Lecture 19:

Introduction to Color Science

Computer Graphics and Imaging

UC Berkeley CS184

Color defines our visual perception

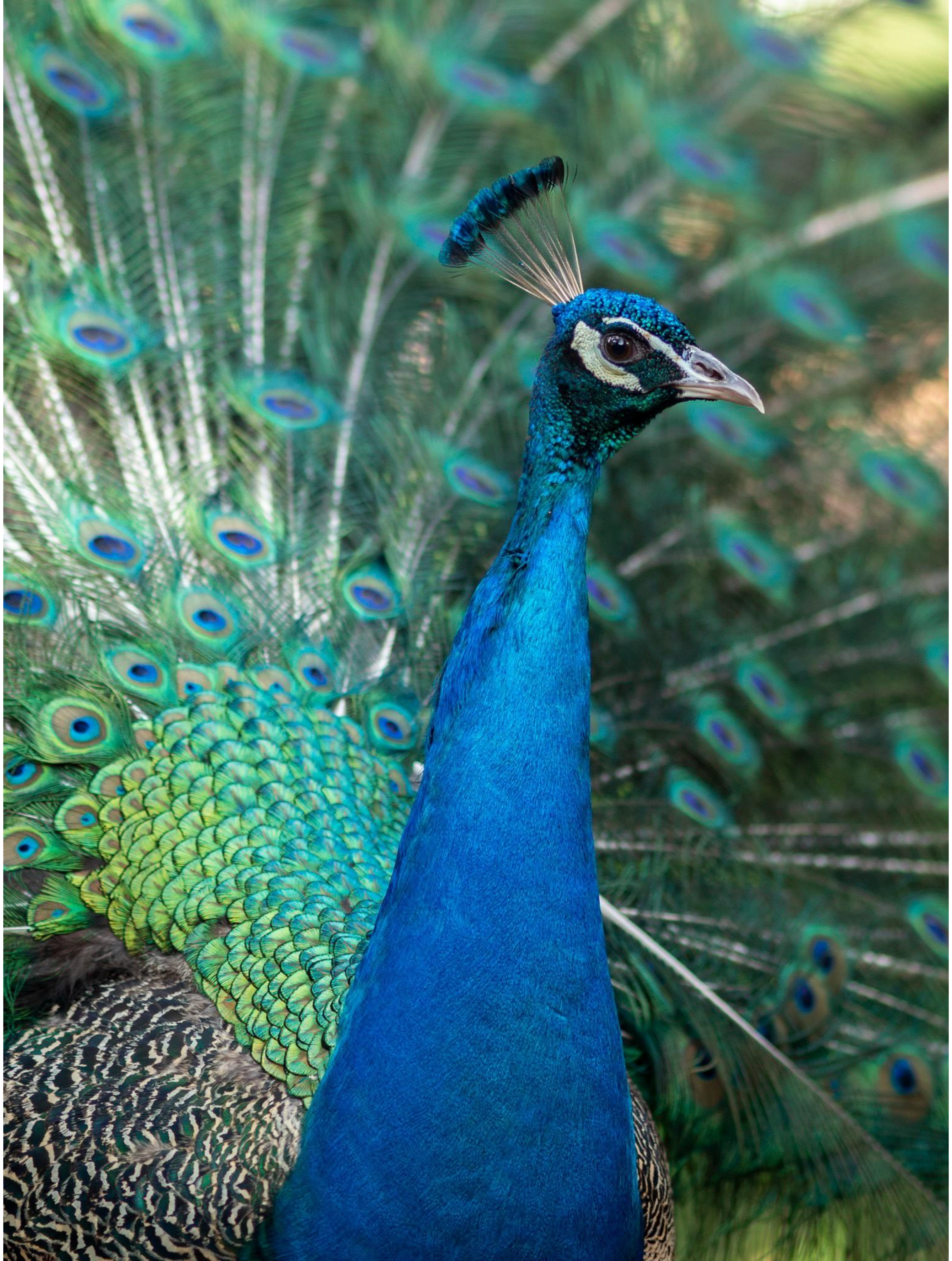
We Render for the human observer

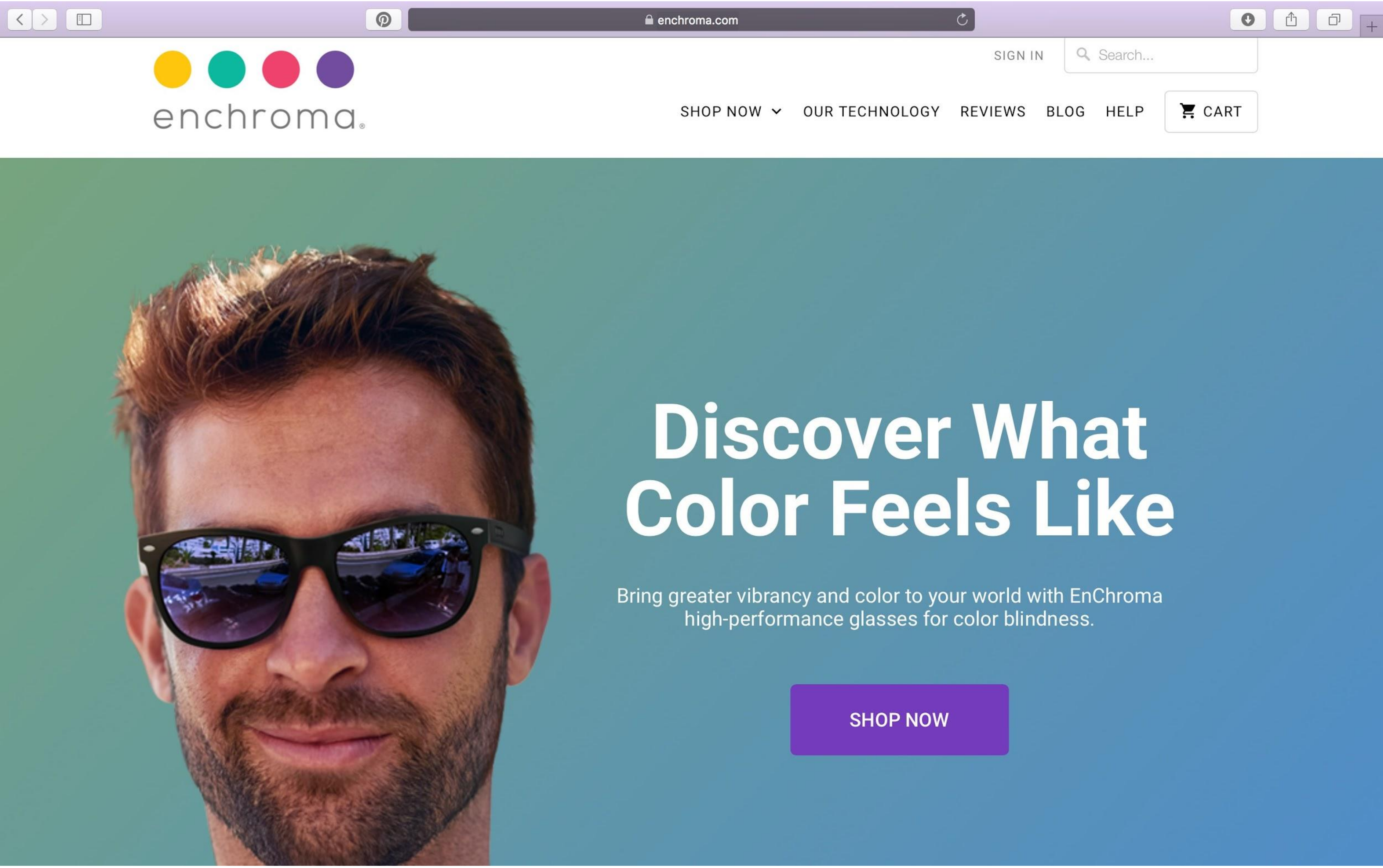

UMBRA GEBRANNT
BURNT UMBER
0 94376-89704
SIENNA
8 712079 143084
0 94376-89814
WINSOR & NEWTON
YELLOW
GELB

Johannes Vermeer *The Music Lesson*

Wassily Kandinsky, Color Study. Squares with Concentric Circles, 1913 Munich, The Städtische Galerie im Lenbachhaus

Mark Rothko
No. 61. Rust and Blue
1953,
Museum of Contemporary Art, Los Angeles

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Bring greater vibrancy and color to your world with EnChroma high-performance glasses for color blindness.
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Color-Blind Reactions to Perceiving New Colors

Enchroma, https://www.youtube.com/watch?v=-rMjUsG--zo

Simulation of Color Blind Perception
(Color Vision Deficiency)

