Color

15-463, 15-663, 15-862
Computational Photography
Fall 2017, Lecture 11

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Homework 2 grades have been posted on Canvas.
  - Mean: 81.6% (HW1: 102.6%)
  - Median: 87.5% (HW1: 105.0%)

- Homework 3 is out.
  - Due October 12th.
  - Shorter, but longer bonus component.

- Final project details posted on website.

Overview of today’s lecture

- Recap: color and human color perception.
- Retinal color space.
- Color matching.
- Linear color spaces.
- Chromaticity.
- Non-linear color spaces.
- Some notes about color reproduction.

Slide credits

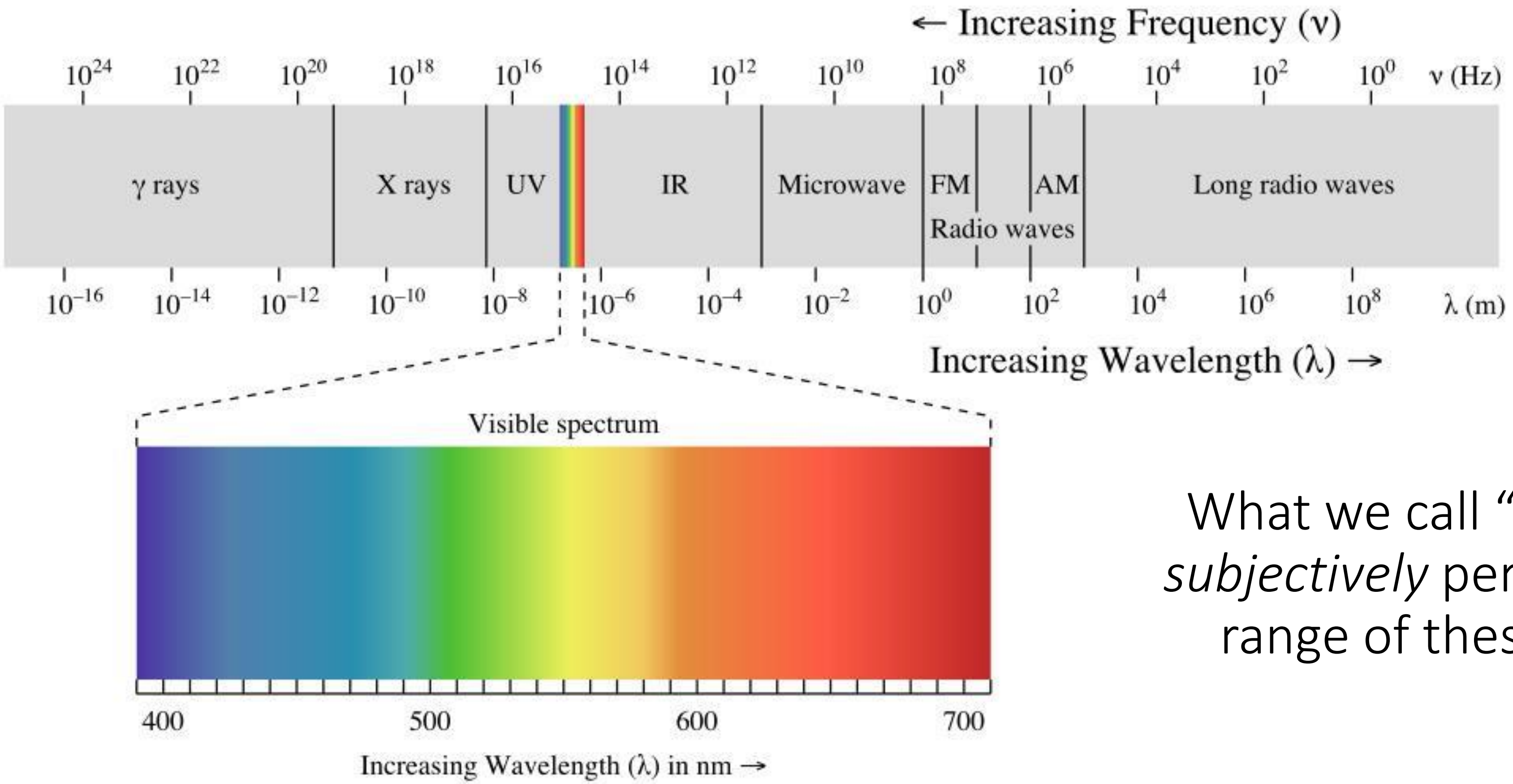
Many of these slides were inspired or adapted from:

- Todd Zickler (Harvard).
- Fredo Durand (MIT).

Recap: color and human color perception

Color is an artifact of human perception

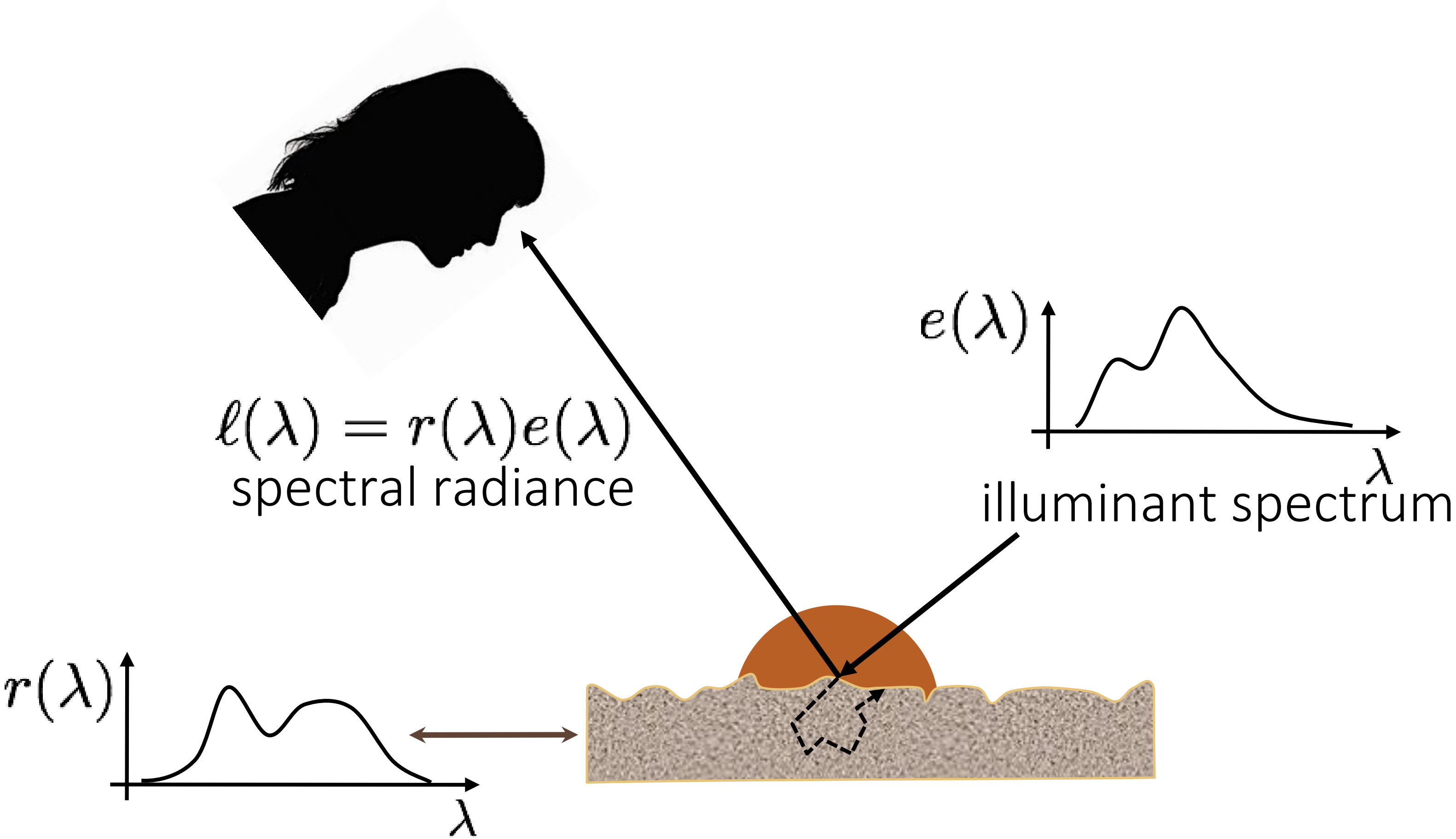
- "Color" is not an *objective* physical property of light (electromagnetic radiation).
- Instead, light is characterized by its wavelength.



electromagnetic spectrum

What we call "color" is how we *subjectively* perceive a very small range of these wavelengths.

Light-material interaction



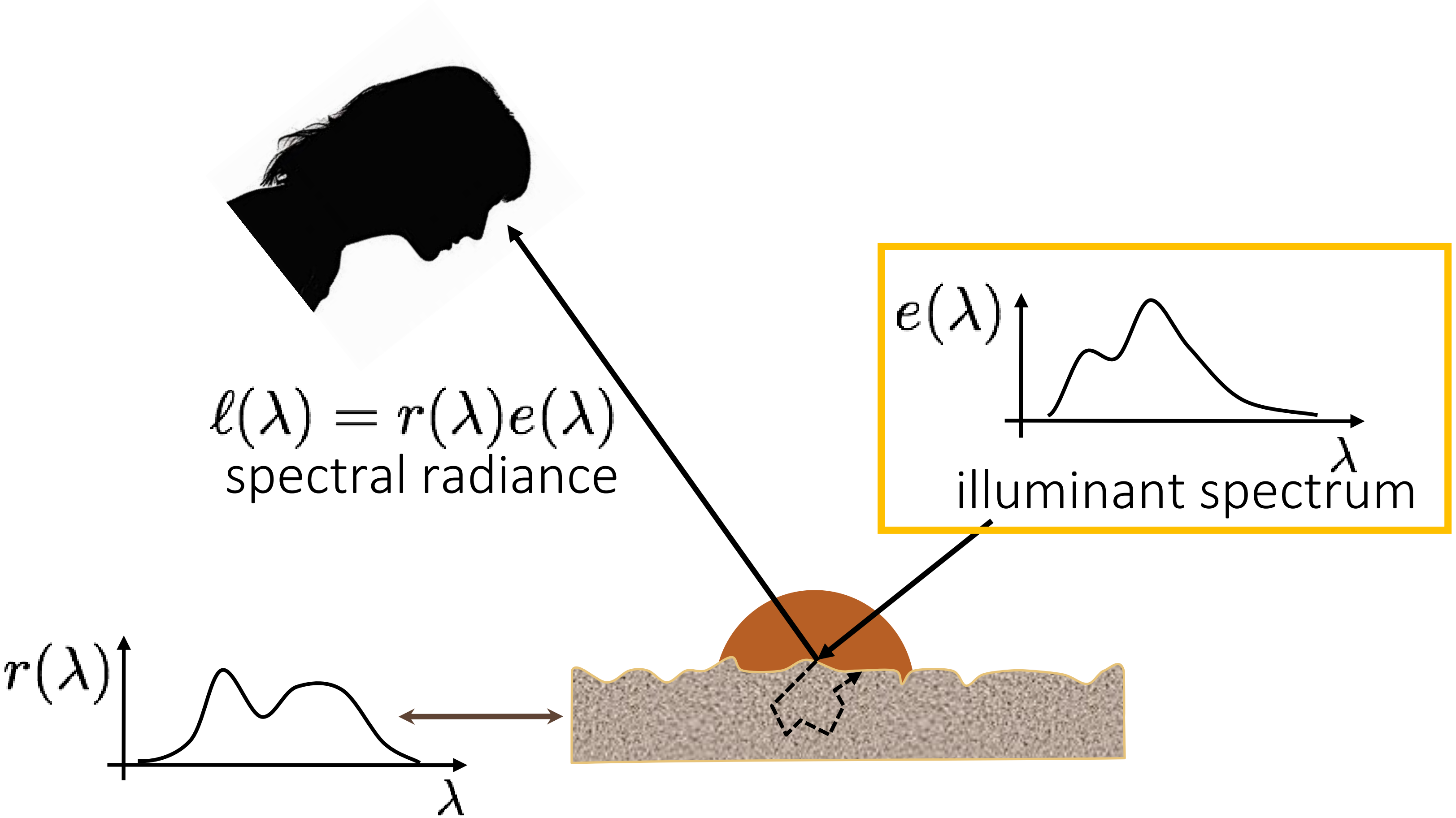
$\ell(\lambda) = r(\lambda)e(\lambda)$

spectral radiance

illuminant spectrum

spectral reflectance

Light-material interaction



$$\ell(\lambda) = r(\lambda)e(\lambda)$$

spectral radiance

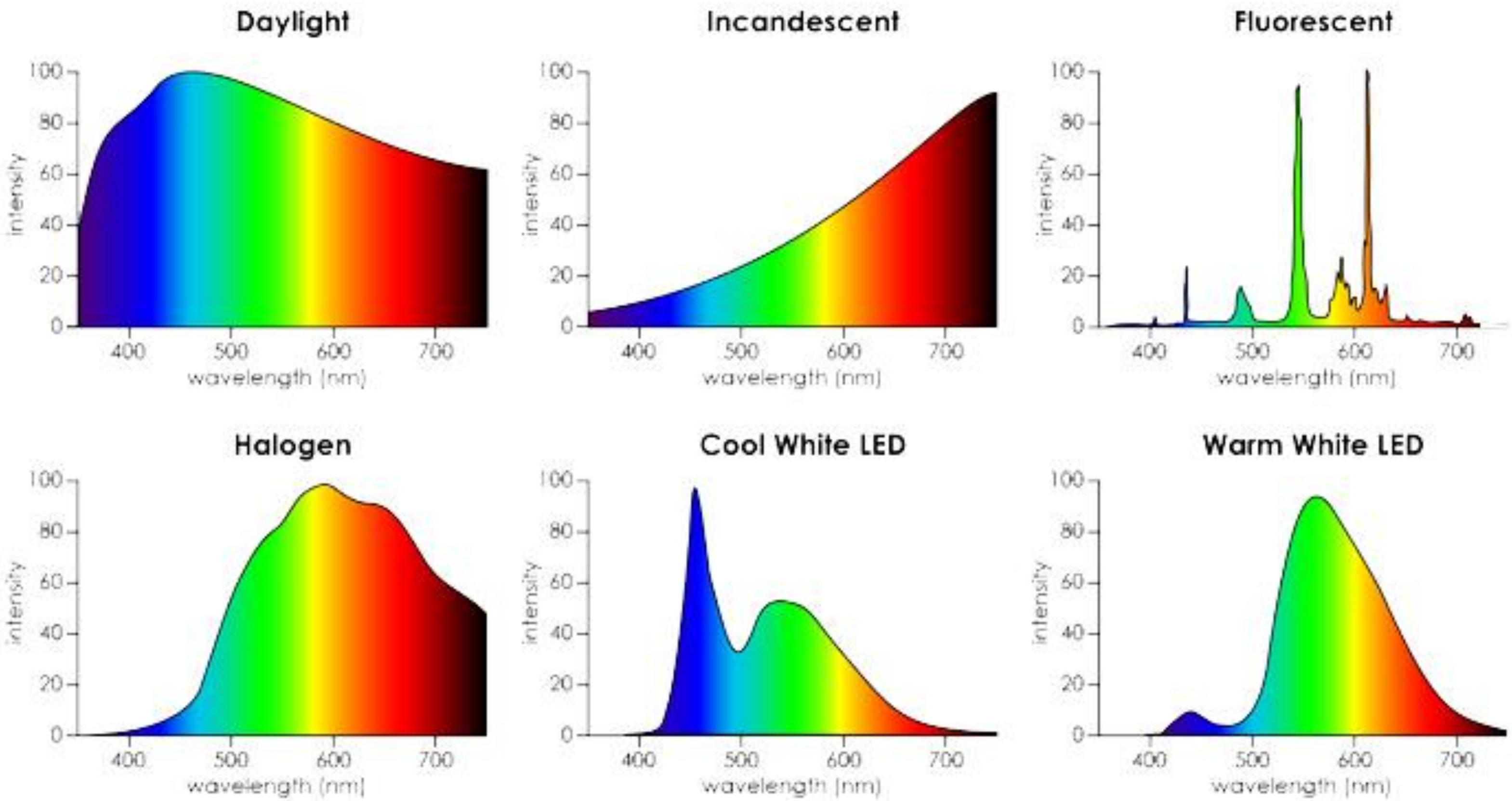
illuminant spectrum

spectral reflectance

Illuminant Spectral Power Distribution (SPD)

- Most types of light “contain” more than one wavelengths.
- We can describe light based on the distribution of power over different wavelengths.

We call our sensation of all of these distributions “white”.



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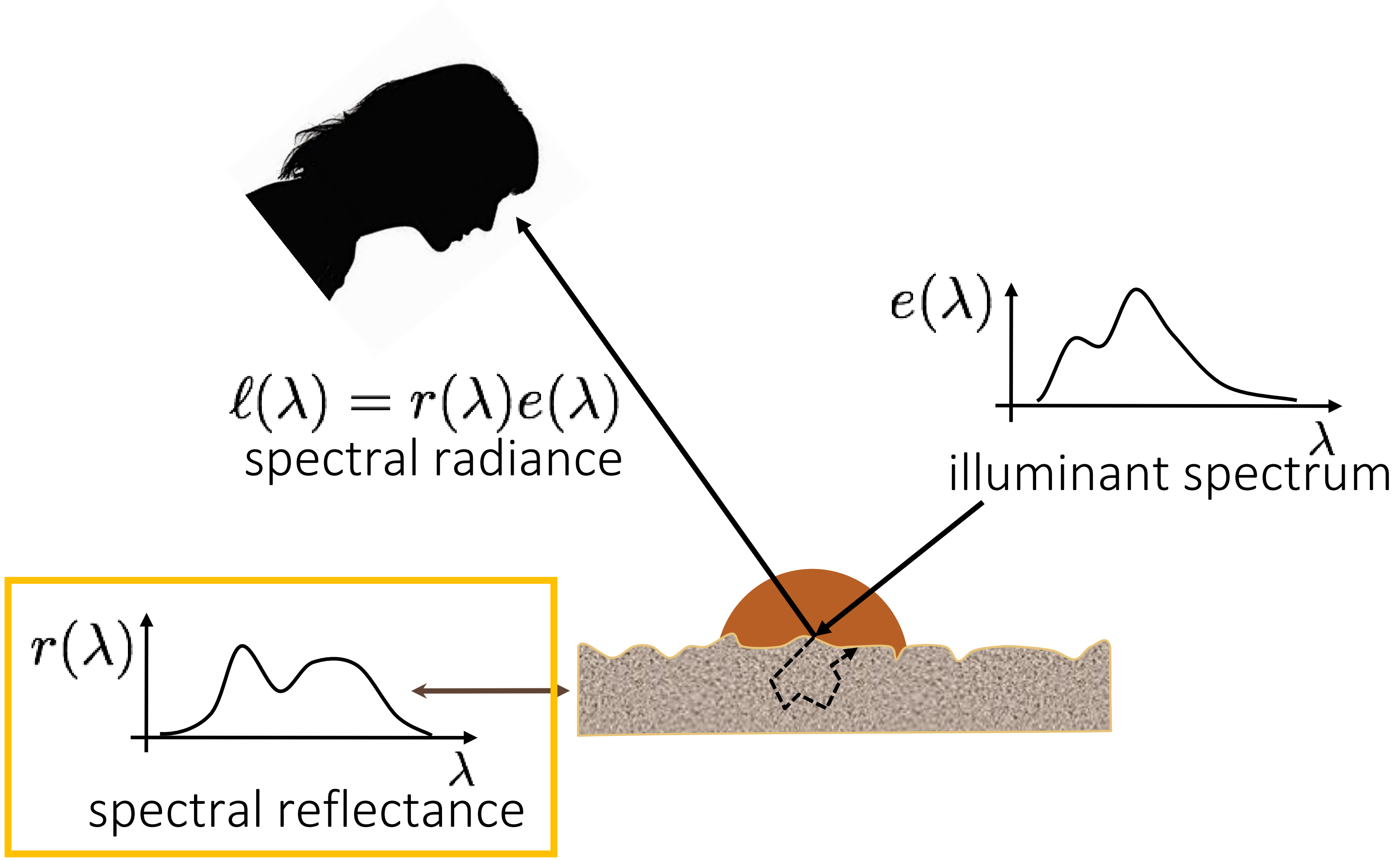


$$\ell(\lambda) = r(\lambda)e(\lambda)$$

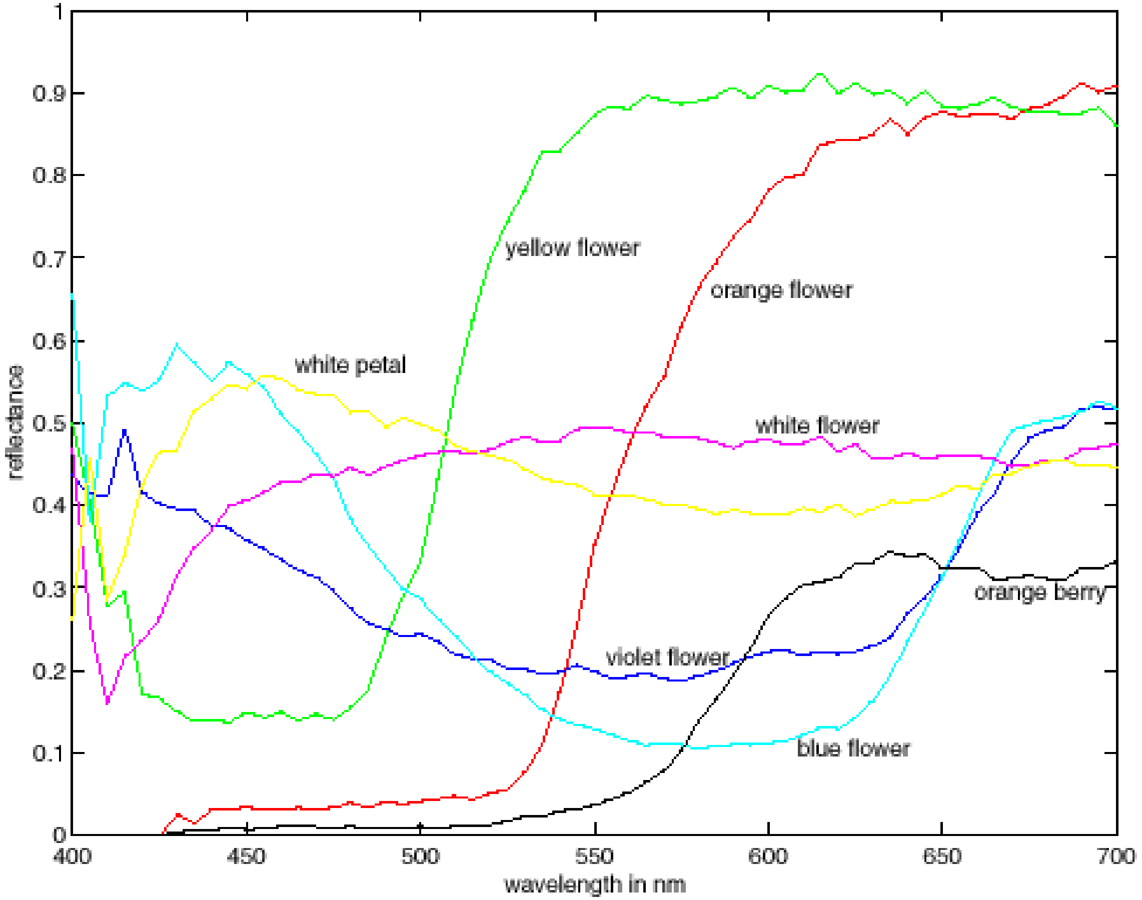
spectral radiance

illuminant spectrum

spectral reflectance

Spectral reflectance

- Most materials absorb and reflect light differently at different wavelengths.
- We can describe this as a ratio of reflected vs incident light over different wavelengths.



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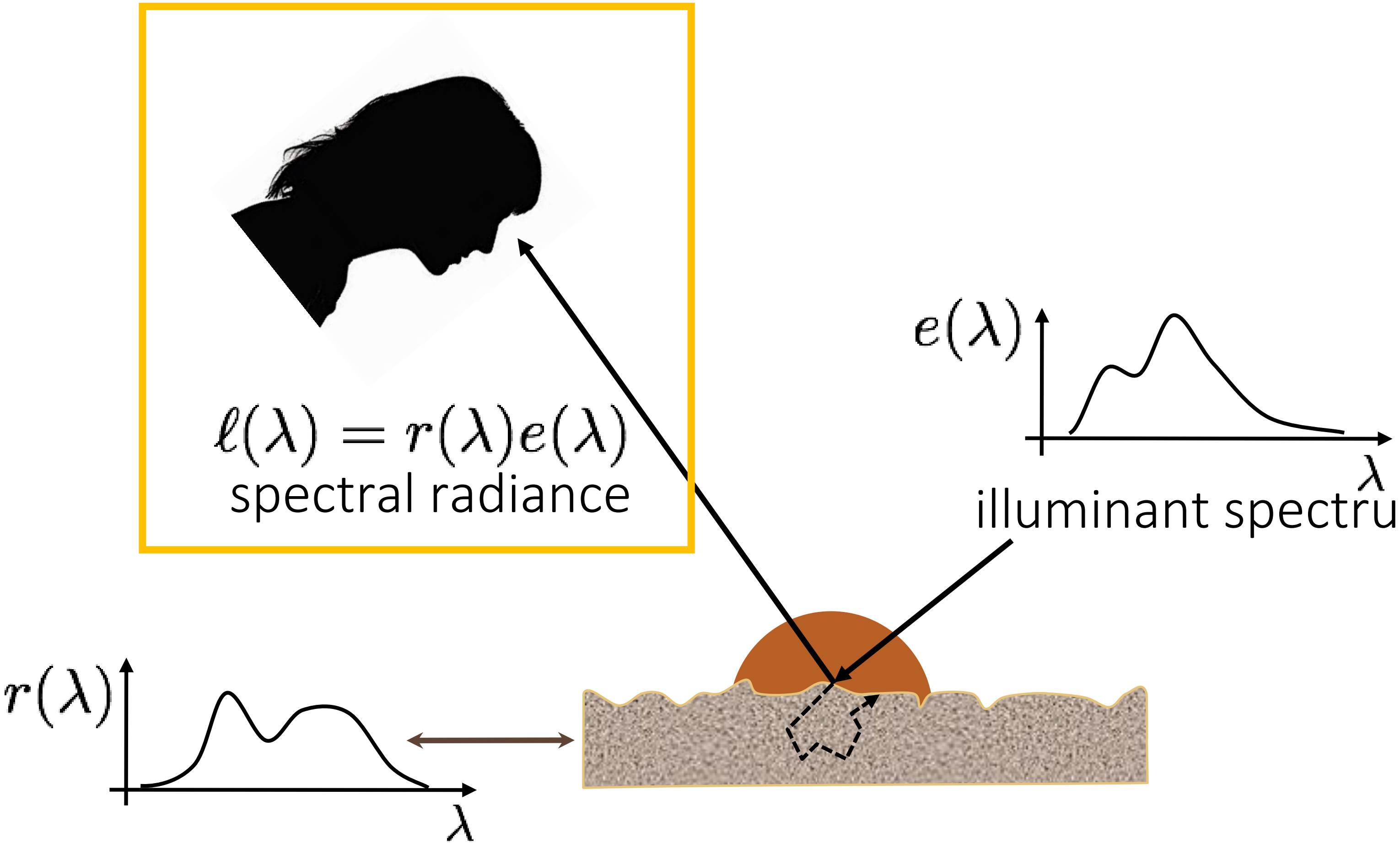


$$\ell(\lambda) = r(\lambda)e(\lambda)$$

spectral radiance

illuminant spectrum

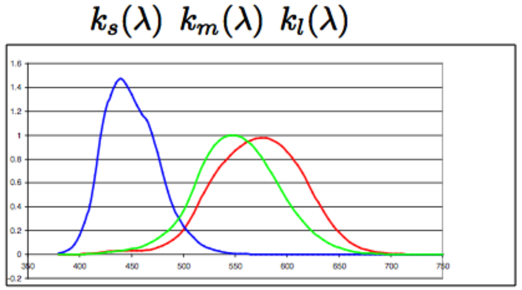
spectral reflectance

Human color vision

retinal color

$$\mathbf{c}(\ell(\lambda)) = (c_s, c_m, c_l)$$

$$c_s = \int k_s(\lambda)\ell(\lambda)d\lambda$$

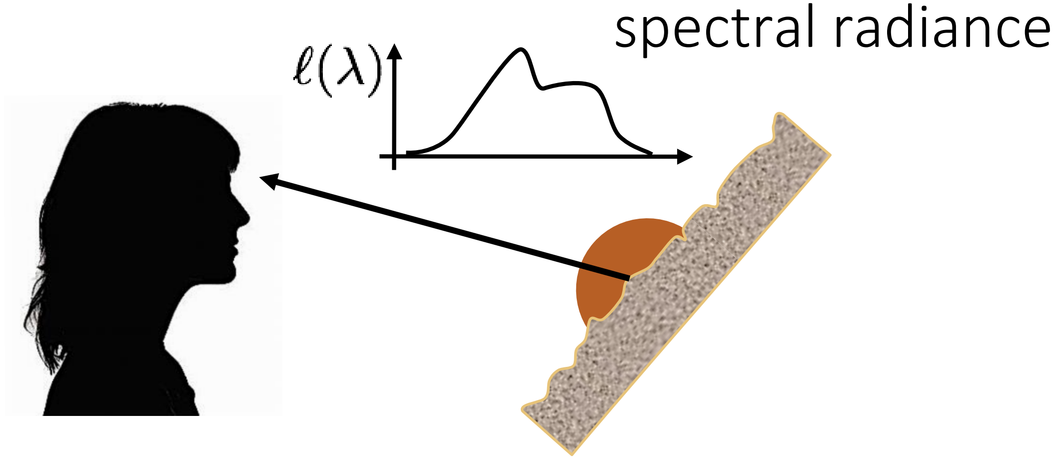


LMS senstivity functions

perceived color

object color

color names



Retinal vs perceived color

Retinal vs
perceived color.

