SURPRISE! IT'S NOT PINK: LIGHTING DESIGN AND COLOR MIXING WITH GEL FILTERS

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Abstract — *Lighting design is deeply situated in physics and colorimetry. Yet, lighting design students are seldom taught these principles. This paper will explore the physics of light and color, specifically with a focus on Roscolux color filters and their Spectral Energy Distribution curves and CIE coordinates. It will examine the ways in which designers can effectively use key concepts from these topics for their designs. Designers that understand these physics principles will be more apt to choose gels that make their design stronger and more cohesive, and these principles could open the door for technologically innovative research on practical lighting design and color filter mixing.*

Index Terms — Color filters, color mixing, lighting design, theatre, chromaticity, physics of light, physics of color, CIE.

BACKGROUND ON STAGE LIGHTING AND COLOR FILTERS

The ancient Greeks are often thought of as the beginning of theatre history as we know it. Their plays were mostly performed outdoors during the day using natural sunlight as a luminary [1]. Ancient scribe, Valerius Maximus described one of the first attempts at coloring stage lighting by the Greeks and Romans using thin sheets of fabric held in front of sunlight in 78 B.C. [1]. In the 14th century, as theatre performances moved indoors and at night, the need for artificial stage lighting arose. These primitive lighting instruments were often cressets and candelabras emitting light with fire [1]. In 1551, Sebastiano Serlio, an Italian theatre technician, began putting glass containers of colored liquids (i.e. red wine, saffron) in front of candles to create colored stage lighting [2].

After many years of trial and error, Edison's electrically powered incandescent lights arrived in theatres in 1882 [1]. From there, technicians started coloring lights using colored gelatin sheets, mostly from Germany. When World War I started in 1914, however, access to these sheets was cut off [3]. It was then that Rosco Labs based in Stamford, Connecticut, previously a bulb lacquer manufacturer, began dominating the color filter industry [3]. In the 1970s, Rosco switched from gelatin filters to *body-colored* polycarbonate filters marketed as "Roscolux" in the US and "Supergel" overseas [3]. Today, almost all color filter brands use a polycarbonate substrate, but Roscolux is the only body-colored color filter on the market [3].

There are three ways to color a lighting filter: surface coating, deep-dyeing, and body-coloring. These are visualized in Figure 1, with the white boxes representing undyed substrates (such as plastic sheets) and the red dots representing dye.

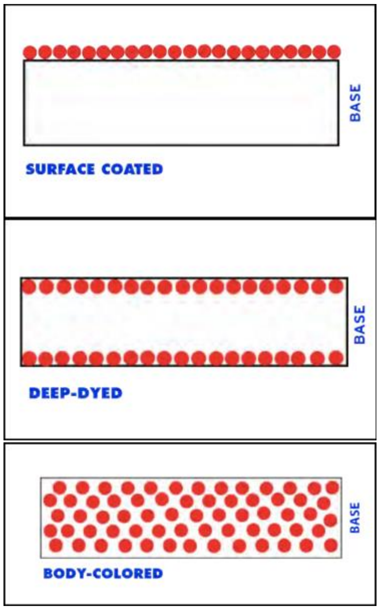


FIGURE 1
VISUALIZATION OF COLOR FILTER DYEING METHODS FROM THE ROSCO GUIDE TO COLOR FILTERS [4]

Surface coating takes a polycarbonate sheet, usually polyester film, or PET, and paints a layer of dye on top. *Deep dyeing* heats the PET to expand it, then dip dyes it, so that when the sheet cools and contracts back to normal, the dye particles are stuck within the polycarbonate. Roscolux's method, *Body-coloring* puts the dye within the plastic substrate, rather than just on top. Putting the dye within the sheet makes the filter more durable against color fading [4]. Also, the plastic substrate Rosco uses is more heat resistant and durable than traditional substrates and includes a flame retardant additive [4].

Because of Roscolux's advantages in body-coloring, durability, heat resistance, and its wide variety of available colors, it is currently the bestselling gel worldwide [3]. This paper will specifically focus on Roscolux brand color filters.