Normal

Protan


Deutan

Tritan

Simulation of Color Blind Perception

Normal

Protan

Deutan

Tritan

Created with Coblis —Color Blindness Simulator

Color is Core to Our Human Visual Sense

Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

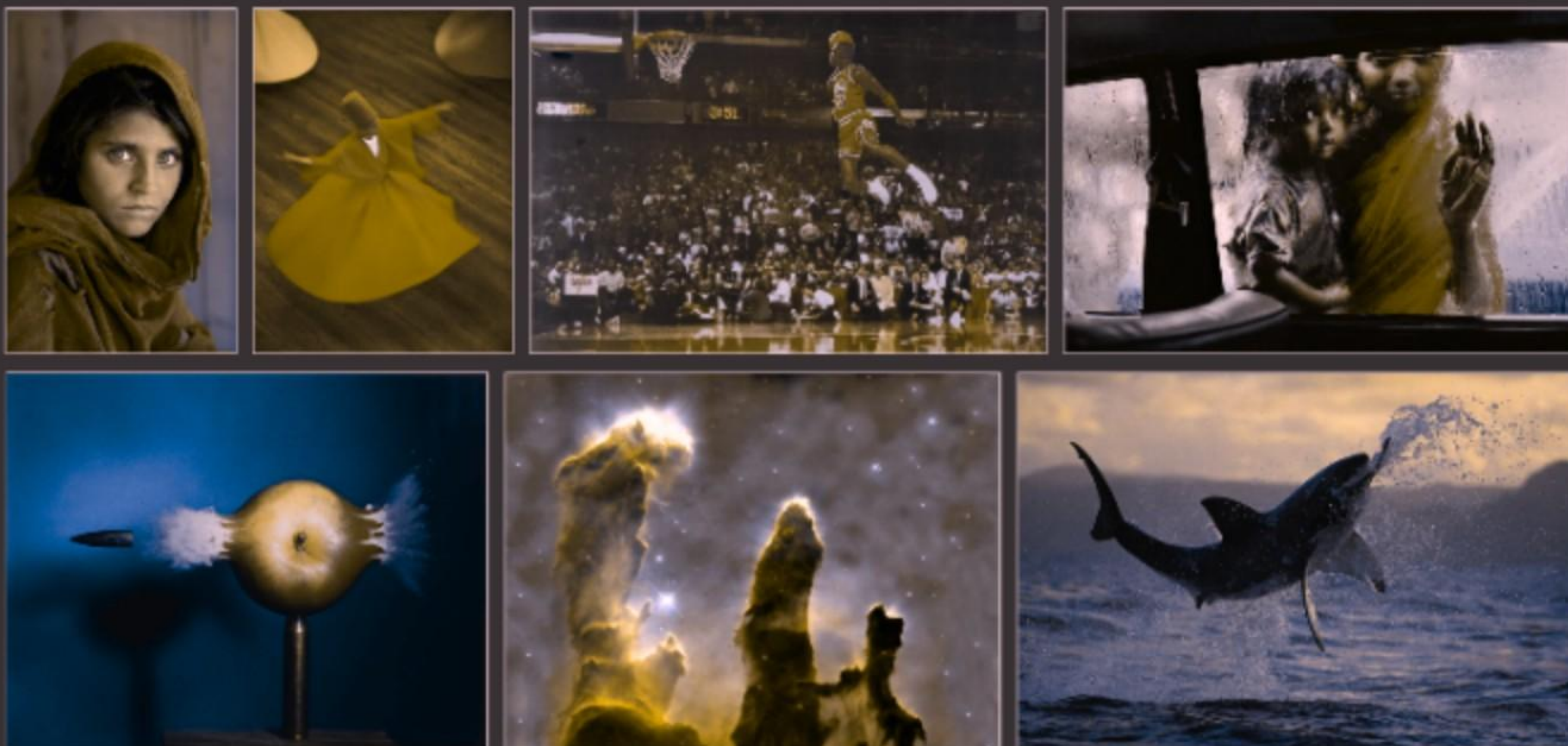
Normal

Color is Core to Our Human Visual Sense

Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

**Prota
n**

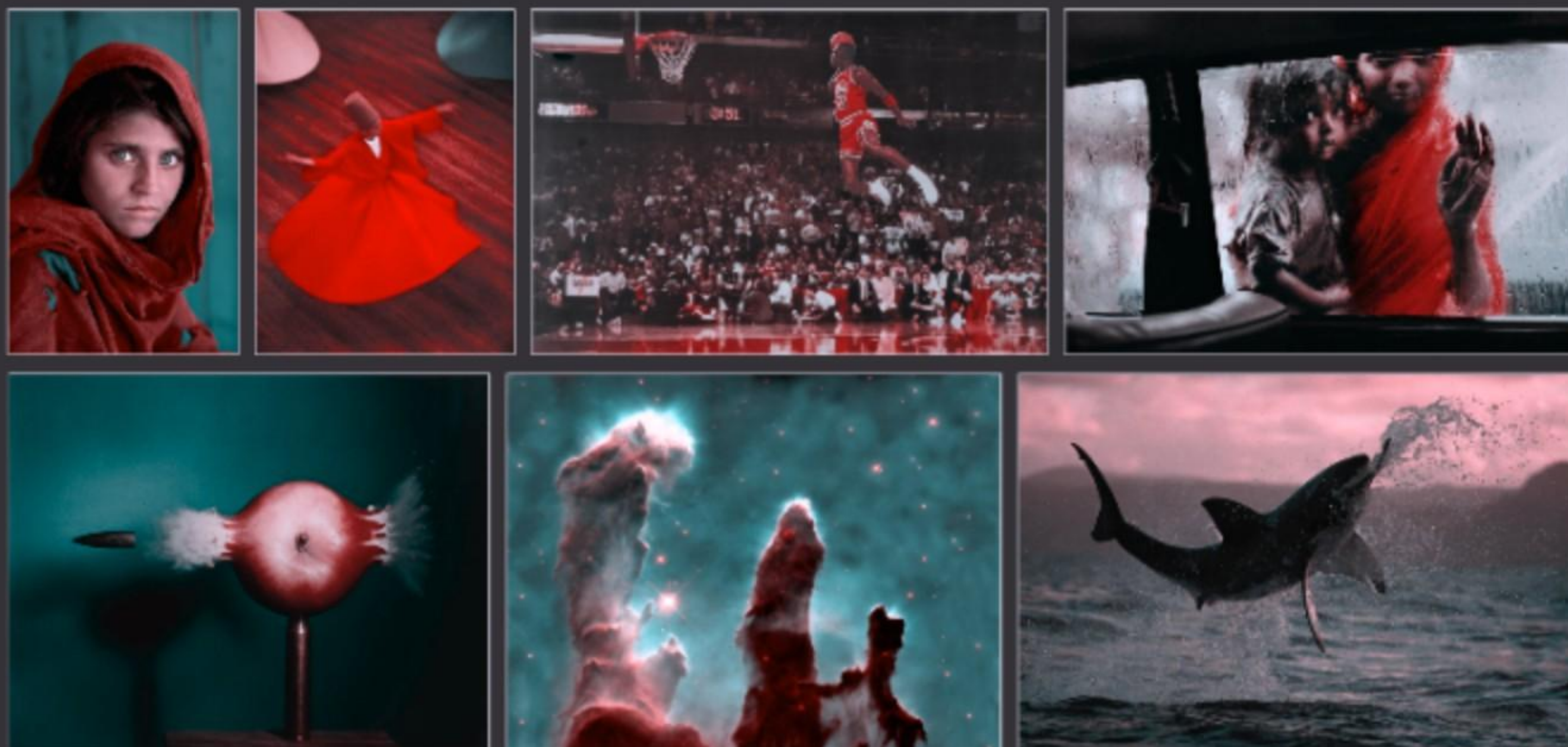
Color is Core to Our Human Visual Sense



Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Deutan

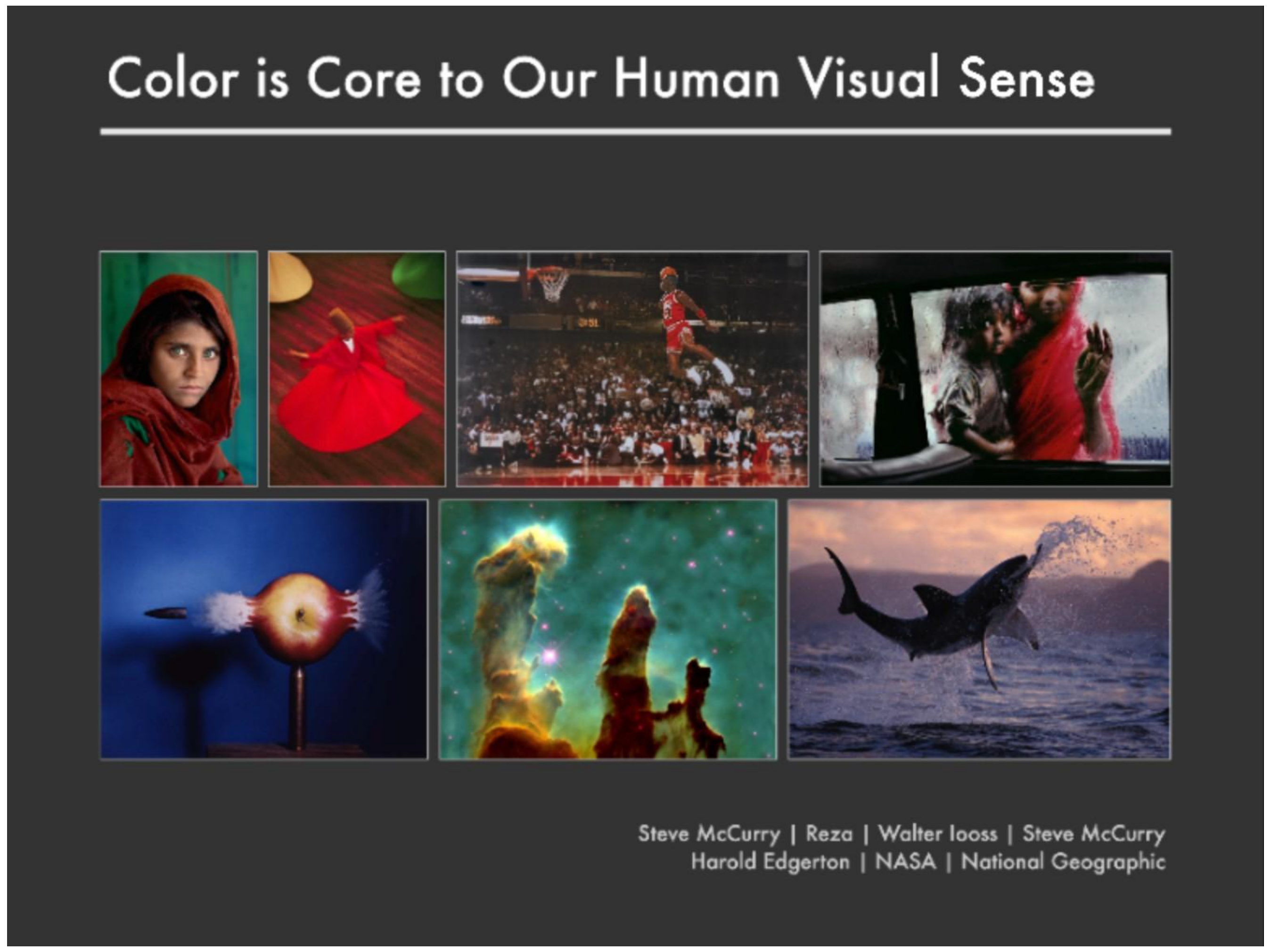
Color is Core to Our Human Visual Sense



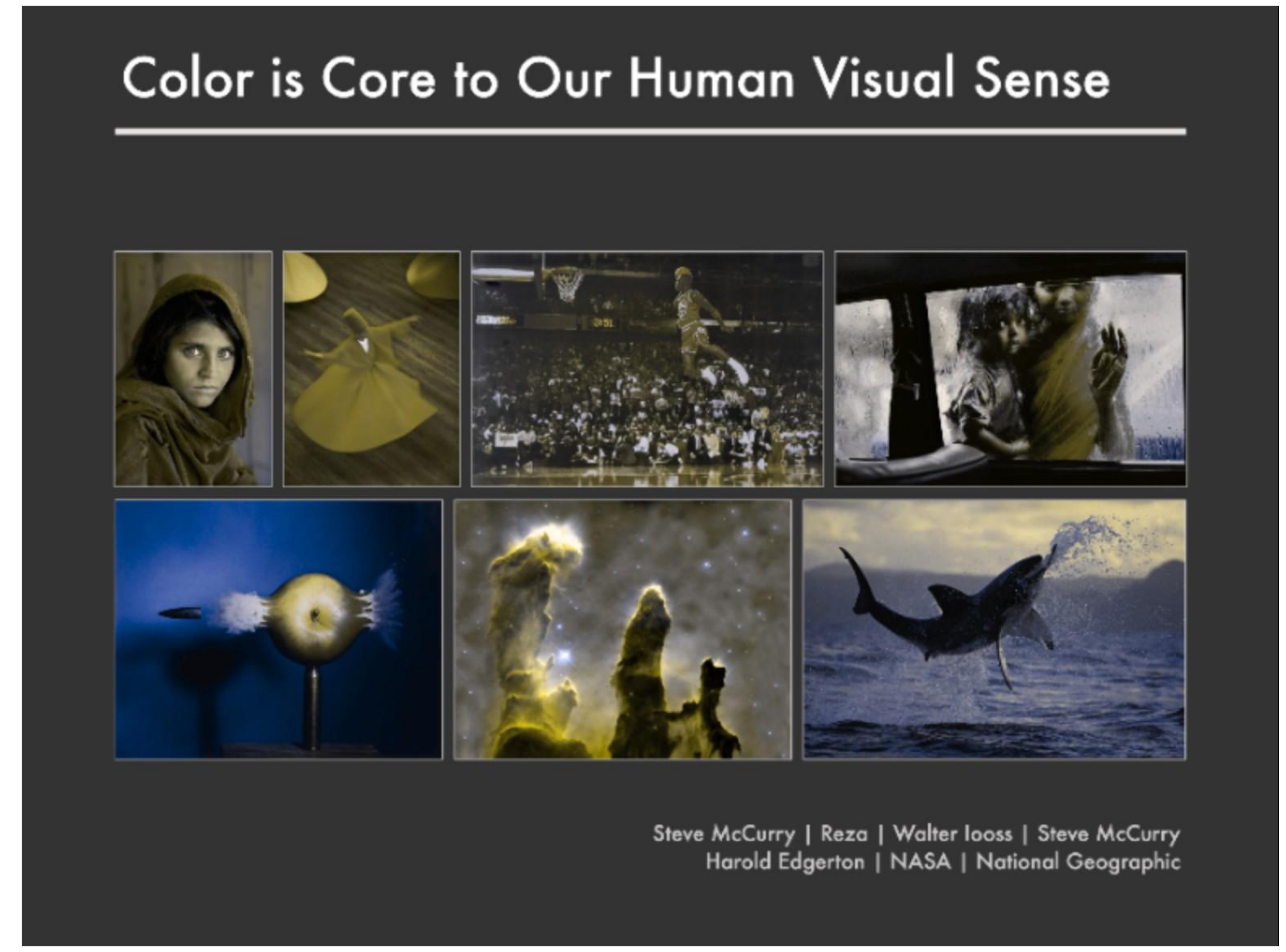
Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Trita
n

Simulation of Color Blind Perception



Normal



Protan

Deutan Tritan

Created with Coblis — Color Blindness Simulator

Chromatic Adaptation

A Person With One Trichromatic Eye and One Deuteranopic Eye

Graham and Hsia, 1959.
"A unilaterally dichromatic subject".

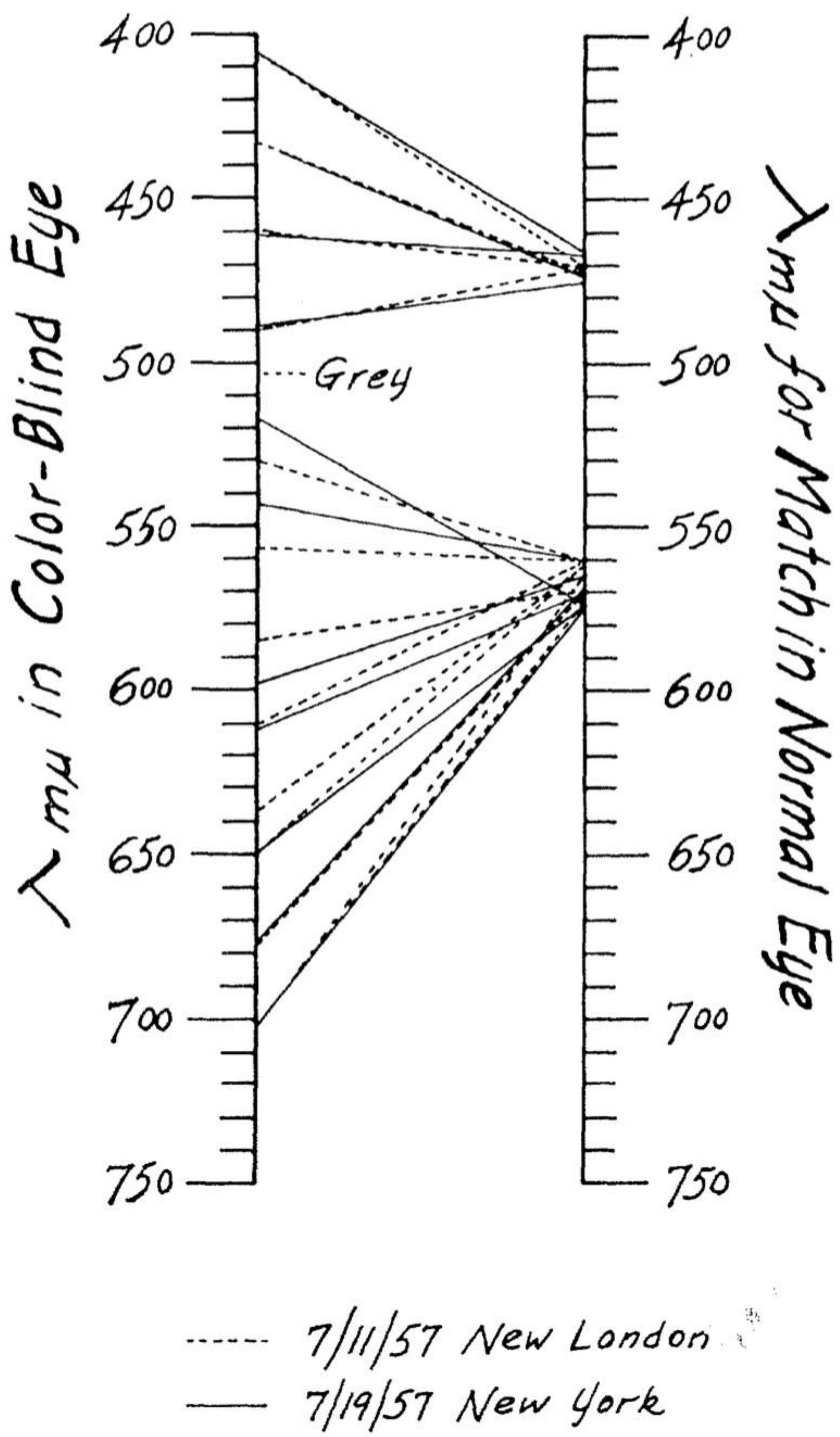


Fig. 2.—Results of the experiment on binocular matching

Studying Chromatic Adaptation

Slide credit: Mark Fairchild

Slide credit: Mark Fairchild

CYAN FILTER

Slide credit: Mark Fairchild

Automatic White Balance - Examples

No white balance (all processed as “daylight”)