Retinal vs perceived color

- Our visual system tries to “adapt” to illuminant.
- We may interpret the same retinal color very differently.

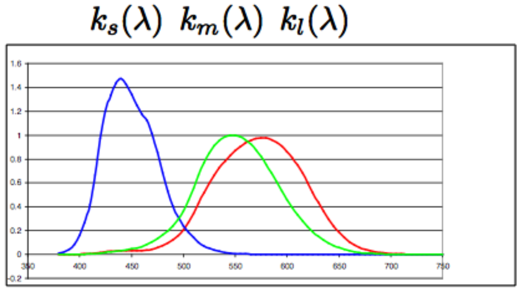
Human color vision

We will exclusively discuss retinal color in this course

retinal color

$$\mathbf{c}(\ell(\lambda)) = (c_s, c_m, c_l)$$

$$c_s = \int k_s(\lambda)\ell(\lambda)d\lambda$$



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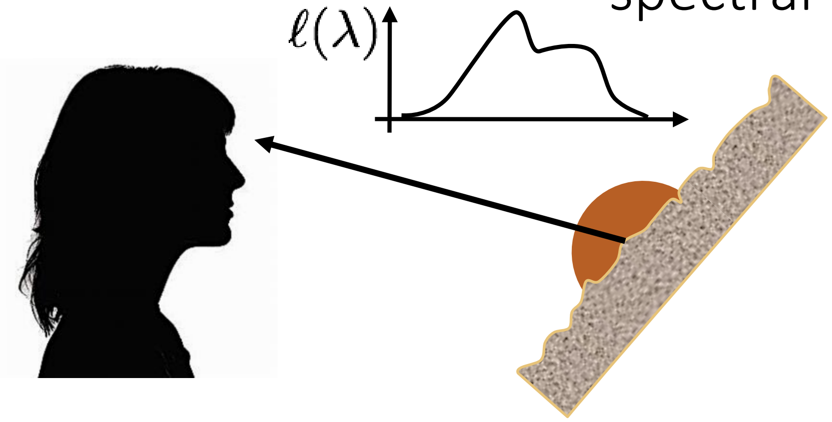


spectral radiance

Retinal color space

Spectral Sensitivity Function (SSF)

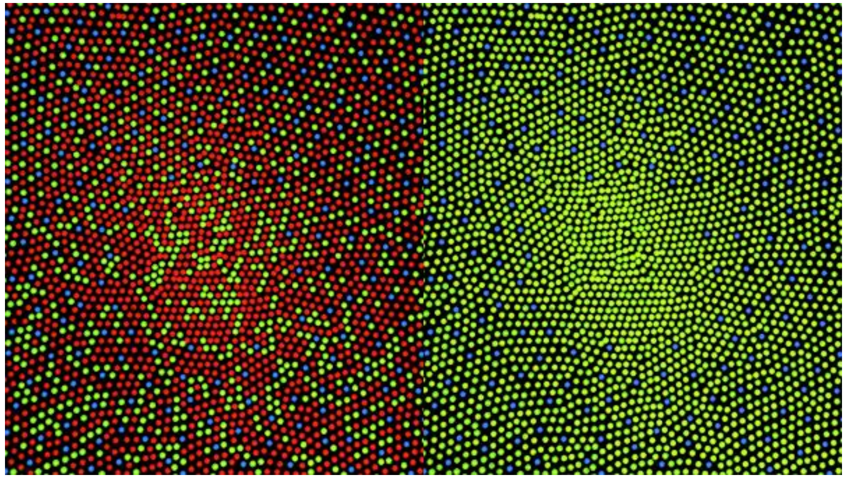
- *Any* light sensor (digital or not) has different sensitivity to different wavelengths.
- This is described by the sensor's *spectral sensitivity function* $f(\lambda)$.
- When measuring light of a some SPD $\Phi(\lambda)$, the sensor produces a *scalar* response:

$$\text{sensor response} \longrightarrow R = \int_\lambda \overset{\text{light SPD}}{\overset{\downarrow}{\Phi(\lambda)}} \overset{\text{sensor SSF}}{\overset{\downarrow}{f(\lambda)}} d\lambda$$

Weighted combination of light's SPD: light contributes more at wavelengths where the sensor has higher sensitivity.

Spectral Sensitivity Function of Human Eye

- The human eye is a collection of light sensors called cone cells.
- There are three types of cells with different spectral sensitivity functions.
- Human color perception is three-dimensional (*tristimulus color*).

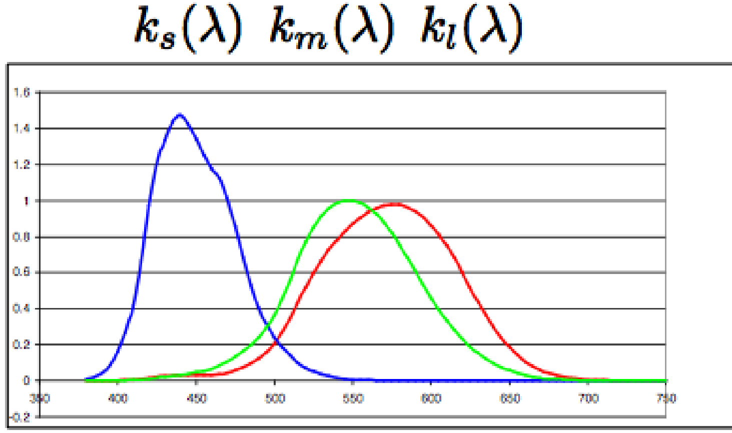


cone distribution
for normal vision
(64% L, 32% M)

“short” $S = \int_\lambda \Phi(\lambda) S(\lambda) d\lambda$

“medium” $M = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$

“long” $L = \int_\lambda \Phi(\lambda) L(\lambda) d\lambda$

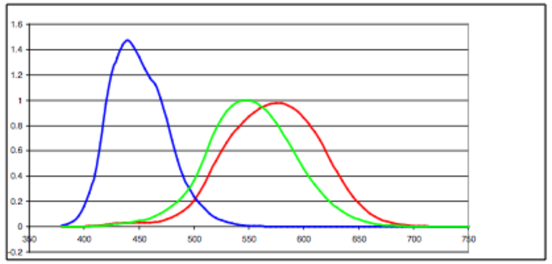


LMS senstivity functions

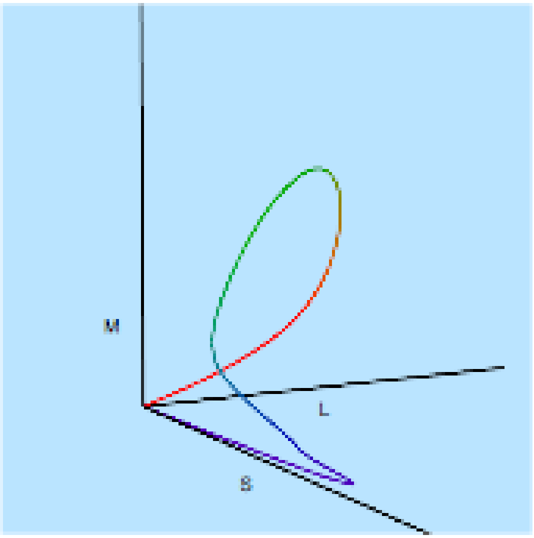
The retinal color space

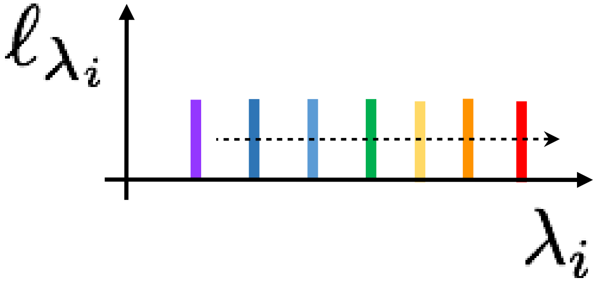
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



LMS senstivity functions



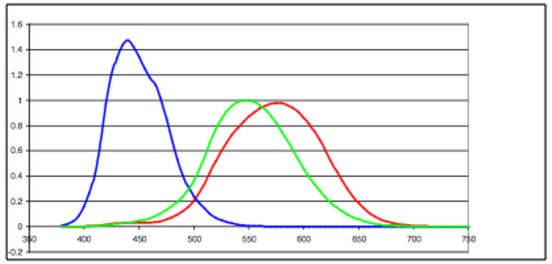


“pure beam” (laser)

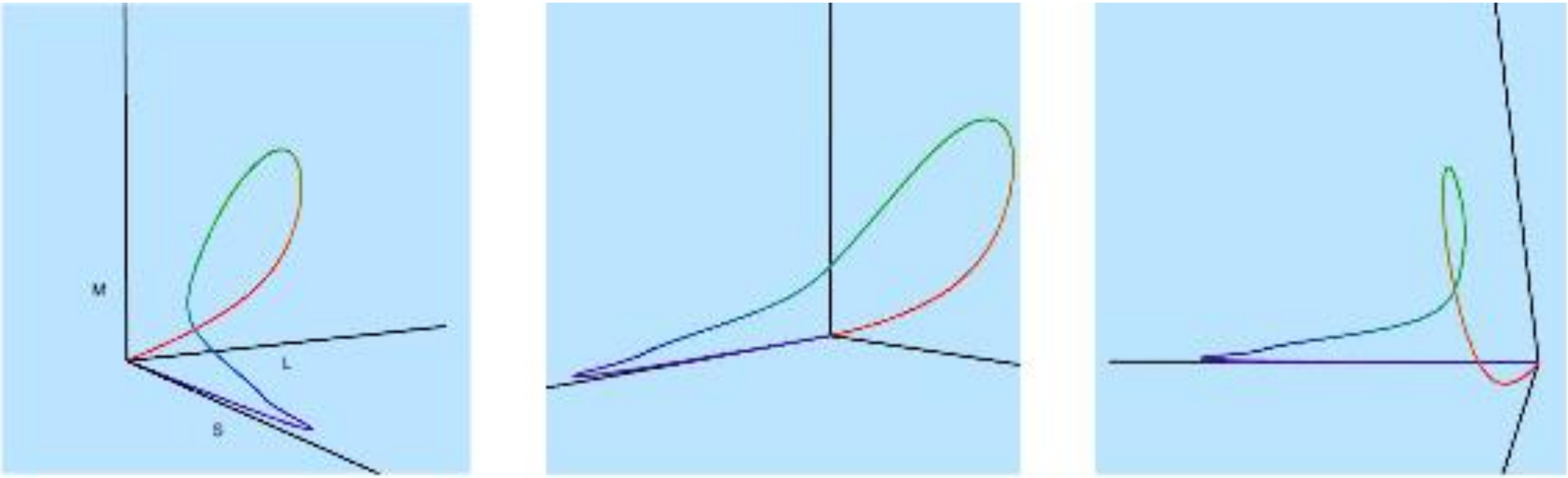
The retinal color space

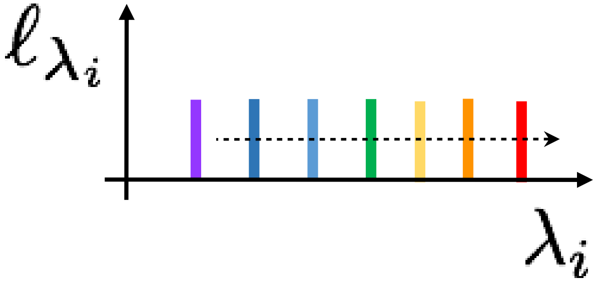
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



LMS senstivity functions





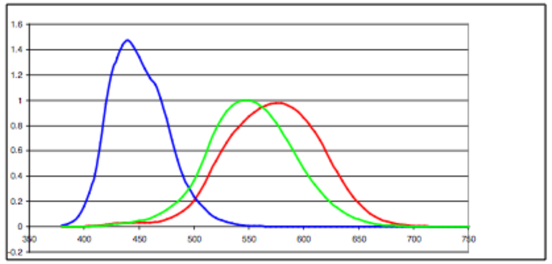
“pure beam” (laser)

- “lasso curve”
- contained in positive octant
- parameterized by wavelength
- starts and ends at origin ← why?
- never comes close to M axis ← why?

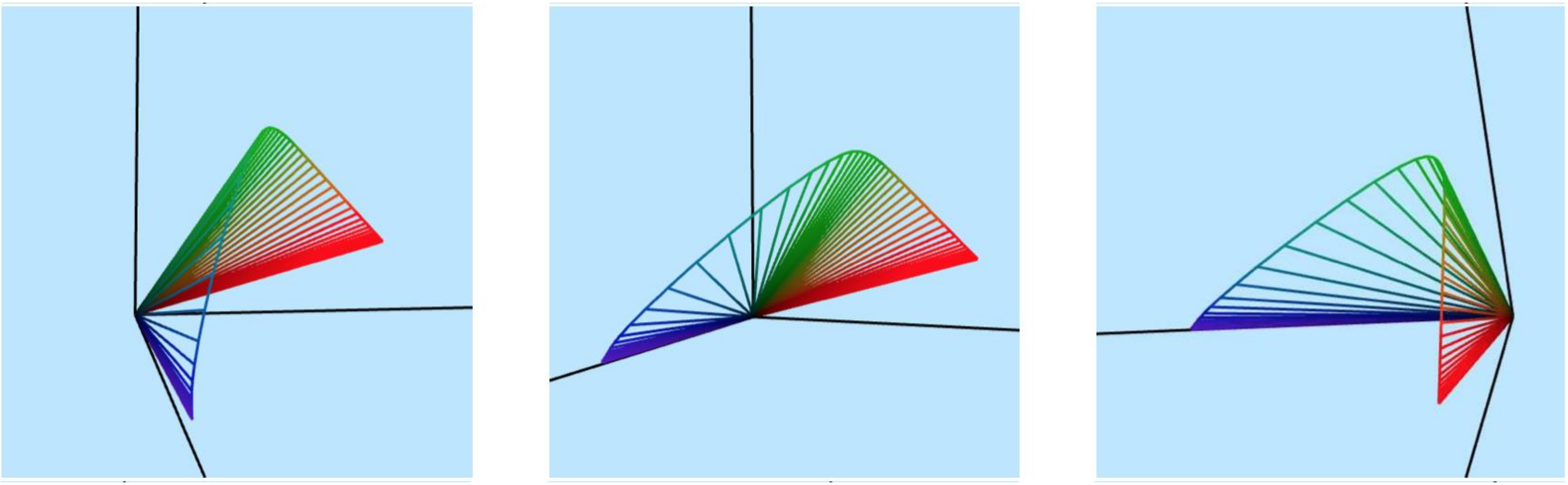
The retinal color space

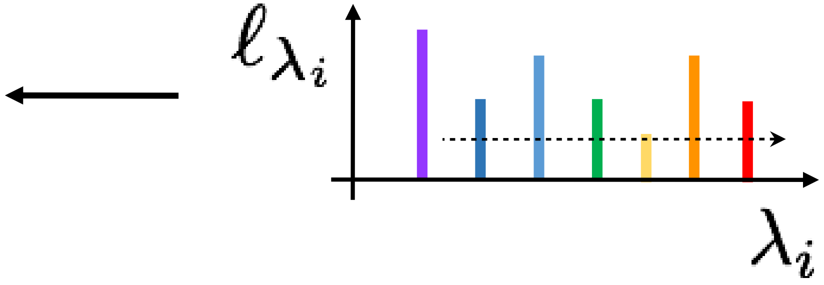
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$$k_s(\lambda) \quad k_m(\lambda) \quad k_l(\lambda)$$



LMS senstivity functions



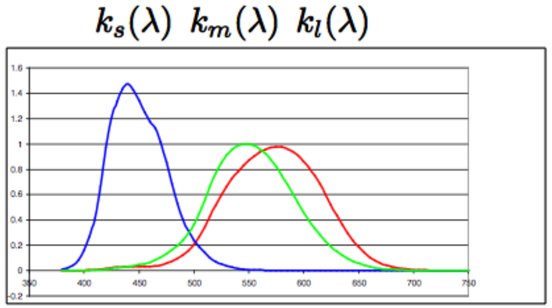


“pure beam” (laser)

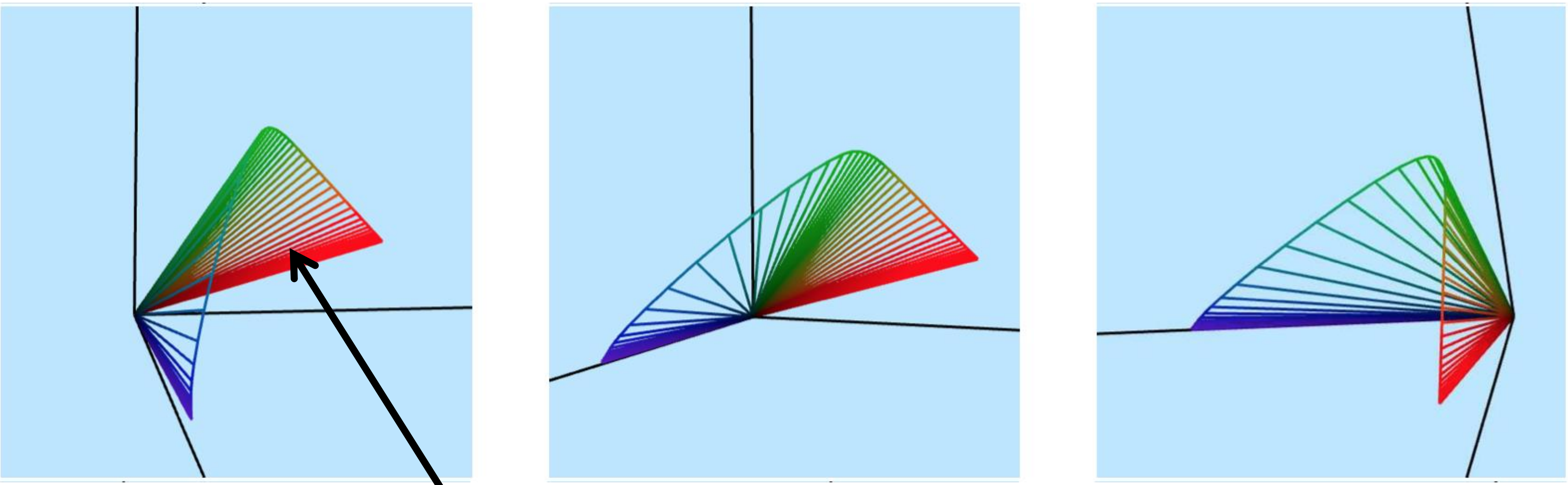
if we also consider variations in the *strength* of the laser this “lasso” turns into (convex!) radial cone with a “horse-shoe shaped” radial cross-section

The retinal color space

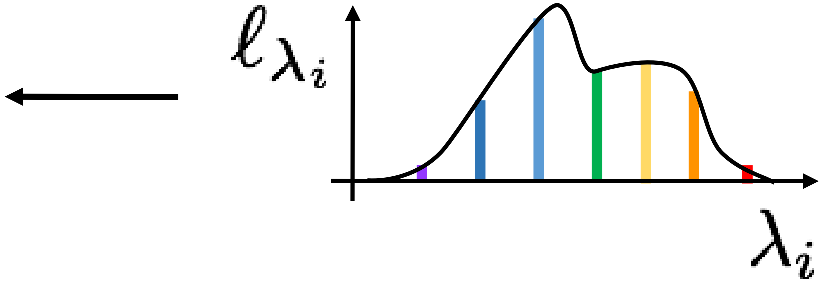
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$



LMS senstivity functions



colors of mixed beams are inside of convex cone



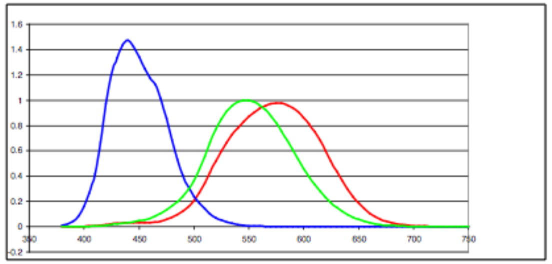
“mixed beam”

= positive combination of pure colors

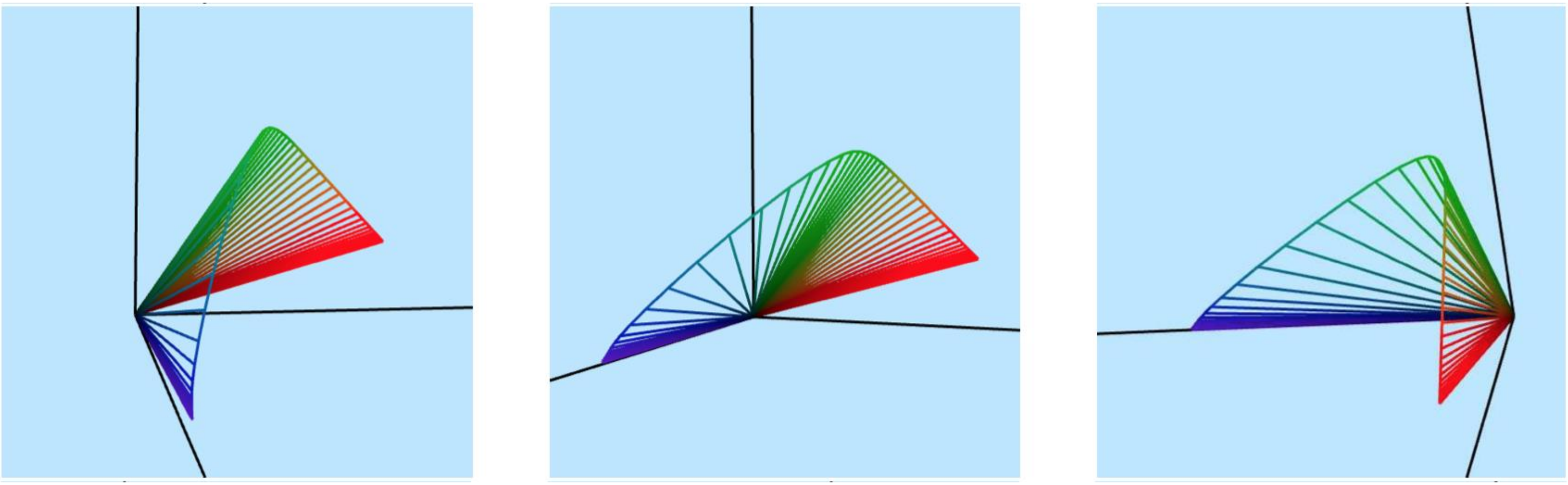
The retinal color space

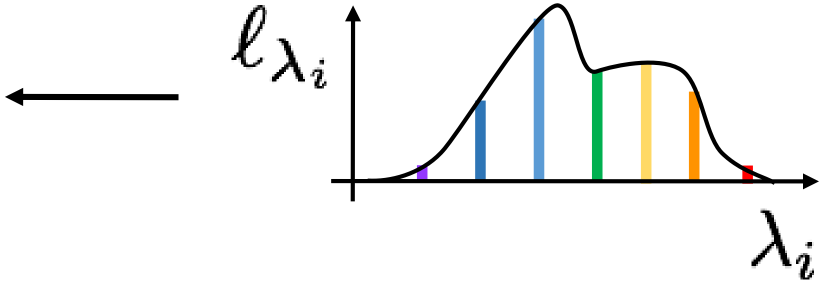
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



LMS senstivity functions



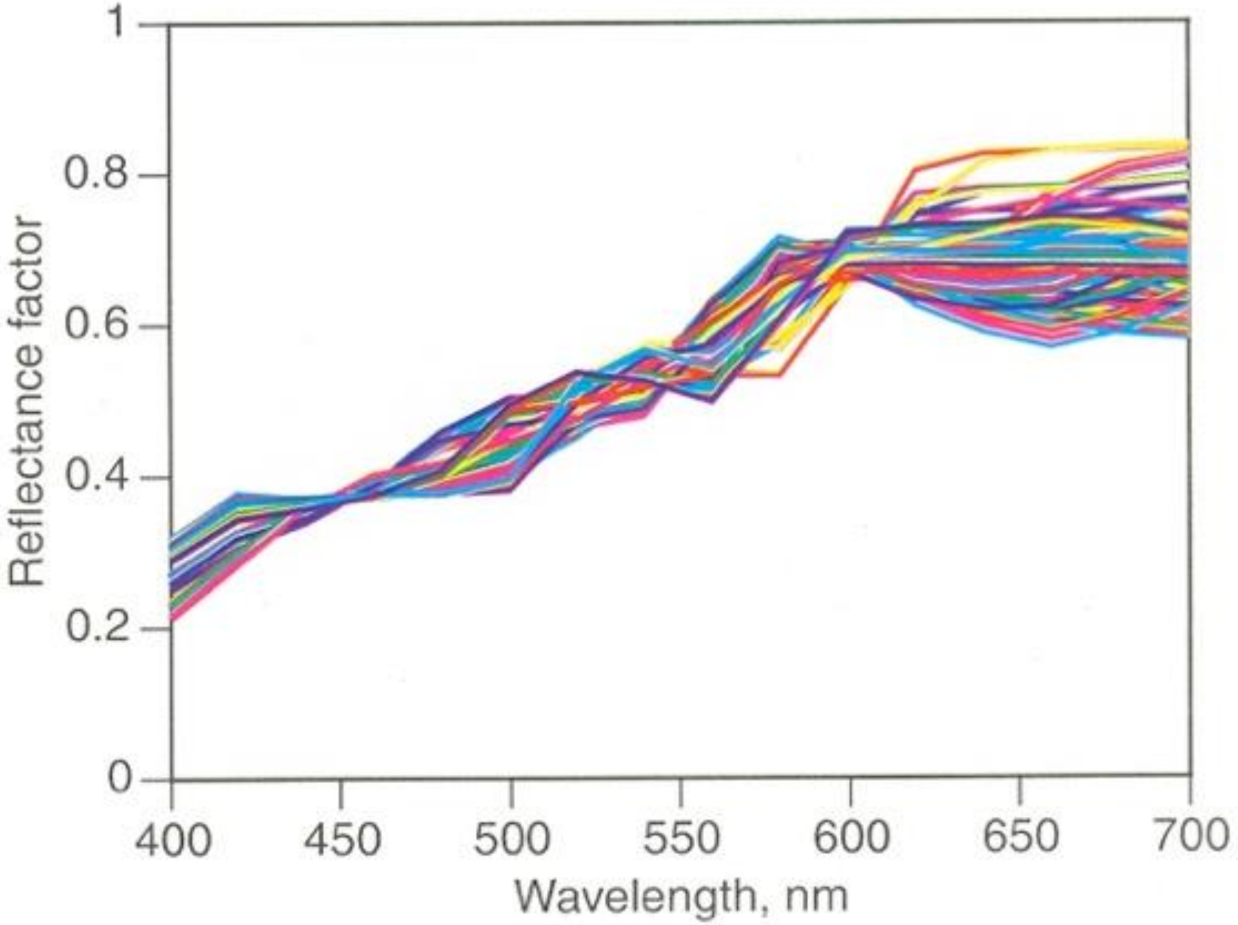


"mixed beam"

= positive combination of pure colors

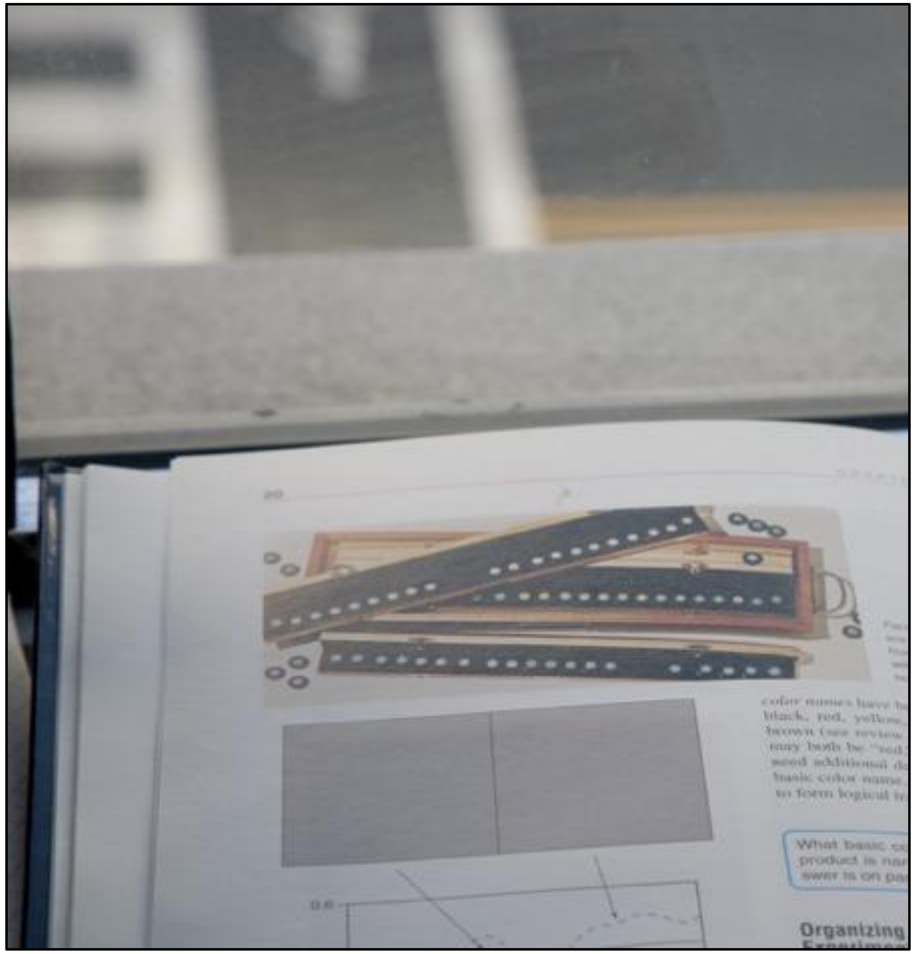
- distinct mixed beams can produce the same retinal color
- These beams are called *metamers*