At the turn of the 21st century, light emitting diode (LED) lighting instruments became a viable alternative to incandescent theatre lights, colloquially known as ‘tungstens’ [5]. Rob Sayer, a theatre professor at Bath Spa University, lists the advantages of LED lighting instruments (versus traditional tungstens) as using less power per amount of light emitted, emitting less heat (lowering fire hazard risk), having less mass and volume, and having digital color mixing capabilities [5]. It is likely that with the rise of LEDs and their digital color mixing capabilities, the color filter industry will eventually be phased out. Currently, however, the technology is not advanced enough to completely replace gels. This lack of technology along with the high cost of LEDs, slow conversion rate from tungstens to LEDs by theatres, especially smaller theatres, and lighting designers and theatre technicians’ attachment to color filters as design tools are keeping the gel industry alive and well. Due to the scope of this paper, LED color mixing will not be addressed.

THE ELECTROMAGNETIC SPECTRUM

Light is the way humans see the world, and it’s the only thing we see. Light exists as an electromagnetic wave, as illustrated in Figure 2. An electromagnetic wave is made up of an oscillating electric field, shown in pink on Figure X, and an oscillating magnetic field, shown in blue. These two fields run perpendicular to each other, and their oscillations complement each other so perfectly, they keep each other oscillating continually through space. All electromagnetic waves travel at the same speed: 300,000 kilometers per second. Only at this speed do the electric and magnetic fields’ oscillations line up to produce an electromagnetic wave. The electric fields and magnetic fields are not only perpendicular to each other, but also to the direction the electromagnetic wave travels [17].

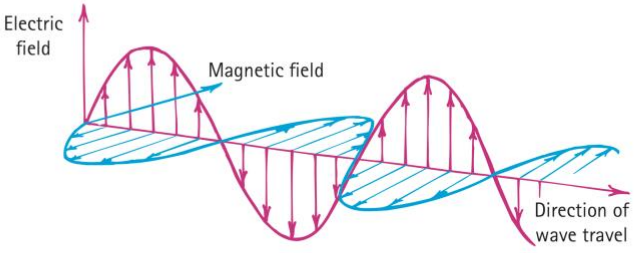


FIGURE 2
AN ELECTROMAGNETIC WAVE [17]

Electromagnetic waves travel to our eyes as light, allowing us to see. However, not all electromagnetic waves are visible to the human eye. Electromagnetic waves are categorized on the electromagnetic spectrum (Figure 3) [17].

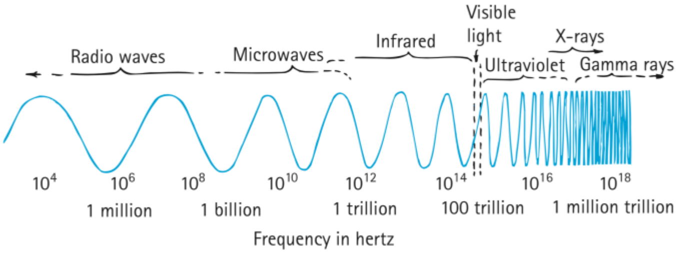


FIGURE 3
THE ELECTROMAGNETIC SPECTRUM [17]

Although all electromagnetic waves travel at the same speed, they differ in frequencies. Common lower frequency categories on the electromagnetic spectrum include radio waves and microwaves, and common higher frequency categories include X-rays and Gamma rays [17]. Light visible to the human eye occupies a tiny section of the electromagnetic spectrum with wavelengths of approximately 400-700 nanometers [4]. Within the spectrum of visible light, waves are further divided into what colors we perceive them as. Because the speed of light is constant, the higher a wave’s frequency, the shorter its wavelengths must be. For instance, the color red has the lowest frequency and thus the longest wavelength [4]. Visible light waves can be named in terms of their frequency or wavelength, but because Roscolux names them in terms of wavelength, this paper will, too. The visible light spectrum is divided into five main colors with wavelengths peaking at 650 nm for red, 570 nm for yellow, 520 nm for green, 480 nm for blue, and 440 for violet nm [4].

THE ROSCOLUX SWATCHBOOK

The Roscolux swatchbook is the lighting designer’s best friend. It contains swatches of every single Roscolux color filter and a small data sheet for each. Each data sheet includes the filter’s name, number, transmission percentage, and Spectral Energy Distribution (SED) graph. The names of color filters are sometimes helpful, but often arbitrary and mythical within the field. For instance, probably the most famed color filter is Roscolux’s #02 named “Bastard Amber.” Legend has it, Bastard Amber was a screw-up filter that a lighting designer picked up off of the floor of Rosco Labs. After using it in a design and taking a liking to it, he returned to Rosco and asked them to make him more of “that bastard amber,” hence the name [3]. While “Bastard Amber” is descriptive of the filter in that the filter is actually amber, some aren’t so descriptive. Roscolux’s 51 “Surprise Pink” is part of a joke about this: the lighting student asks, “Why is it called surprise pink if the filter is purple?” and the lighting teacher responds, “Surprise. It’s not pink!” Because of the inconsistency with filter names, they are categorized by a number system.

