Color Science for Photographers

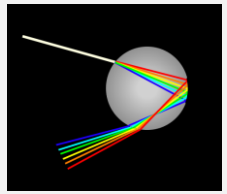
Presentation to the Fort Collins Digital Camera Club

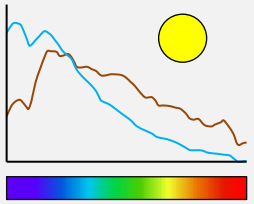
April 11, 2023

Andy Goris

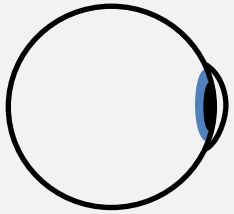
Color is a Broad Topic

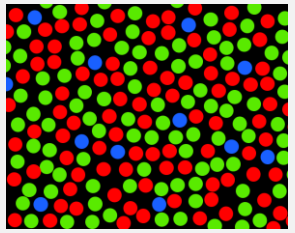
Physics



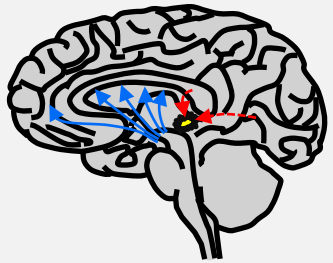


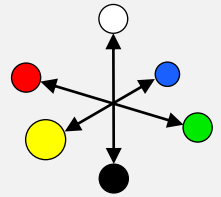
Physiology



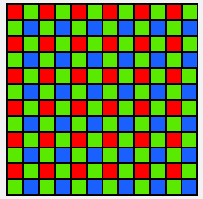


Perception





Capture

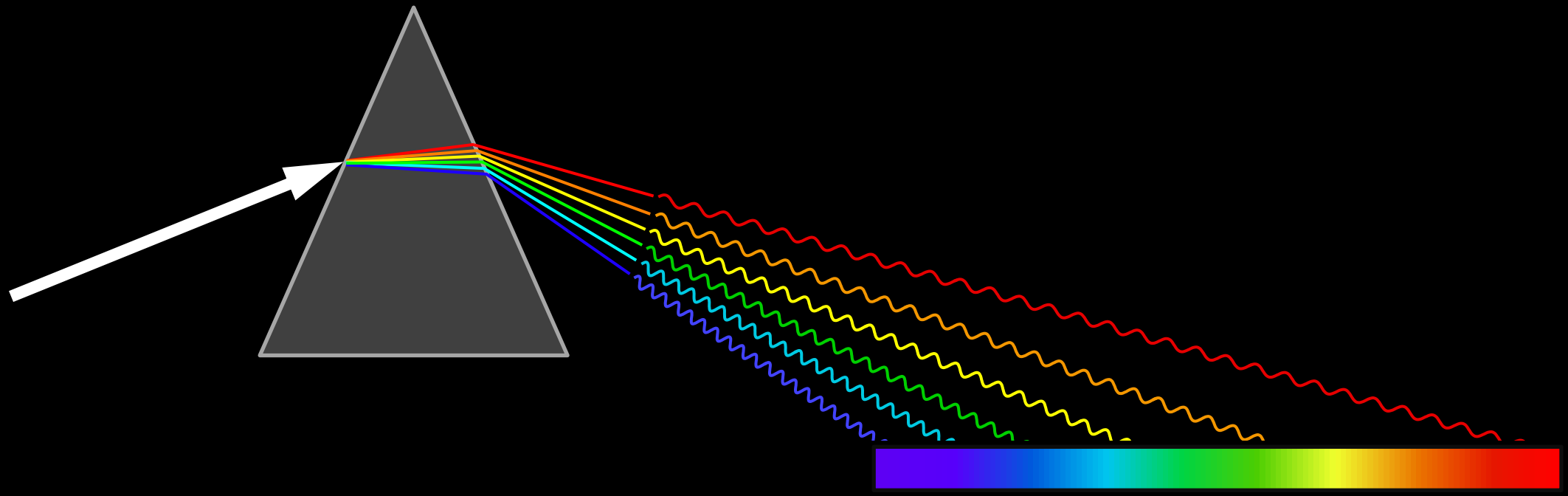


Editing

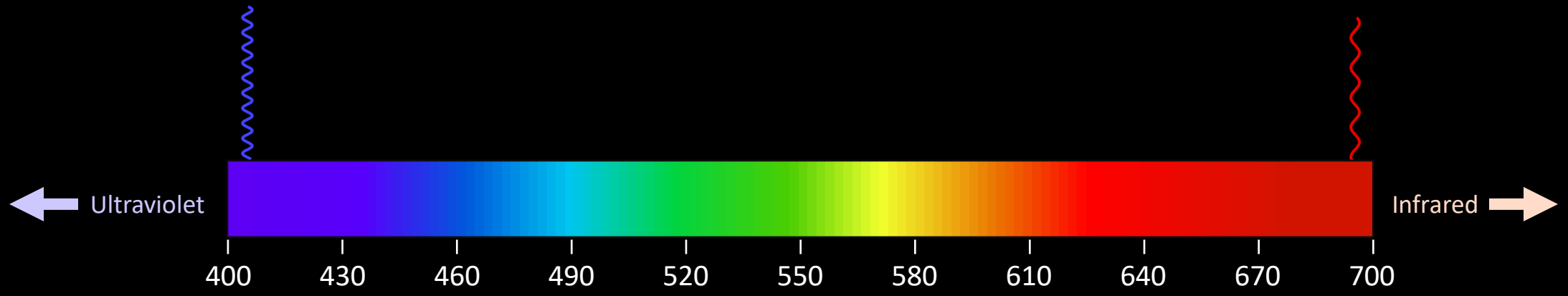
Display & Print

Useful Things to Know about Light

1. White light, such as from the sun or a camera strobe, contains all the colors of the rainbow.
2. Light is made of electromagnetic waves. These electromagnetic waves are the same as the radio waves used cell phones, WIFI, GPS, and AM/FM radio, except much smaller. The wavelength of visible light is measured in nanometers
3. Color is not a property of light nor objects. Color is how we perceive the range of electromagnetic waves that enter our eyes.



Putting Some Numbers to the Spectrum of Visible Light

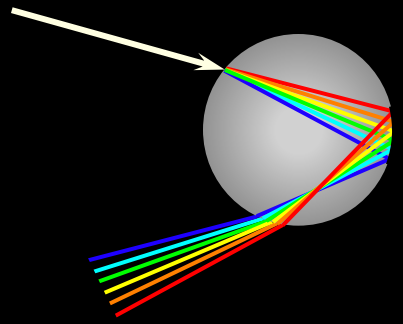


Wavelength in nm (nanometers, billionths of a meter)

These are the purest colors we can see, but they aren't common in nature.

Seeing a spectrum in nature

Each Raindrop acts
Like a prism

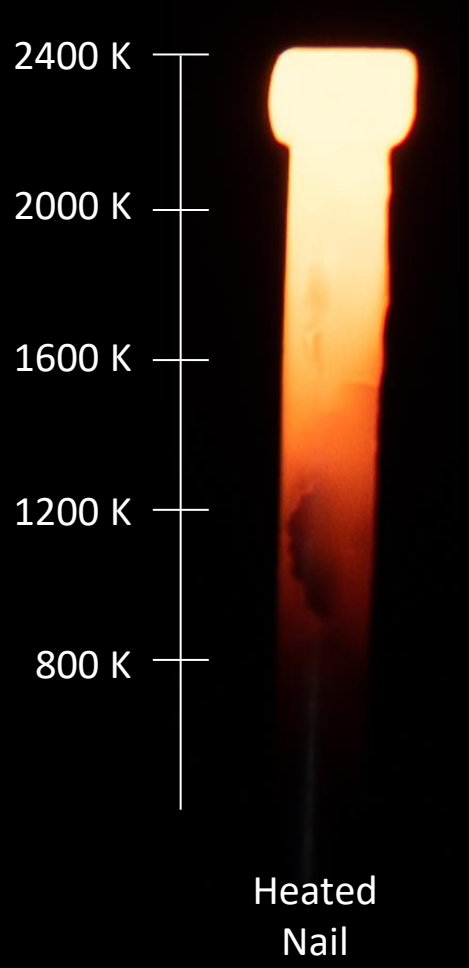


- Like a prism, each wavelength of light is bent a different amount.
- In a double rainbow, light bounces twice inside each rain drop, which is why the colors are reversed.

Trivia: Rainbow light is polarized. If you put a polarizer on your lens and rotate it you can make parts of the rainbow arc brighter or make them disappear

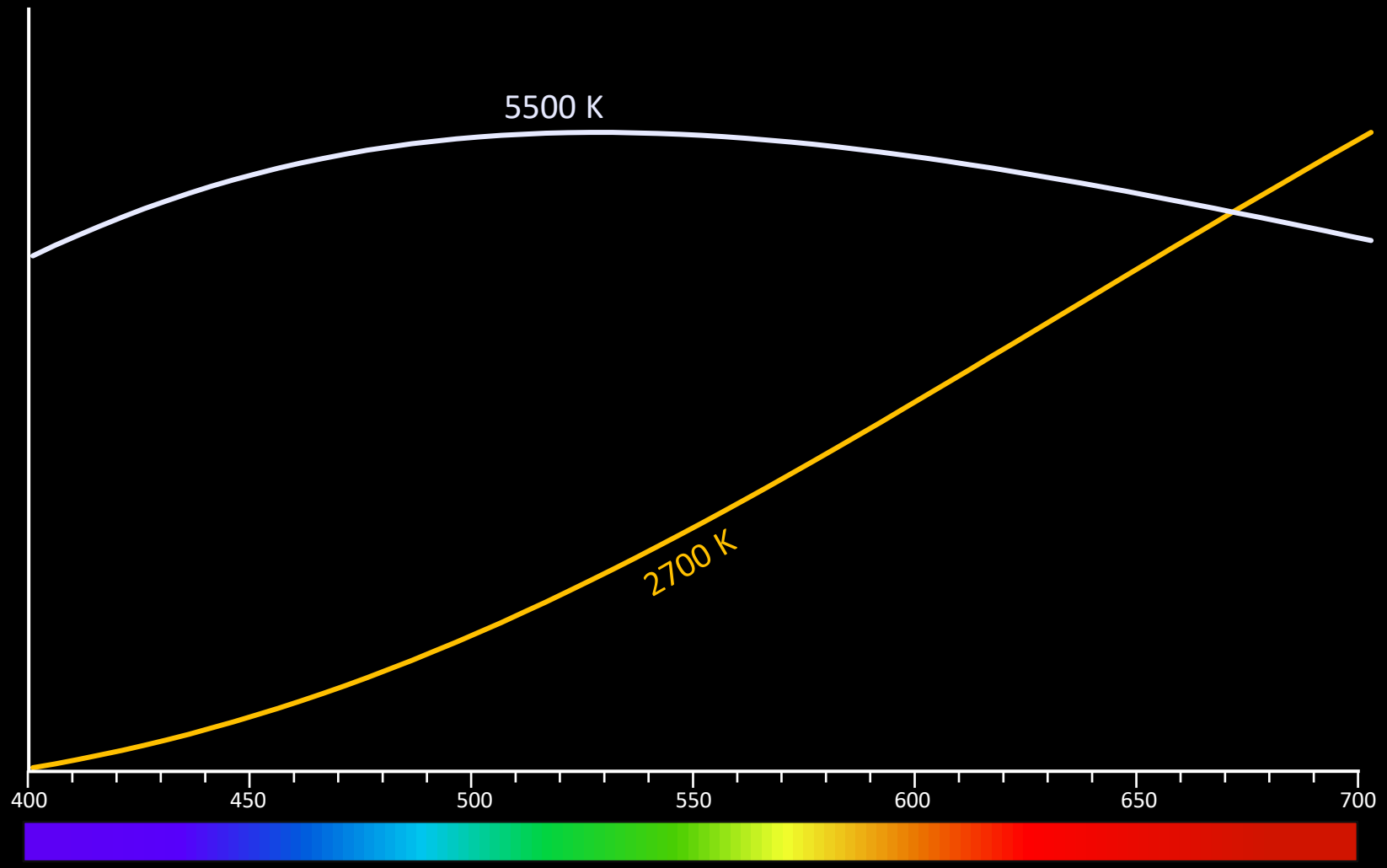
The Concept of Color Temperature

or.... how can you describe a light with just one number ???

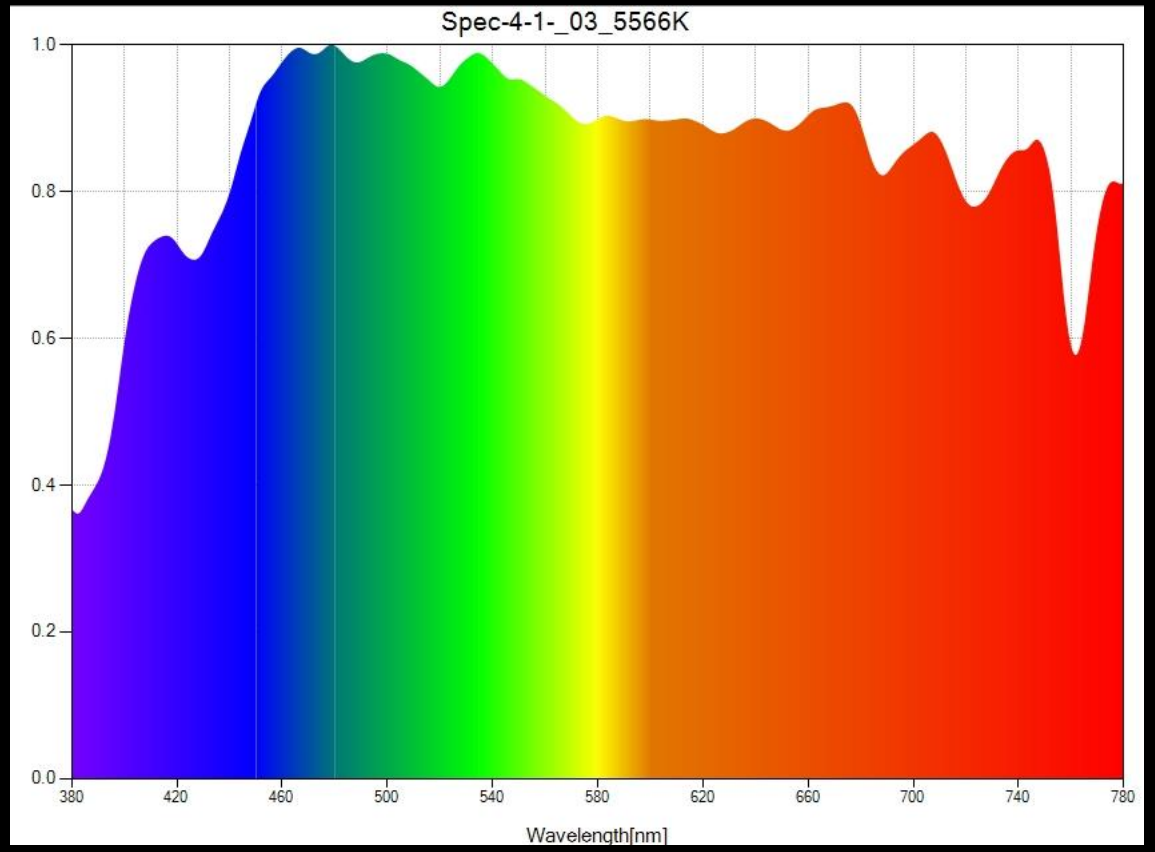


- All objects emit light based on their temperature. This is in addition to any light they reflect.
- If there is no reflected light, we call it a black body, and all light is emitted light.
- We don’t see light emitted by objects at room temperature because its in the long infrared.
- When objects get hot enough their emitted light is visible.
- The spectrum emitted is a function of temperature. As an object gets hotter, the color we see goes from red to orange to yellow to white.