Automatic White Balance - Examples

Automatic white balance applied (Lightroom implementation)

Automatic White Balance - Examples






AWB + light manual editing

Automatic White Balance

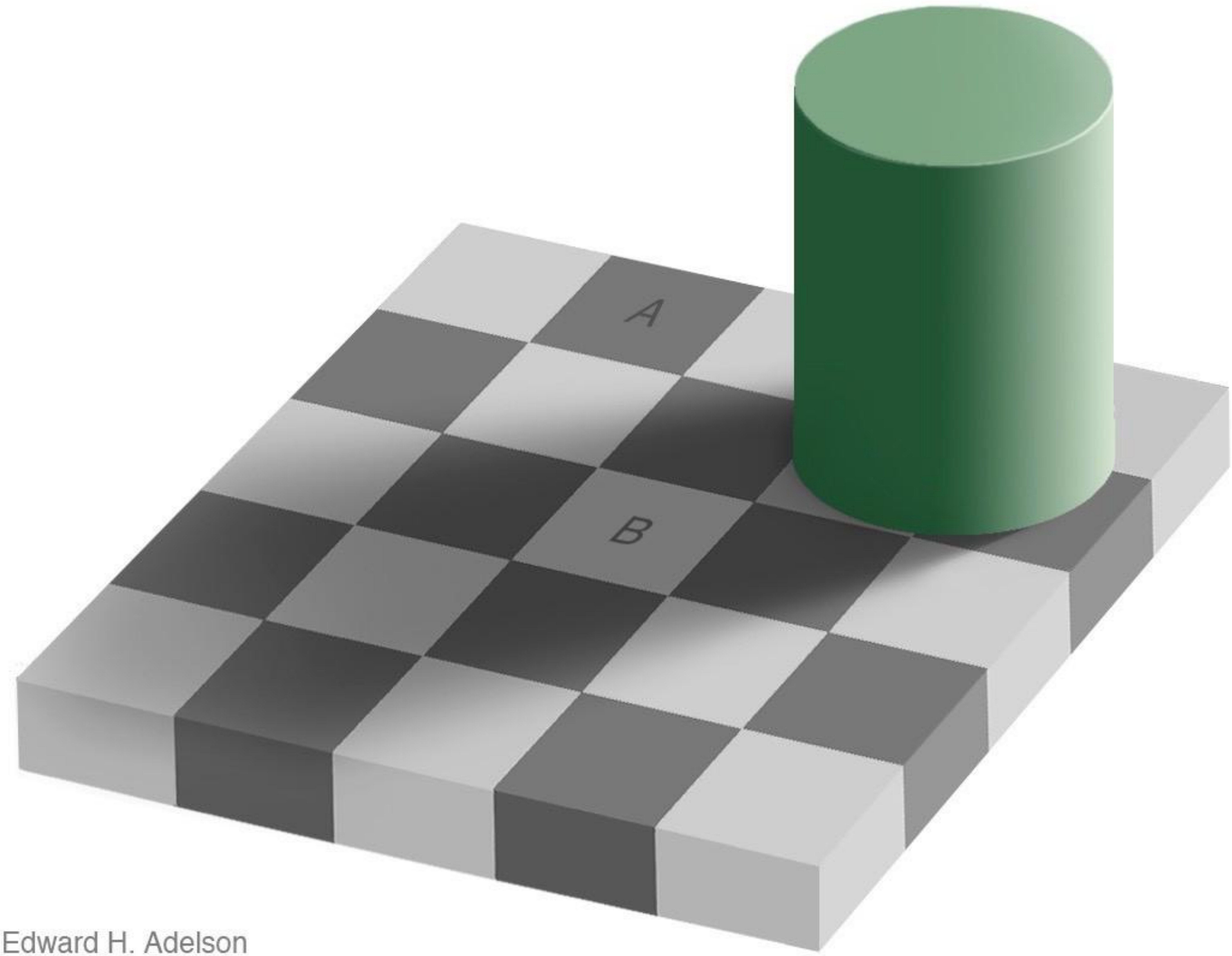
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \frac{1}{R'_W} & 0 & 0 \\ 0 & \frac{1}{G'_W} & 0 \\ 0 & 0 & \frac{1}{B'_W} \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

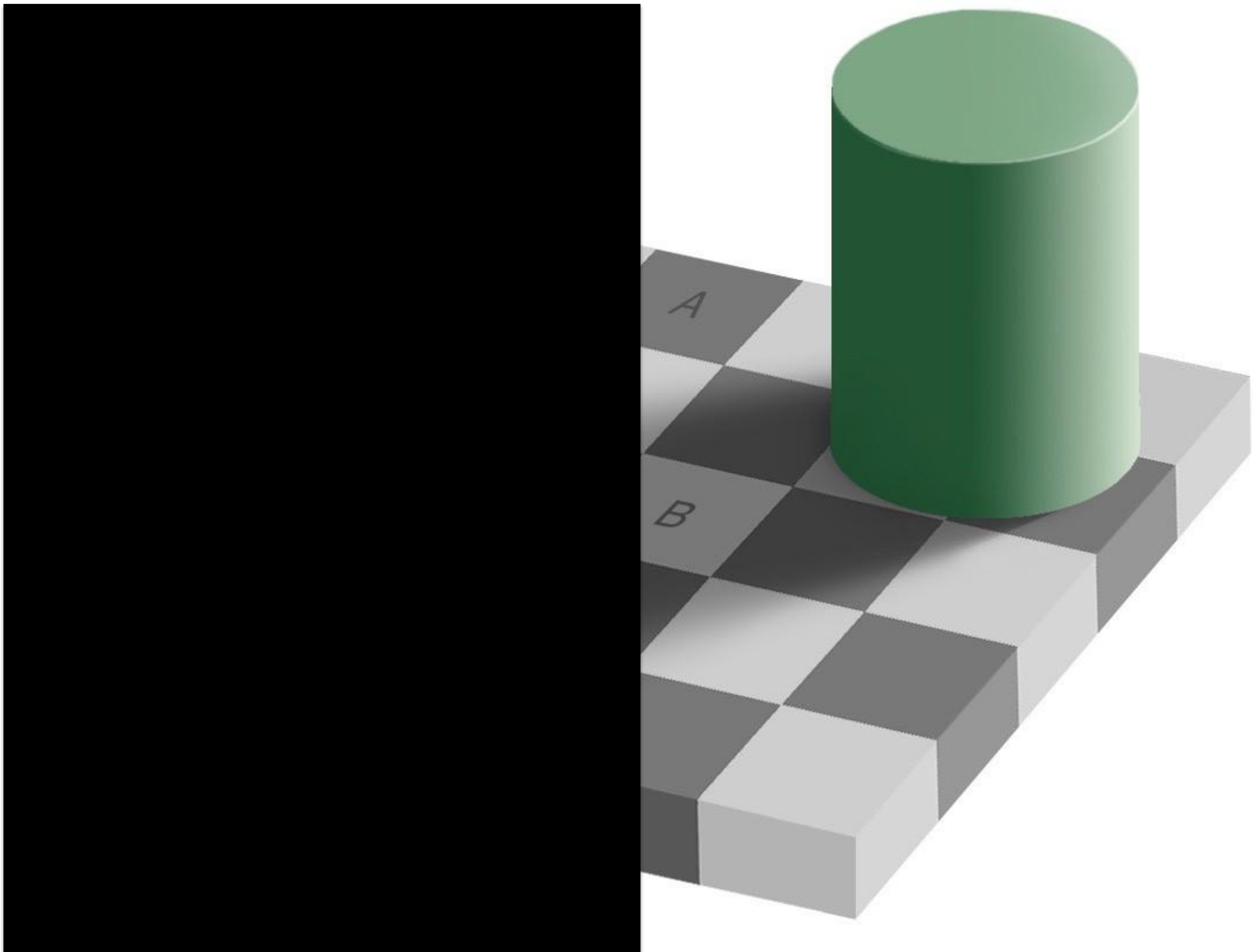
R, G, B - automatic white balanced output

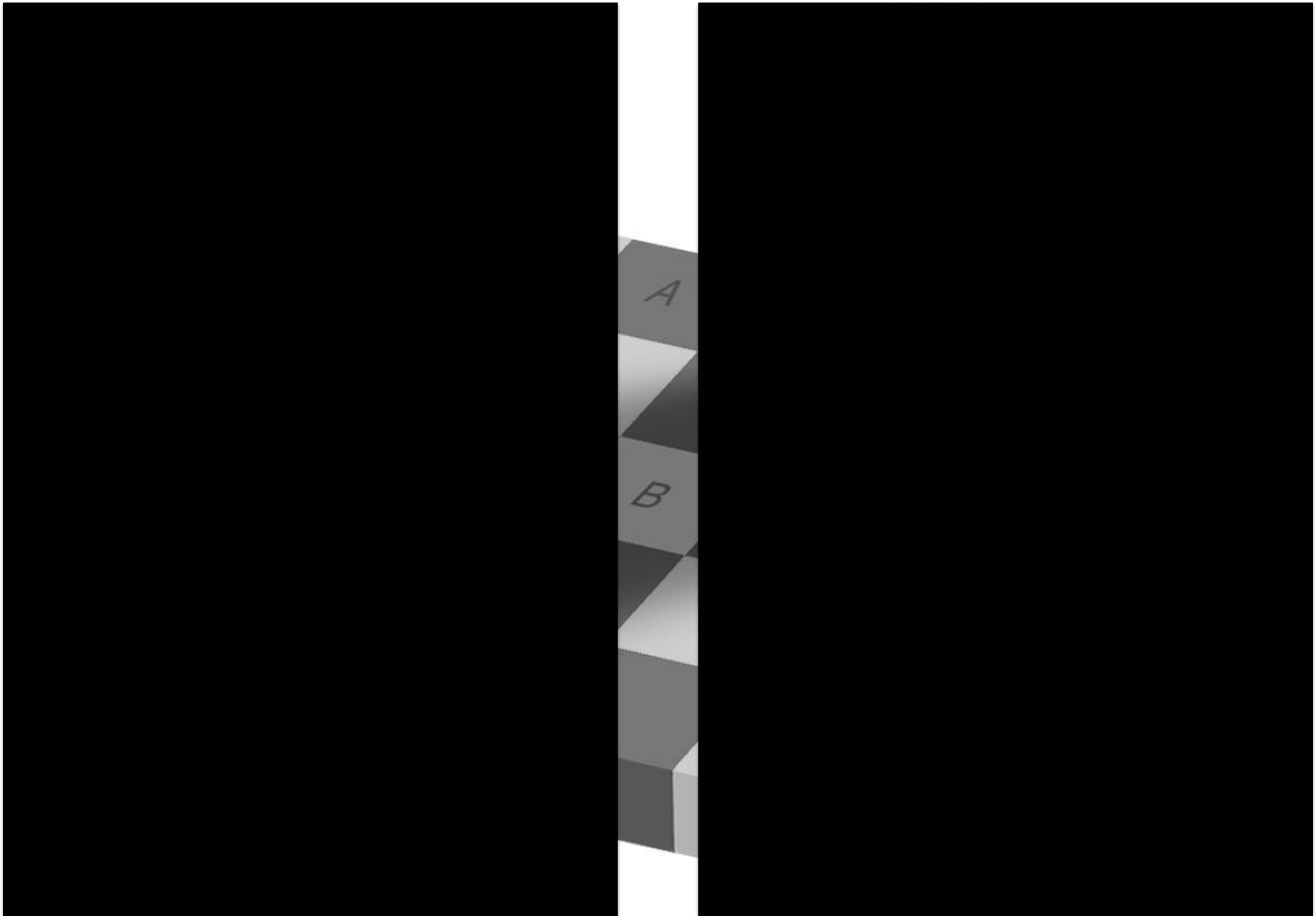
R'_W, G'_W, B'_W - raw input of white object