There is an infinity of metamers

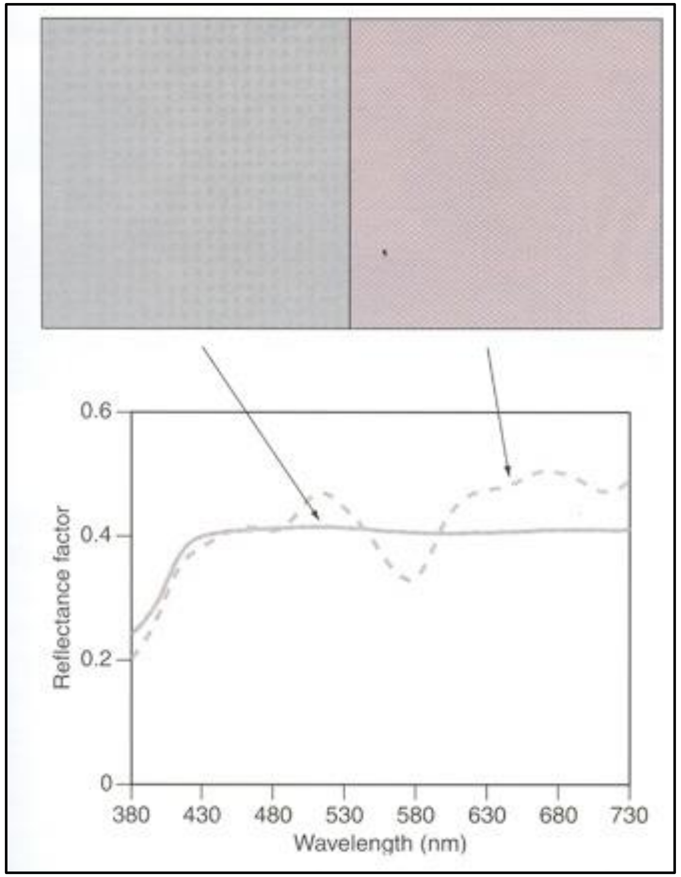


Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]

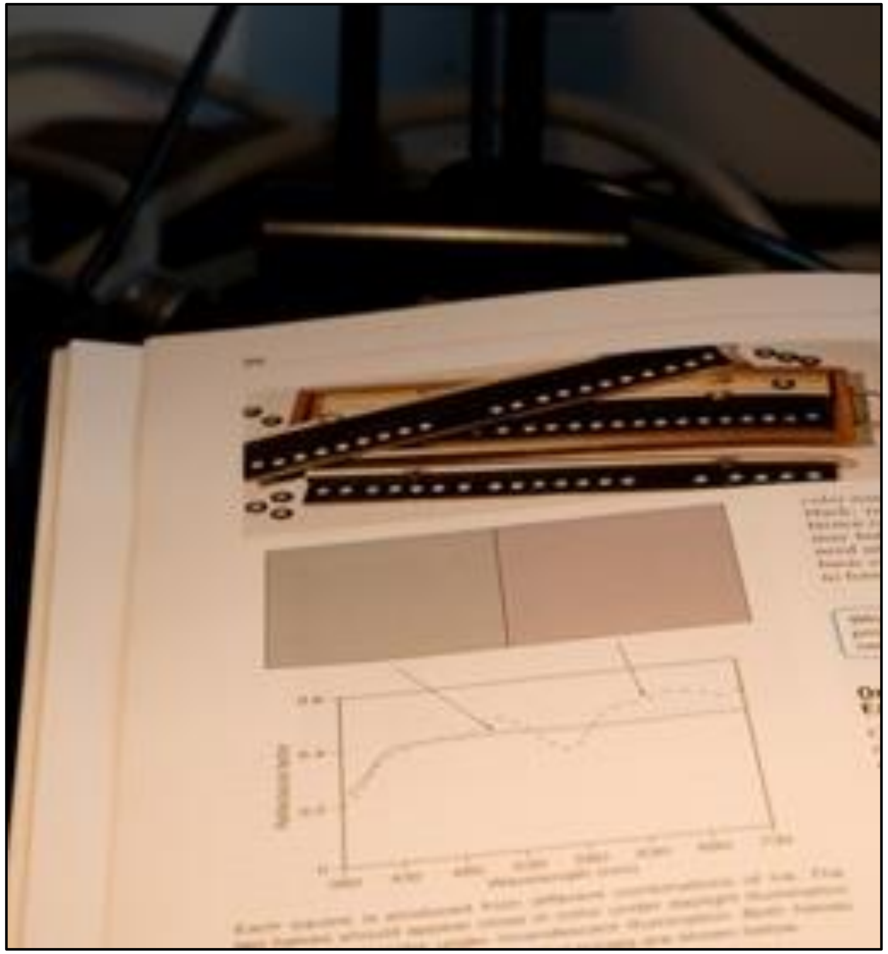
Example: illuminant metamerism



day light



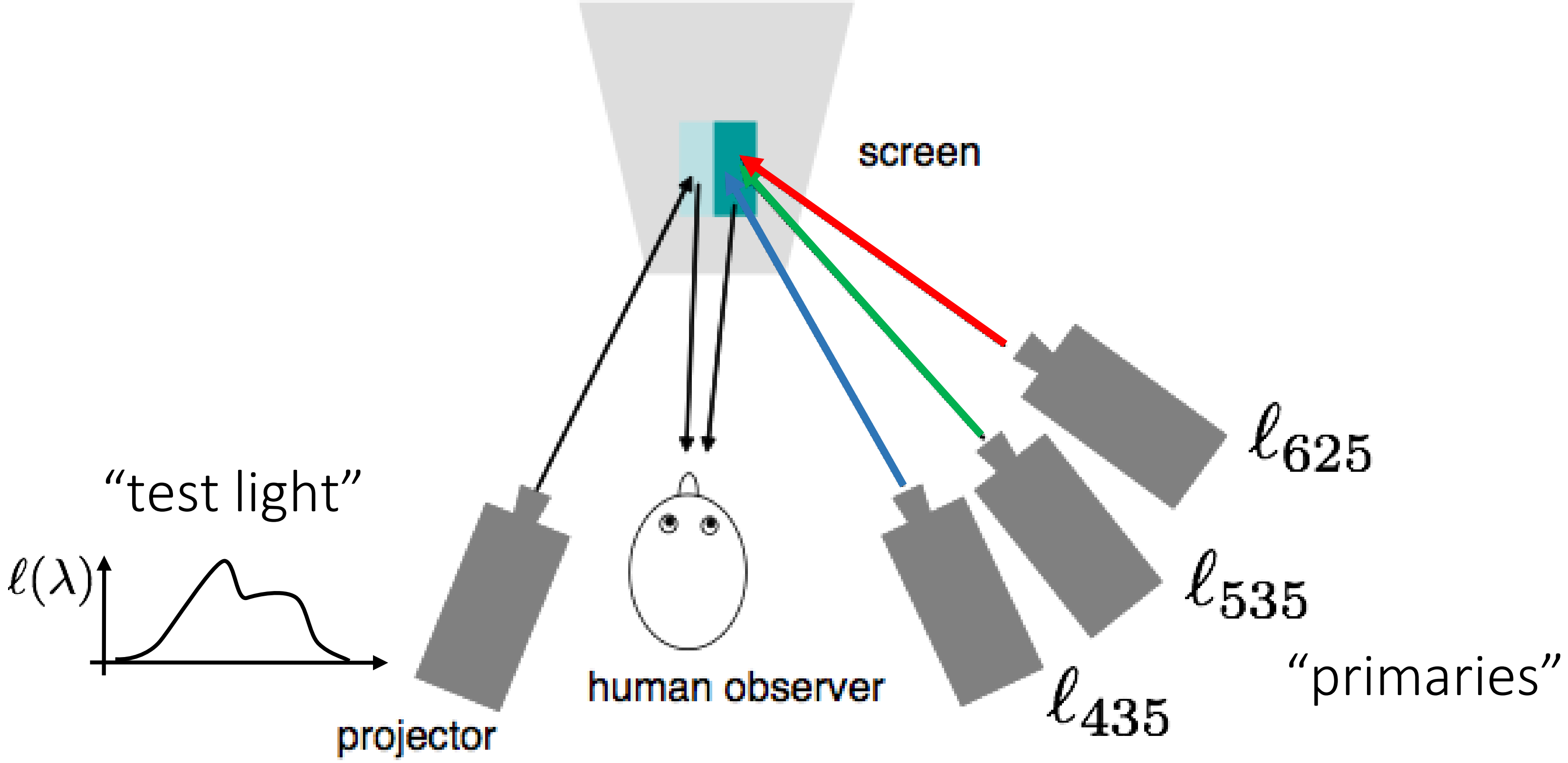
scanned copy



hallogen light

Color matching

CIE color matching

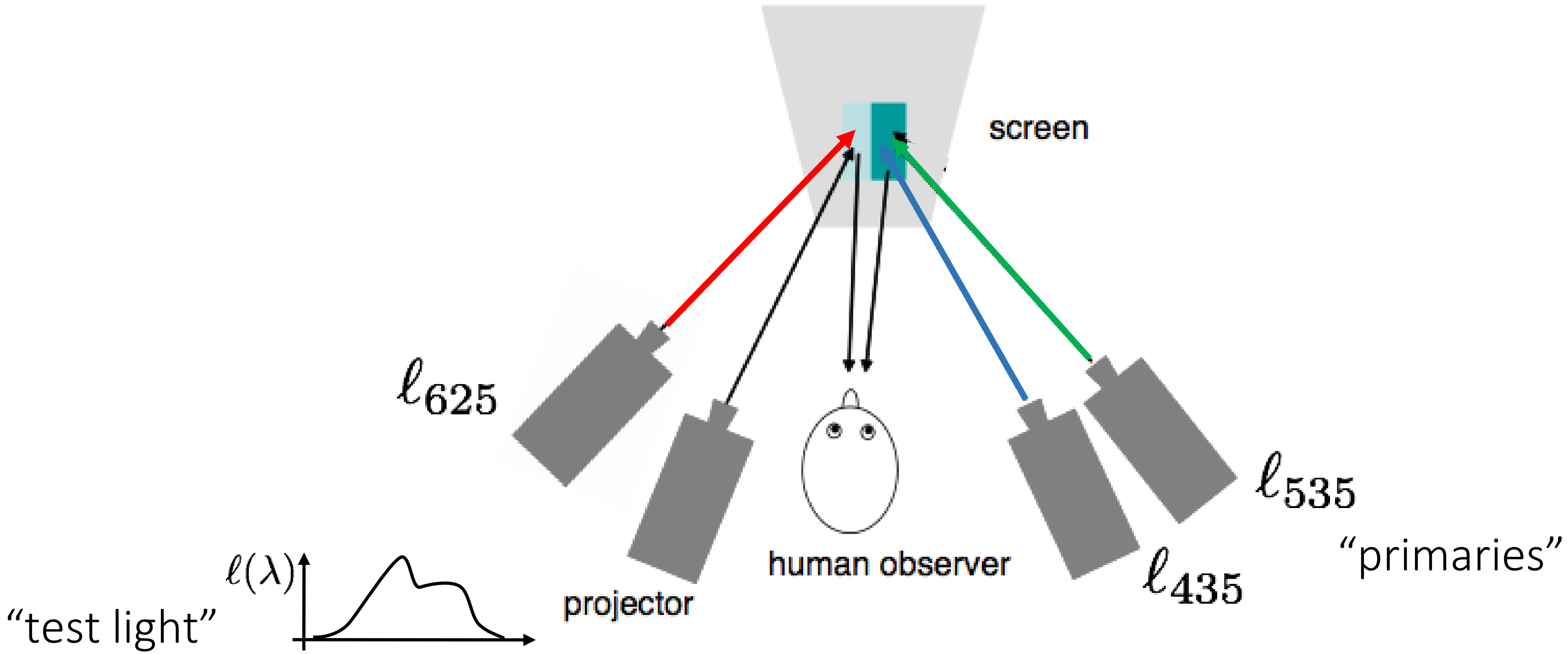


Adjust the strengths of the primaries until they re-produce the test color. Then:

$$\mathbf{c}(\ell(\lambda)) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535}) + \gamma\mathbf{c}(\ell_{625})$$

equality symbol means "has the same retinal color as" or "is metameric to"

CIE color matching

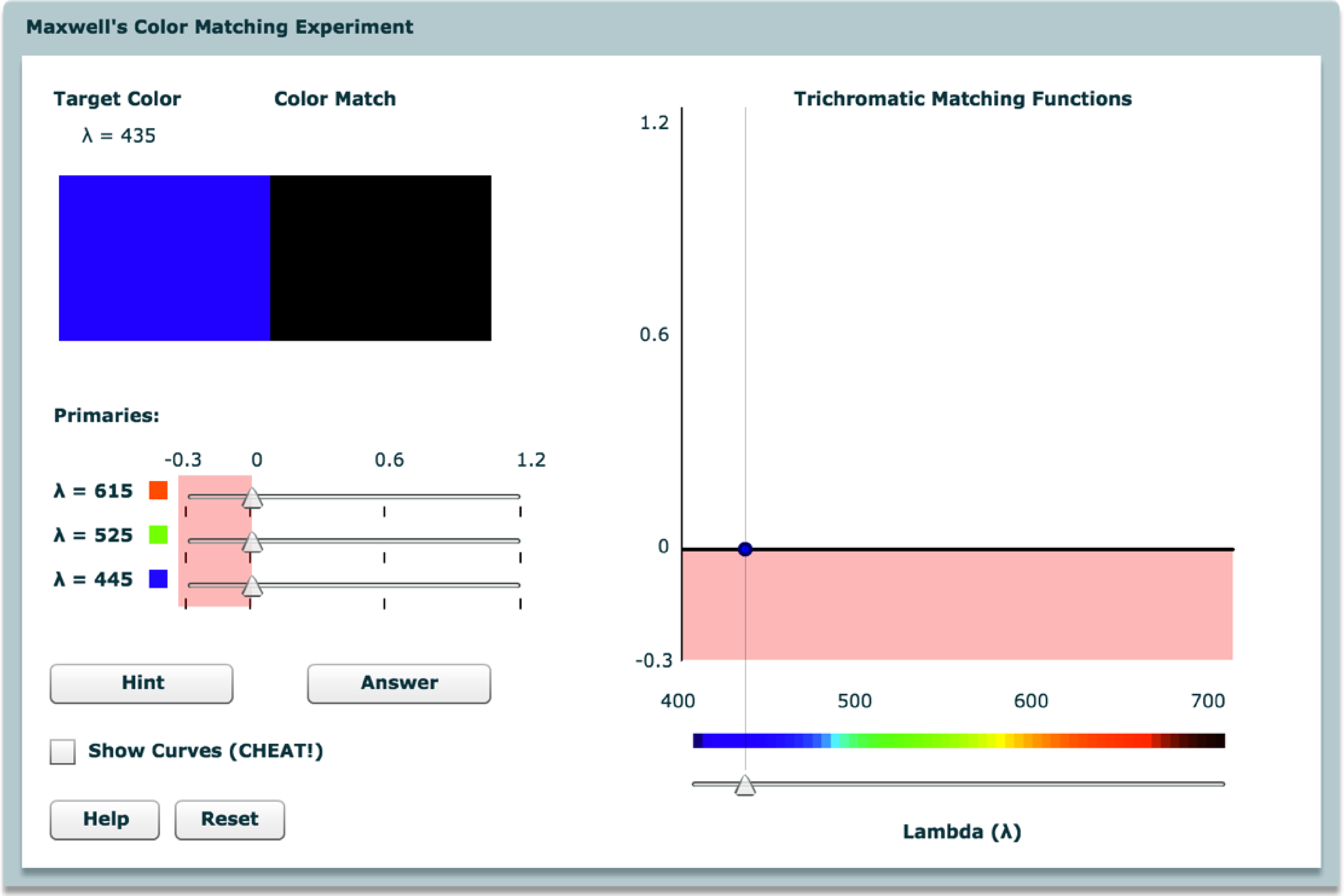


To match some test colors, you need to add some primary beam on the left (same as "subtracting light" from the right)

$$\mathbf{c}(\ell(\lambda)) + \gamma\mathbf{c}(\ell_{625}) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535})$$

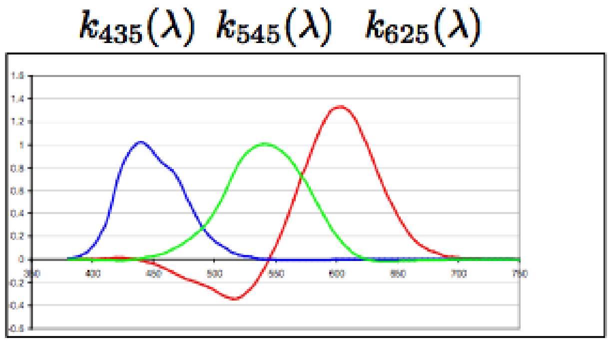
$$\longrightarrow \mathbf{c}(\ell(\lambda)) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535}) - \gamma\mathbf{c}(\ell_{625})$$

Color matching demo

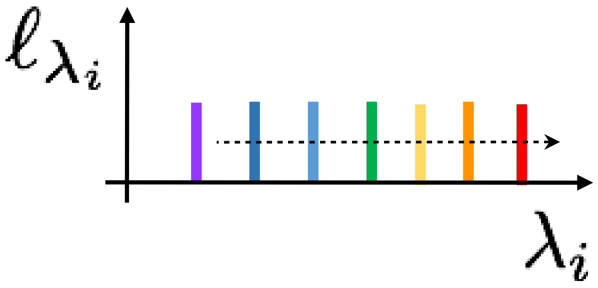


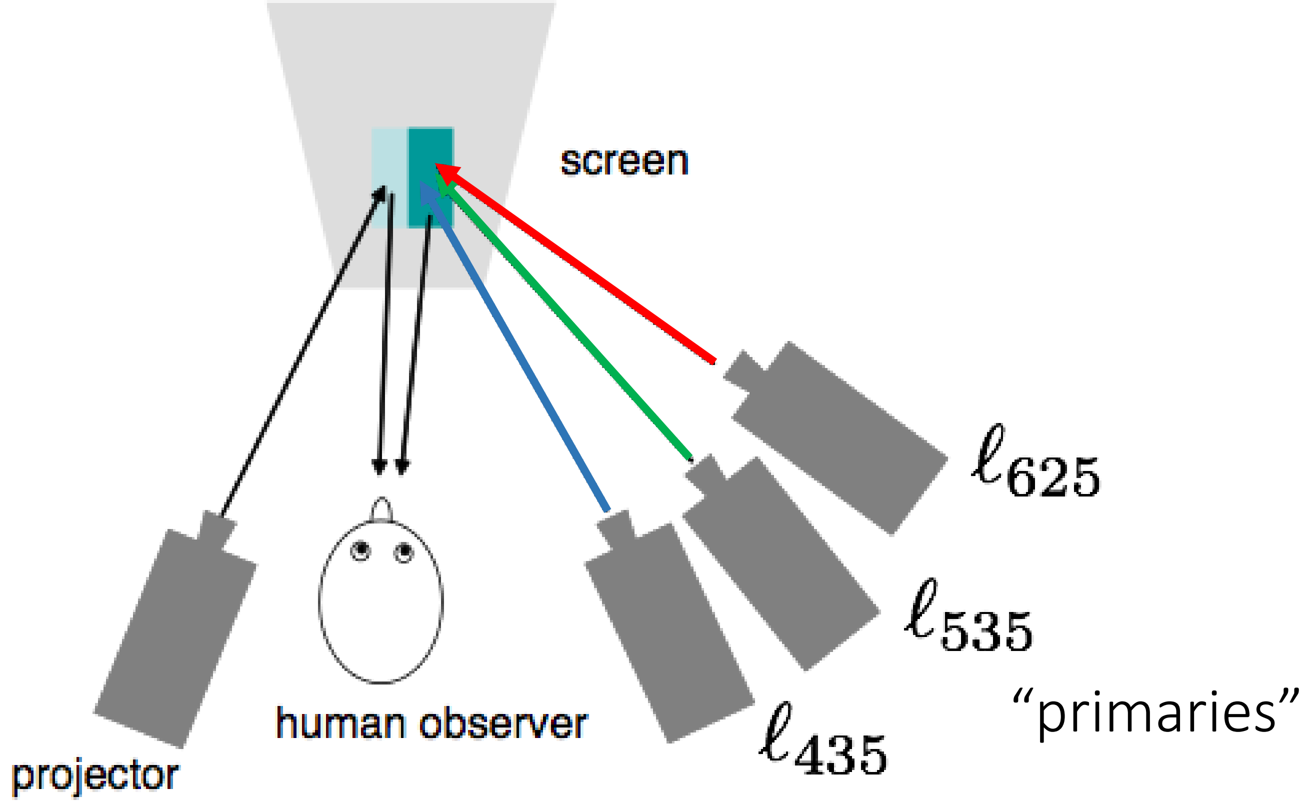
http://graphics.stanford.edu/courses/cs178/applets/colormatching.html

CIE color matching



Matching experiment matching functions



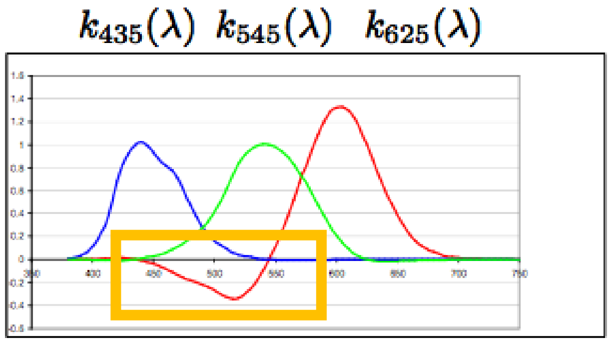


Repeat this matching experiments for pure test beams at wavelengths λ_i and keep track of the coefficients (negative or positive) required to reproduce each pure test beam.

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

CIE color matching

note the negative values



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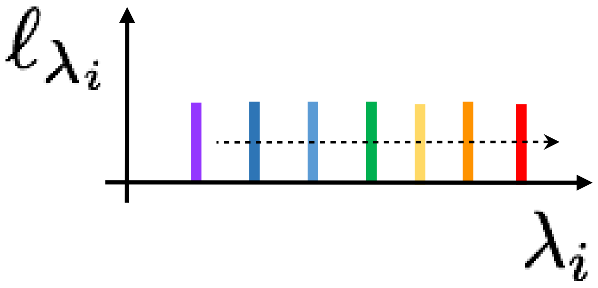

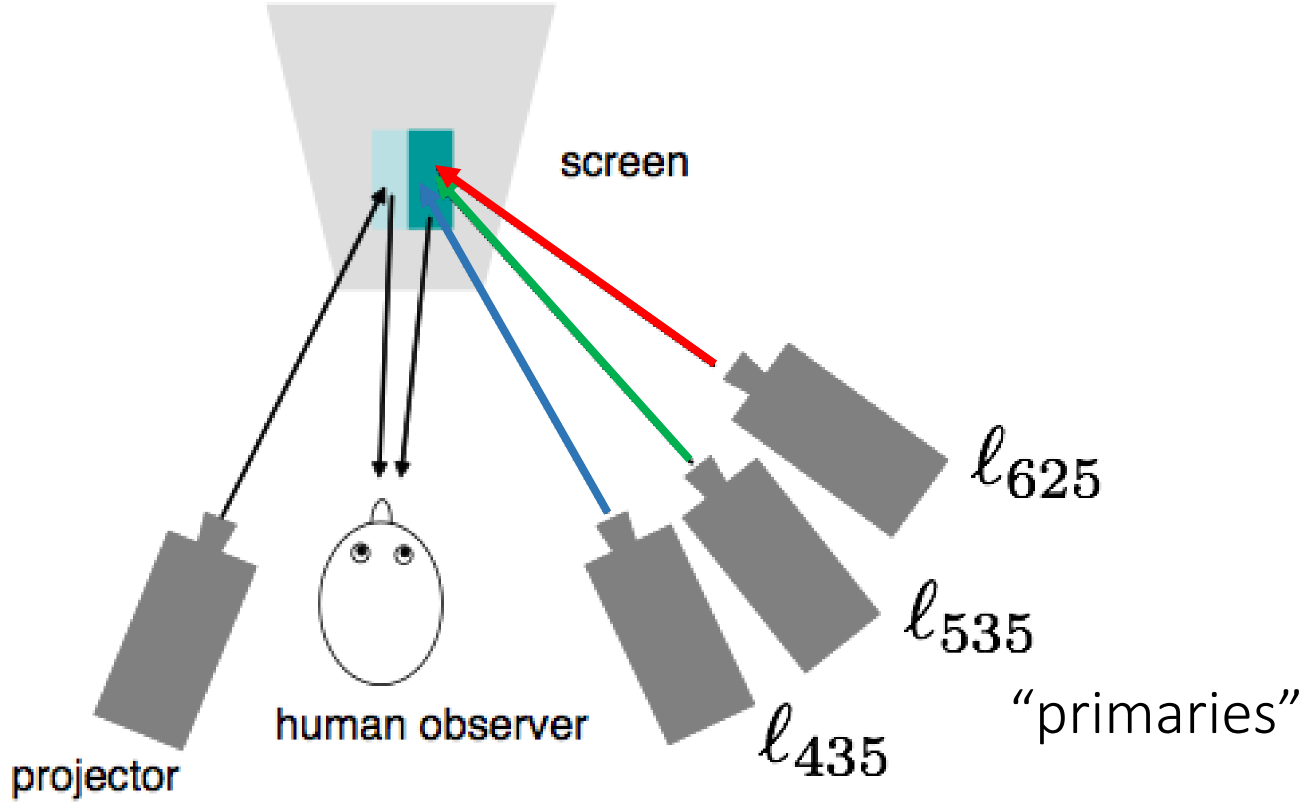

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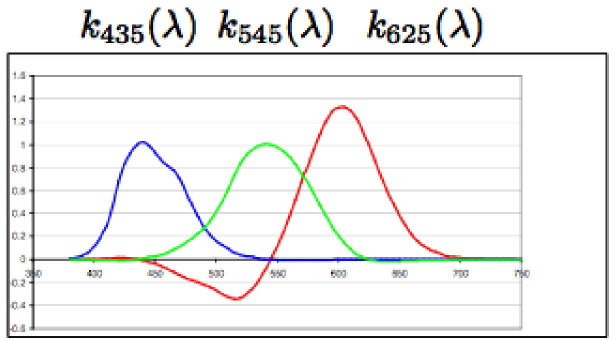
CIE color matching



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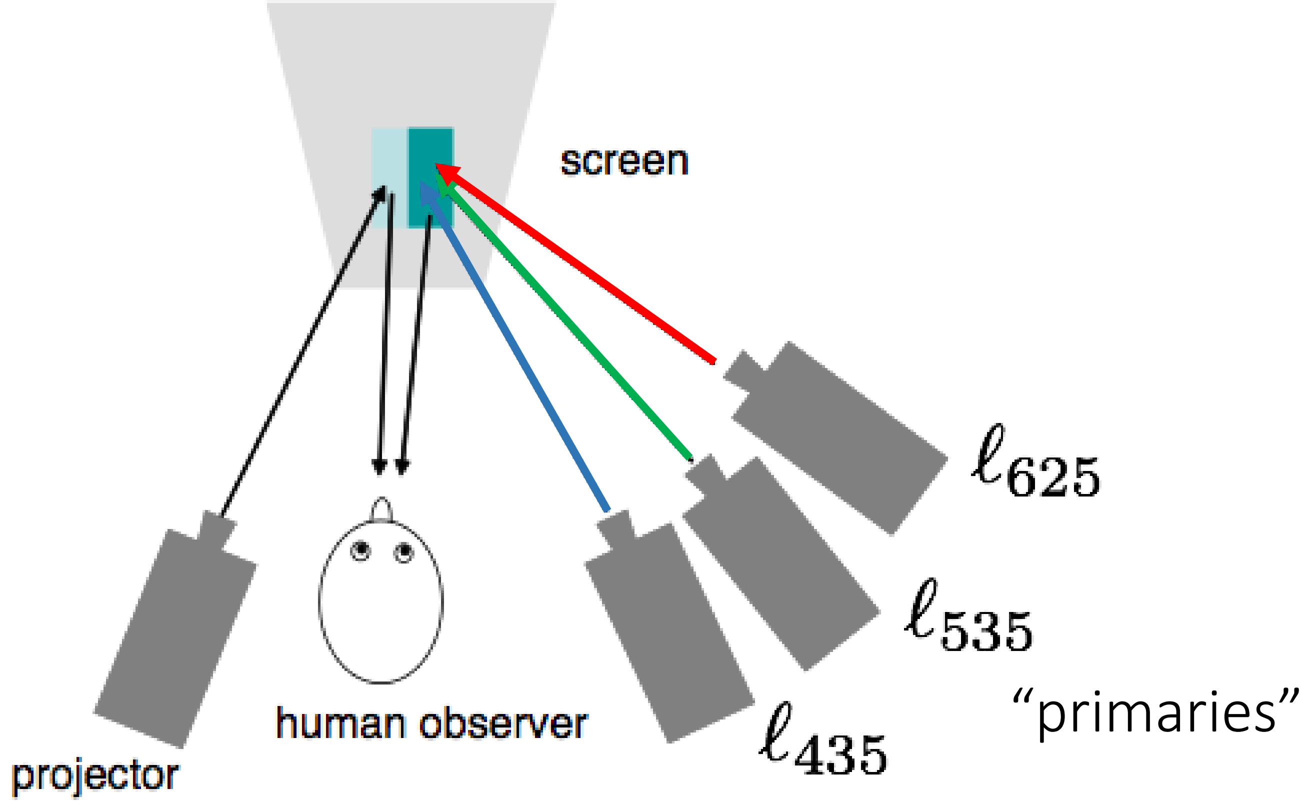
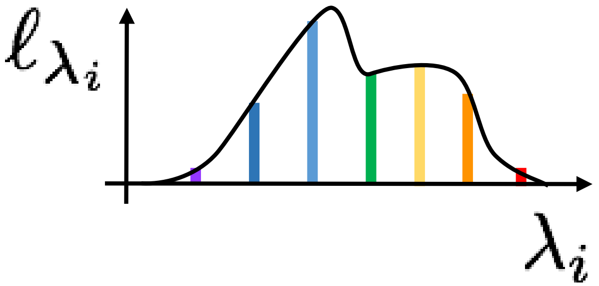
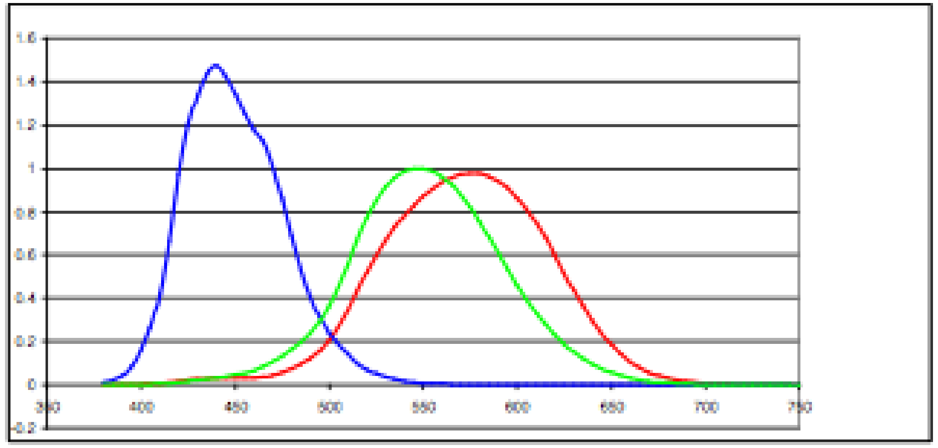




What about "mixed beams"?