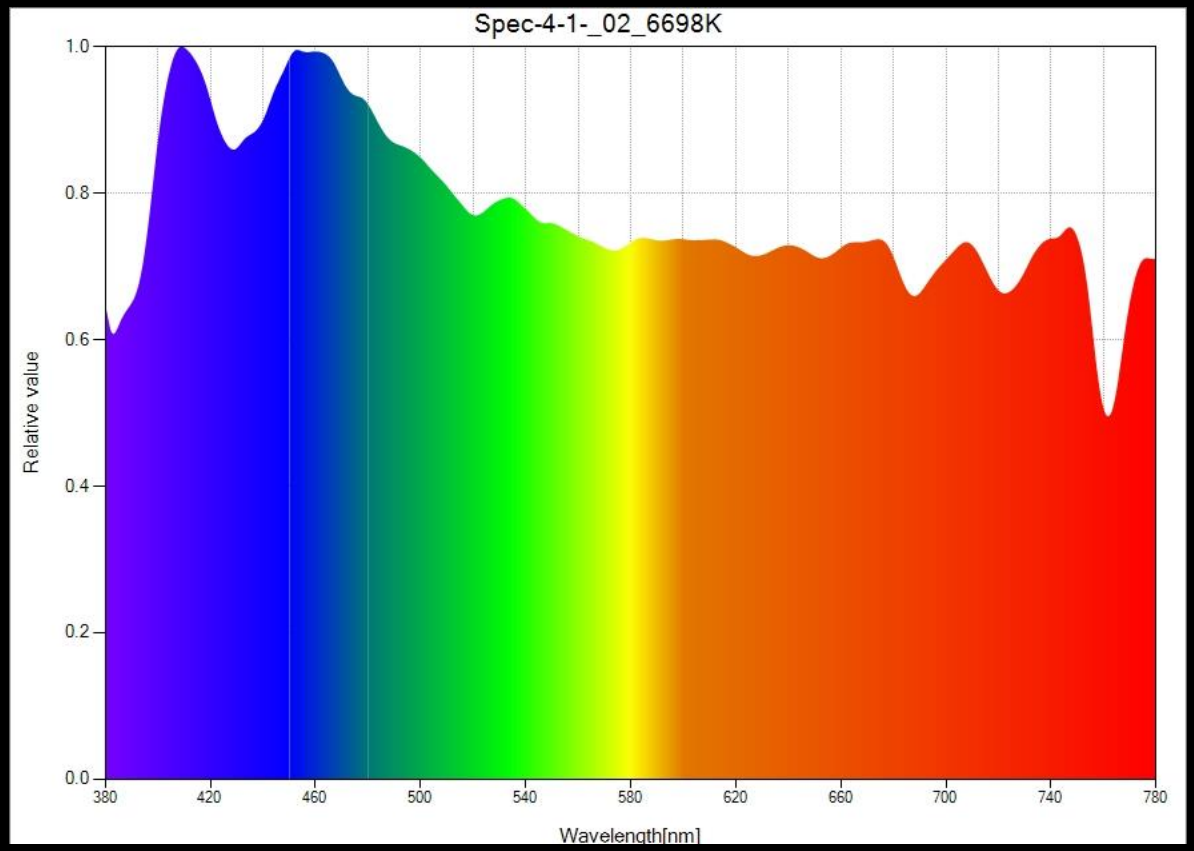
Spectral Emission of Black Bodies at 2 Temperatures



Solar Spectrum at my house a week ago in the morning

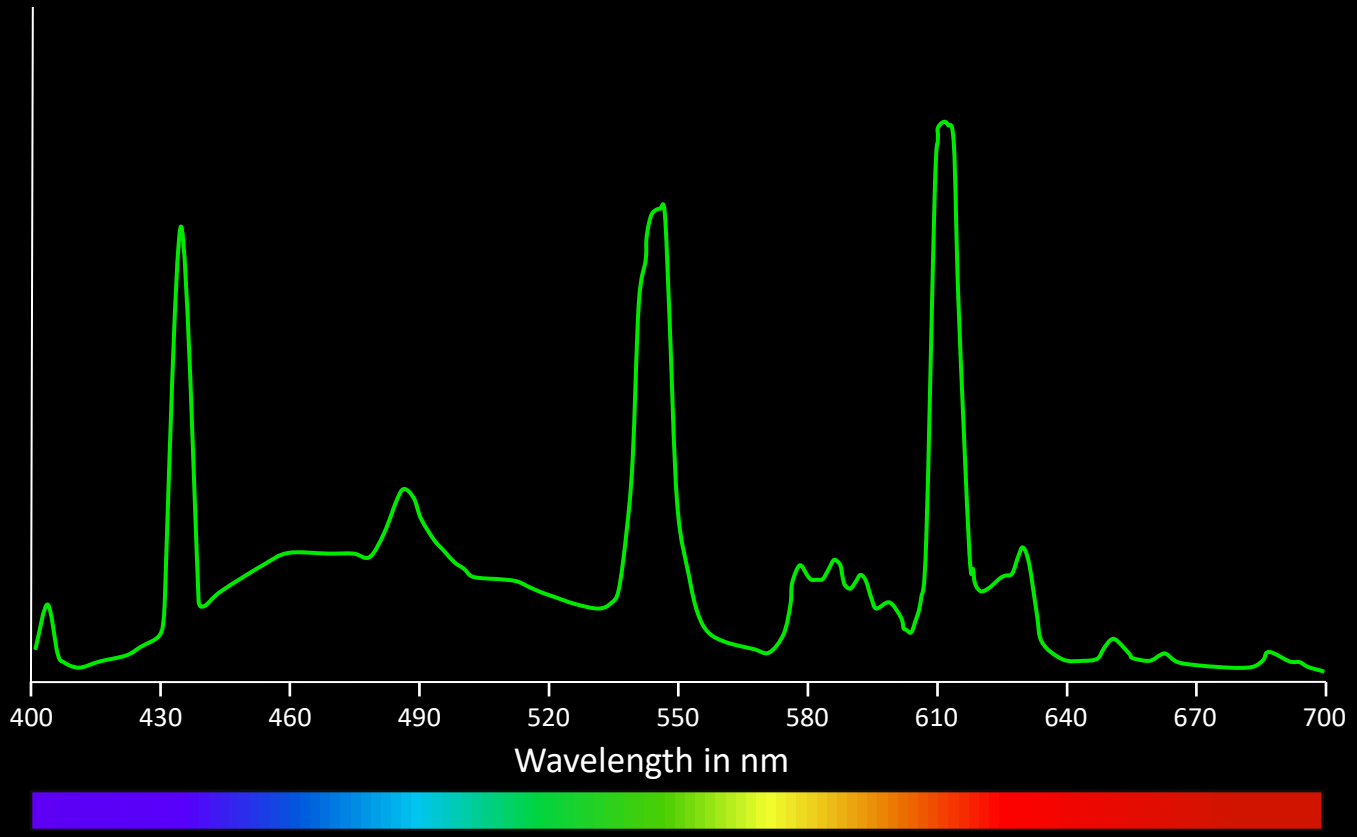


In Sun
Color Temperature: 5566 K



In Shade
Color Temperature: 6698 K

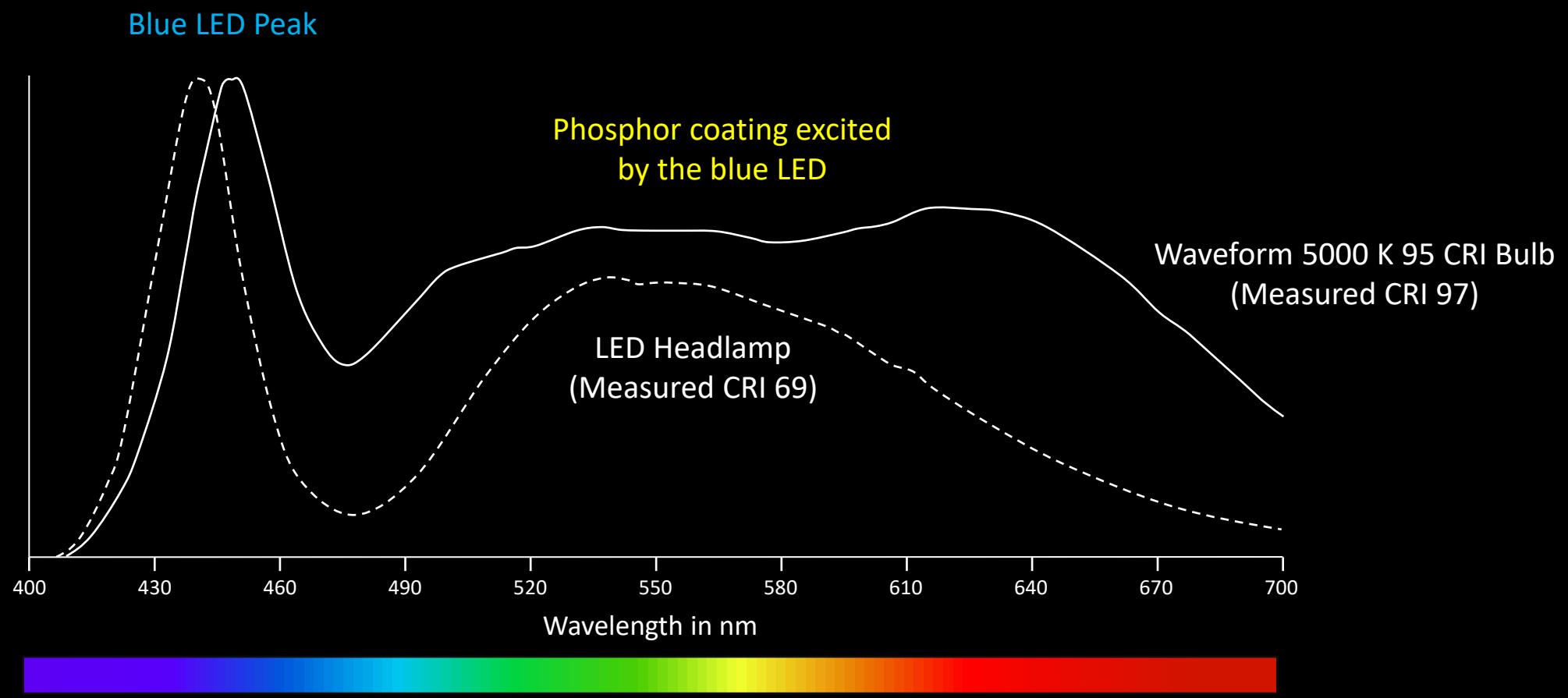
Spectra for a fluorescent light



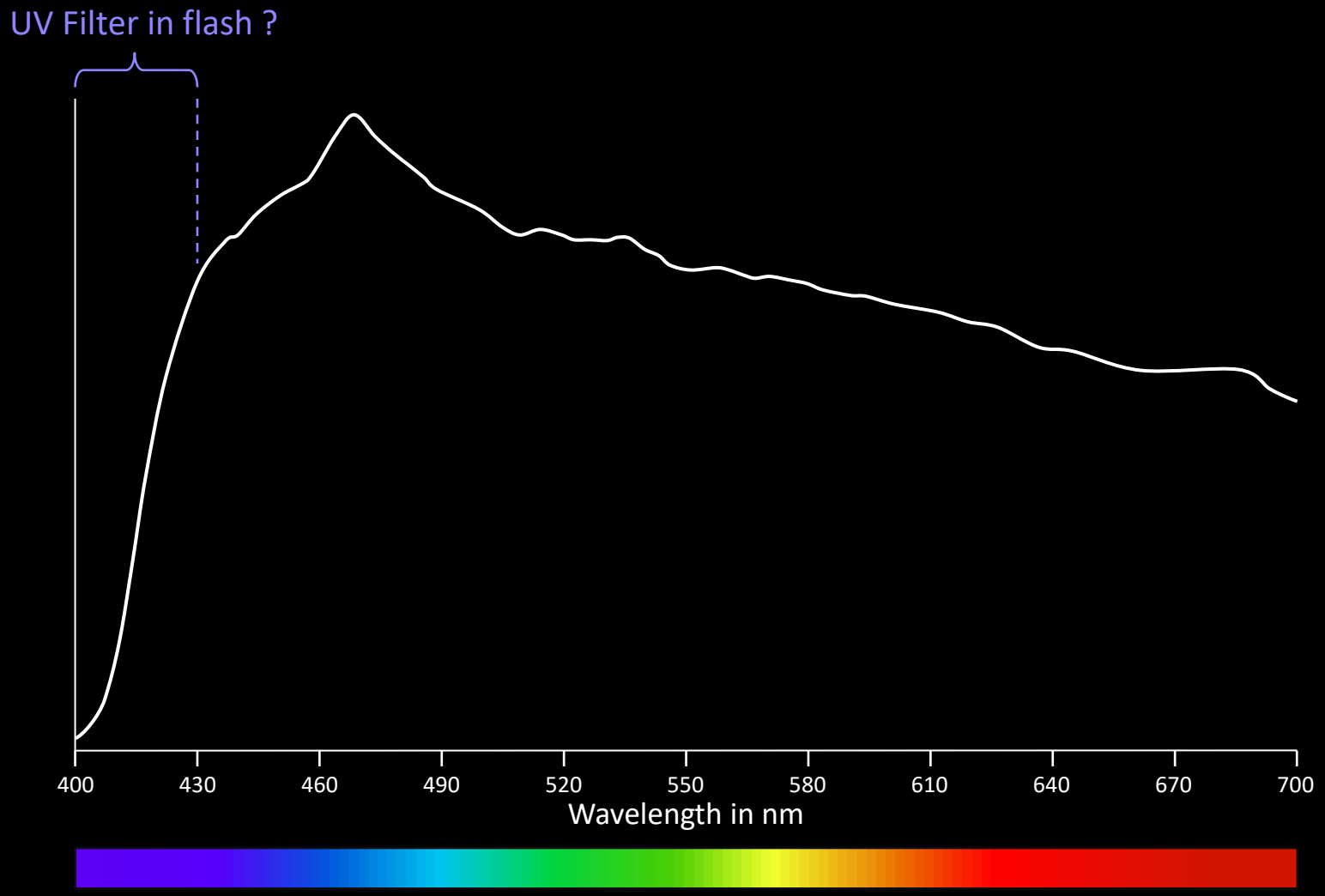
Most fluorescent bulbs have poor color for photography.

Fluorescent bulbs designed for photography typically have extra phosphors coated on the glass tube producing more peaks and a more even response than shown here.

