
Calvin and HOBBES
by WATTERSON
WOW, HONEY, YOU'RE MISSING A BEAUTIFUL SUNSET OUT HERE!
I'LL COUNT TO 10, AND THEN... POW!
DAD, HOW COME OLD PHOTOGRAPHS ARE ALWAYS BLACK AND WHITE? DIDN'T THEY HAVE COLOR FILM BACK THEN?
SURE THEY DID. IN FACT, THOSE OLD PHOTOGRAPHS ARE IN COLOR. IT'S JUST THE WORLD WAS BLACK AND WHITE THEN.
REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.
THAT'S REALLY WEIRD.
WELL, TRUTH IS STRANGER THAN FICTION.
BUT THEN WHY ARE OLD PAINTINGS IN COLOR?! IF THE WORLD WAS BLACK AND WHITE, WOULDN'T ARTISTS HAVE PAINTED IT THAT WAY?
NOT NECESSARILY. A LOT OF GREAT ARTISTS WERE INSANE.
BUT... BUT HOW COULD THEY HAVE PAINTED IN COLOR ANYWAY? WOULDN'T THEIR PAINTS HAVE BEEN SHADES OF GRAY BACK THEN?
OF COURSE, BUT THEY TURNED COLORS LIKE EVERYTHING ELSE DID IN THE '30s.
SO WHY DIDN'T OLD BLACK AND WHITE PHOTOS TURN COLOR TOO?
BECAUSE THEY WERE COLOR PICTURES OF BLACK AND WHITE, REMEMBER?
THE WORLD IS A COMPLICATED PLACE, HOBBES.
WHENEVER IT SEEMS THAT WAY, I TAKE A NAP IN A TREE AND WAIT FOR DINNER.

Lecture 20:

Introduction to Color Science (Continued)

Computer Graphics and Imaging
UC Berkeley CS184/284A

Recall Discussion: What is The Dimensionality of Color?

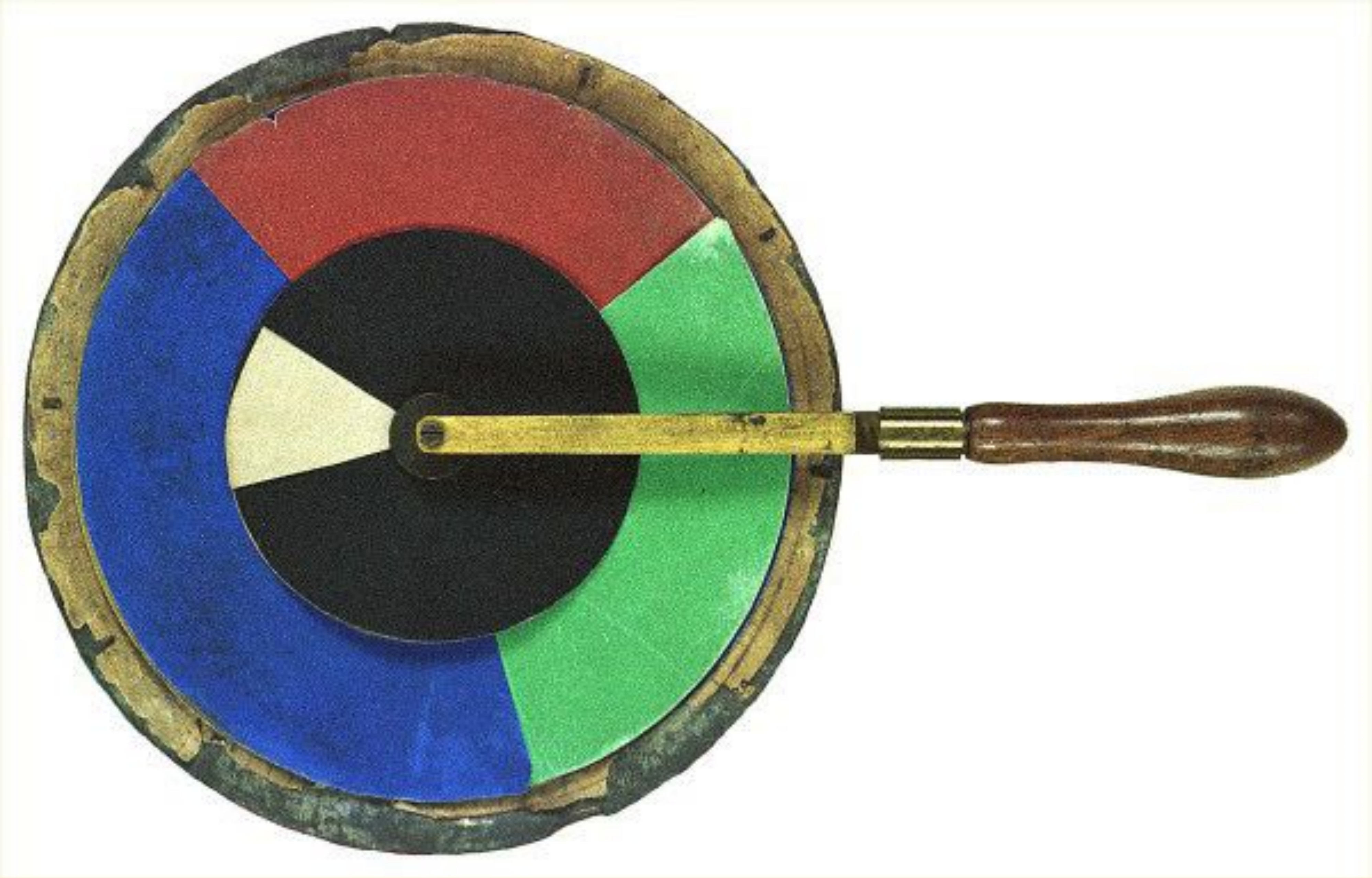
How do we know?

- 1D? A point on a rainbow?
- 2D? A point on a wheel with rainbow on the outside, white in the middle and continuous gradients in between

- Perhaps we can try to find a basis for all colors in a linear algebra sense -- find a set of colors that can span all possible colors, and show that the set is a minimum number of colors.

Searching for a Basis for Colors: Color Matching Experiment

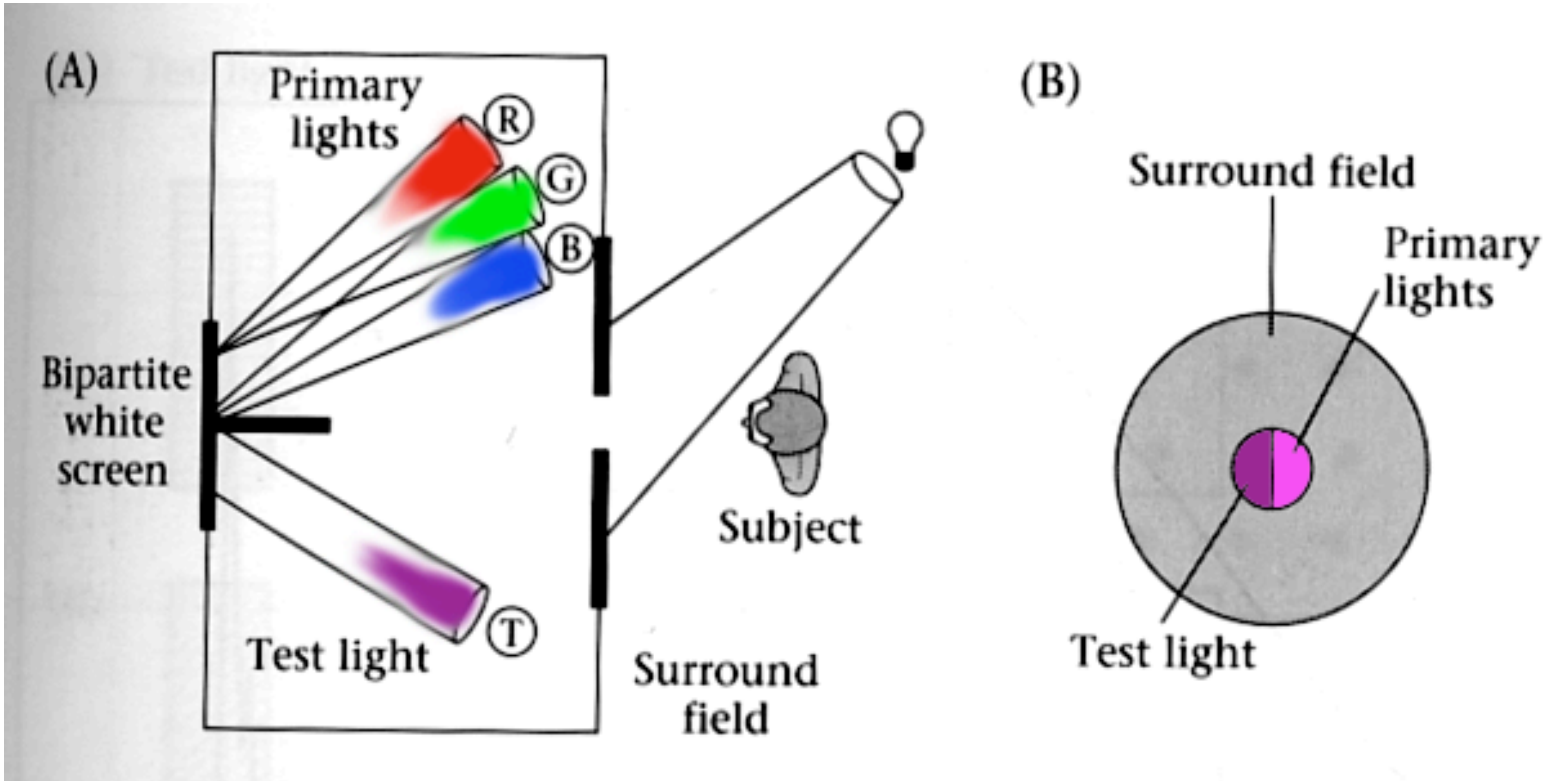
Maxwell's Crucial Color Matching Experiment



http://designblog.rietveldacademie.nl/?p=68422

Portrait: http://rsta.royalsocietypublishing.org/content/366/1871/1685

Color Matching Experiment



Same idea as spinning top, fancier implementation (Maxwell did this too)

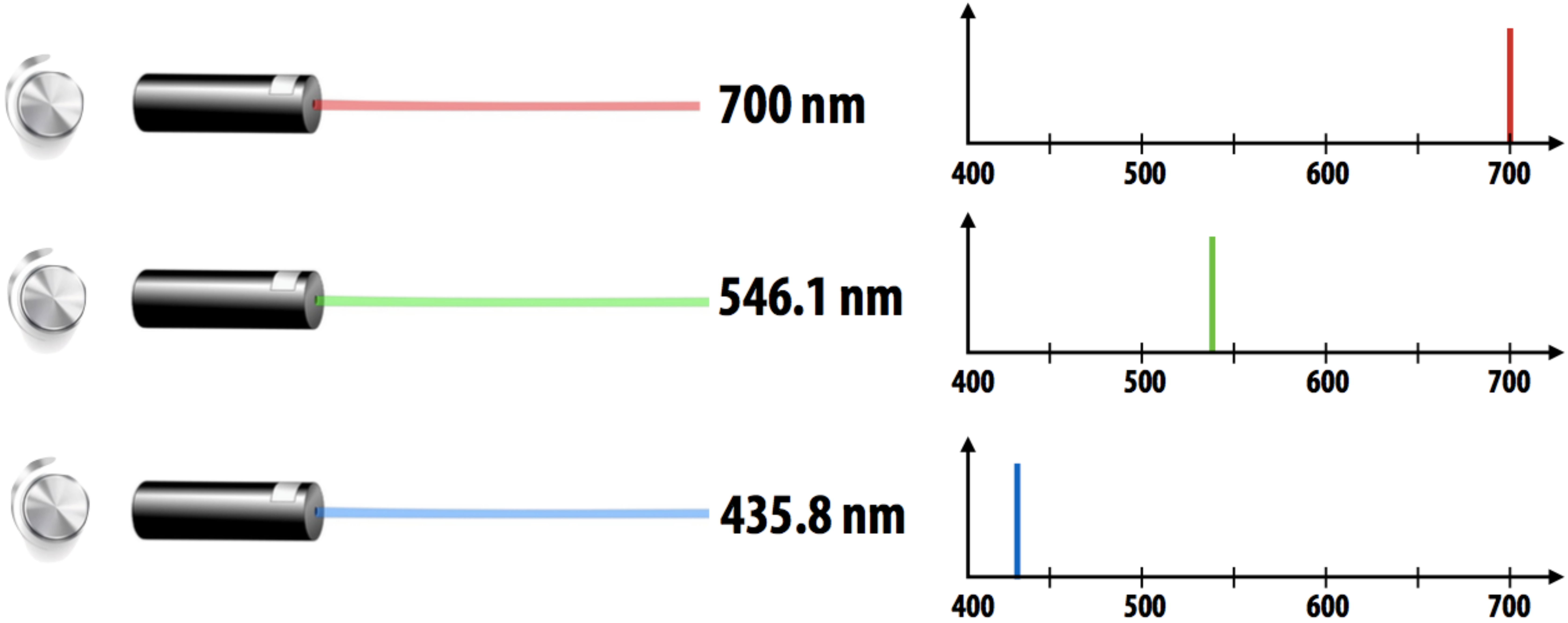
Show test light spectrum on left

Mix "primaries" on right until they match

The primaries need not be RGB

CIE RGB Color Matching Experiment

Same setup as additive color matching before, but primaries are monochromatic light (single wavelength) of the following wavelengths defined by CIE RGB standard

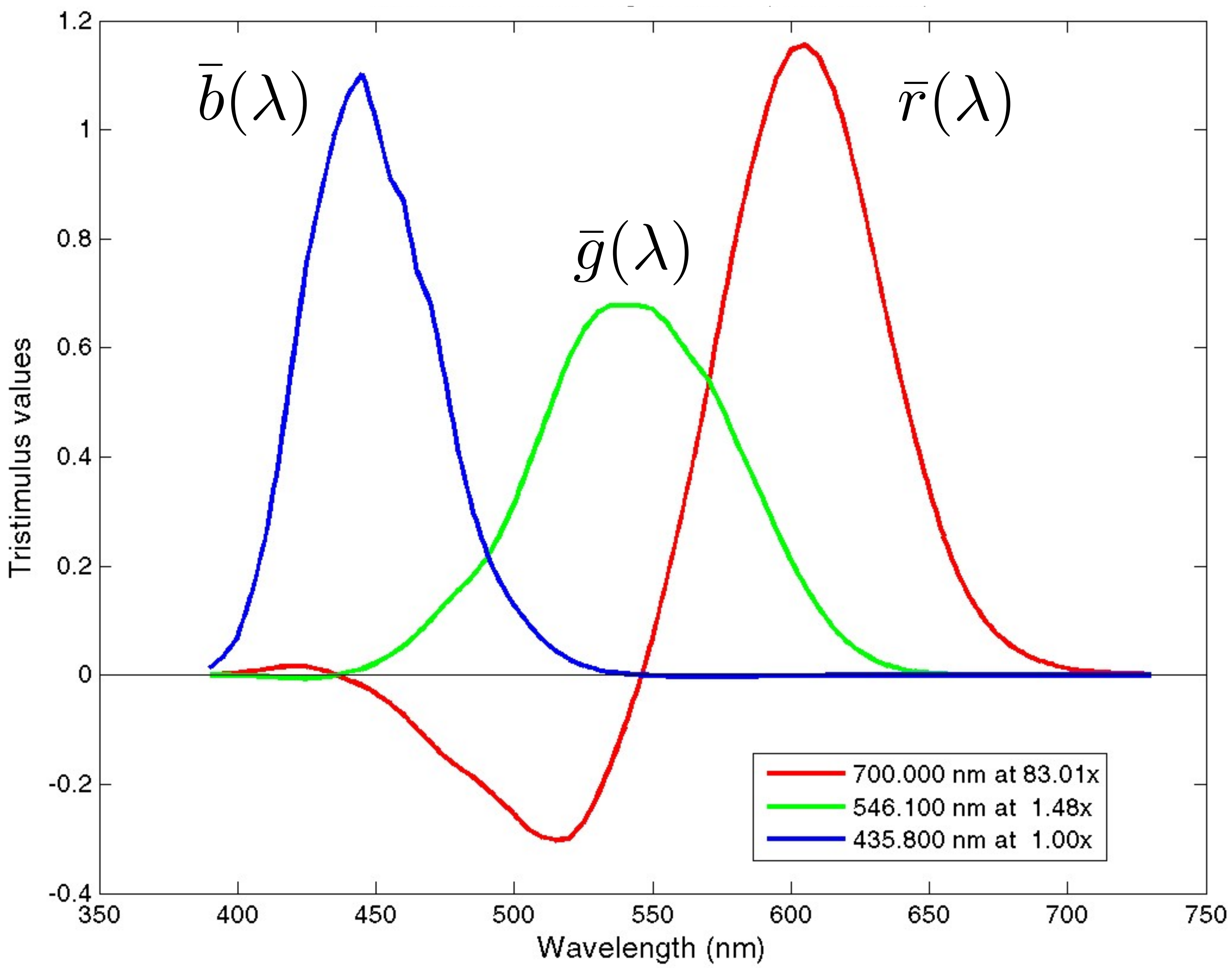


Kayvon Fatahalian

The test light is also a monochromatic light

CIE RGB Color Matching Functions

Graph plots how much of each CIE RGB primary light must be combined to match a monochromatic light of wavelength given on x-axis



Careful: these are not response curves or primary spectra!

Tristimulus Theory of Color

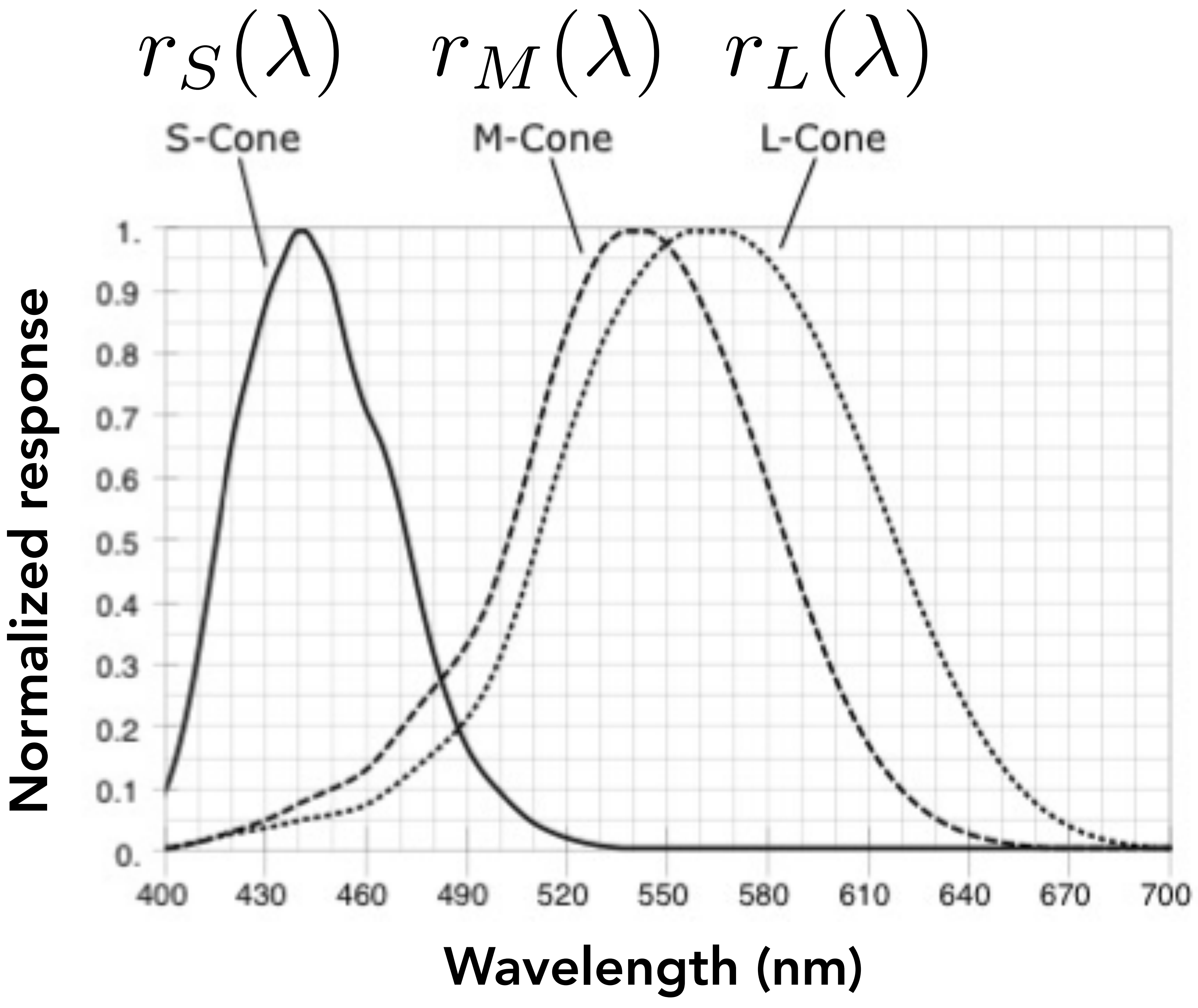
Spectral Response of Human Cone Cells

Instead of one detector as before, now we have three detectors (S, M, L cone cells), each with a different spectral response curve

$$S = \int r_S(\lambda) s(\lambda)\, d\lambda$$

$$M = \int r_M(\lambda) s(\lambda)\, d\lambda$$

$$L = \int r_L(\lambda) s(\lambda)\, d\lambda$$



Example: Spectral Response of Human Cone Cells

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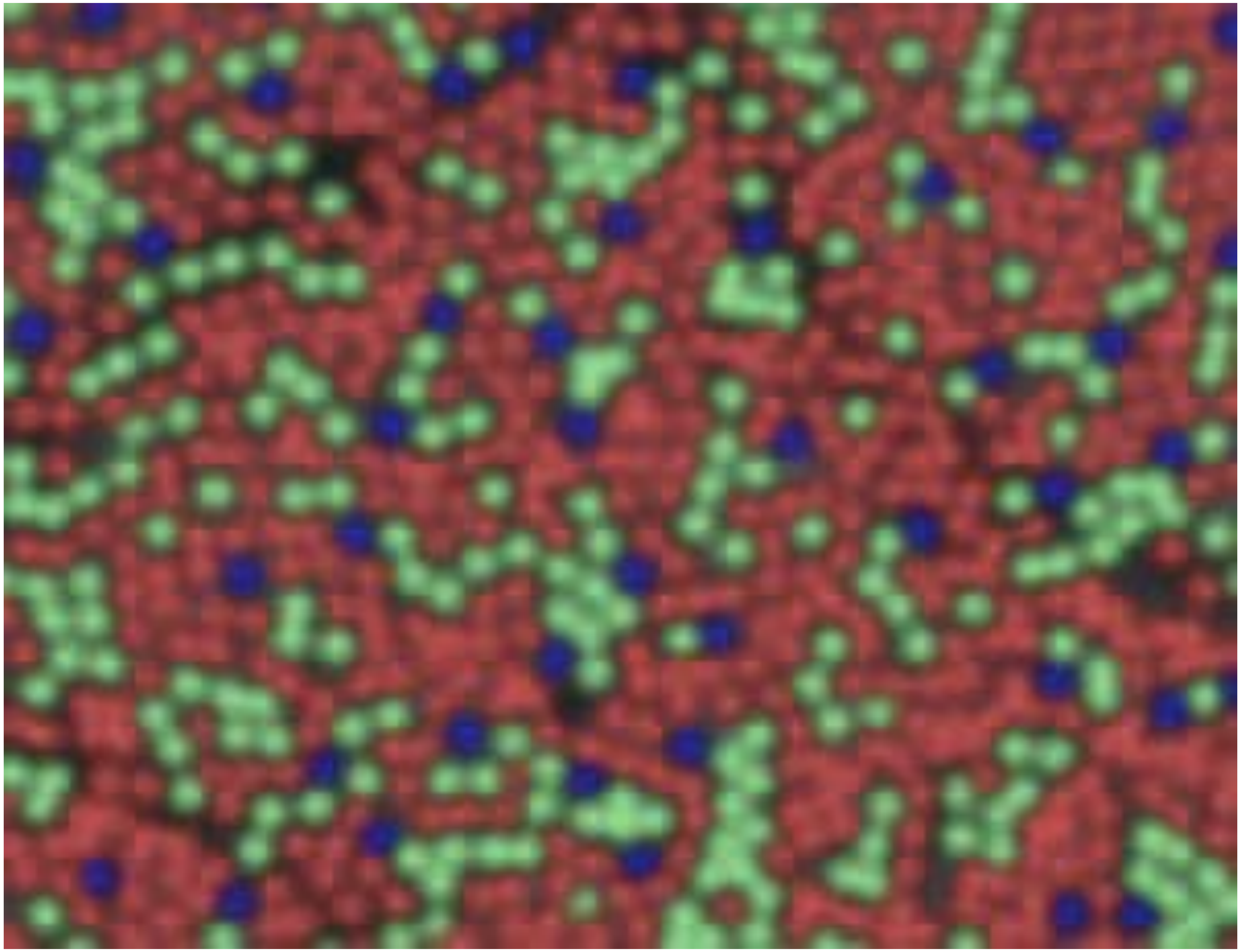
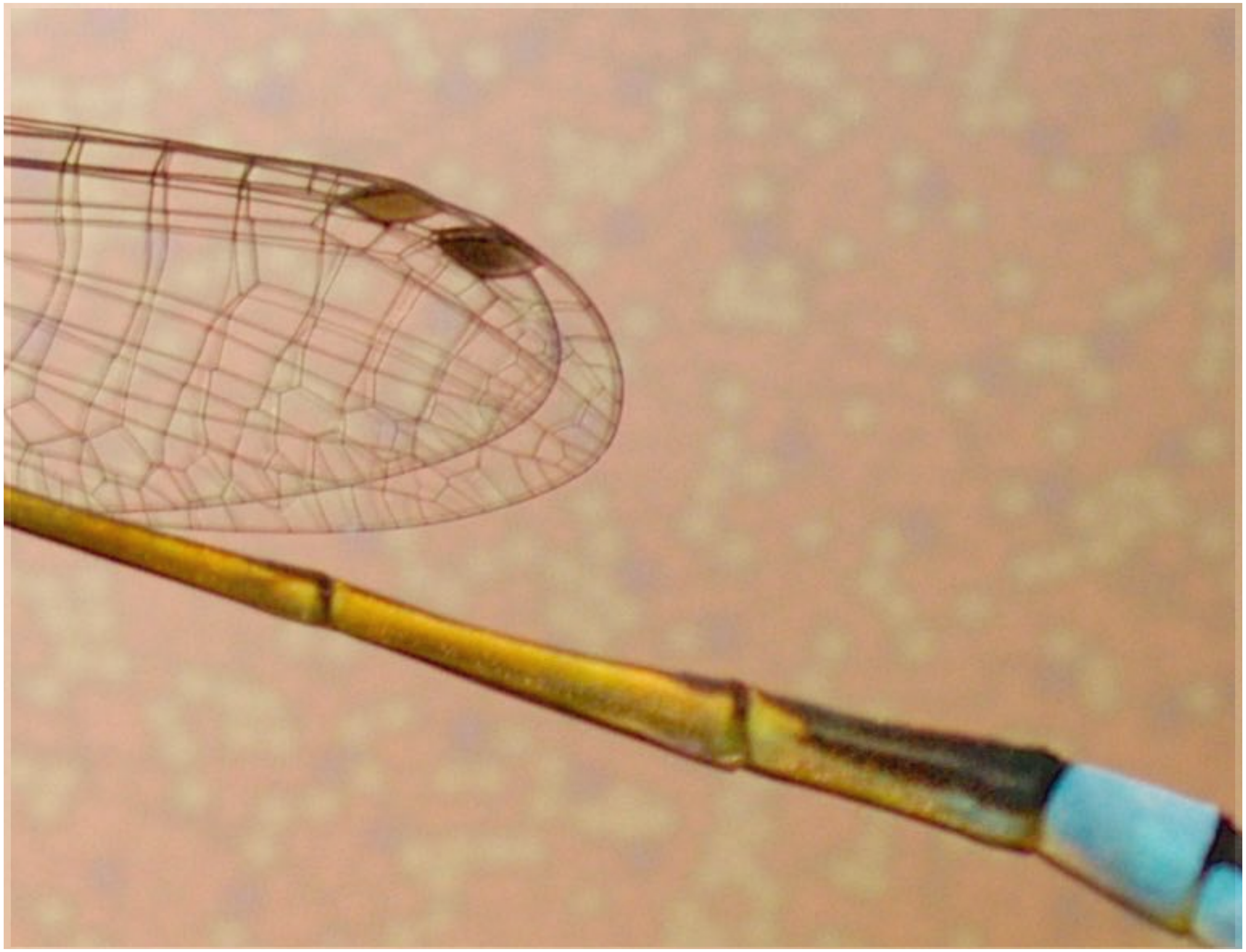


