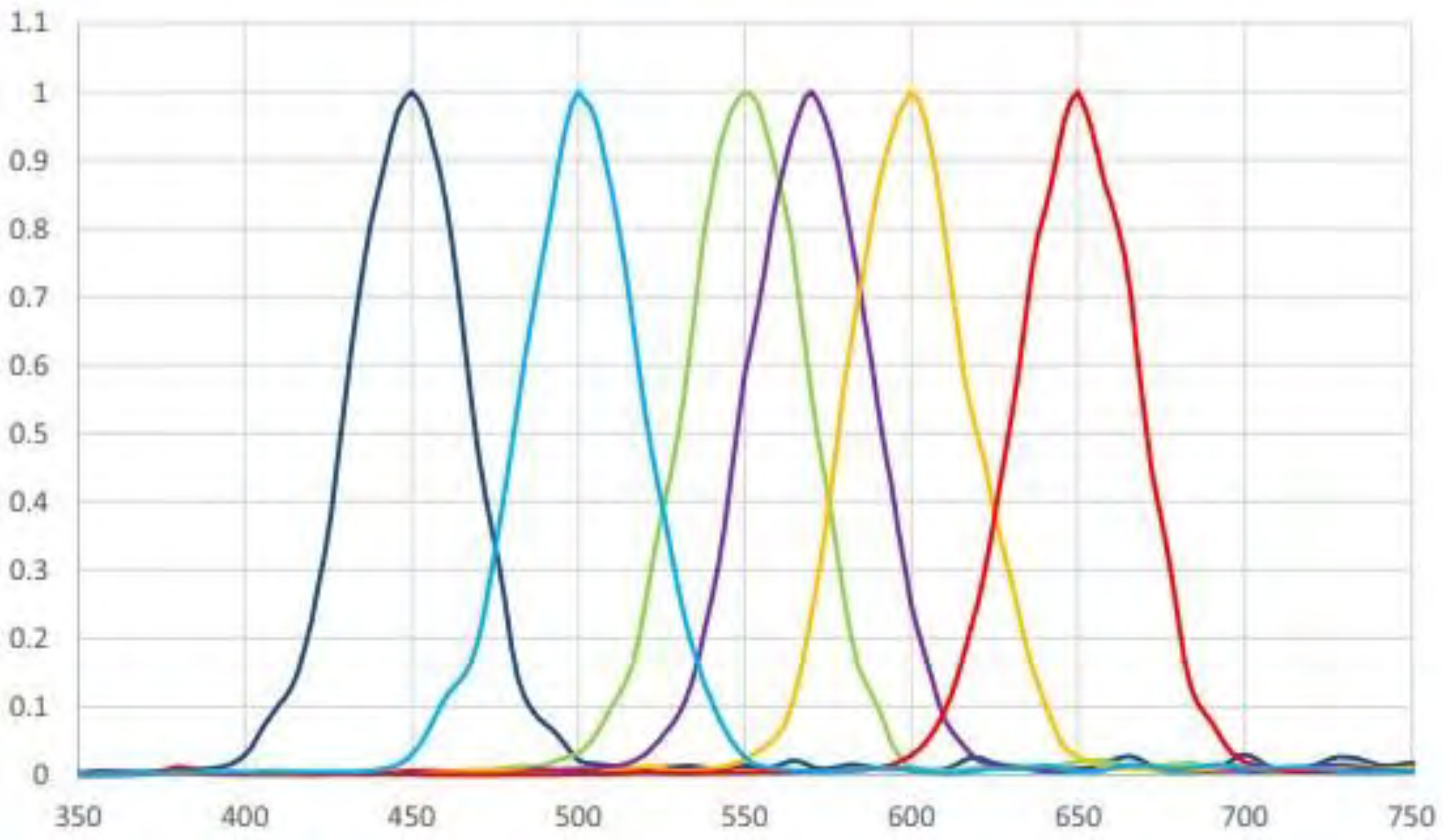
- 4 channels
  - •Each outputs 0 –> 5V
- Easy to set the voltages across each channel.
  - •Could vary voltage using Arduino IDE.
  - •Could vary voltage using potentiometers.
  - •Granularity: 2^{12}



AS7262 Spectral Sensor

- Contains six channels that each sense intensity at different wavelengths.
- Detects light using silicon interference filters.
  - Thin layers of silicon that have different indices of refraction.
  - Causes unwanted light to destructively interfere leaving only the light within the target wavelength.
- Granularity: 2^{16}