Spectra for a Great and a Terrible LED Light

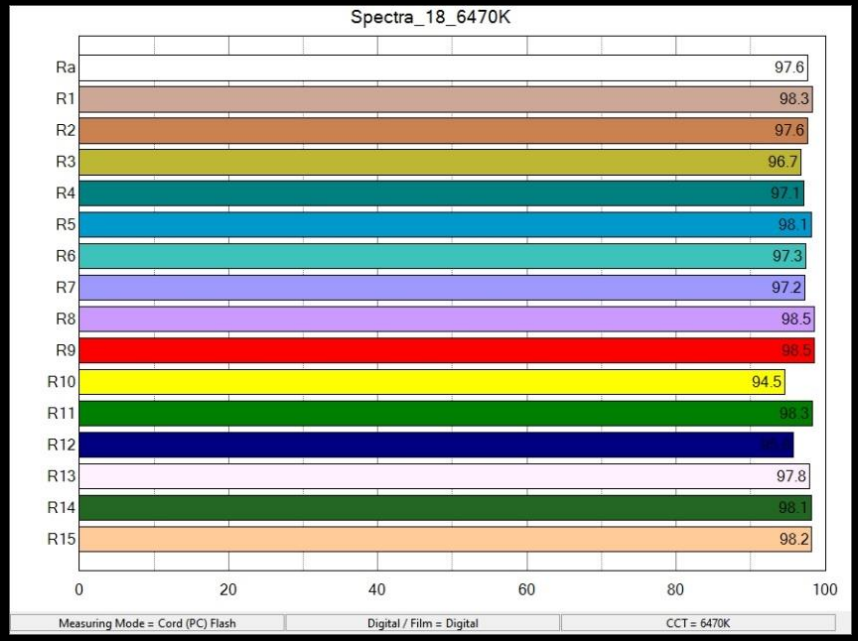


Spectrum of Canon 600EX-RT Flash

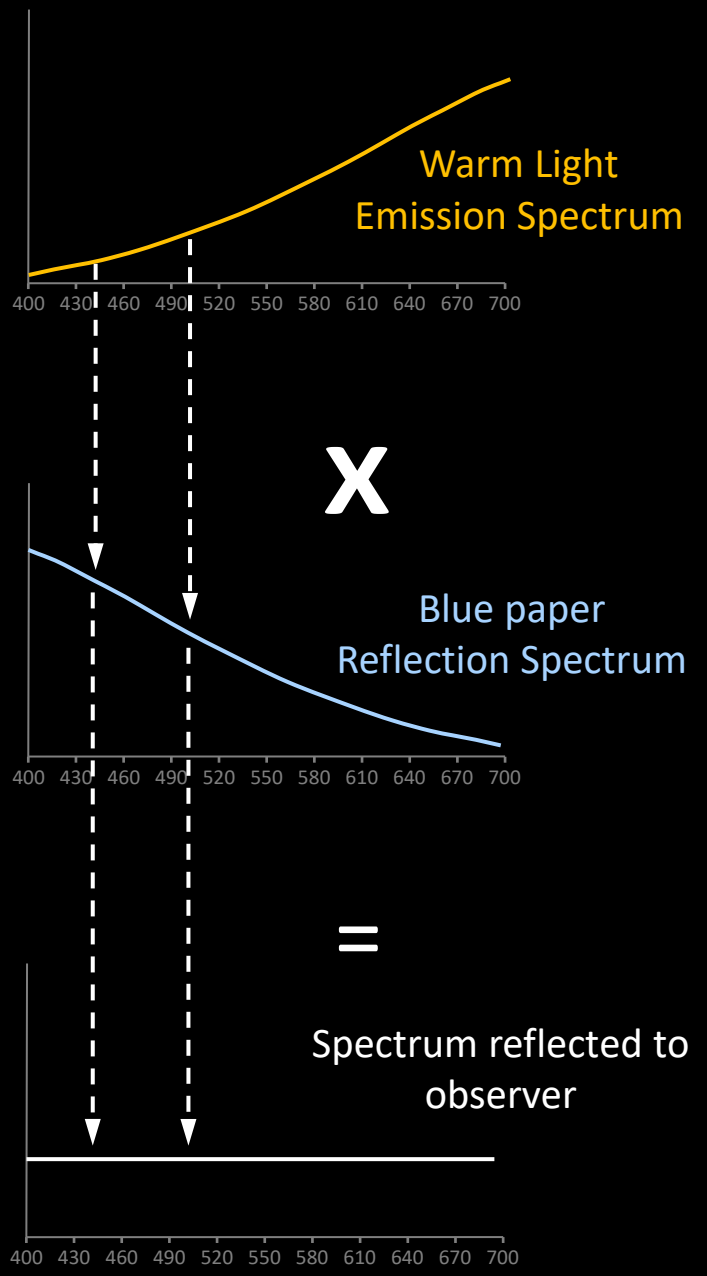


Color Temperature: 6470 K

Color Rendering Index: 97.6

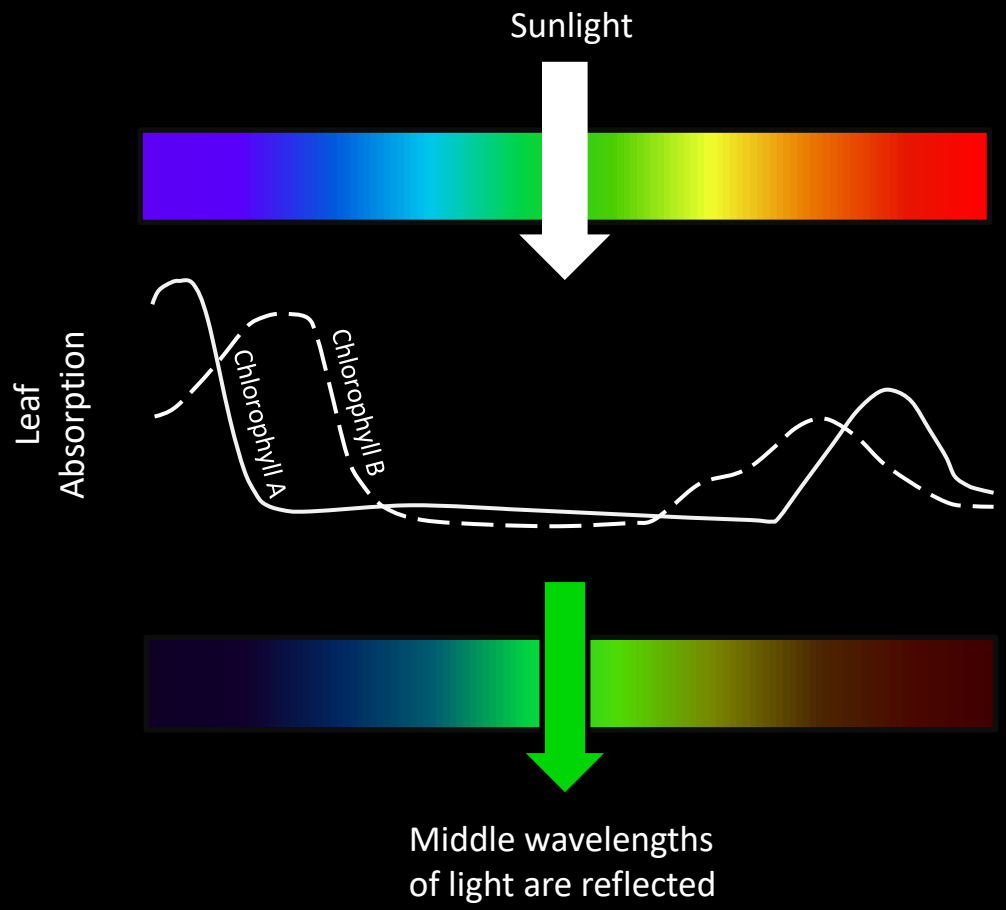


What happens to light when it reflects off a surface ?

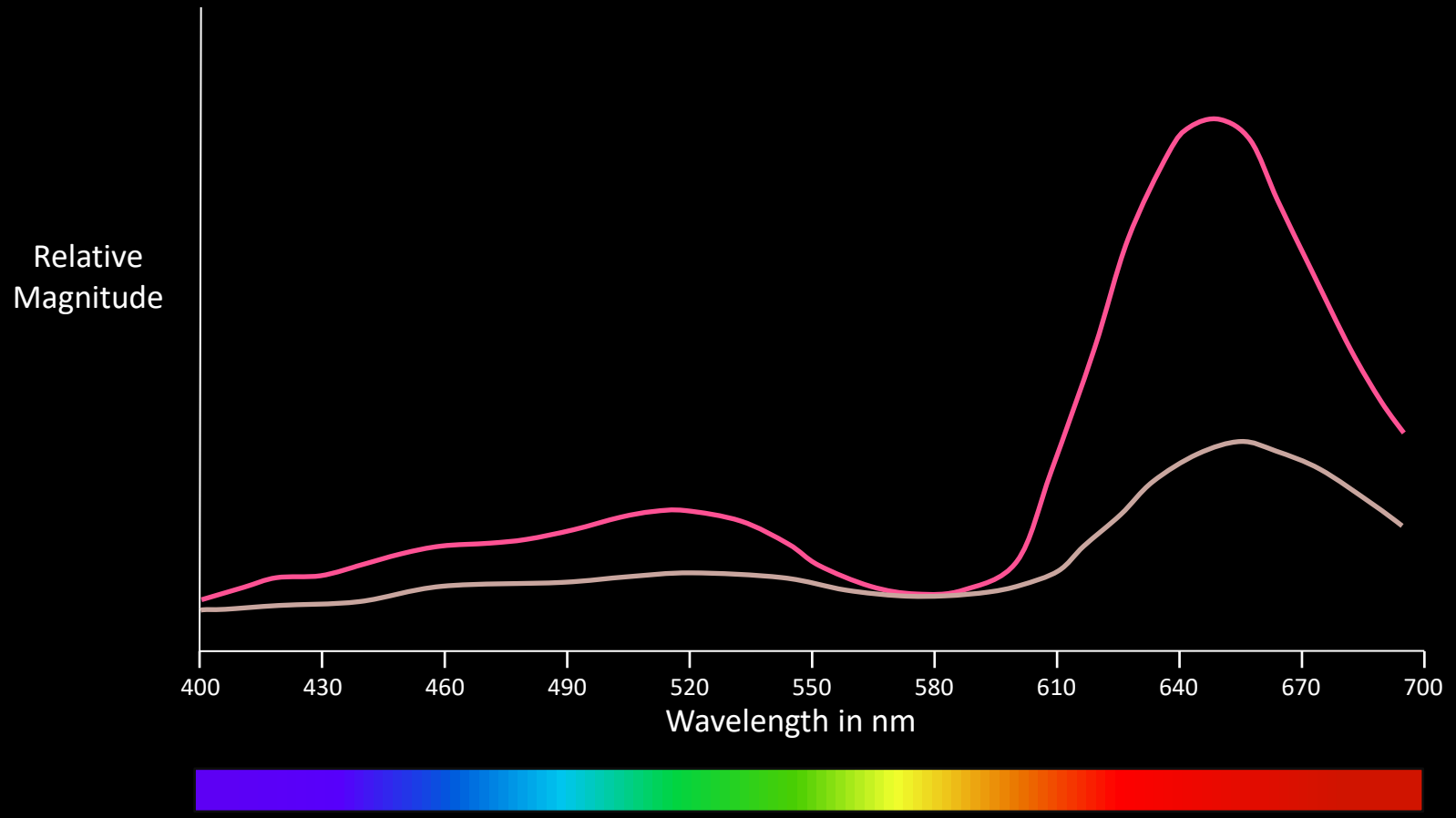


- When light reflects off a surface, the reflected energy *at each wavelength* is the product of the light energy at each wavelength times the surface reflectivity at each wavelength.
- For photography it's important to have a light with a smooth spectrum. Large peaks or valleys in the light could cause color shifts in the appearance of surfaces.
- Reflectance spectra can be angle dependent. Car paint is a good example.
- At shallow angles, most surfaces become specular reflectors and the reflected color is closer to the light's color.

Leaves are green because chlorophyll absorbs long and short wavelengths of light to make glucose

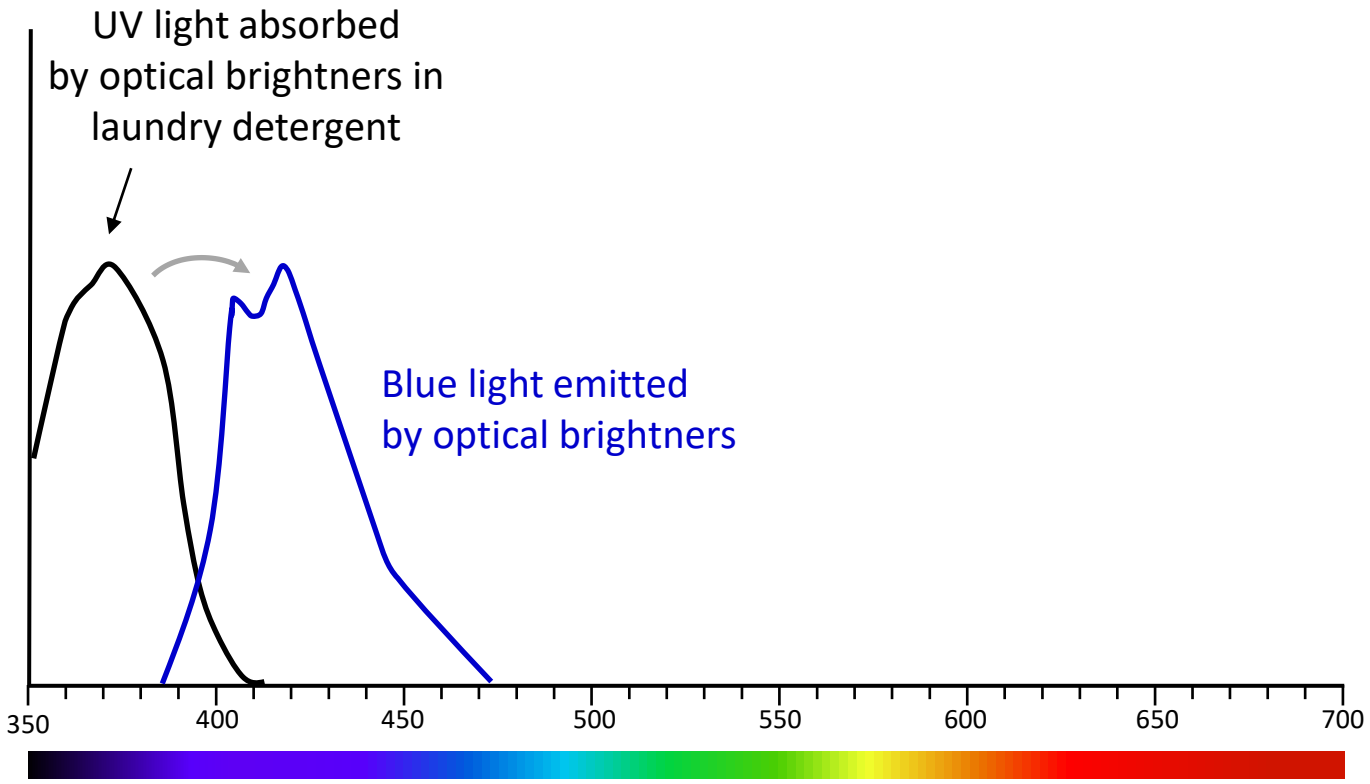


Angle-dependent reflectance spectra of Hummingbird gorget (throat)



Fluorescence

- Usually, when a given wavelength of light hits a surface it is either absorbed or reflected *at the same wavelength*.
- Fluorescence is when light at a short wavelengths is absorbed and reemitted at a longer wavelength.
- Examples:
  - Bright green and orange clothing worn by safety workers.
  - Fluorescent light bulbs
  - White LEDs
  - Optical brightners in laundry detergent (shown to the right)



Trivia: Your teeth fluoresce.

Summary of Lighting Spectra

- For most modern lights, the light-producing mechanism is not black body radiation, but other mechanisms.
- Color Temperature a measure of hue, not color quality. Being a single number, it is an approximation.
- Lights *designed* for photography have better spectra – smooth, and has light across the full visible spectrum.
- A common measure for a light's color quality is CRI, Color Rendering Index. Values > 90 are good and values >95 are excellent.
- CRI is a measure of quality *for a human observer*.
- TLCI and SSI are measures of color quality *for digital cameras*.

Lighting Color Quality Standards

If you're shopping for lights for home or photography, look at these numbers.

Standard	Reported Values	Notes
CIE CRI	R1-R15 values for 15 test colors (0-100) Ra (aka CRI, CRI (Ra)) = average of R1-R8, the less saturated colors R9 often reported by itself as indicator of quality of deep red Re (aka Extended CRI, CRI (e), CRI (Re) = average of R1-R14	*Color Rendering Index* CRI (Ra) Oldest and most commonly used Based on CIE 1964 UV Re not used much
CIE TM-30	R_f (aka CFI, Color Fidelity Index) – color quality, (0-100) R_g – Saturation effect. Can be negative if light unsaturates colors. Color fidelity for 16 hue ranges and for 99 color samples	CIE recommends over CRI, but not as widely used
NIST CQS	Q_a (0-100)	*Color Quality Scale* Based on CIELAB
EBU TLCI	TLCI (0-100)	*Television Lighting Consistency Index* Popular in video capture applications Describes color quality as seen by digital cameras
SMPTE SSI	SSI [reference light source] (0-100) Reference light source can be CIE A, CIE D50, CIE sID65, CIE Source B, Pnnnn (for a Plankian/Black Body at nnnn K), etc.	*Spectral Similarity Index* Developed by The Acadamy of Motion Picture Arts & Science for comparing lights, especially as seen by digital cameras.