Scene projected onto retina

Credit: Sabesan, http://depts.washington.edu/sabaolab/

Example: Spectral Response of Human Cone Cells



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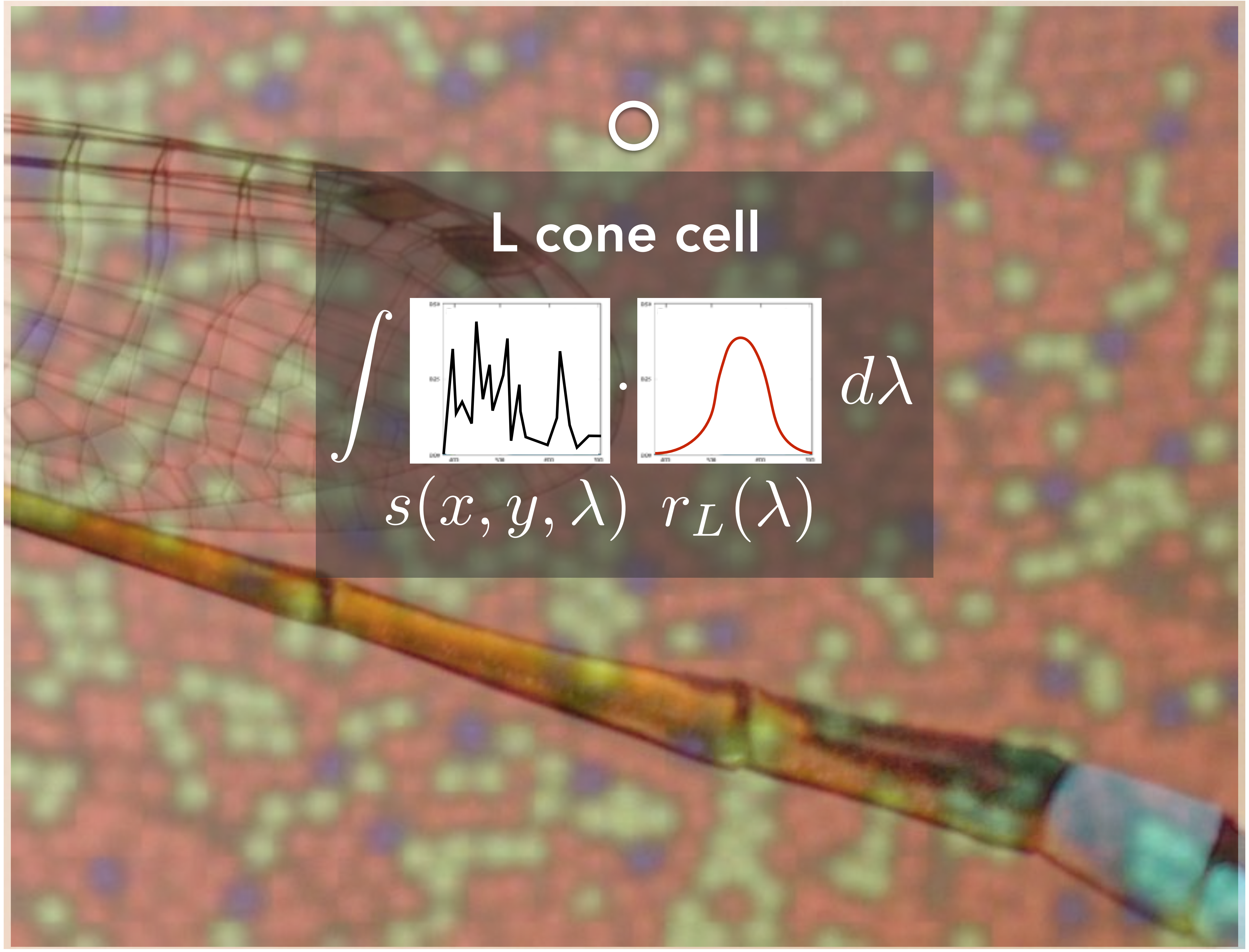
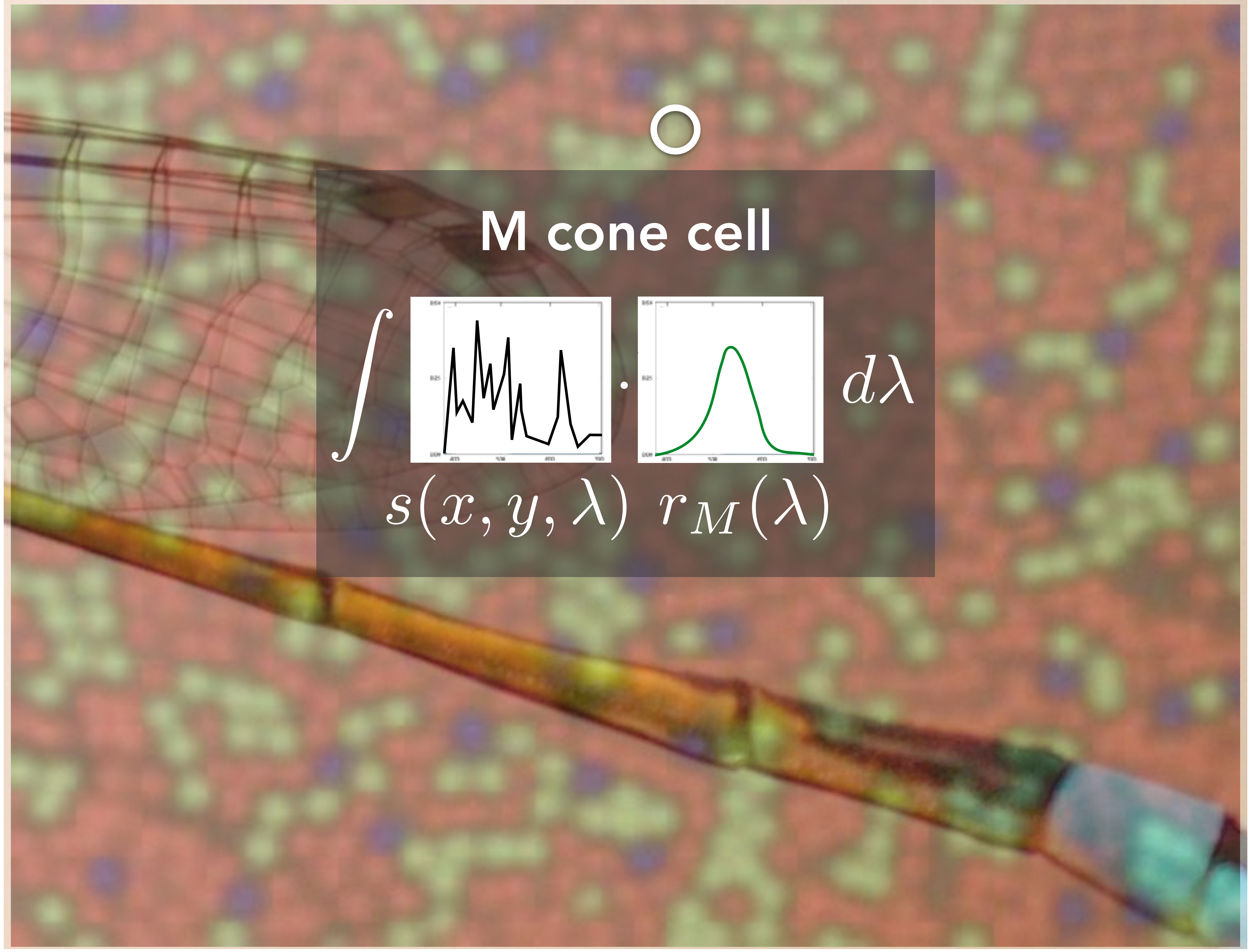


L cone cell

$$\int s(x, y, \lambda) \cdot r_L(\lambda) \, d\lambda$$

Credit: Sabesan, http://depts.washington.edu/sabaolab/

Example: Spectral Response of Human Cone Cells

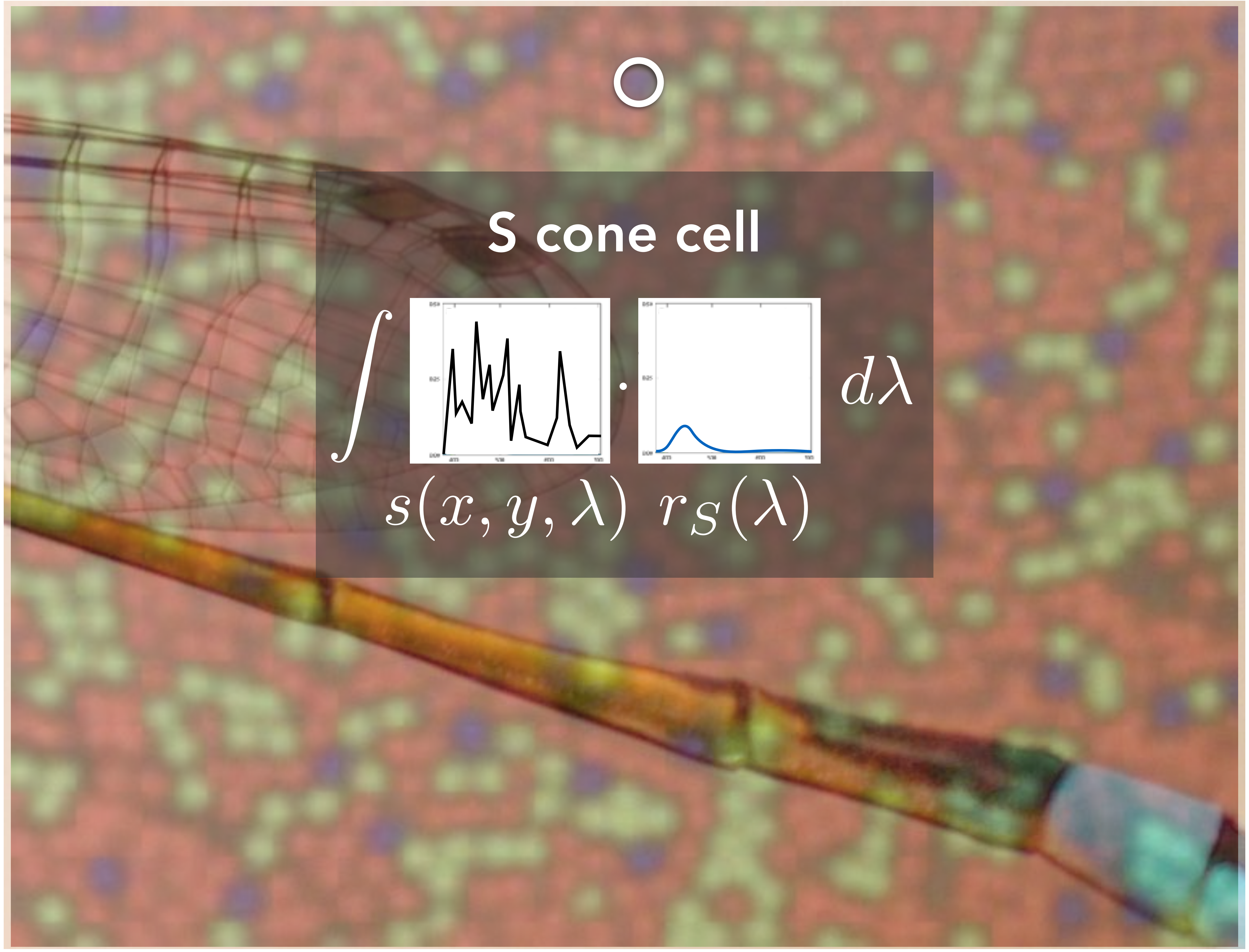


M cone cell

$$\int s(x, y, \lambda) \cdot r_M(\lambda) \, d\lambda$$

Credit: Sabesan, http://depts.washington.edu/sabaolab/

Example: Spectral Response of Human Cone Cells



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Spectral Response of Human Cone Cells

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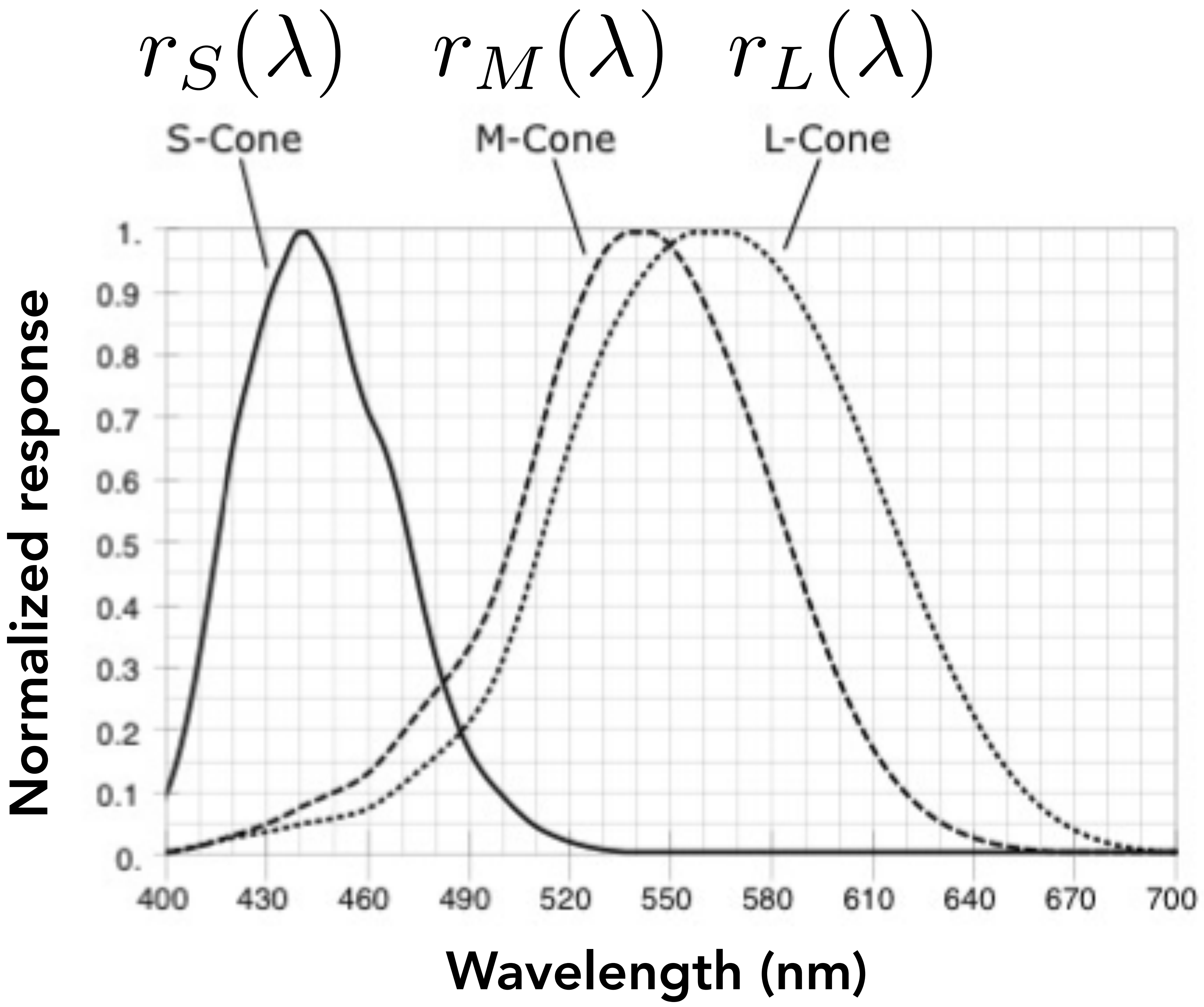


Spectral Response of Human Cone Cells

Instead of one detector as before, now we have three detectors (S, M, L cone cells), each with a different spectral response curve

Written as vector dot products:

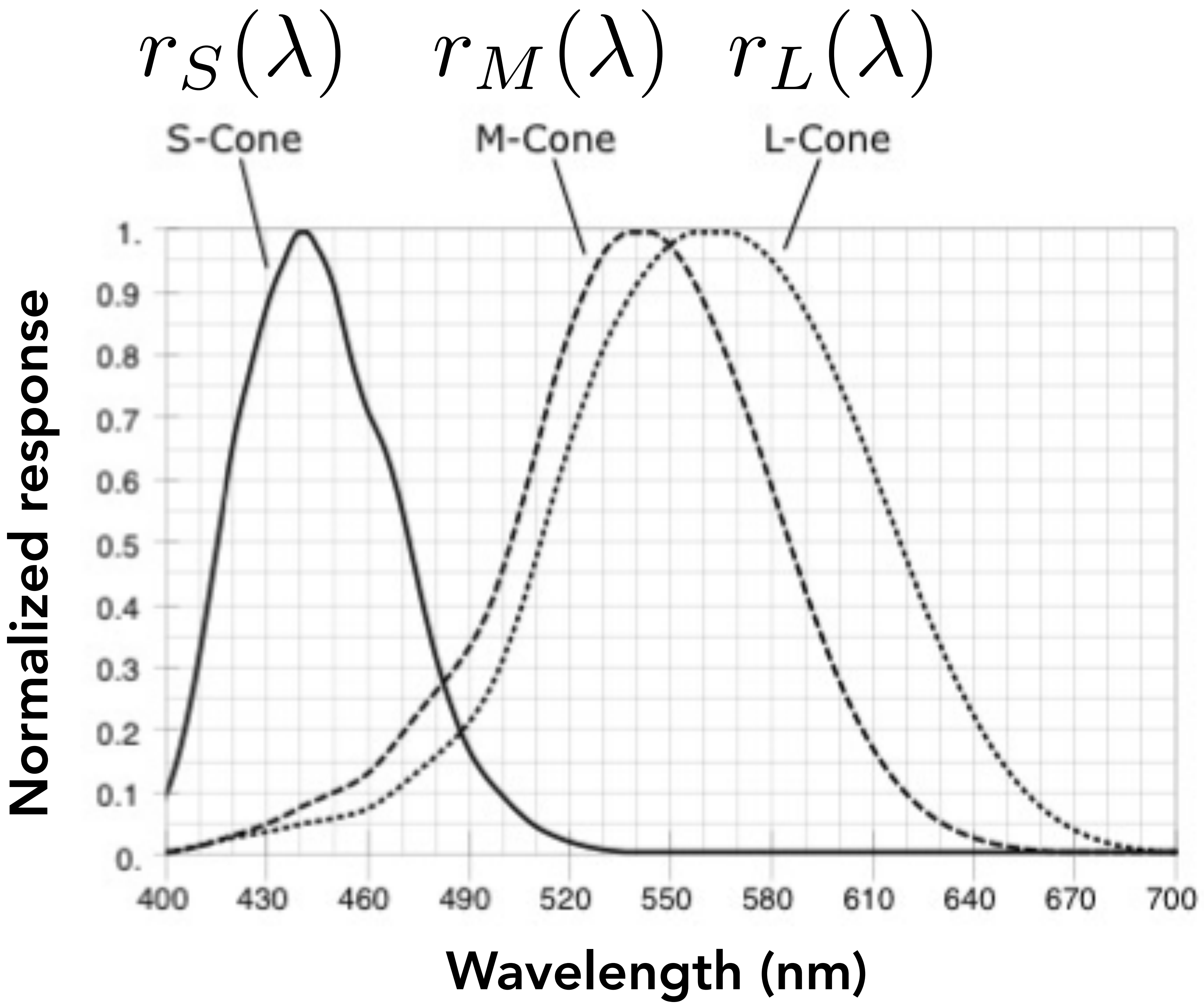
$$S = r_S \cdot s$$

$$M = r_M \cdot s$$

$$L = r_L \cdot s$$

Matrix formulation:

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} \text{---} & r_S & \text{---} \\ \text{---} & r_M & \text{---} \\ \text{---} & r_L & \text{---} \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$



Dimensionality Reduction From ∞ to 3

At each position on the human retina:

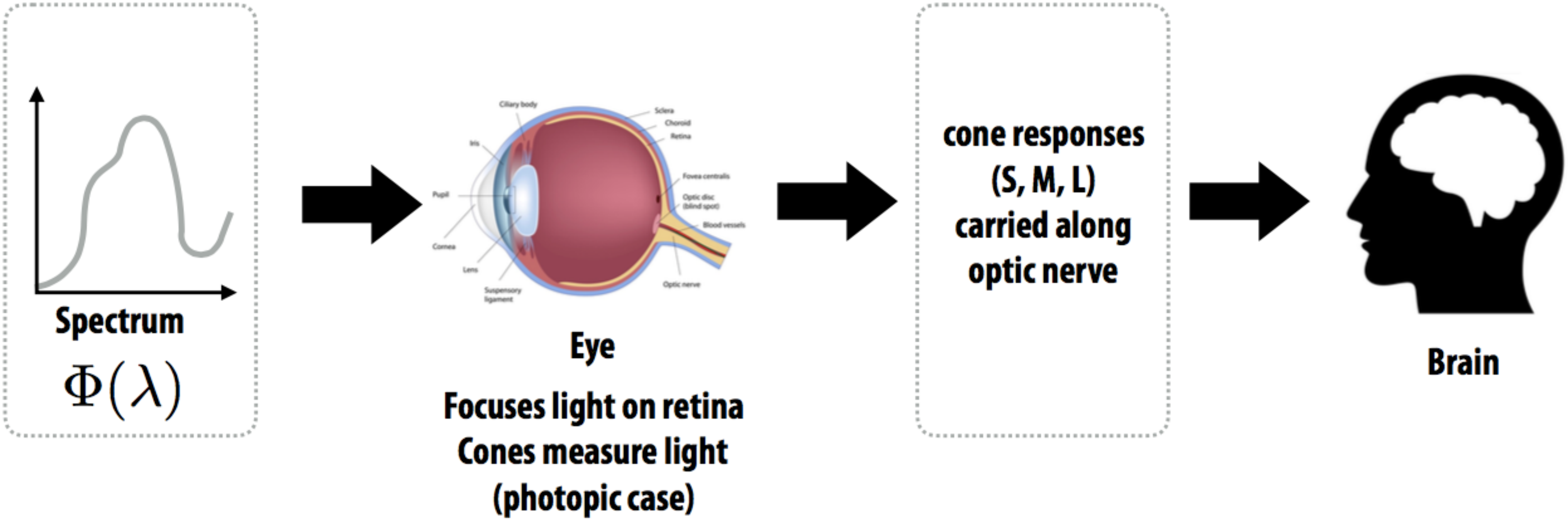
- SPD is a function of wavelength (∞ - dimensional signal)
- 3 types of cones near that position produce three scalar values (3 - dimensional signal)

What about 2D images?

- The dimensionality reduction described above is happening at every 2D position in our visual field

The Human Visual System

- Human eye does not measure and brain does not receive information about each wavelength of light
- Rather, the eye measures three response values only (S, M, L) at each position in visual field, and this is only spectral info available to brain
    - This is the result of integrating the incoming spectrum against response functions of S, M, L cones



Spectrum

$\Phi(\lambda)$

Eye

Focuses light on retina
Cones measure light
(photopic case)

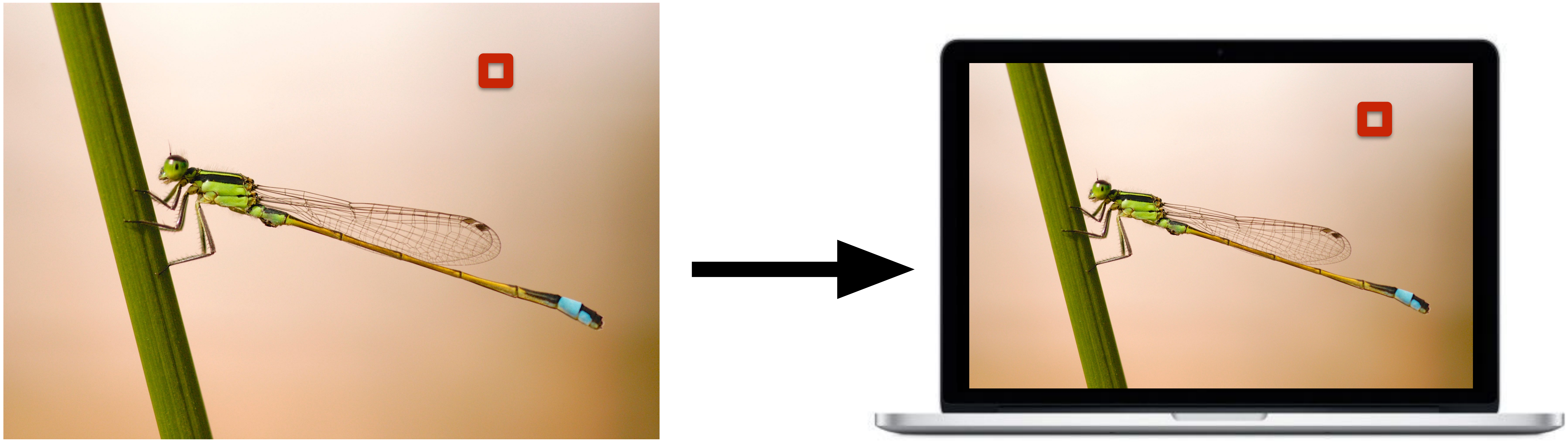
cone responses (S, M, L) carried along optic nerve

Brain

Kayvon Fatahalian

Color Reproduction Problem

Color Reproduction Problem



Target real spectrum $s(\lambda)$

Display outputs spectrum
$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$

Goal: at each pixel, choose R, G, B values for display so that the output color matches the appearance of the target color in the real world.

Metamerism

Metamers

Metameters are two different spectra (∞-dim) that project to the same (S,M,L) (3-dim) response.

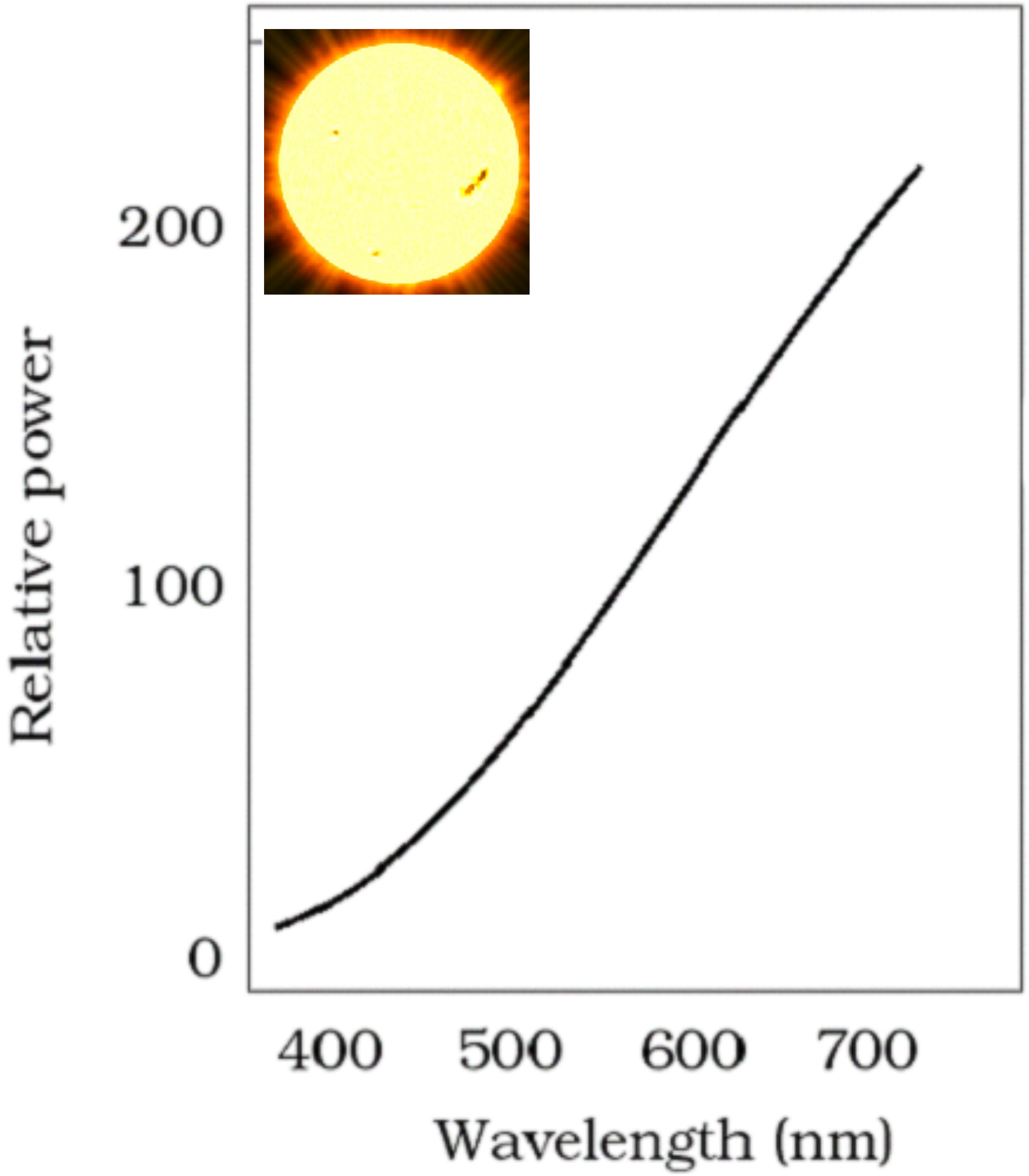
- These will appear to have the same color to a human

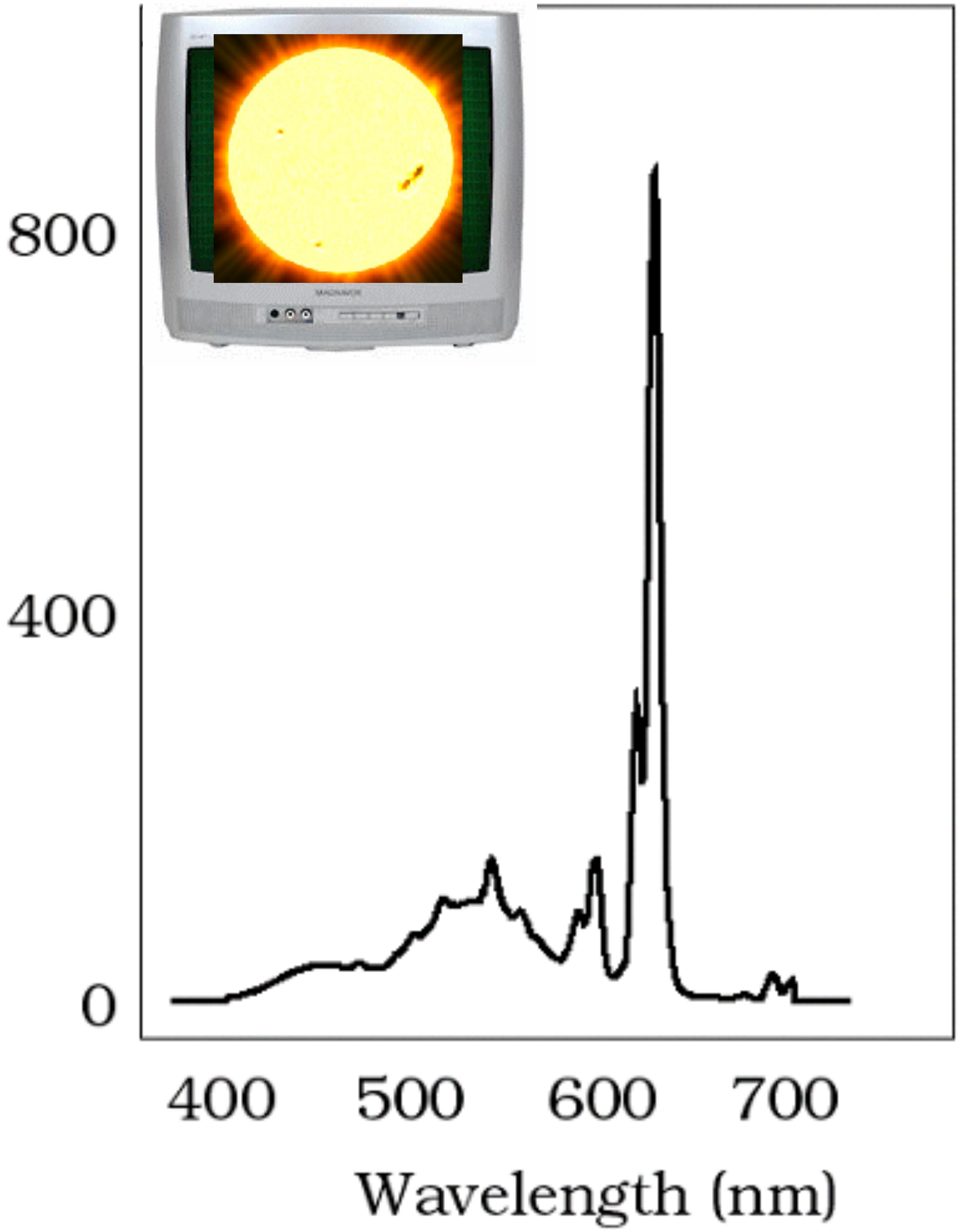
The existence of metamers is critical to color reproduction

- Don’t have to reproduce the full spectrum of a real world scene
- Example: A metamer can reproduce the perceived color of a real-world scene on a display with pixels of only three colors