Spectral Sensor Responses

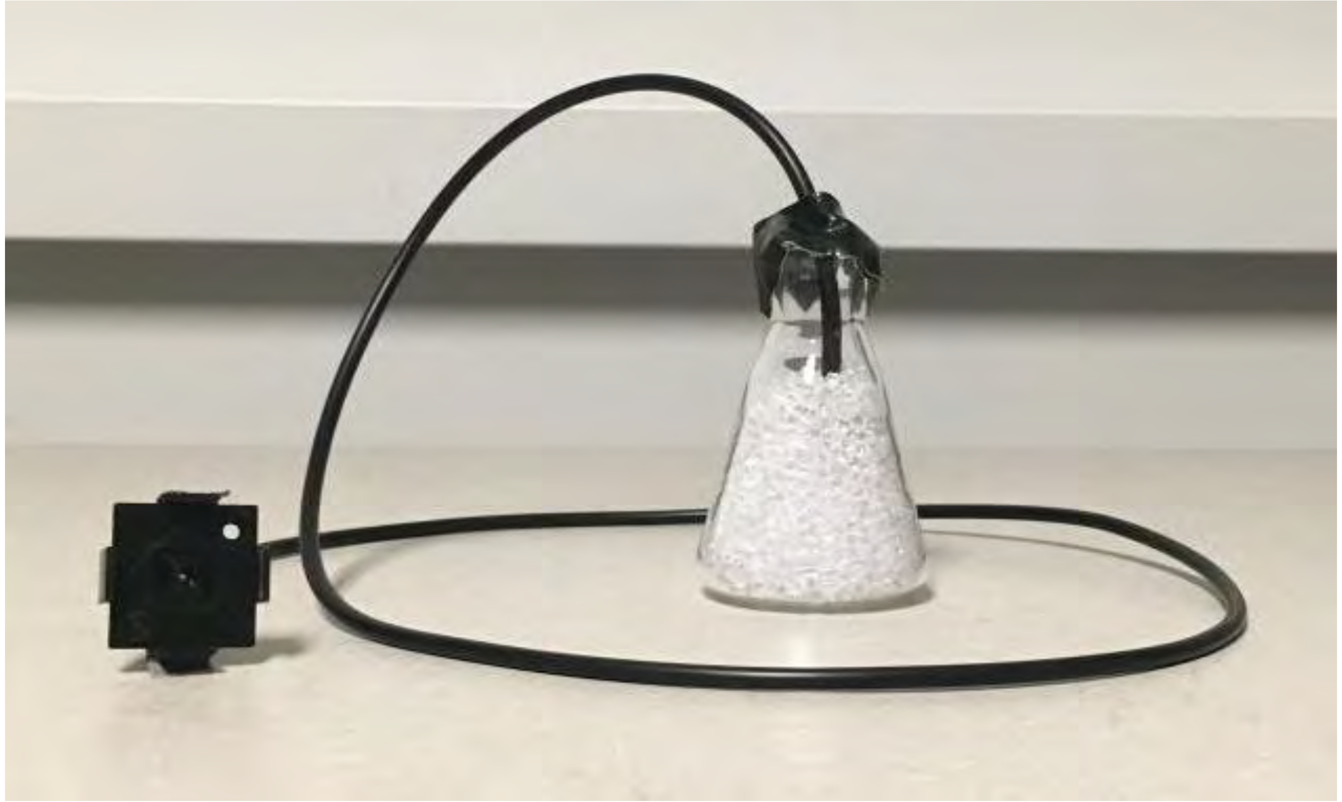


Transistors

- NPN BJT
  - Components:
    - Collector
    - Base
    - Emitter
  - The current output of the emitter is the sum of the current in the base and collector.
- Pulling current
  - Used to amplify current.
  - Used to vary the current going through LEDs.

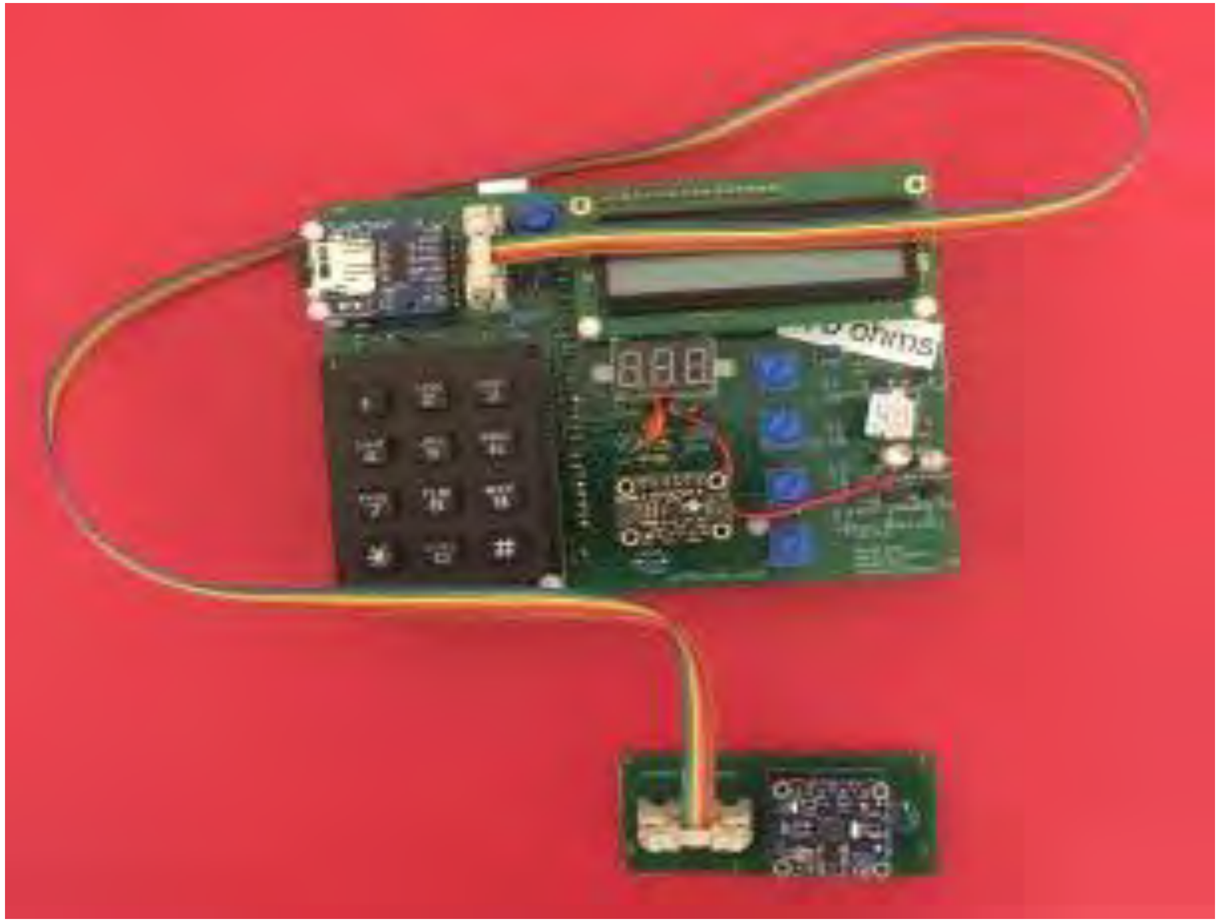
Fiber-Optic Cable & Diffuser

- Container:
  - Erlenmeyer flask
- Contained:
  - Many plastic beads to refract light
  - One end of the cable
- Tape to hold the cable in place
- 3D printed colorimeter end
- Total internal reflection