These standards describe the quality of a light for color discrimination, color accuracy, and saturation.
They do not describe color temperature, brightness, or efficiency.
Newer standards better describe peaky lights like LEDs and consider both human viewing and camera capture

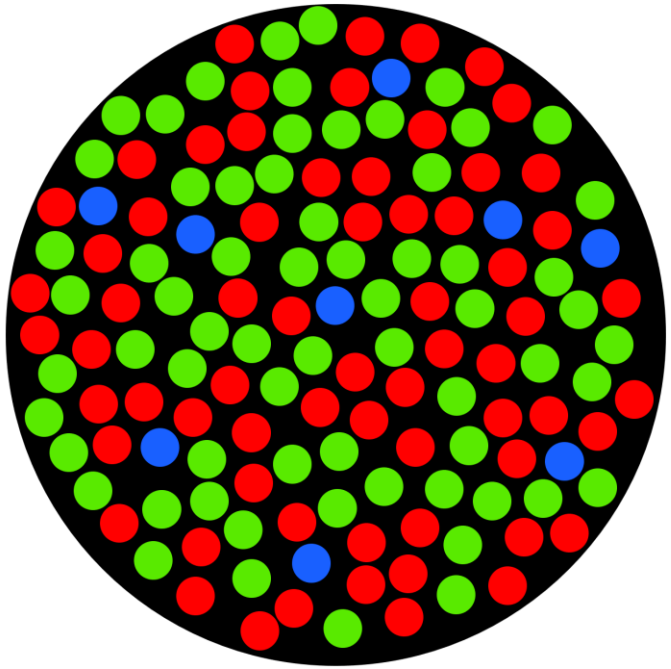
What we've learned so far

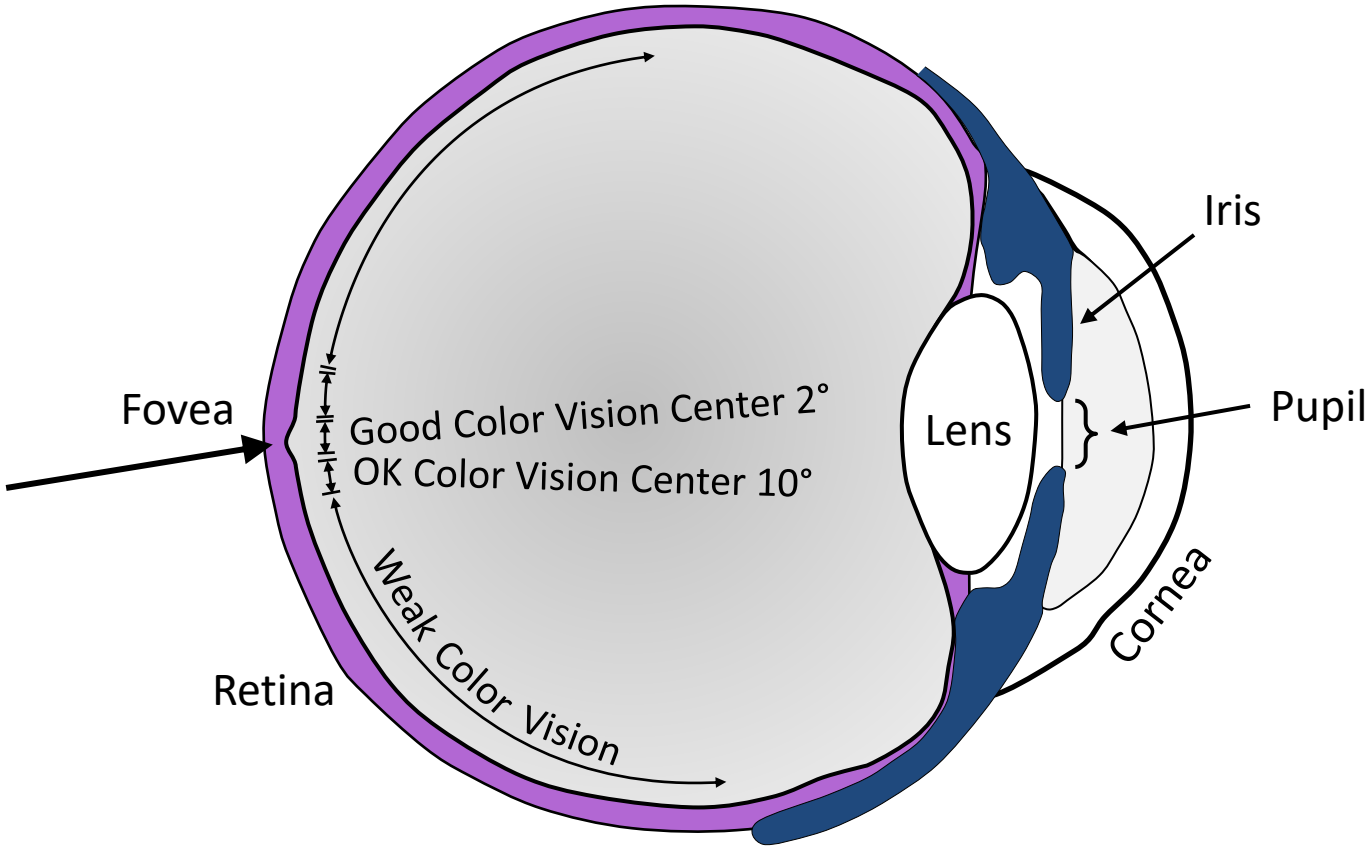
- Visible light is made of a continuous spectrum of wavelengths.
- Lights can have many types of emission spectra; surfaces have a reflection spectrum
- When light reflects off a surface, the resulting spectrum is the product of the light spectrum and the surface reflectance spectrum.
- Color temperature is an approximate way to describe the spectrum of light, measured in Kelvins. Being a single number, it is a rough approximation of hue, and says nothing about a light's color rendering qualities.

Trivia: In the early 1900's, the French/Luxembourg physicist Gabriel Lippman invented a photographic process that reproduced the entire spectrum. He won the Nobel Prize for his invention in 1908. It uses an extremely fine-grained emulsion to exploit interference, like a hologram, and must be illuminated and viewed under specific conditions, making it impractical for general use.

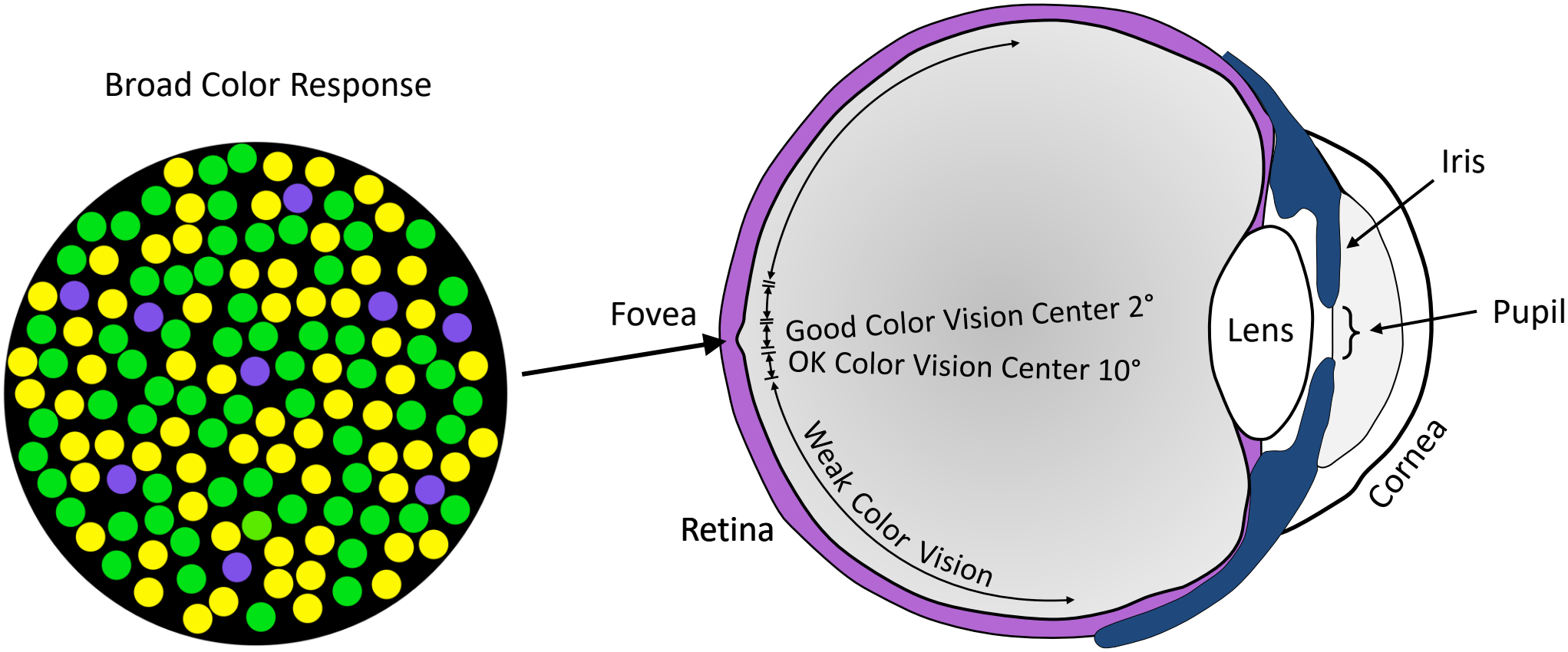
Color vision comes from 3 types of color sensors, called cones.

Distribution of Cones in the Fovea

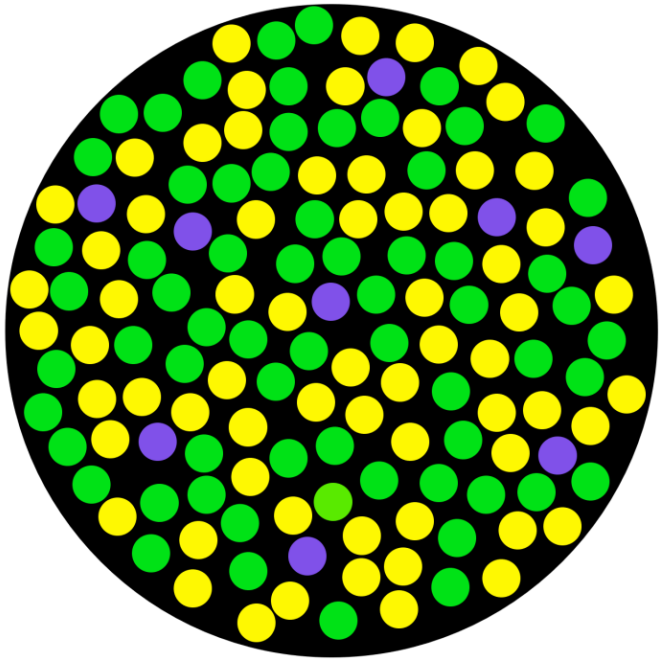


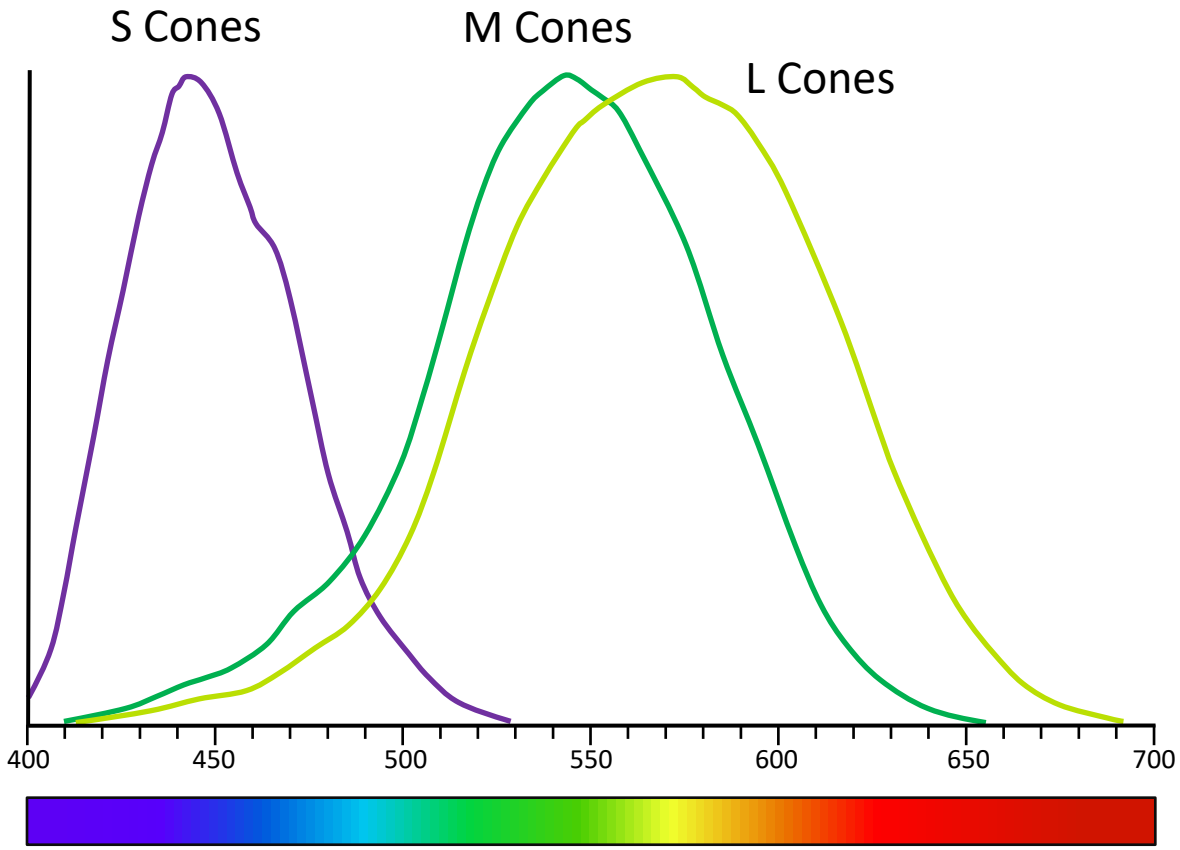


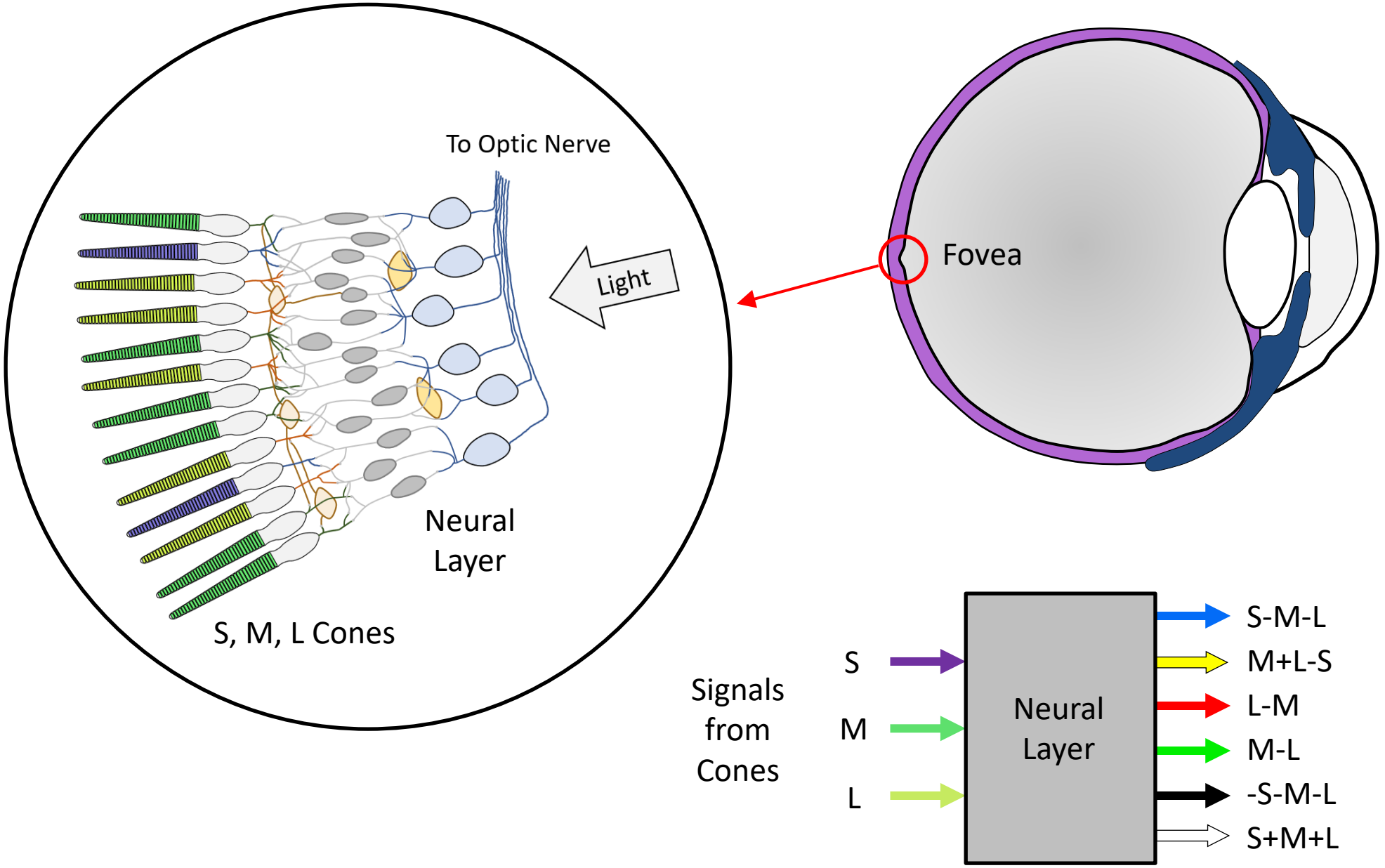
Although sometimes referred to as Red, Green, Blue, our cones are actually purple-blue, green, and yellow-green.