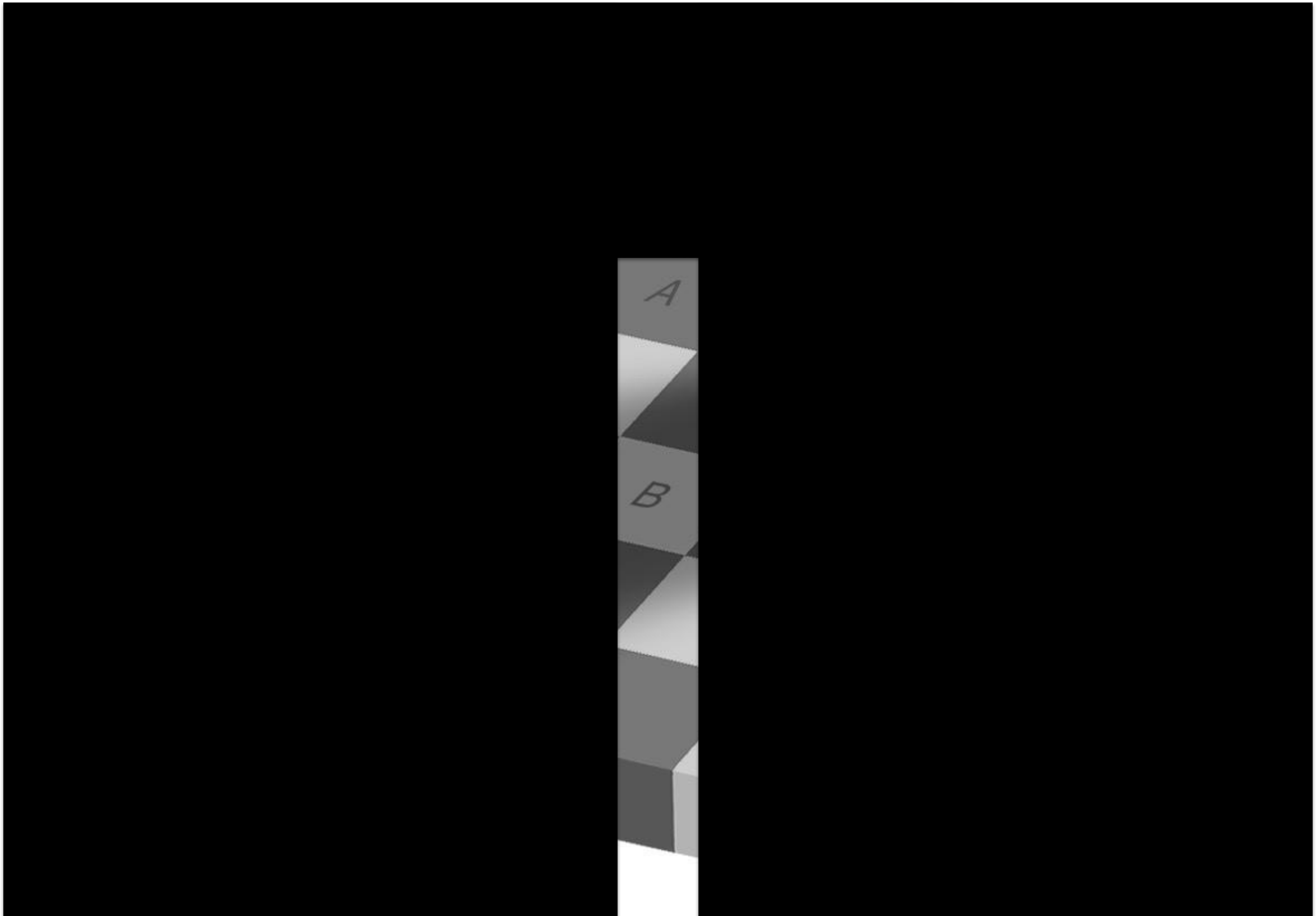
R', G', B' - raw input

Color Perception is Highly Adaptive

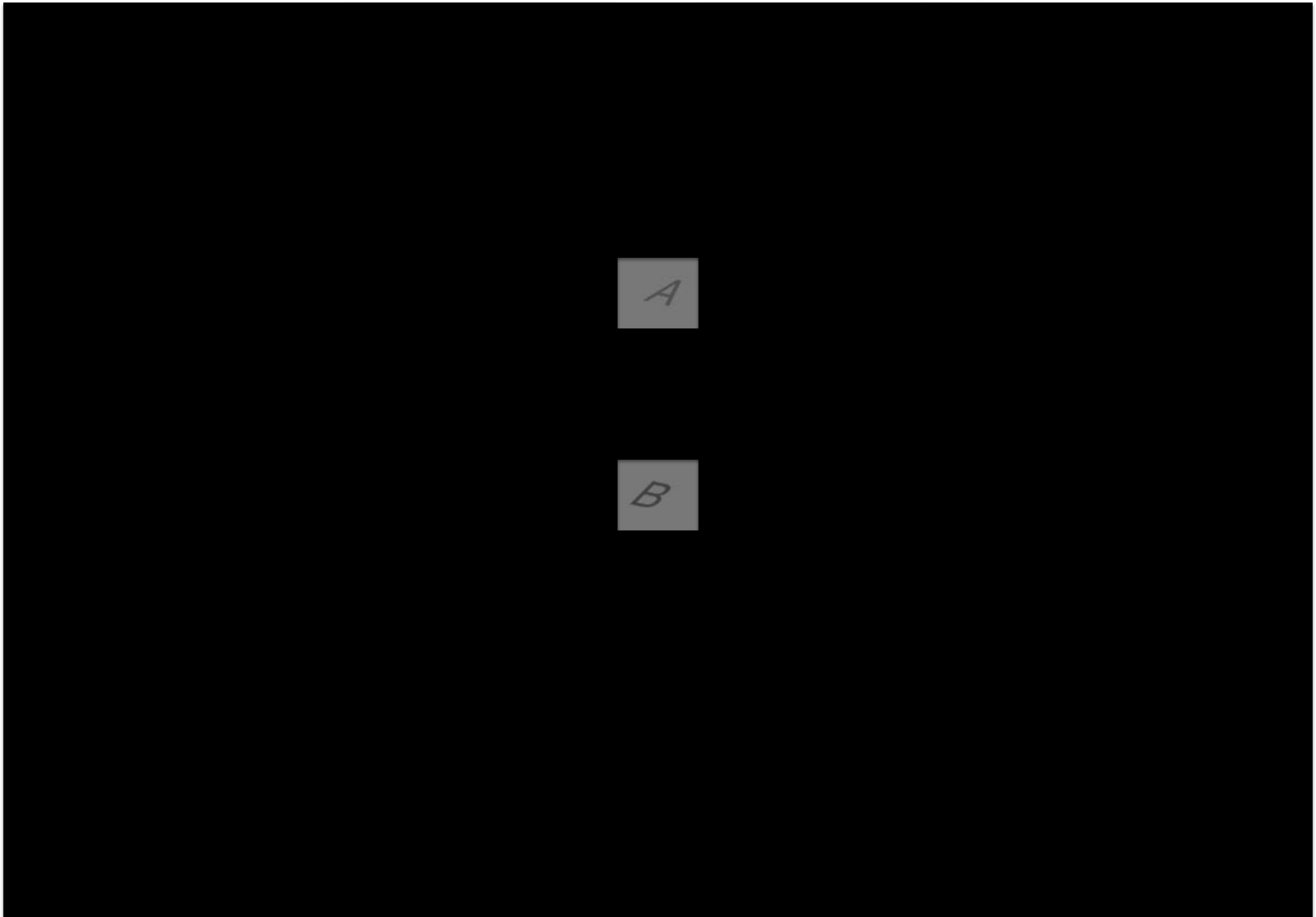

A
B
Edward H. Adelson

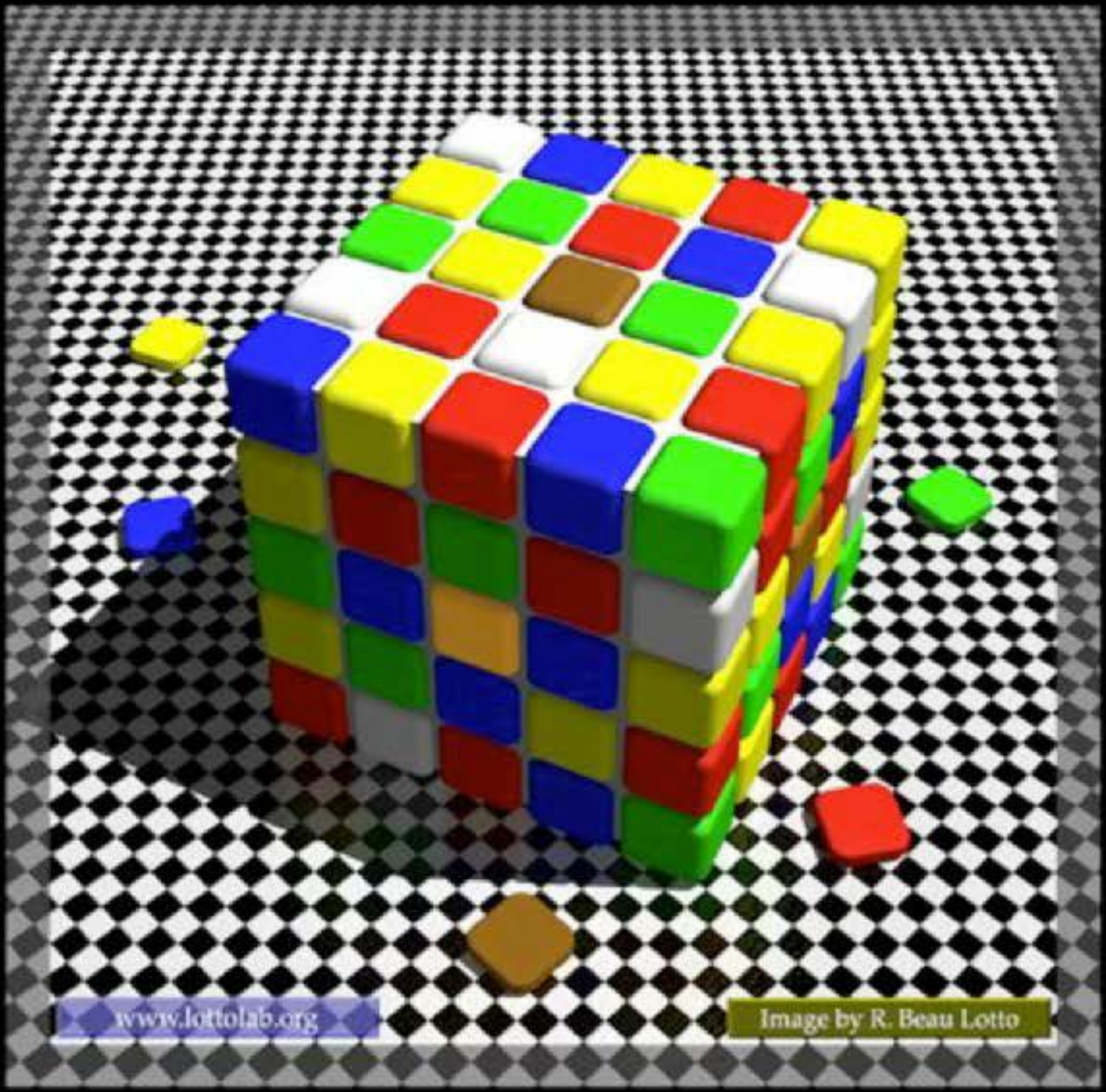

A
B

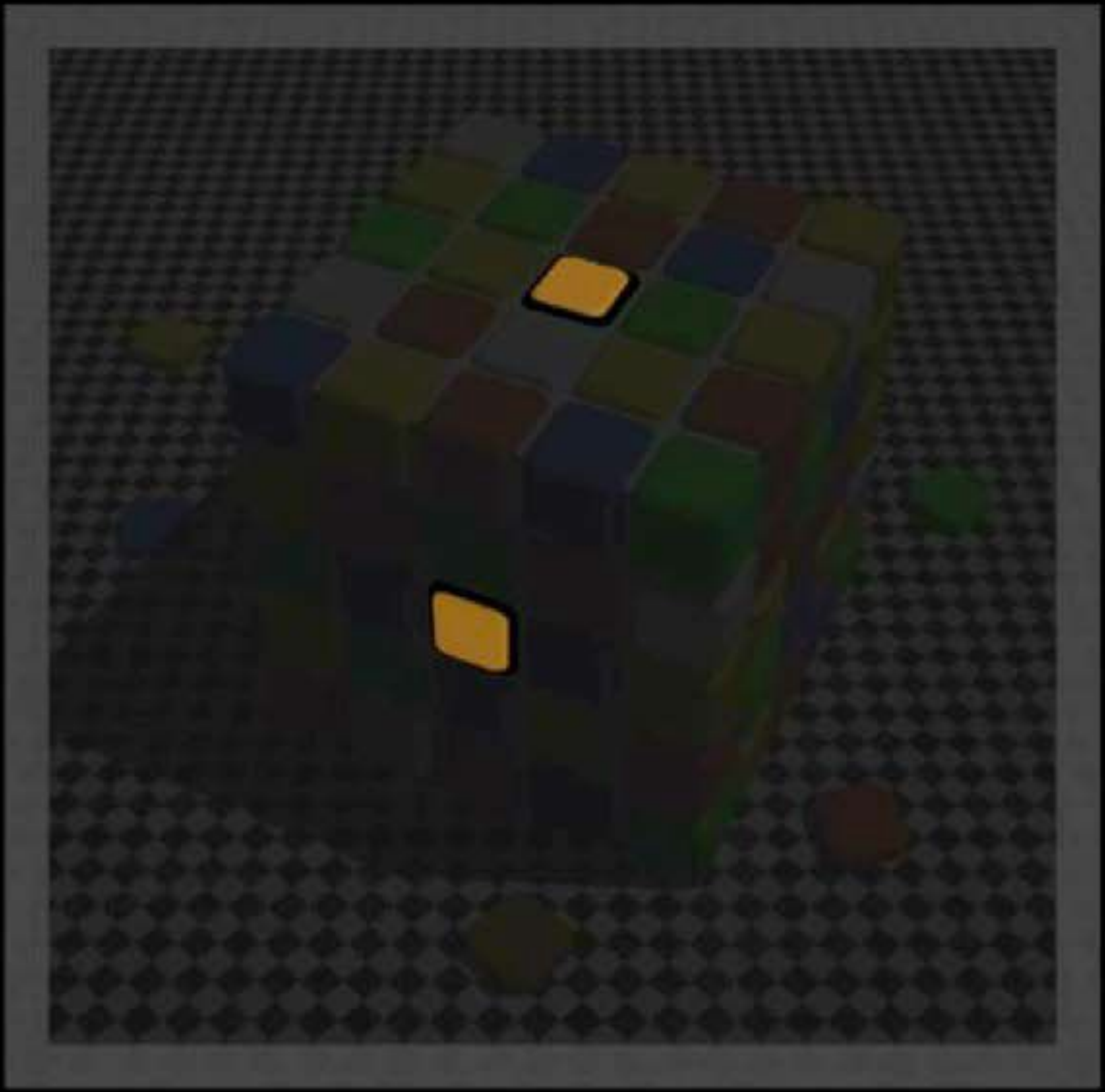

A
B


A
B


A
B


A
B