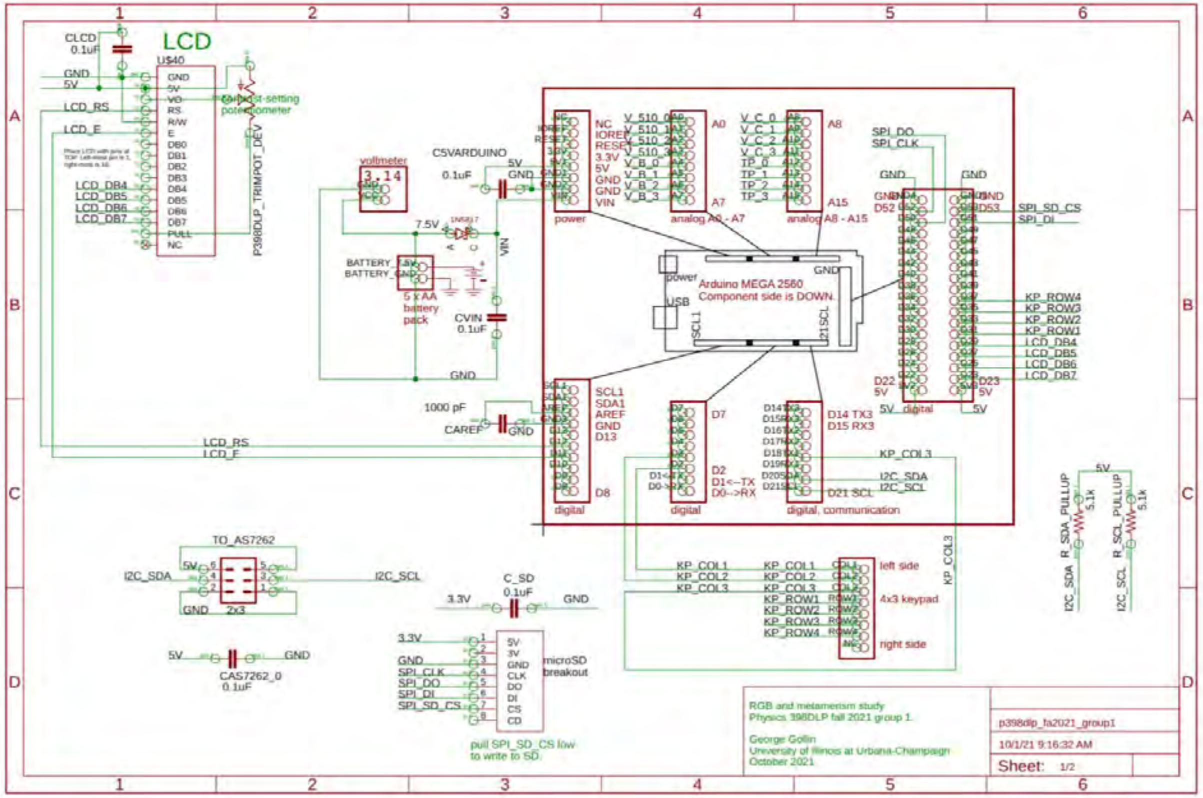


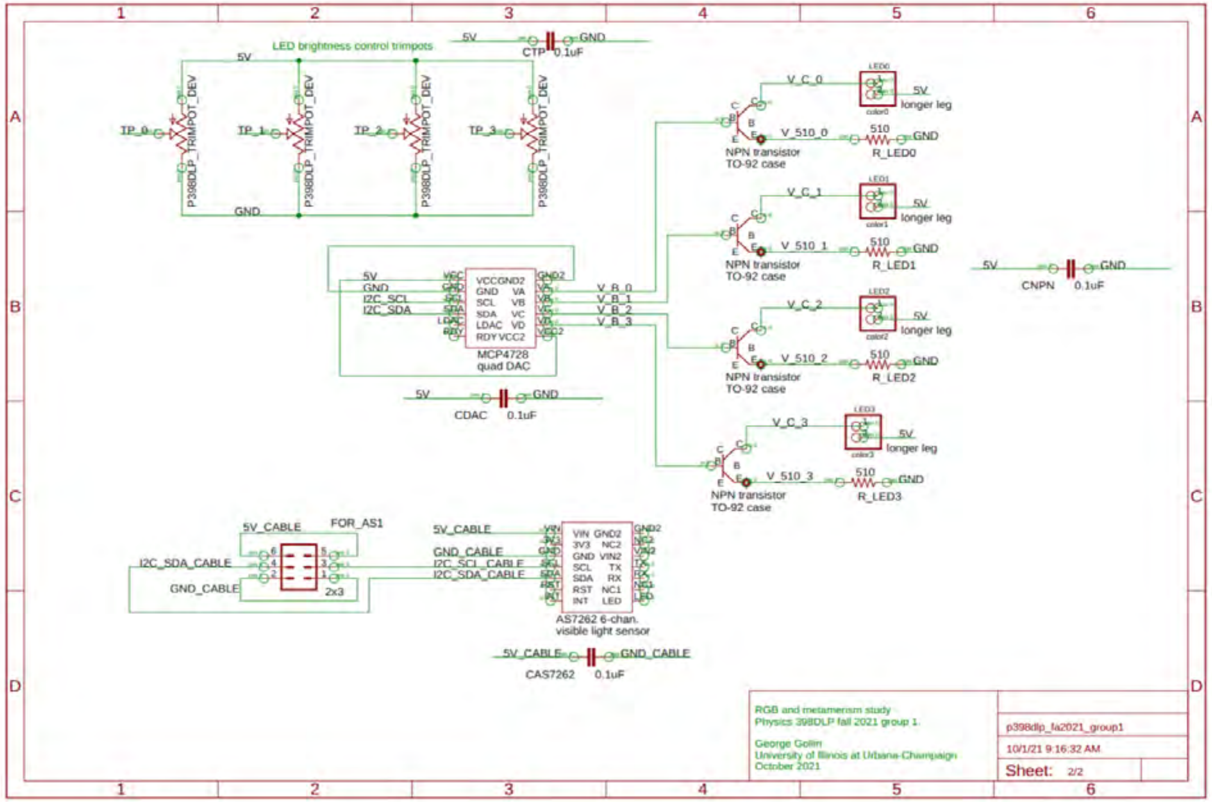
Other Hardware Used

- Arduino
- LCD
- Potentiometers (trimpots)
- Resistors
- Capacitors
- Batteries



PCB Schematics





Software

Arduino:

- Collected data from colorimeter.
- Adjusted DAC output from trimpots or manual code input.

Processing (Python):

- Spectra –> cone responses
- Cone Responses –> LED intensities
- LED intensities –> DAC output

Procedures

- Metamer determination
- Determining LED spectra and peak intensities
- Data collection
- Data processing

Getting Cone Responses

	A	B	C	D
1	Wavelength (nm)	Long Cone Response	Medium Cone Response	Short Cone Response
2	391	5.03E-04	4.48E-04	1.15E-02
3	430	2.82E-02	3.95E-02	8.03E-01
4	480	1.40E-01	2.36E-01	3.90E-01
5	530	7.71E-01	9.36E-01	1.26E-02
6	580	9.69E-01	6.53E-01	1.09E-04
7	630	4.01E-01	6.21E-02	0
8	680	2.54E-02	1.64E-03	0
9	730	6.39E-04	4.16E-05	0
10	780	2.07E-05	1.63E-06	0
11	830	9.74E-07	9.53E-08	0

- Collecting this data would be out of the scope for this class, so we:
  - Pulled the data from the Internet.