Actual Cone Colors





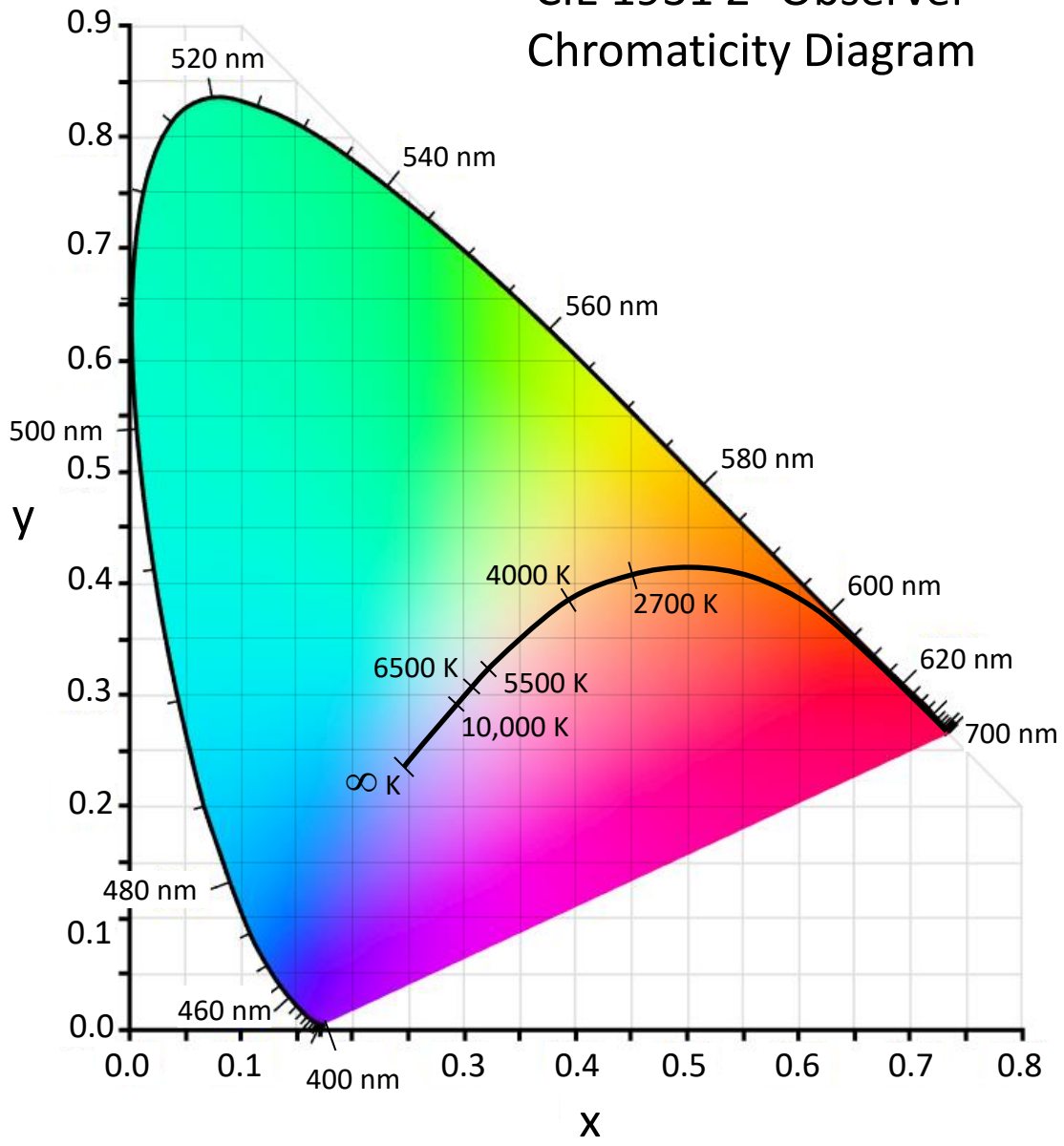


Rods and non-color mechanism not shown

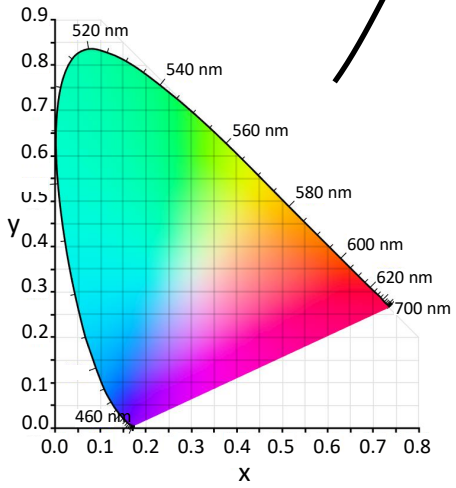
Color Spaces that describe human perception

- As we move from the scientific world of spectra to the human world of color, we need some way to describe color.
- One of the first color spaces to cover all colors humans can see was 1931 CIEXYZ.
    - Based on extensive testing of people with normal color vision.
    - Refers to how we see color in the center 2° of our field of view.
    - Still used widely today.
- There are dozens of commonly used color spaces, many of which only cover part of the colors we can see.

CIE 1931 2° Observer Chromaticity Diagram



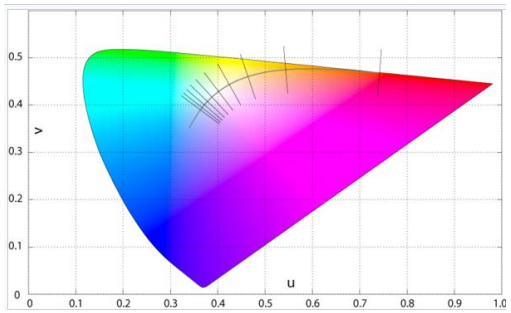
Evolution of CIE Color Spaces



CIE 1931 XYZ 2°

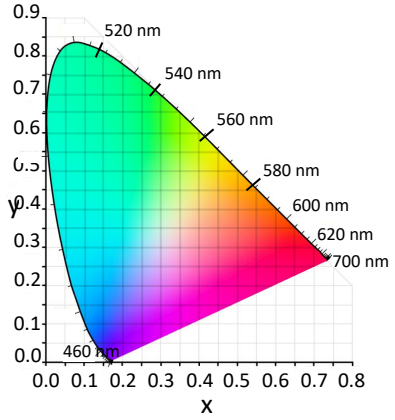
- First widely used color reference
- Only 17 people were tested
- Still widely used

Simple Math



CIE 1960, 1964 UV

- More uniform than CIE 1931 XYZ
- 1960 version Obsolete
- 1964 version used to calculate CRI



CIE 1964 XYZ_{10} 10°

- More accurate than 2° observer
- Used in food packaging

Complicated Math

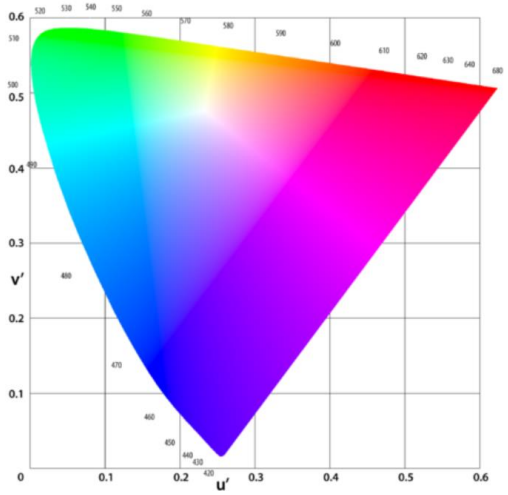
Complicated Math

CIELAB 1976

- Lightness (L) , a* (red-green) and b* (blue-yellow) resemble optic-nerve signals shown earlier
- Perceptually uniform
- Widely used

CIE 2006 2° & 10° Observers

- Best model for predicting OLED displays



CIELUV 1976

CIE 1976 committee couldn't decide, so published both.

Color Spaces

Color Space	% Human Gamut	Features, Where Used
CIE 1931 2° XYZ	~100 %	Used to define colors and standards
CIE 1976 LUV / LAB	~100%	Roughly perceptually uniform. Used to define colors and standards.
NTSC 1953	38.1 %	U.S. & western hemisphere TV for amost 70 years
sRGB	33.2 %	Everything on the internet. JPG. Uses same primaries as Rec. 709.
Adobe RGB	38.7 %	Expanded cyan-green coverage to better cover printer gamuts. Used in HDMI, Adobe Lightroom Classic.
Adobe Wide Gamut RGB	76.1 %	Uses pure spectral primaries
ProPhoto RGB	76.5 %	Kodak, Adobe Lightroom Classic CC, Adobe raw
Rec. 709	33.2 %	Youtube, HDTV, same as sRGB
REC 2020	57.2 %	UHD-TV
DCI-P3	41.7%	Digital Cinema

The CIE color spaces describe human perception

All Other color spaces are described in terms of the CIE color spaces

These describe the meaning of bits that travel to/from files, displays, streaming platforms, browsers, photo editing programs, printers, etc.

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- Most of the things we encounter in photography are within the gamut, or close to within the gamut of most color spaces.
- For example, sRGB's 33.2% coverage of the human gamut is a small limitation, not a disaster.
- Examples of colors outside most color spaces are very saturated colors, pure colors like LED Christmas lights and some neon colors. Bright structural colors in birds can also fall outside some color spaces.

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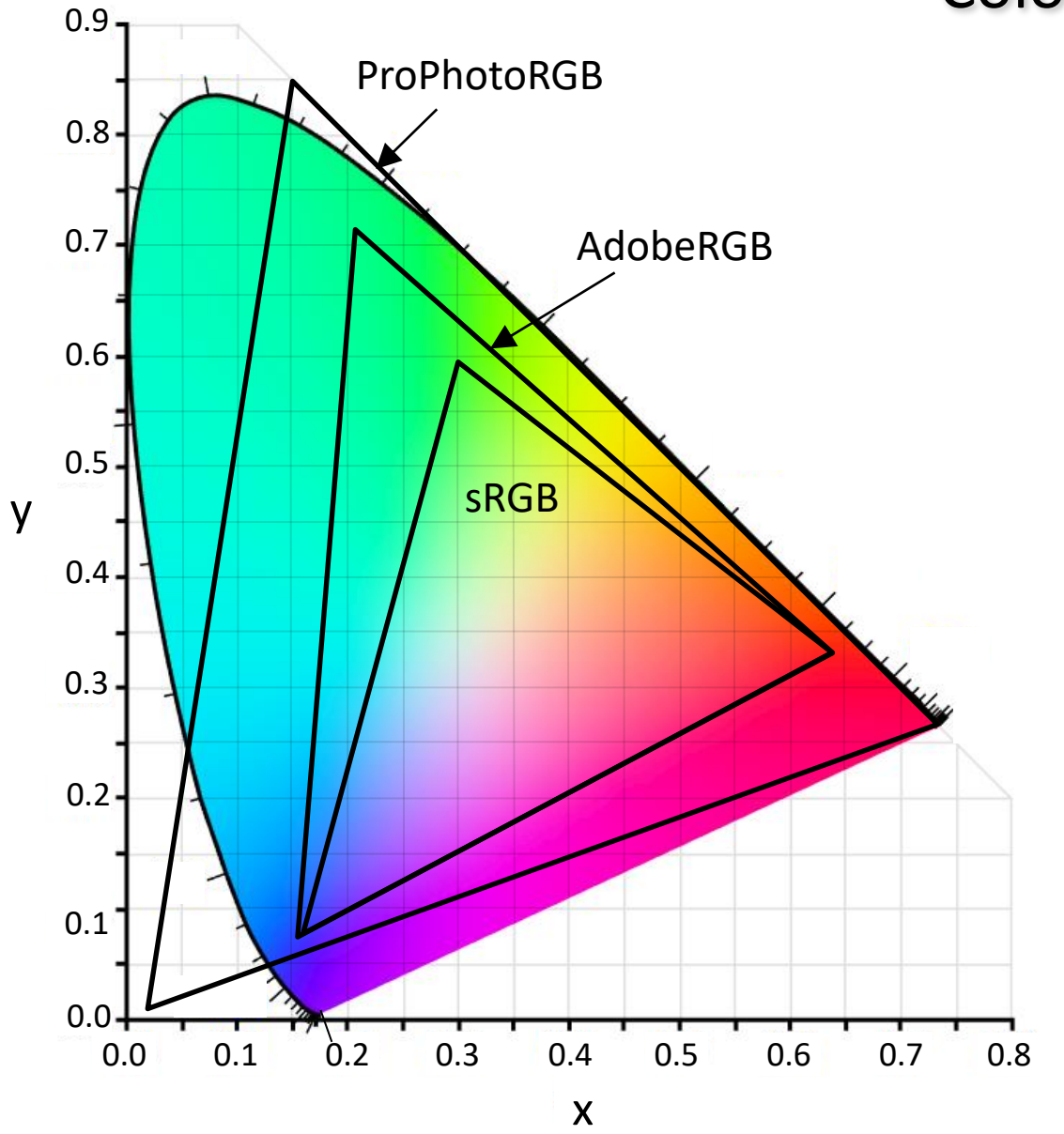
There are many ways to calculate these numbers. I have used 1976 LUV because it is close to perceptually uniform. Using CIE 1931 is more common. Some people do volume calculations rather than area. Take them all with a grain of salt.

Color Space Gamuts



- This often-shown image makes the differences in color spaces look much larger than it is. The 1931 CIE diagram is not perceptually uniform.
- The best monitors out there ($4000 and up) can cover 99% of AdobeRGB, but not PhoPhotoRGB due to the intense primaries required to hit the corners.
- Non sRGB color spaces only make sense for printing. Photo sharing sites, browsers, social media sites, and pretty much the entire internet uses sRGB.
- When editing, remember that displays reach max saturation on bright colors, where printers reach max saturation on dark colors.

Best advice: Use sRGB for everything except very high-end printing.

If, your pictures are taken in raw format, *and*

you have a picture that has colors significantly outside the sRGB gamut, *and*

you plan to make your own prints or use a printing service that accepts non-sRGB, *and*

you have a high-end printer with 10 inks, *and*

you plan to use a high-end paper like premium photo luster, *and*

you have an ICC profile for that printer/paper combination, or have calibrated that printer/paper combination yourself, *and*

you have a wide-gamut 10-bit monitor and a colorimeter to calibrate it, *and*

you realize that some of the colors you want to print may be outside the gamut of your monitor while editing, even though your printer can reproduce them, *and*

when done you will display the print somewhere with a bright continuous-spectrum light, ideally 5000 K Halogen or WaveformLighting D50 95 CRI LED, then

you might see a benefit from a ProPhotoRGB or AdobeRGB workflow.

Go to digitaldog.net, which has tons of great information on color managed workflows.

Must-watch video at digitaldog.net: The Benefits of Wide Gamut working spaces.

Color Constancy

- Color Constancy is the phenomenon where we tend to perceive colors the same, even when the color of light is different.
    - White paper always looks white.
    - Red apples always look red.
    - Skin always looks like skin.
- Your visual system adjusts your perception of colors by considering everything in your visual field.
- Our perception of color, like lightness, is *relative*.
- This has some huge implications for photography.

What enters our eye

What we see

Implications of having our full visual field influence our perception of color

1. The visual surround where we edit pictures will almost never represent the environment where we took them.

2. We can't control the environment where others will view our pictures.

3. Printed pictures will experience varying lighting throughout the day from the mix of window light and artificial light.

4. But it mostly works. Why?

    - Colorimetric accuracy isn't usually the goal. The goal is a picture that looks good, and reproduces a feeling or memory.

    - Our visual system is surprisingly accommodating.