The number system is used for ordering filters, swatchbook organization, and for annotation on lighting plots, for all color filters, not just Roscolux. The numbers are generally denoted with the first letter of the company’s name (for Roscolux, ‘R’) followed by the filter’s number (i.e. Rosco’s #02 Bastard Amber is written as R02). The oldest filters are generally numbered 2-99 from ambers through warm colors to cool colors through violets. New colors are placed next to their closest match, and a 3 is added to the beginning of their number. For instance, R337 True Pink follows R37 Pale Rose Pink. The newest filters are generally placed at the beginning of the classic swatchbook as an extension called “Added Colors” and are numbered with four digits (i.e. R3152 Urban Vapor). The last class of Roscolux filters are textured filters, often colorless and used as diffusers, which are placed at the back of the swatchbook. A picture of Roscolux swatchbooks is shown below (Figure 4).

FIGURE 4
ROSCOLUX SWATCHBOOKS THROUGHOUT HISTORY [3]

The total transmission percentage, or “Trans.” percentage, is at the top of the filters’ data sheets and describes how much light will pass through the filter, or how opaque or transparent it is. Under that is the Spectral Distribution (SED) graph. The SED graph (Figure 5) has an x axis of wavelength in nanometers and a y axis of transmission percentage (which is, counterintuitively, not the same as the “Trans.” percentage). The line of the graph shows what percentage of each wavelength will be able to pass through the light. Figure 5 shows R342 Rose Pink’s SED graph. Notice from 460 nm to 580 nm the transmission is 0%, so R342 will absorb these wavelengths (mostly yellow and green), not allowing them to pass, while from 620 nm to 740 nm the transmission is mostly 75%; those wavelengths (red and orange) will mostly be allowed to pass through the filter. This presence and absence of certain wavelengths is what creates colored light [4].

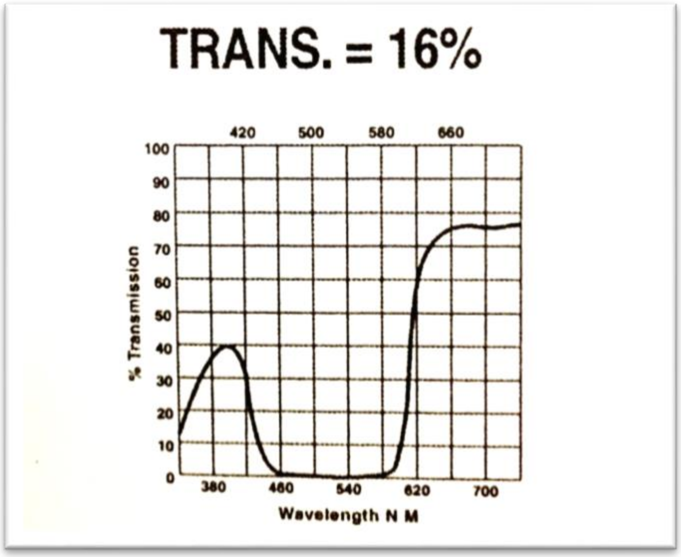

TRANS. = 16%

FIGURE 5
DATA SHEET OF R342 ROSE PINK COLOR FILTER [7]

TO GEL A LIGHT

Once the lighting designer picks a gel from their swatchbook, they must cut a piece of it from a gel sheet and attach it to a light. To attach a color filter to a lighting instrument, or *to gel* the instrument, the filter is placed in a metal gel frame which slides into the front of the instrument. Figure 6 shows several stacks of silver and dark grey gel frames with gel filters within them.