Metamerism

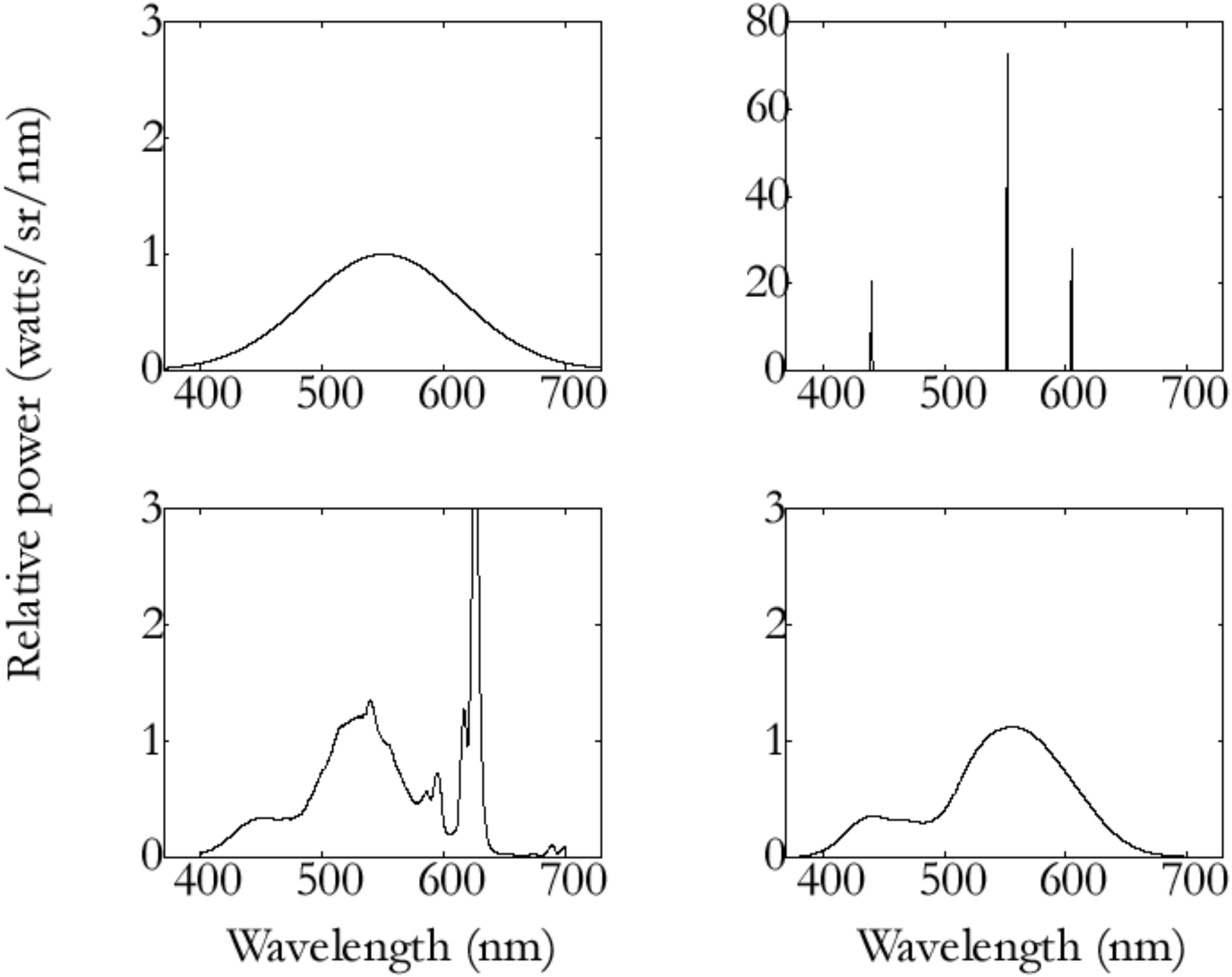
Color matching is an important illusion that is understood quantitatively





Brian Wandell

Metamerism is a Big Effect

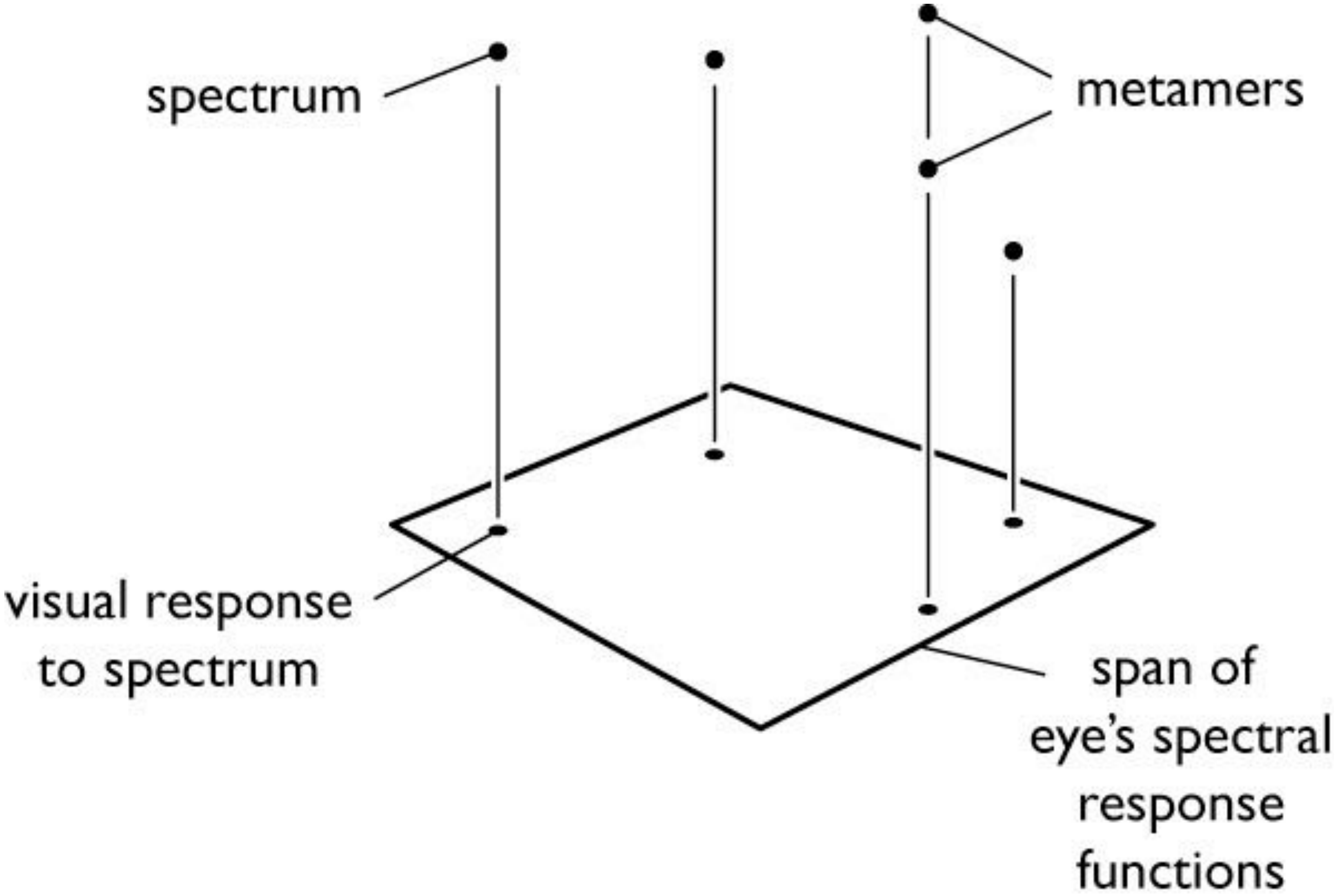


Brian Wandell

Pseudo-Geometric Interpretation

We are projecting a high dimensional vector (wavelength spectrum function) onto a low-dimensional subspace (SML visual response)

- Differences that are perpendicular to the basis vectors of the low-dimensional space are not detectable



Slide credit: Steve Marschner

Color Reproduction

Additive Color

- Given a set of primary lights, each with its own spectral distribution (e.g. R,G,B display pixels):

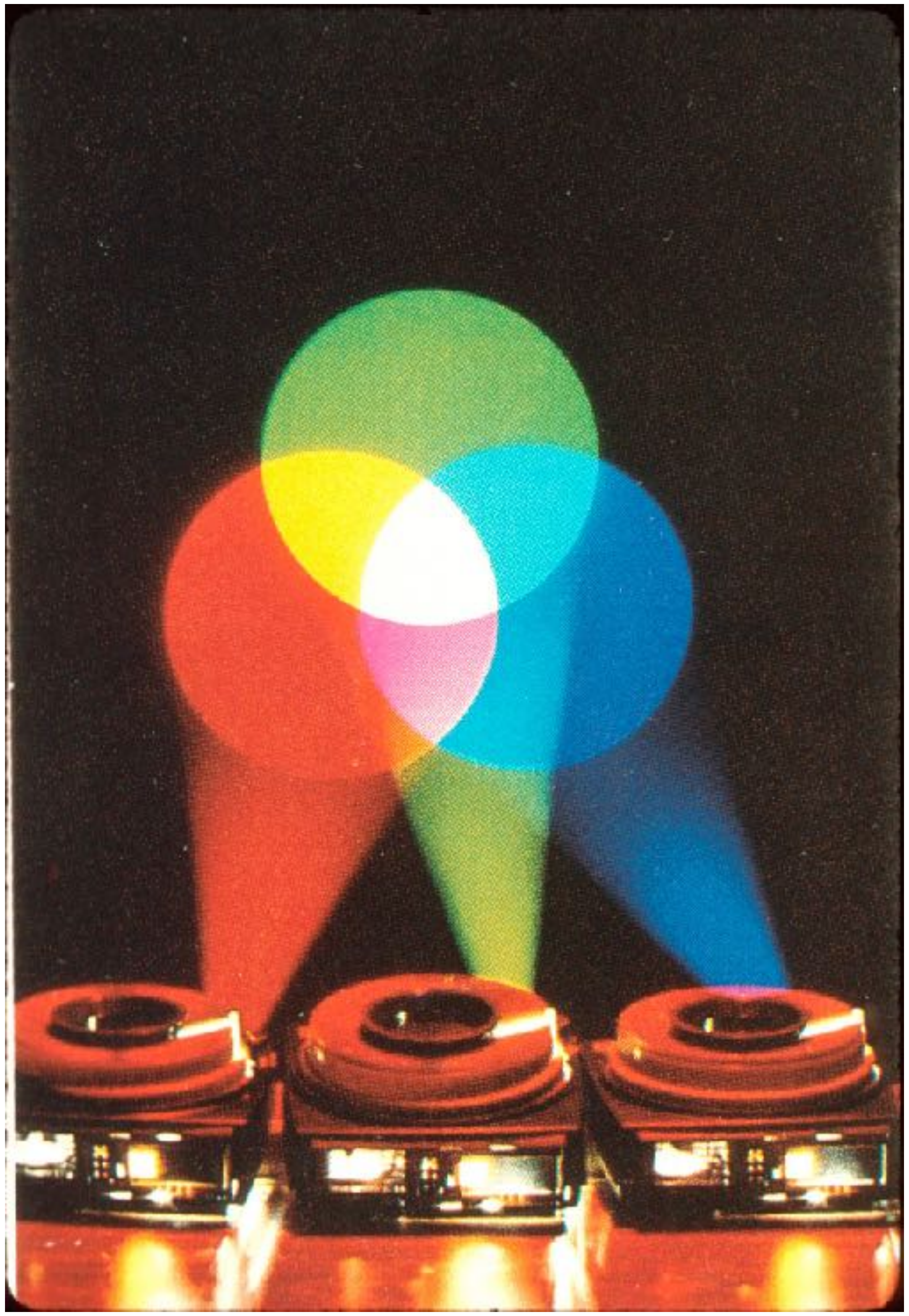
$$s_R(\lambda),\ \ s_G(\lambda),\ \ s_B(\lambda)$$

- We can adjust the brightness of these lights and add them together to produce a linear subspace of spectral distribution:

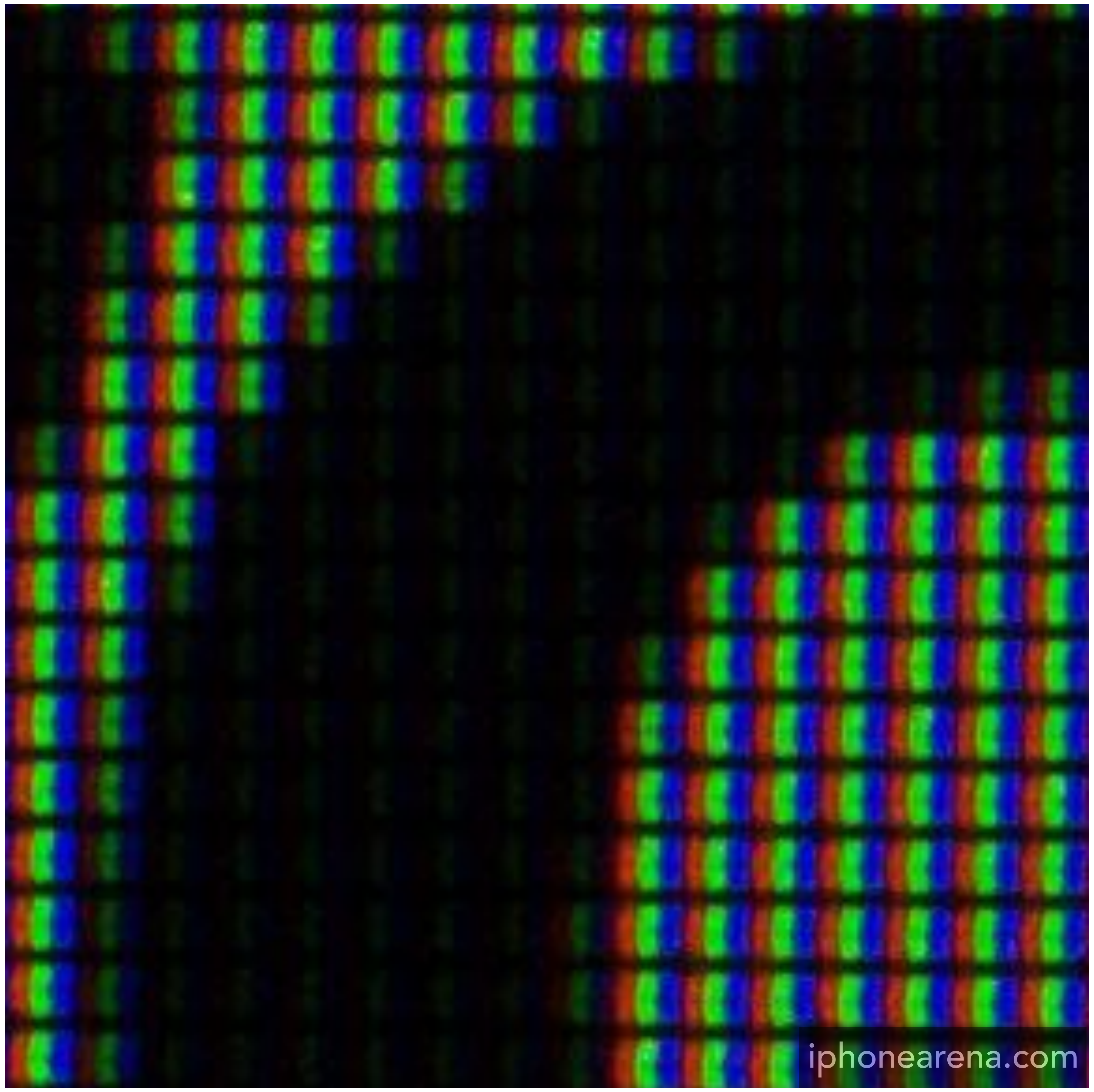
$$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

- The color is now described by the scalar values:

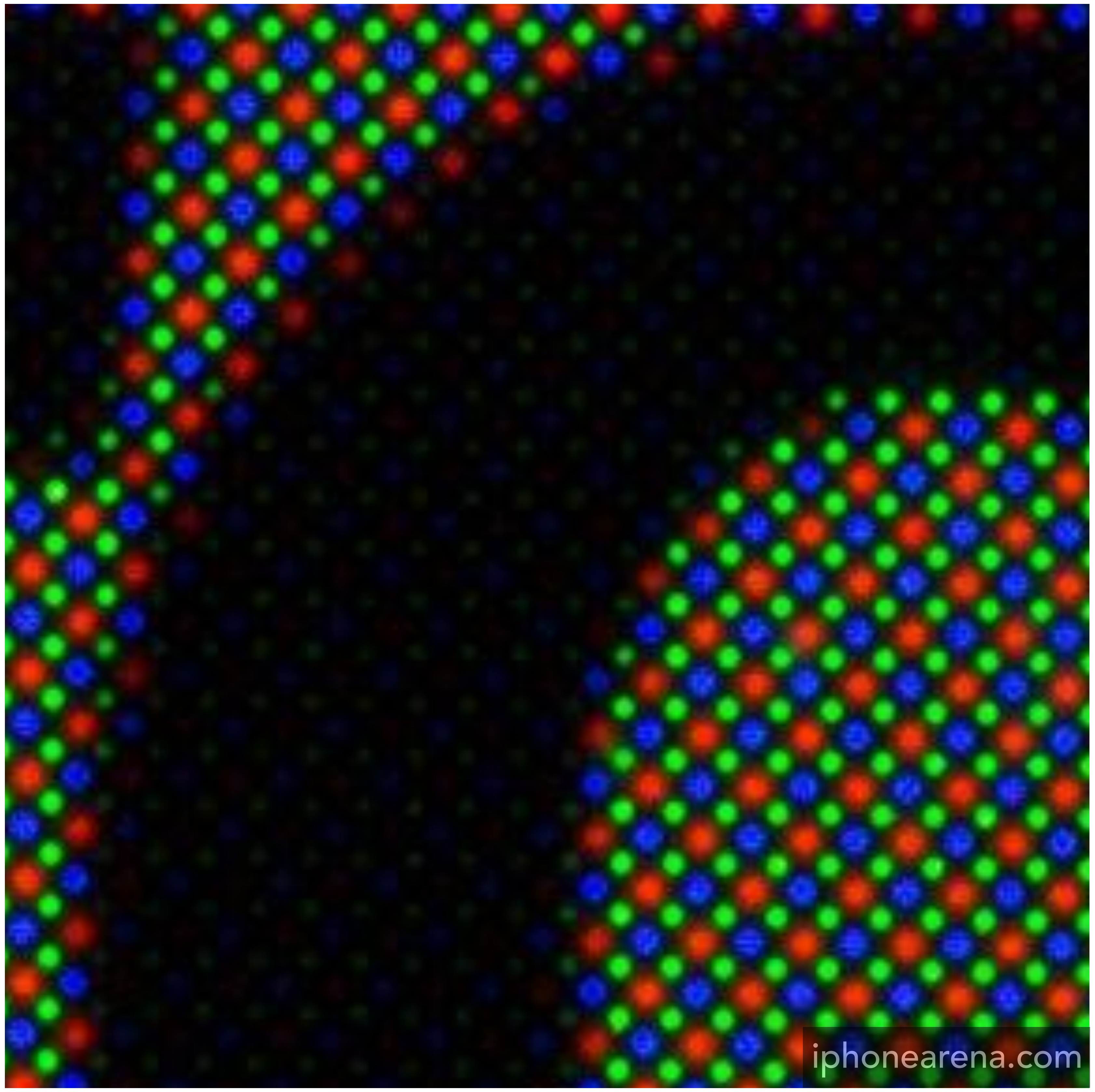
$$R,\ G,\ B$$



Recall: Real LCD Screen Pixels (Closeup)



iPhone 6S

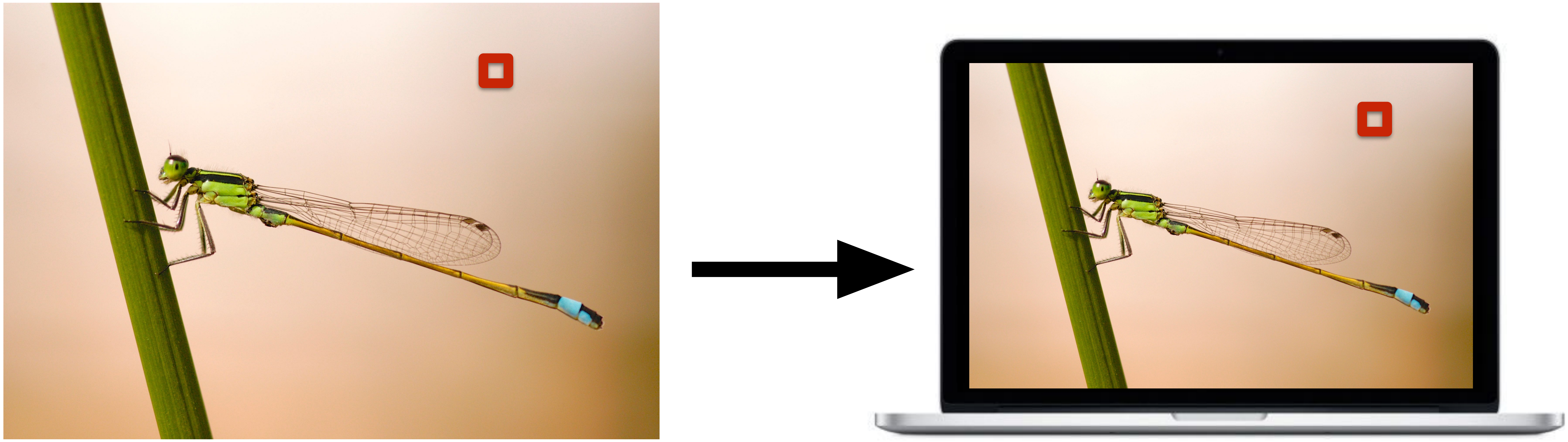


Galaxy S5

Notice R, G, B sub-pixel geometry.

Effectively three lights at each (x,y) location.

Color Reproduction Problem



Target real spectrum $s(\lambda)$

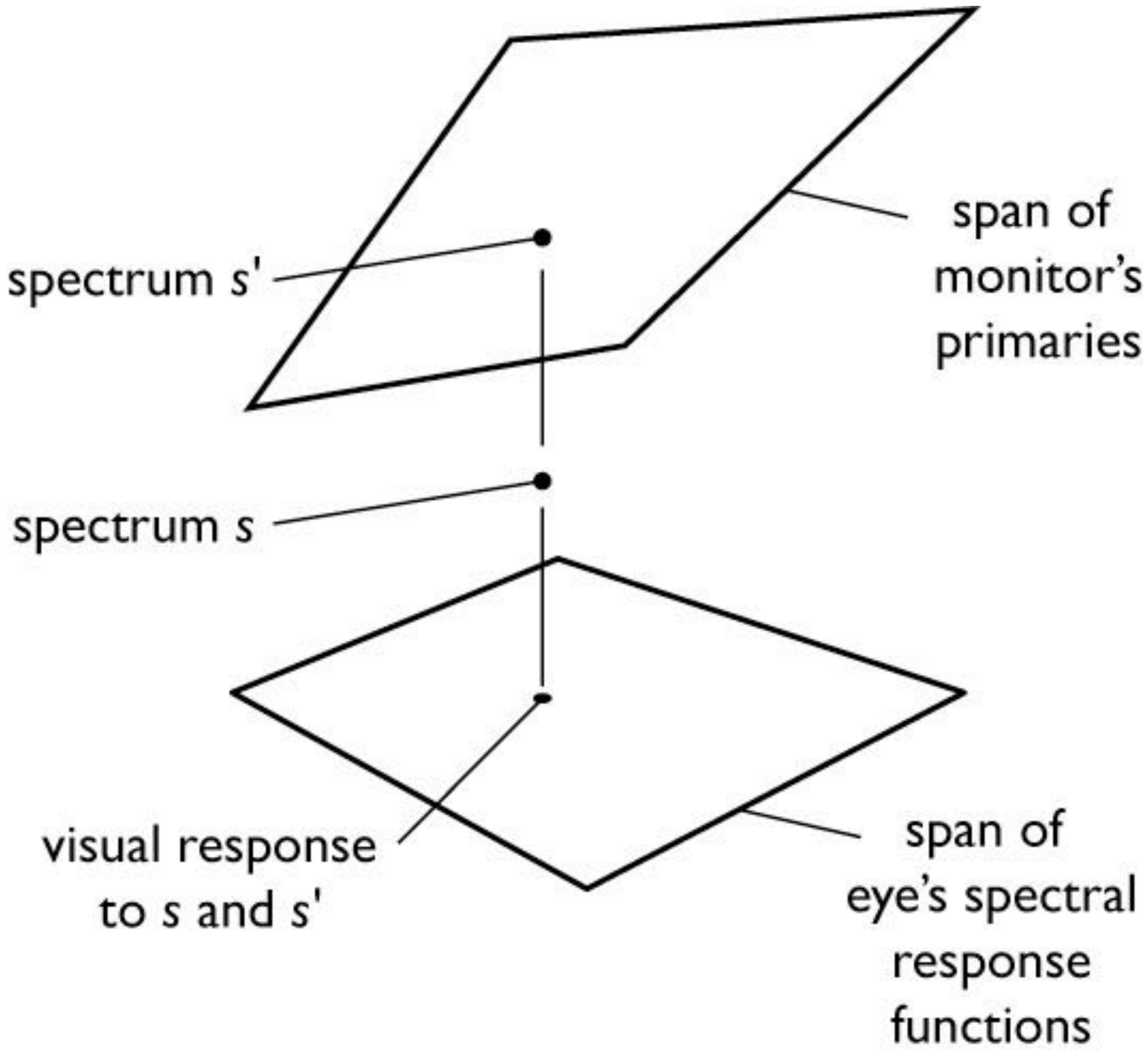
Display outputs spectrum

$$R\,s_R(\lambda) + G\,s_G(\lambda) + B\,s_B(\lambda)$$

Goal: at each pixel, choose R, G, B values for display so that the output color matches the appearance of the target color in the real world.

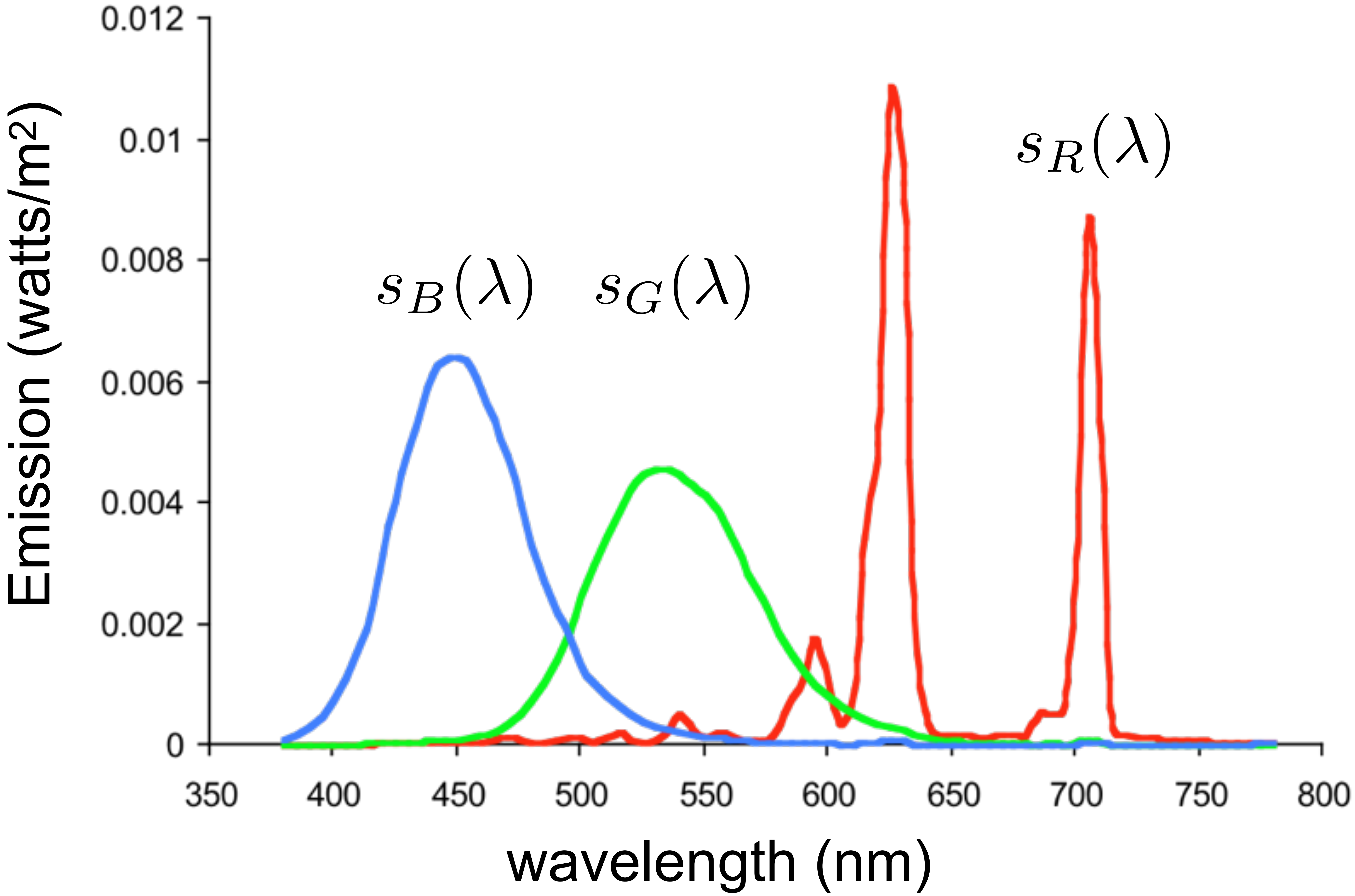
Pseudo-Geometric Interpretation of Color Reproduction

- The display can only produce a low-dimensional subspace of all possible (linear combinations of display primaries)
- In color reproduction, for a given spectrum s (high dimensional), we want to choose a spectrum s’ in the display’s low-dimensional subspace, such that s’ and s project to the same response in the low-dimensional subspace of the eye’s SML response