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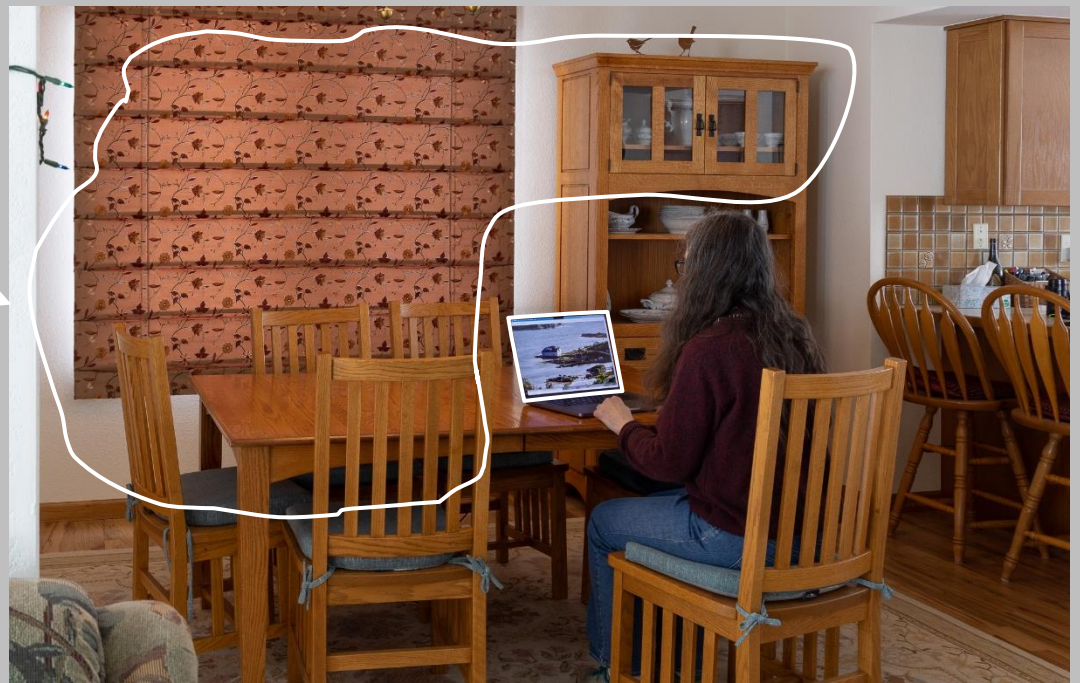
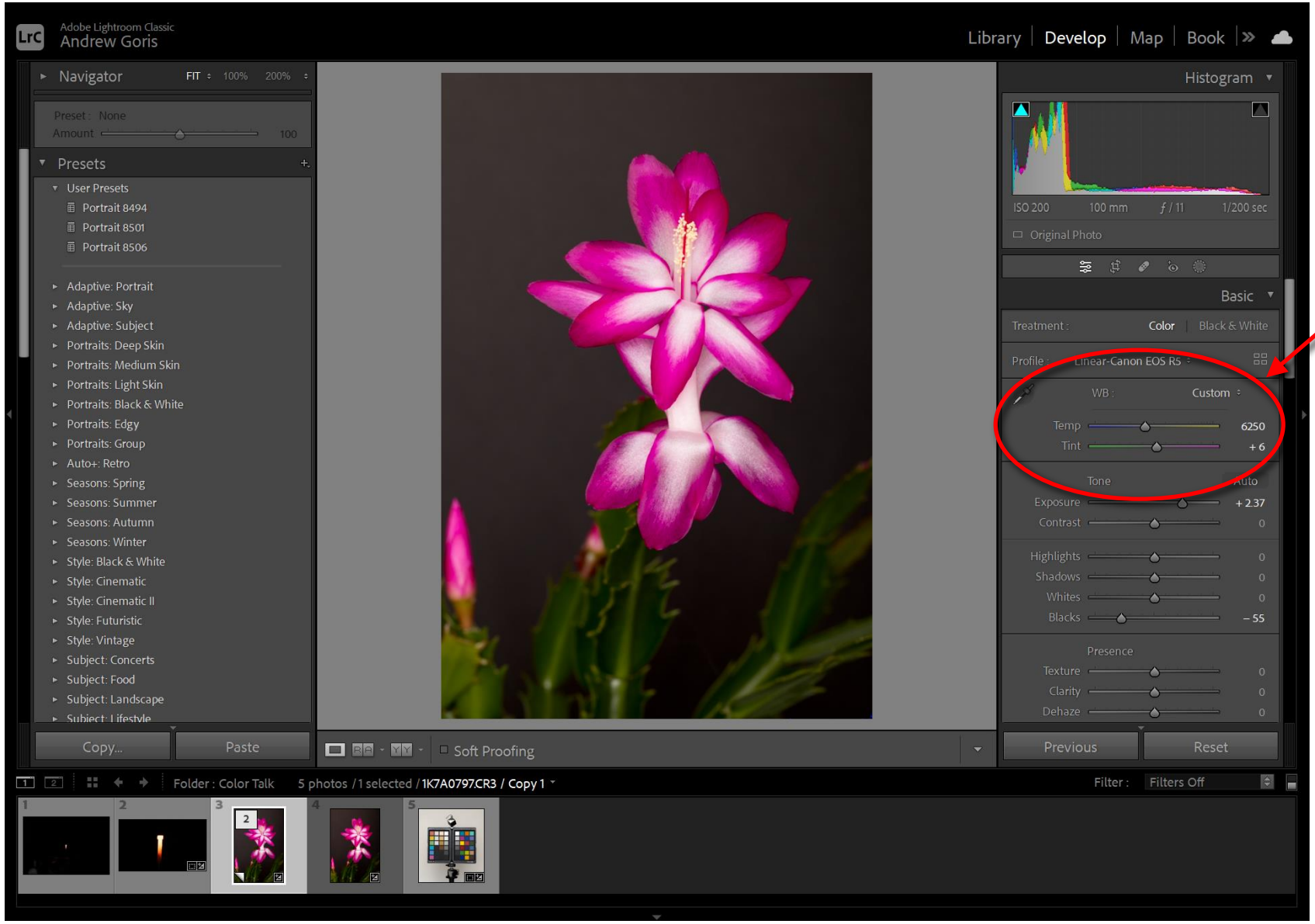
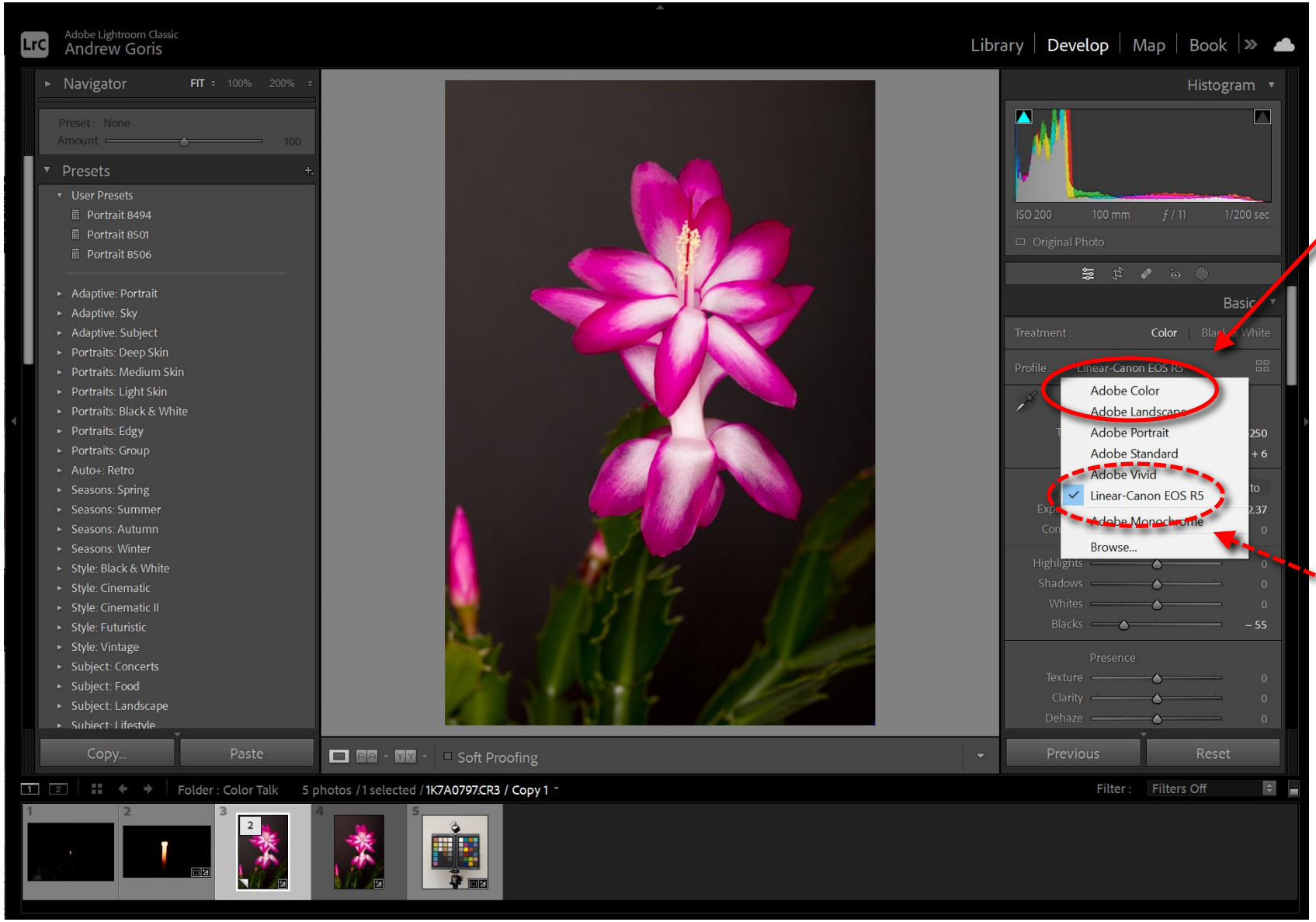




White Balance: Step 1

good enough >90% of the time

- Everyone's familiar with the white balance sliders.
- The first slider adjusts for the color temperature of the illuminant and the second slider adjusts the orthogonal color axis to color temperature.

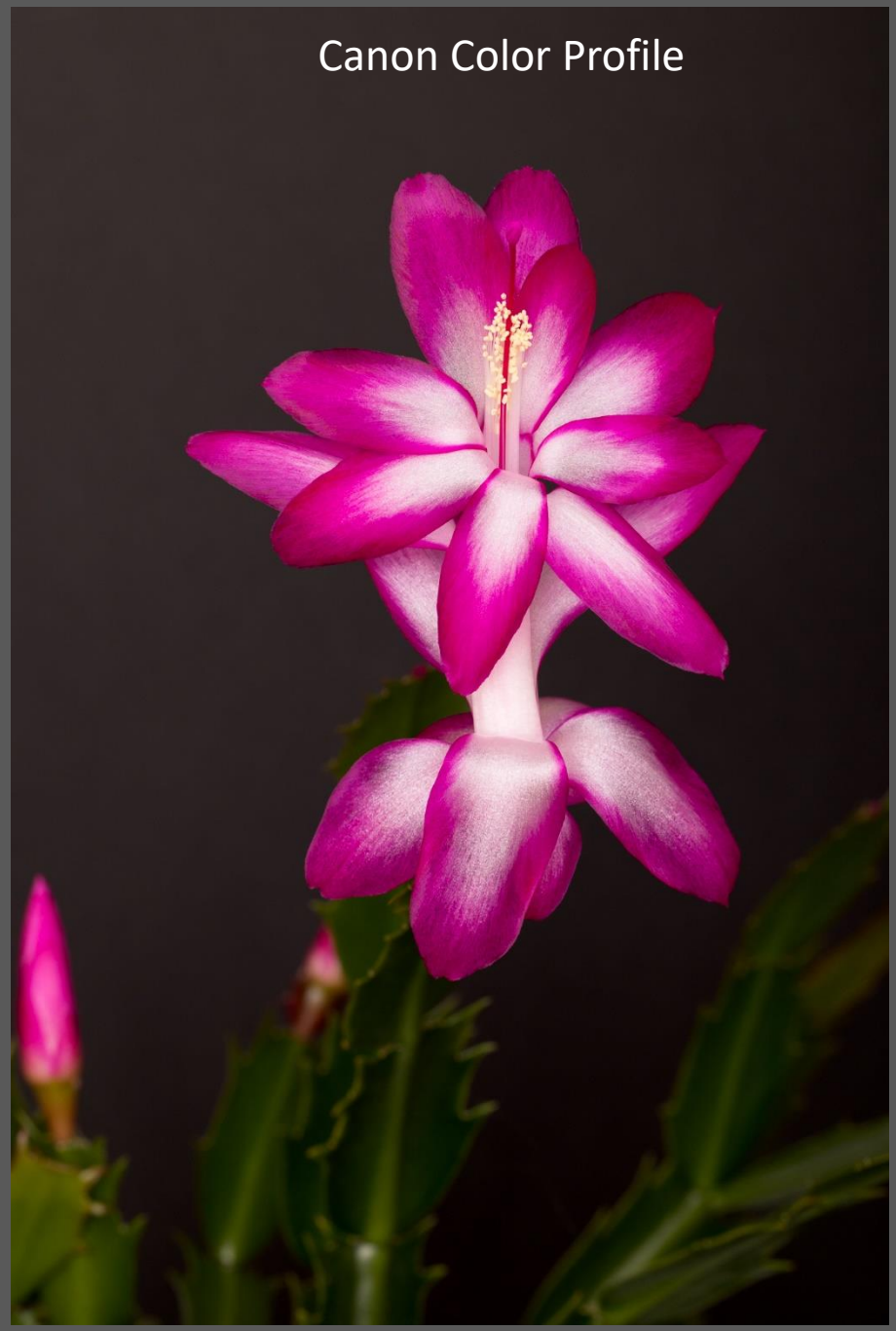


White Balance: Optional Step 2

- If you can't get the colors you want with the white balance sliders, experiment with color profiles.
- Profiles contain color conversion information plus tone curves.
- The Adobe profiles have strong built-in tone curves. When you adjust a tone curve in Lightroom, your adjustment is being applied on top of the Adobe curve.
- When I want certain colors and don't want Adobe anything, I'll start with a linear profile designed for my camera model.

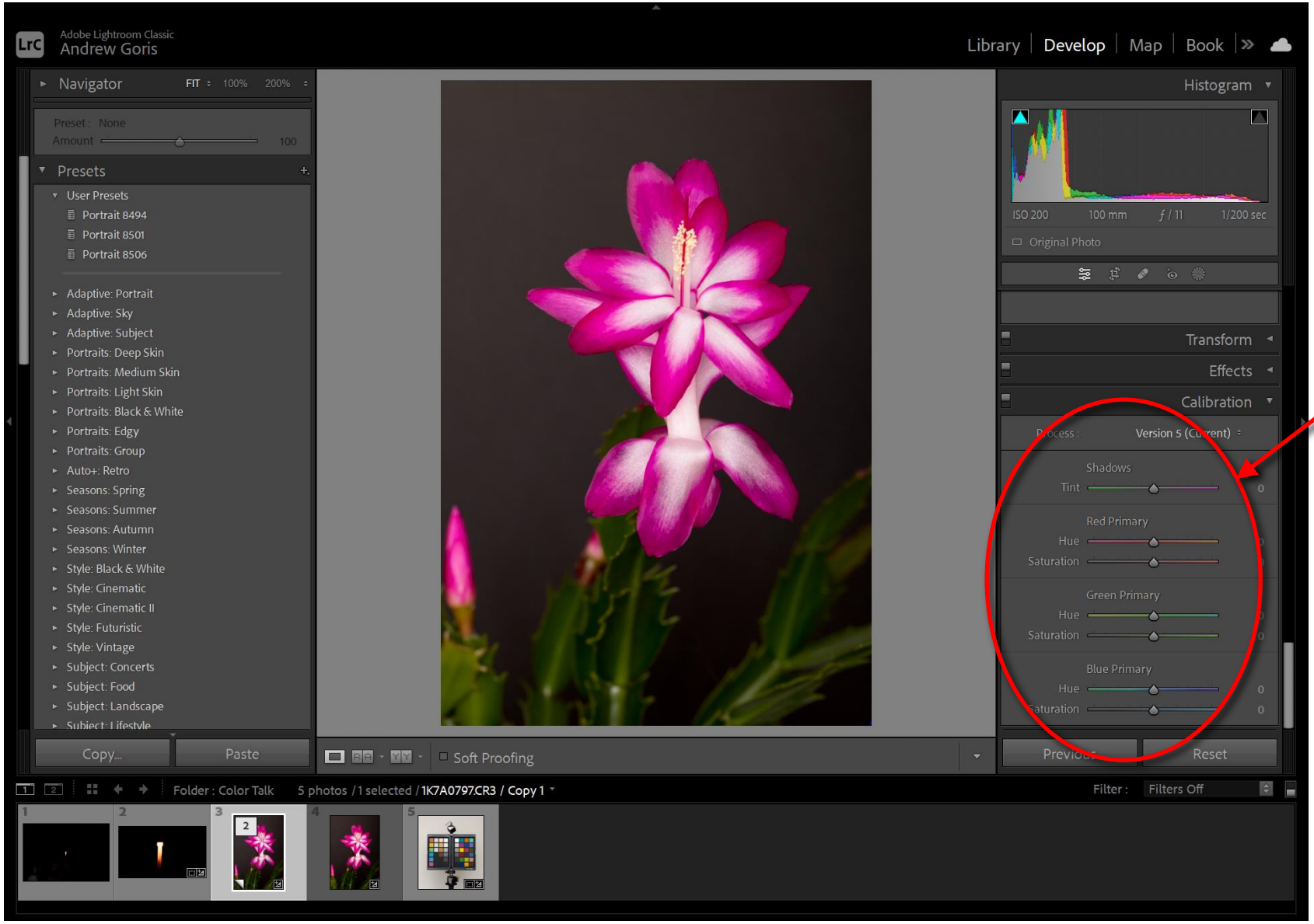
Adobe Default Color Profile

Canon Color Profile



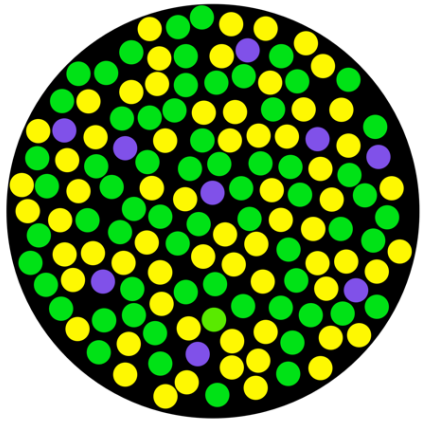
- The color differences are sublte.
- Canon profile requires adding your own tone curve.
- Canon color profile is more accurate – the petals with the Adobe profile shift from red to magenta. The actual petals shades of magenta
- 100% color accuracy is not a goal unless you’re copying artwork or doing scientific research.