Converting Cone Responses into Intensity Values

We needed to:

- Convert cone response matrix into XYZ color space for each LED and desired wavelength.
- Convert XYZ color matrices into RGB values.
- Set up linear system and solve for intensity coefficients.
- Normalize intensity matrix.

$$\Gamma_{cr} = \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

$$T_{LMS->XYZ} = \begin{bmatrix} 1.91 & -1.11 & 0.201 \\ 0.371 & 0.629 & 0 \\ 0 & 0 & 1.0 \end{bmatrix} \quad T_{XYZ->RGB} = \begin{bmatrix} 0.418 & -0.159 & -0.0828 \\ -0.0912 & 0.252 & 0.0157 \\ 0.000921 & -0.00255 & 0.179 \end{bmatrix}$$

$$\Gamma_{RGB} = T_{XYZ->RGB} \times T_{LMS->XYZ} \times \Gamma_{cr}$$

$$\Gamma_{RGB_\lambda} = \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix} \Gamma_{RGB_{rLED}} = \begin{bmatrix} R_{rLED} \\ G_{rLED} \\ B_{rLED} \end{bmatrix} \Gamma_{RGB_{gLED}} = \begin{bmatrix} R_{gLED} \\ G_{gLED} \\ B_{gLED} \end{bmatrix} \Gamma_{RGB_{bLED}} = \begin{bmatrix} R_{bLED} \\ G_{bLED} \\ B_{bLED} \end{bmatrix}$$

$$\begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix} = I_r \begin{bmatrix} R_{rLED} \\ G_{rLED} \\ B_{rLED} \end{bmatrix} + I_g \begin{bmatrix} R_{gLED} \\ G_{gLED} \\ B_{gLED} \end{bmatrix} + I_b \begin{bmatrix} R_{bLED} \\ G_{bLED} \\ B_{bLED} \end{bmatrix}$$

$$I = \begin{bmatrix} I_r \\ I_g \\ I_b \end{bmatrix}$$

$$I = \begin{bmatrix} 0.5 \\ 0.333 \\ 1 \end{bmatrix}$$

–> Red LED intensity

–> Green LED intensity

–> Blue LED intensity

Determining Metamers

- By hand – compare and adjust
- Algorithmically:
  - Spectra –> cone responses
  - Cone Responses –> LED intensities
  - LED intensities –> DAC output

$$P = \frac{V_{DAC} - 0.7}{Resistance} * Bandgap$$

$$V_{DAC} = \frac{Resistance * P}{Bandgap} + 0.7$$

$$photon\ count\ per\ second = \frac{power}{bandgap}$$

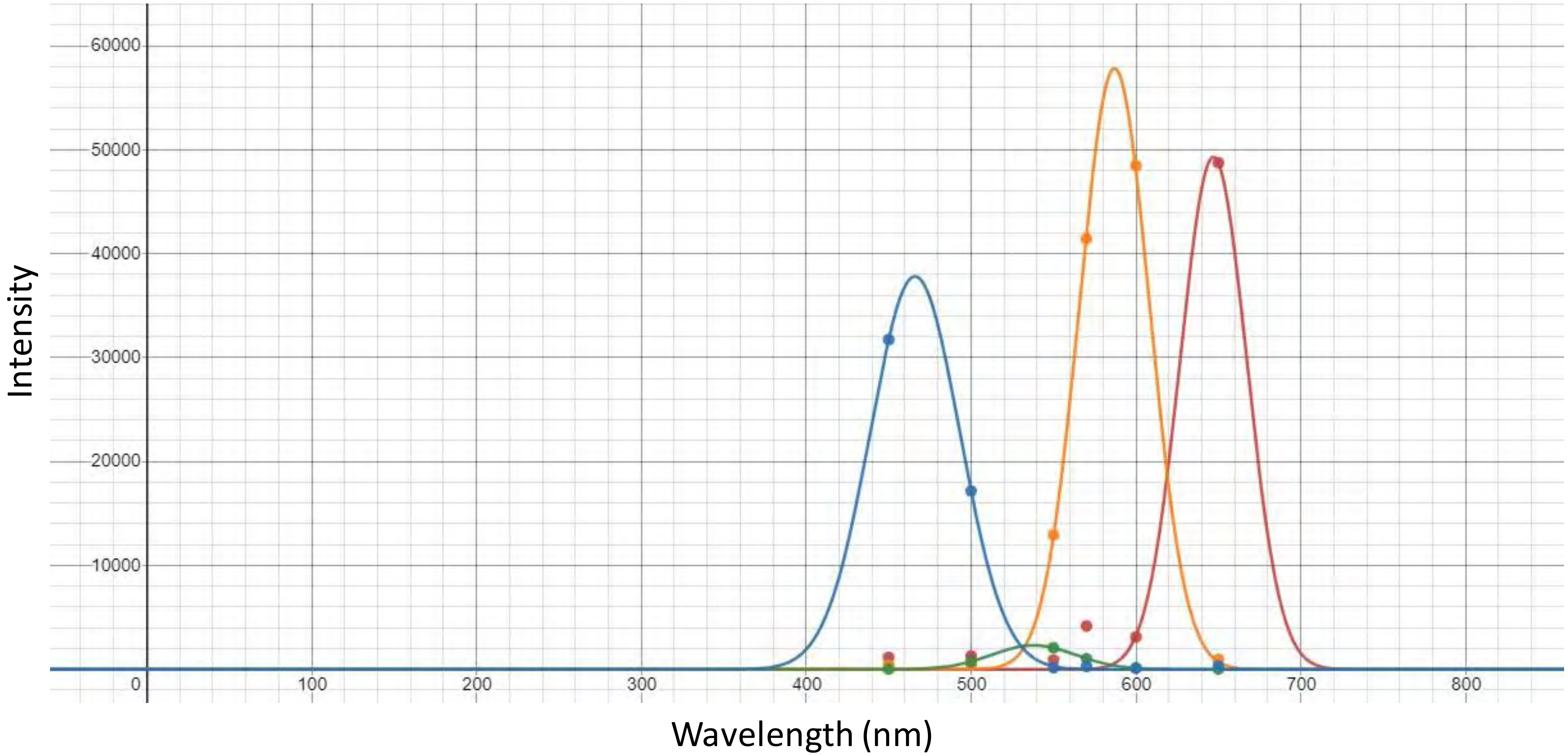
Determining LED Spectra

- Unable to find information on spec sheets, we took the data ourselves.
- Set LED to max brightness and took data through the spectrometer.
  - Used same code for data collection.
- Found average intensity (in spectrometer counts) for each wavelength measured.
- Found best fit curves of the form.
  - Varied b
  - λ
  - Set a to maximum intensity

  (as given in the spec sheets)

$$I = ae^{-\frac{1}{b}(x-\lambda)^2}$$

Determining LED Spectra



Determining LED Peak Intensities

- Provided in spec sheets.
- Soldered three red LEDs together to more closely match other colors.

