Idea Bank: Versatile 3D printed colorimetry toolkits
Supplementary Information

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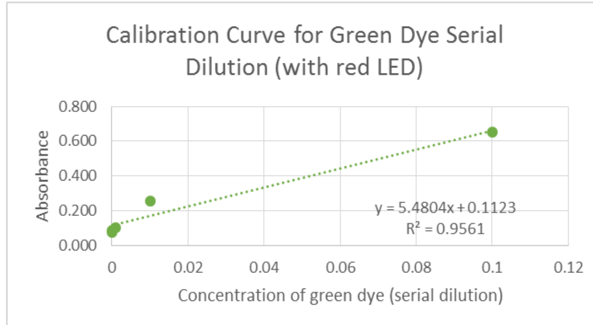
Part 1. How to use the Beer-Lambert Law with the homemade colorimeters

Example Data: Red LED with Green Dye serial dilution

Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	650	4.483	0.652
0.01	262	1.807	0.257
0.001	183	1.262	0.101
0.0001	176	1.214	0.084
0.00001	173	1.193	0.077
0 (blank)	145		



Note: the toolkit colorimeters give resistance data, which must be converted to absorbance as follows

Absorbance is defined by this equation: $A = -\log_{10} I / I_0$

A is absorbance

I is the intensity of light passing through the sample

I_0 is the intensity of the light passing through the blank

Commercial colorimeters measure the absorbance for the user, but the toolkit colorimeters measure resistance. So, the user must manually convert resistance to absorbance as follows:

$A = \log_{10} R_{sample} / R_{blank}$

A is absorbance, R_{sample} is for the resistance of the sample, R_{blank} is the resistance for the blank

Note: This equation no longer needs to have the negative because the resistance measurements are proportional to the reciprocal of the light intensity values (I and I_0)

Beer-Lambert Law Equation:

A = E x b x c

A is Absorbance

E is a constant that is dependent on the solute, temperature and pressure

b is the path length that the light travels (a constant distance for all the samples)

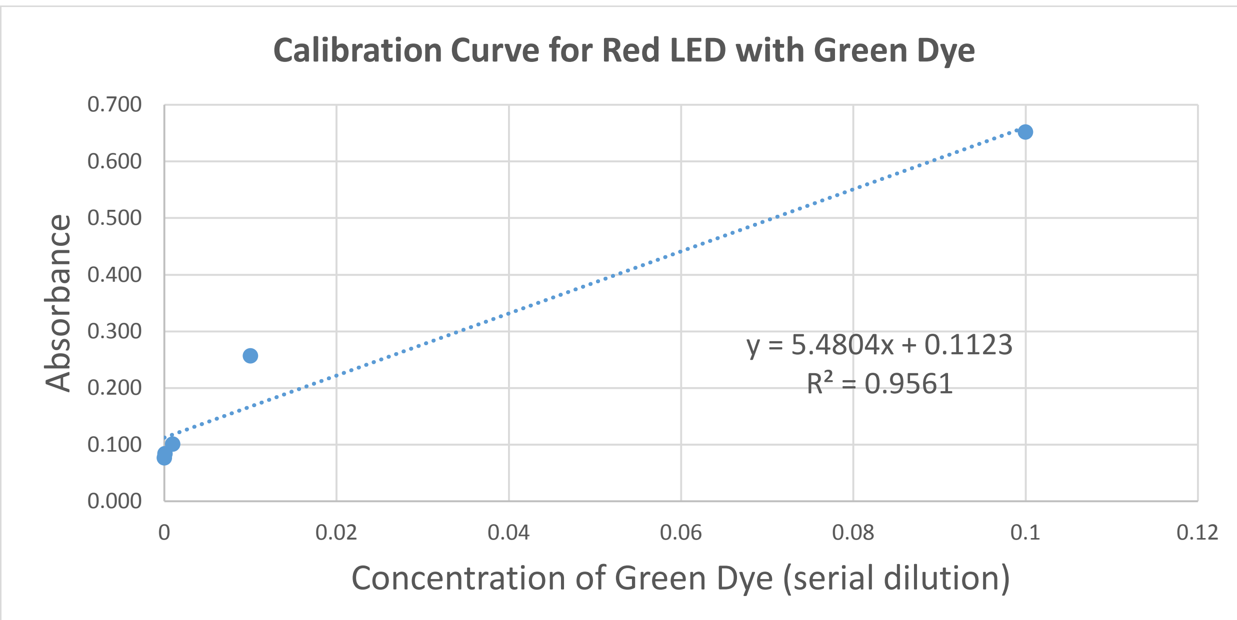
c is the concentration of the solution

So, if you plot the Absorbance for several known concentrations, you will get a straight line. The equation for the line is the Beer-Lambert equation, which can be used to calculate the concentration for an unknown sample. Just measure the unknown sample's Absorbance, plug this value into the equation, and then solve for x (concentration).