Two views of retinal color

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$

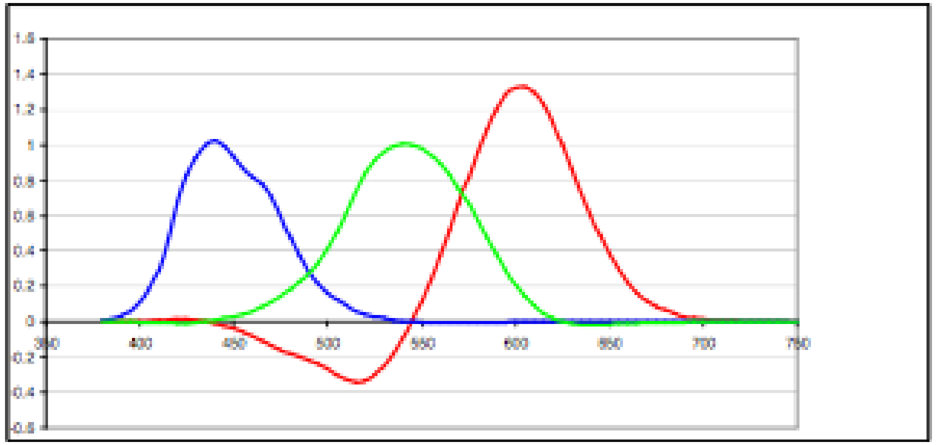


LMS senstivity functions

?

↔

$k_{435}(\lambda)$ $k_{545}(\lambda)$ $k_{625}(\lambda)$

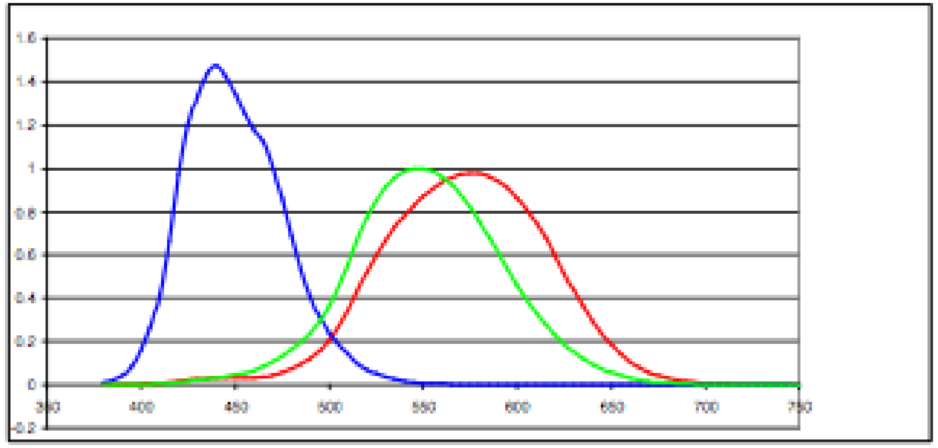


Matching experiment matching functions

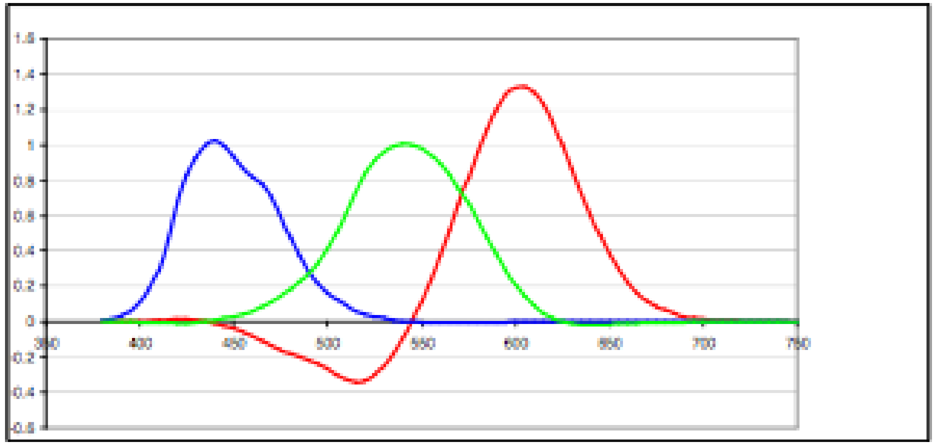
Analytic: Retinal color is produced by analyzing spectral power distributions using the color sensitivity functions.

Synthetic: Retinal color is produced by synthesizing color primaries using the color matching functions.

Two views of retinal color


$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$

LMS senstivity functions


$k_{435}(\lambda)$ $k_{545}(\lambda)$ $k_{625}(\lambda)$

Matching experiment matching functions

Analytic: Retinal color is produced by analyzing spectral power distributions using the color sensitivity functions.

Synthetic: Retinal color is produced by synthesizing color primaries using the color matching functions.

The two views are equivalent: Color matching functions are also color sensitivity functions. For each set of color sensitivity functions, there are corresponding color primaries.

Linear color spaces

Linear color spaces

1) Color matching experimental outcome:

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

same in matrix form:

$$\begin{bmatrix} | \\ \mathbf{c}(\lambda_{\mathbf{i}}) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} k_{435} \\ k_{535} \\ k_{625} \end{bmatrix}$$

how is this matrix formed?

Linear color spaces

1) Color matching experimental outcome:

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

same in matrix form:

$$\begin{bmatrix} | \\ \mathbf{c}(\lambda_{\mathbf{i}}) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} k_{435} \\ k_{535} \\ k_{625} \end{bmatrix}$$

2) Implication for arbitrary mixed beams:

$$\begin{bmatrix} | \\ \mathbf{c}(\ell(\lambda)) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} \int k_{435}(\lambda)\ell(\lambda)d\lambda \\ \int k_{535}(\lambda)\ell(\lambda)d\lambda \\ \int k_{625}(\lambda)\ell(\lambda)d\lambda \end{bmatrix}$$

where do these terms come from?

Linear color spaces

1) Color matching experimental outcome:

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

same in matrix form:

$$\begin{bmatrix} | \\ \mathbf{c}(\lambda_{\mathbf{i}}) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} k_{435} \\ k_{535} \\ k_{625} \end{bmatrix}$$

2) Implication for arbitrary mixed beams:

$$\begin{bmatrix} | \\ \mathbf{c}(\ell(\lambda)) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} \int k_{435}(\lambda)\ell(\lambda)d\lambda \\ \int k_{535}(\lambda)\ell(\lambda)d\lambda \\ \int k_{625}(\lambda)\ell(\lambda)d\lambda \end{bmatrix}$$

what is this similar to?

Linear color spaces

1) Color matching experimental outcome:

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

same in matrix form:

$$\begin{bmatrix} | \\ \mathbf{c}(\boldsymbol{\lambda_i}) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} k_{435} \\ k_{535} \\ k_{625} \end{bmatrix}$$

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representation of retinal color in LMS space

change of basis matrix

representation of retinal color in space of primaries

Linear color spaces

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Linear color spaces

basis for retinal color ⇔ color matching functions ⇔ primary colors ⇔ color space

$$\begin{bmatrix} | \\ \mathbf{c}(\ell(\lambda)) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}_1 & \mathbf{c}_2 & \mathbf{c}_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \int k_1(\lambda)\ell(\lambda)d\lambda \\ \int k_2(\lambda)\ell(\lambda)d\lambda \\ \int k_3(\lambda)\ell(\lambda)d\lambda \end{bmatrix}$$

$$\begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \mathbf{M}^{-1}$$

$$\begin{bmatrix} k_1(\lambda) \\ k_2(\lambda) \\ k_3(\lambda) \end{bmatrix} = \mathbf{M} \begin{bmatrix} k_{435}(\lambda) \\ k_{545}(\lambda) \\ k_{625}(\lambda) \end{bmatrix}$$

$\mathbf{M}^{-1}\mathbf{M}$ can insert any invertible M

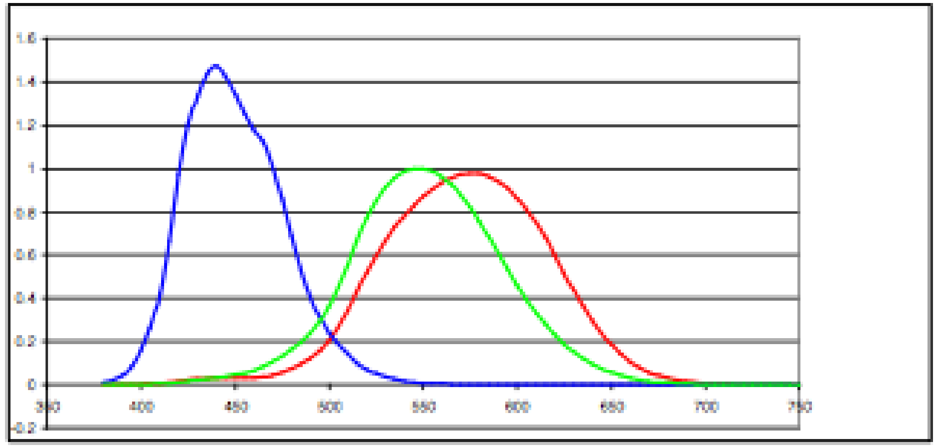
$$\begin{bmatrix} | \\ \mathbf{c}(\ell(\lambda)) \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ \mathbf{c}(\ell_{\mathbf{435}}) & \mathbf{c}(\ell_{\mathbf{545}}) & \mathbf{c}(\ell_{\mathbf{625}}) \\ | & | & | \end{bmatrix} \begin{bmatrix} \int k_{435}(\lambda)\ell(\lambda)d\lambda \\ \int k_{535}(\lambda)\ell(\lambda)d\lambda \\ \int k_{625}(\lambda)\ell(\lambda)d\lambda \end{bmatrix}$$

representation of retinal color in LMS space

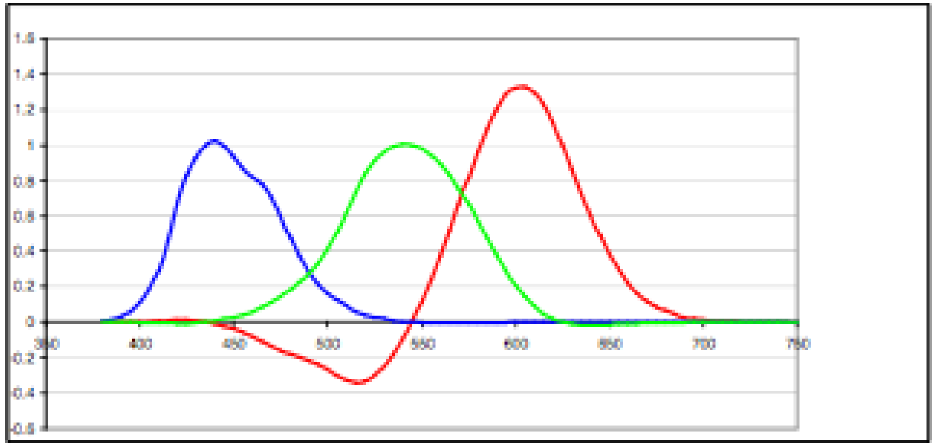
change of basis matrix

representation of retinal color in space of primaries

A few important color spaces



LMS color space



CIE RGB color space

not the “usual” RGB color
space encountered in practice

Two views of retinal color

Analytic: Retinal color is three numbers formed by taking the dot product of a power spectral distribution with three color matching/sensitivity functions.

Synthetic: Retinal color is three numbers formed by assigning weights to three color primaries to match the perception of a power spectral distribution.

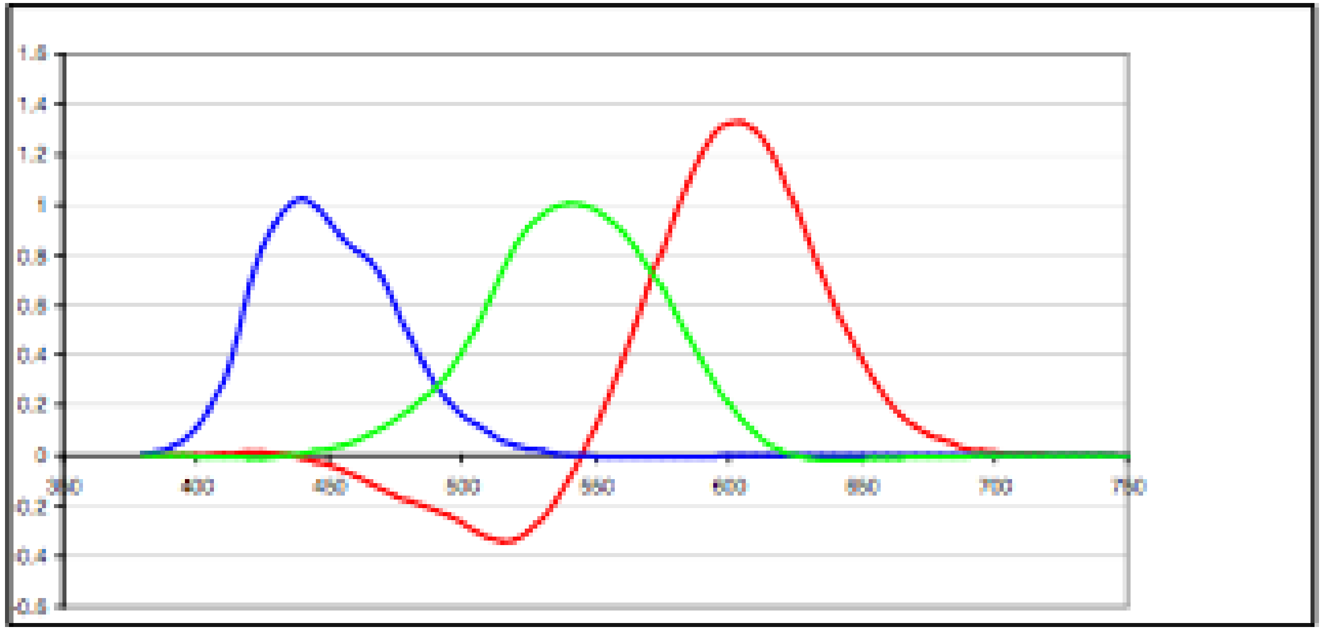
How would you make a color measurement device?

How would you make a color measurement device?

Do what the eye does:

- Select three spectral filters (i.e., three color matching functions.).
- Capture three measurements.

Can we use the CIE RGB color matching functions?



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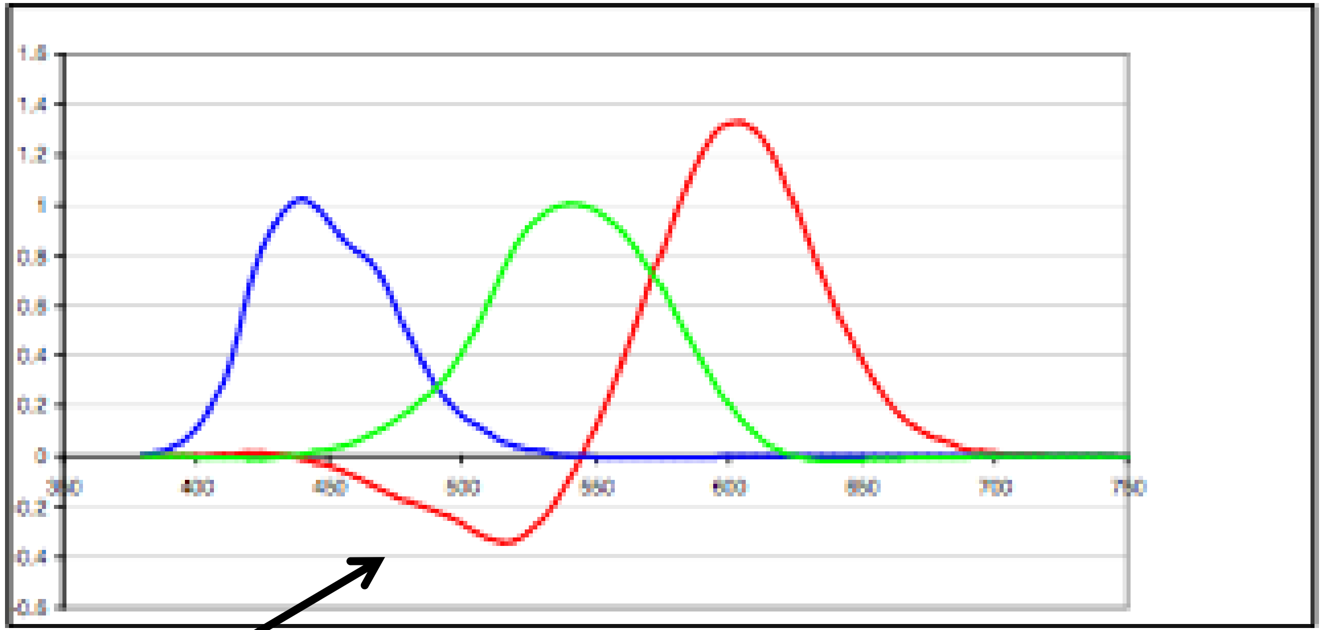

CIE RGB color space

Negative values are an issue (we can’t “subtract” light at a sensor)

How would you make a color measurement device?

Do what the eye does:

- Select three spectral filters (i.e., three color matching functions.).
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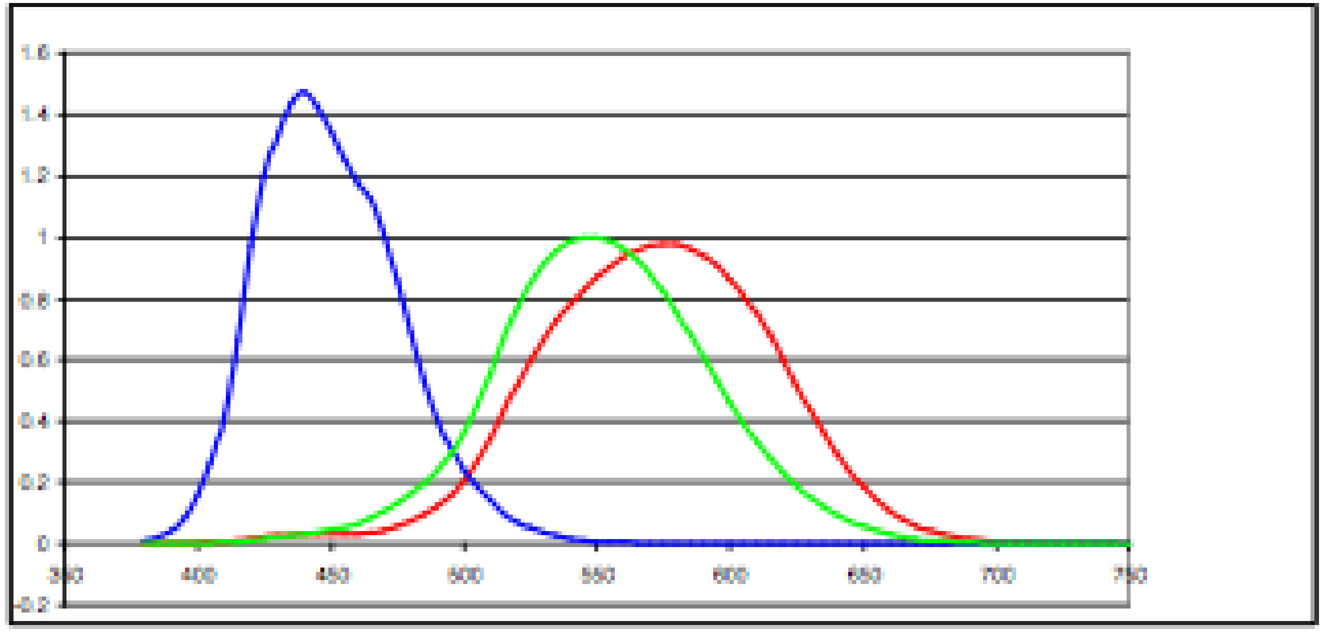
Can we use the LMS color matching functions?



LMS color space

How would you make a color measurement device?

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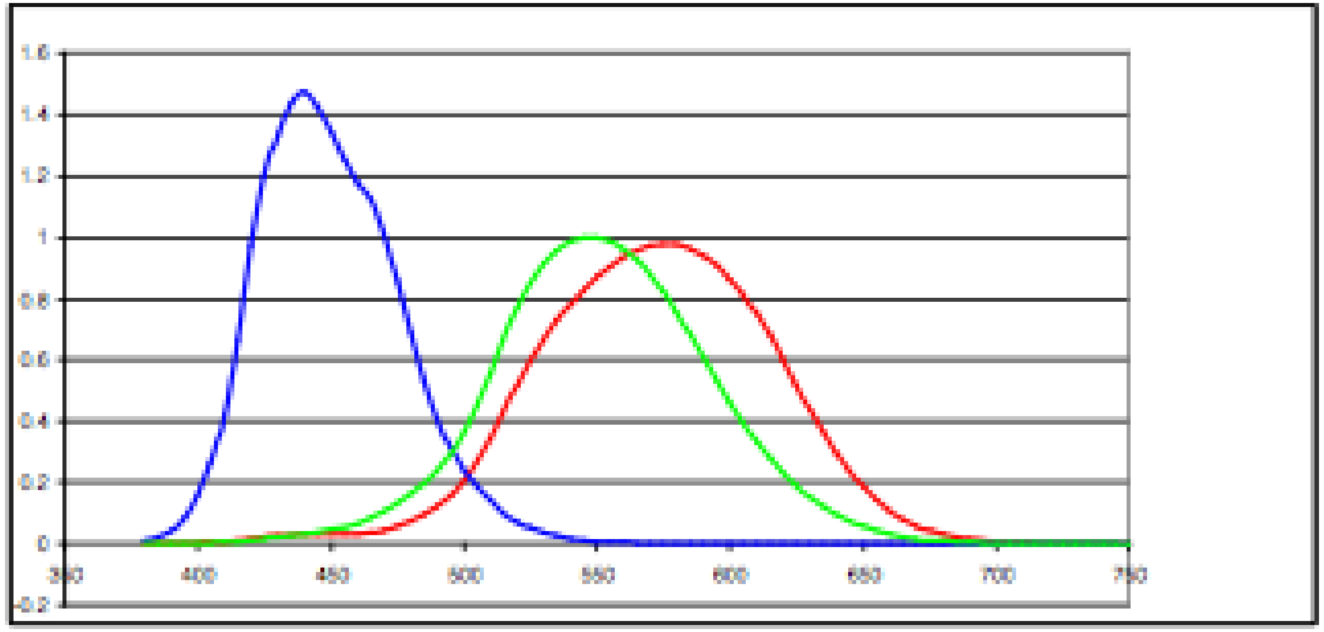
Can we use the LMS color matching functions?

- They weren’t known when CIE was doing their color matching experiments.
- We’ll see later they create other issues.



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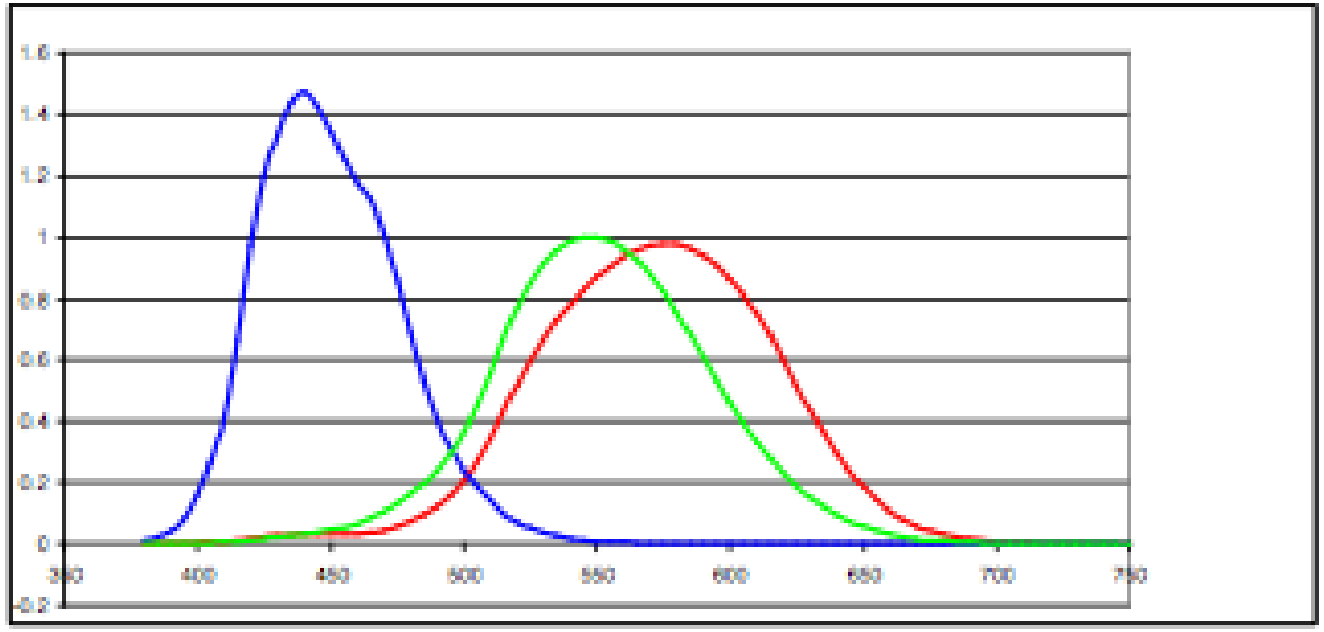

LMS color space

Can we use the LMS color matching functions?

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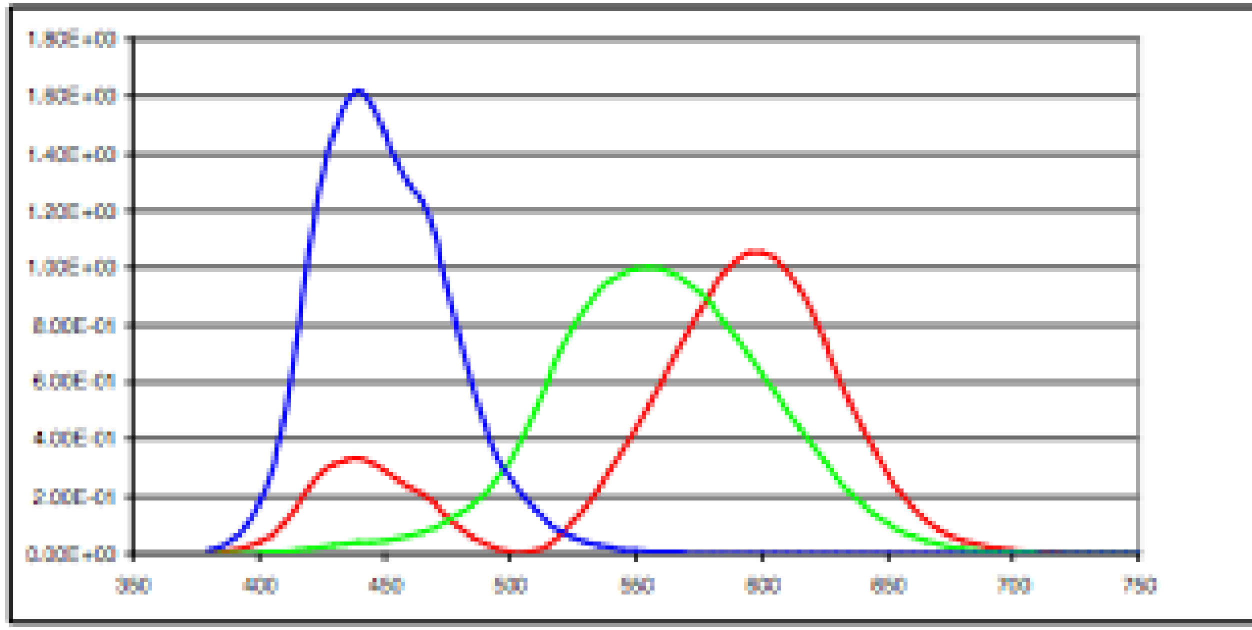
The CIE XYZ color space

- Derived from CIE RGB by adding enough blue and green to make the red positive.
- Probably the most important *reference* (i.e., device independent) color space.