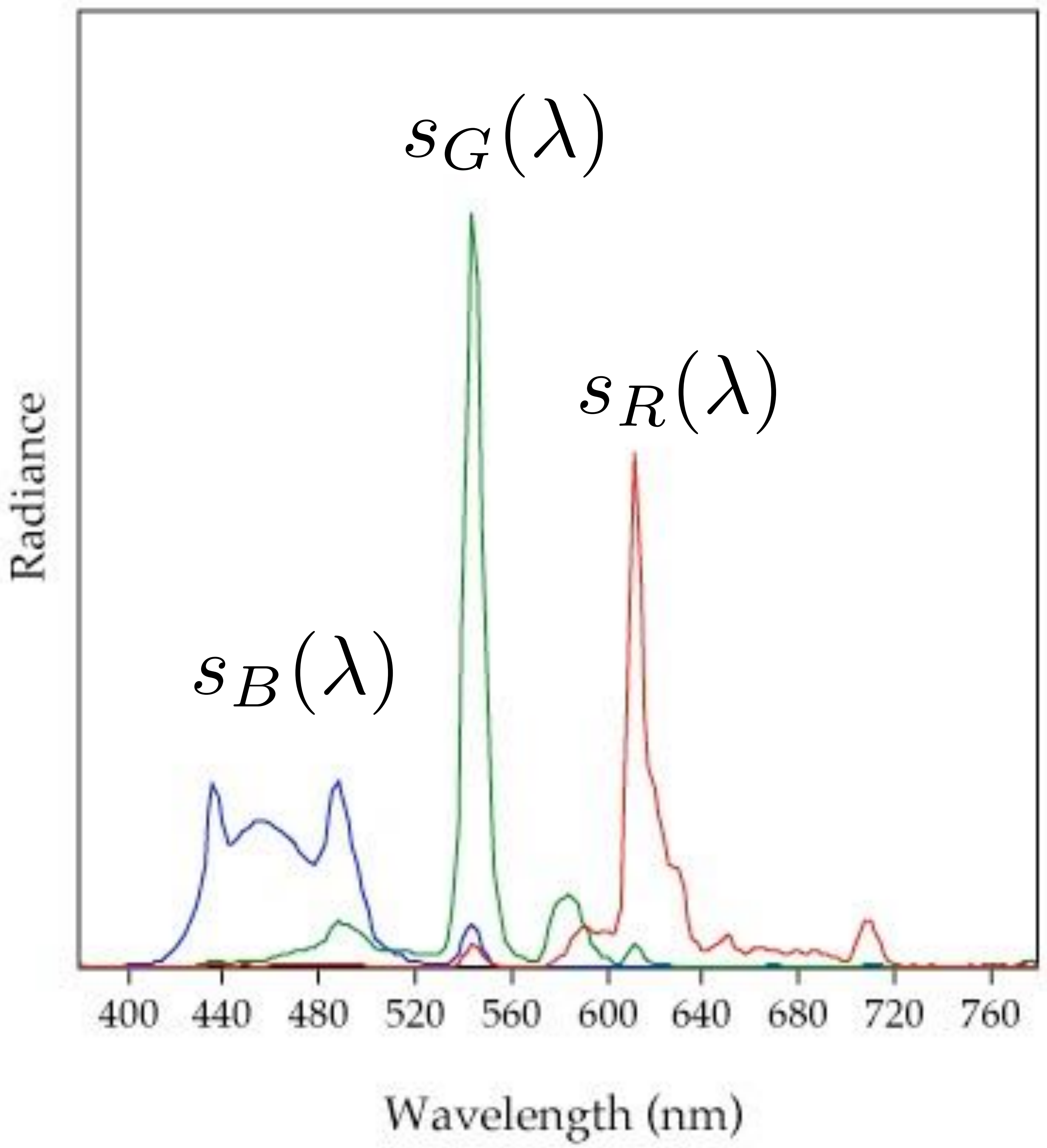
Slide credit: Steve Marschner

Example Primaries for CRT Display



- **Curves determined by phosphor emission properties**

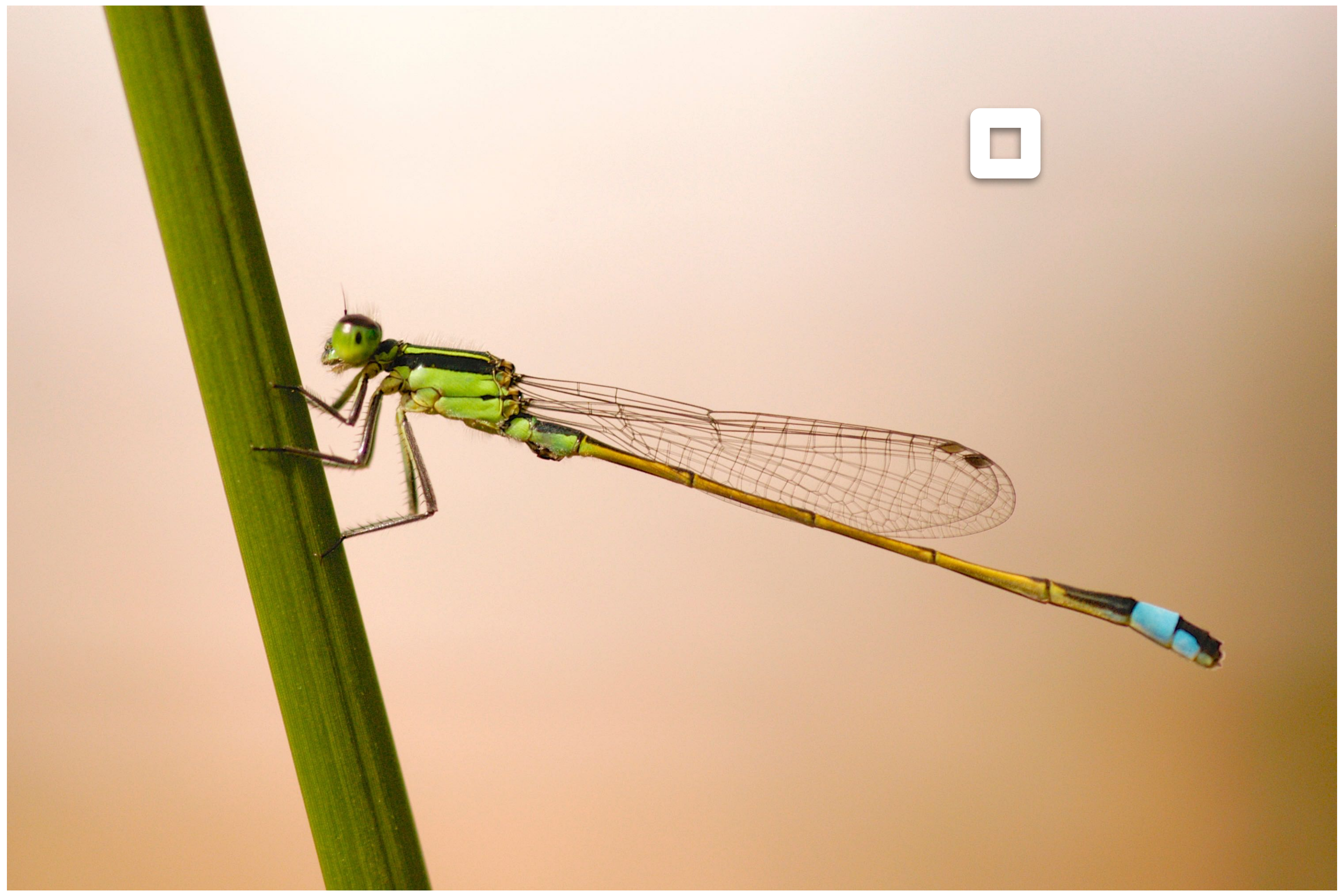
Example Primaries: LCD Display



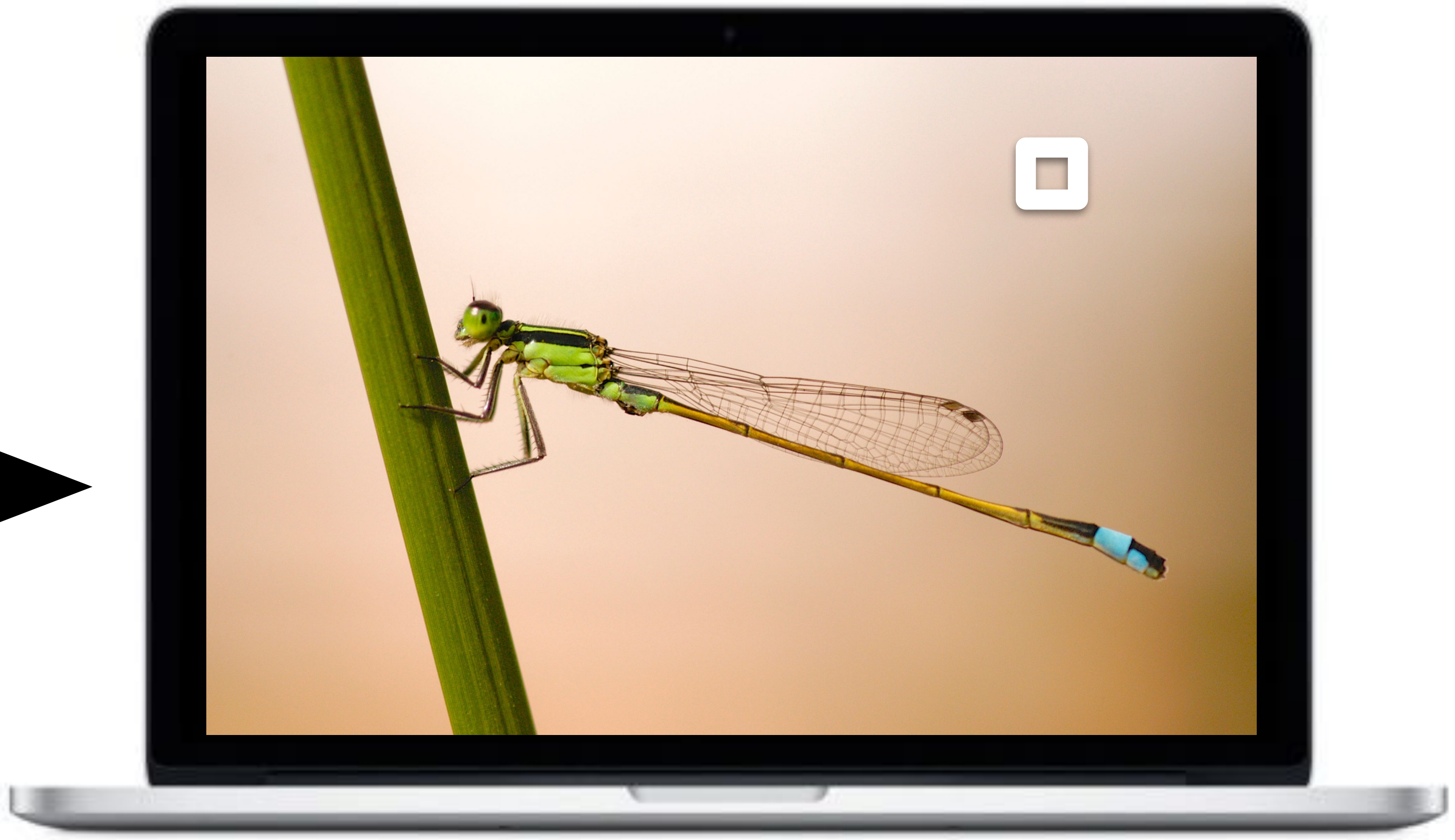
[Fairchild 97]

- Curves determined by backlight and color filters

Color Reproduction as Linear Algebra



Input spectrum *s*



What R, G, B values?

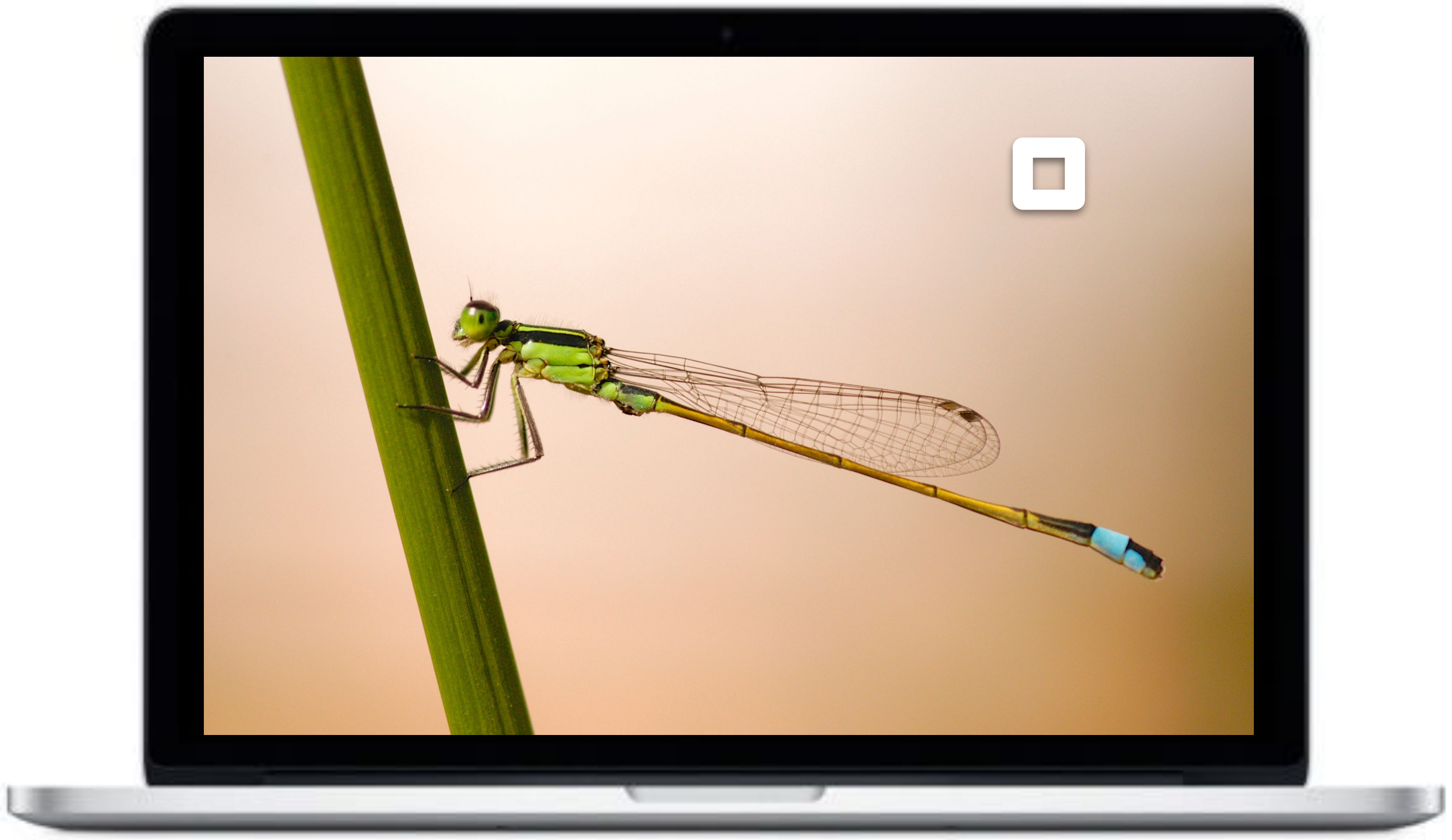
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \text{---} & ? & \text{---} \\ \text{---} & ? & \text{---} \\ \text{---} & ? & \text{---} \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

Color Reproduction as Linear Algebra

Spectrum produced by display given values R,G,B:

$$s_{\text{disp}}(\lambda) = R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

$$\Longrightarrow \begin{bmatrix} | \\ s_{\text{disp}} \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



Color Reproduction as Linear Algebra

What color do we perceive when we look at the display?

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{disp}} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | \\ s_{\text{disp}} \\ | \end{bmatrix}$$

$$= \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

We want this displayed spectrum to be a metamer for the real-world target spectrum.

Color Reproduction as Linear Algebra

Color perceived for display spectra with values R,G,B

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{disp}} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color perceived for real scene spectra, s

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{real}} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

How do we reproduce the color of s? Set these lines equal and solve for R,G,B as a function of s!

Color Reproduction as Linear Algebra

Solution:

$$\begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

$$\Longrightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \left(\begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \right)^{-1} \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

Color Reproduction as Linear Algebra

Solution (form #1):

$$\underset{\text{1x3}}{\begin{bmatrix}R\\G\\B\end{bmatrix}} = \left(\underbrace{\underset{\text{Nx3}}{\begin{bmatrix}\text{—} & r_S & \text{—}\\ \text{—} & r_M & \text{—}\\ \text{—} & r_L & \text{—}\end{bmatrix}}\underset{\text{3xN}}{\begin{bmatrix}| & | & |\\ s_R & s_G & s_B\\ | & | & |\end{bmatrix}}}_{\text{3x3}}\right)^{-1}\underbrace{\underset{\text{Nx3}}{\begin{bmatrix}\text{—} & r_S & \text{—}\\ \text{—} & r_M & \text{—}\\ \text{—} & r_L & \text{—}\end{bmatrix}}\underset{\text{1xN}}{\begin{bmatrix}|\\ s\\ |\end{bmatrix}}}_{\text{1x3}}$$

Solution (form #2):

$$\underset{\text{1x3}}{RGB} = \underbrace{(\underset{\text{Nx3}}{\mathbf{M}_{SML}}\,\underset{\text{3xN}}{\mathbf{M}_{RGB}})^{-1}\underset{\text{Nx3}}{\mathbf{M}_{SML}}}_{\text{Nx3}}\,\underset{\text{1xN}}{s}$$

Color Reproduction as Linear Algebra

Solution (form #3):

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \underbrace{\begin{bmatrix} r_S \cdot s_R & r_S \cdot s_G & r_S \cdot s_B \\ r_M \cdot s_R & r_M \cdot s_G & r_M \cdot s_B \\ r_L \cdot s_R & r_L \cdot s_G & r_L \cdot s_B \end{bmatrix}^{-1} \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix}}_{\text{Nx3}} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

Color Matching Functions

Recall the color matching functions from the matching experiment

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \left(\begin{bmatrix} \text{---} & r_S & \text{---} \\ \text{---} & r_M & \text{---} \\ \text{---} & r_L & \text{---} \end{bmatrix} \begin{bmatrix} \vert & \vert & \vert \\ s_R & s_G & s_B \\ \vert & \vert & \vert \end{bmatrix} \right)^{-1} \begin{bmatrix} \text{---} & r_S & \text{---} \\ \text{---} & r_M & \text{---} \\ \text{---} & r_L & \text{---} \end{bmatrix} \begin{bmatrix} \vert \\ s \\ \vert \end{bmatrix}$$

$$= \underbrace{\begin{bmatrix} r_S \cdot s_R & r_S \cdot s_G & r_S \cdot s_B \\ r_M \cdot s_R & r_M \cdot s_G & r_M \cdot s_B \\ r_L \cdot s_R & r_L \cdot s_G & r_L \cdot s_B \end{bmatrix}^{-1} \begin{bmatrix} \text{---} & r_S & \text{---} \\ \text{---} & r_M & \text{---} \\ \text{---} & r_L & \text{---} \end{bmatrix}}_{\text{Nx3}} \begin{bmatrix} \vert \\ s \\ \vert \end{bmatrix}$$

This Nx3 matrix contains, as row vectors,
"color matching functions"
associated with the primary lights s_R, s_G, s_B.

Color Reproduction Issue: No Negative Light

R,G,B values must be positive

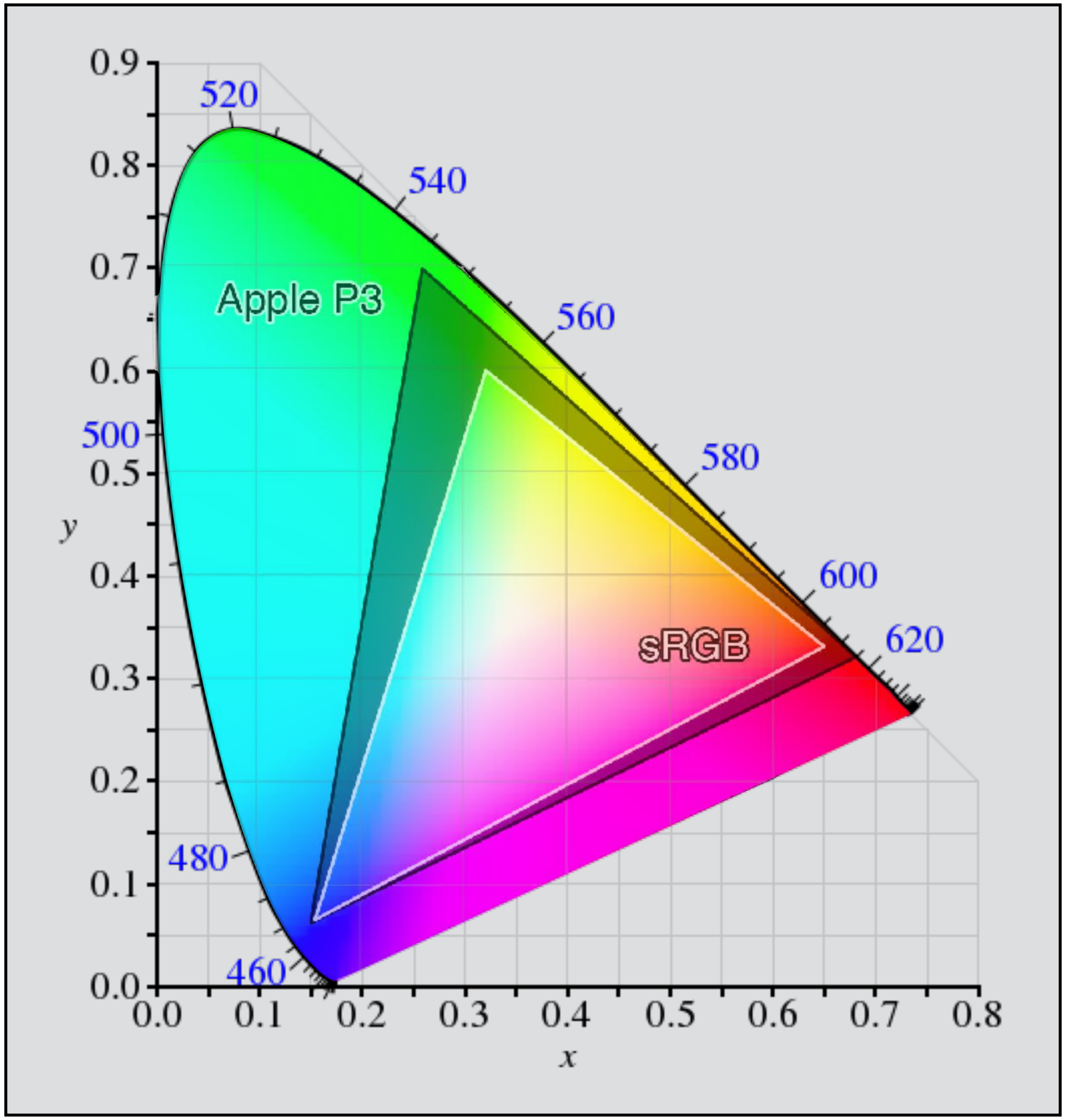
- Display primaries can’t emit negative light
- But solution formulas can certainly produce negative R,G,B values

What do negative R,G,B values mean?

- Display can’t physically reproduce the desired color
- Desired color is outside the display’s color gamut

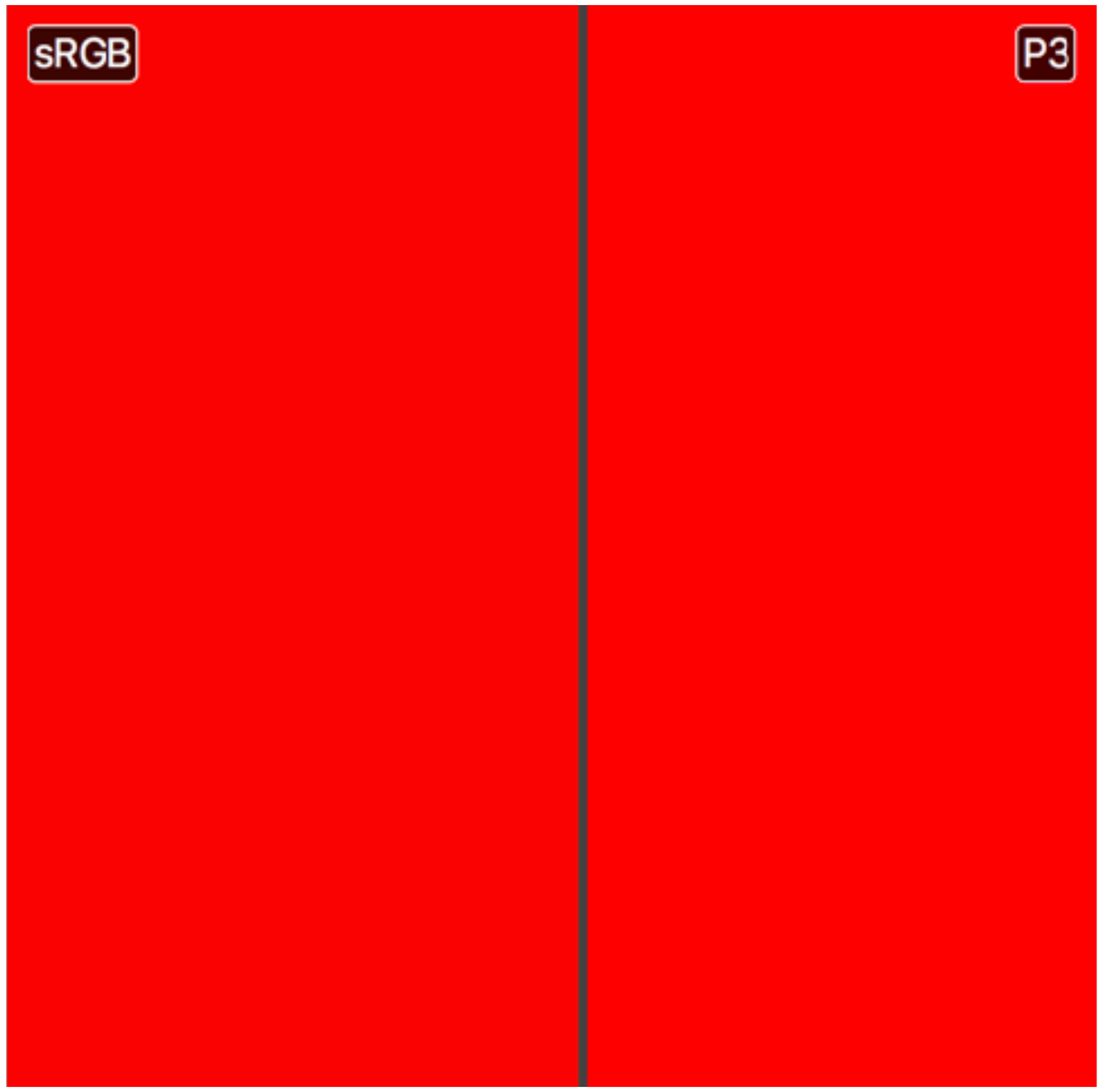
Gamut

Example: Color Gamut for sRGB and Apple P3



Wikipedia

Comparing sRGB and Wide Gamut P3 Color Spaces

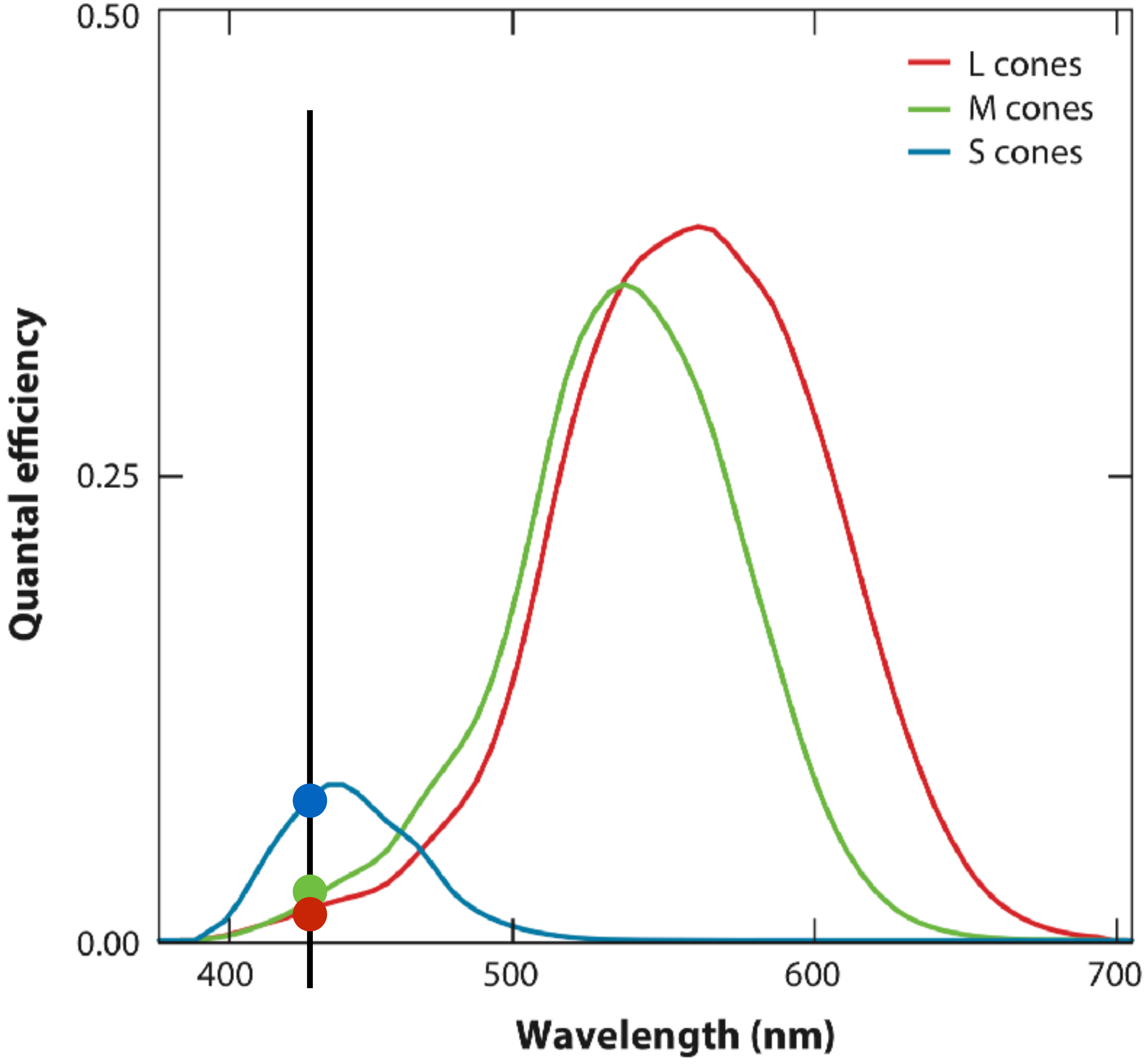


Interactive Color Space Comparison:

https://webkit.org/blog-files/color-gamut/comparison.html

- Needs a wide-gamut physical display
- I can see differences clearly on my MacBook Pro 2017

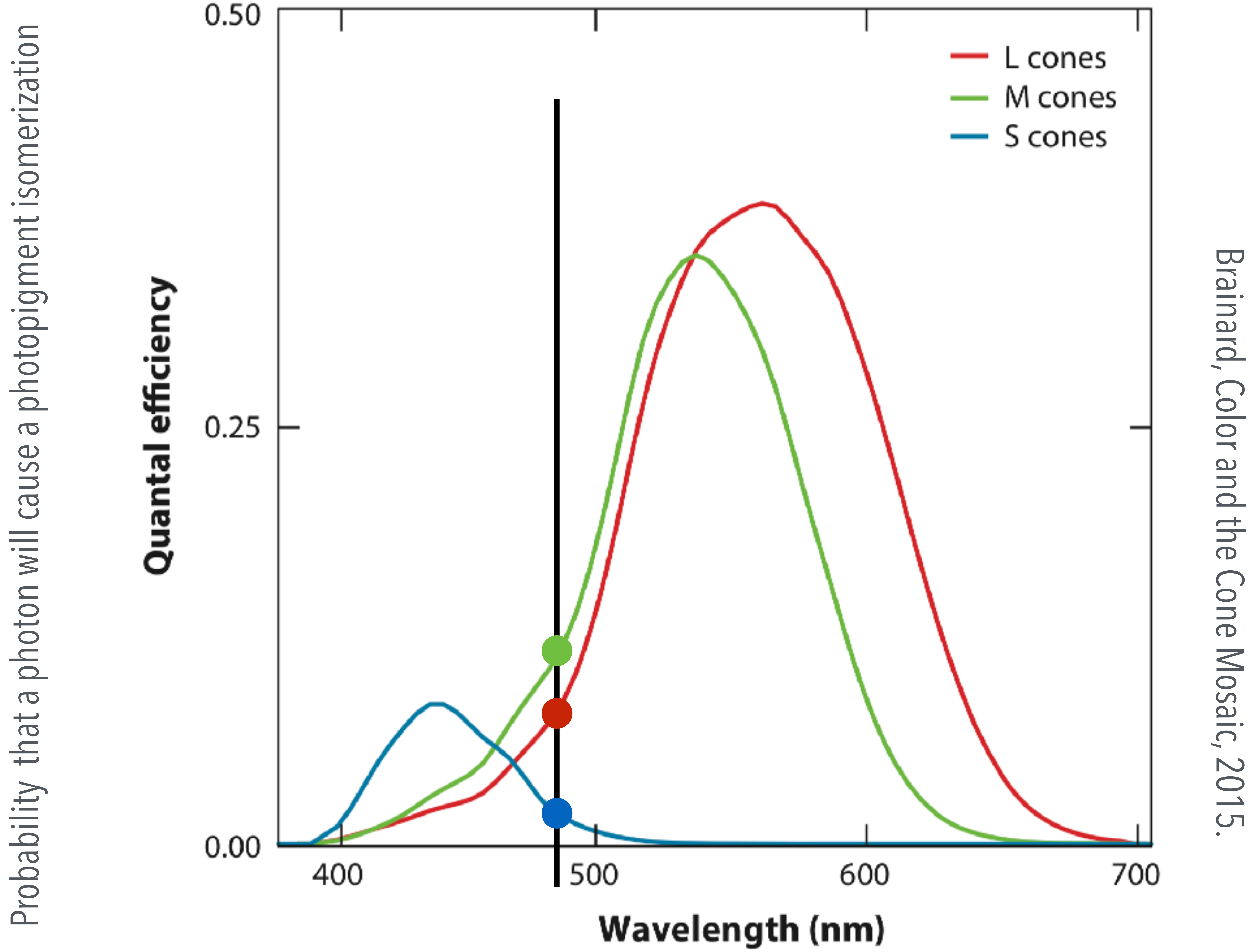
LMS Response Values for Each Wavelength



Probability that a photon will cause a photopigment isomerization

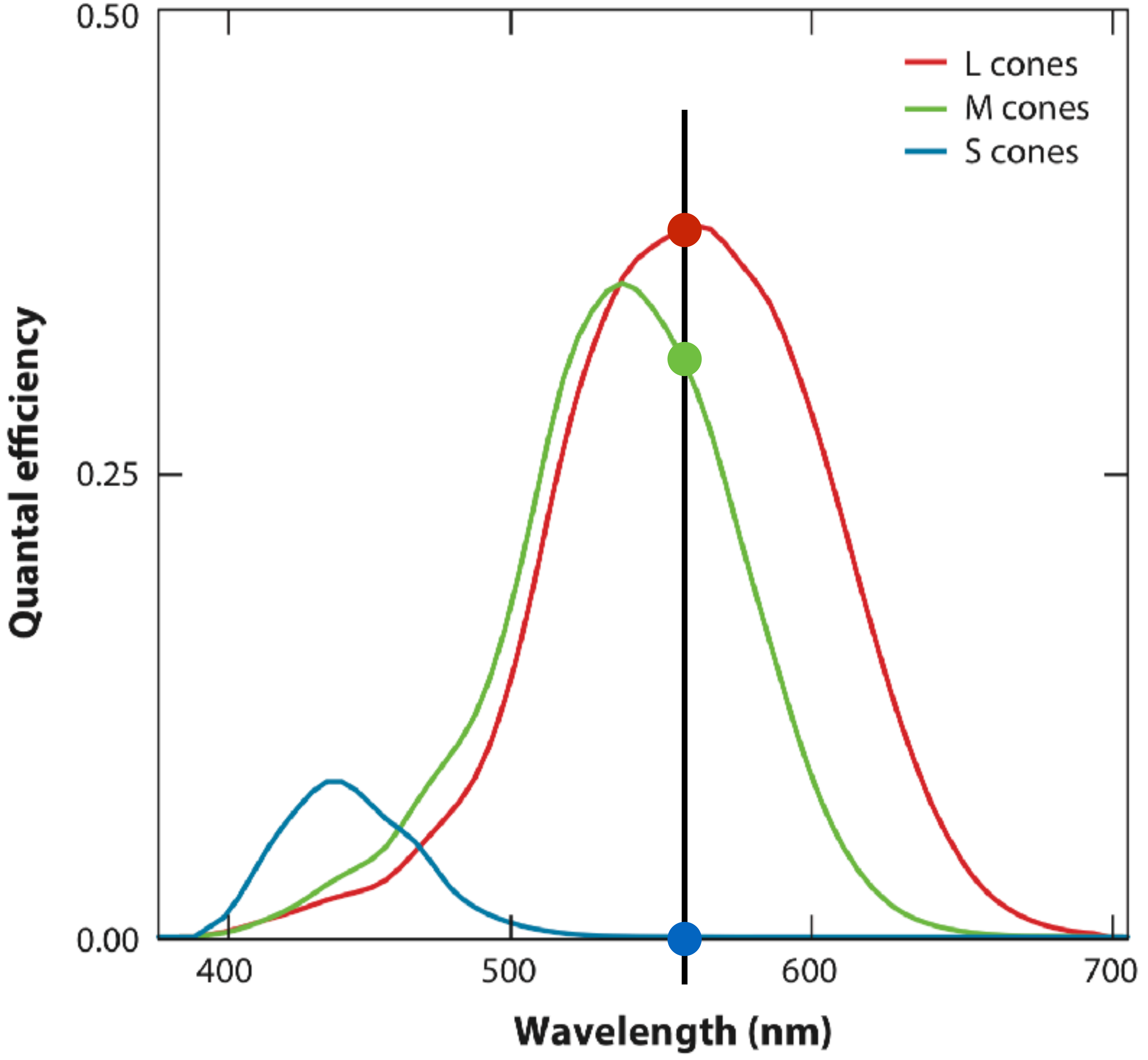
Brainard, Color and the Cone Mosaic, 2015.