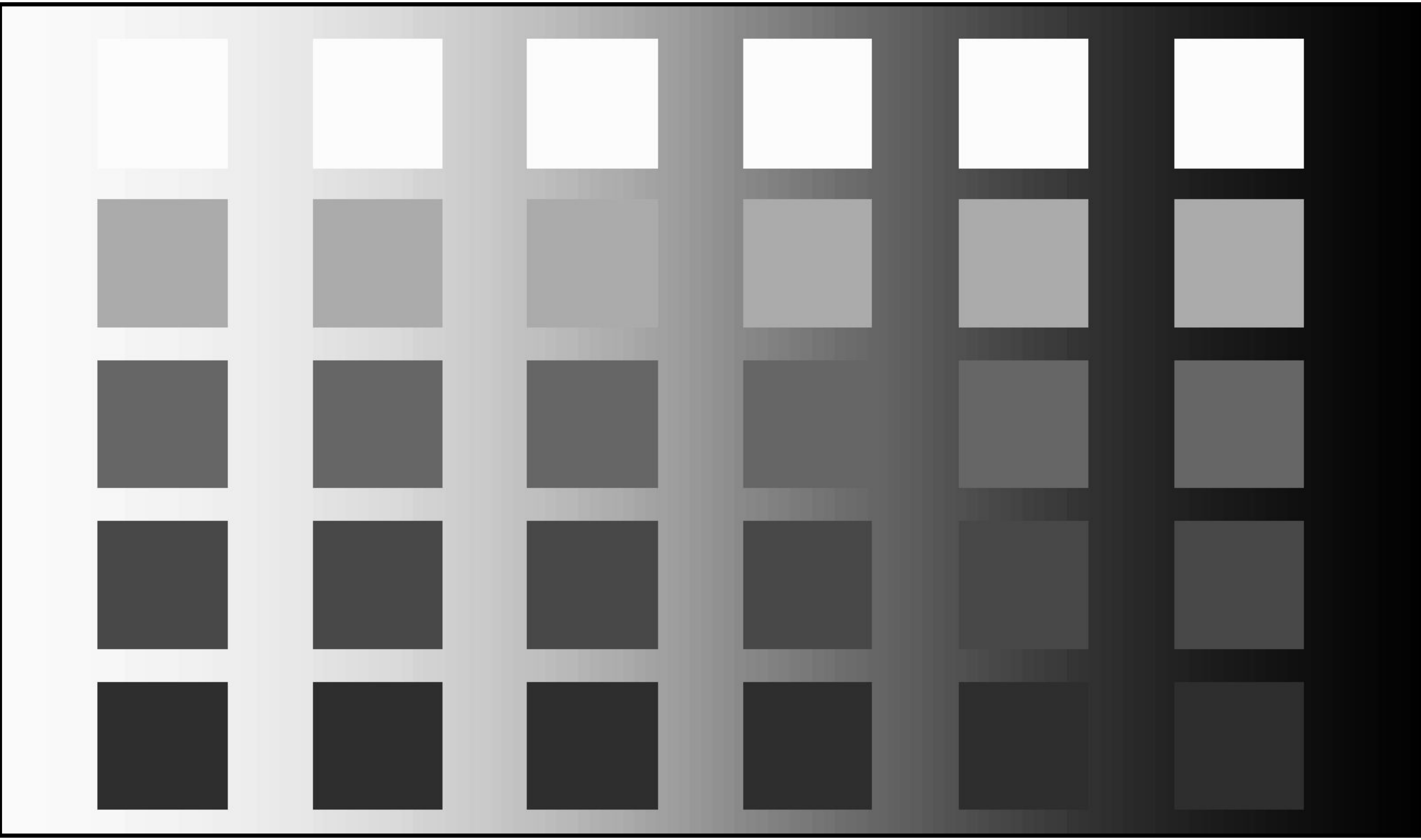

www.lottolab.org
Image by R. Beau Lotto



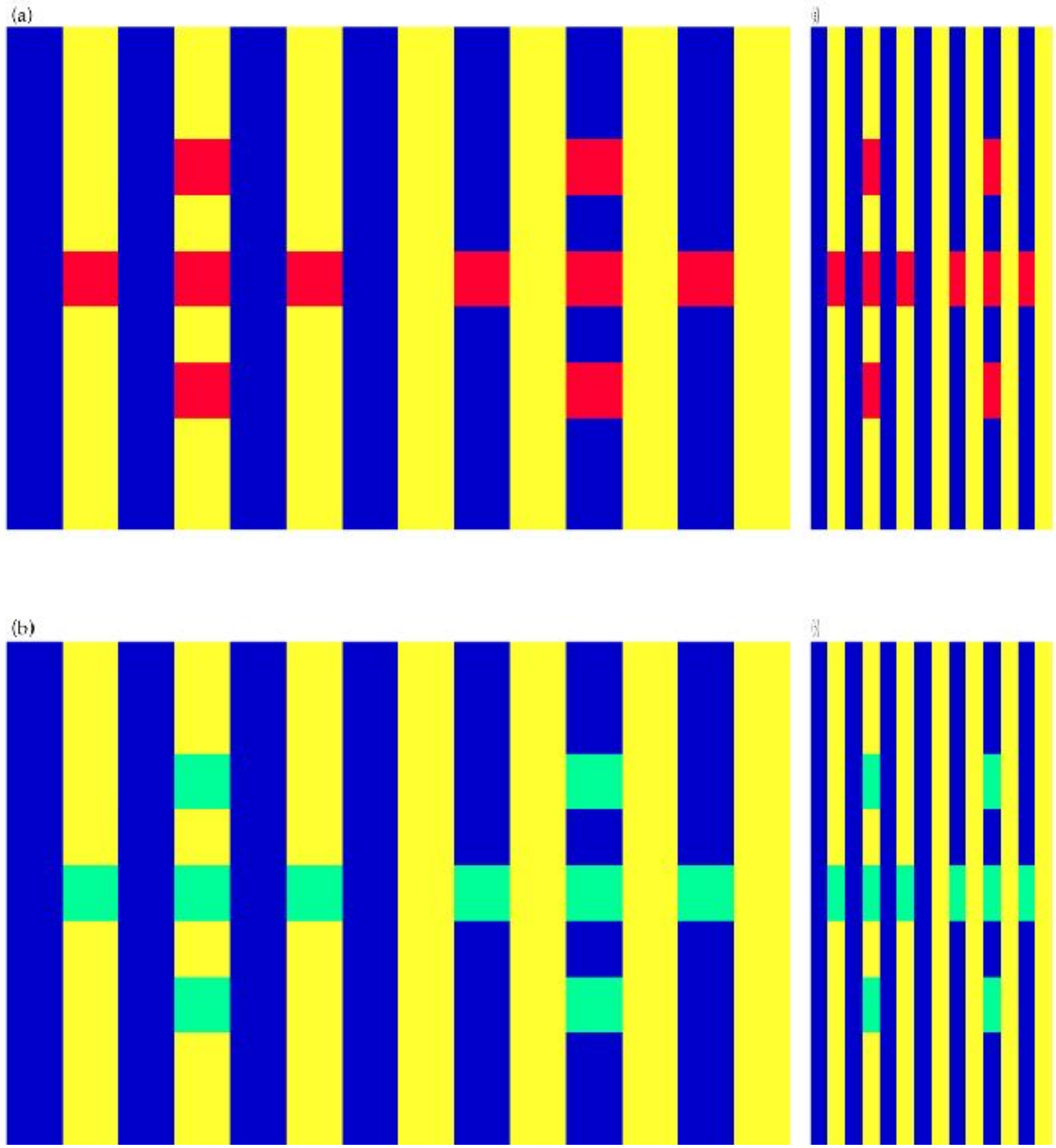
Even simple judgment, such as lightness, depend on brain processing

(Anderson and Winawer, Nature, 2005)

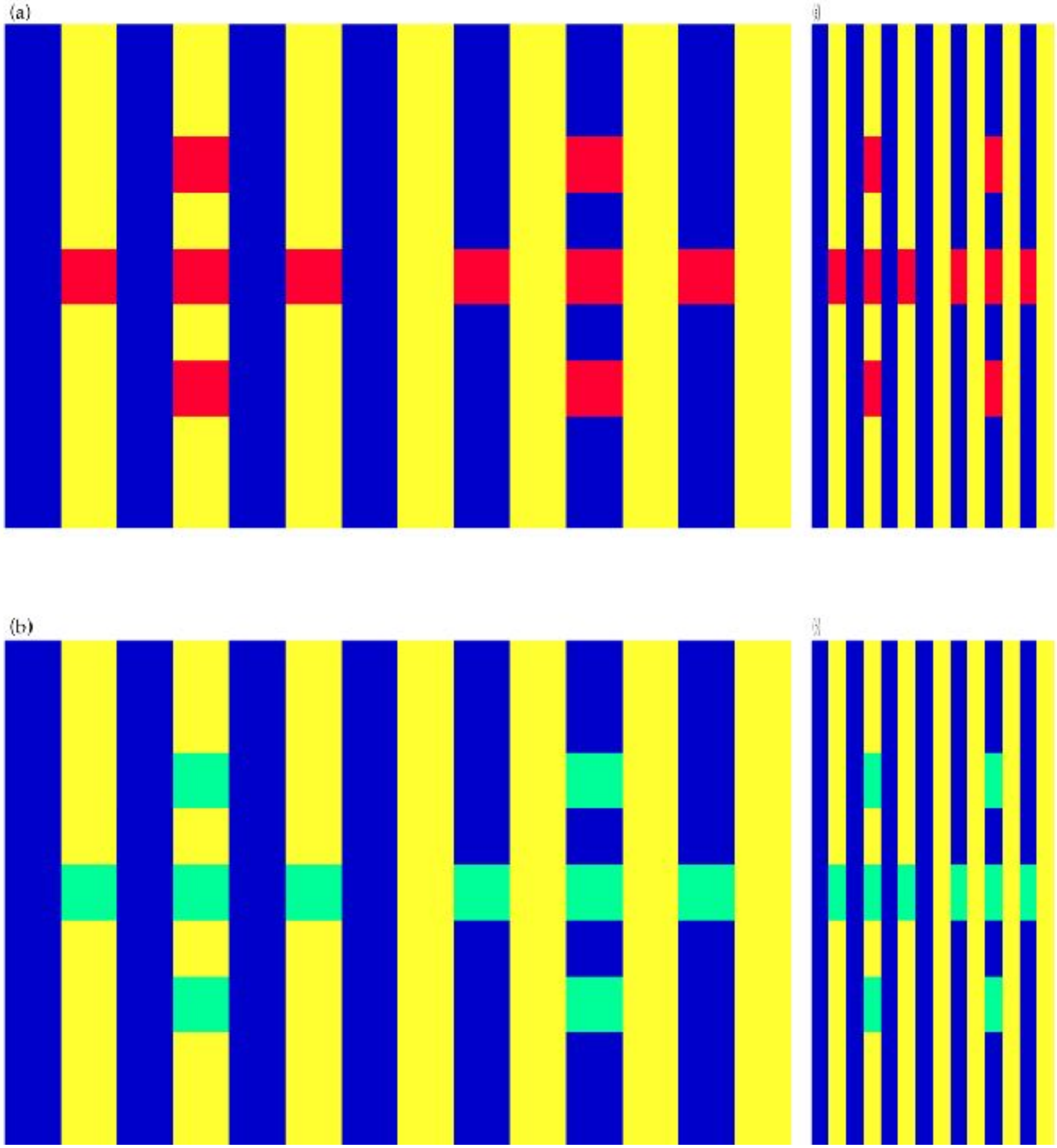
Simultaneous Contrast and Surround Effect