	Red	Yellow	Green	Blue
Peak Intensity	$1500 \times 3 = 4500$	18000	8000	6000

Data Collection

Manual Adjustment

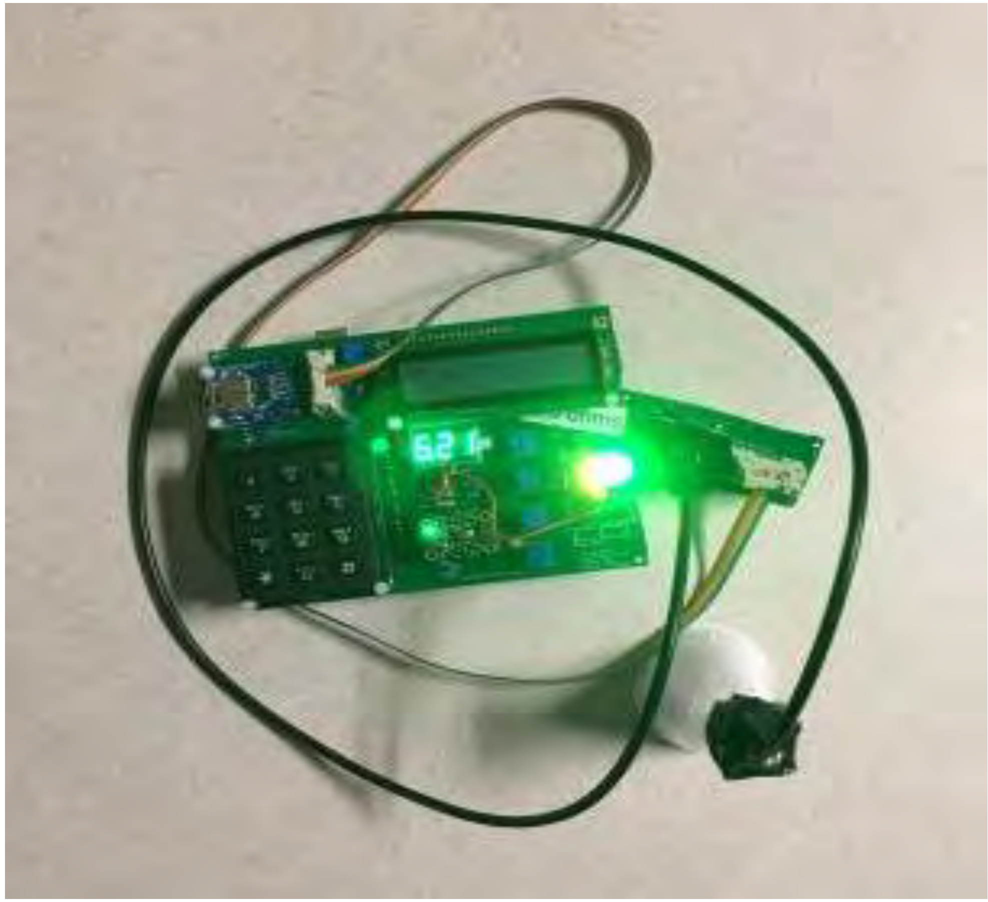
- Used two identical setups.
- Looked at colors through diffuser.
- Adjusted trimpots to match output colors.

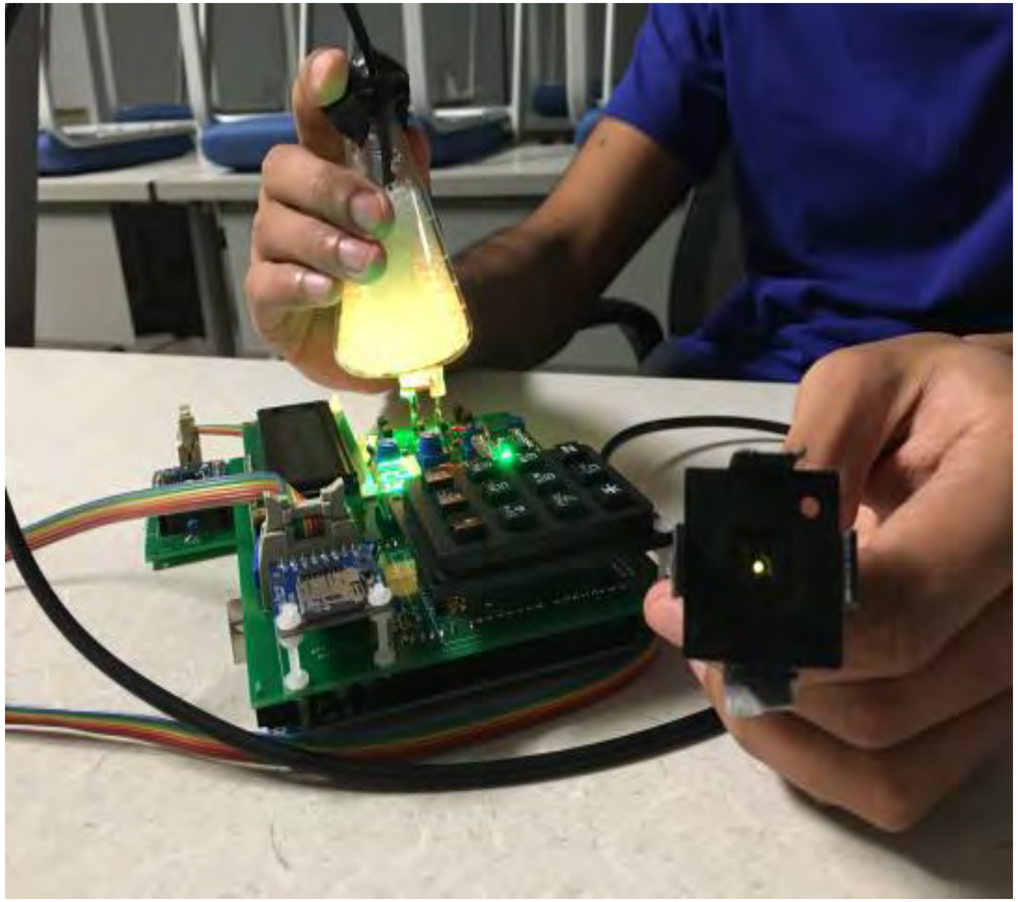
Code Output

- Calculated necessary powers from comparative intensities.
- Calculated necessary DAC output to generate proper current.

➢ Collected spectra through diffuser for numerical analysis.

Data Collection





Data Processing

- Colorimeter data –> spectra
- Spectra –> cone responses
- Cone responses –> color space
- Proximity of results

$$\Gamma_{RGB_\lambda} = \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix} \Gamma_{RGB_{rLED}} = \begin{bmatrix} R_{rLED} \\ G_{rLED} \\ B_{rLED} \end{bmatrix} \Gamma_{RGB_{gLED}} = \begin{bmatrix} R_{gLED} \\ G_{gLED} \\ B_{gLED} \end{bmatrix} \Gamma_{RGB_{bLED}} = \begin{bmatrix} R_{bLED} \\ G_{bLED} \\ B_{bLED} \end{bmatrix}$$