LMS Response Values for Each Wavelength



Brainard, Color and the Cone Mosaic, 2015.

LMS Response Values for Each Wavelength



Probability that a photon will cause a photopigment isomerization

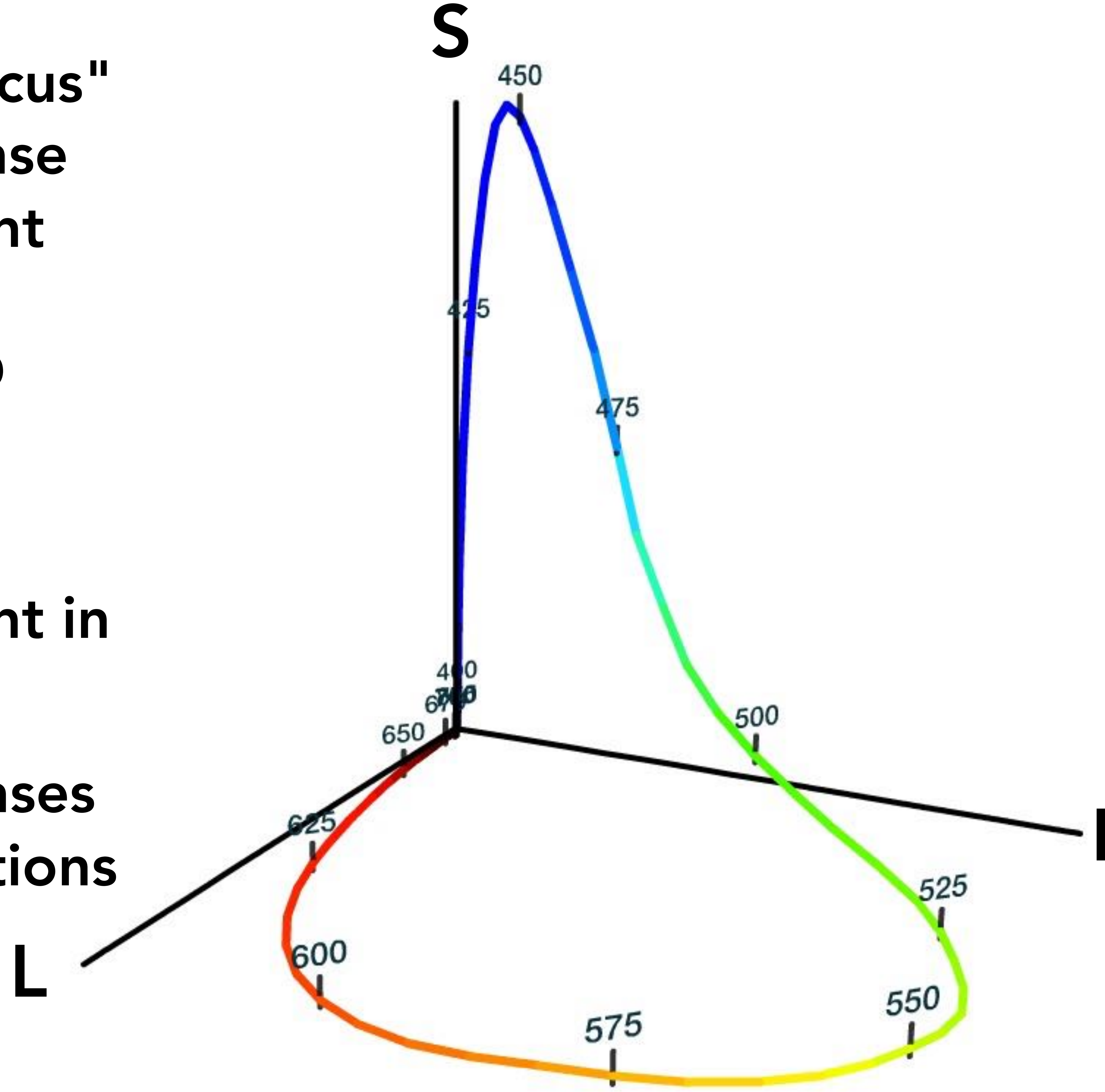
Brainard, Color and the Cone Mosaic, 2015.

LMS Responses Plotted as 3D Color Space

Visualization of "spectral locus" of human cone cells' response to monochromatic light (light with energy in a single wavelength) as points in 3D space.

This is a plot of the S, M, L response functions as a point in 3D space.

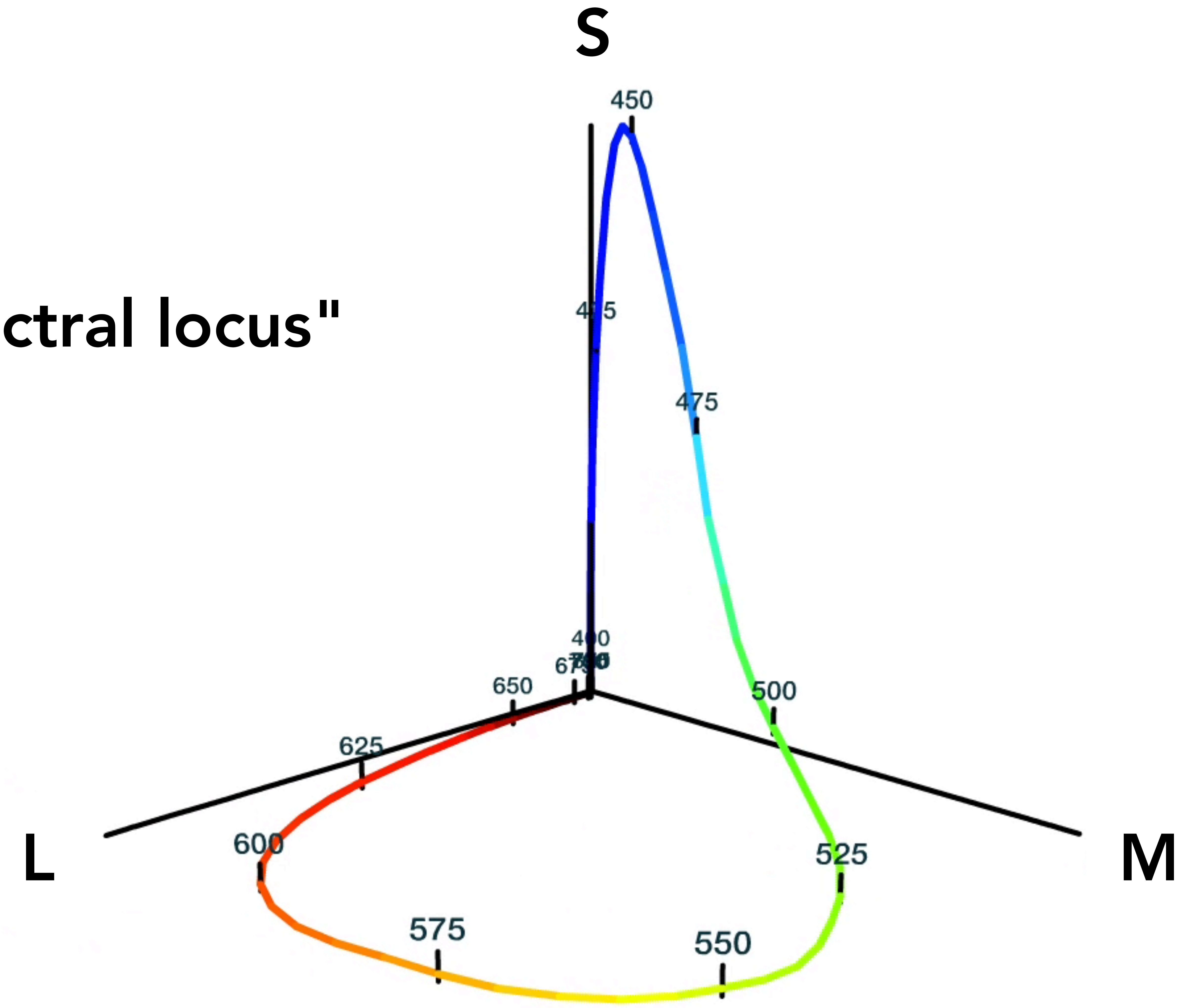
Space of all possible responses are positive linear combinations of points on this curve.



Marc Levoy

LMS Responses Plotted as 3D Color Space

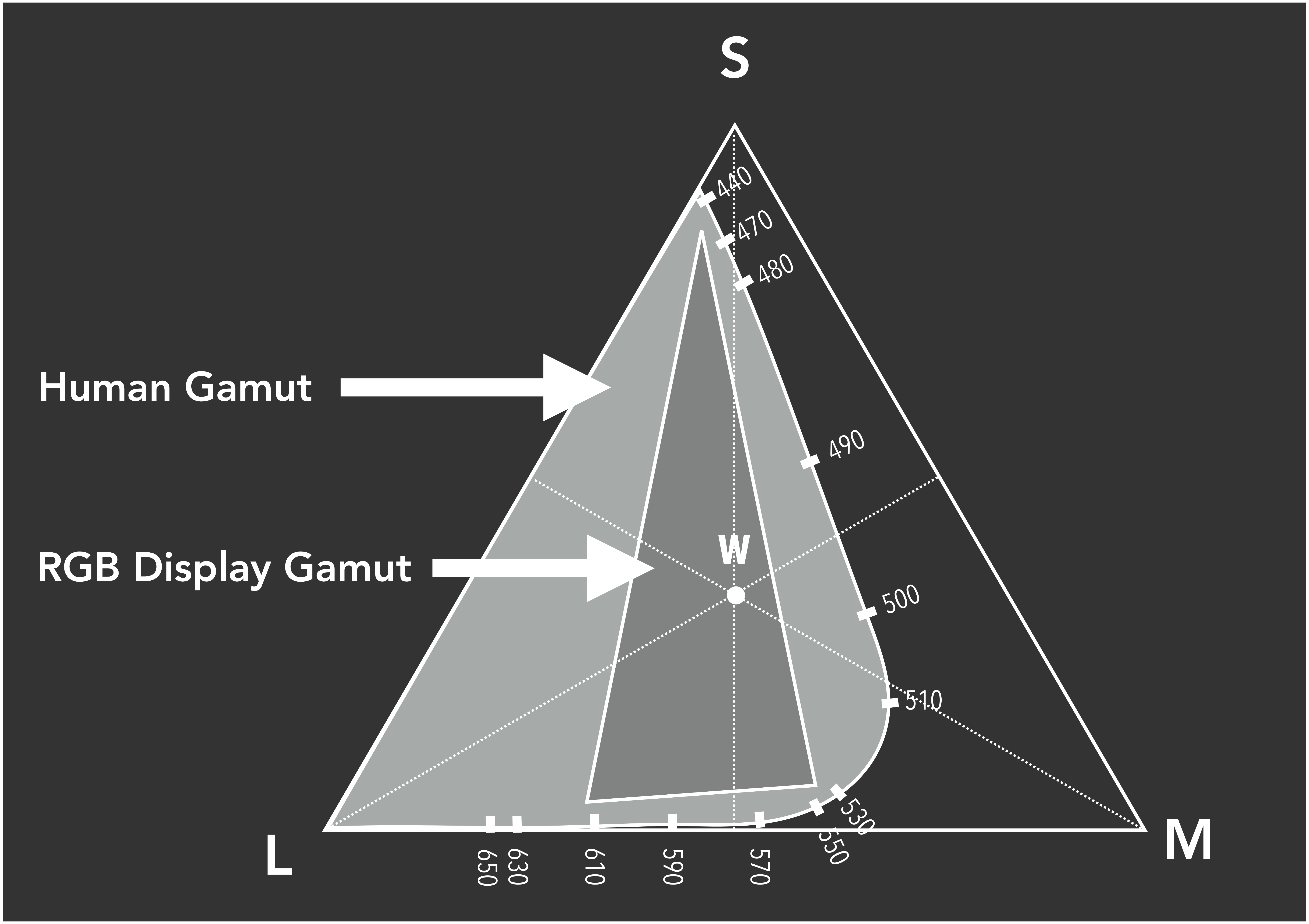
"Spectral locus"



https://graphics.stanford.edu/courses/cs178-10/applets/locus.html

Dektar, Adams, Levoy

Chromaticity Diagram (Maxwellian)



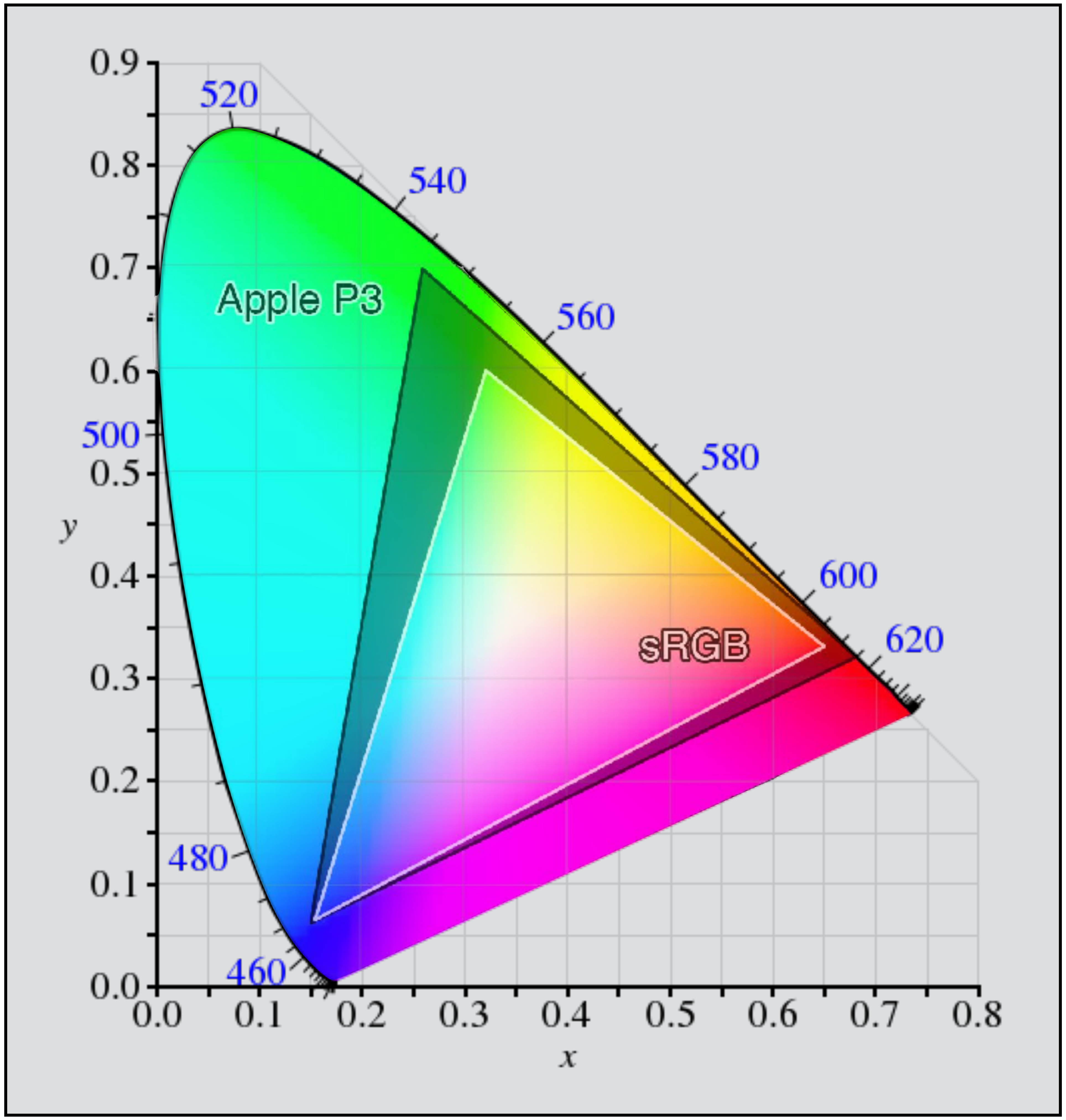
Perspective projection of spectral locus
looking diagonally down at origin from (1,1,1)

Chromaticity Diagram (CIE 1931 xy)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.9121 & -1.1121 & 0.2019 \\ 0.3709 & 0.6291 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

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

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



Wikipedia

Chromaticity Diagram (CIE 1931 xy)

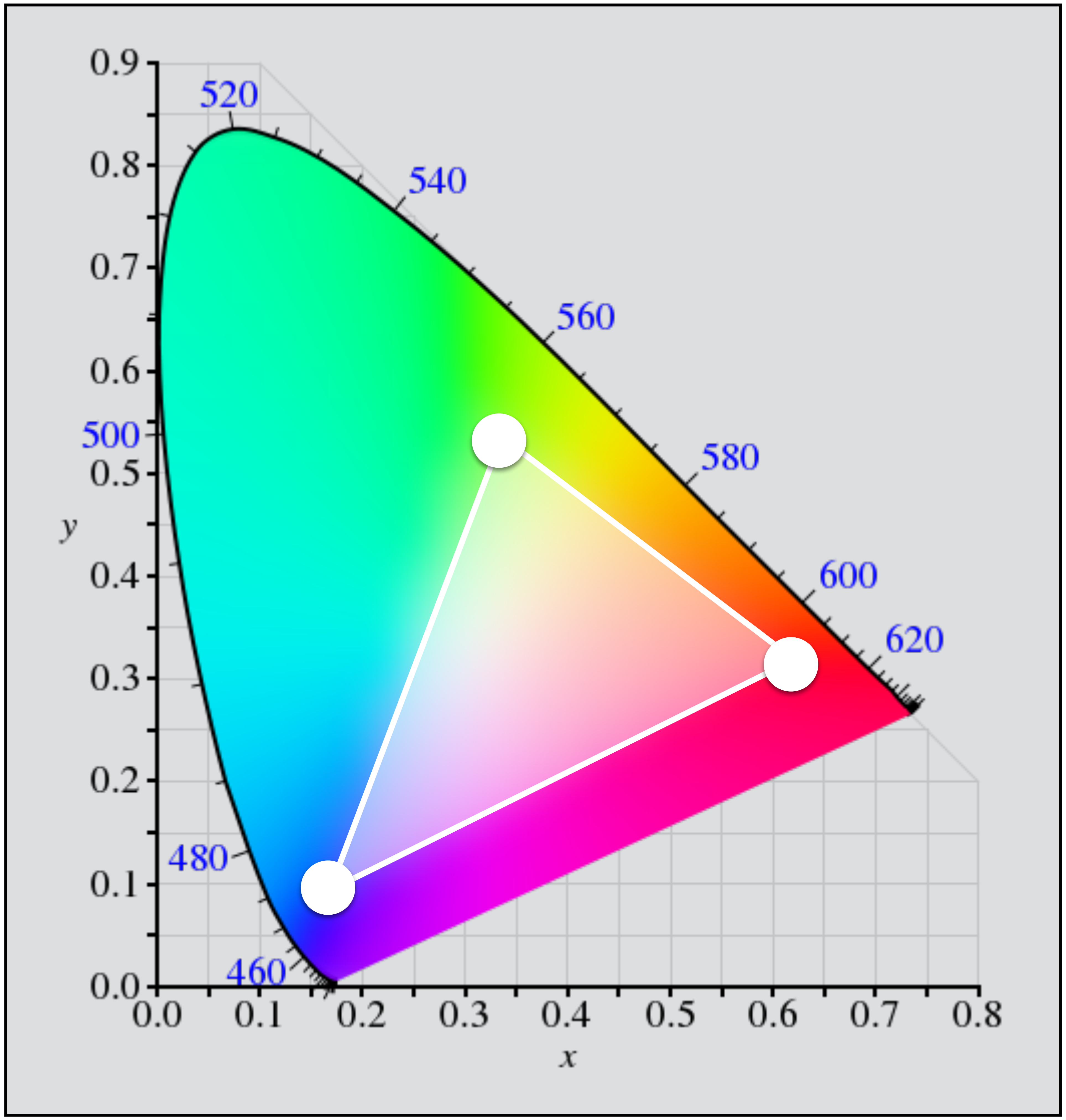
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.9121 & -1.1121 & 0.2019 \\ 0.3709 & 0.6291 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

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

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

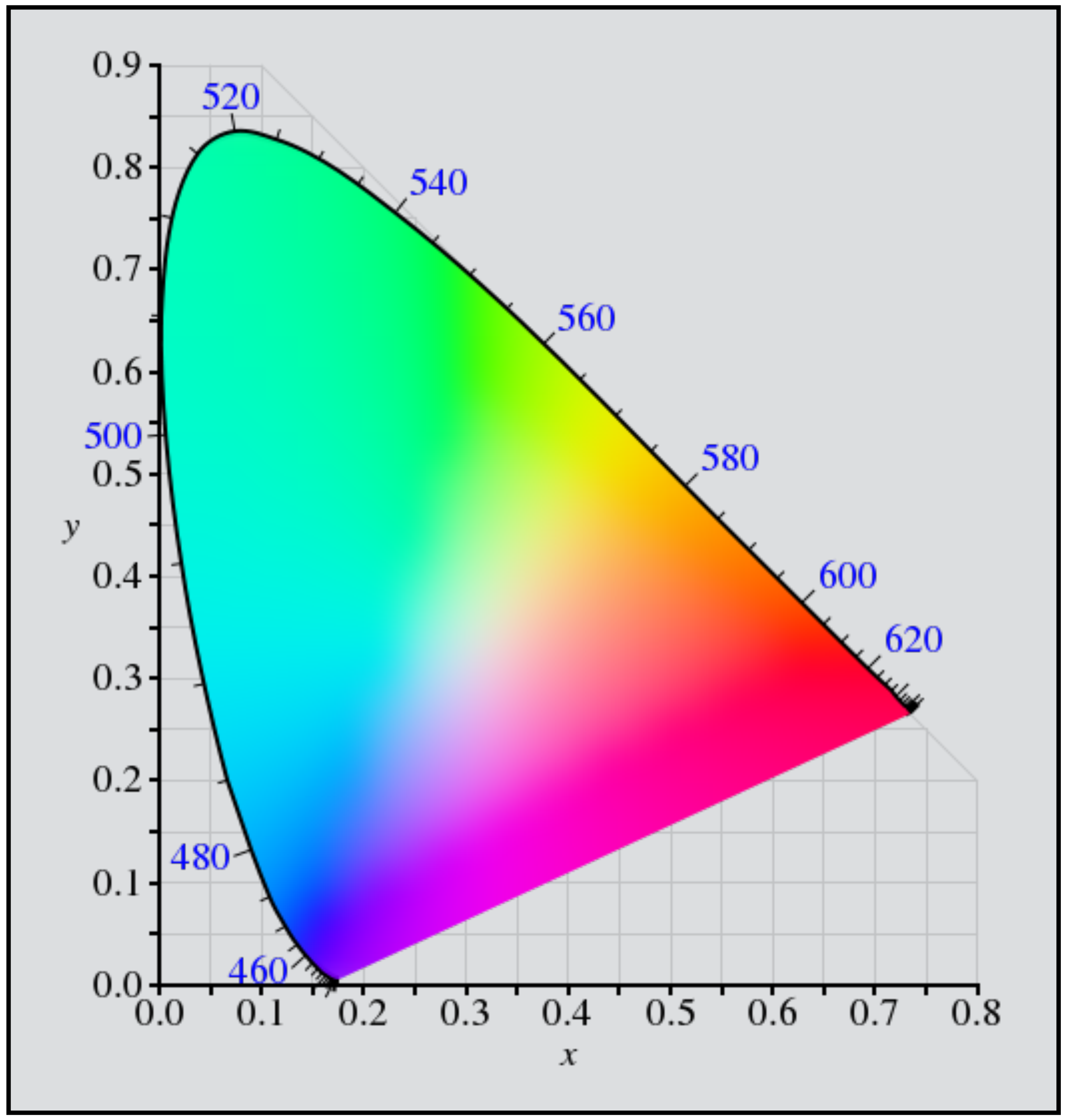
To find a gamut for a display:

- Calculate xy coordinates for emission spectra of red, green, blue pixels
- These are corners of triangle at right



Wikipedia

Chromaticity Diagram (CIE 1931 xy)



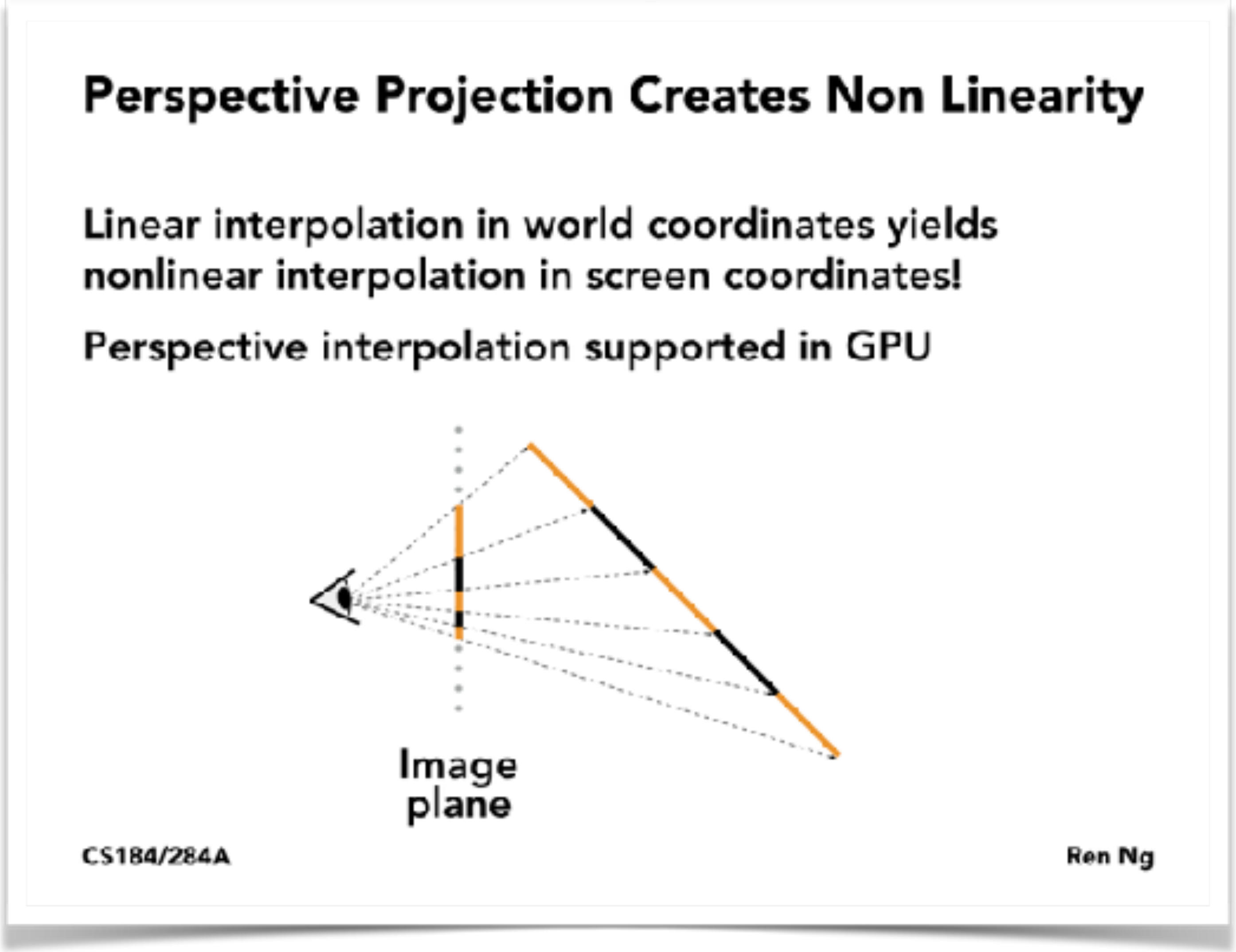
Wikipedia

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.9121 & -1.1121 & 0.2019 \\ 0.3709 & 0.6291 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

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

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

Careful! Non-linearity!



Perspective Projection Creates Non Linearity

Linear interpolation in world coordinates yields nonlinear interpolation in screen coordinates!