CIE XYZ color space

Remarkable and/or scary: 80+ years of CIE XYZ is all down to color matching experiments done with 12 “standard observers”.

The CIE XYZ color space

- Derived from CIE RGB by adding enough blue and green to make the red positive.
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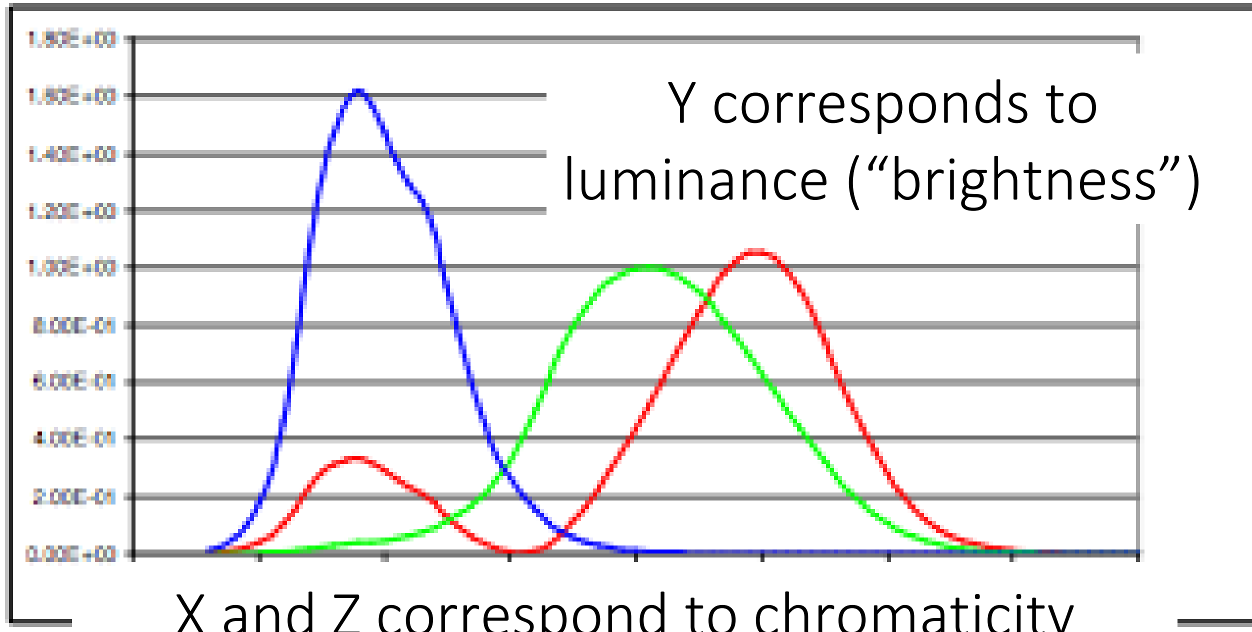
How would you convert a color image to grayscale?

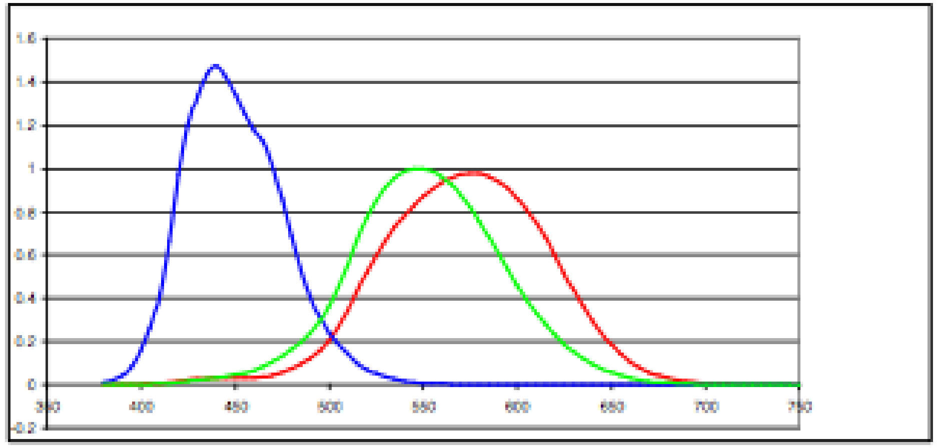


Y corresponds to luminance (“brightness”)

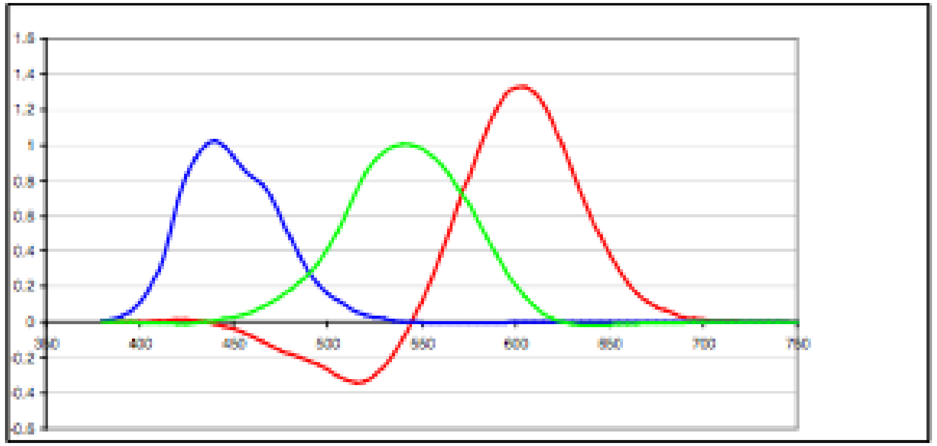
X and Z correspond to chromaticity

CIE XYZ color space

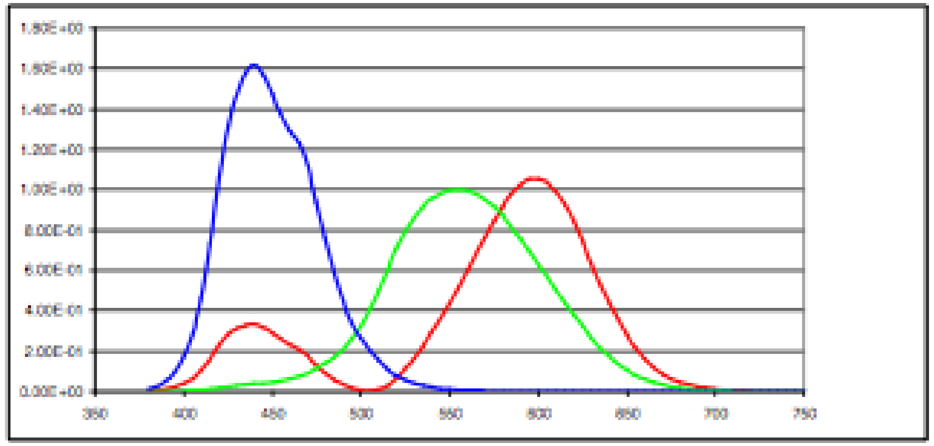
A few important color spaces



LMS color space



CIE RGB color space



CIE XYZ color space

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How would you make a color reproduction device?

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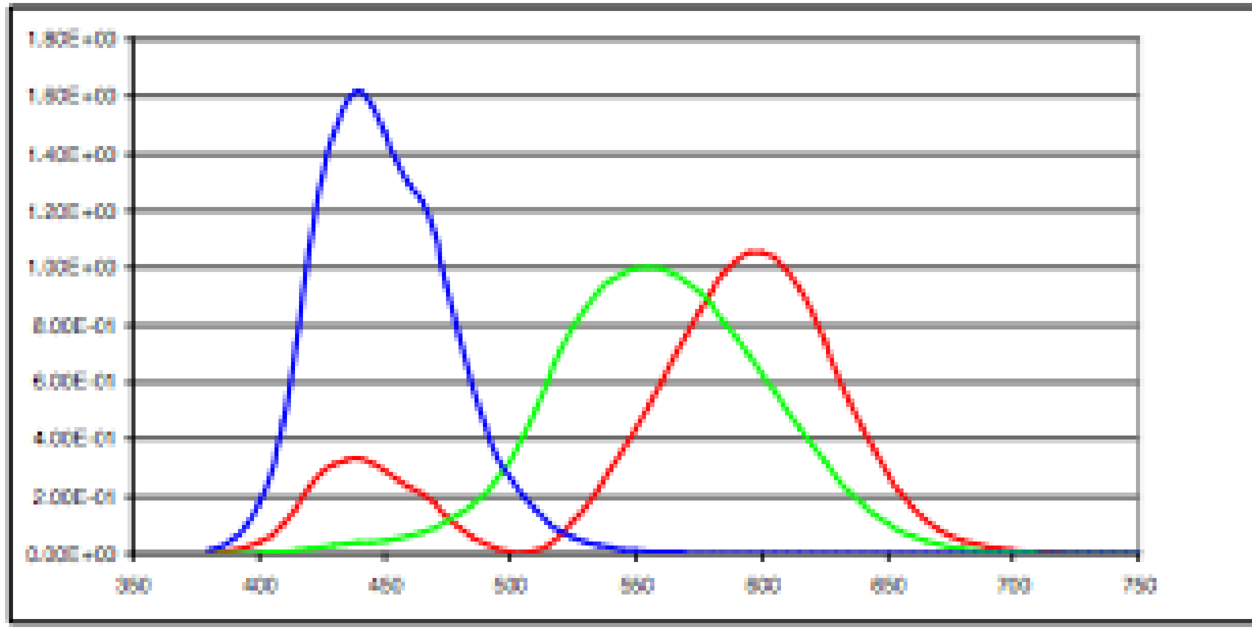
Do what color matching does:

- Select three color primaries.
- Represent all colors as mixtures of these three primaries.

Can we use the XYZ color primaries?



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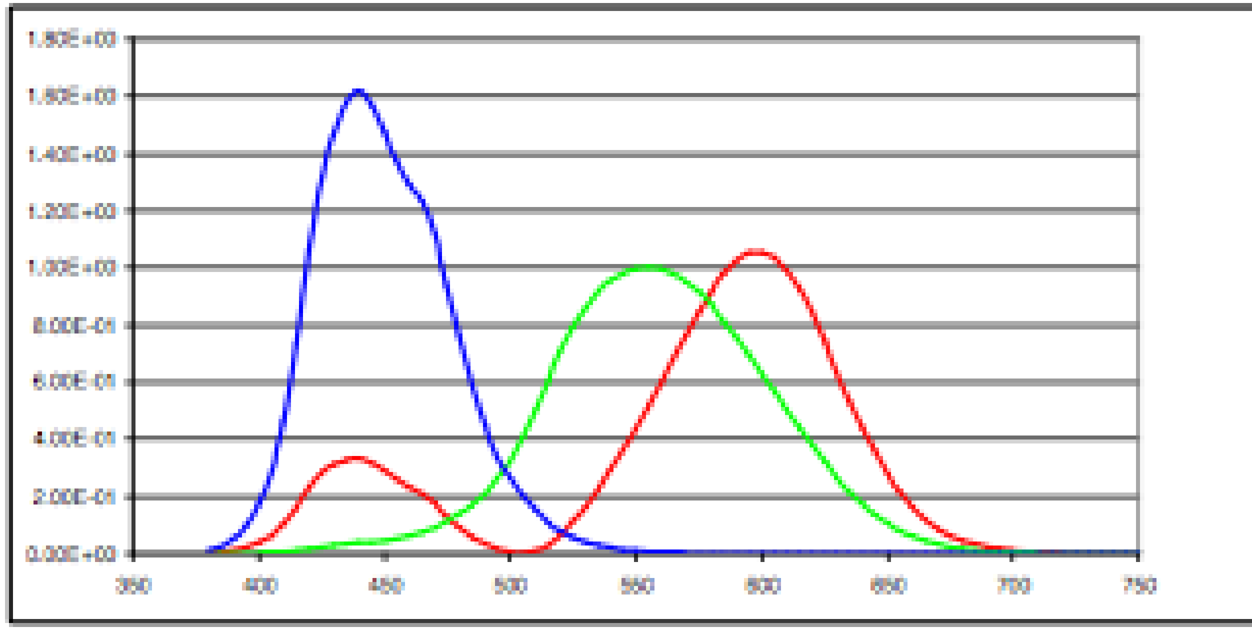


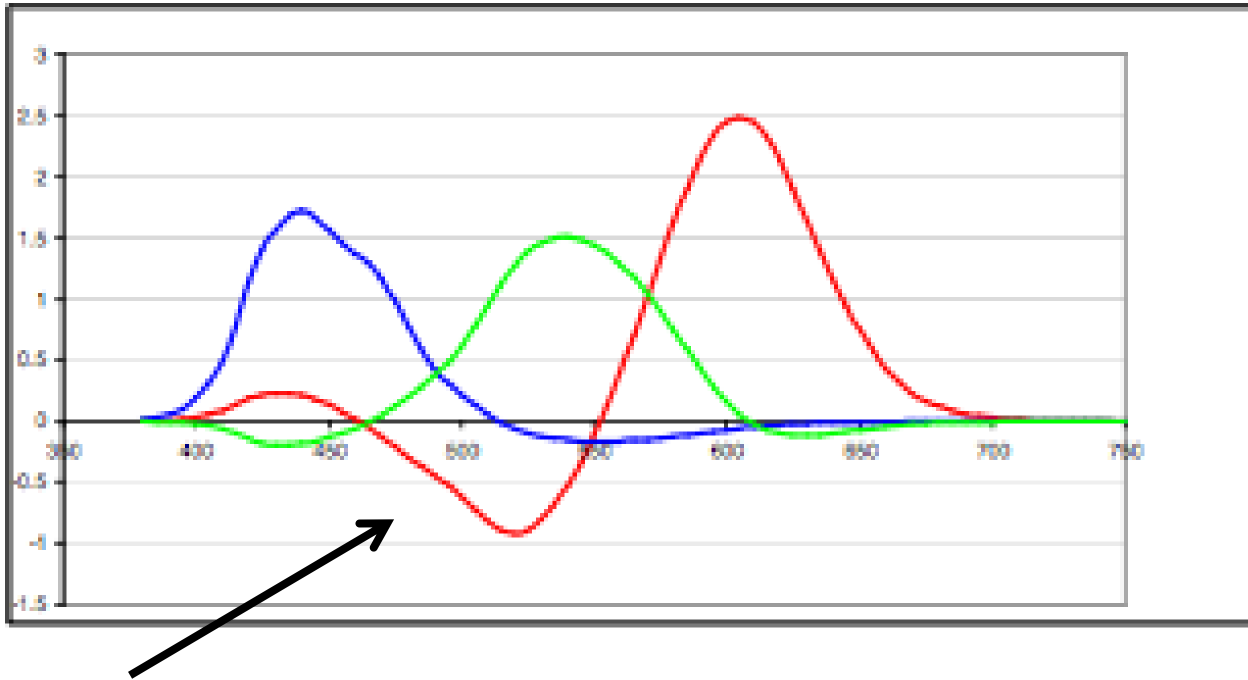
CIE XYZ color space

Can we use the XYZ color primaries?

- No, because they are not “real” colors (they require an SPD with negative values).
- Same goes for LMS color primaries.

The Standard RGB (sRGB) color space

- Derived by Microsoft and HP in 1996, based on CRT displays used at the time.
- Similar but not equivalent to CIE RGB.

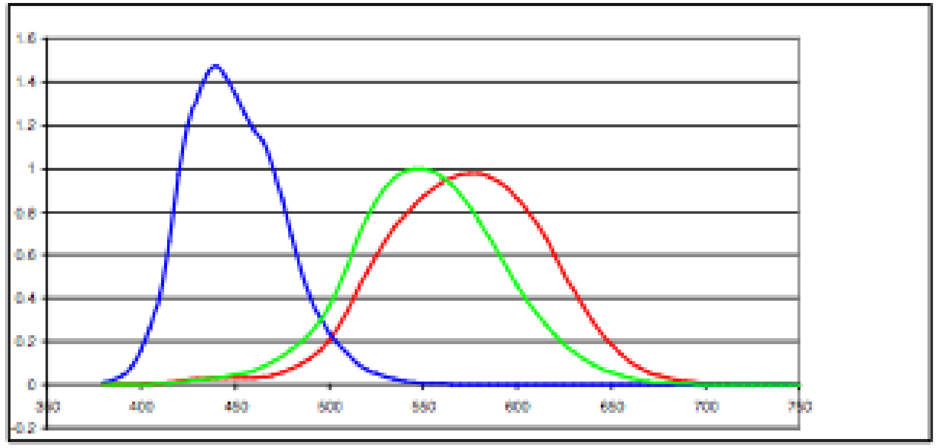


Note the negative values

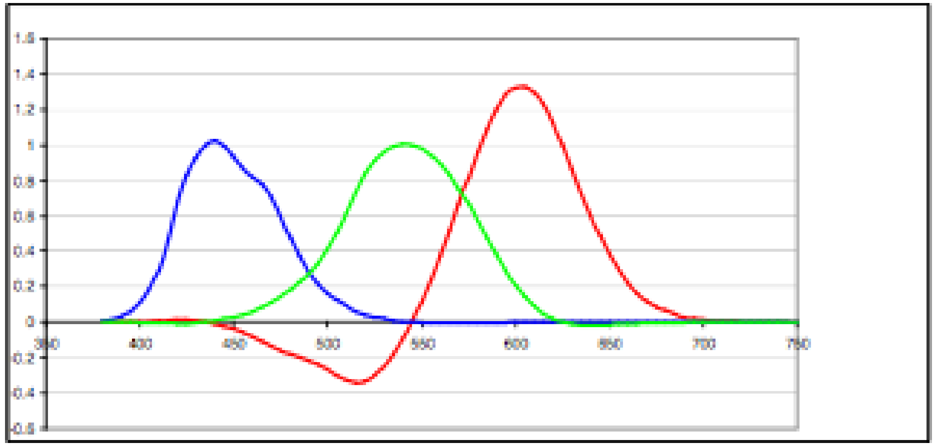
sRGB color space

While it is called “standard”, when you grab an “RGB” image, it is highly likely it is in a different RGB color space…

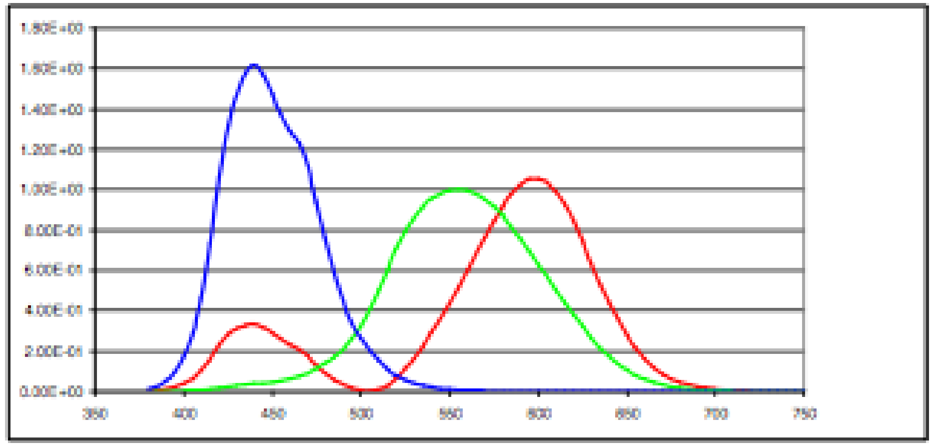
A few important color spaces



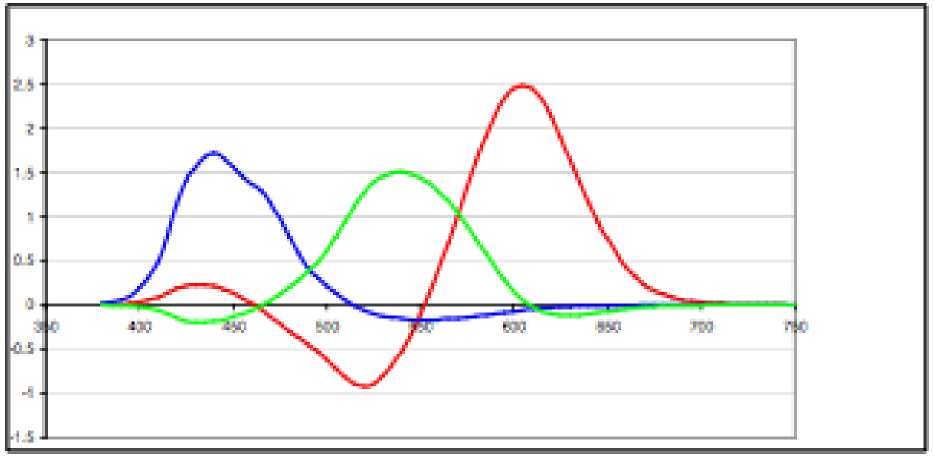
LMS color space



CIE RGB color space

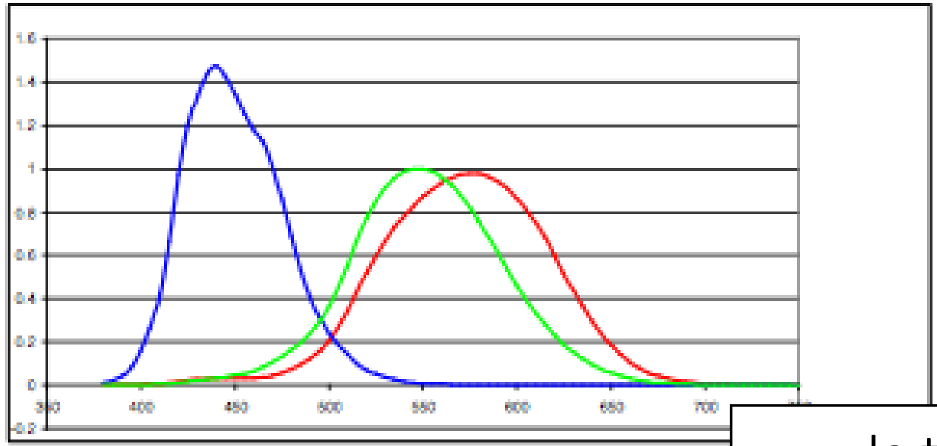


CIE XYZ color space



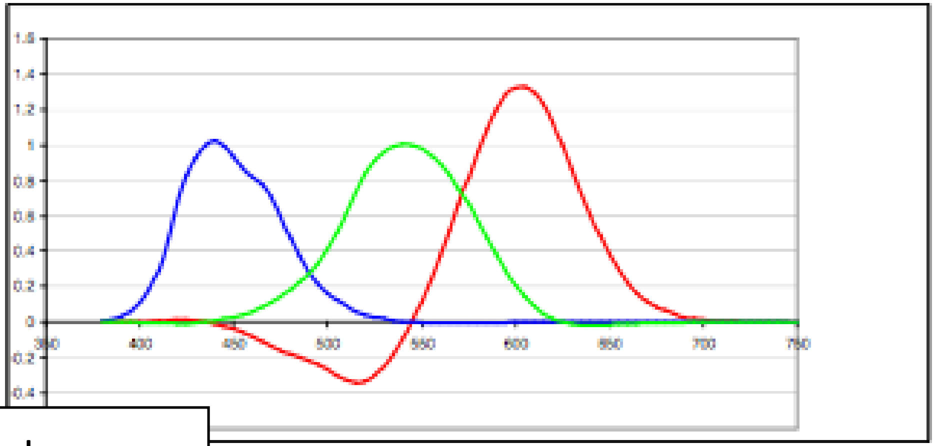
sRGB color space

A few important color spaces

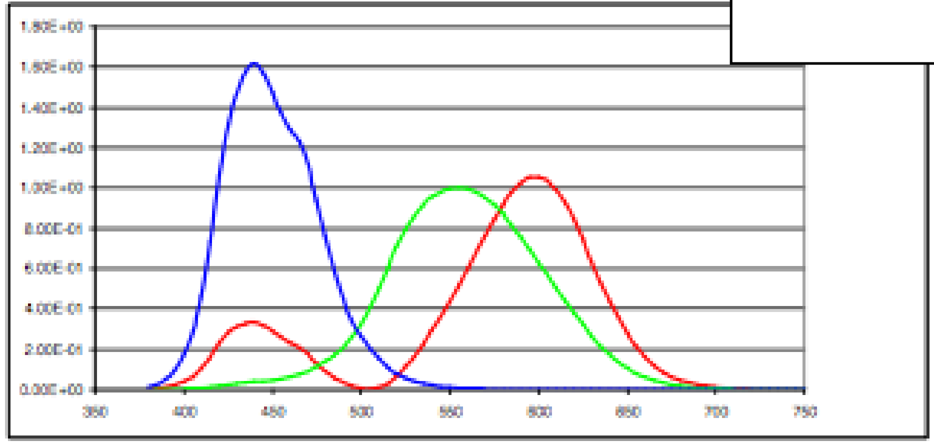


LMS color space

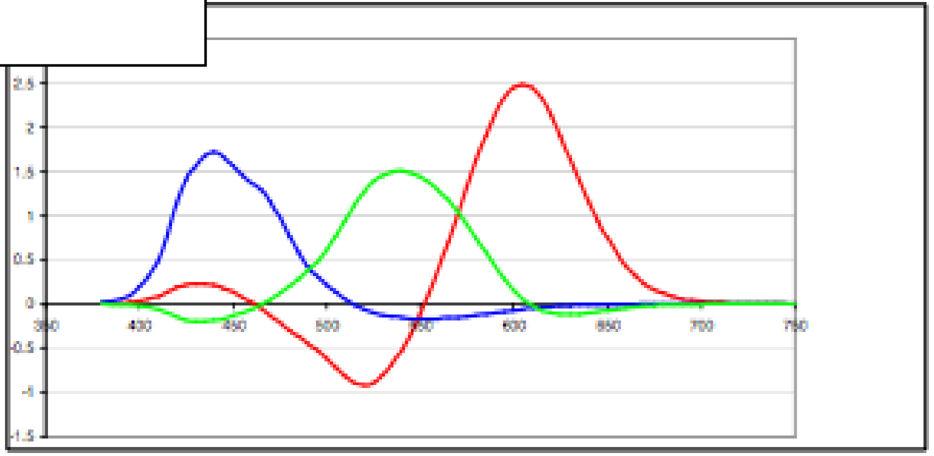
Is there a way to “compare” all these color spaces?