Part 2. Example data collected by the toolkit colorimeter with the Red LED setup

Red LED Experiment with Green Dye

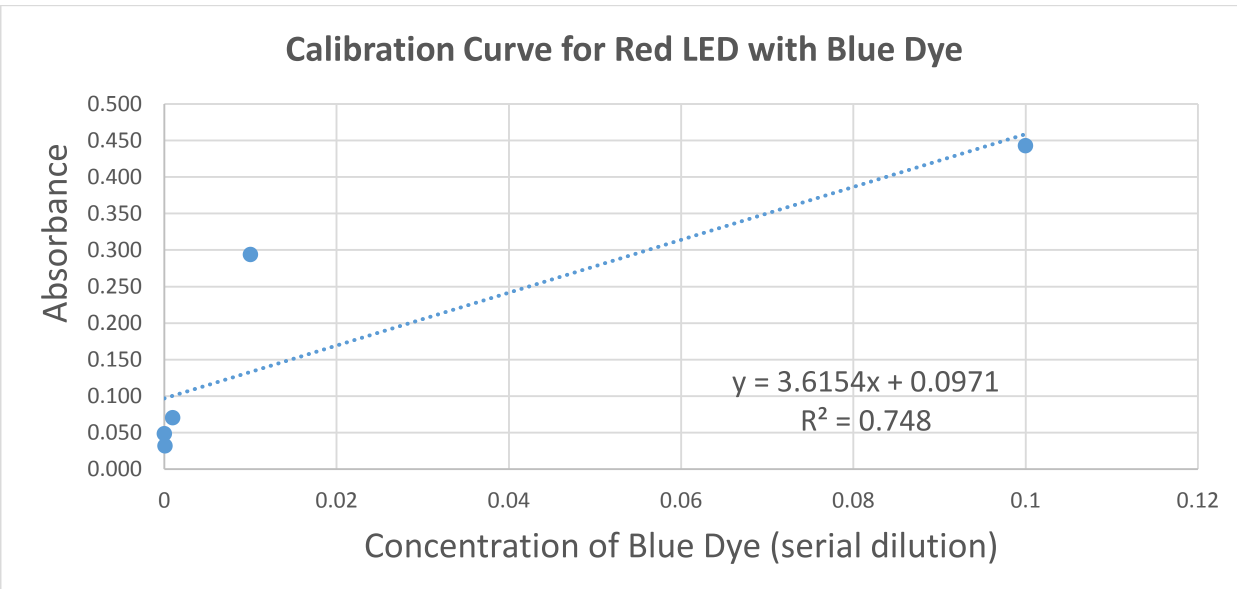
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	650	4.483	0.652
0.01	262	1.807	0.257
0.001	183	1.262	0.101
0.0001	176	1.214	0.084
0.00001	173	1.193	0.077
0	145		



The RED LED light gives the best fit calibration curve for green dye, as noted by the higher R-squared value (0.956). The closer this value is to 1.0, the closer the line passes through all of the data points. The green dye strongly absorbs red light, its complementary color on the color wheel. For more detail, see Part 5 on page 12, and this reference: Reusch, William. 2013. Visible and Ultraviolet Spectroscopy, https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/spectrpy/uv-vis/spectrum.htm.