Perspective interpolation supported in GPU

CS184/284A

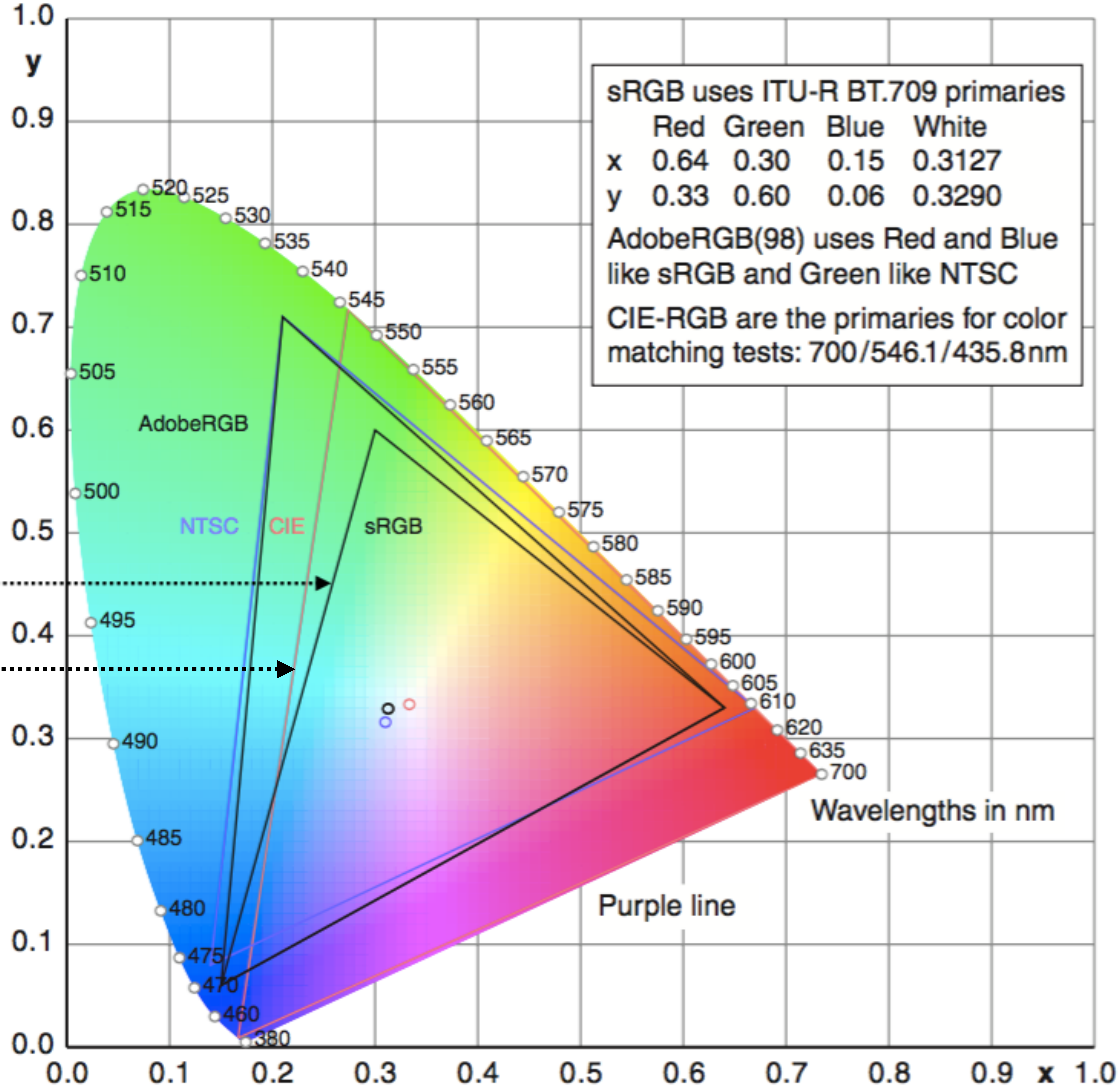
Ren Ng

Note: the xy formulas are a projective transform, similar to perspective projection we studied in Transforms. Recall that after projective transform, we cannot use simple linear (e.g. Barycentric) interpolation. That is, we cannot linearly interpolate colors on the chromaticity diagram.

Color Gamut

sRGB is a common color space used throughout the internet

CIE RGB are the monochromatic primaries used for color matching tests described earlier



sRGB uses ITU-R BT.709 primaries

	Red	Green	Blue	White
x	0.64	0.30	0.15	0.3127
y	0.33	0.60	0.06	0.3290

AdobeRGB(98) uses Red and Blue like sRGB and Green like NTSC

CIE-RGB are the primaries for color matching tests: 700/546.1/435.8nm

Attendance Time

If you are seated in class, go to this form and sign in:

- https://tinyurl.com/184lecture

Notes:

- Time-stamp will be taken when you submit form. Do it now, won't count later.
- Don't tell friends outside class to fill it out now, because we will audit at some point in semester.
- Failing audit will have large negative consequence. You don't need to, because you have an alternative!

Color Representation

Color Spaces

Need three numbers to specify a color

- but what three numbers?
- a color space is an answer to this question

Common example: display color space

- define colors by what R, G, B scalar values will produce them on your monitor
  - (in math, s = rR + gG + bB for some spectra r, g, b)
- device dependent (depends on gamma, phosphors, gains, …)
  - therefore if I choose R,G,B by looking at my display and send it to you, you may not see the same color
- also leaves out some colors (limited gamut), e.g. vivid yellow

Standard Color Spaces

Standardized RGB (sRGB)

- makes a particular monitor RGB standard
- other color devices simulate that monitor by calibration
- sRGB is usable as an interchange space; widely adopted today
- gamut is still limited

A Common Historical Color Space: CIE XYZ

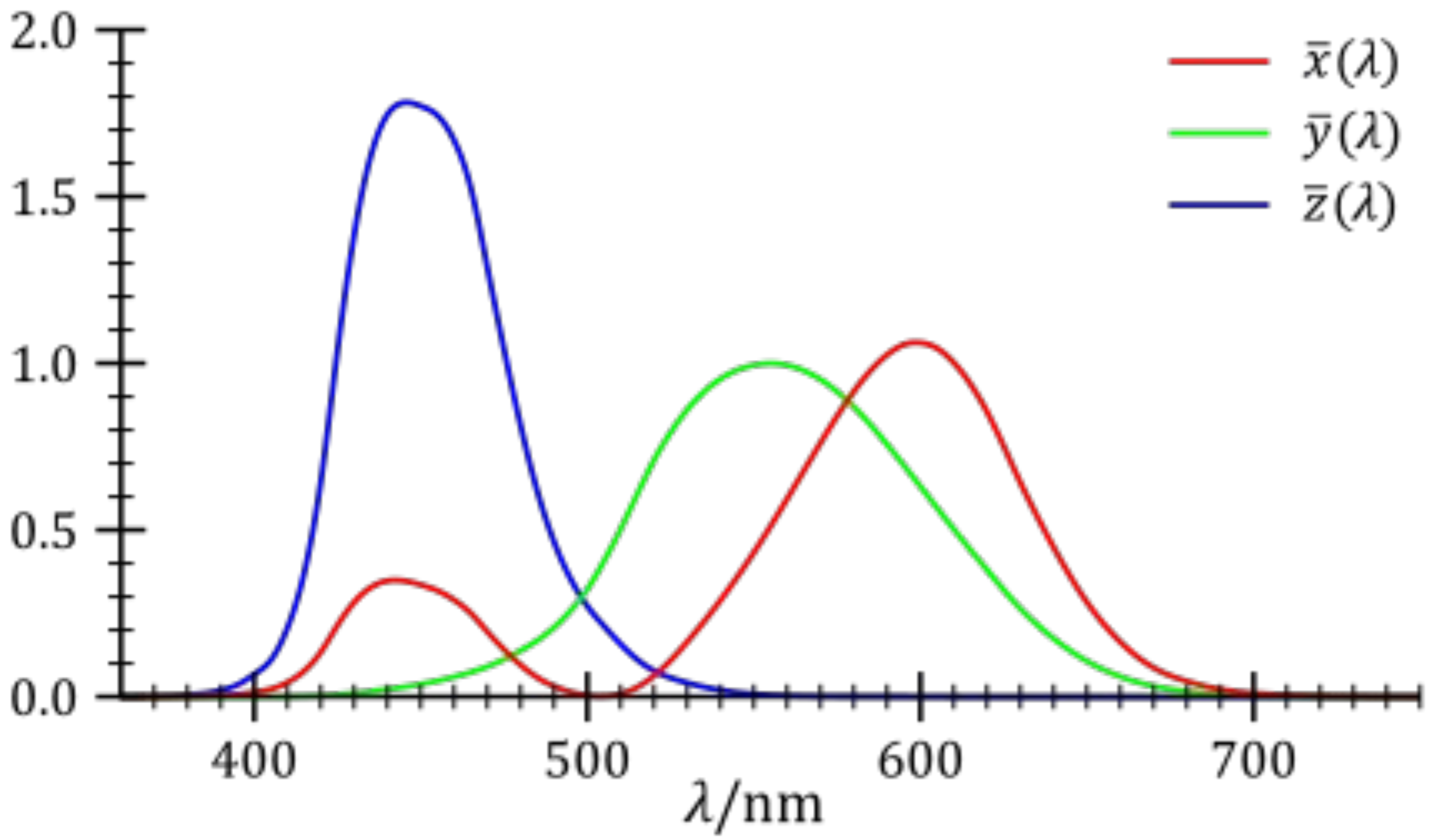
Imaginary set of standard color primaries X, Y, Z

Designed such that

- X, Y, Z span all observable colors
- Matching functions are strictly positive
- Y is luminance (brightness absent color)

Imaginary because can only be realized with primaries that are negative at some wavelengths

CIE XYZ color matching functions

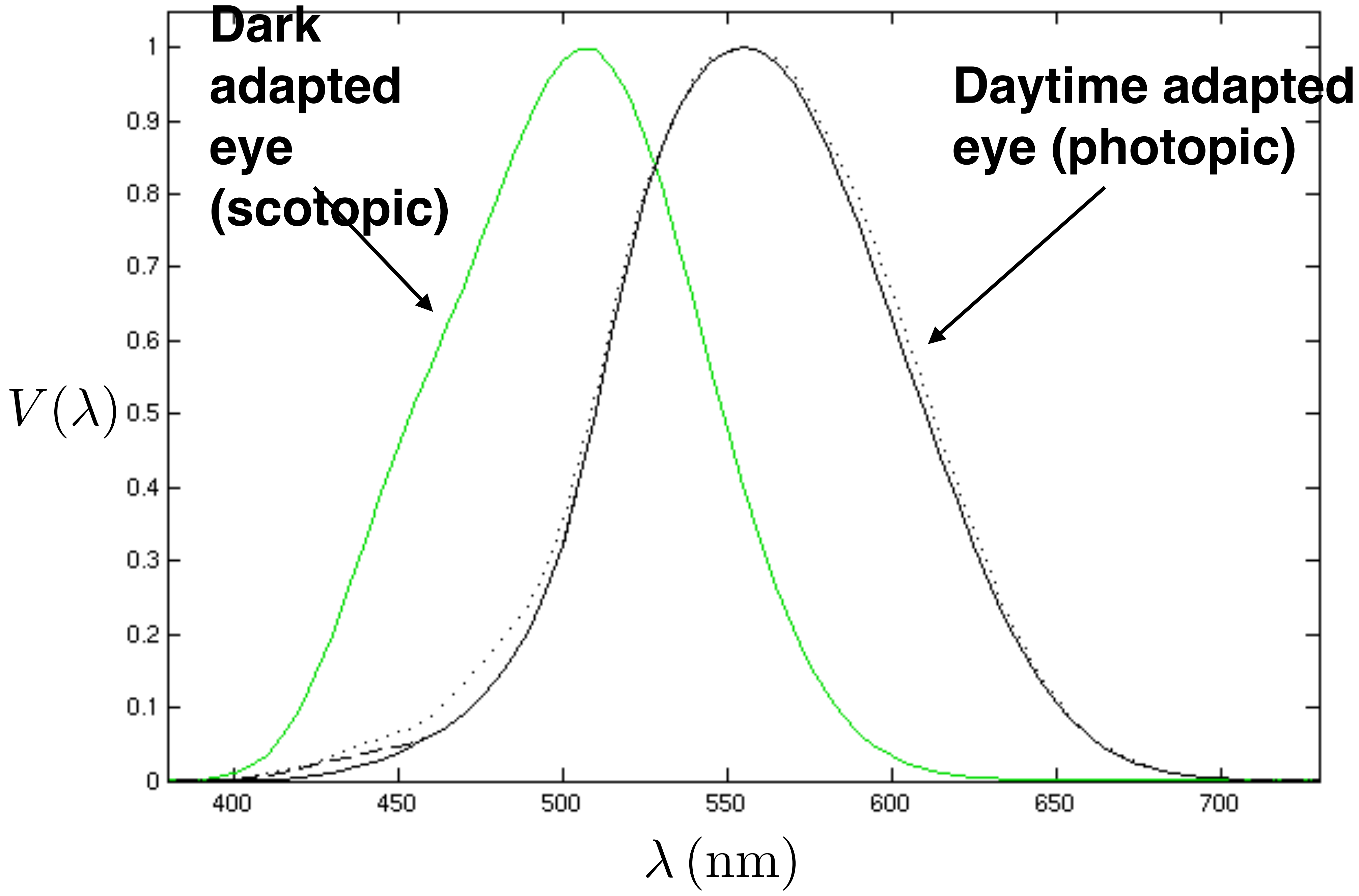


Luminance (Lightness)

Integral of radiance scaled by the visual luminous efficiency

$$Y = \int \Phi(\lambda)\, V(\lambda)\, \mathrm{d}\lambda$$

Luminous efficiency $V(\lambda)$ is a measure of how bright a light at a given wavelength is perceived by a human



https://upload.wikimedia.org/wikipedia/commons/a/a0/Luminosity.png

Separating Luminance, Chromaticity

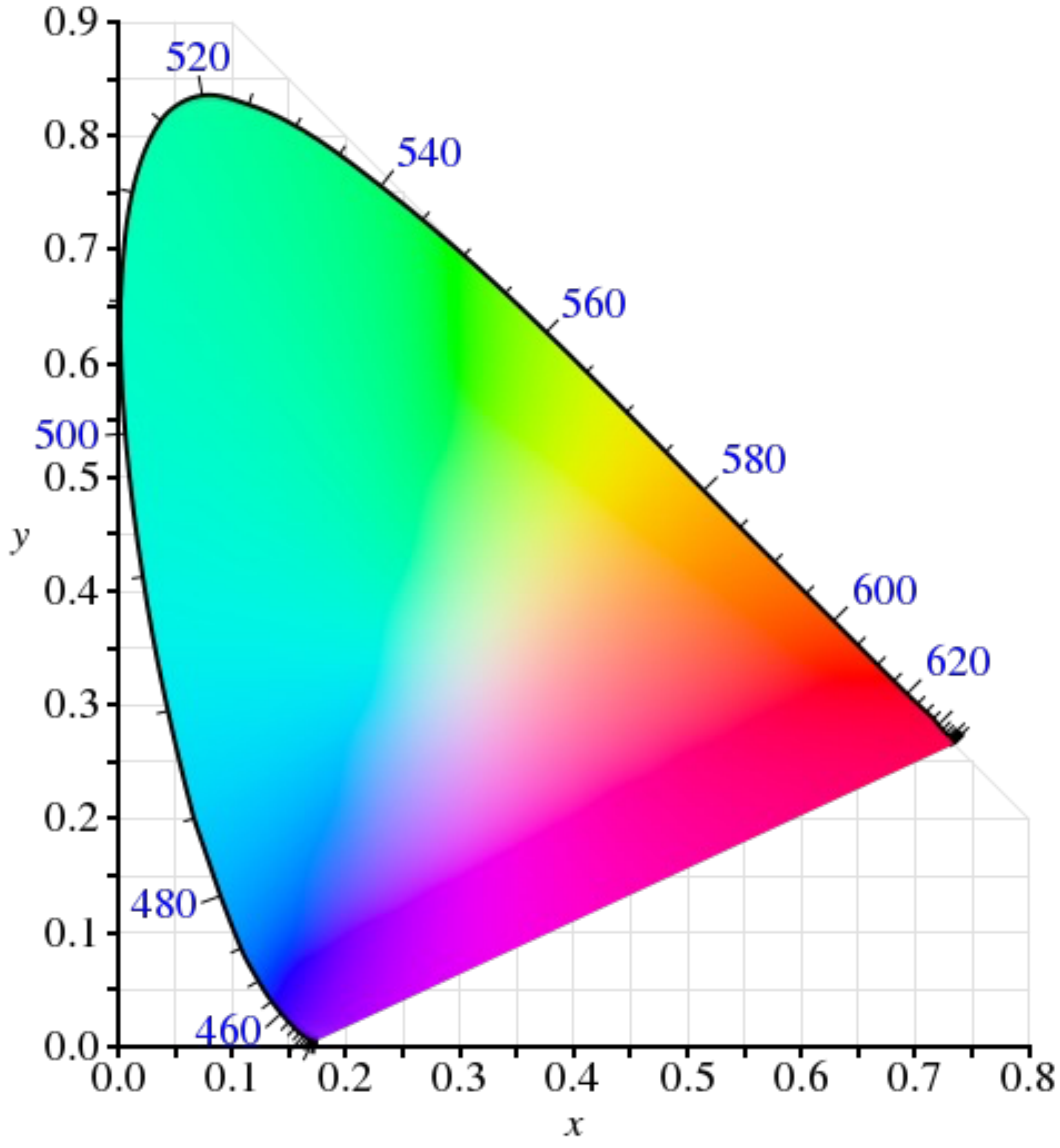
Luminance: *Y*

Chromaticity: *x, y, z,* defined as

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

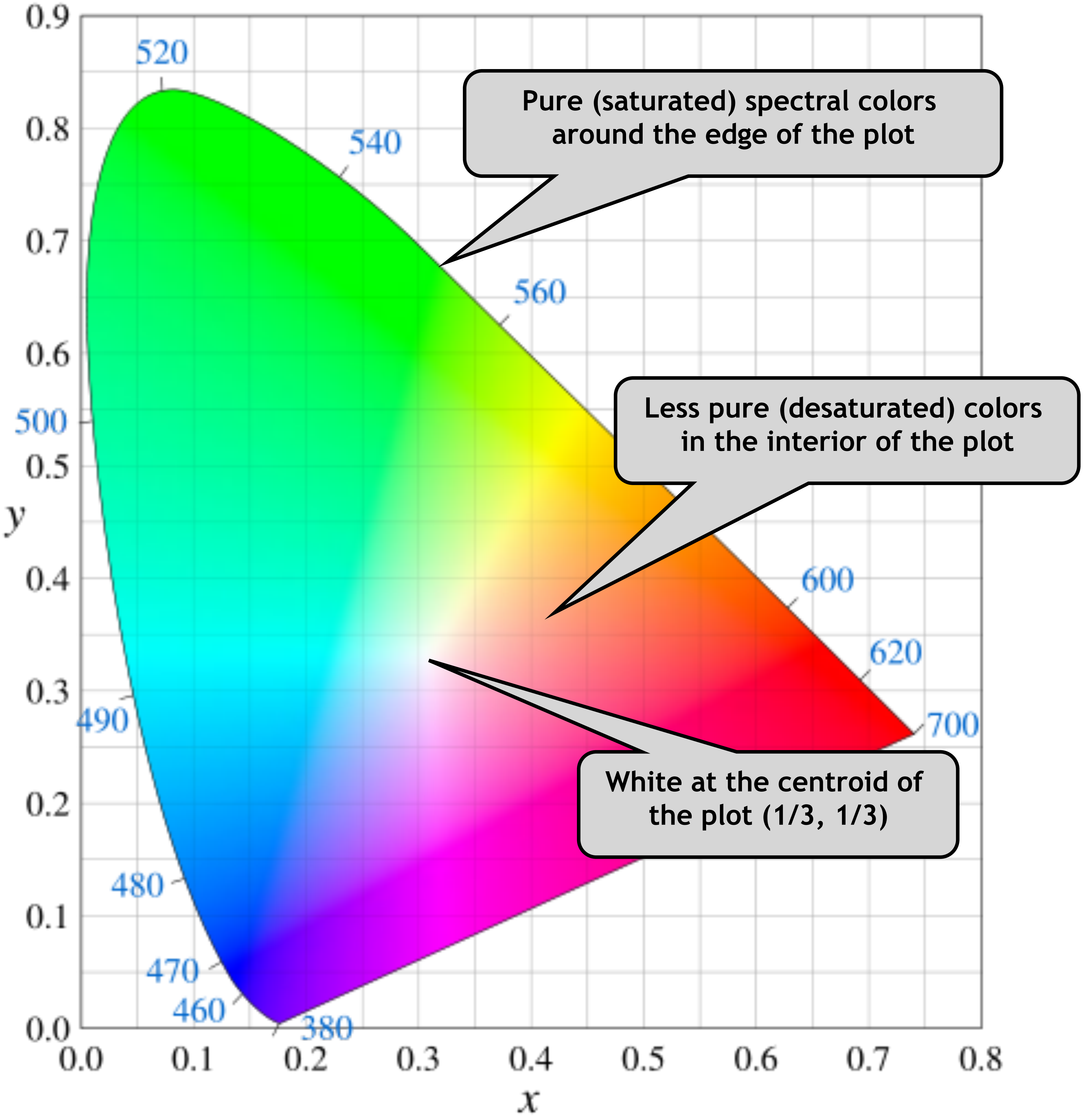
$$y = \frac{Y}{X+Y+Z}$$

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



- since *x* + *y* + *z* = 1, we only need to record two of the three
  - usually choose *x* and *y*, leading to (*x, y, Y*) coords

CIE Chromaticity Diagram



Pure (saturated) spectral colors around the edge of the plot

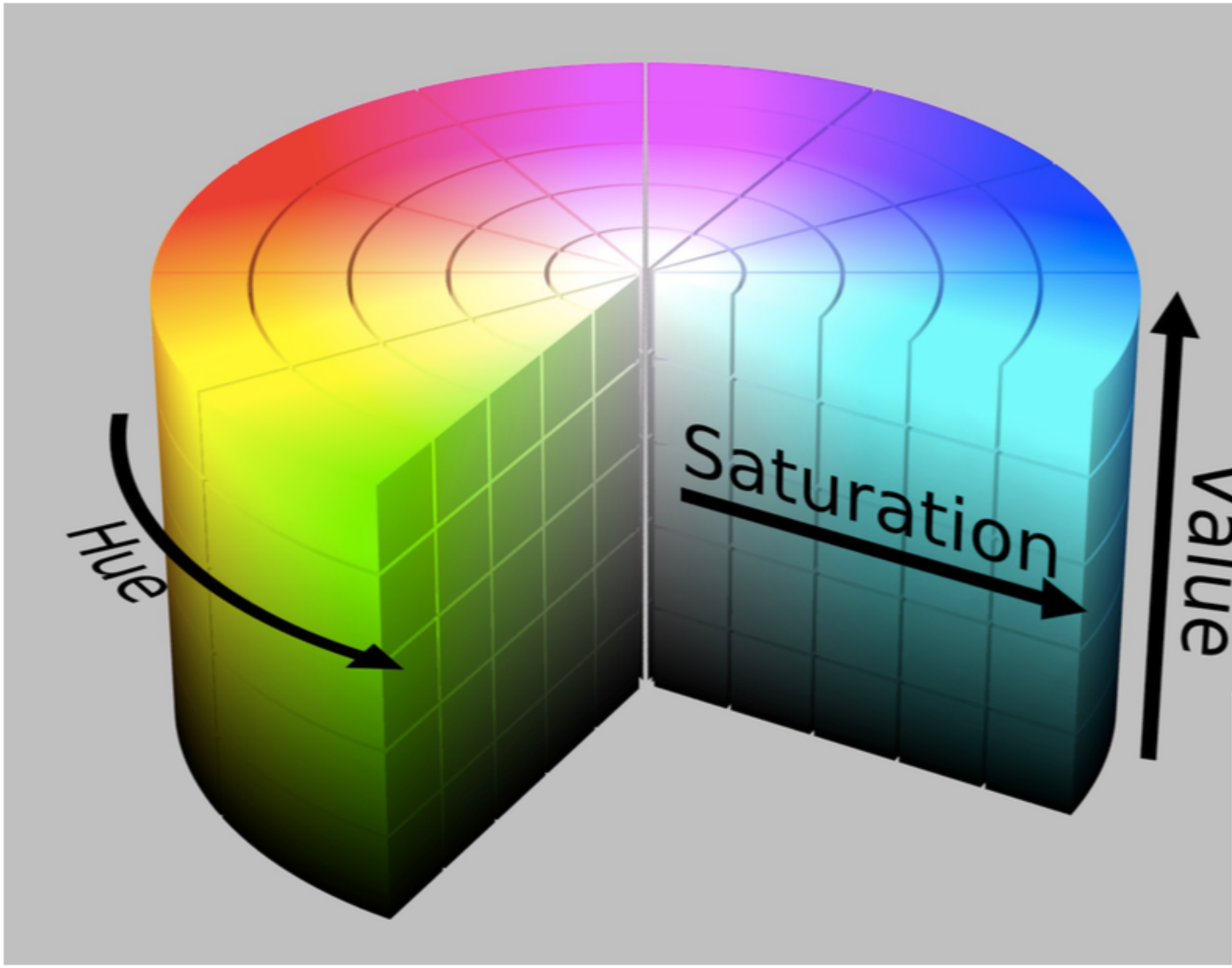
Less pure (desaturated) colors in the interior of the plot

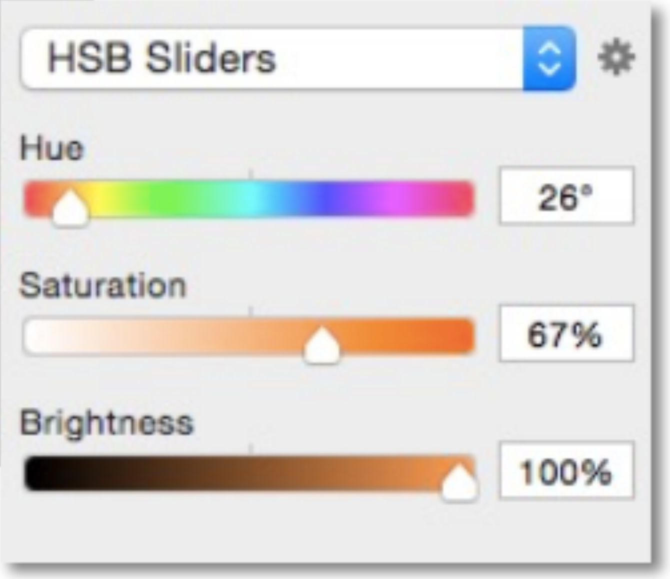
White at the centroid of the plot (1/3, 1/3)

Perceptually Organized Color Spaces

HSV Color Space (Hue-Saturation-Value)

Axes correspond to artistic characteristics of color



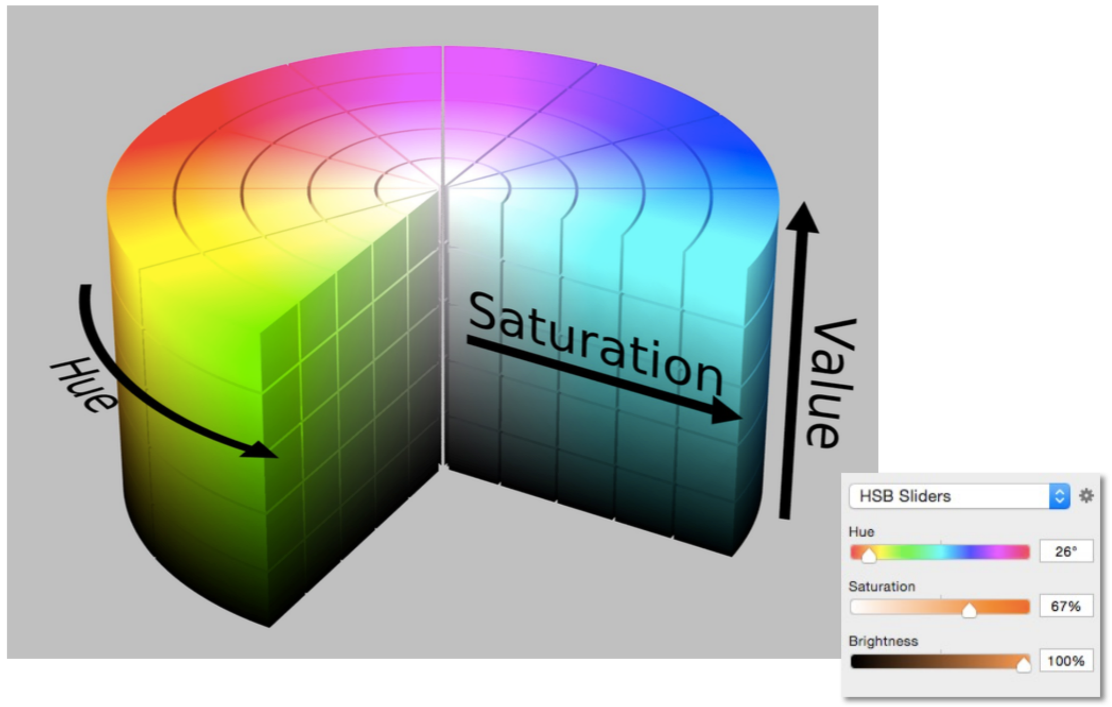

HSB Sliders

Hue 26°

Saturation 67%

Brightness 100%

Perceptual Dimensions of Color



Hue 26°

Saturation 67%

Brightness 100%

Hue

- the "kind" of color, regardless of attributes
- colorimetric correlate: dominant wavelength
- artist's correlate: the chosen pigment color

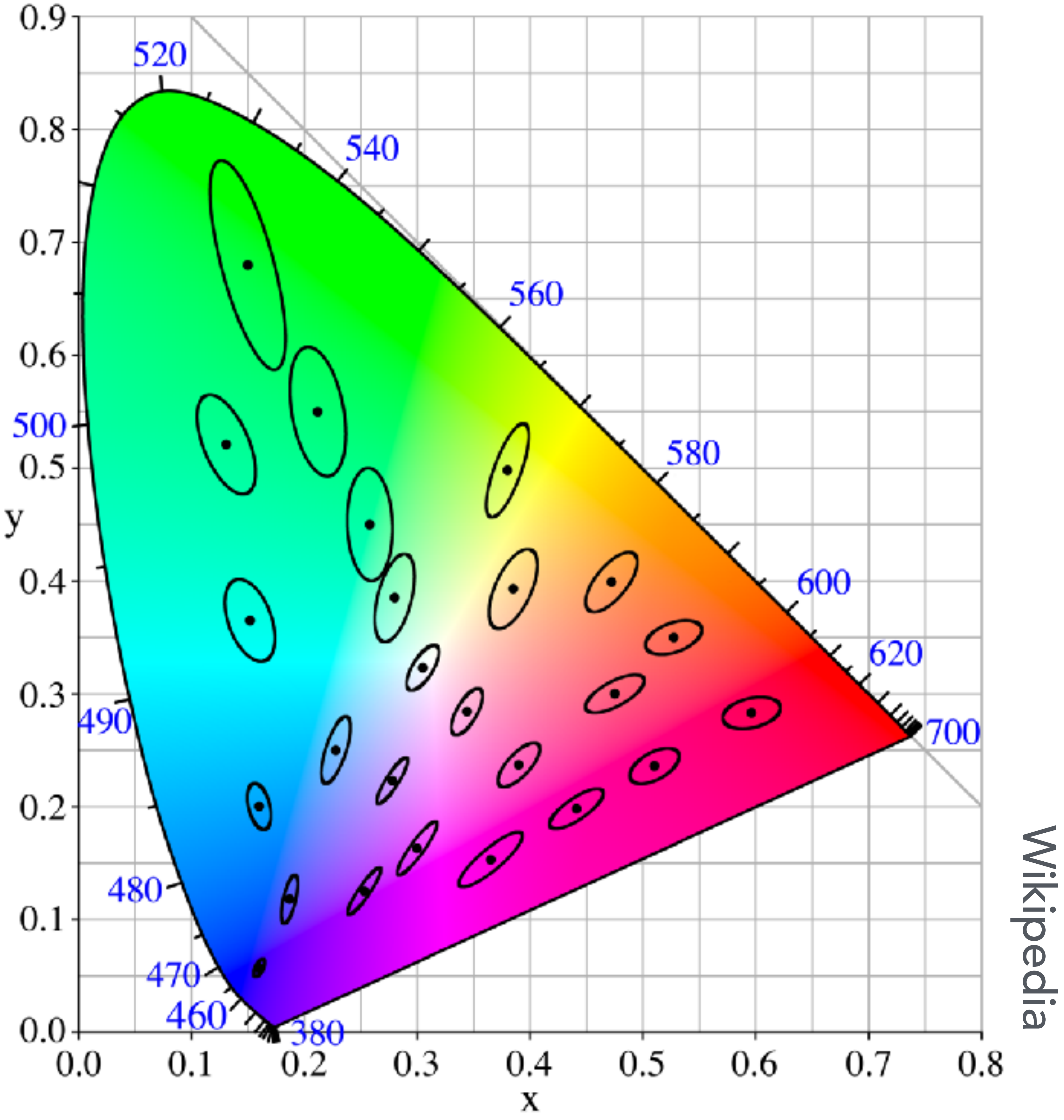
Saturation

- the "colorfulness"
- colorimetric correlate: purity
- artist's correlate: fraction of paint from the colored tube