$$\Gamma_{RGB} = T_{XYZ->RGB} \times T_{LMS->XYZ} \times \Gamma_{cr}$$

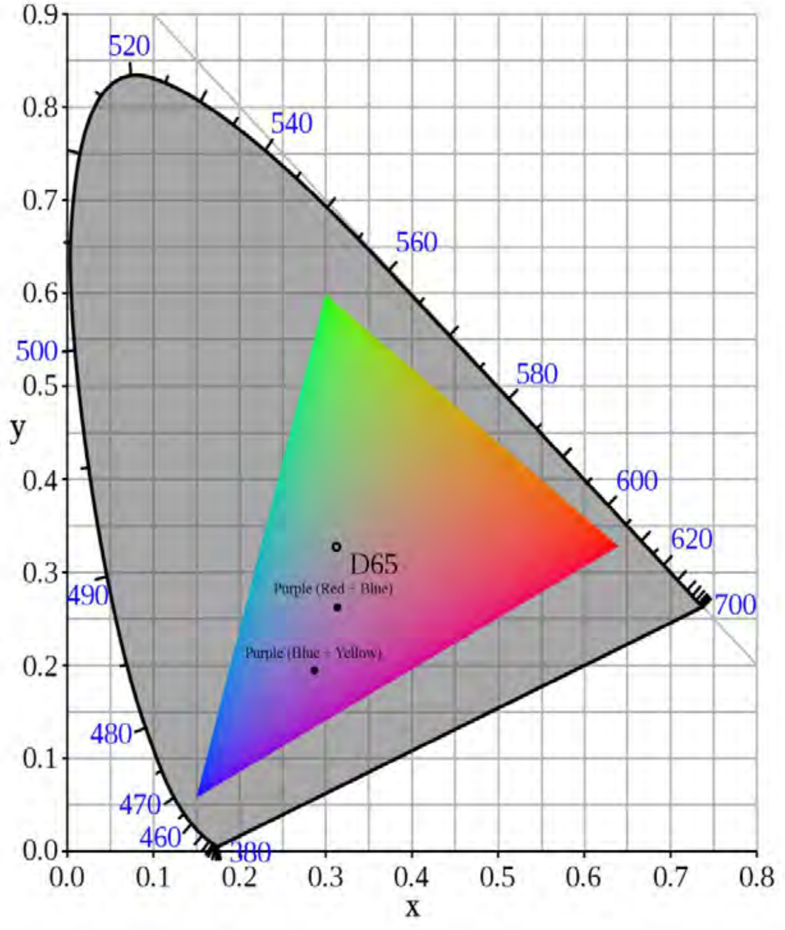
Results

Results Formatting

Metamer Color Name					
LED Combo	DAC Counts	Spectrum	Cone response <R, G, B>	xy Color Space values	Outside sRGB?
The combination of LEDs used to produce the metamer.	The DAC output (between 0 and 1023) that was sent to the transistor controlling the specific LED.	The spectrum of the diffused light as measured by the colorimeter with responses from the six wavelengths recorded as a set in [brackets].	The normalized vector containing the red, green, and blue cone responses in that order for the spectrum provided.	The location in the xy color space.	Whether or not the measured point lies outside of the sRGB triangle in the xy color space.

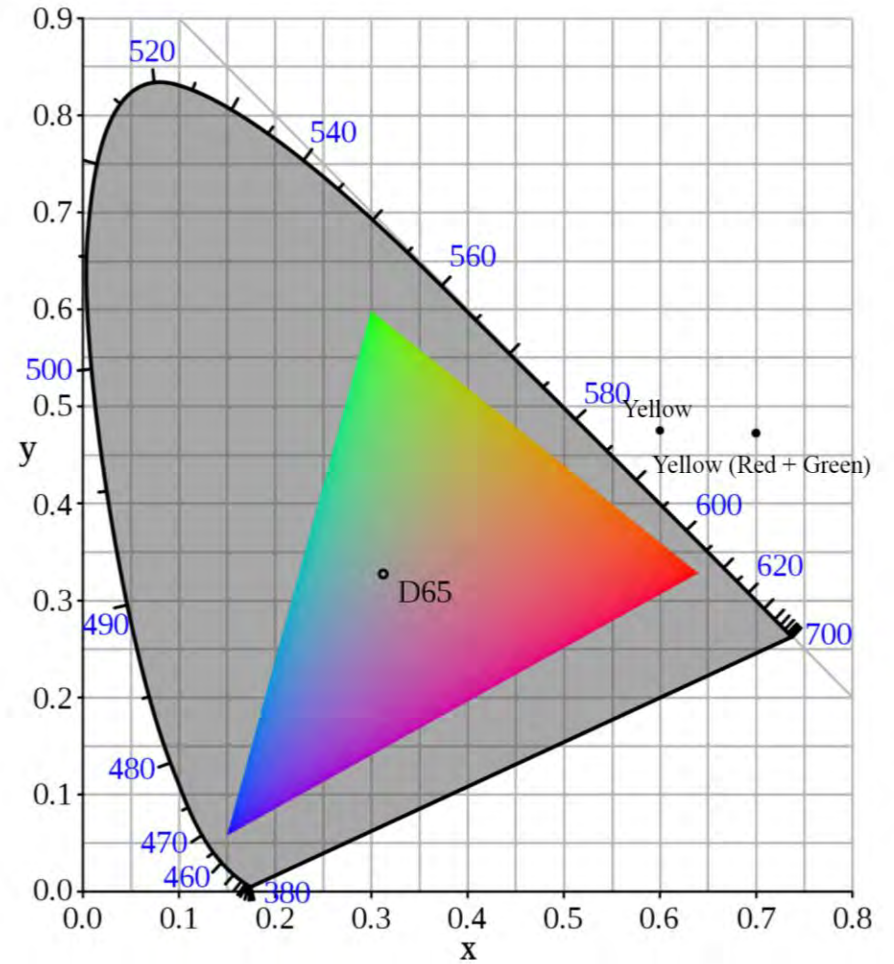
Purple

Purple					
LED Combo	DAC Counts	Spectrum	Cone response <R, G, B>	xy Color Space values	Outside sRGB?
Red Blue	799 911	[344, 111, 6, 7, 47, 60]	<0.201, 0.191, 0.608>	<0.284,0.195>	No
Blue Yellow	711 883	[107, 46, 5, 23, 17, 1]	<0.267, 0.257, 0.475>	<0.320, 0.260>	No
Difference	Yes	Significantly Different (GOOD)	<28.2, 29.5, 24.6> (in terms of %)	<11.92, 28.57> (in terms of %)	No