Red LED Experiments with Blue Dye

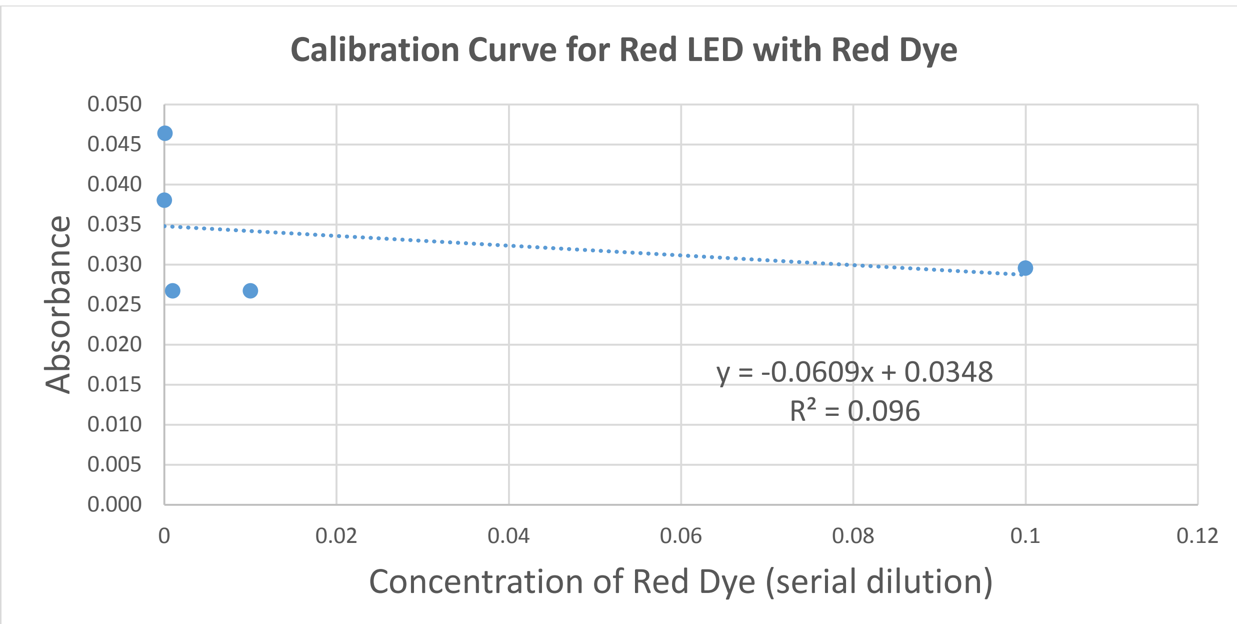
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	330	2.773	0.443
0.01	234	1.966	0.294
0.001	140	1.176	0.071
0.0001	128	1.076	0.032
0.00001	133	1.118	0.048
0	119		



The RED LED light shows some changes in absorbance for the blue dye but not as well as for the green dye. Note the poor R-squared value (0.748). The closer this number is to 1.0 the better the fit and the more data points that fall on the regression line.

Red LED Experiments with Red Dye

Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	152	1.070	0.030
0.01	151	1.063	0.027
0.001	151	1.063	0.027
0.0001	158	1.113	0.046
0.00001	155	1.092	0.038
0	142		



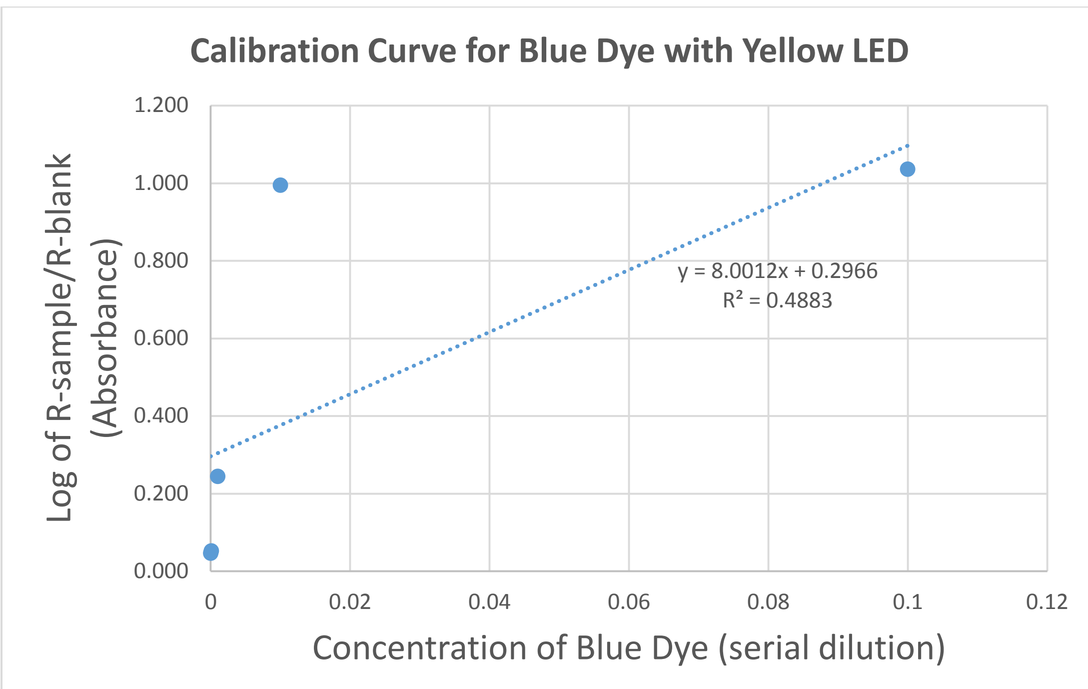
The RED LED light shows basically no change in resistance for the red dye. This is because red LED's emit light wavelengths that are reflected by the red dye (and not absorbed).