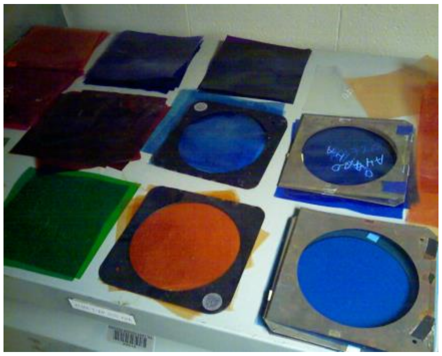


FIGURE 6
COLOR FILTERS IN GEL FRAMES [6]

The light comes from the center of the instrument and goes through the color filter (Figure 7). This light, called a beam, is in a conic shape (Figure 8). There are several important measurements concerning beams which are labeled on Figure 9. The red angle *B* is the beam angle. Lighting instruments are typically categorized by their type and their beam angle. The center of the beam, or the purple line *d*, is where the light is most intense. The beam angle (*B*) is twice the angle in the cone of light where the intensity at the cosine of the distance from the ground (*d)* and the radius of the circle of light that hits the ground (r), is at least 50% of the intensity of the center of the beam ($\boldsymbol{I_d}$), shown in Equation 1. The light within the beam angle is considered the part of the light that is usable to light actors.

$$\boldsymbol{\frac{I_d}{2} \leq 2 \times \tan\frac{d}{r}} \tag{1}$$

Where the intensity of the cone is at least 10% of the center intensity is called the field angle, or *ghosting* [18].

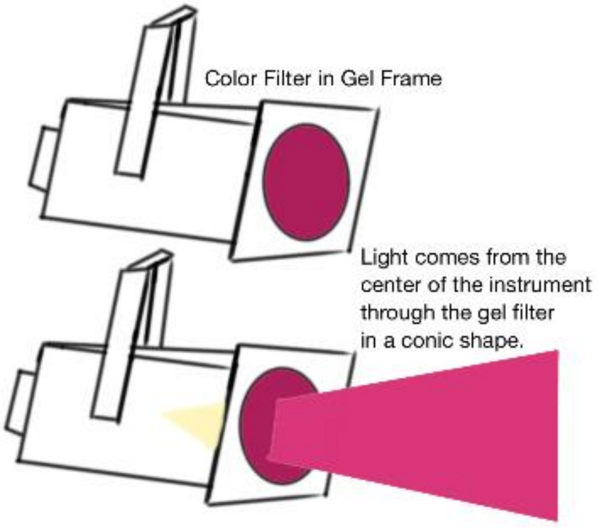


FIGURE 7
ILLUSTRATION OF INSTRUMENT BEAM

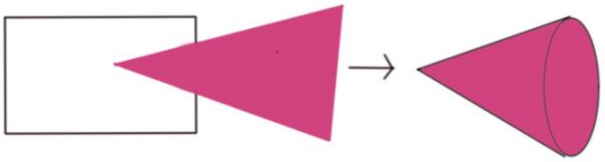


FIGURE 8
THE TRIANGLE SHOWN IN FIGURE 7 AS A CONE

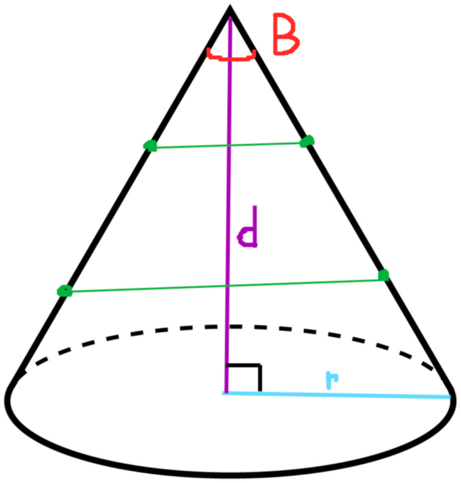


FIGURE 9
A DIAGRAM OF A LIGHT BEAM [18]

Depending on what type of lighting instrument it is, the light beam will be somewhere on the Kelvin color temperature scale. Traditional tungsten instruments are around 3000K, therefore of a warmer tone, and LEDs can range from 3000-7000K, traditionally of a white or bluish tone, but also come in the lower range to imitate tungsten color tones. [9, 10]. The Kelvin color temperature illustrates 'natural' light, and ranges from ambers associated with sunlight to blues associated with light from the sky. The scale is shown below (Figure 3).