CIE RGB color space



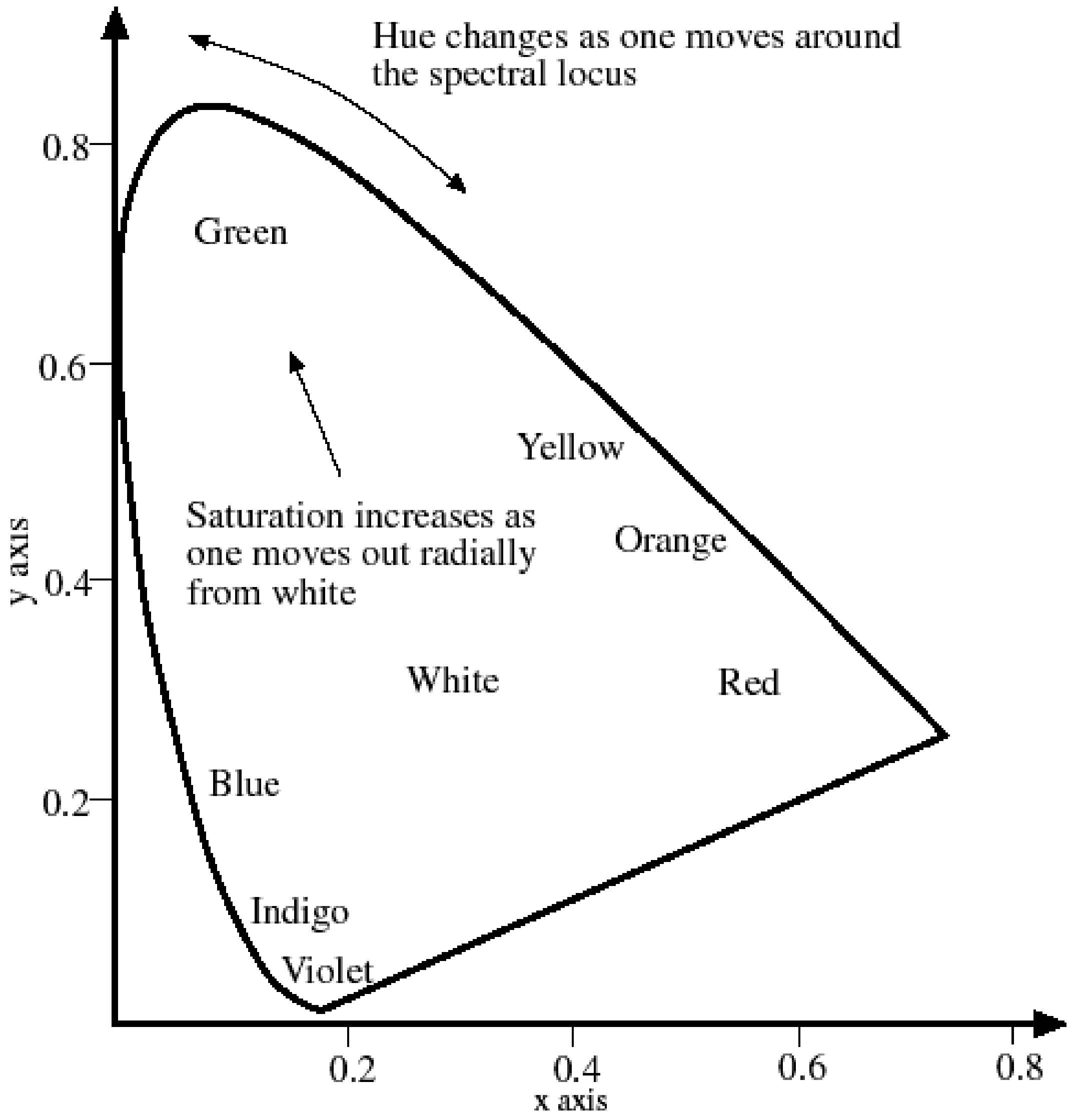
CIE XYZ color space



sRGB color space

Chromaticity

CIE xy (chromaticity)



$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

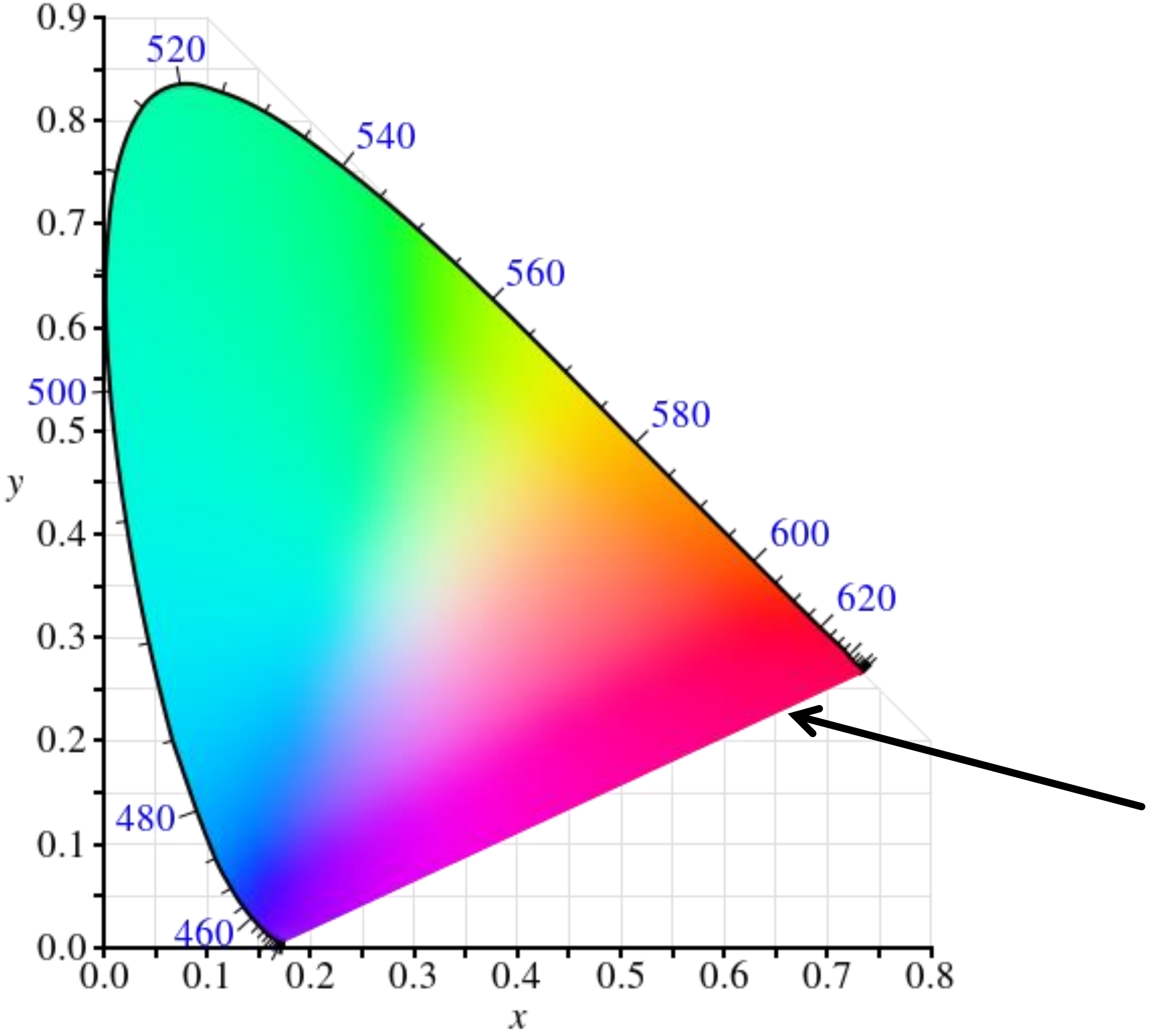
$$(X,Y,Z) \longleftrightarrow (\underline{x,y},Y)$$

chromaticity

luminance/brightness

Perspective projection of 3D retinal color space to two dimensions.

CIE xy (chromaticity)



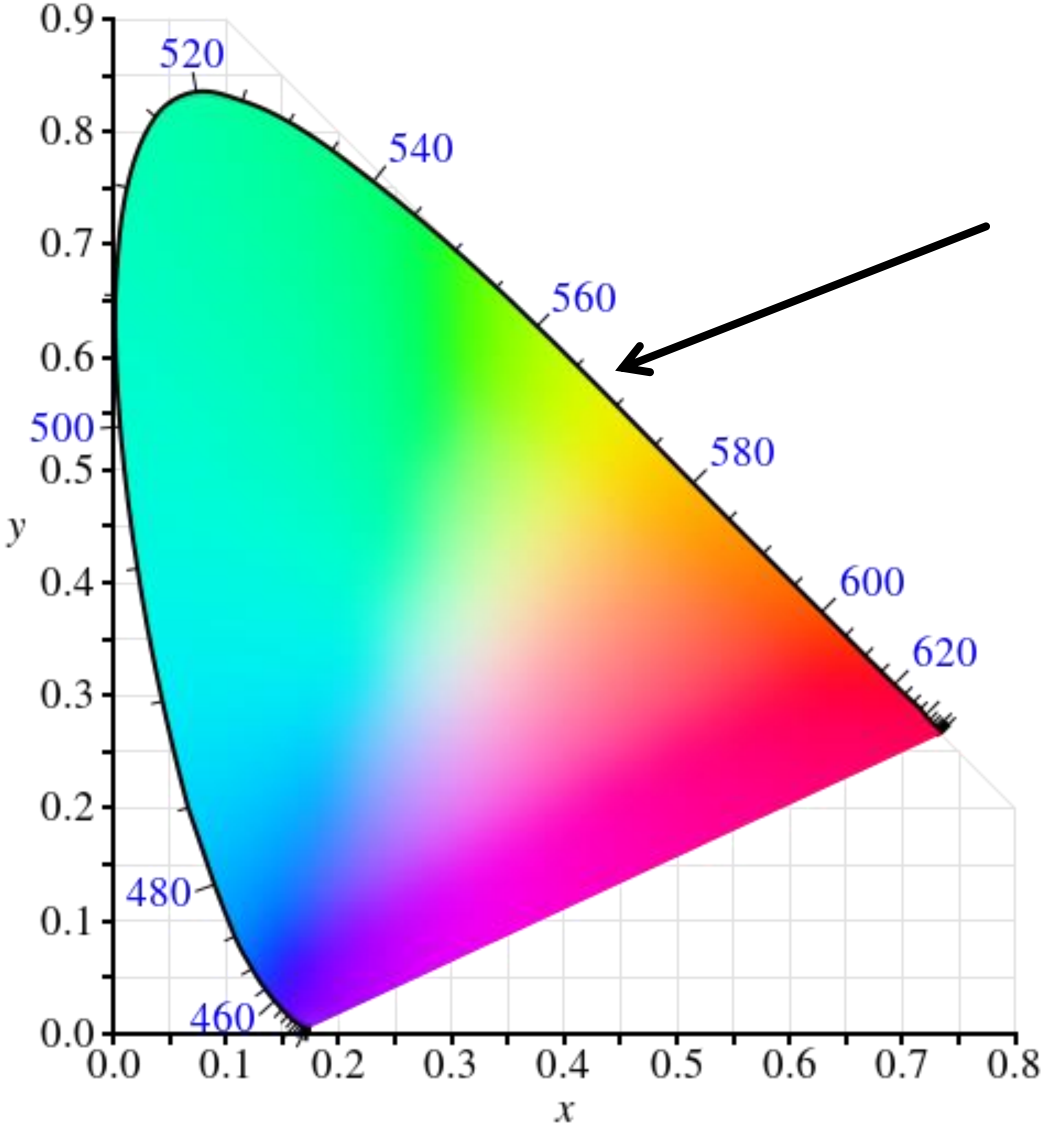
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$(X, Y, Z) \longleftrightarrow (x, y, Y)$$

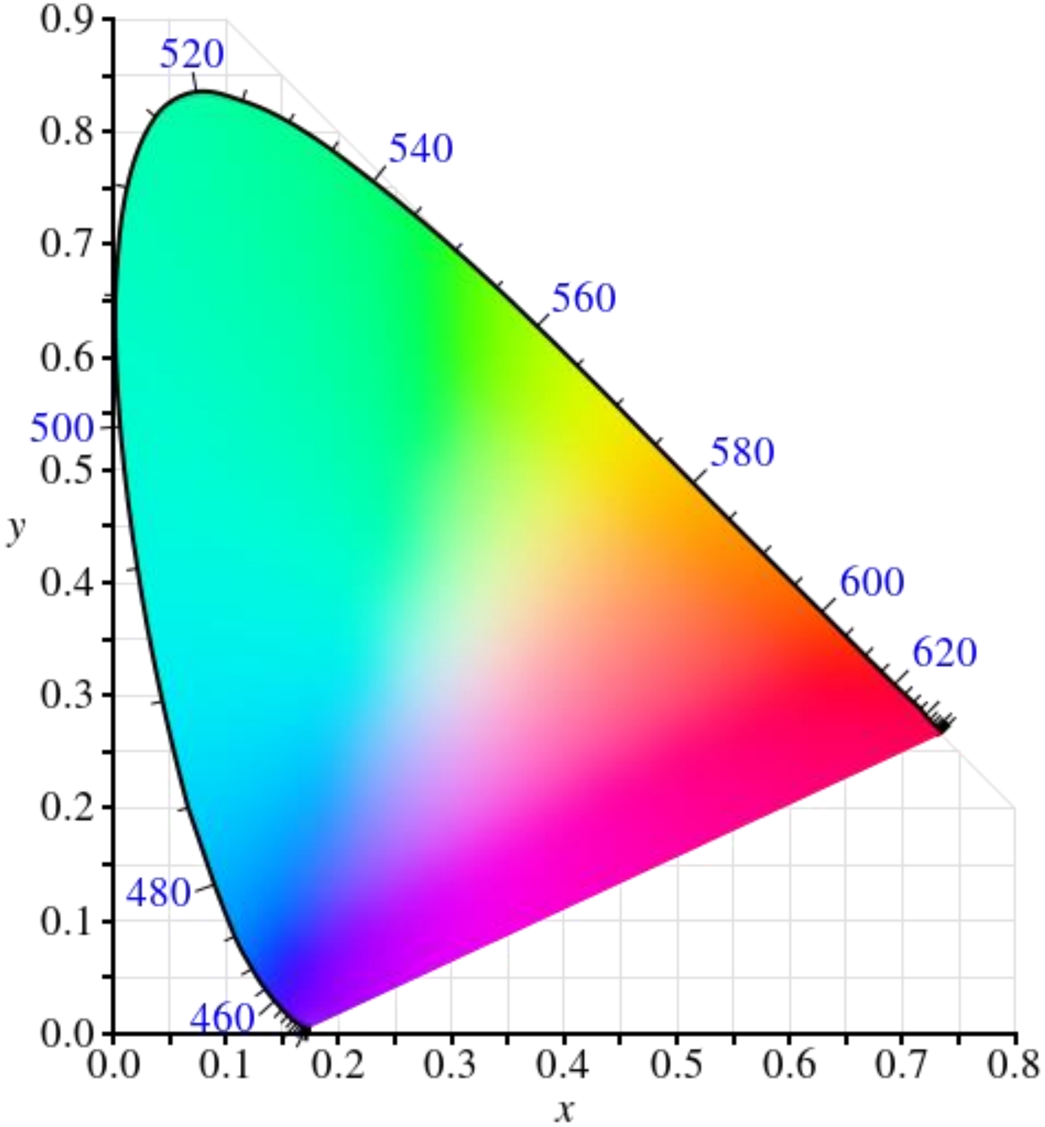
Note: These colors can be extremely misleading depending on the file origin and the display you are using

CIE xy (chromaticity)



What does the boundary of the chromaticity diagram correspond to?

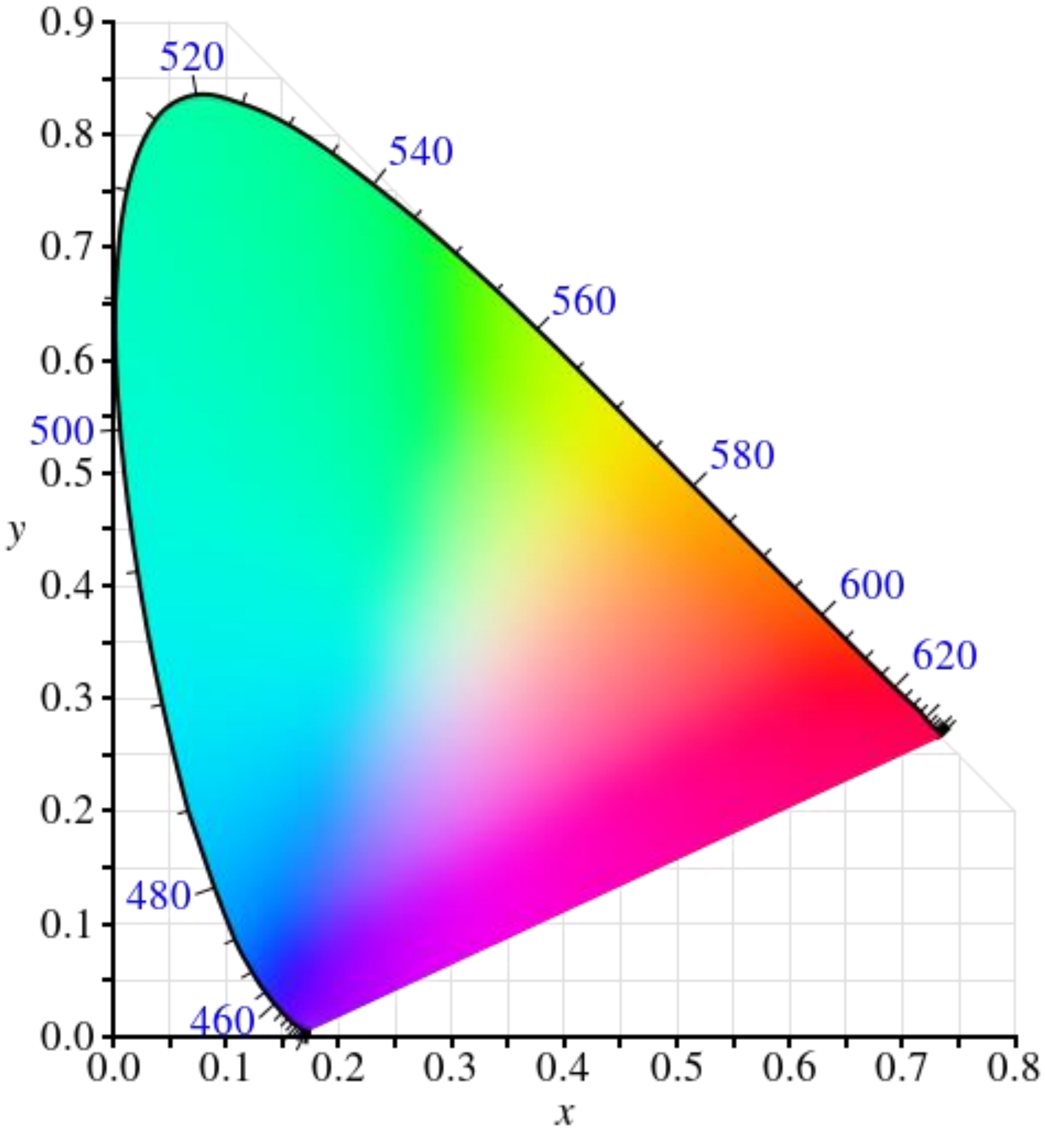
Color gamuts



We can compare color spaces by looking at what parts of the chromaticity space they can reproduce with their primaries.

But why would a color space not be able to reproduce all of the chromaticity space?

Color gamuts

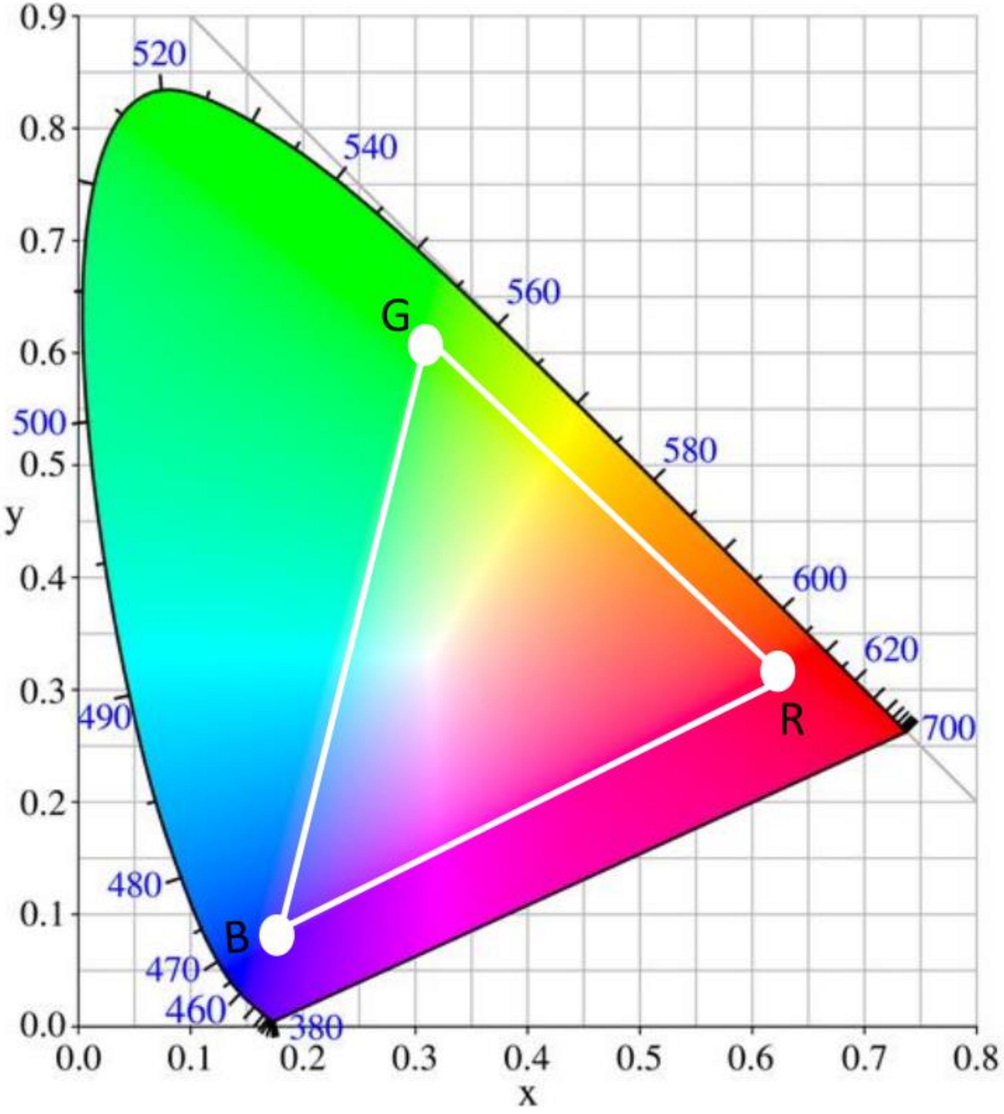


We can compare color spaces by looking at what parts of the chromaticity space they can reproduce with their primaries.

But why would a color space not be able to reproduce all of the chromaticity space?

- Many colors require negative weights to be reproduced, which are not realizable.

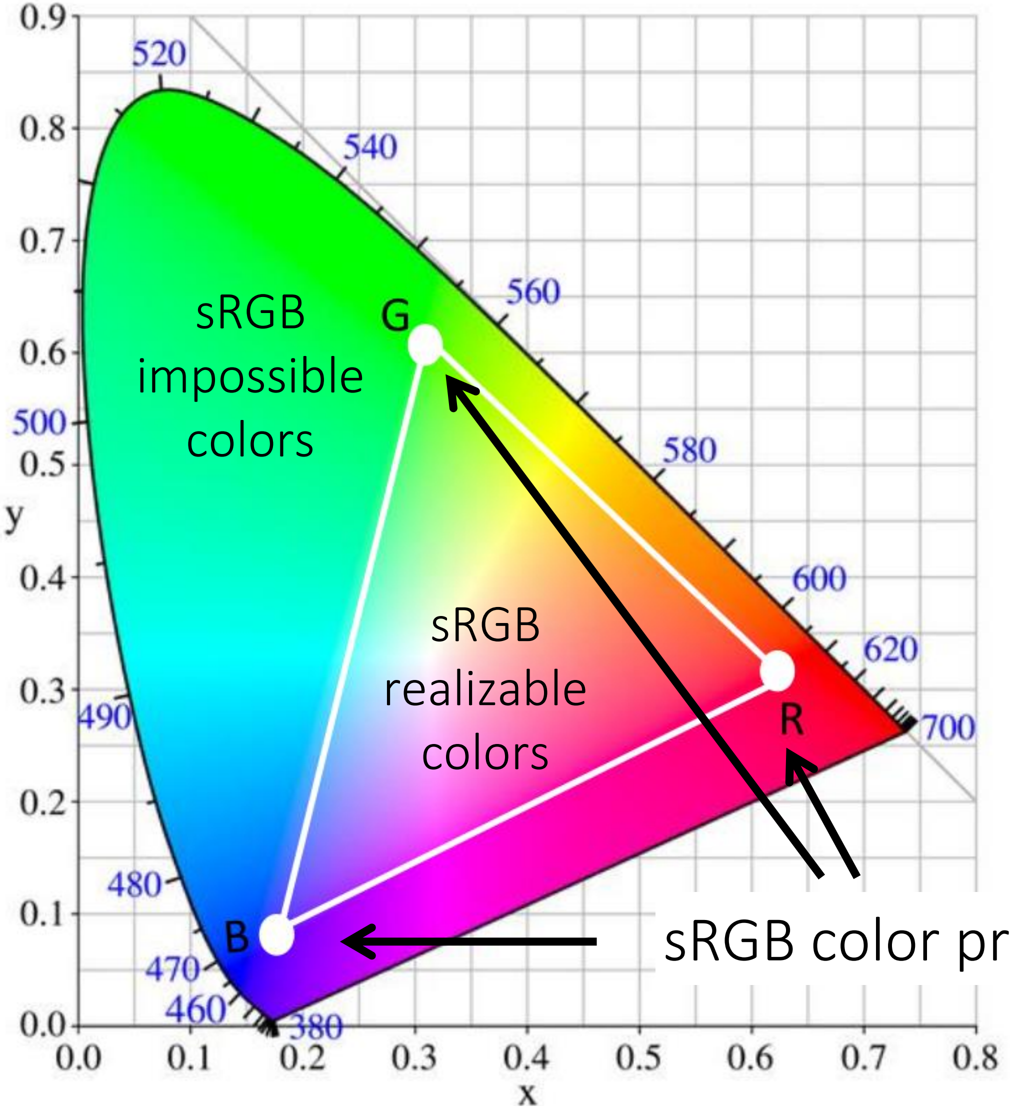
Color gamuts



sRGB color gamut:

- What are the three triangle corners?
- What is the interior of the triangle?
- What is the exterior of the triangle?