Note: This effect is similar for all the light/dye combinations that are of the same color.

Part 3. Example data from the toolkit colorimeter with the Yellow LED setup

Yellow LED Experiments with Blue Dye

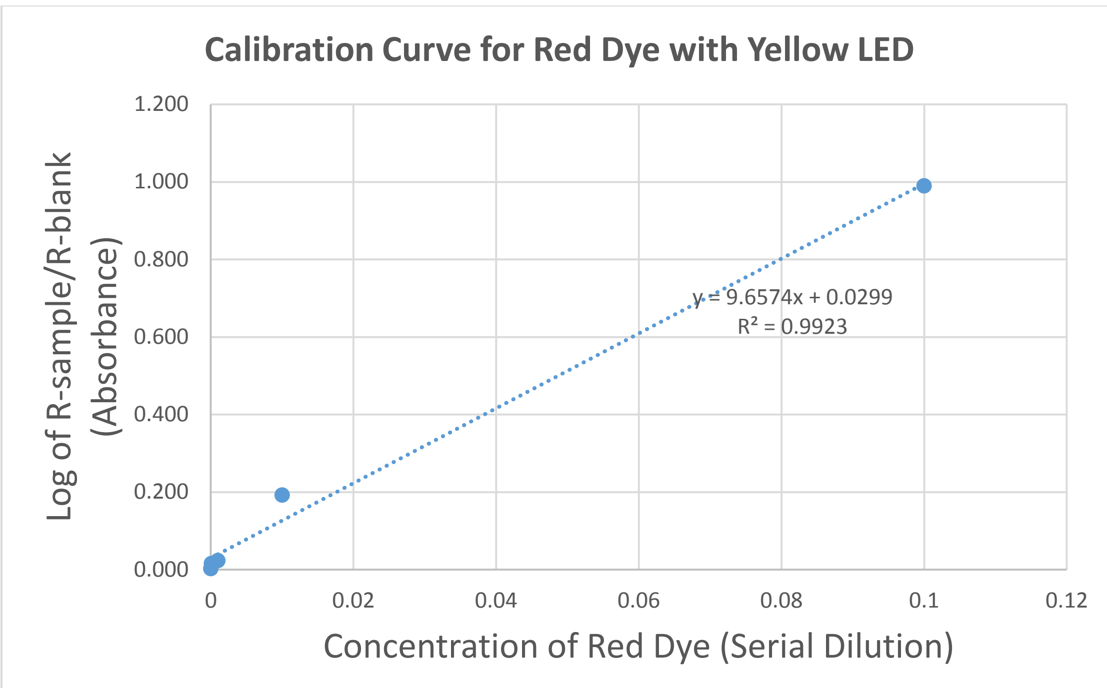
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	1640	10.861	1.036
0.01	1490	9.868	0.994
0.001	265	1.755	0.244
0.0001	170	1.126	0.051
0.00001	168	1.113	0.046
0	151		



The Yellow LED light shows changes in absorbance for the blue dye but not as well as for the red dye. Note the poor R-squared value (0.488), which reflects that fewer points fall on the regression line.