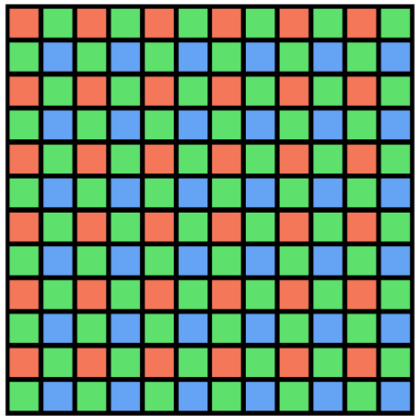
White Balance: Optional Step 3

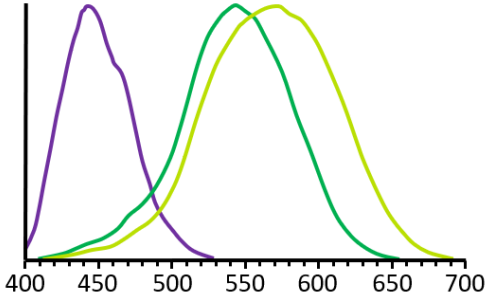


- This panel will give you lots of control.
- Trying to adjust 7 sliders is like playing color whack-a-mole.
- You will probably never need to use these controls unless you have an unusual lighting situation.
- The easiest way to good settings is to photograph a color calibration chart and software that calculates these automatically.

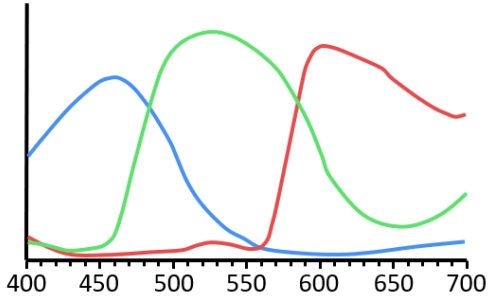
How Cameras Capture Color







Human Cone Response



Camera Sensor

- Camera sensors have a repeating pattern of red, green and blue pixels. While many patterns and colors have been used, the pattern and colors shown here are the most common, and referred to as a Bayer pattern.
- The broad spectral response of the pixels is a design tradeoff between color discrimination, color accuracy, and capturing the most light.
- In the camera industry the color space of the sensor is referred to as SensorRGB. Colors in SensorRGB are somewhat dull due to their broad spectral response. They are unique to each camera.

Rendering Intent: Adjusting colors when moving between color spaces

Rendering Intent	What it does	When to use it
Perceptual 	• Out-of-gamut colors pulled into gamut. • In-gamut colors near edge of gamut pulled in. This keeps a distinction between colors near the gamut boundary, but can desaturate a little.	• Scans of slides and prints • When overall color relationships and color balance is more important than absolute color match.
Relative Colorimetric 	• Preserves white point and in-gamut colors. • Out-of-gamut colors mapped to nearest in-gamut color.	Relative Colorimetric and Perceptual are both useful for general photography
Absolute Colorimetric	• Preserves white point • Maps input colors exactly to output colors	• Used for proofing where the printer being used for the proof has a much wider gamut than the process that will be used for products. • Not applicable for our photography.
Saturation	Pulls saturated colors towards the edge of the output gamut. Increases color punch and exploits the full output gamut.	Graphics, charts, line art when you want to take advantage of the full gamut of the output device.

Another setting:

Black Point Compensation 	Adjusts black level to prevent black clipping or clogging of shadow details.	If you have important shadow detail you want to preserve.

The Ultimate Color Correction

Datacolor SpyderCHECKR Color Chart and Calibration Tool. $139 at B&H.

Tip: don't print your own color chart. The colors will be metamers that won't behave the same as a true color chart under different lighting conditions.

When you might want it:

- Color critical work, like copying art, textiles, botany
- In unusual lighting situations
- When you want to get perfect skin tones

Nice features:

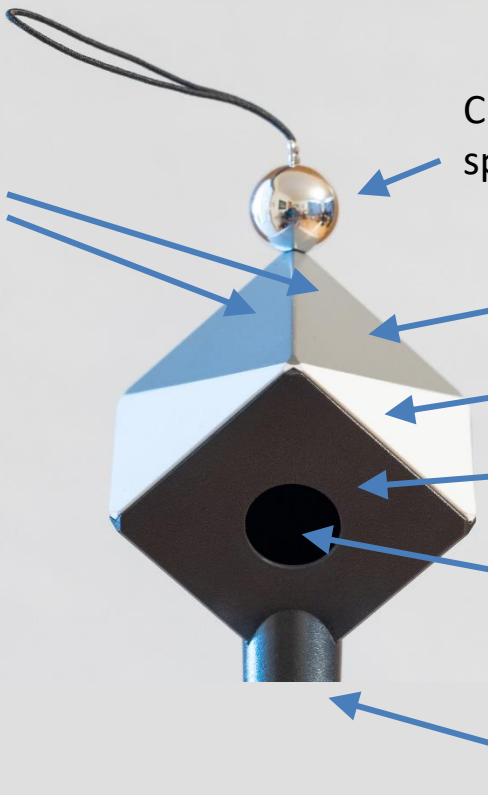
- 48 colors with nice set of skin tones
- Fade indicator so you know when to replace
- Software for generating color profiles
- ¼" threaded hole on bottom, ¼" threaded post on top
- Portable and rugged. Folds to protect the color squares

How to use:

- Shoot raw.
- Place target very close to subject, take test shot, remove.
- Simple: In editing, observe the grey scale and color patches when adjusting exposure, white balance, tone curve, black levels, and white levels.
- Pro: Use included software to generate Adobe calibration settings for your preferred profile. I recommend using a camera-specific linear profile for this step.

Really Simple Tool: Data Color Spyder Cube

$54 at B&H.



Great for understanding mixed lighting.

For example, I took this picture in a doorway. The left side of the Spyder Cube faced windows and the right side faced a room with warm lighting. You can see the color difference between the two grey patches

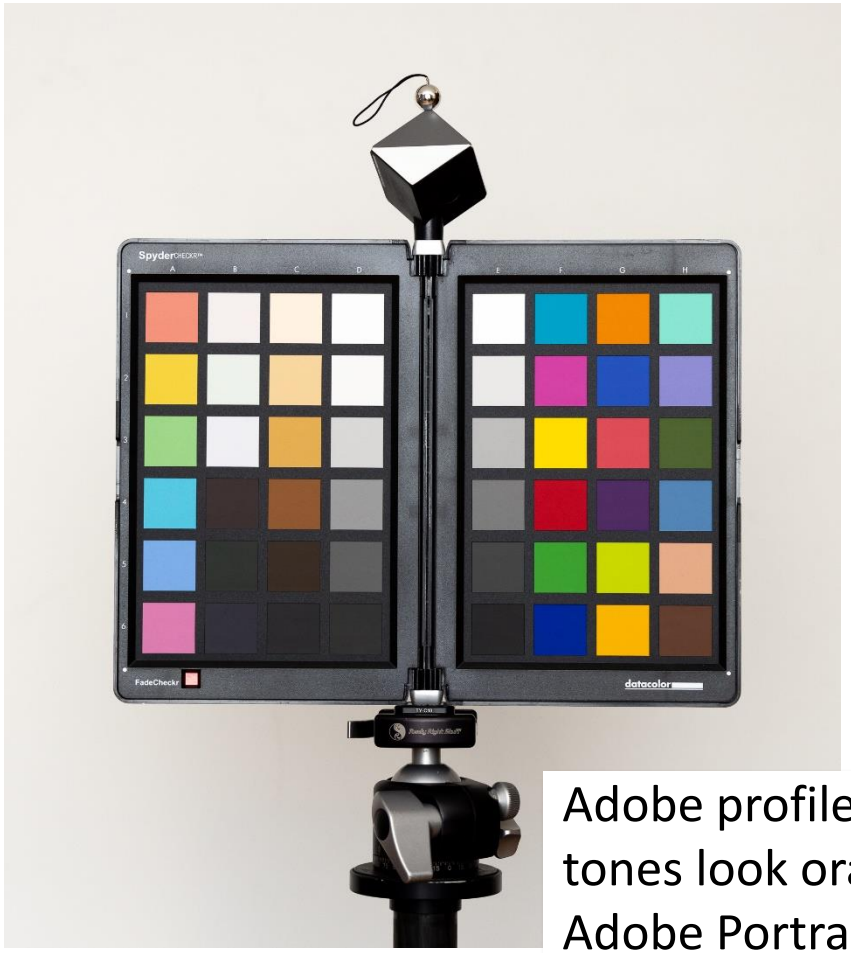
Three Flash Pictures Processed with Different Lightroom Color Profiles

Adobe Color

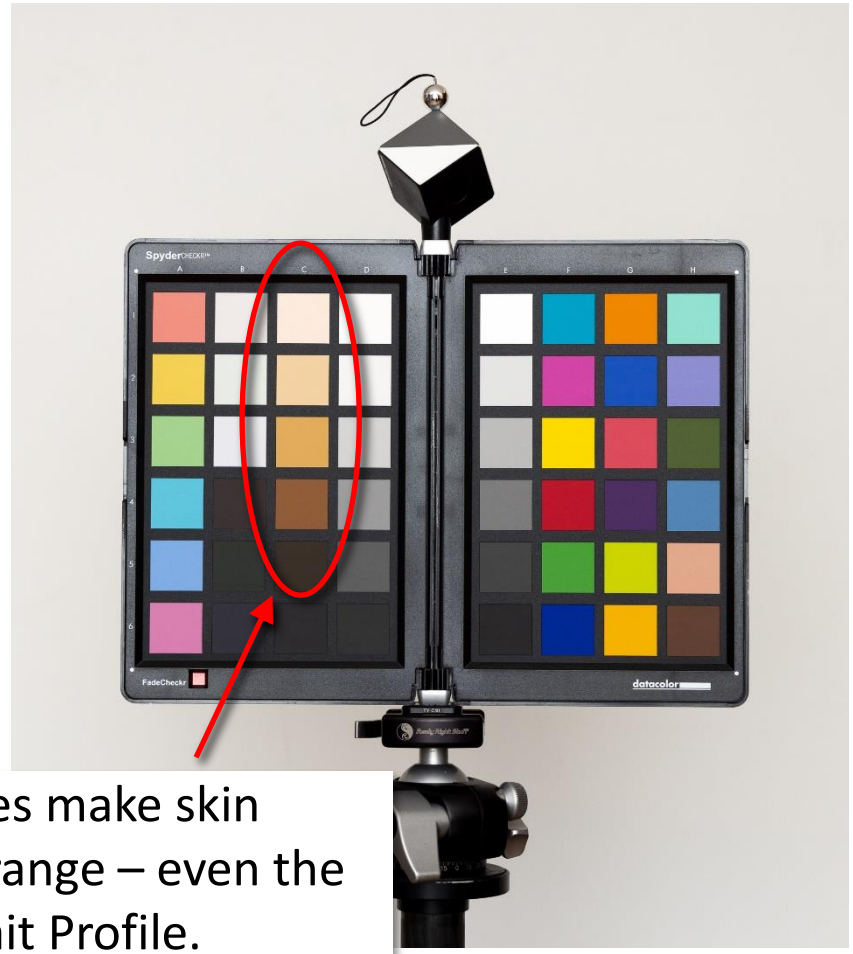
Adobe Portrait

Canon Linear

Three Flash Pictures Processed with Different Lightroom Color Profiles



Adobe Color

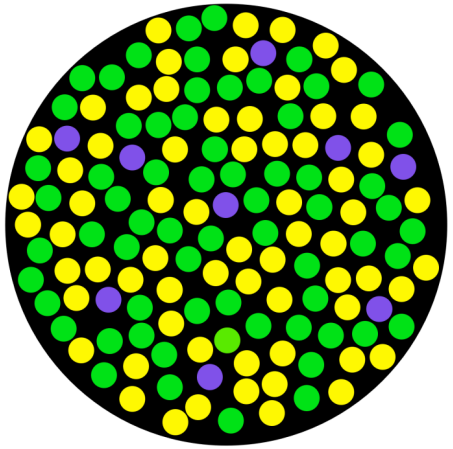


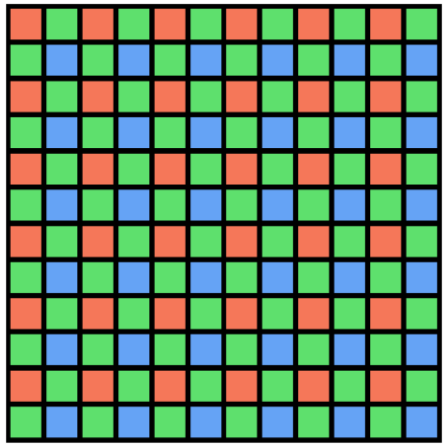
Adobe profiles make skin tones look orange – even the Adobe Portrait Profile.