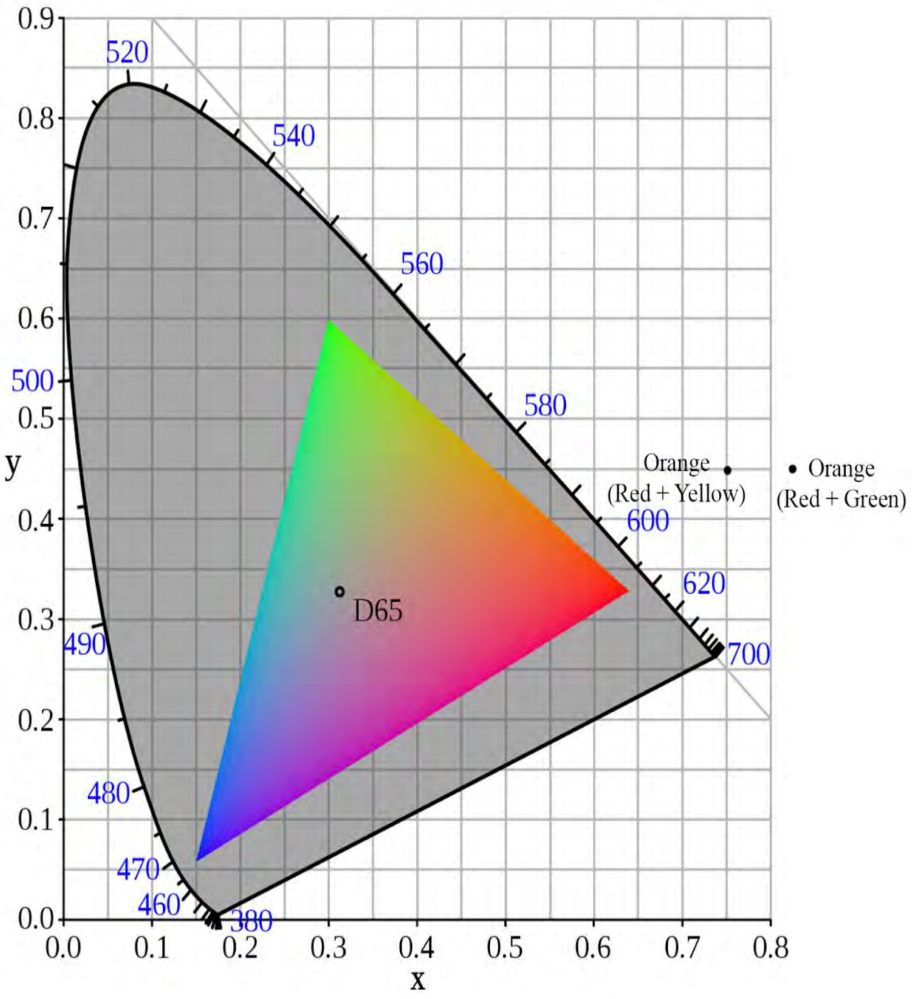
Yellow

Yellow					
LED Combo	DAC Counts	Spectrum	Cone response <R, G, B>	xy Color Space values	Outside sRGB?
Yellow	3500	[419, 421, 12944, 41443, 48476, 958]	<0.598,0.398,0.003>	<0.700,0.473>	Yes
Red Green	2255 1119	[1, 25, 40, 22, 41, 56]	<0.561, 0.418, 0.021>	<0.611,0.471>	Yes
Difference	Yes	Significant	<6.38, 4.90, 150> (in terms of %)	<13.6,0.424> (in terms of %)	No

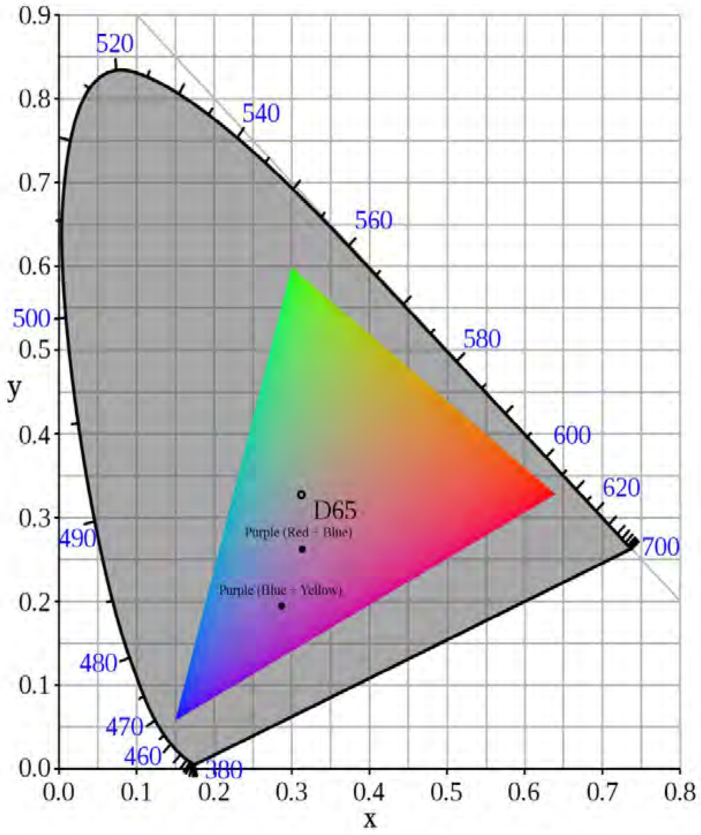


Orange

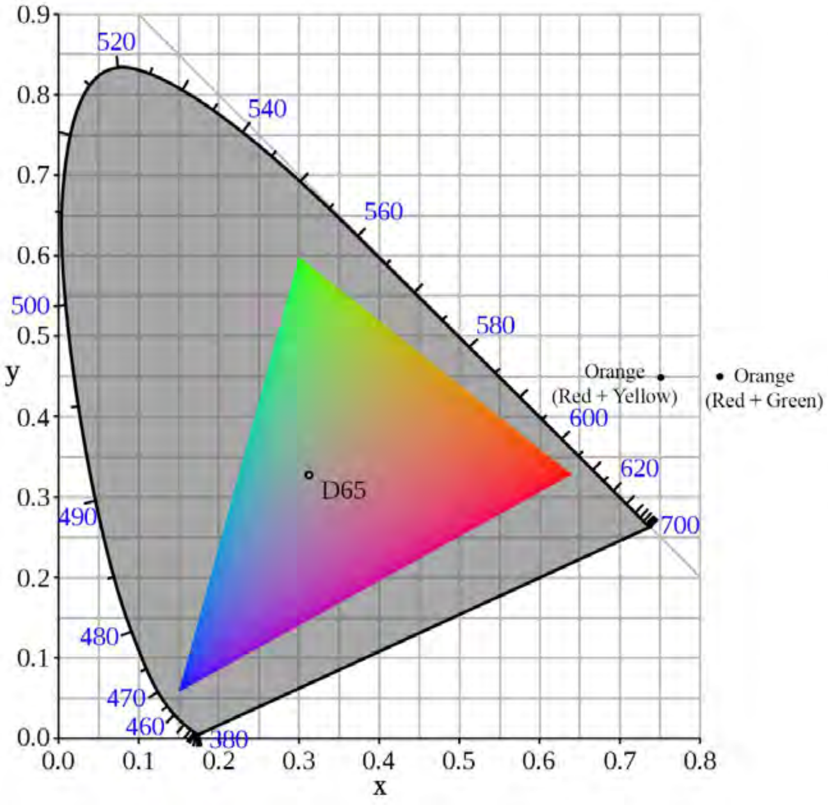
Orange					
LED Combo	DAC Counts	Spectrum	Cone response <R, G, B>	xy Color Space values	Outside sRGB?
Red Green	1227 535	[1,6,15,12,69,49]	<0.640, 0.348, 0.012>	<0.838, 0.456>	Yes
Red Yellow	703 947	[0,1,9,40,62,7]	<0.618, 0.381, 0.001>	<0.751, 0.463>	Yes
Difference	Yes	High	<3.498, 9.053, 169> (in terms of %)	<10.95, 1.52> (in terms of %)	No