Yellow LED Experiments with Red Dye

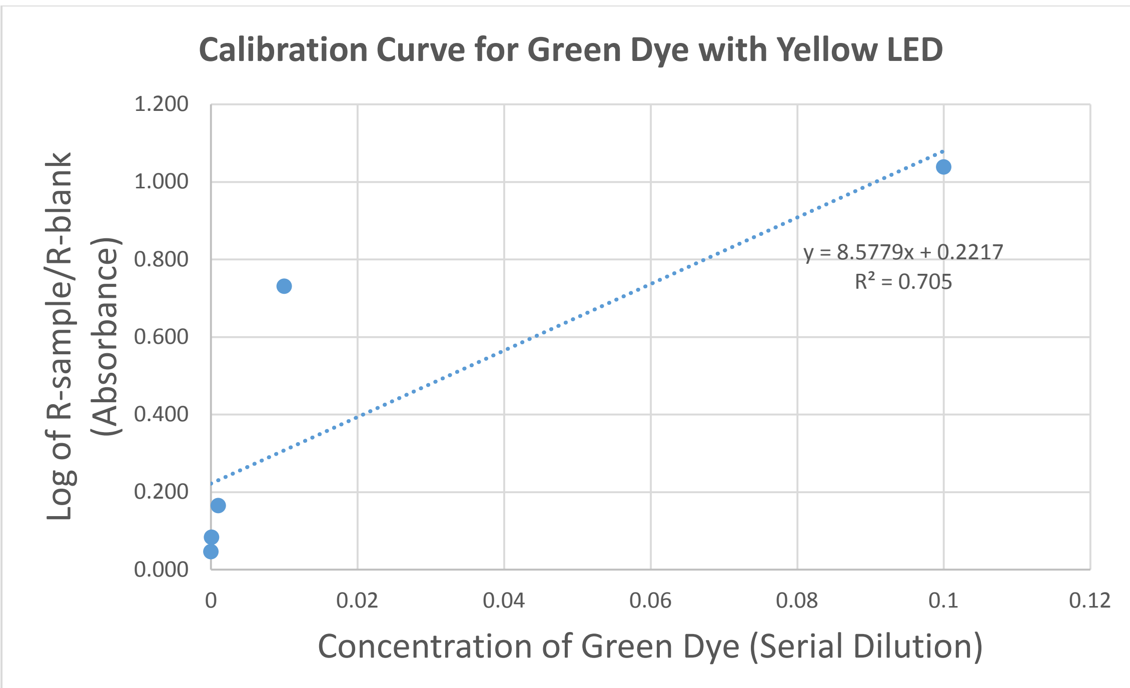
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	1600	9.756	0.989
0.01	255	1.555	0.192
0.001	173	1.055	0.023
0.0001	170	1.037	0.016
0.00001	165	1.006	0.003
0	164		



The Yellow LED light works very well with the red dye. Note the good R-squared value (0.9923)

Yellow LED Experiments with Green Dye

Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1	1561	10.916	1.038
0.01	768	5.371	0.730
0.001	209	1.462	0.165
0.0001	173	1.210	0.083
0.00001	159	1.112	0.046
0	143		



The Yellow LED light shows changes in absorbance for the green dye but the data collected does not fit the line very well, as noted by the poor R-squared value (0.705).