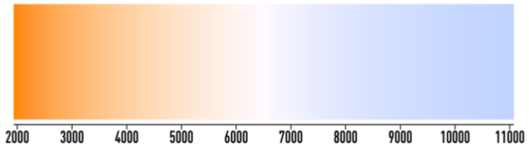


FIGURE 10
KELVIN COLOR TEMPERATURE SCALE 2000-11000K [8]

The light beam starts off with a color temperature, goes through a color filter, and then may cross or mix with another light beam gelled a different color. This means there are three possible ways the light beam may be color mixed.

COLOR MIXING

Colored light is created by the presence and absence of certain wavelengths [4]. Color mixing lights is additive. When the three primaries (red, green, and blue) are mixed together, or rather, when their wavelengths are present, white light is produced.

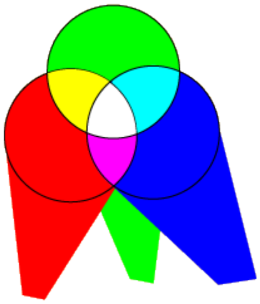


FIGURE 11
ADDITIVE COLOR MIXING WITH RED, GREEN, AND BLUE ADDITIVE PRIMARY COLORS [12]

Pure red and pure blue light mixed together produce magenta. Blue and green produce cyan, and green and red produce yellow. So, if a green and a red color filter with the same Trans. percentages are placed in front of two separate lighting instruments that are white, or around 6500K on the Kelvin Temperature Scale, and the lights are mixed, the green and red should make the output yellow. This is because yellow is the presence of green and red and absence of blue. When complementary colors (opposite on the color wheel) are mixed, all of the primary color wavelengths are absorbed, and the color of the original light beam remains the same. So, if a red and a cyan color filter were placed in front of a lighting instrument with a temperature of 3000K, the light beam output would still be 3000K, because cyan is the presence of green and blue, and red plus green and blue makes white. However, color mixing is much more complicated in practice, as lighting designers almost never mix with the six pure primary and secondary colors on top of pure white light. Therefore, a more exact approach is needed to calculate color output.

CIE AND SED

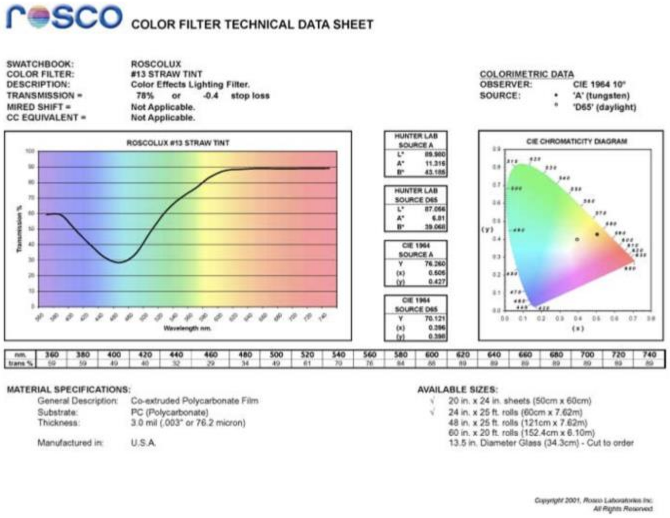
In 1931, and again in 1964, the International Commission on Illumination (CIE) found exact quantities for new basic additive color primaries called X, Y, and Z, that consider subjective human color perception [14]. X, Y, and Z create white when mixed in equal amounts, can produce any color through mixing, and are relative to the human eye [12]. The proportions of X, Y, and Z in a color output are known as the CIE chromaticity coordinates. These coordinates come from the spectral power distribution (SPD) of a light which shows its spectral signature, or color. SPD is measured with a spectrophotometer that measures chromaticity (X and Y), or color, and luminance (Z), how light or dark the color is [12]. The spectral energy distribution (SED) graph used by Roscolux is a variation of the SPD graph.

SED graphs are usually good enough for designers to estimate color output. Designers can effectively 'eyeball' the small SED graphs in their swatchbooks to see which wavelengths will transmit through the filter and compare these to other filters used through additive color mixing [4]. For more accurate color mixing, though, CIE coordinates can be used. For equations, the data points are converted to CIE L*a*b* coordinates where L is the luminance, or Y, 'a', or 'x' represents red/green and 'b', or 'y' represents blue/yellow. The equation for color mixing output ($\boldsymbol{x_m}$, $\boldsymbol{y_m}$) of colors with known chromaticity coordinates ($\boldsymbol{x_n}$, $\boldsymbol{y_n}$) and brightness parameters ($\boldsymbol{Y_n}$) is:

$$\boldsymbol{x_m} = \frac{(\boldsymbol{Y_1}\times\frac{\boldsymbol{x_1}}{\boldsymbol{y_1}}+\boldsymbol{Y_2}\times\frac{\boldsymbol{x_2}}{\boldsymbol{y_2}}+\cdots+\boldsymbol{Y_n}\times\frac{\boldsymbol{x_n}}{\boldsymbol{y_n}}}{\frac{\boldsymbol{Y_1}}{\boldsymbol{y_1}}+\frac{\boldsymbol{Y_2}}{\boldsymbol{y_2}}+\cdots+\frac{\boldsymbol{Y_n}}{\boldsymbol{y_n}}} \qquad (2)$$

$$\boldsymbol{y_m} = \frac{(\boldsymbol{Y_1}+\boldsymbol{Y_2}+\cdots+\boldsymbol{Y_n})}{\frac{\boldsymbol{Y_1}}{\boldsymbol{y_1}}+\frac{\boldsymbol{Y_2}}{\boldsymbol{y_2}}+\cdots+\frac{\boldsymbol{Y_n}}{\boldsymbol{y_n}}} \qquad (3)$$

Technical data sheets for Roscolux [13] include chromaticity coordinates and brightness coordinates. They are already adjusted for human perception according to the CIE 1964 study and include data for a traditional tungsten instrument (Source A) and for a daylight source (Source D65, or 6500K [15] which is quite close to pure white on the Kelvin color temperature scale [8]). A technical data sheet, available on Rosco's website, of R13 is shown in Figure 12. The data sheet includes the SED graph, the chromaticity graph, and the colorimetric data.



rosco COLOR FILTER TECHNICAL DATA SHEET

SWATCHBOOK: ROSCOLUX
COLOR FILTER: #13 STRAW TINT
DESCRIPTION: Color Effects Lighting Filter.
TRANSMISSION = 78% or -0.4 stop loss
MIRED SHIFT = Not Applicable.
CC EQUIVALENT = Not Applicable.

COLORIMETRIC DATA
OBSERVER: CIE 1964 10°
SOURCE: • 'A' (tungsten)
° 'D65' (daylight)

HUNTER LAB SOURCE A	
L*	89.980
A*	11.316
B*	43.185

HUNTER LAB SOURCE D65	
L*	87.056
A*	6.81
B*	39.068

CIE 1964 SOURCE A	
Y	76.260
(x)	0.506
(y)	0.427

CIE 1964 SOURCE D65	
Y	70.121
(x)	0.396
(y)	0.390

nm.	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700	720	740
trans %	59	59	49	40	32	29	34	49	61	70	76	84	88	89	89	89	89	89	89	89

MATERIAL SPECIFICATIONS:
General Description: Co-extruded Polycarbonate Film
Substrate: PC (Polycarbonate)
Thickness: 3.0 mil (.003" or 76.2 micron)

Manufactured in: U.S.A.

AVAILABLE SIZES:
√ 20 in. x 24 in. sheets (50cm x 60cm)
√ 24 in. x 25 ft. rolls (60cm x 7.62m)
48 in. x 25 ft. rolls (121cm x 7.62m)
60 in. x 20 ft. rolls (152.4cm x 6.10m)
13.5 in. Diameter Glass (34.3cm) - Cut to order

FIGURE 12
EXAMPLE OF ROSCOLUX DATA SHEET (R13) [13]

ROSCOLUX EXAMPLE

In the StageLight Theatre's production of *Zombie Prom* (Memphis, TN; March 2017), the lighting design was based around the widely popular McCandless method. The McCandless method involves crossing warm toned lights with cool toned lights at 45° to the line of symmetry of the stage. This is illustrated in Figure 13. The McCandless method uses a warm side and a cool side of lights, rather than just making all of the lights white, to create depth, and to allow for slight tone shifts if one side is set to be brighter than the other.