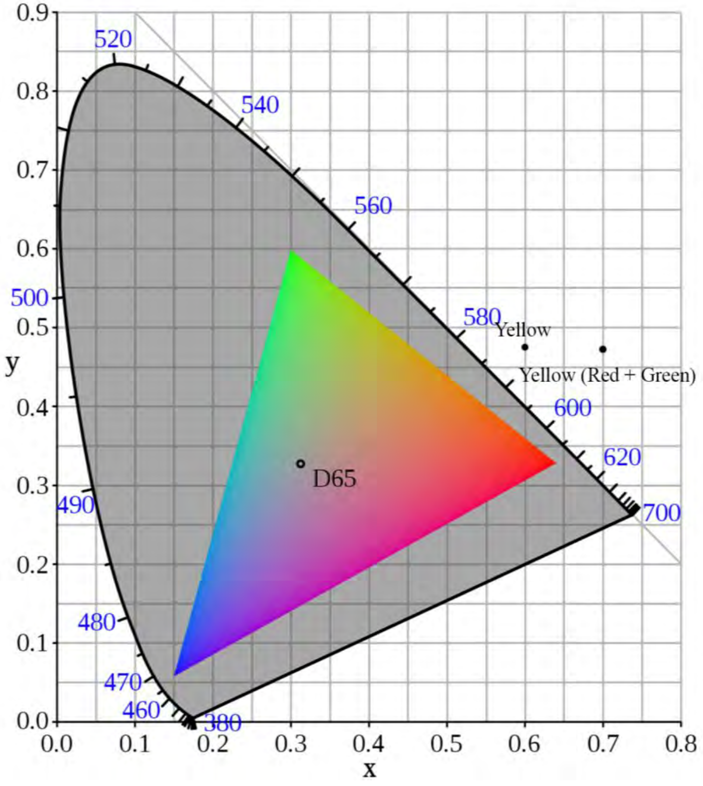
Metamers on the xy color space



Purple



Orange



Yellow

Discussion

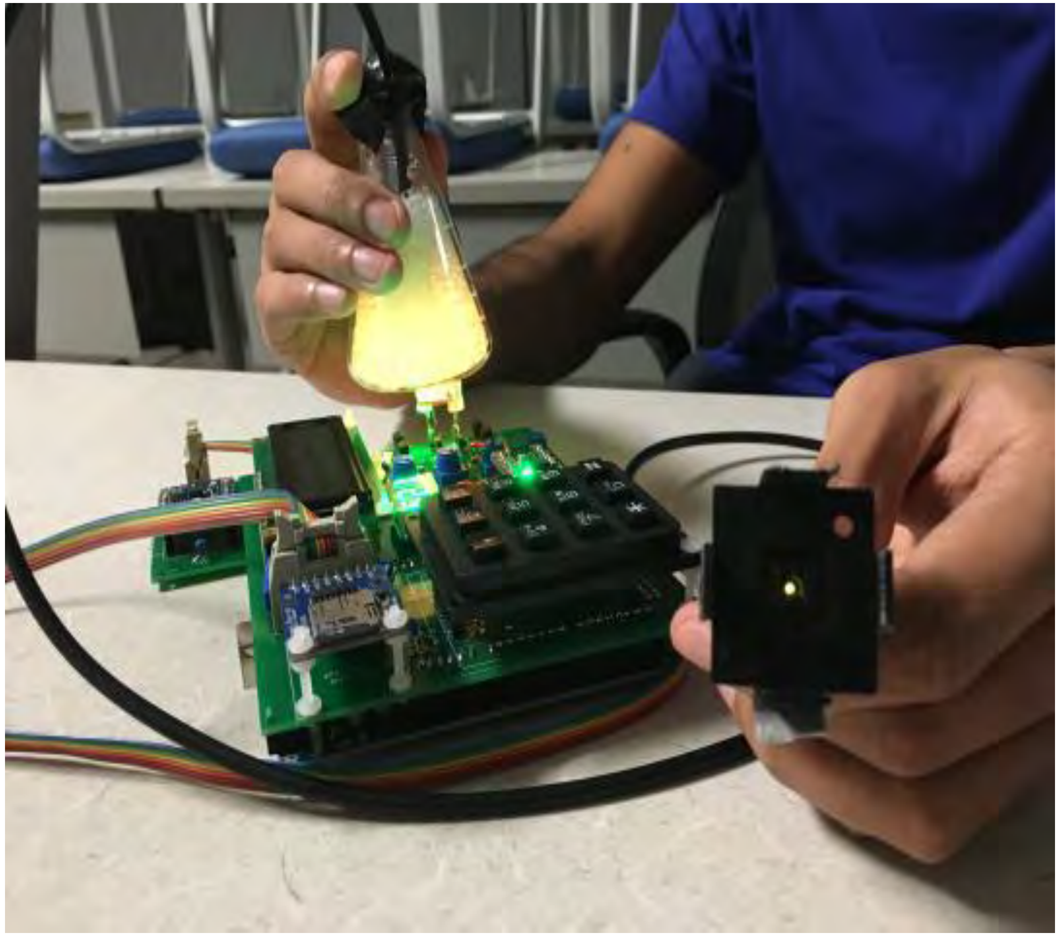
Problems

- Transistor saturation
  - Needed more voltage.
- Diffuser troubles
  - Tight bounds for placing the cable within the beads for capturing mixed light.
  - Adjusted distance between diffuser and LEDs by hand for each trial.
- Spectra, not points
  - Hard to map onto xyY color space.

Conclusion

What did we accomplish?

- Eventually, we created 3 metamers: purple, yellow, and orange.
- Their placement inside or outside sRGB was tenuous.
  - Yellow LED helped the most.



What did we learn?

- Potentially useful for research in light perception.
- With specific LEDs (that are economically viable), it has potential use as pixels in monitors/screens.
- Having 4 LEDs for color reproduction is not necessarily better than just having 3.

Acknowledgements

We would like to thank Professor George Gollin and Ivan Velkovsky in providing the materials and guidance needed to design and test our project.

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