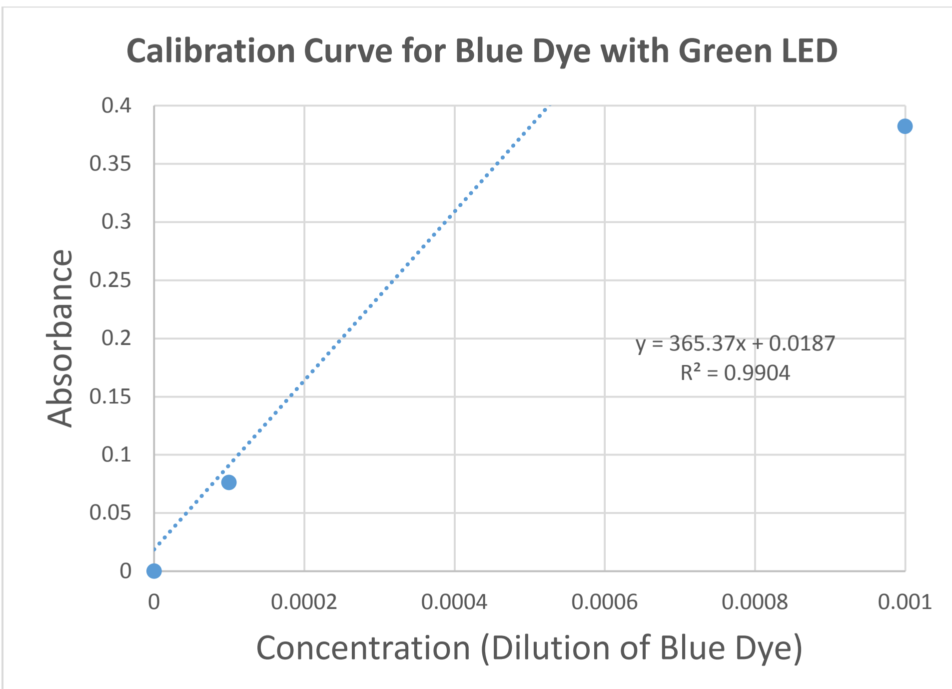
Yellow LED Experiments with Yellow Dye

Note: The Yellow LED light shows no changes in absorbance for the yellow dye. Data not shown.

Part 4. Example data from the toolkit colorimeter with the Green LED setup

Green LED Experiments with Blue Dye

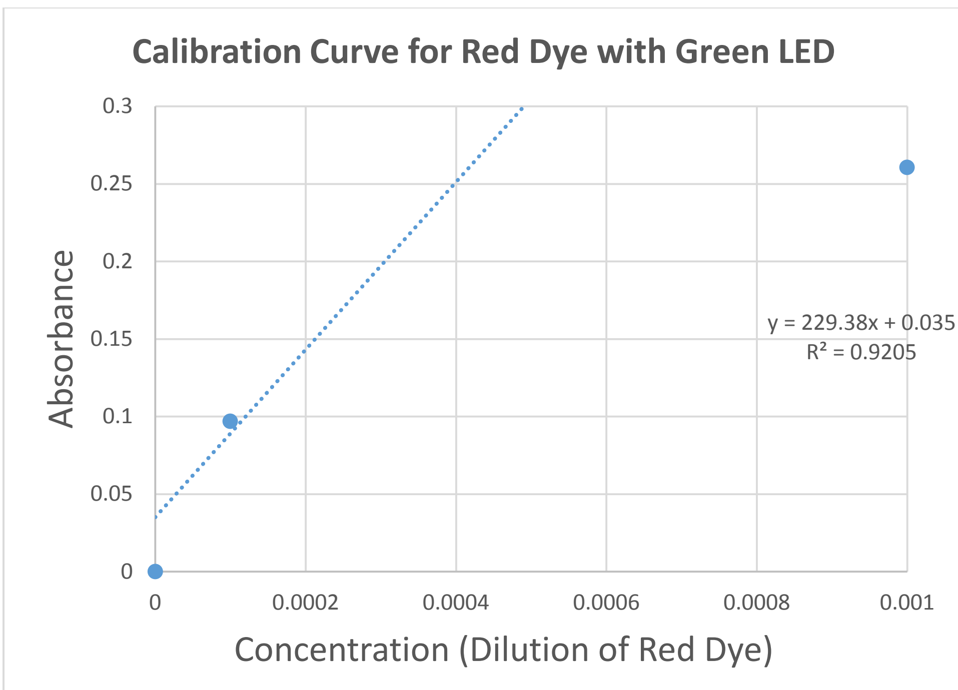
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1			
0.01			
0.001	882	2.40983607	0.3819875
0.0001	436	1.19125683	0.076005404
0.00001			
0	366		0



The Green LED light did not work well for any dye colors at the more concentrated solutions. In part, this might be because the green LED is much dimer compared to the red and yellow LEDs. Not enough light seems to penetrate the more concentrated dye solutions.