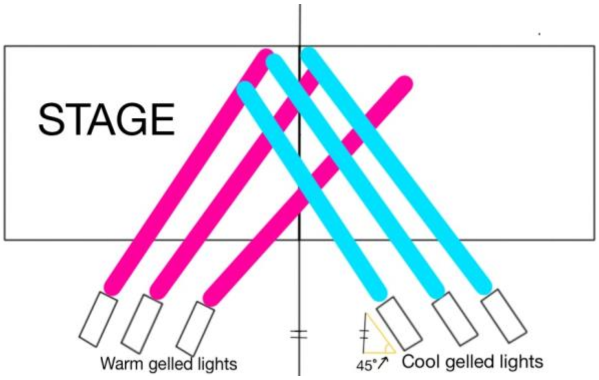


FIGURE 13
THE MCCANDLESS METHOD

The warm color was R337 True Pink (Color 1), and the cool color was R4360 CalColor 60 Cyan (Color 2). Using Source A, or the tungsten, coordinates from the technical data sheet, the actual color output of these two gels when mixed can be calculated. First, the Xxy coordinates from the Roscolux must be converted to L*a*b* coordinates. I used an online tool [19] to convert R4390's Xxy coordinates adjusted for Source A (since the example show was done using tungsten lights) from Xxy(46.584, 0.350, 0.436) to CIE L*a*b*(73.92, -21.22, 36.16). I did the same for R337 from Xxy(58.504, 0.483, 0.368) to CIE L*a*b*(75.14, 29.72, 38.40). I used another online tool [20] to convert the CIE L*a*b* colors to RGB for easier mixing. R4360 came out as RGB(145, 196, 107) and R337 came out as RGB(245, 159, 116). Using a color mixer [21] I determined R4360 and R337 mixed produced RGB(190,178,107) pictured below.

FIGURE 14
RGB(190,178,107)

Since the tungstens had a yellowish/amber tint to begin with, the original light beams contained mostly green and red waves. R4390 (a cyan) absorbed the red waves and let the green waves and the few blue waves pass, creating a greenish tint. R337 (a light pink) absorbed some green waves and allowed the red waves and the few blue waves to pass. The end result contained mostly red waves, closely followed by green waves, with a bit of blue waves. There were very few blue waves to begin with because of the source light, so it makes sense for there to be little in the output despite blue being the common color between the two gel filters. The source light had a majority of red waves and the pink R337 filter allowed nearly all of these to pass through. Some of these red waves were 'cancelled out' in the final output because of the blue and green waves. There were also many green waves in the source light, and both color filters allowed some of these to pass through, so it makes sense for the final output to be high in green waves. The color mixing is illustrated in Figure 14 below.

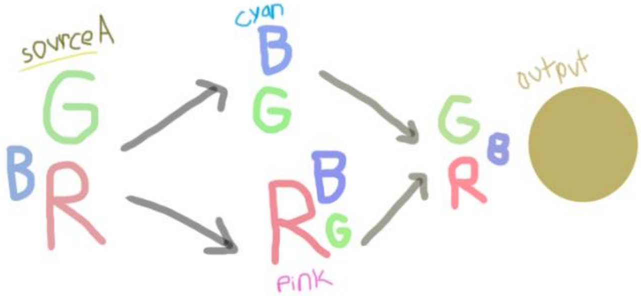


FIGURE 14
R337 AND R4360 THROUGH SOURCE A TUNGSTEN LIGHTS MIXING BREAKDOWN

SUMMARY

Understanding light as an electromagnetic wave on a spectrum should be the foundation for a lighting design education. Other people that could benefit from learning about the physics behind lighting design are researchers. It is much like film production versus film theory: lighting design is practical, while color and light research is more theoretical, with the goal of bettering the actual practice. Perhaps a new breed of stage lighting technicians is needed on the research side of lighting that can keep up with the technological innovations being invented every day that could be applied to the field, but are not.

My research on the matter was inspired by the SED graphs and CIE coordinates listed on Roscolux data sheets which, over years in lighting design, have always been a mystery to me. Researching the physics of light and color, specifically the electromagnetic spectrum, have helped me understand how to use SED graphs in my designs. It has also given me a foundation in the science components of lighting design that were neglected in my technical theatre education. While the SED graphs and light and color physics answered many of my questions and helped me learn about concepts I had never even thought of, the CIE coordinates remain a point of research that I hope to continue in order to better understand lighting design and color theory. Tracking down data convertors and going back and forth between them was confusing and cumbersome. As I look forward to a Computer Science major concentration in lighting systems, I hope to understand these conversions and data types (CIE Xxy, CIE XYZ, CIE Lab, RGB, RGBA) to the point that I can create an easy to use tool for lighting designers and designers in general.

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