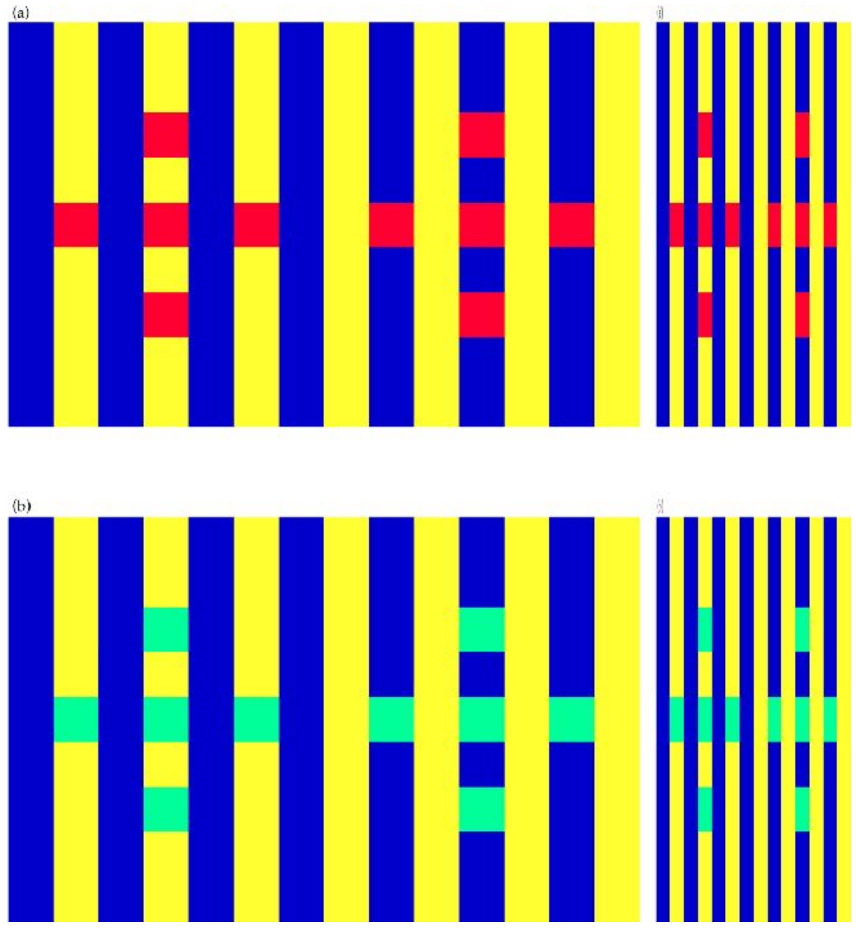


Surround Effects



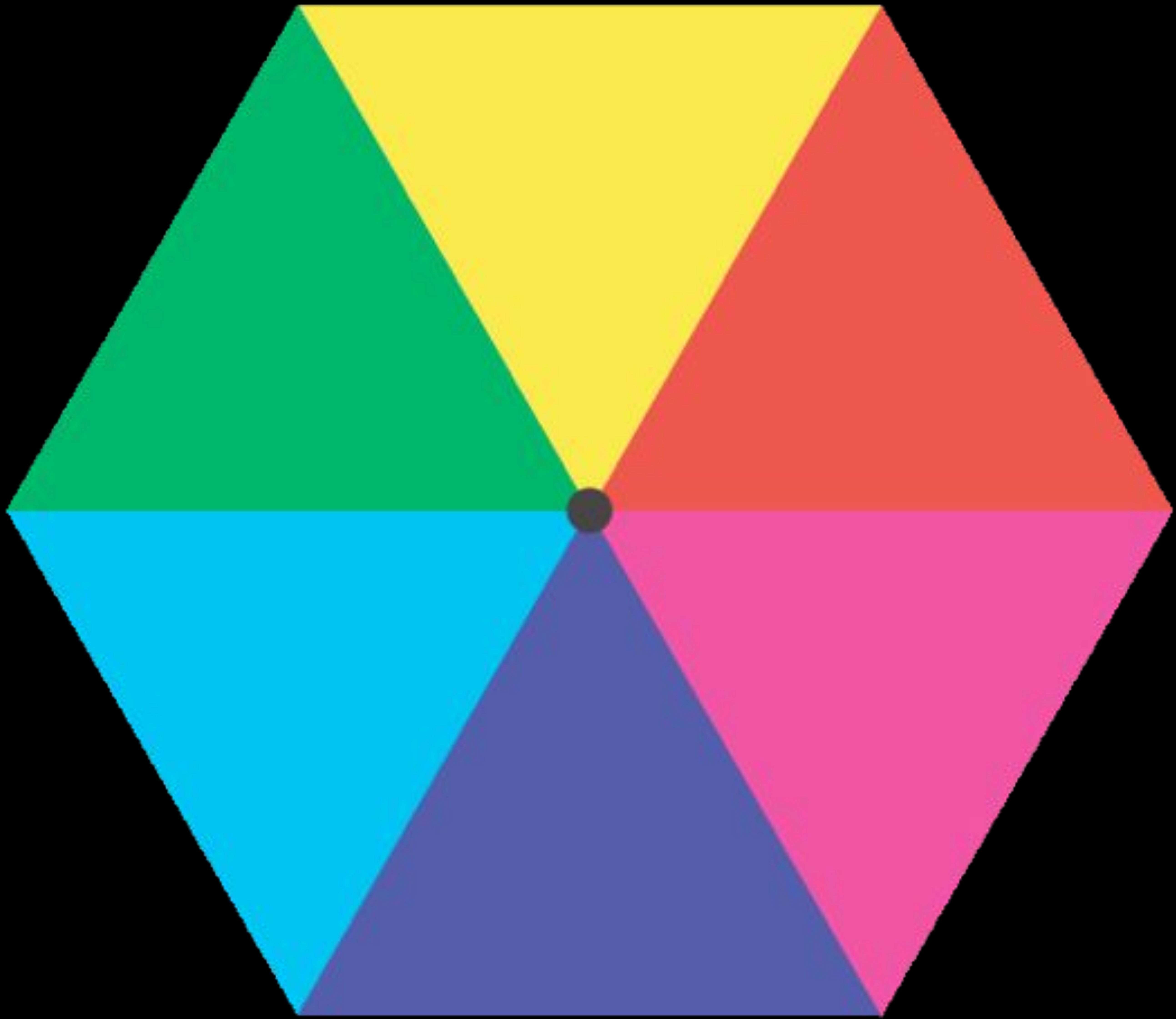
Surround Effects

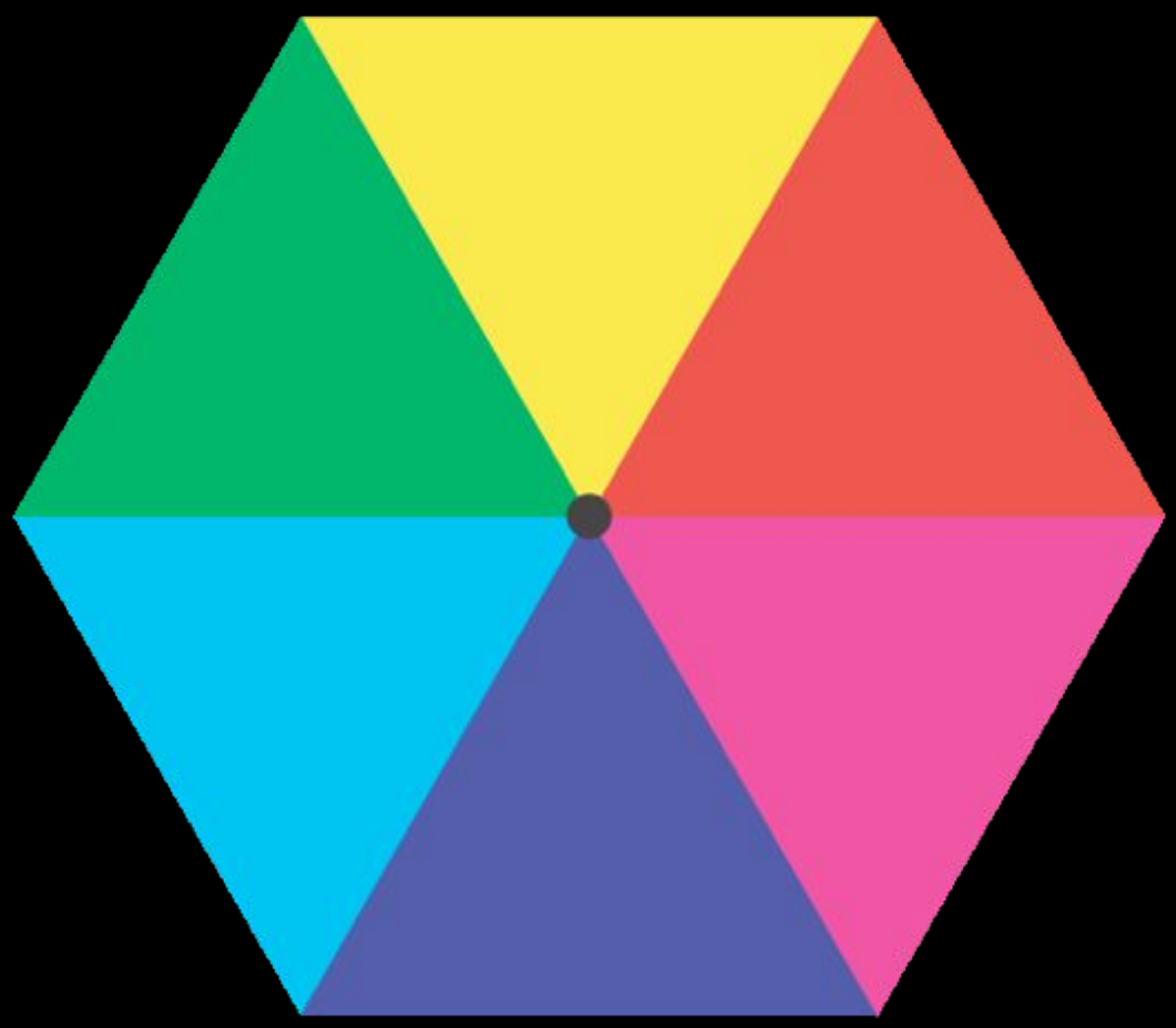




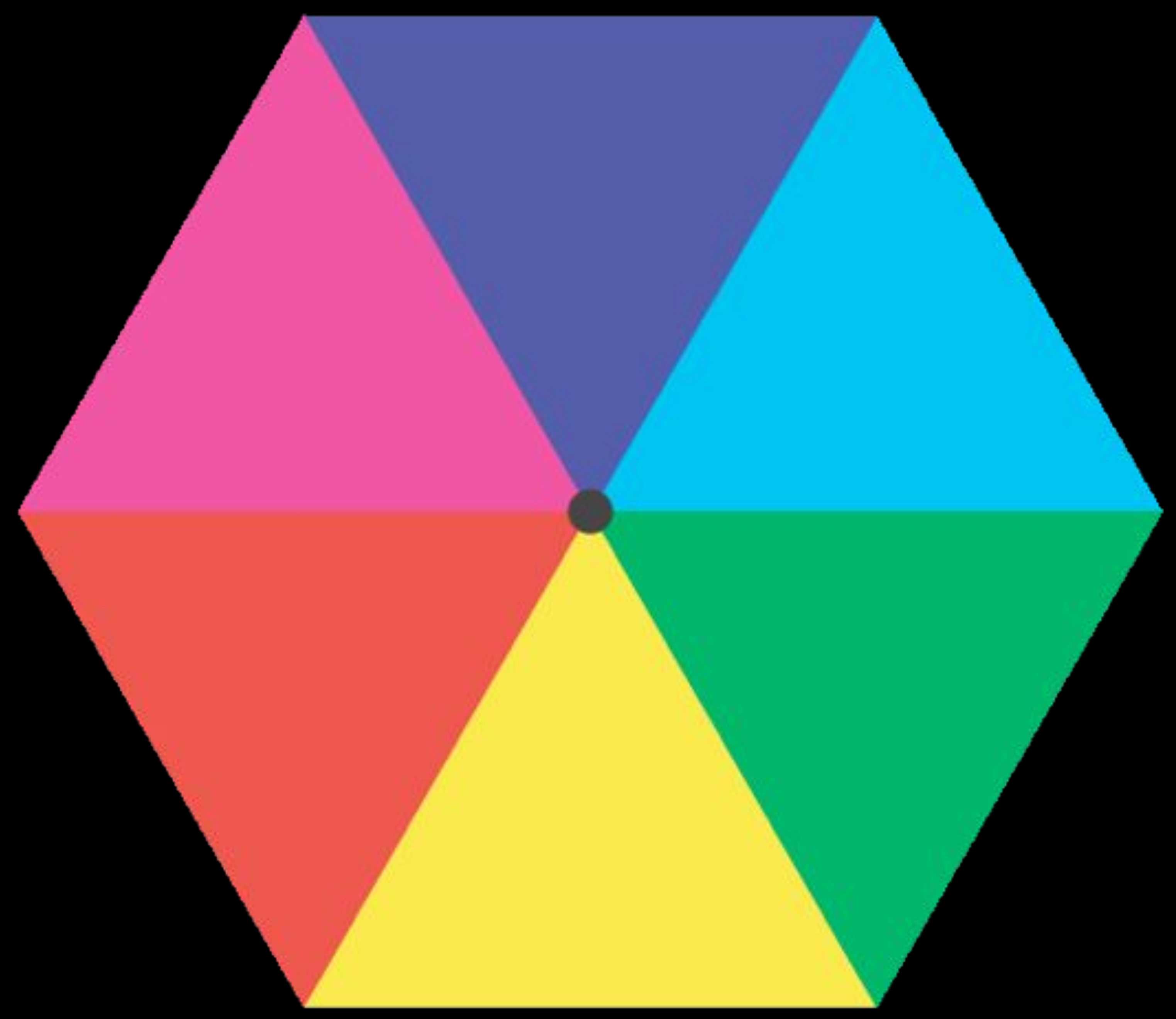
AfterImages:

Perception Operates on “Opponent” Color Axes

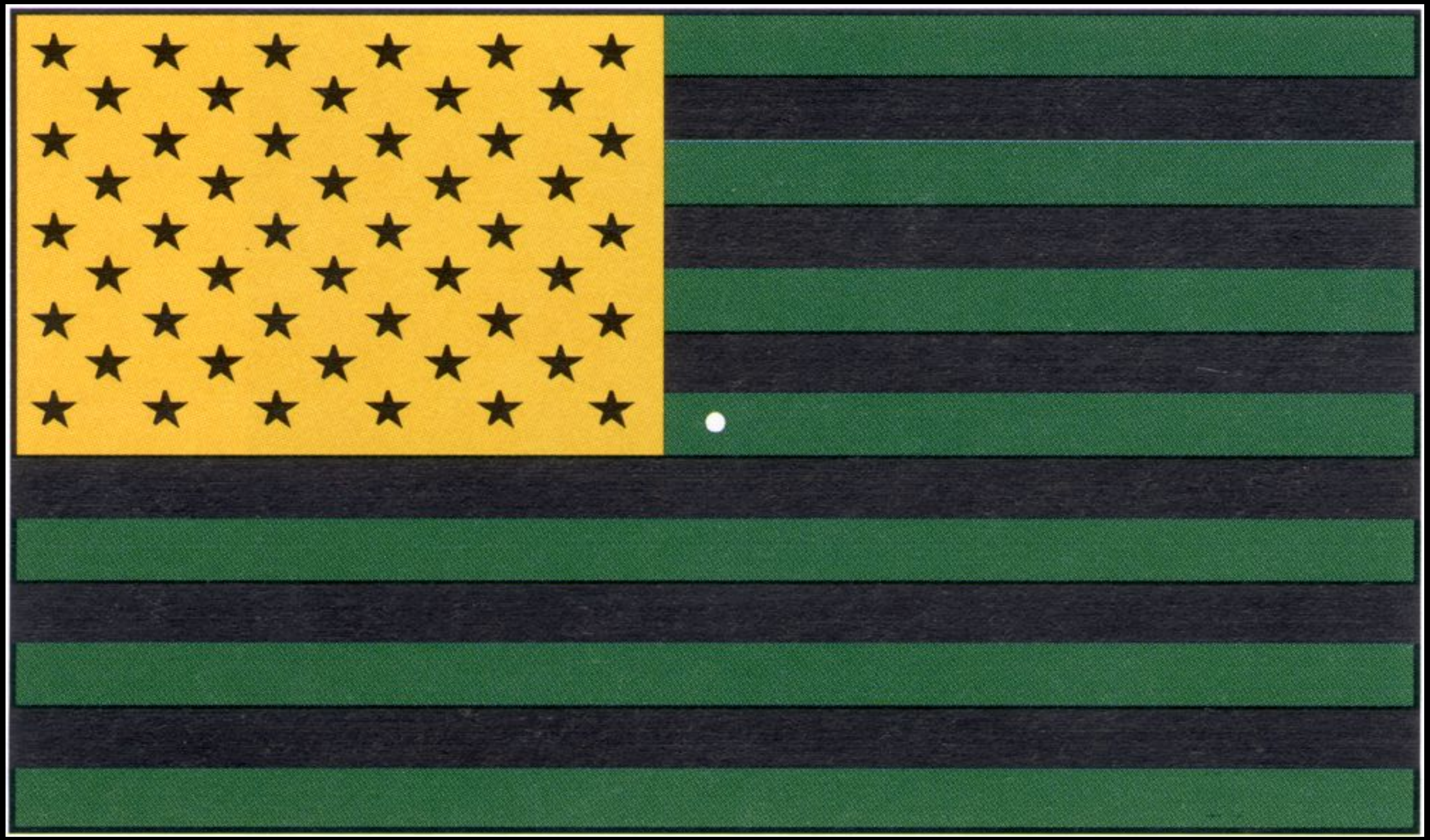




Image



Afterimage

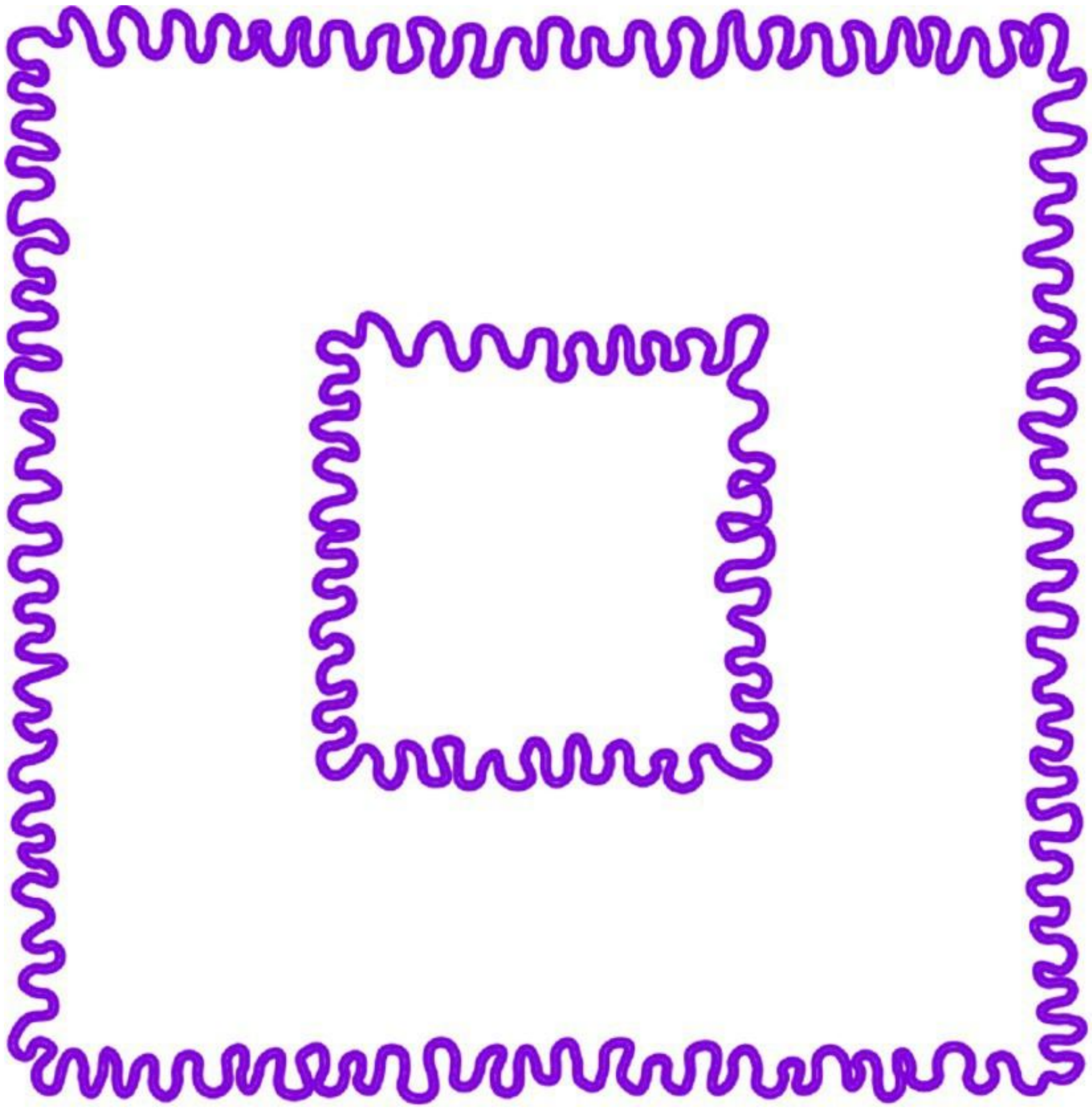



keep staring at the black dot.