Green LED Experiments with Red Dye

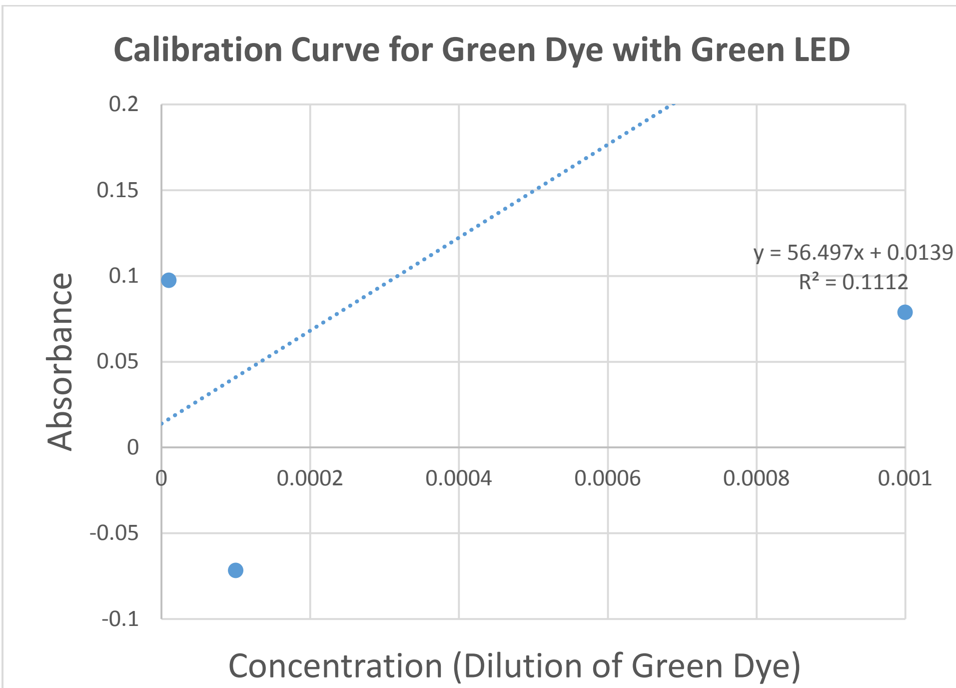
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1			
0.01			
0.001	532	1.82191781	0.260528781
0.0001	365	1.25	0.096910013
0.00001			
0	292		0



The Green LED light did not work well for any dye colors at the more concentrated solutions. In part, this might be because the green LED is much dimmer compared to the red and yellow LEDs. Not enough light seems to penetrate the more concentrated dye solutions.

Green LED Experiments with Green Dye

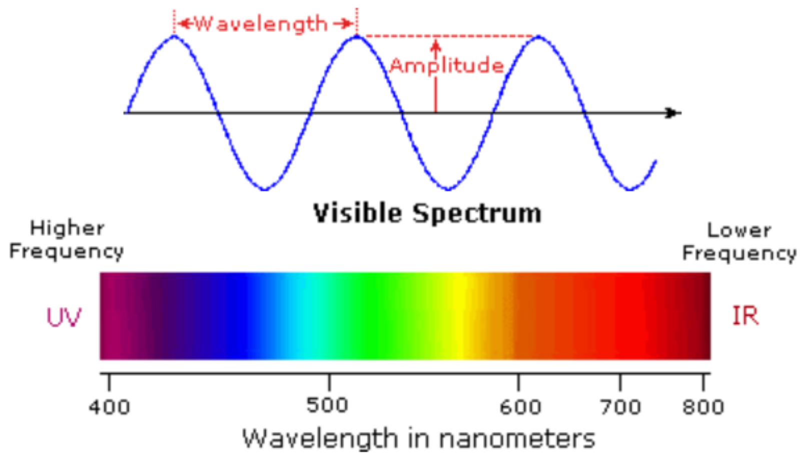
Dilution	Resistance (ohms)	Resistance for sample/ Resistance for blank)	Absorbance (log of Resistance of Sample/ Resistance of Blank)
0.1			
0.01			
0.001	362	1.1986755	0.078701628
0.0001	256	0.84768212	-0.071766978
0.00001	378	1.25165563	0.097484857
0	302		



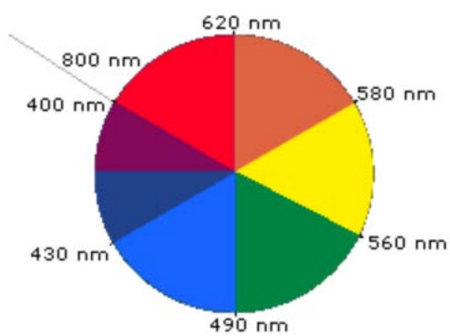
The Green LED light shows wacky resistance readings with green dye solutions. This is partly because green LED's emit light wavelengths that are reflected by the green dye (and not absorbed). And, it is partly a result of the fact that the green LED is dimmer than the other LEDs.