Lightness (or value)

- the overall amount of light
- colorimetric correlate: luminance
- artist's correlate: tints are lighter, shades are darker

Perceptual Non-Uniformity

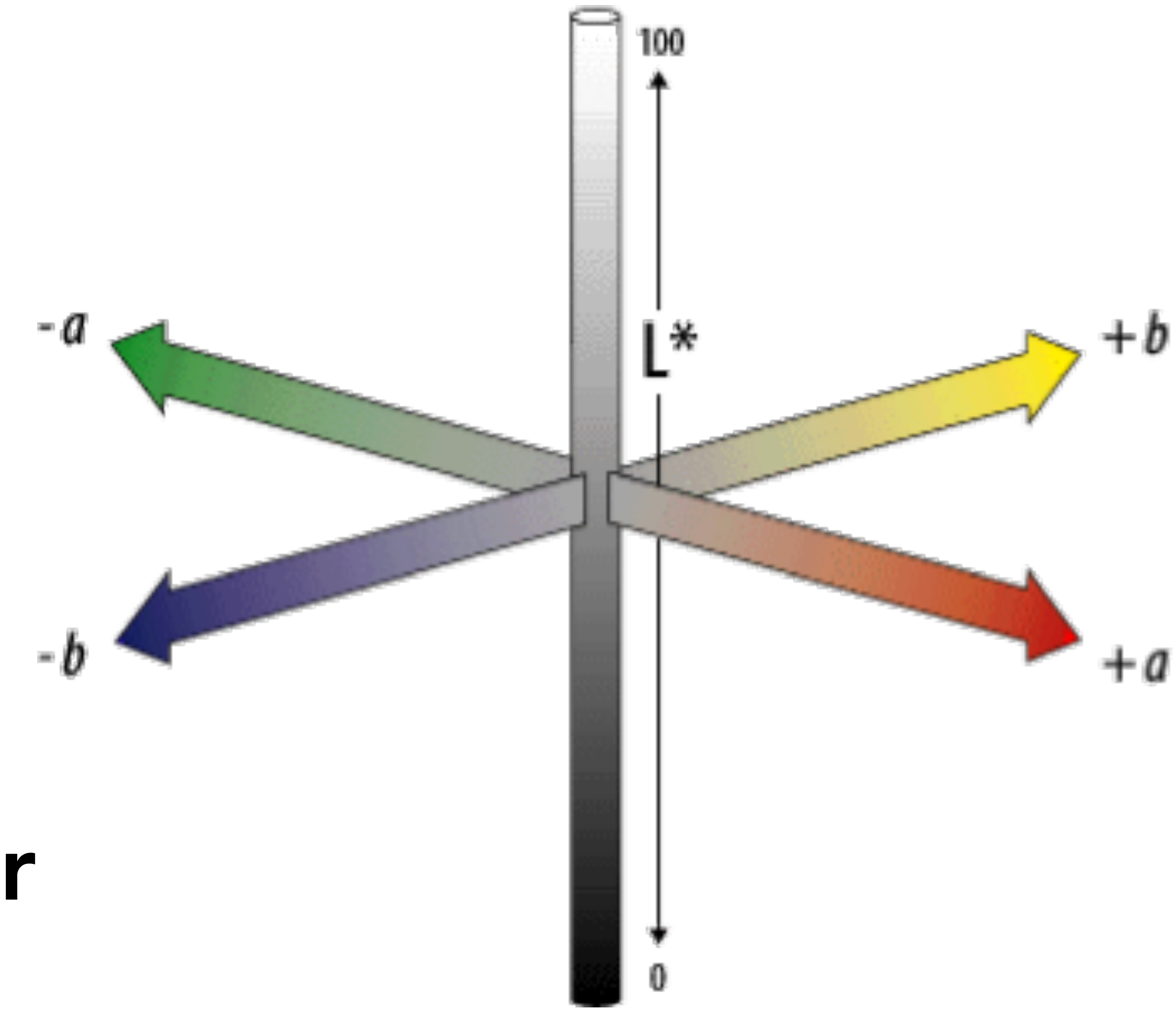


- In the xy chromaticity diagram at left, MacAdam ellipses show regions of perceptually equivalent color (ellipses enlarged 10x)
- Must non-linearly warp the diagram to achieve uniform perceptual distances

CIELAB Space (AKA L*a*b*)

A commonly used color space that strives for perceptual uniformity

- L* is lightness
- a* and b* are color-opponent pairs
    - a* is red-green, and b* is blue-yellow
- A gamma transform is used for warping because perceived brightness is proportional to scene intensity$^\gamma$, where $\gamma \approx 1/3$



Opponent Color Theory

There is some neurological basis for the color space dimensions in CIE LAB

- the brain seems to encode color early on using three axes:
  - white — black, red — green, yellow — blue
- the white — black axis is lightness; the others determine hue and saturation
- one piece of evidence: you can have a light green, a dark green, a yellow-green, or a blue-green, but you can't have a reddish green (just doesn't make sense)
  - thus red is the *opponent* to green
- another piece of evidence: afterimages (following slides)

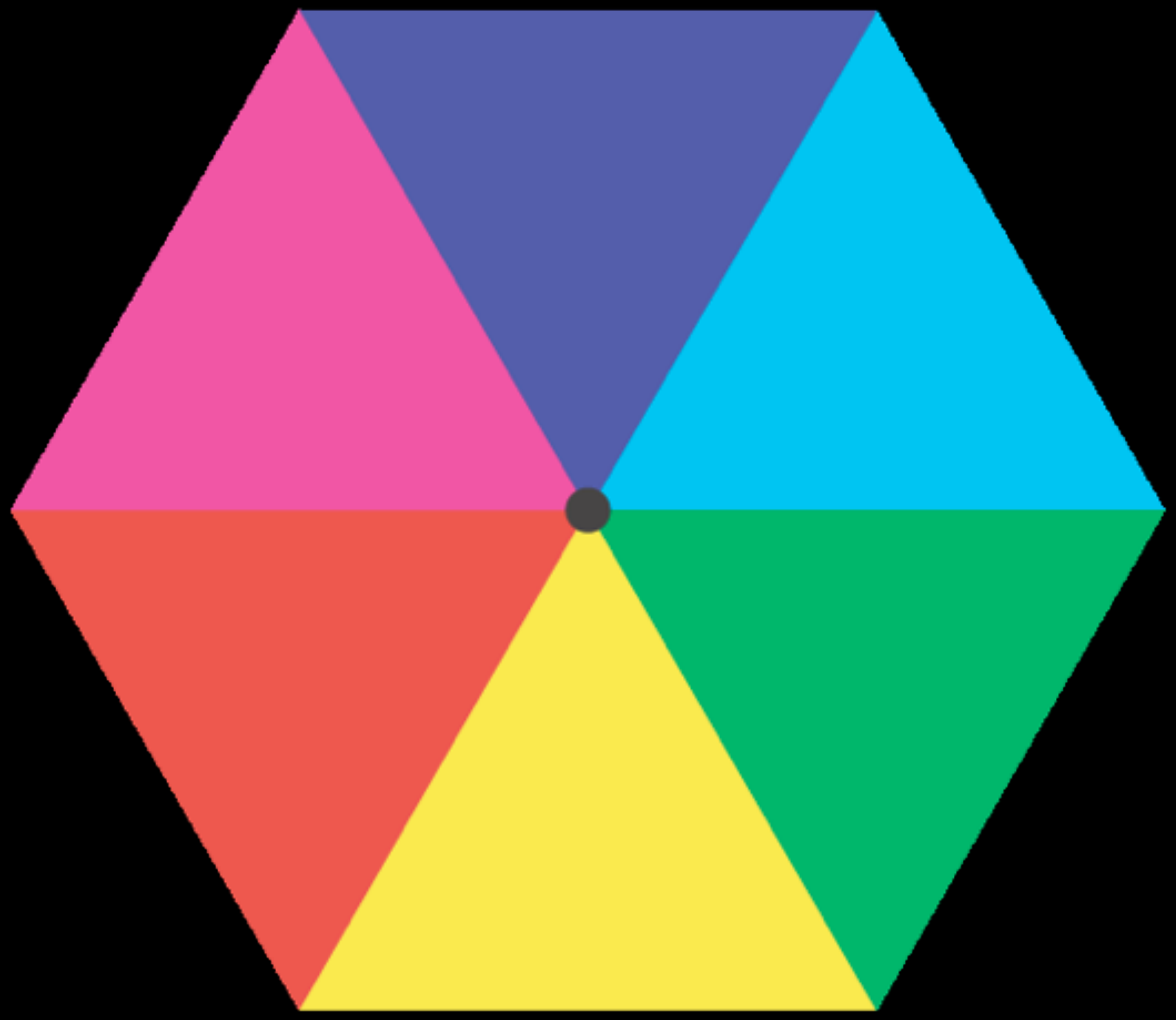
slide credit: Steve Marschner


TOTH^{3}

keep staring at the black dot.

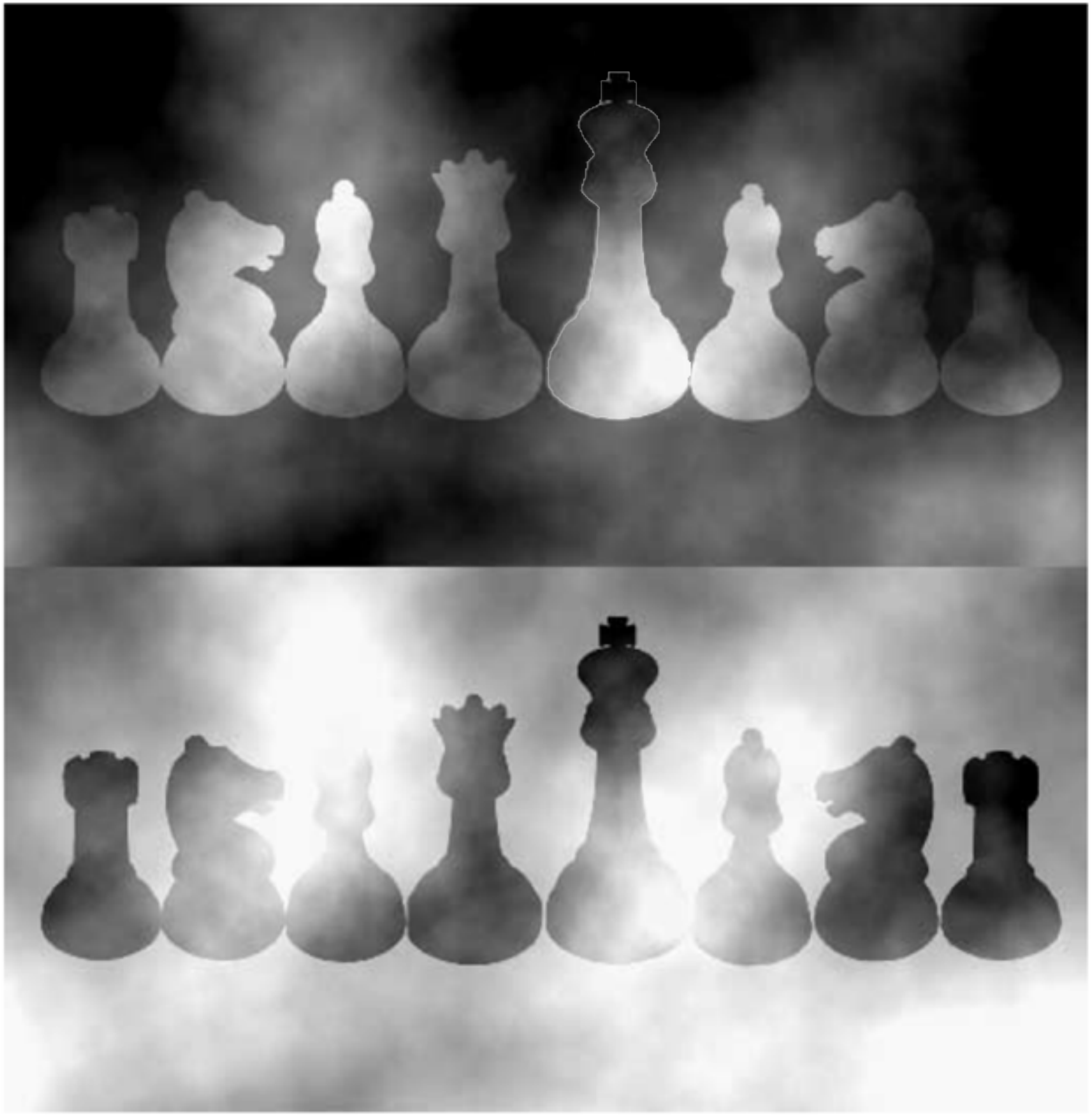

johnsadowski.com

Image

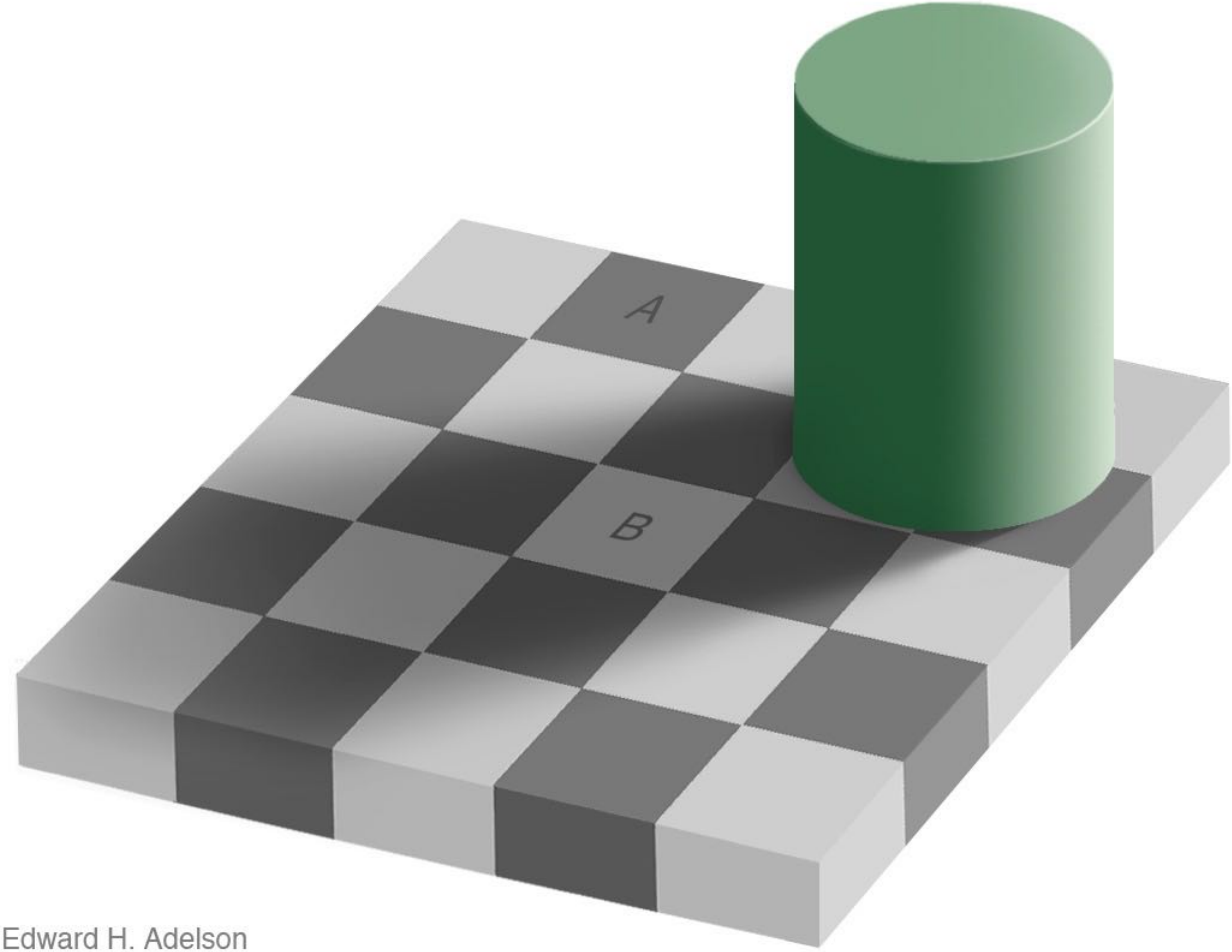


Afterimage

Even simple judgments – such as lightness - depend on brain processing (Anderson and Winawer, Nature, 2005)

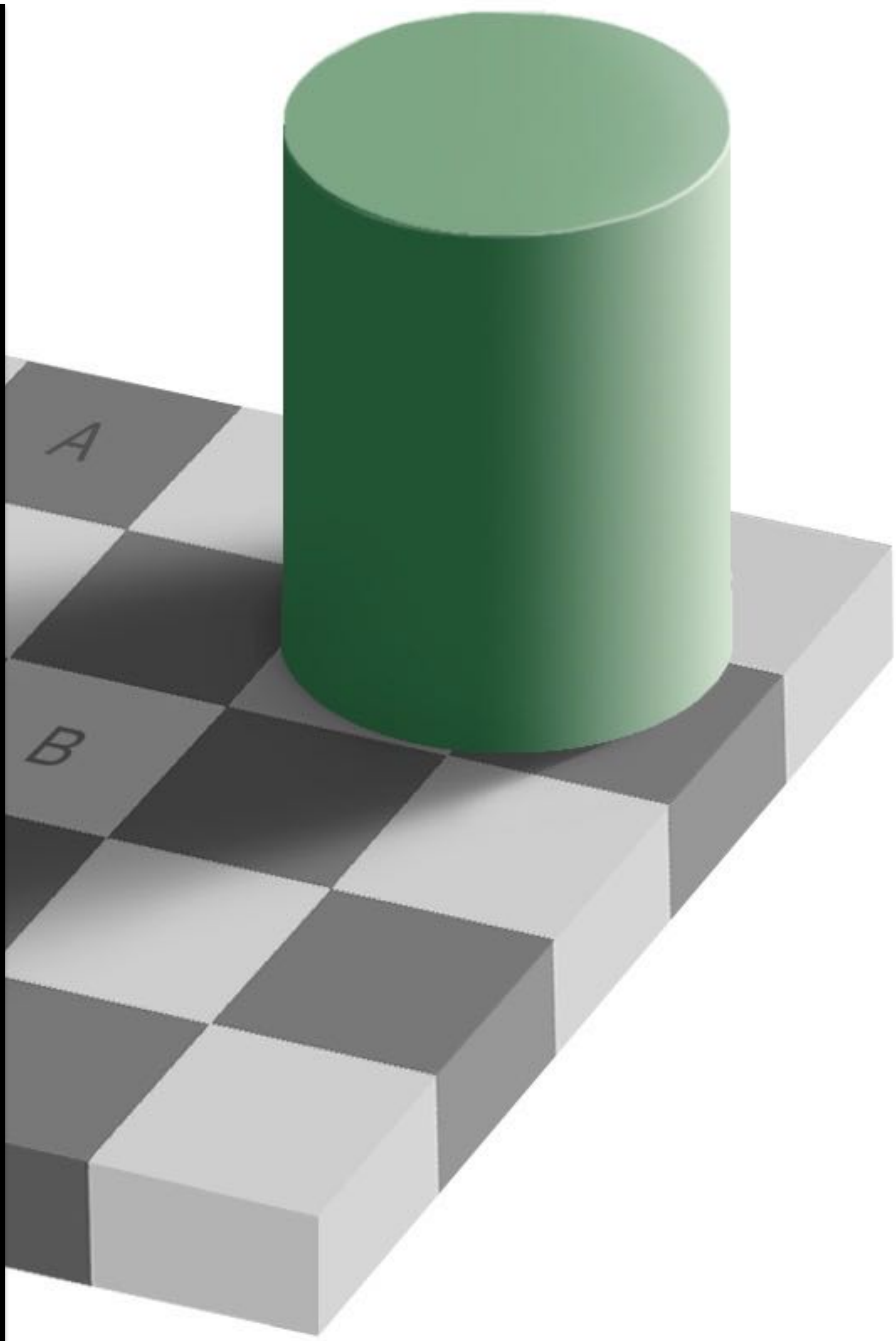


Everything is Relative



Edward H. Adelson

Everything is Relative



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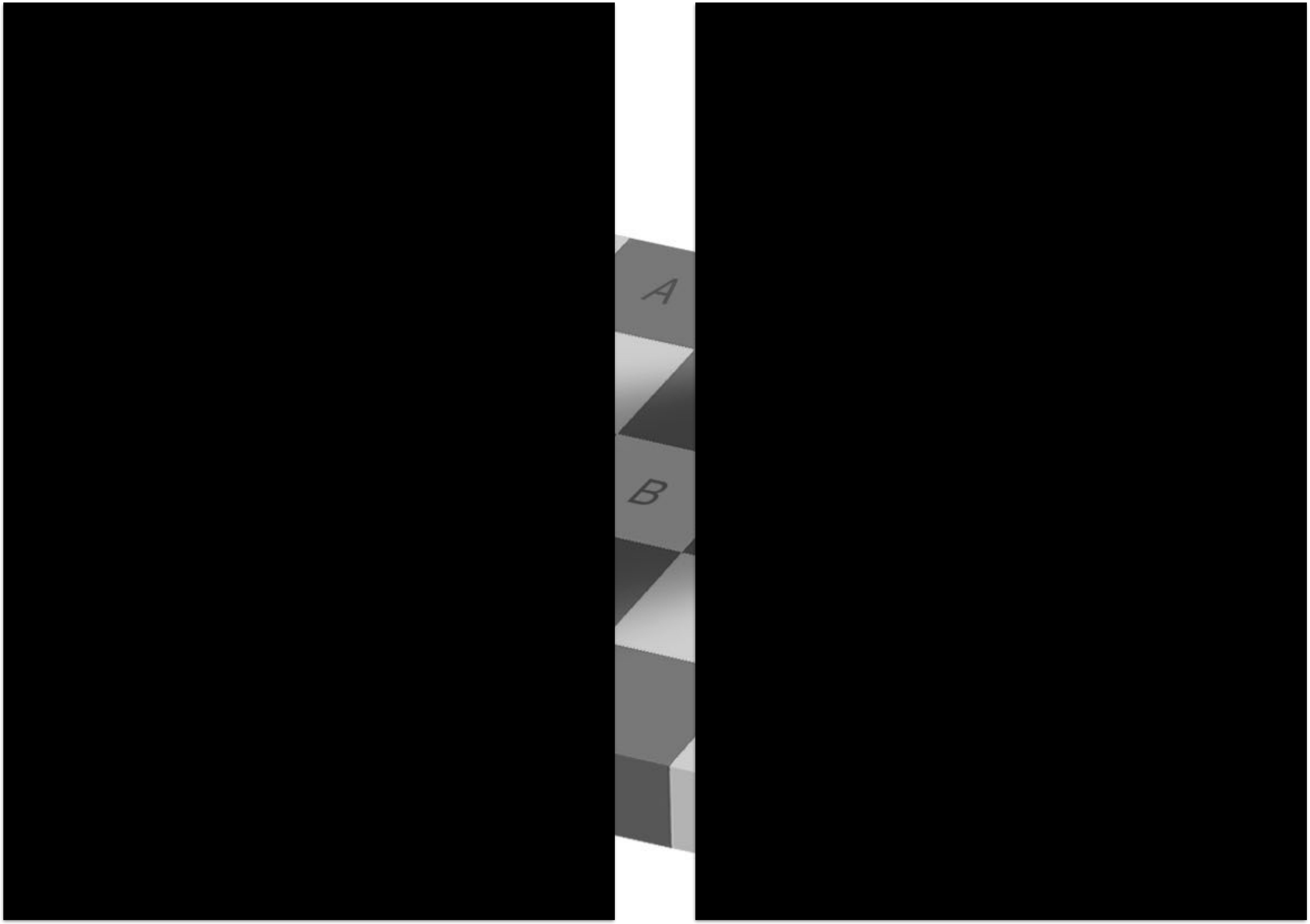

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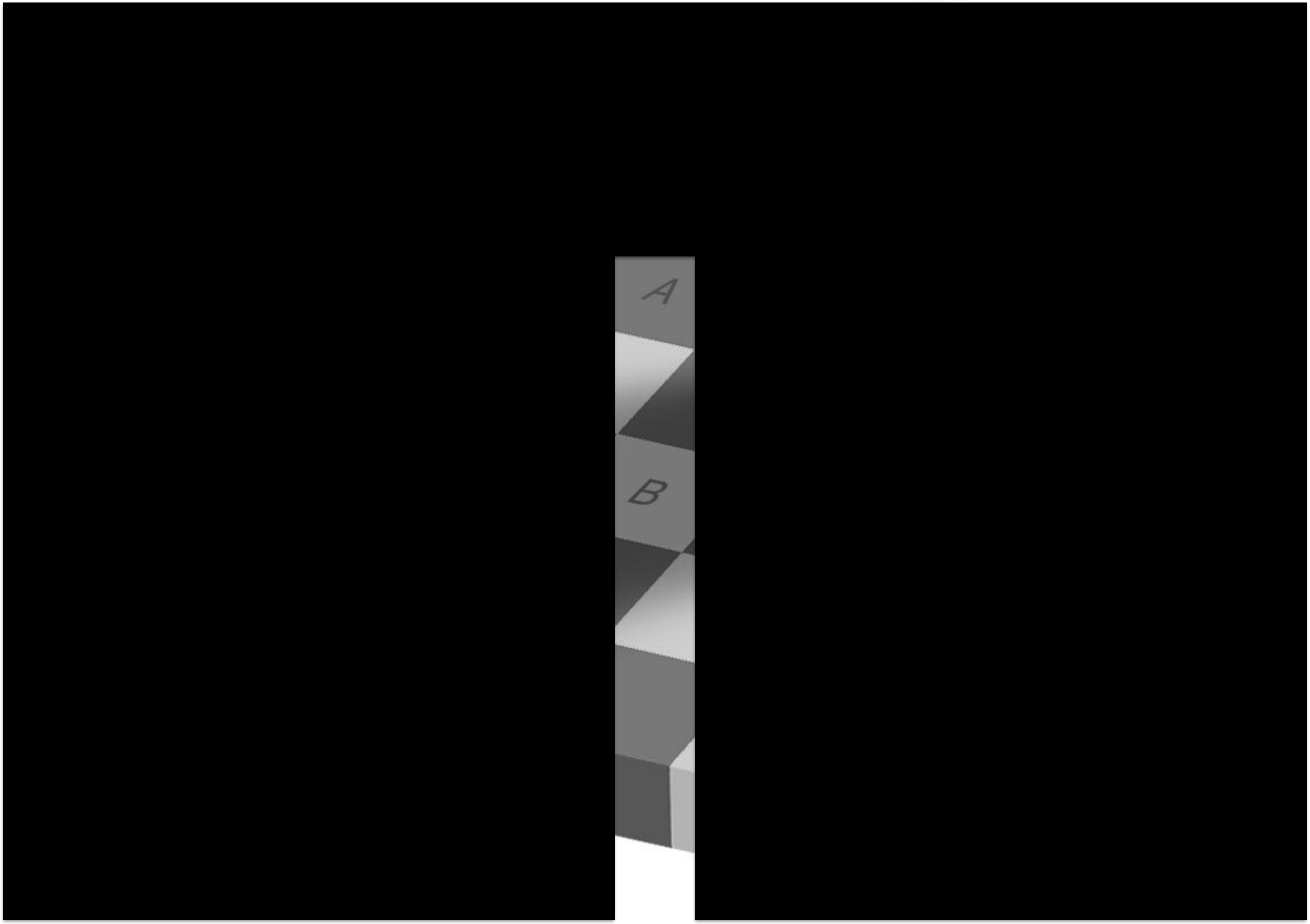

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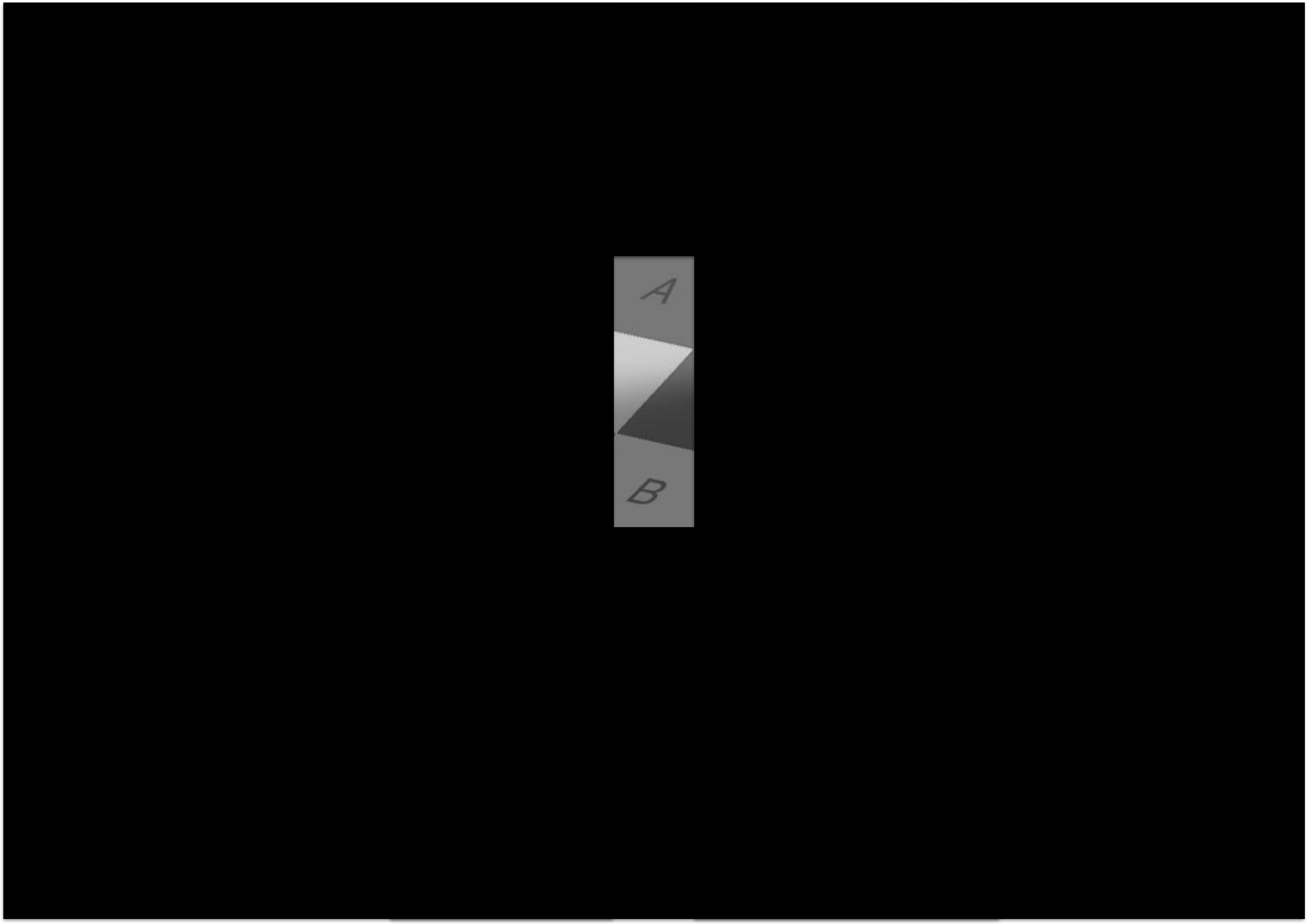