Color gamuts



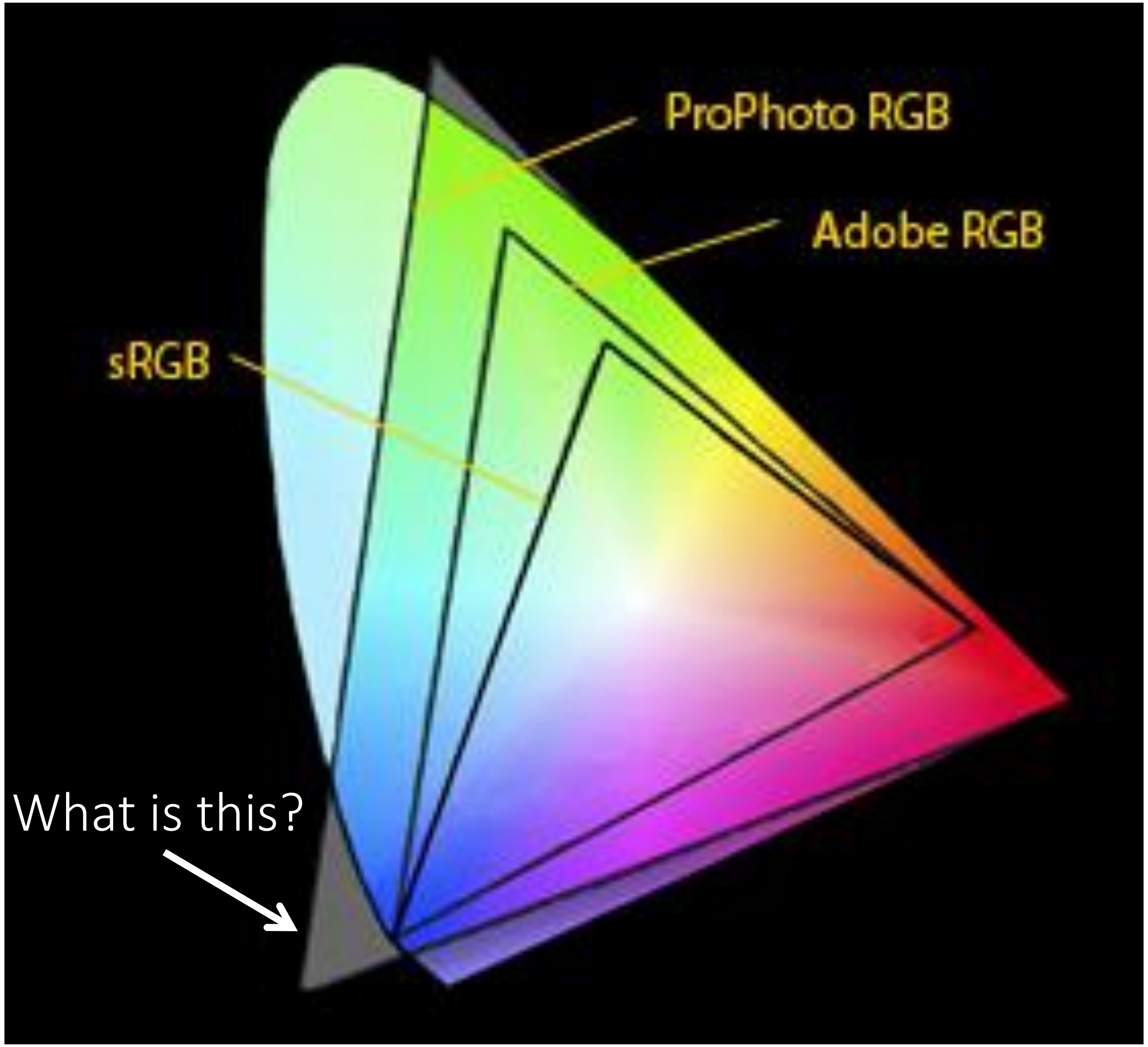
sRGB impossible colors

sRGB realizable colors

sRGB color primaries

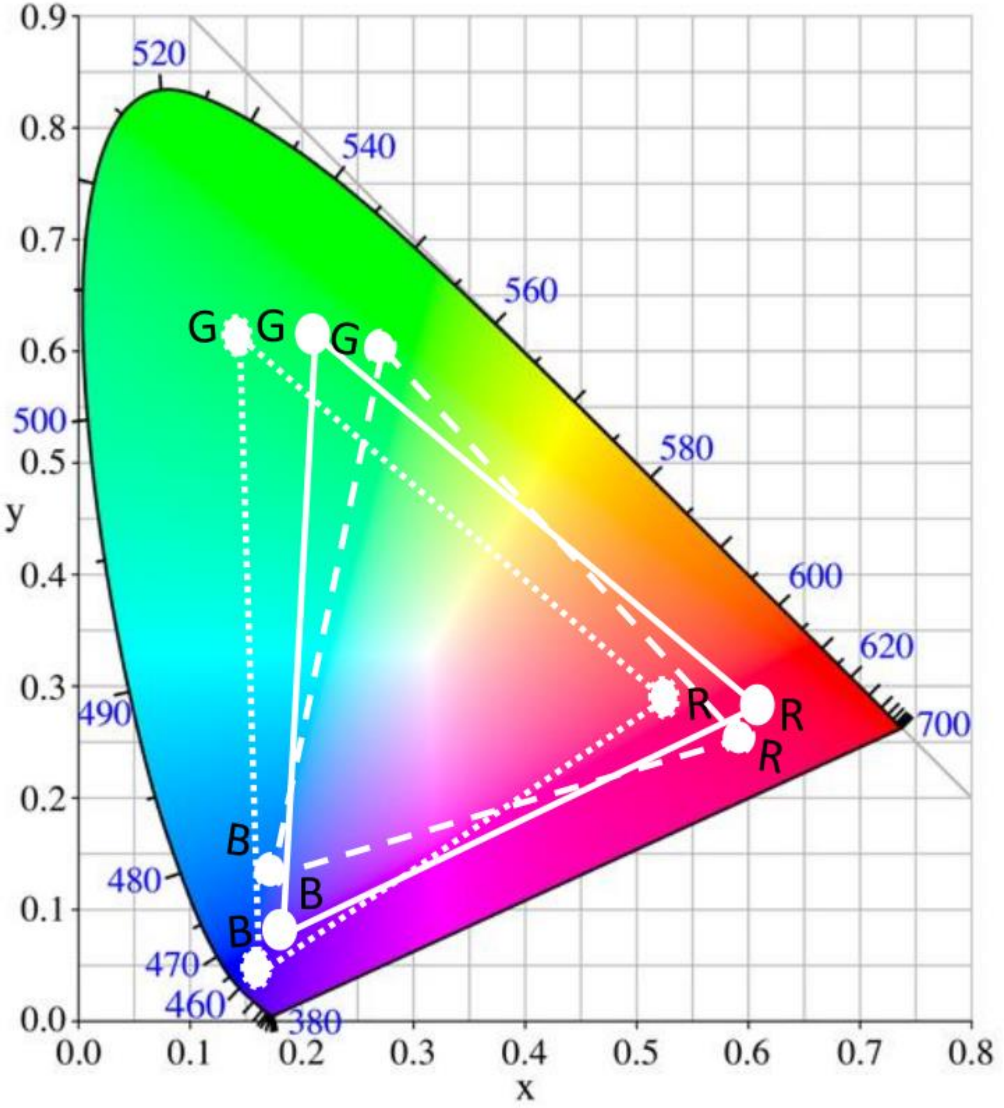
sRGB color gamut

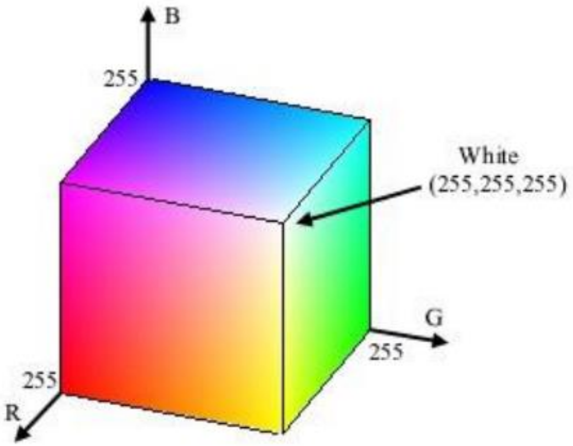
Color gamuts



Gamuts of various common industrial RGB spaces

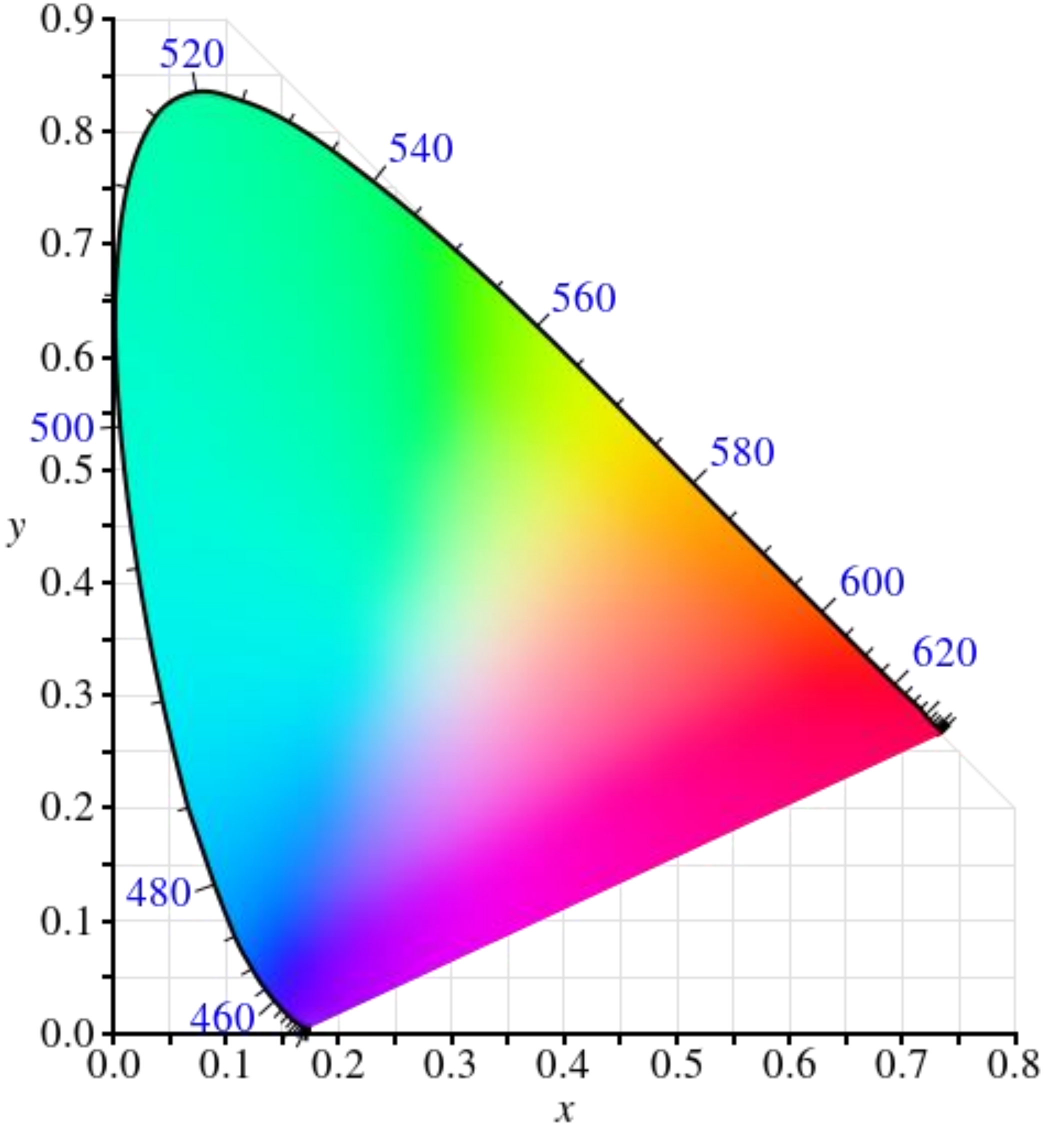
The problem with RGBs visualized in chromaticity space





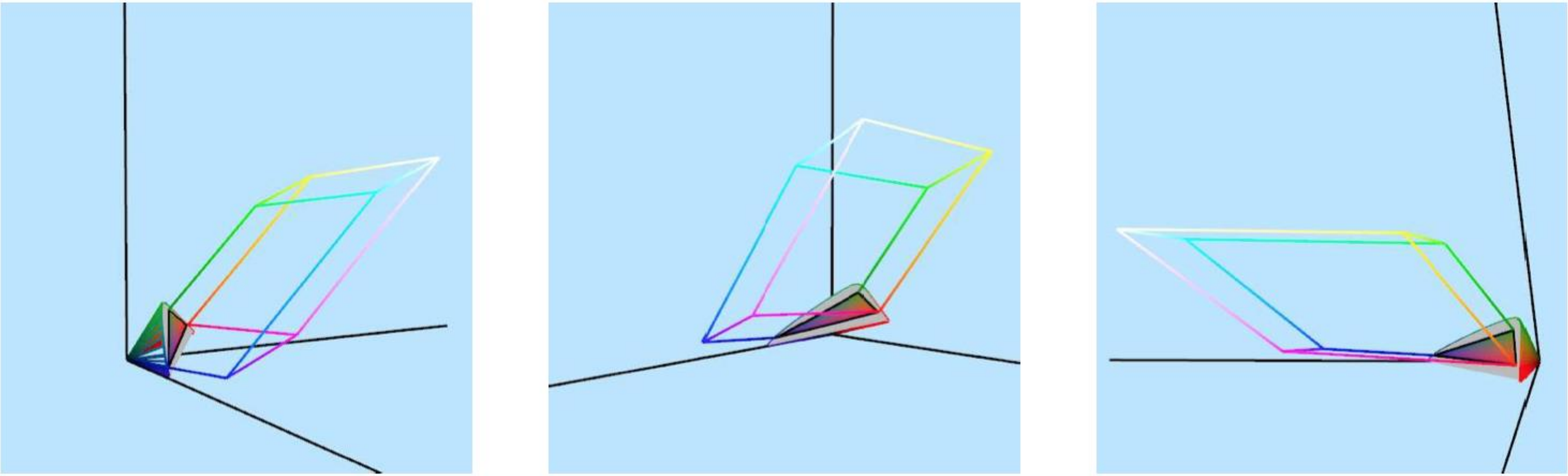
RGB values have no meaning if the primaries between devices are not the same!

Color gamuts



- Can we create an RGB color space that reproduces the entire chromaticity diagram?
- What would be the pros and cons of such a color space?
- What devices would you use it for?

Chromaticity diagrams can be misleading



Different gamuts may compare very differently when seen in full 3D retinal color space.

Two views of retinal color

Analytic: Retinal color is three numbers formed by taking the dot product of a power spectral distribution with three color matching/sensitivity functions.

Synthetic: Retinal color is three numbers formed by assigning weights to three color primaries to match the perception of a power spectral distribution.

How would you make a color reproduction device?

Some take-home messages about color spaces

Analytic: Retinal color is three numbers formed by taking the dot product of a power spectral distribution with three color matching/sensitivity functions.

Synthetic: Retinal color is three numbers formed by assigning weights to three color primaries to match the perception of a power spectral distribution.

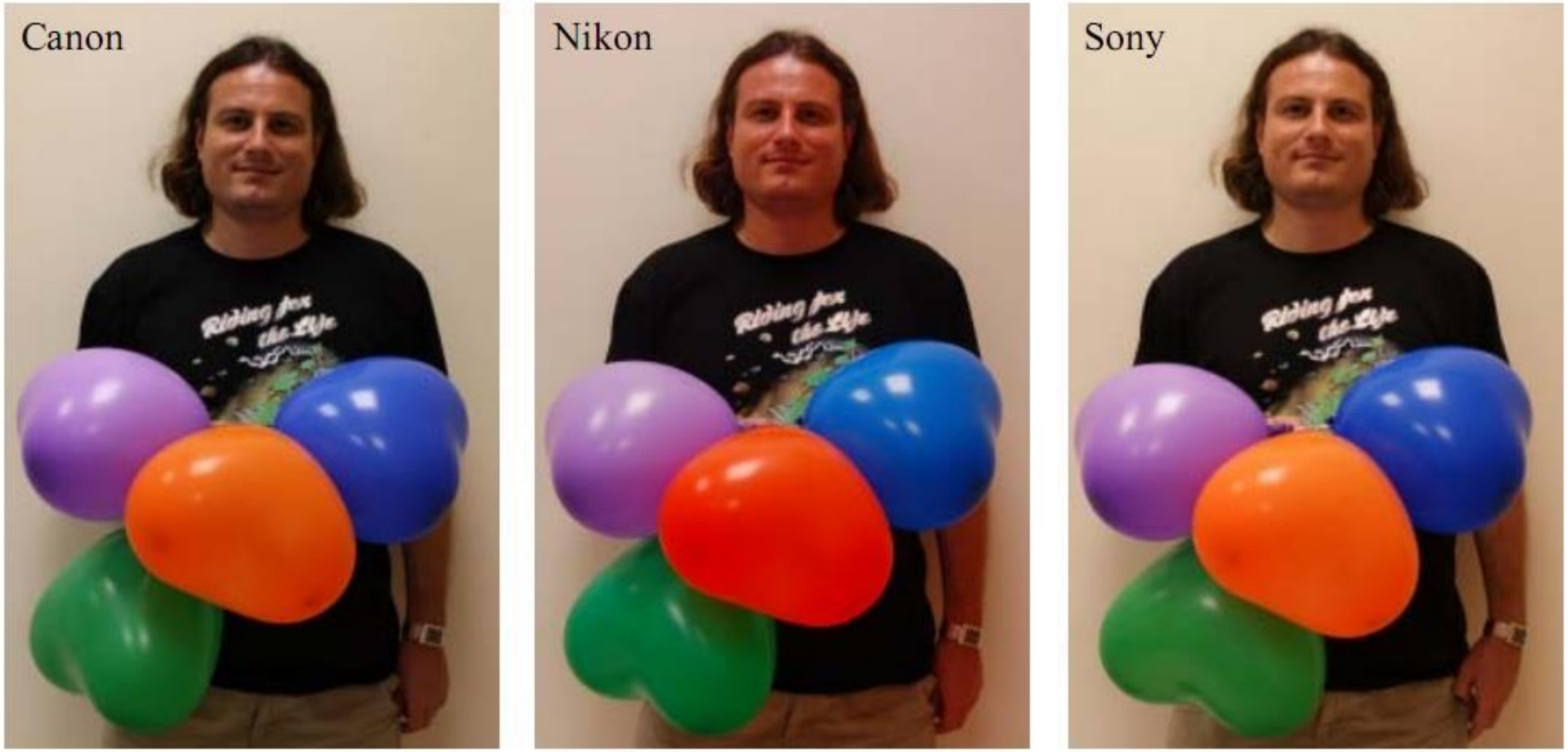
Fundamental problem: Analysis spectrum (camera, eyes) cannot be the same as synthesis one (display) - impossible to encode all possible colors without something becoming negative

- CIE XYZ only needs positive coordinates, but need primaries with negative light.
- RGB can use physical (non-negative) primaries, but needs negative coordinates for some colors.

Problem with current practice: Many different RGB color spaces used by different devices, without clarity of what exactly space a set of RGB color values are in.

- Huge problem for color reproduction from one device to another.

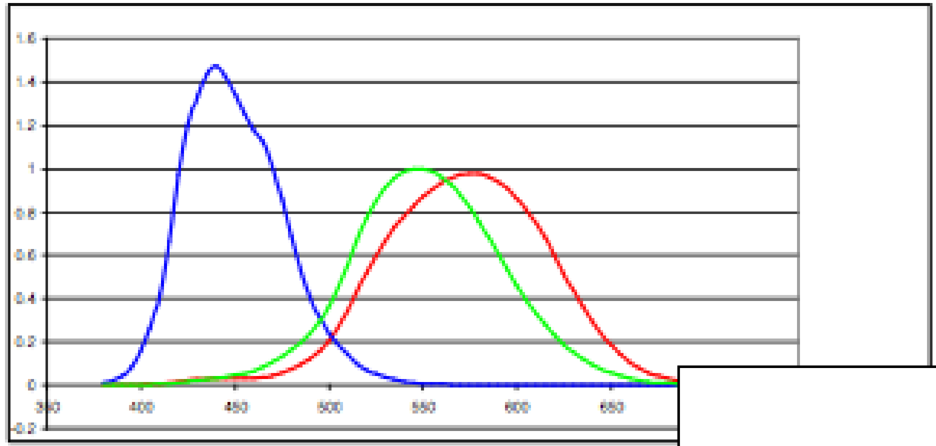
See for yourself



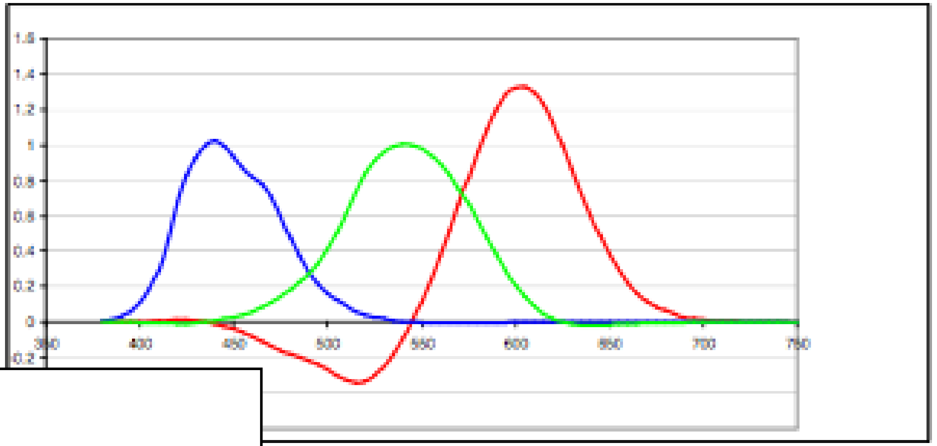
Images of the same scene captured using 3 different cameras with identical settings, supposedly in sRGB space.

Non-linear color spaces

A few important linear color spaces

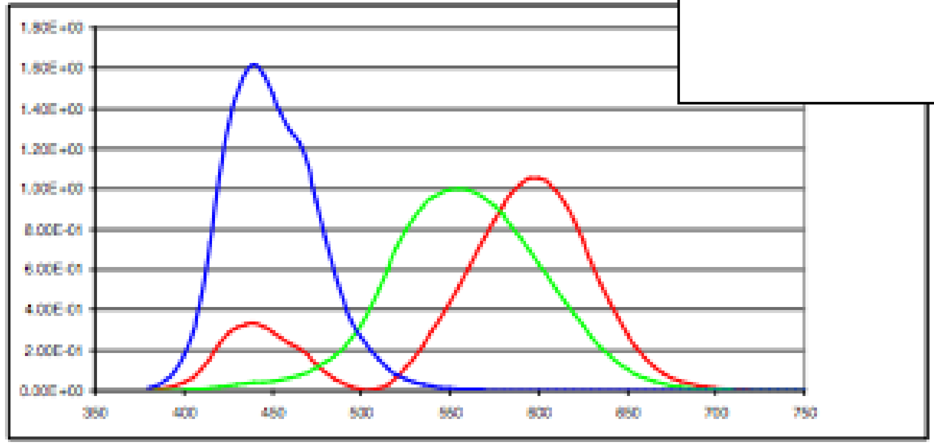


LMS color space

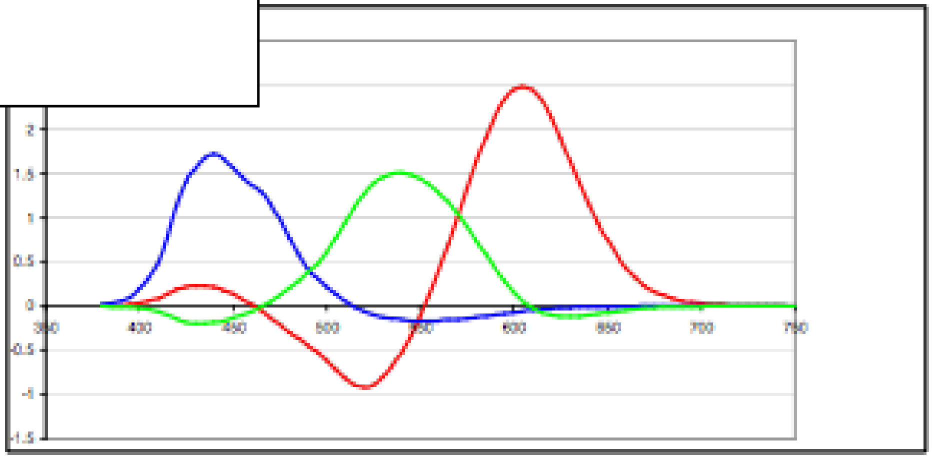


E RGB color space

What about non-linear color spaces?

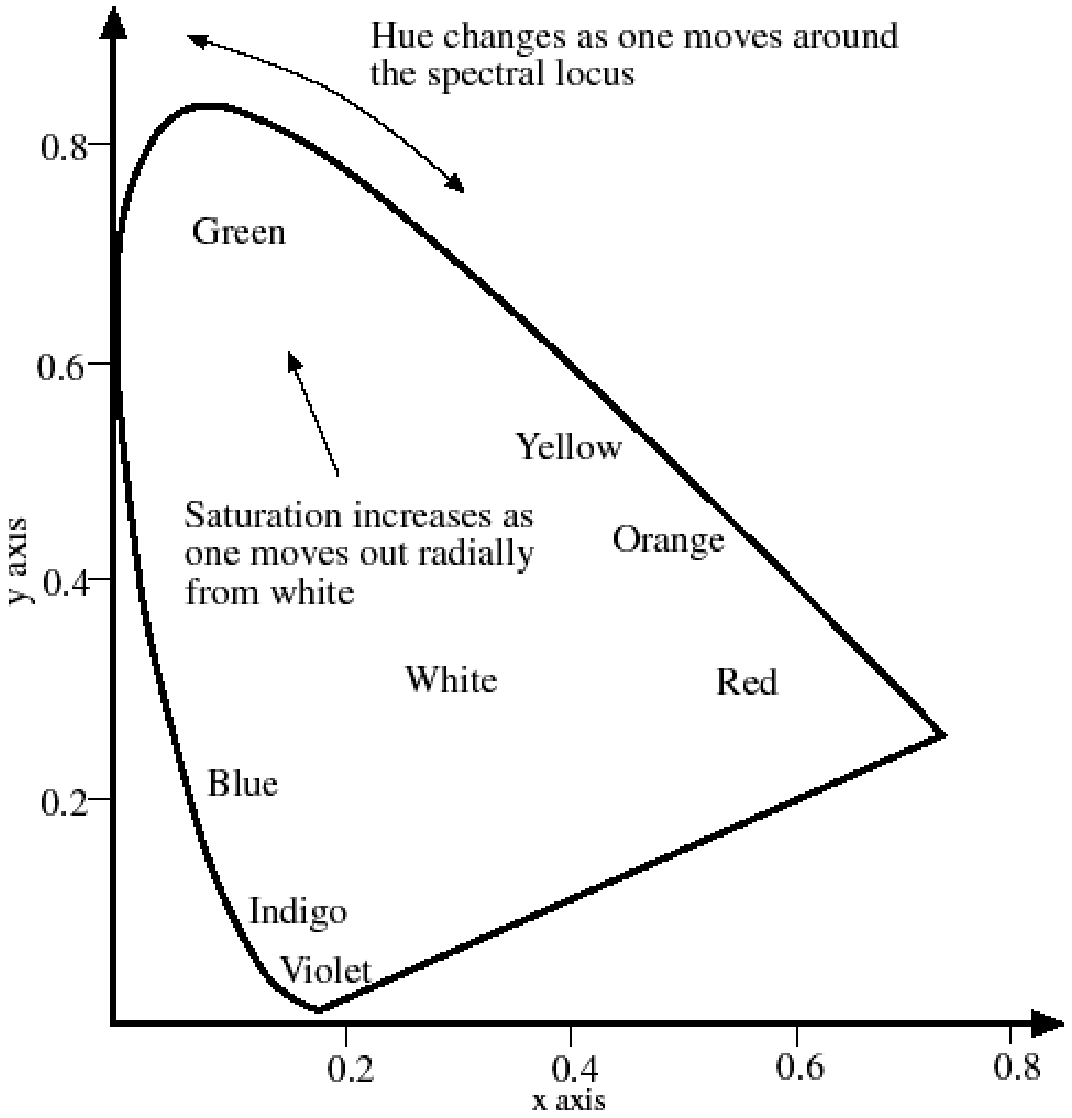


CIE XYZ color space



sRGB color space

CIE xy (chromaticity)



$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$(X, Y, Z) \longleftrightarrow (\underbrace{x, y}_{\text{chromaticity}}, Y)$$

↑

luminance/brightness

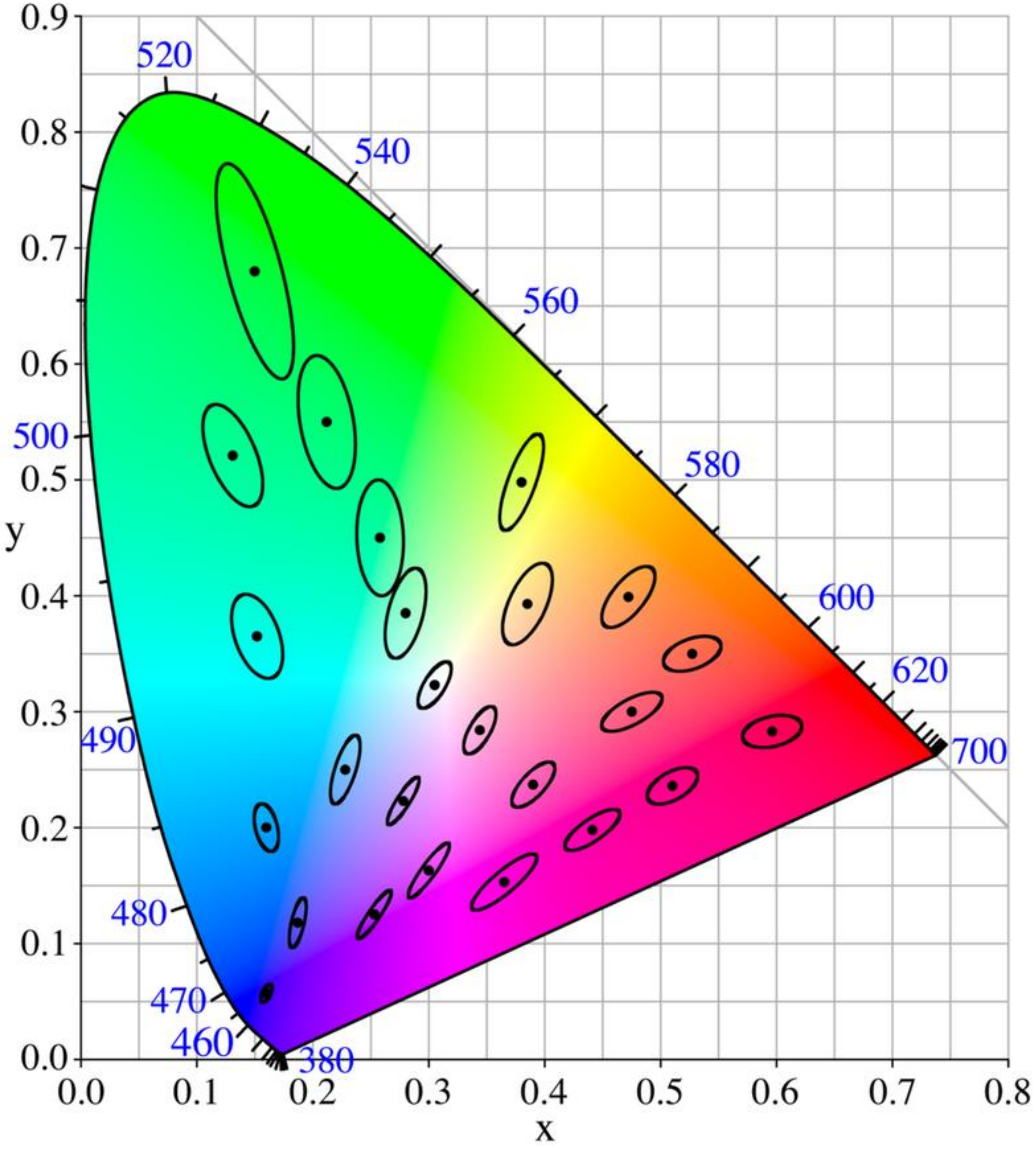
CIE xyY is a non-linear color space.