Part 5. Information about the visible spectrum of light

Images taken from:
Reusch, William. 2013. Visible and Ultraviolet Spectroscopy.
https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/spectrpy/uv-vis/spectrum.htm



- **Violet:** 400 - 420 nm
- **Indigo:** 420 - 440 nm
- **Blue:** 440 - 490 nm
- **Green:** 490 - 570 nm
- **Yellow:** 570 - 585 nm
- **Orange:** 585 - 620 nm
- **Red:** 620 - 780 nm



Complementary colors are diametrically opposite each other on the color wheel. Thus, absorption of 420-430 nm light renders a substance yellow, and absorption of 500-520 nm light makes it red. Green is unique in that it can be created by absoption close to 400 nm as well as absorption near 800 nm.

Part 6. Information about the Photocell Sensor used in the toolkit colorimeter

Cadmium Sulfide Photocell (CdS) is a photoresistor with the following resistance range:

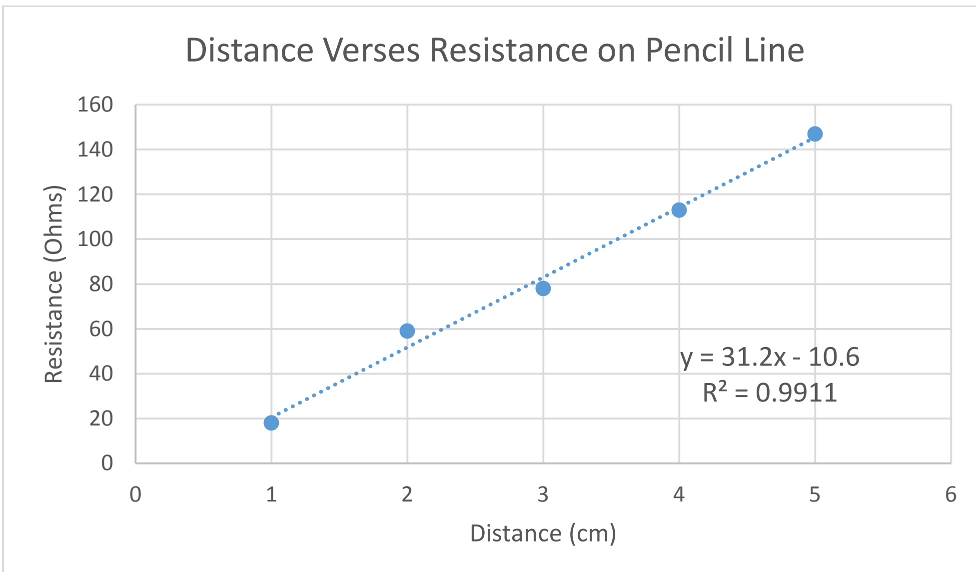
- Resistance in the dark: 300 kOhms
- Resistance in the light 4 kOhms
- CdS Photocells respond to light between 400 nm (violet) and 600 nm (orange), peaking at 520 nm

Part 7. Pitfalls that might affect data from the toolkit colorimeters

- Carefully add drops of water and dye to the cuvette to make your serial dilutions; make sure the drops go down to the bottom of the cuvette otherwise the volume will be less than expected.
- Mix well by tapping cuvette repeatedly, otherwise the colorimeter might not detect the correct resistance for the solution
- Avoid air bubbles in the solution (tap cuvette to remove)
- Avoid smudging the sides of the cuvette
- Make sure to put the cuvette into the holder in the same direction each time, with the flat sides facing toward the LED and light sensor
- Small tweaks to the position of the LED and photosensor can affect data -- keep it consistent between samples
- Rinse out cuvettes well between different tests; and dry well before adding new solution to avoid mistakenly diluting the next sample tested.
- Rinse out the transfer pipettes well between different solutions to avoid cross-contamination.

Part 8. Example data for the digital multimeter introduction activity (measuring resistance across a pencil mark)

Distance (cm)	Resistance (ohms)
1	18
2	59
3	78
4	113
5	147



Note: the graph shows how longer distances have more resistance, which is a measure of the electrical "friction" as electrons move through a conductor.