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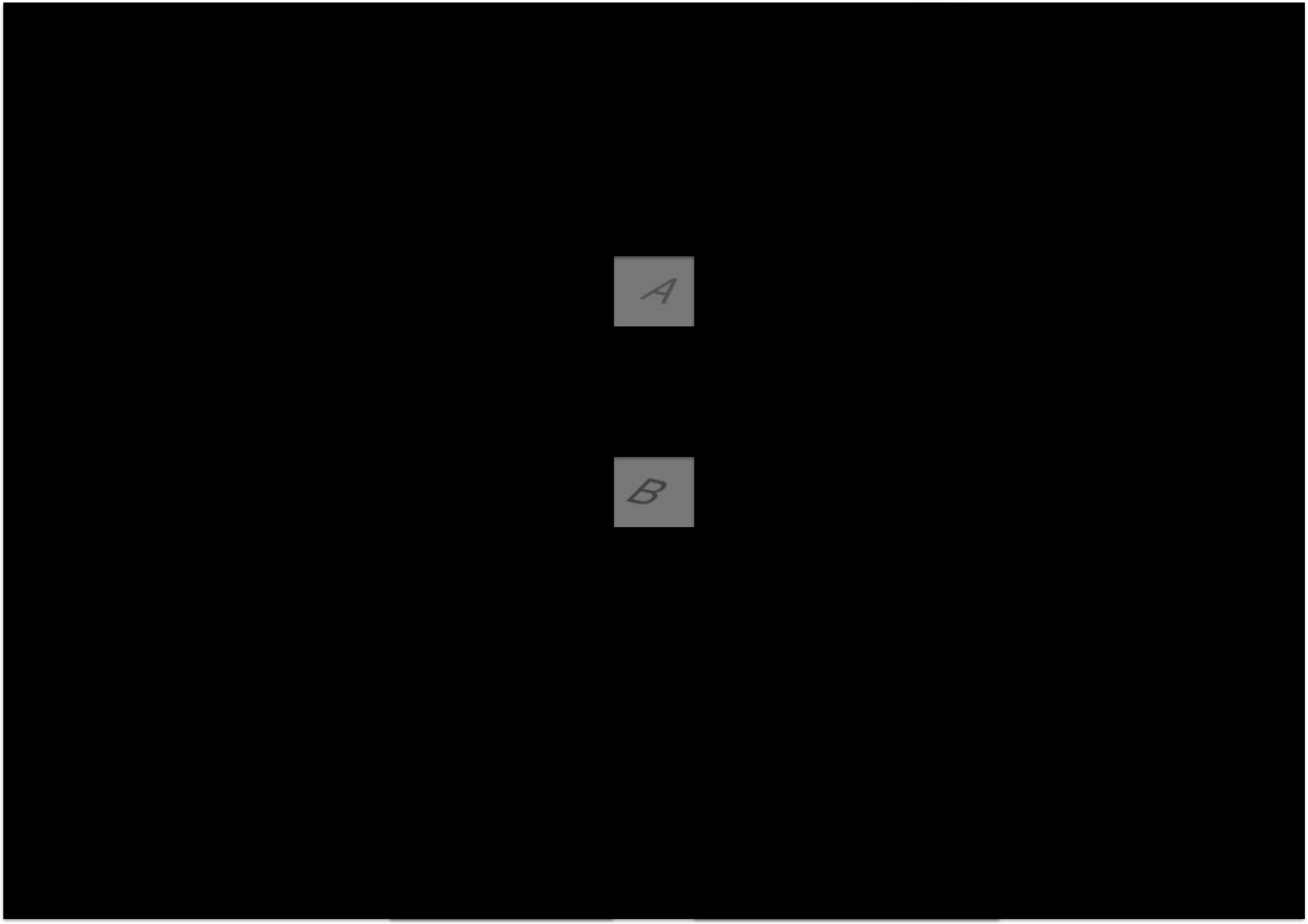

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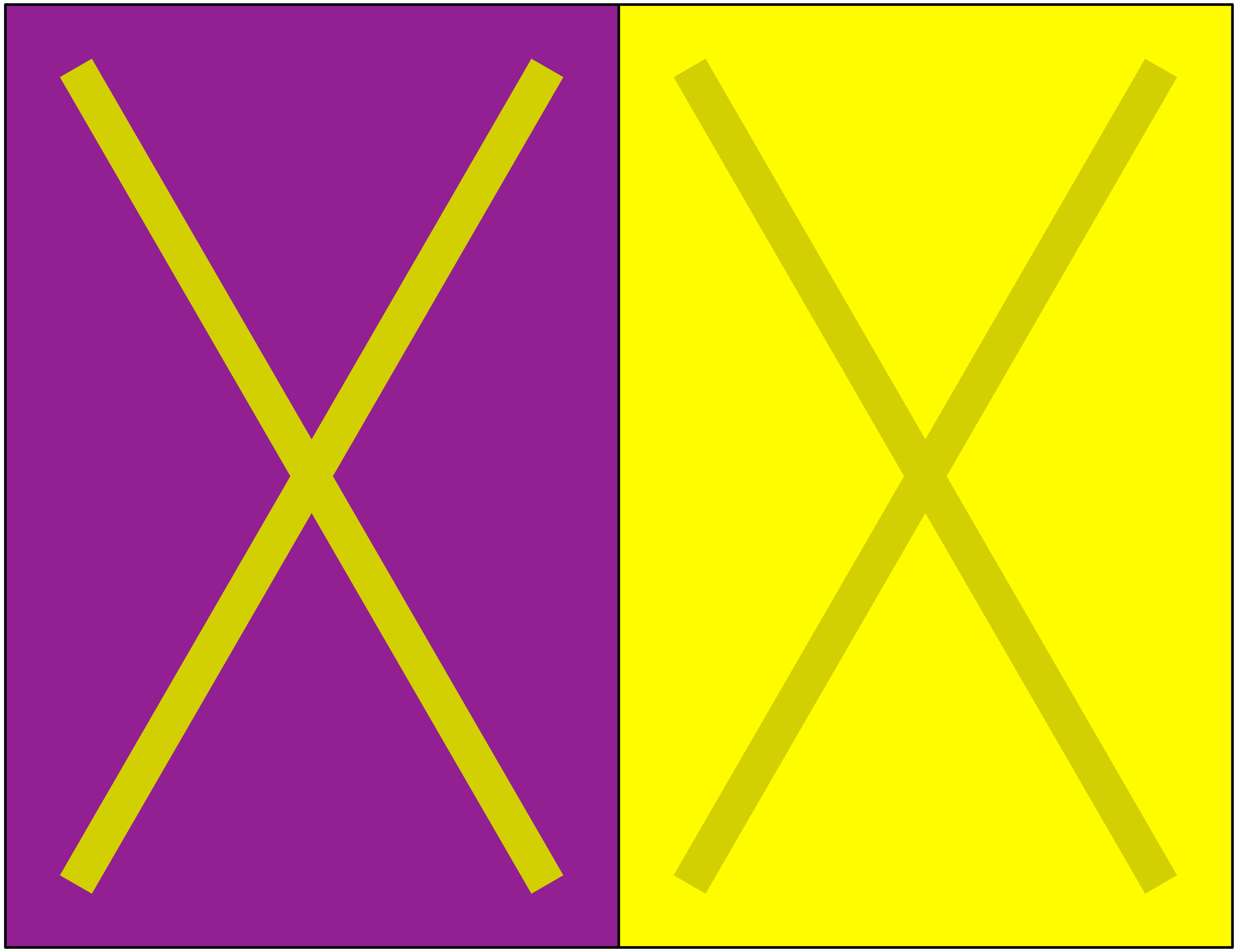
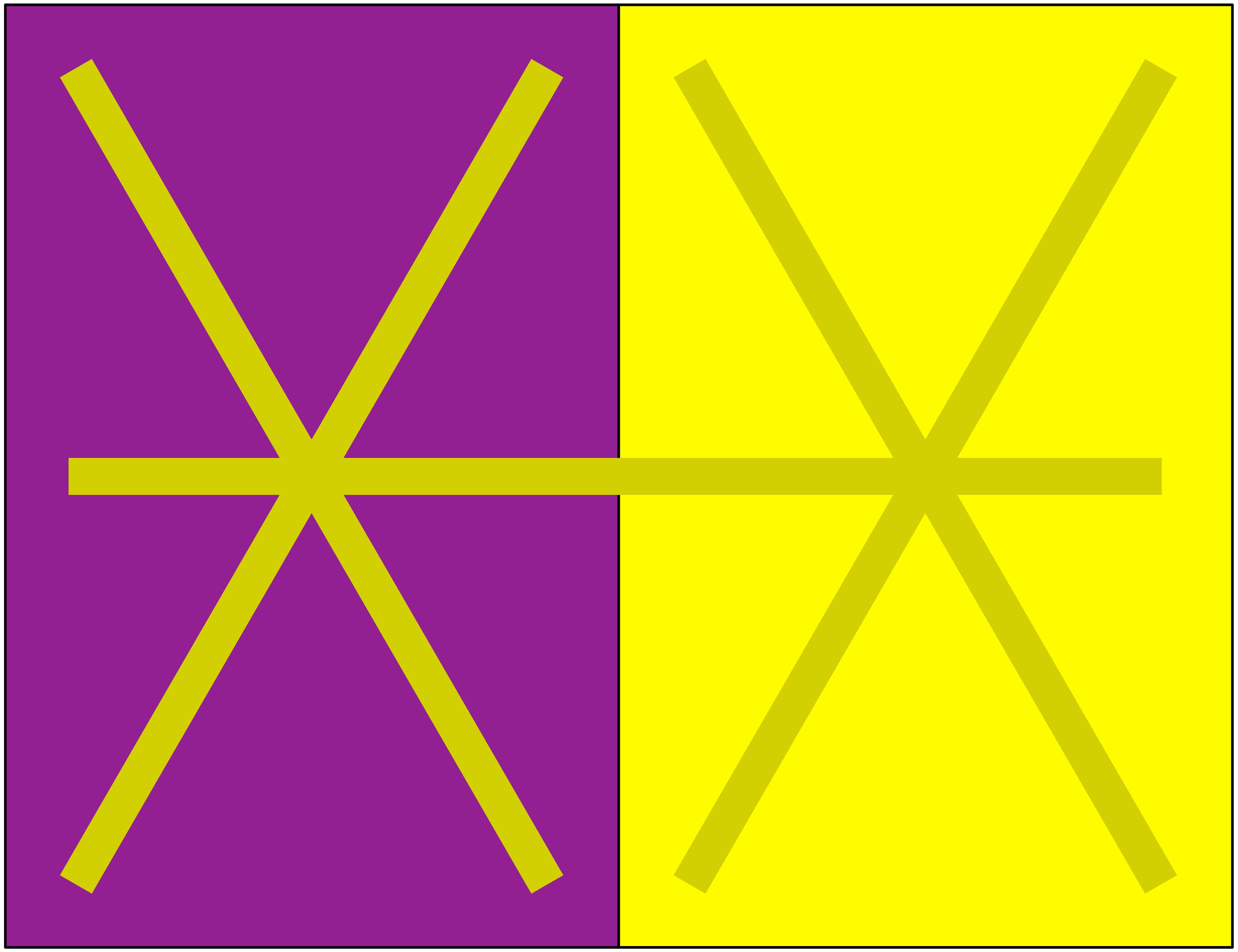
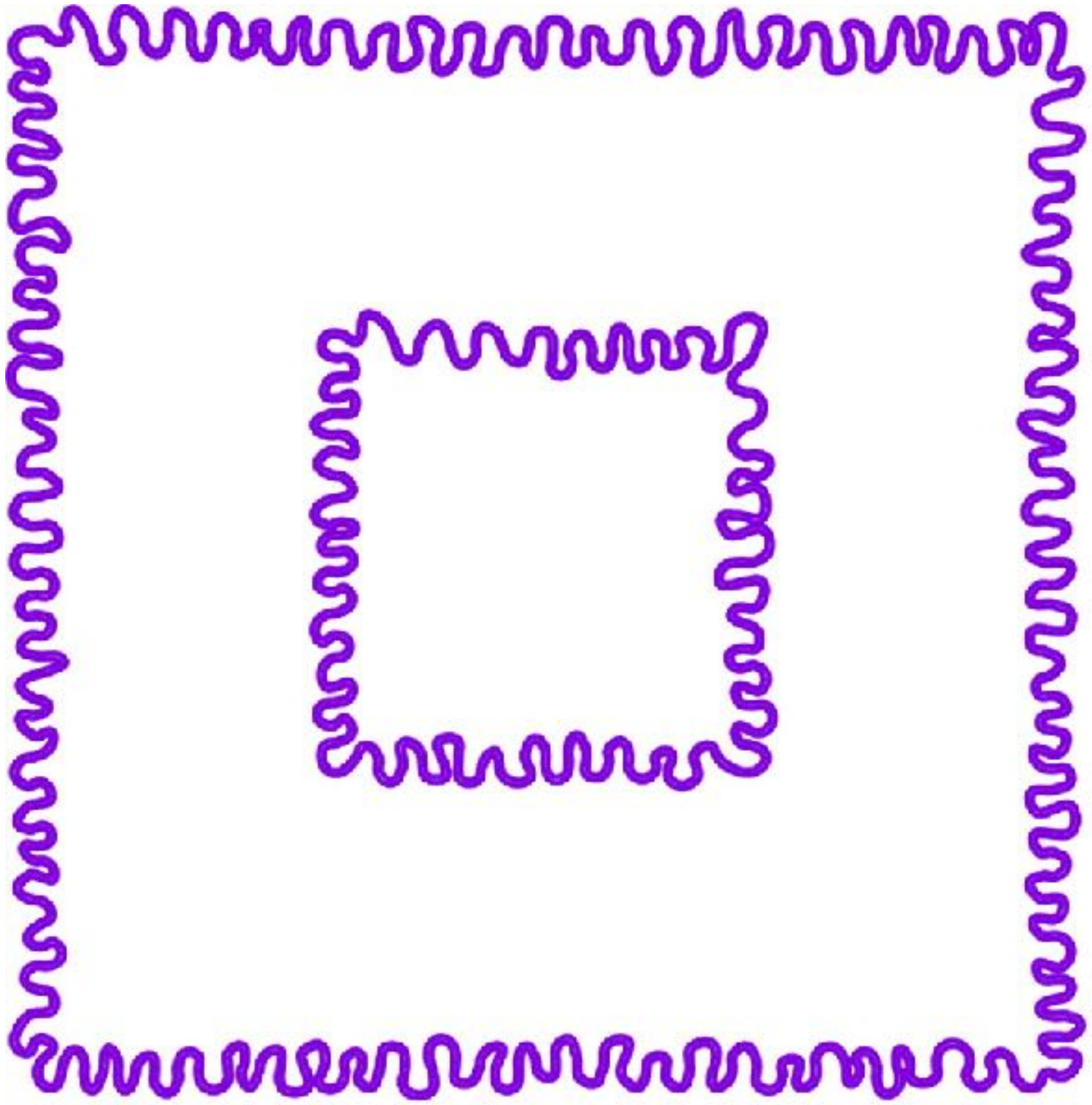


Everything is Relative

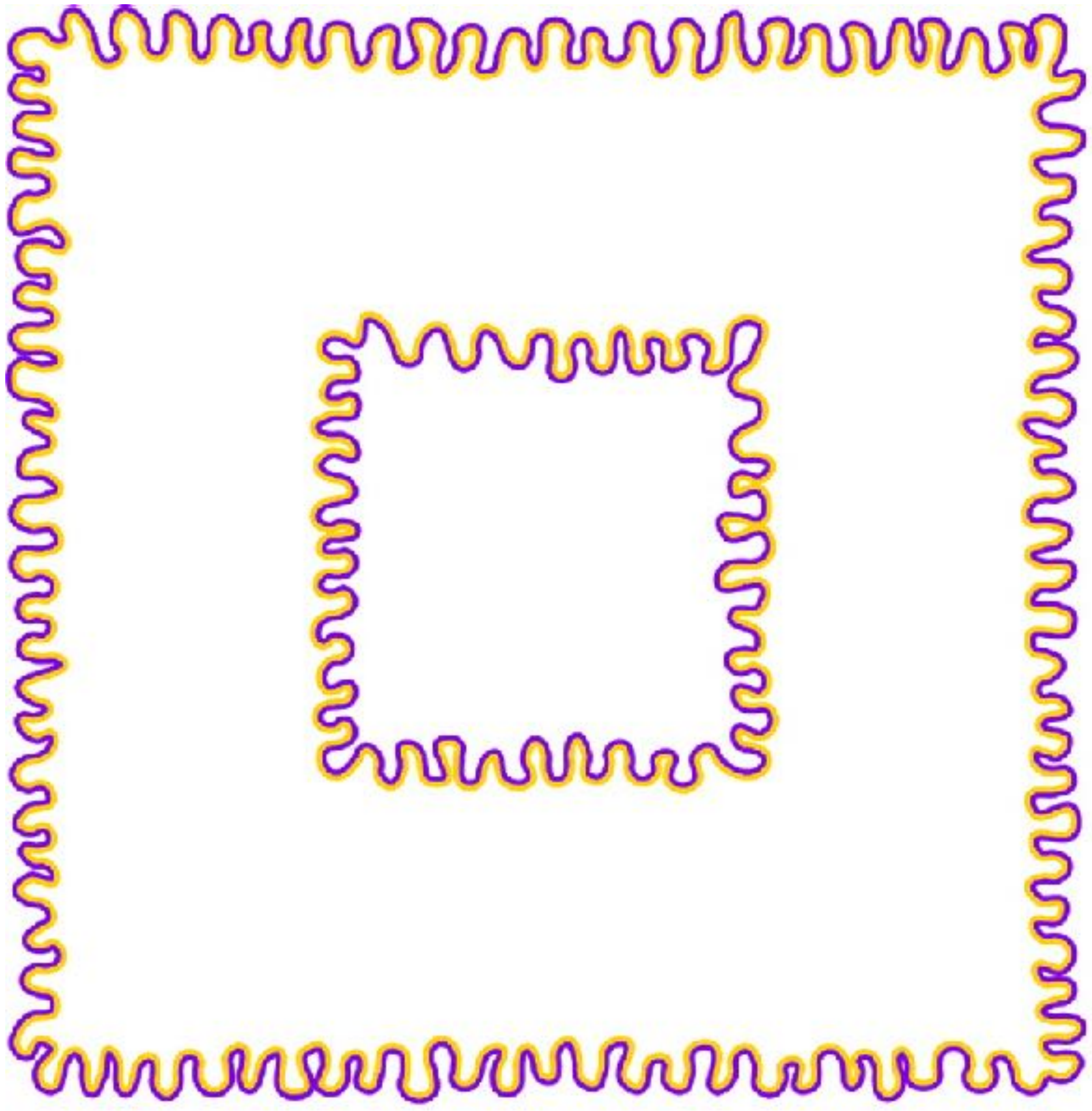


Watercolor Illusion



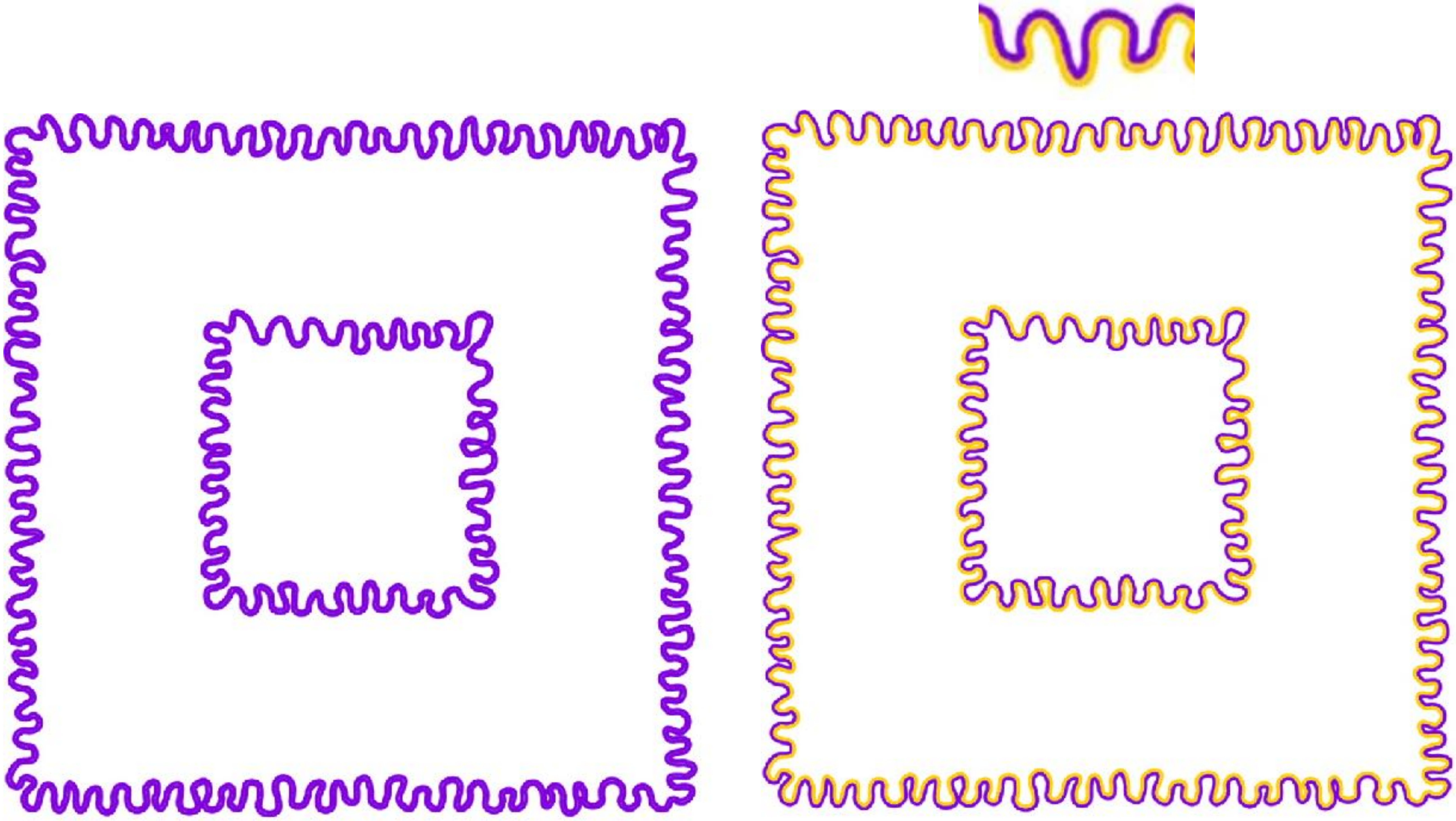
Pinna & Tanca, *JOV*, 2008

Watercolor Illusion



Pinna & Tanca, *JOV*, 2008

Watercolor Illusion



Pinna & Tanca, *JOV*, 2008

Things to Remember

Physics of Light

- Spectral power distribution (SPD)
- Superposition (linearity)

Tristimulus theory of color

- Spectral response of human cone cells (S, M, L)
- Metamers - different SPDs with the same perceived color
- Color reproduction mathematics
- Color matching experiment, per-wavelength matching functions

Color spaces

- CIE RGB, XYZ, xy chromaticity, LAB, HSV
- Gamut

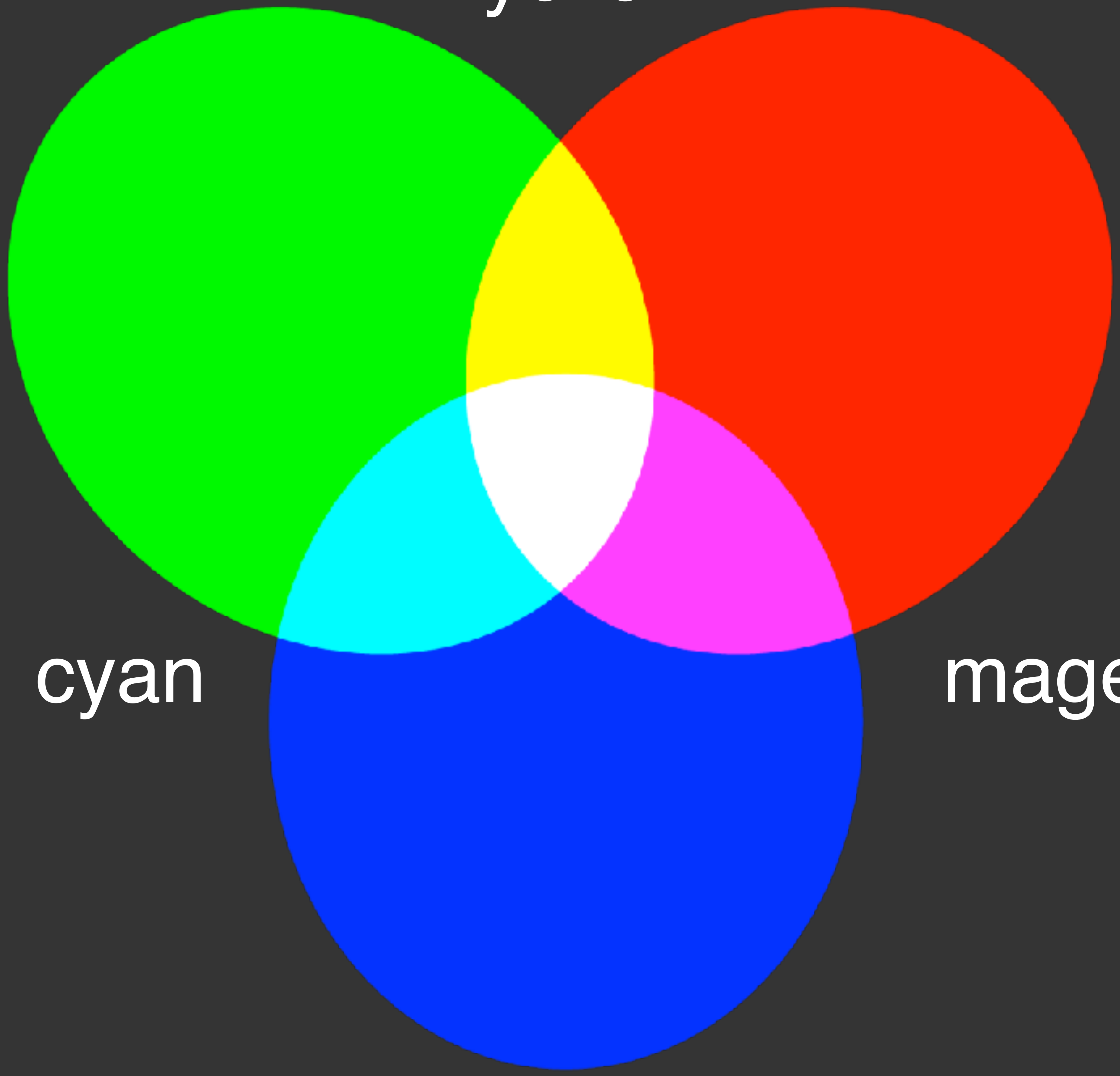
Acknowledgments

Many thanks and credit for slides to Steve Marschner, Kayvon Fatahalian, Brian Wandell, Marc Levoy, Katherine Breeden, Austin Roorda and James O'Brien.

Extra

Additive and Subtractive Models of Light

adding light energy



yellow

green

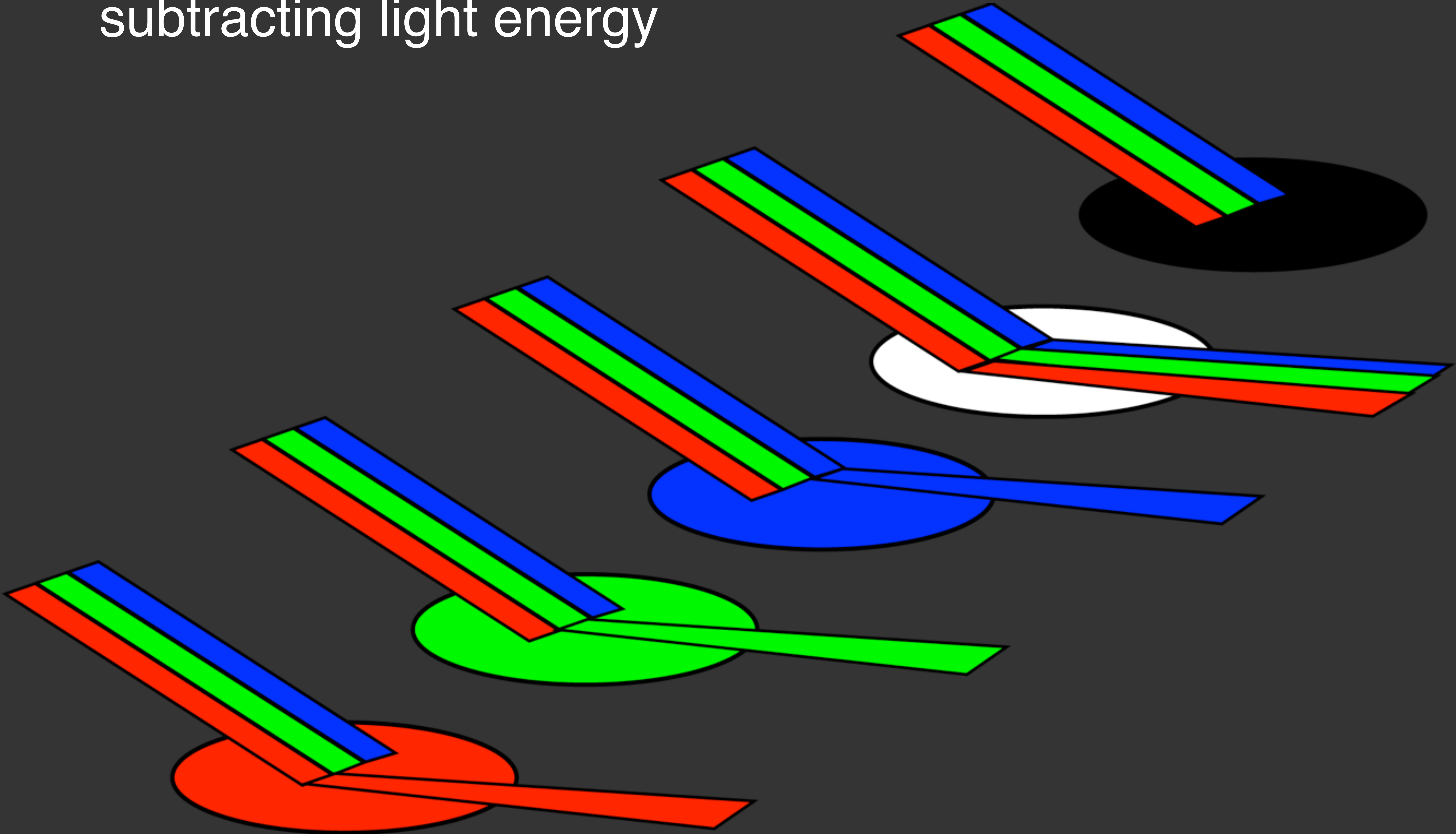
red

cyan

magenta

blue

subtracting light energy



shining white light on various colored pigments