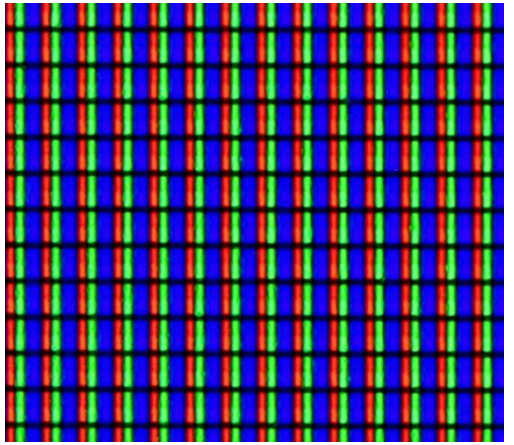
Adobe Portrait

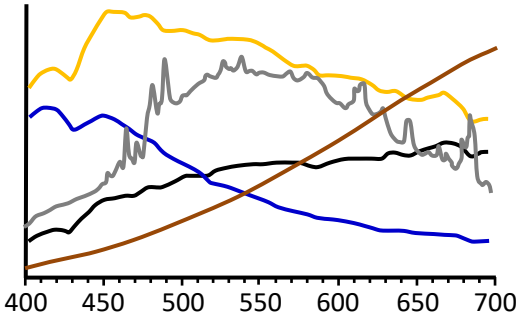
Canon Linear

Monitors use colors with narrow emission spectra to deliver a wide gamut

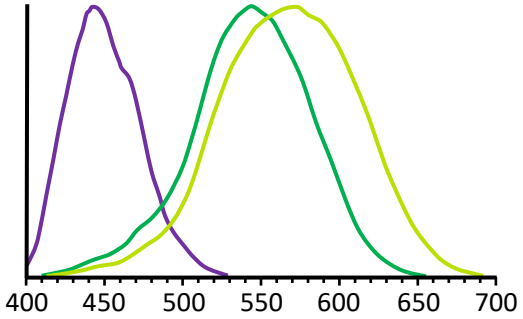




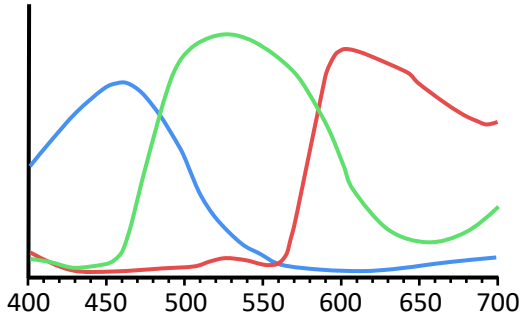




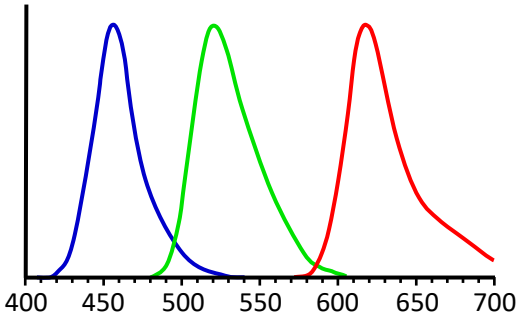
Light Sources



Human Cone Response



Camera Sensor



LG OLED Monitor

Ideal Environment for Editing Pictures

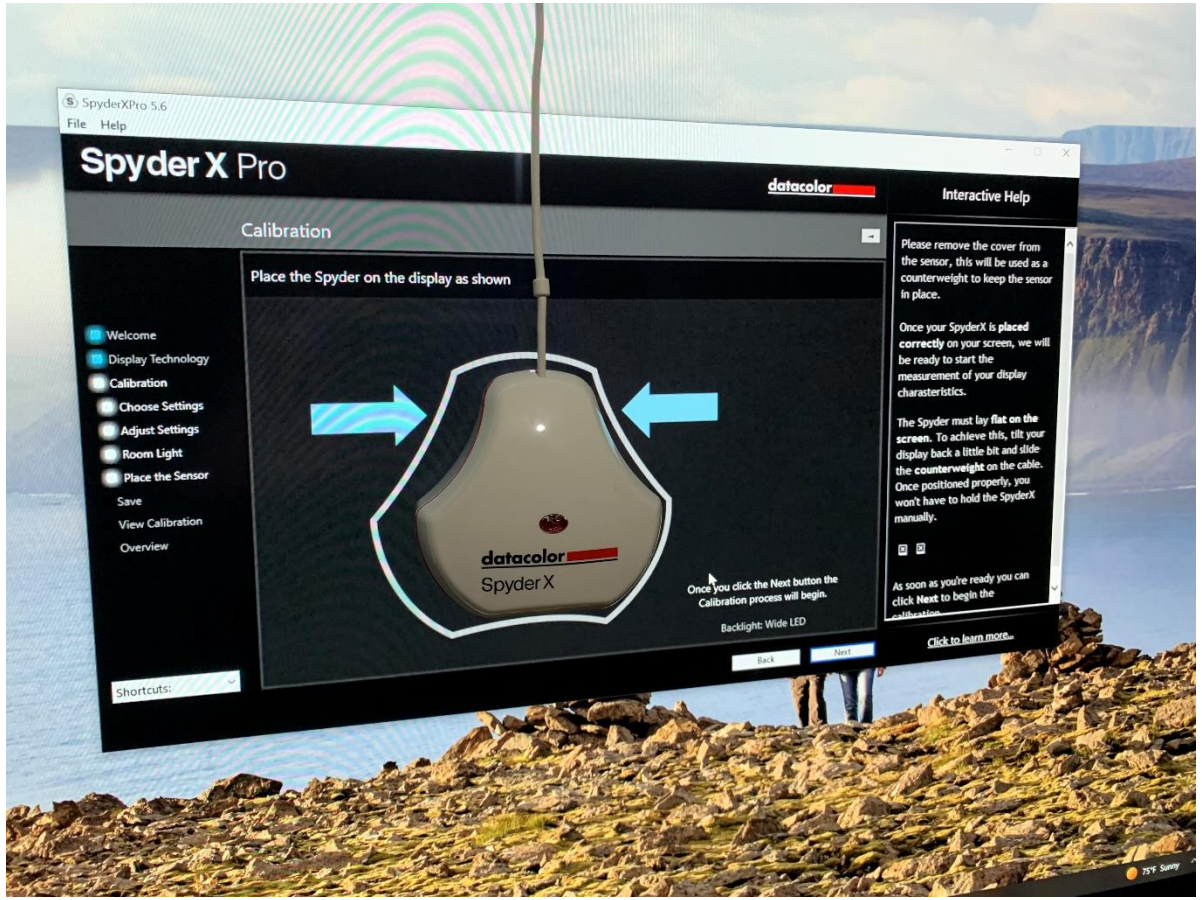
Easy to do:

1. All windows heavily shaded
2. Light level around your workspace fairly low: 32lux to 64 lux, 5000 K
3. Even illumination with CRI >=95. Waveformlighting.com makes 60W equivalent 5000 K bulbs with CRI 95, designed for photographic work. These bulbs also have low flicker. They are not dimmable.
4. Monitor luminance 75 to 100 cd/m^2
5. Monitor white point – D65
6. Monitor set for color space you are working in. For example sRGB.
7. Calibrate your monitor every few months.

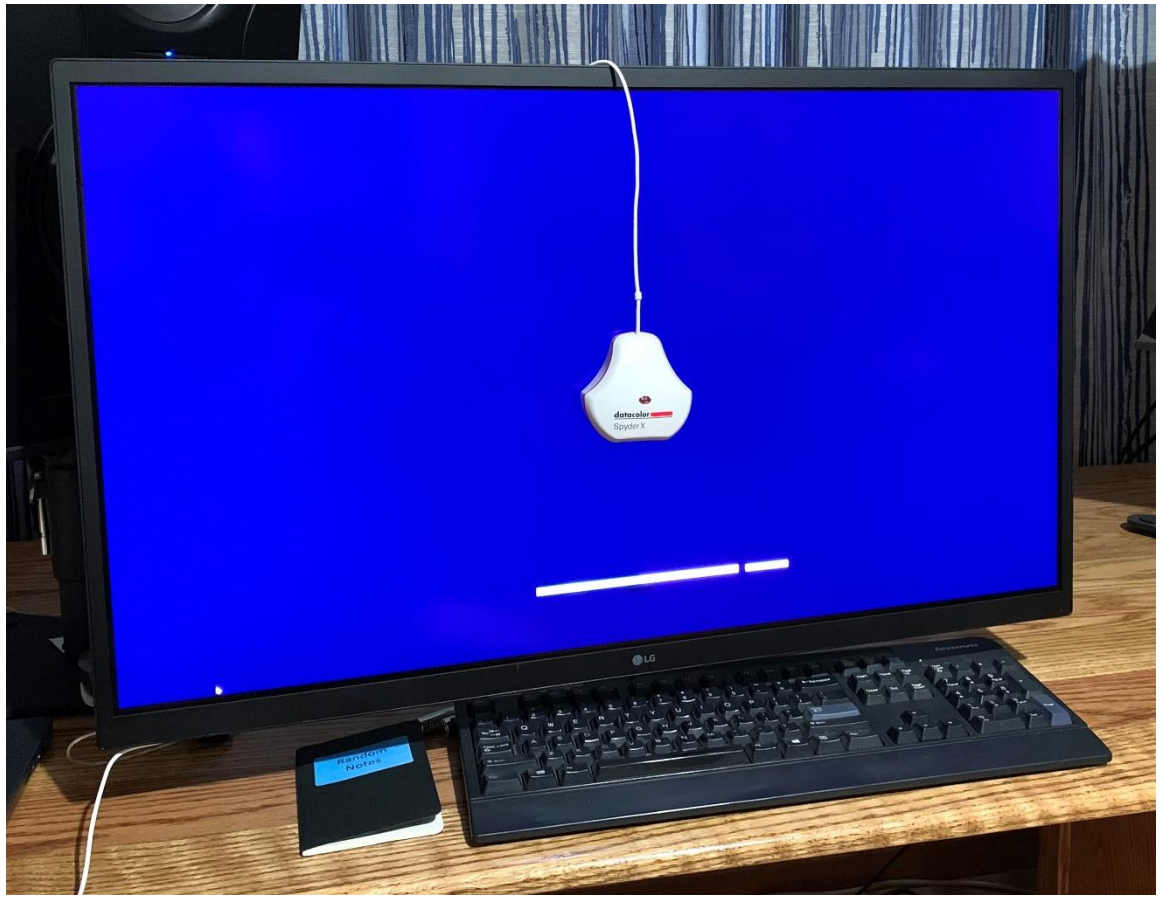
If you're really serious:

7. Wear a dark, neutral shirt. Modern displays have such low reflectivity that this isn't necessary. Just don't wear a bright shirt.
8. Lens hood over your monitor if any ceiling light reflects off of it. Here's a test you can do: Turn the monitor off and see what reflections you see in the monitor. Whatever you see is being superimposed on your pictures as you edit them.
9. Walls and ceilings a neutral gray. Walls 60% reflectance or less. (Usually only done in professional settings)
10. Desk and nearby surfaces should be neutral colors.

Calibrating Your Monitor

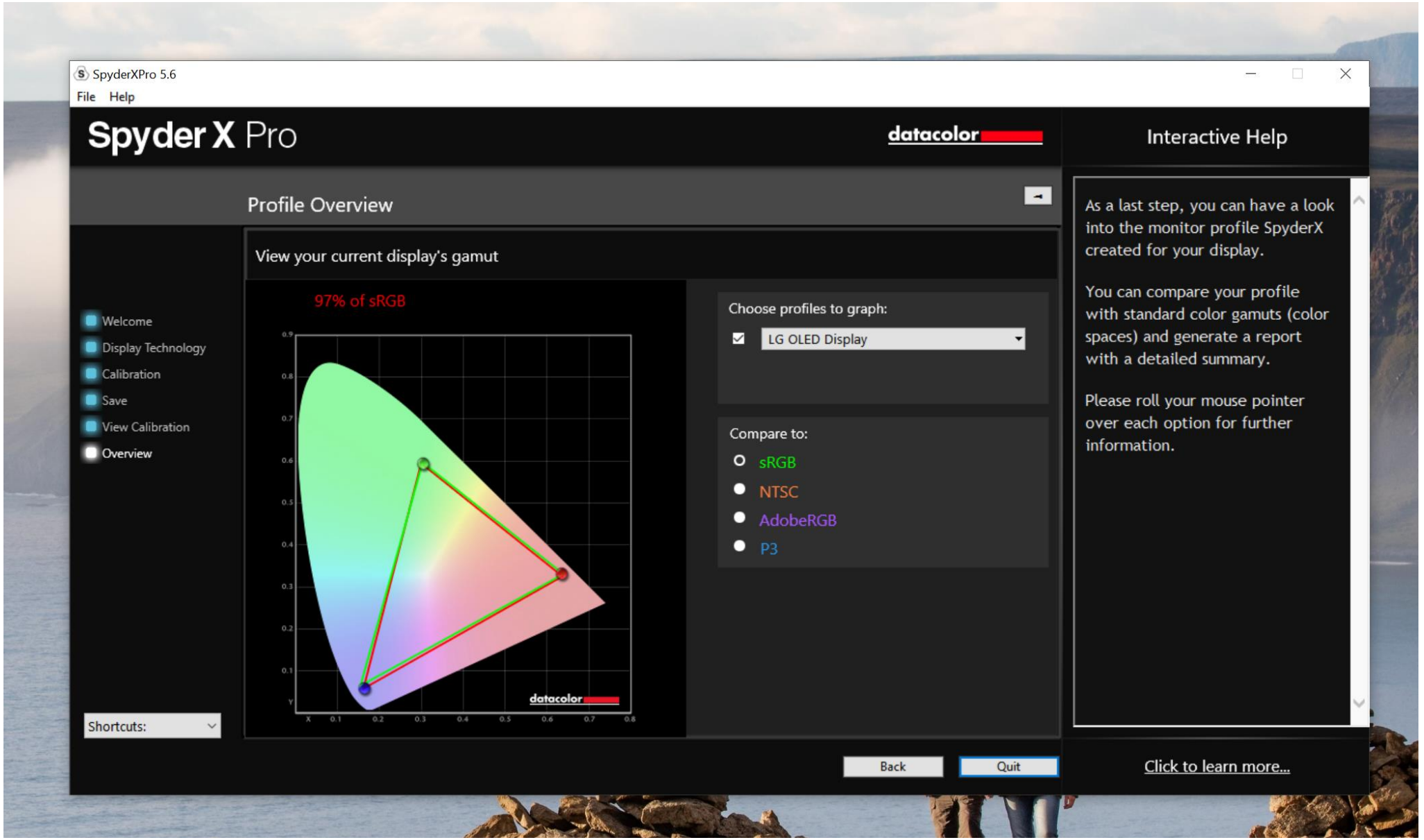


- Place calibration device over montor & run calibration program.
- I like the Spyder X Pro - $129 because the software is easy to use and it has an ambient light sensor.

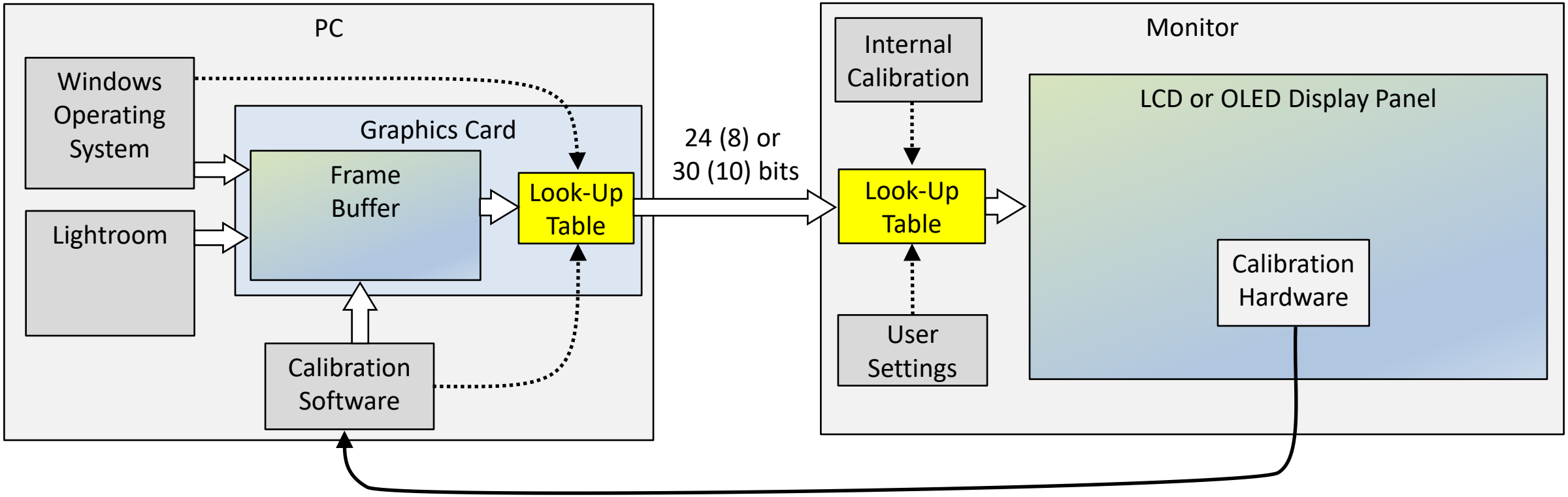


- Spyder X going through its paces.

Final Spyder X Report



At least 2 ways pixels get modified en route to the display panel



If you only remember a few things ...

Physics

- Light, objects, and reflections of light off of objects do not have color. They have spectra.
- The best light sources for photography have continuous, smooth spectra.
- Everything emits or reflects at least some light and has the potential to illuminate the things around it.

Physiology

- The human eye has three types of color photorecepters, called cones.
- This is why we can describe most of the colors we see with three values.
- Cone signals pass to a layers of neurons in the retina wired for discriminating red-green, blue-yellow, and brightness.

Perception

- Color is how we perceive spectra.
- Like all human senses, our perception of color is relative.
- The color we perceive depends on its spectrum *plus everything in our visual field.*
- There are dozens of color spaces used for describing color.

Capture

- Camera sensors use an RGB mosaic of pixels to capture color.
- Color values from the sensor, must be converted to a common color space like ProPhotoRGB for editing.
- White balance is an important part of this color conversion.

Edit

- Do your editing in a neutraly-lit room that is not too bright.
- The 2-slider B-Y / M-G adjustment for white balance is often adequate.
- If you don't like the color gamut you're getting, experiment with different color profiles in your raw converter.

Display & Print

- Monitors and viewing conditions vary wildly in how others will see your pictures. Set your monitor to the color space your editor is using, usually sRGB.
- Printing is an art requiring trial and error.
- Glossy prints will have a larger gamut, especially in contrast range.

The End

Human cone sensitivity vs high-end display emission spectra