Uniform color spaces

Find map $F : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ such that perceptual distance can be well approximated using Euclidean distance:

$$d(\vec{c}, \vec{c}') \approx ||F(\vec{c}) - F(\vec{c}')||_2$$

MacAdam ellipses

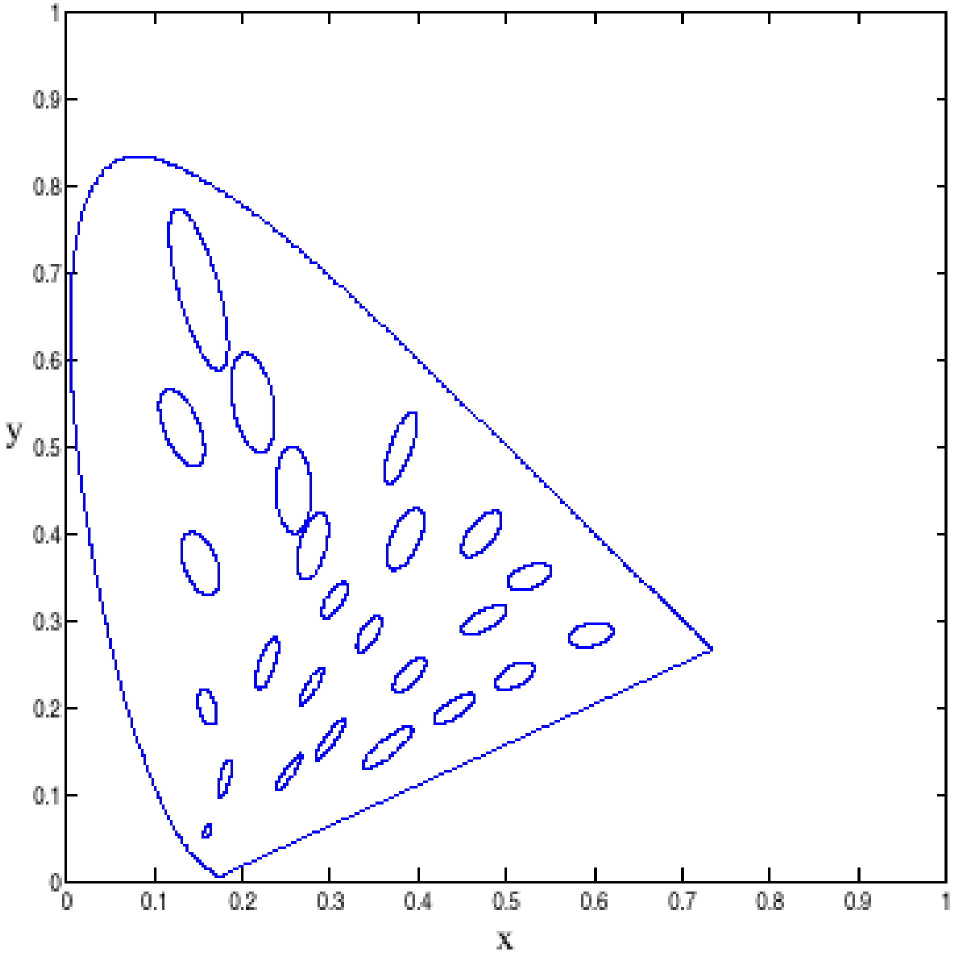


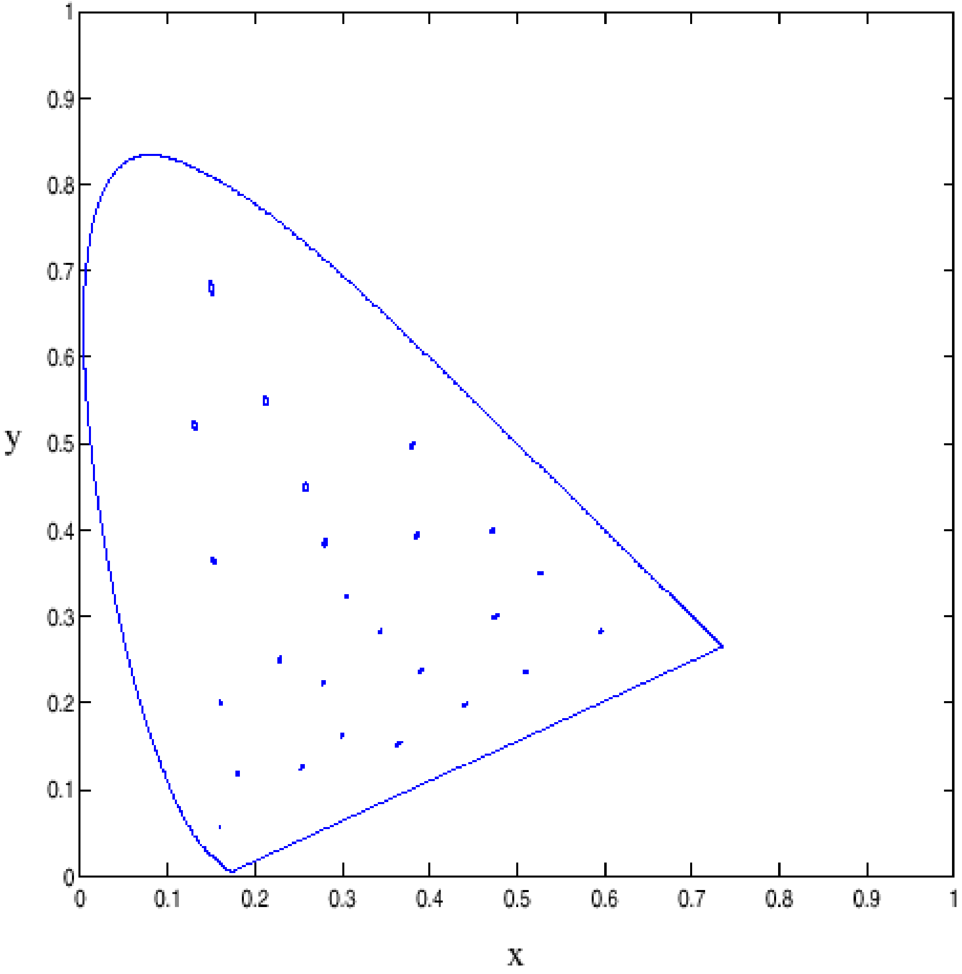
Areas in chromaticity space of imperceptible change:

- They are ellipses instead of circles.
- They change scale and direction in different parts of the chromaticity space.

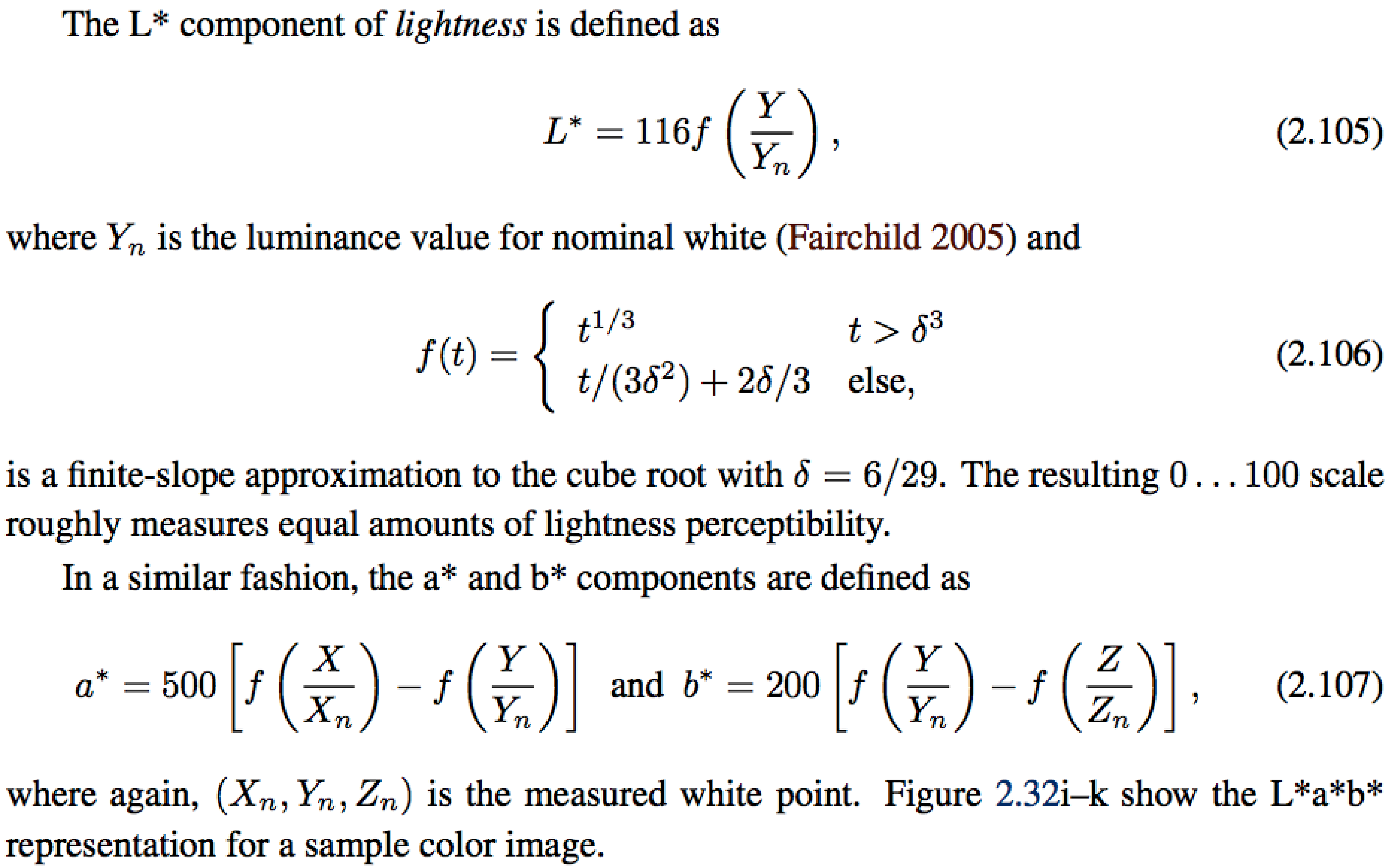
MacAdam ellipses

Note: MacAdam ellipses are almost always shown at 10x scale for visualization. In reality, the areas of imperceptible difference are much smaller.





The Lab (aka L*ab, aka L*a*b*) color space



The L* component of *lightness* is defined as

$$L^* = 116 f\left(\frac{Y}{Y_n}\right), \tag{2.105}$$

where Y_n is the luminance value for nominal white (Fairchild 2005) and

$$f(t) = \begin{cases} t^{1/3} & t > \delta^3 \\ t/(3\delta^2) + 2\delta/3 & \text{else,} \end{cases} \tag{2.106}$$

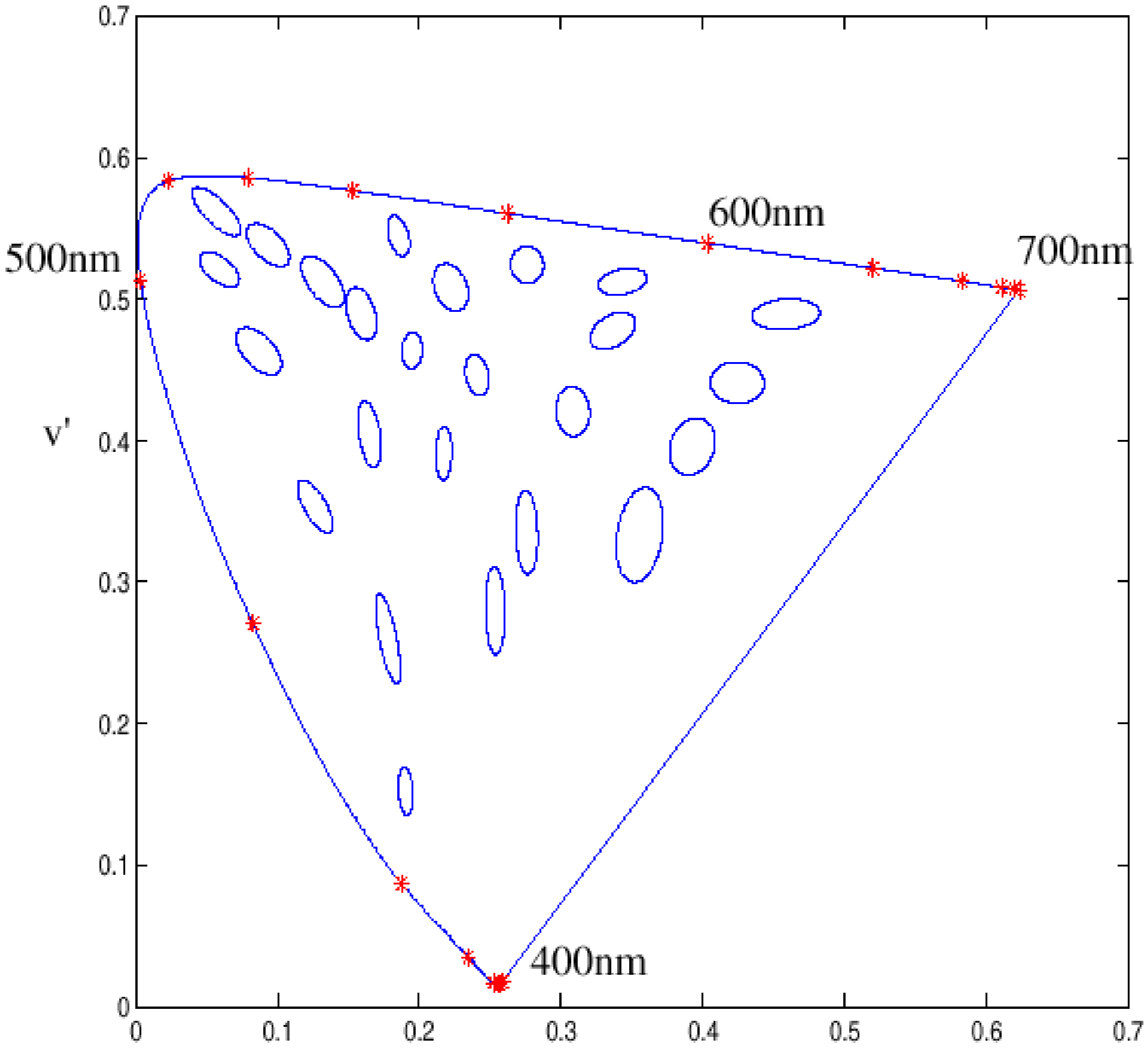
is a finite-slope approximation to the cube root with $\delta = 6/29$. The resulting $0 \ldots 100$ scale roughly measures equal amounts of lightness perceptibility.

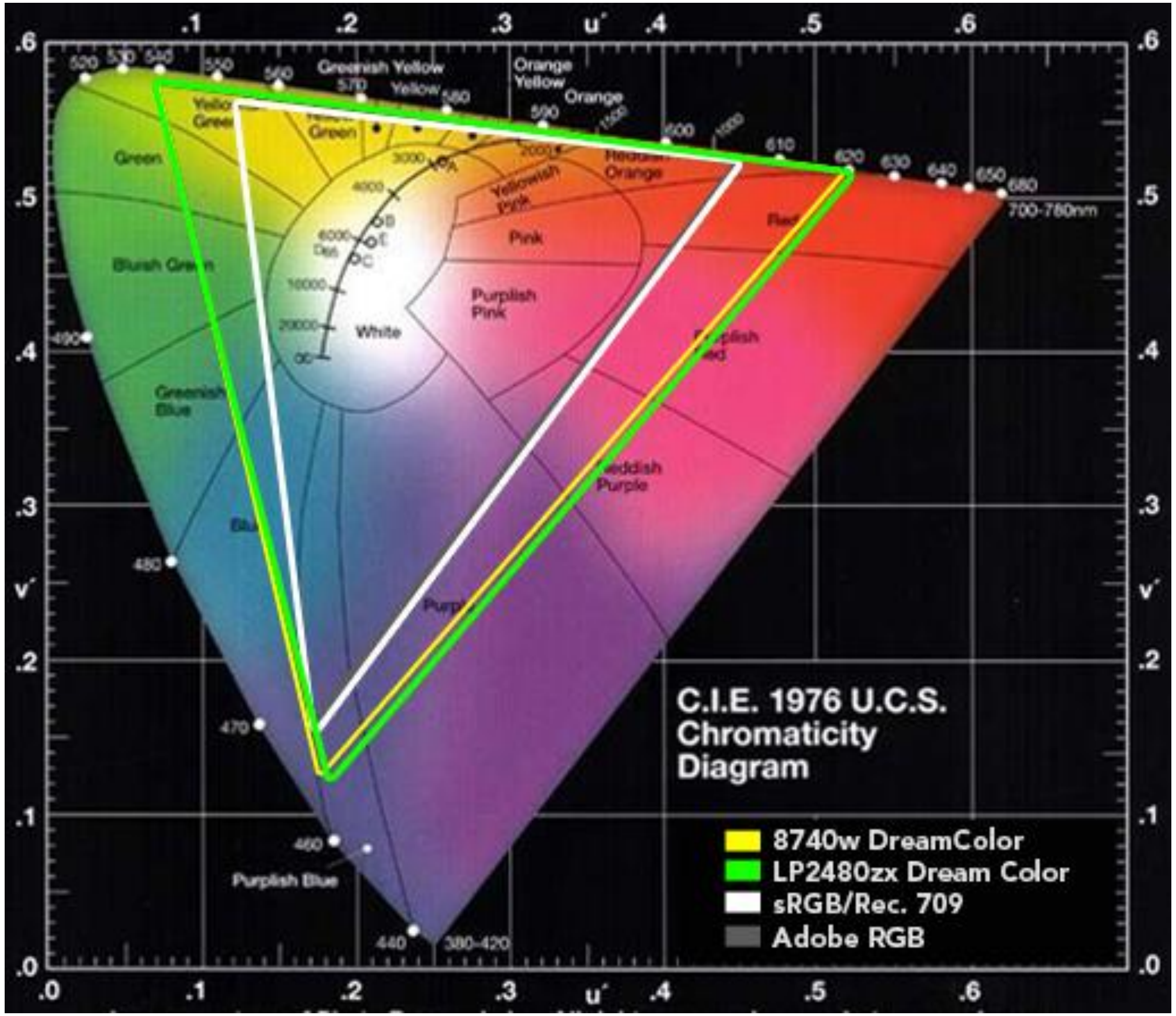
In a similar fashion, the a* and b* components are defined as

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \text{ and } b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right], \tag{2.107}$$

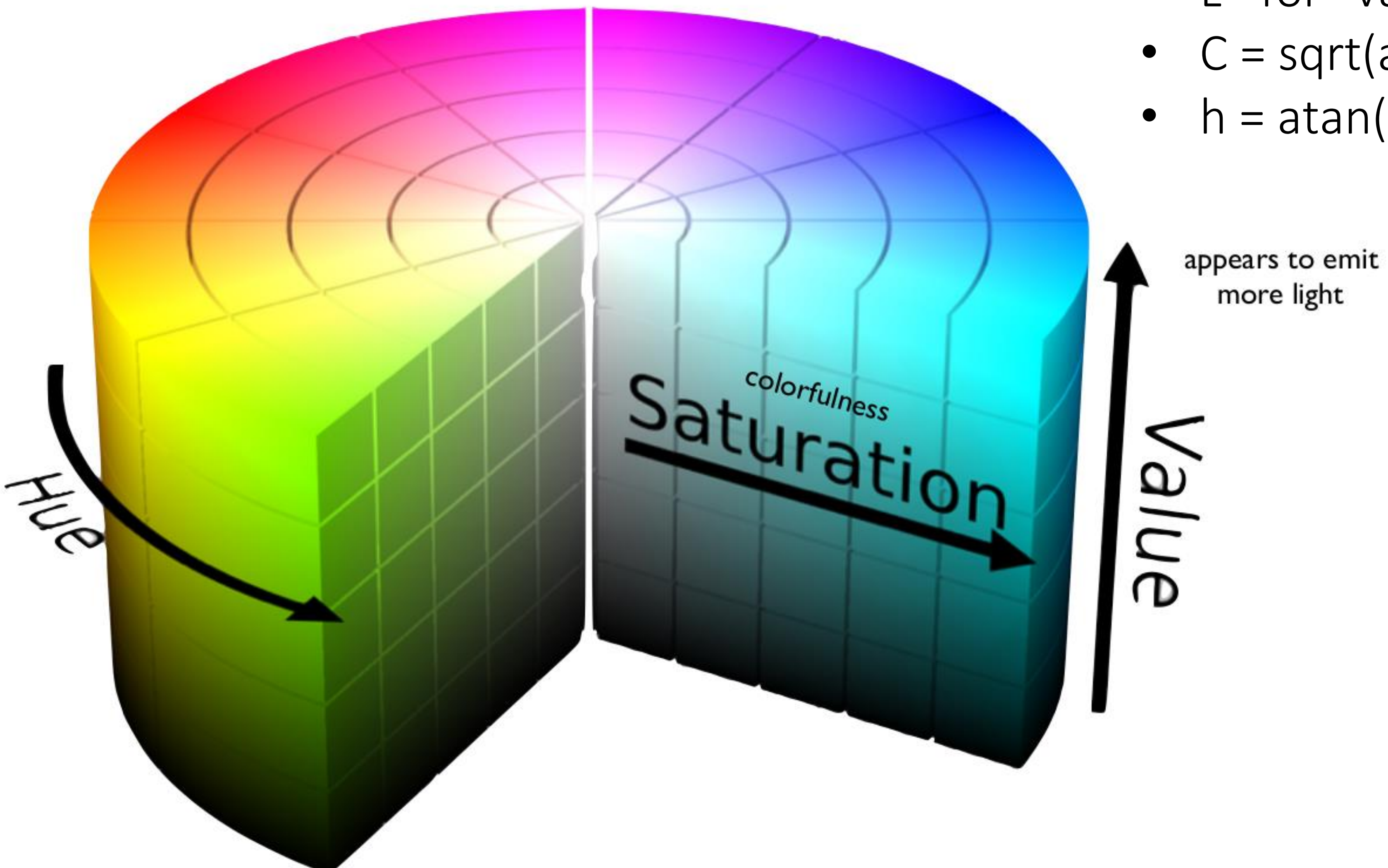
where again, (X_n, Y_n, Z_n) is the measured white point. Figure 2.32i–k show the L*a*b* representation for a sample color image.

The Lab (aka L*ab, aka L*a*b*) color space





Hue, saturation, and value



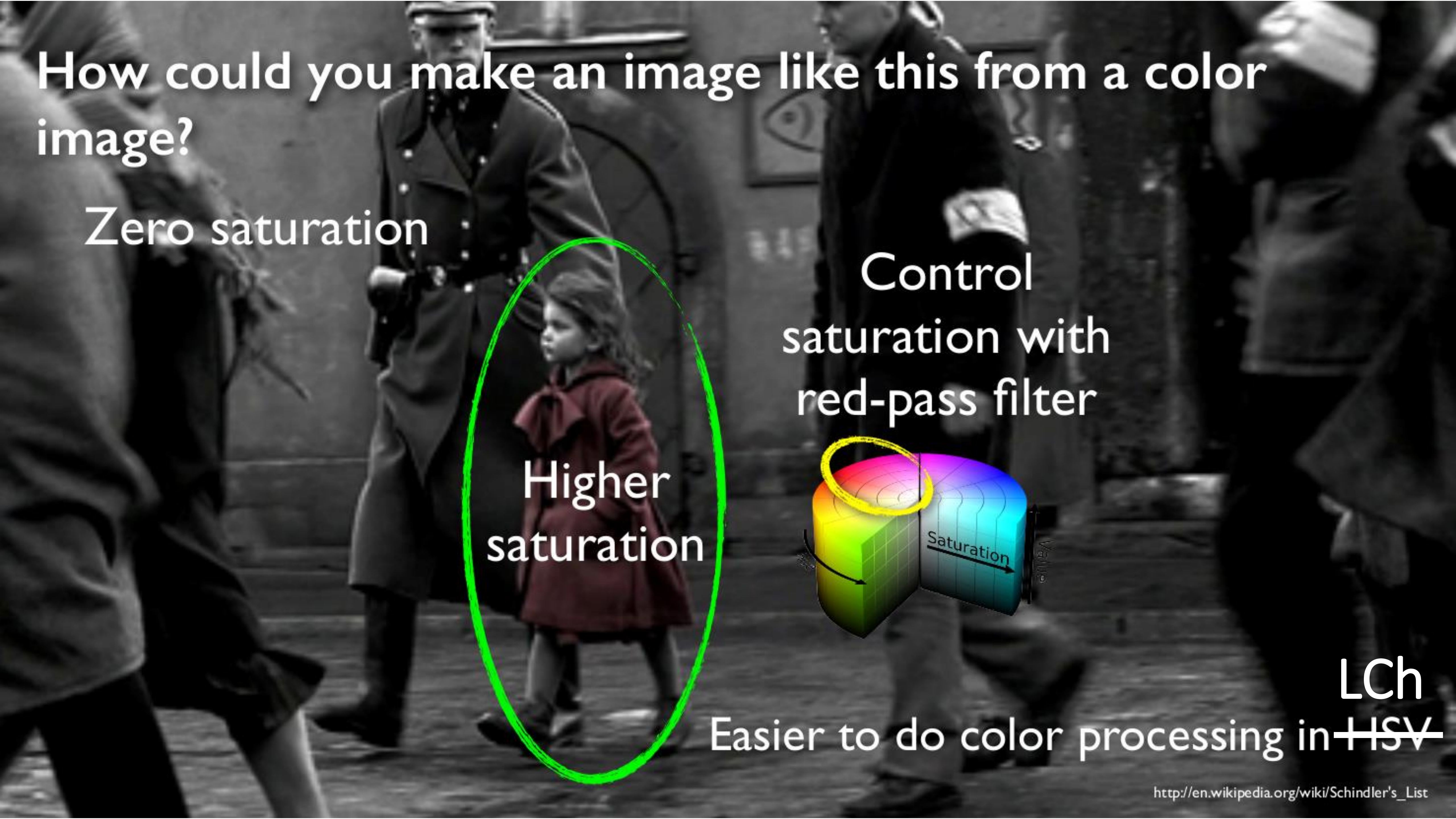
Do not use color space HSV! Use LCh:

- L* for “value”.
- C = sqrt($a^2 + b^2$) for “saturation” (chroma).
- h = atan(b / a) for “hue”.

How could you make an image like this from a color image?

http://en.wikipedia.org/wiki/Schindler's_List

How could you make an image like this from a color image?



Zero saturation

Higher saturation

Control saturation with red-pass filter

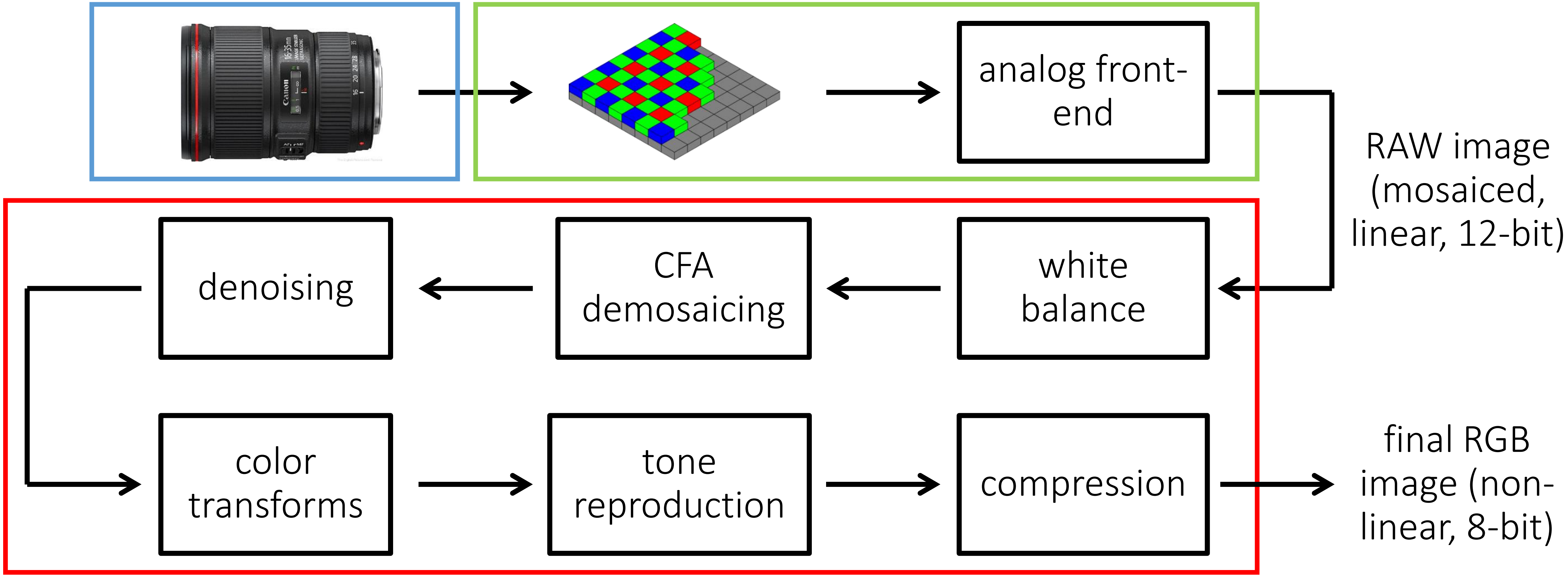
Easier to do color processing in ~~HSV~~ LCh

http://en.wikipedia.org/wiki/Schindler's_List

Some thoughts about color reproduction

The image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



analog front-end

RAW image (mosaiced, linear, 12-bit)

white balance

CFA demosaicing

denoising

color transforms

tone reproduction

compression

final RGB image (non-linear, 8-bit)

Color reproduction notes

To properly reproduce the color of an image file, you need to?

Color reproduction notes

To properly reproduce the color of an image file, you need to convert it from the color space it was stored in, to a reference color space, and then to the color space of your display.

On the camera side:

- If the file is RAW, it *often* has EXIF tags with information about the RGB color space corresponding to the camera's color sensitivity functions.
- If the file is not RAW, you *may* be lucky and still find accurate information in the EXIF tags about what color space the image was converted in during processing.
- If there is no such information and you own the camera that shot the image, then you can do color calibration of the camera.
- If all of the above fails, assume sRGB.

On the display side:

- If you own a high-end display, it likely has accurate color profiles provided by the manufacturer.
- If not, you can use a spectrometer to do color profiling (not color calibration).
- Make sure your viewer does not automatically do color transformations.

Be careful to account for any gamma correction!

Amazing resource for color management and photography: https://ninedegreesbelow.com/

References

Basic reading:

- Szeliski textbook, Section 2.3.2, 3.1.2
- Michael Brown, "Understanding the In-Camera Image Processing Pipeline for Computer Vision," CVPR 2016,
  very detailed discussion of issues relating to color photography and management, slides available at:
  http://www.comp.nus.edu.sg/~brown/CVPR2016_Brown.html
- Gortler, "Foundations of 3D Computer Graphics," MIT Press 2012.
  Chapter 19 of this book has a great coverage of color spaces and the theory we discussed in class, it is available in PDF form from the CMU library.

Additional reading:

- Reinhard et al., "Color Imaging: Fundamentals and Applications," A.K Peters/CRC Press 2008.
- Koenderink, "Color Imaging: Fundamentals and Applications," MIT Press 2010.
- Fairchild, "Color Appearance Models," Wiley 2013.
  all of the above books are great references on color photography, reproduction, and management
- Nine Degrees Below, https://ninedegreesbelow.com/
  amazing resource for color photography, reproduction, and management