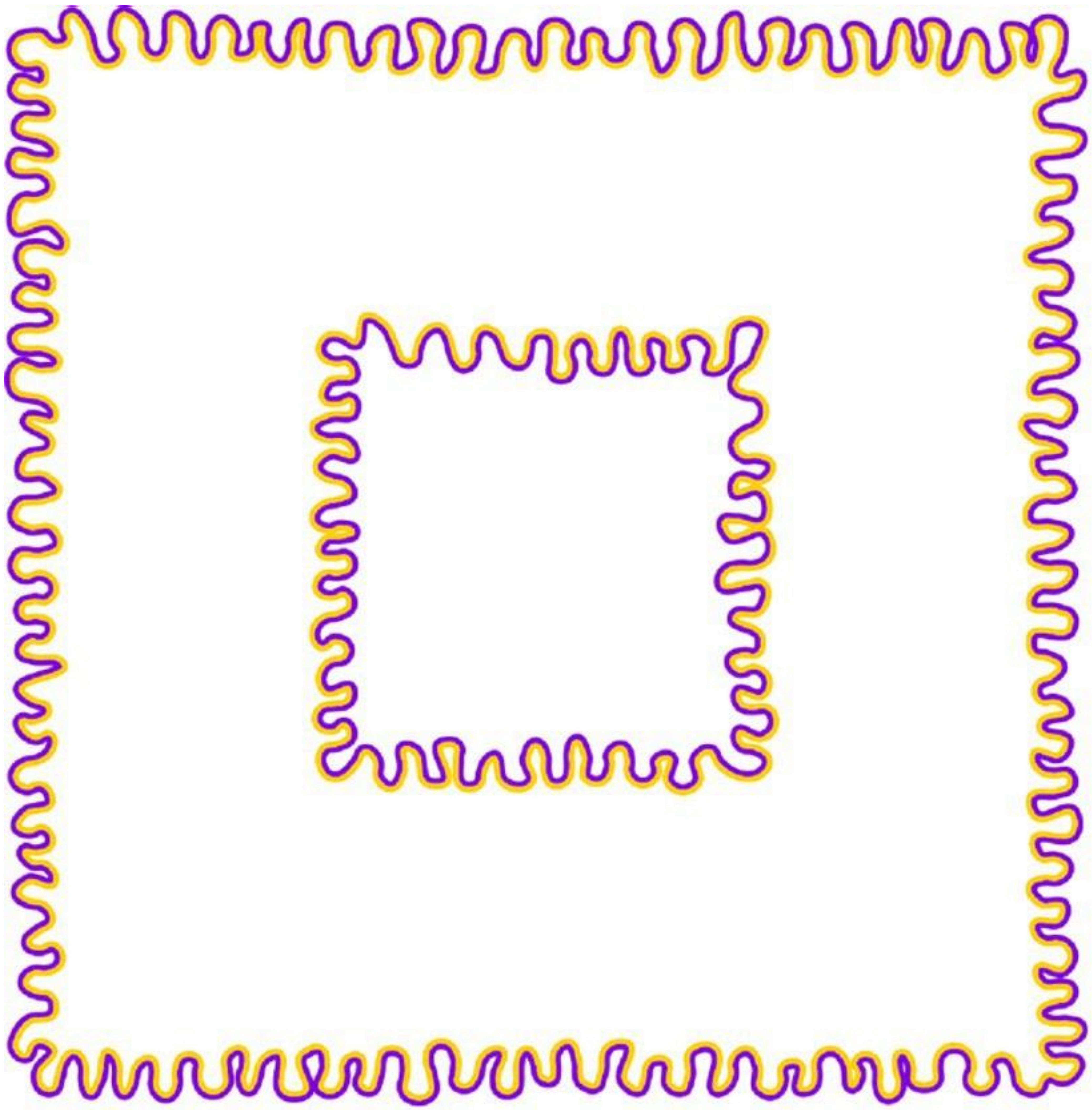

johnsadowski.com

Color Perception is Complex and Surprising

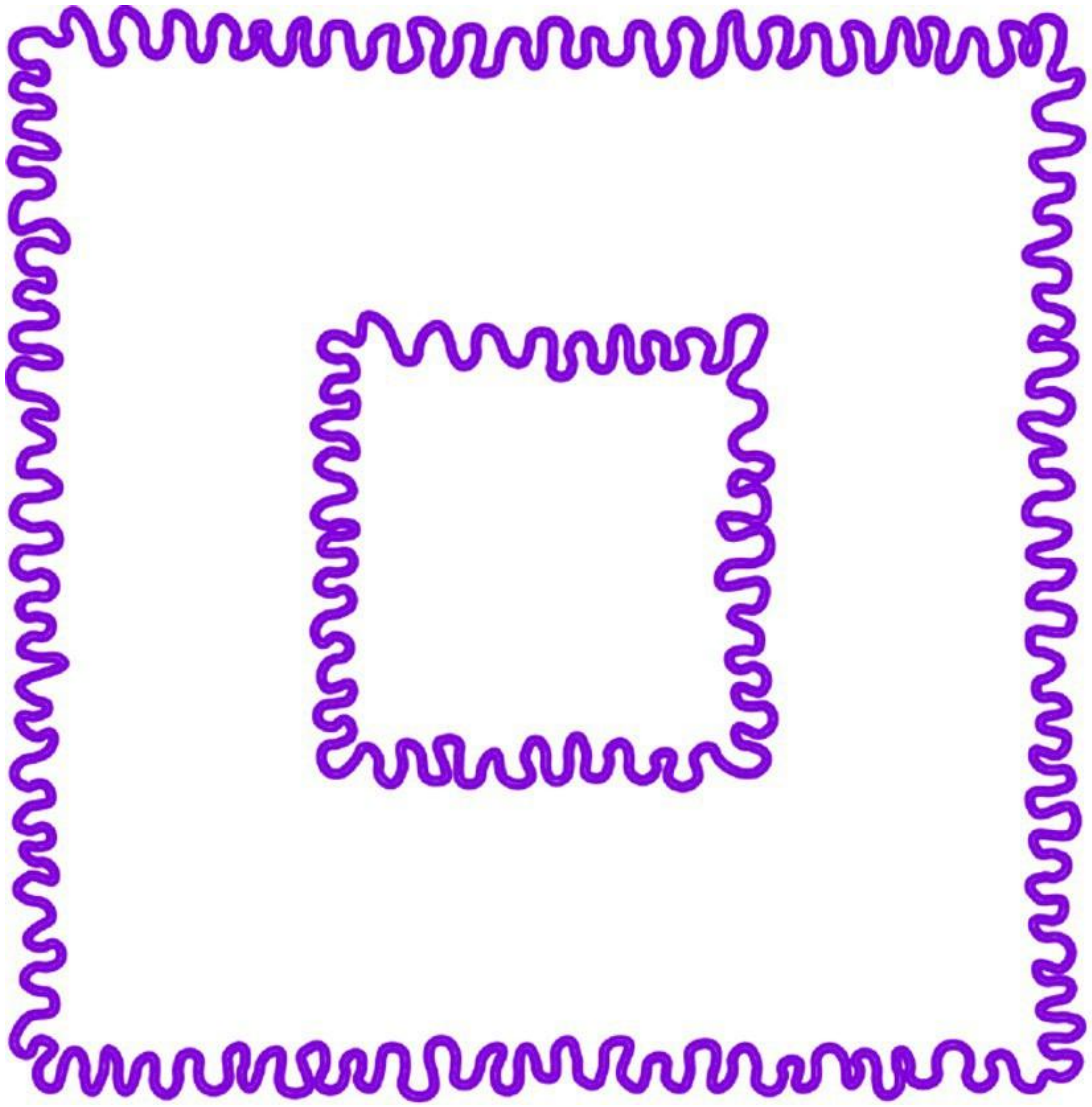
Watercolor Illusion

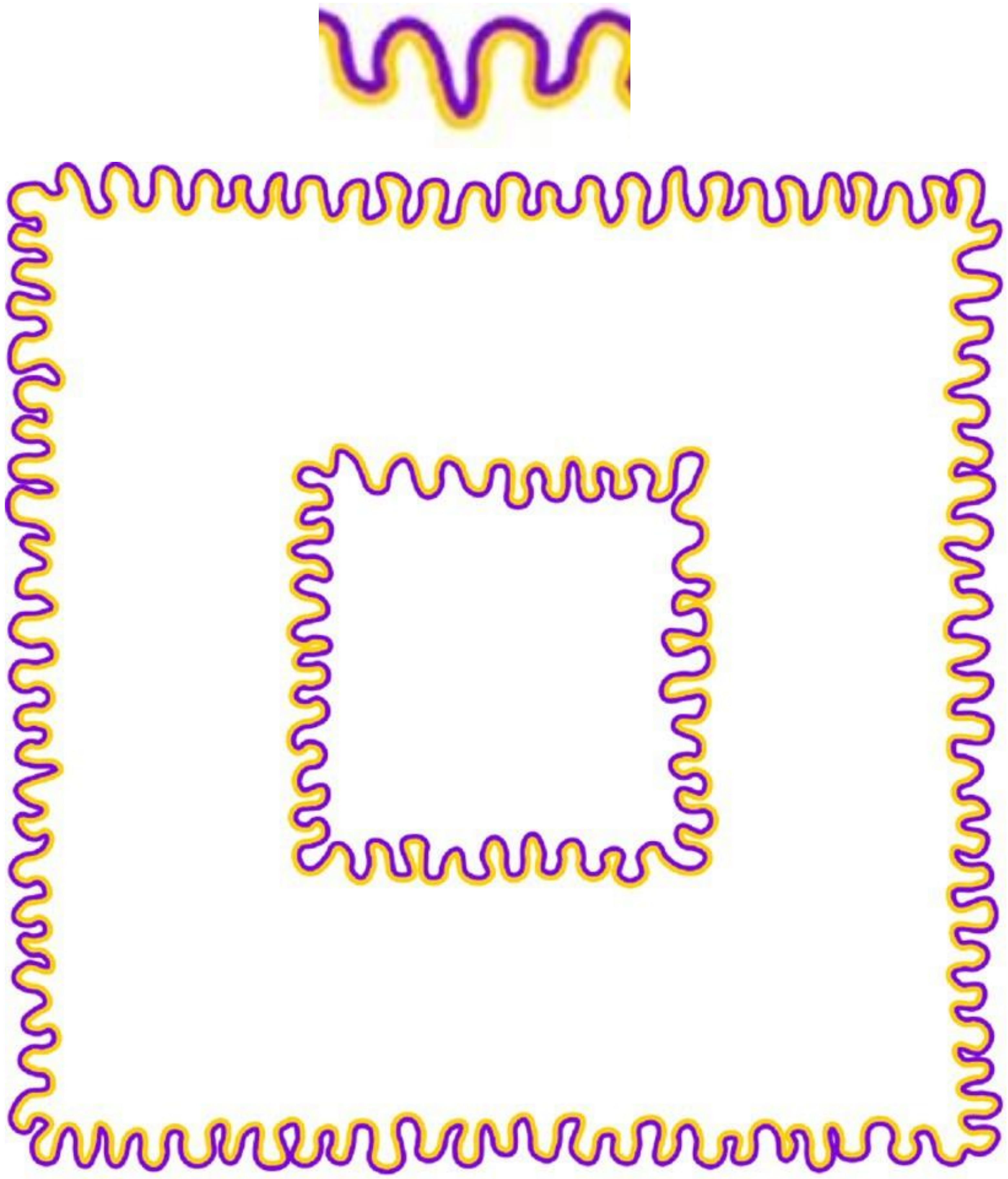


Watercolor Illusion



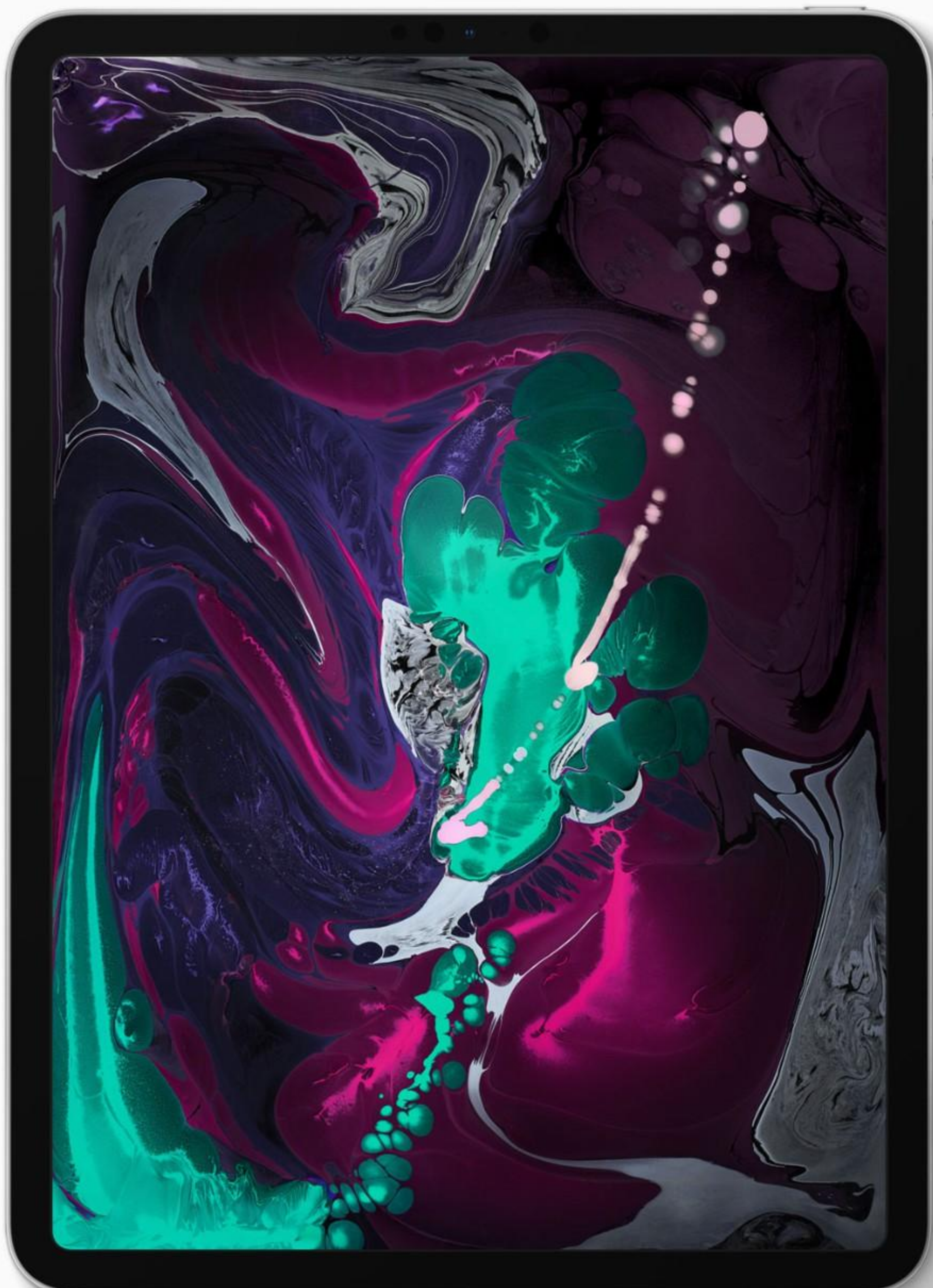
Watercolor Illusion



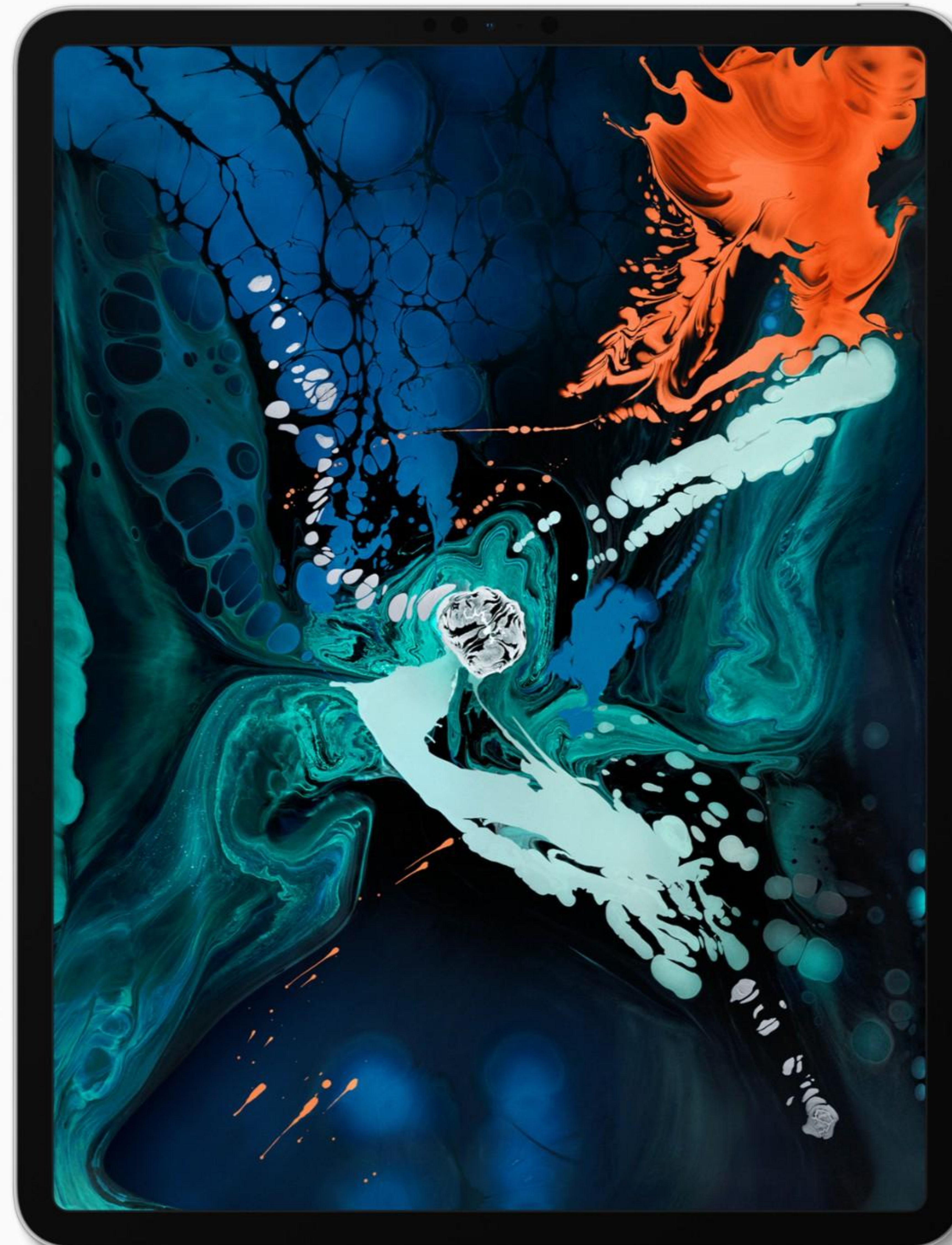


Pinna & Tanca, *JOV*, 2008

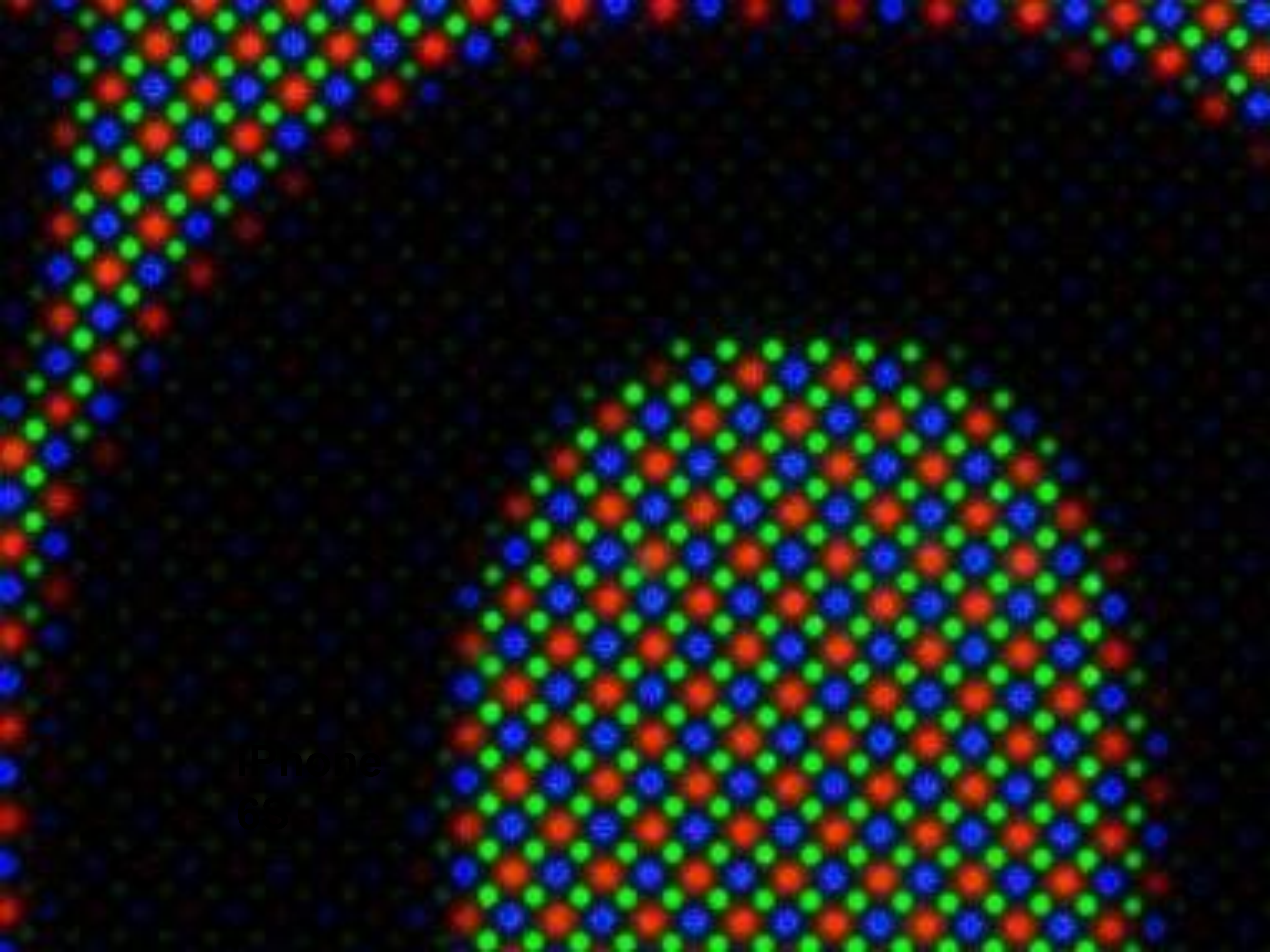
Yet, we understand color reproduction as a quantitative science...



11″

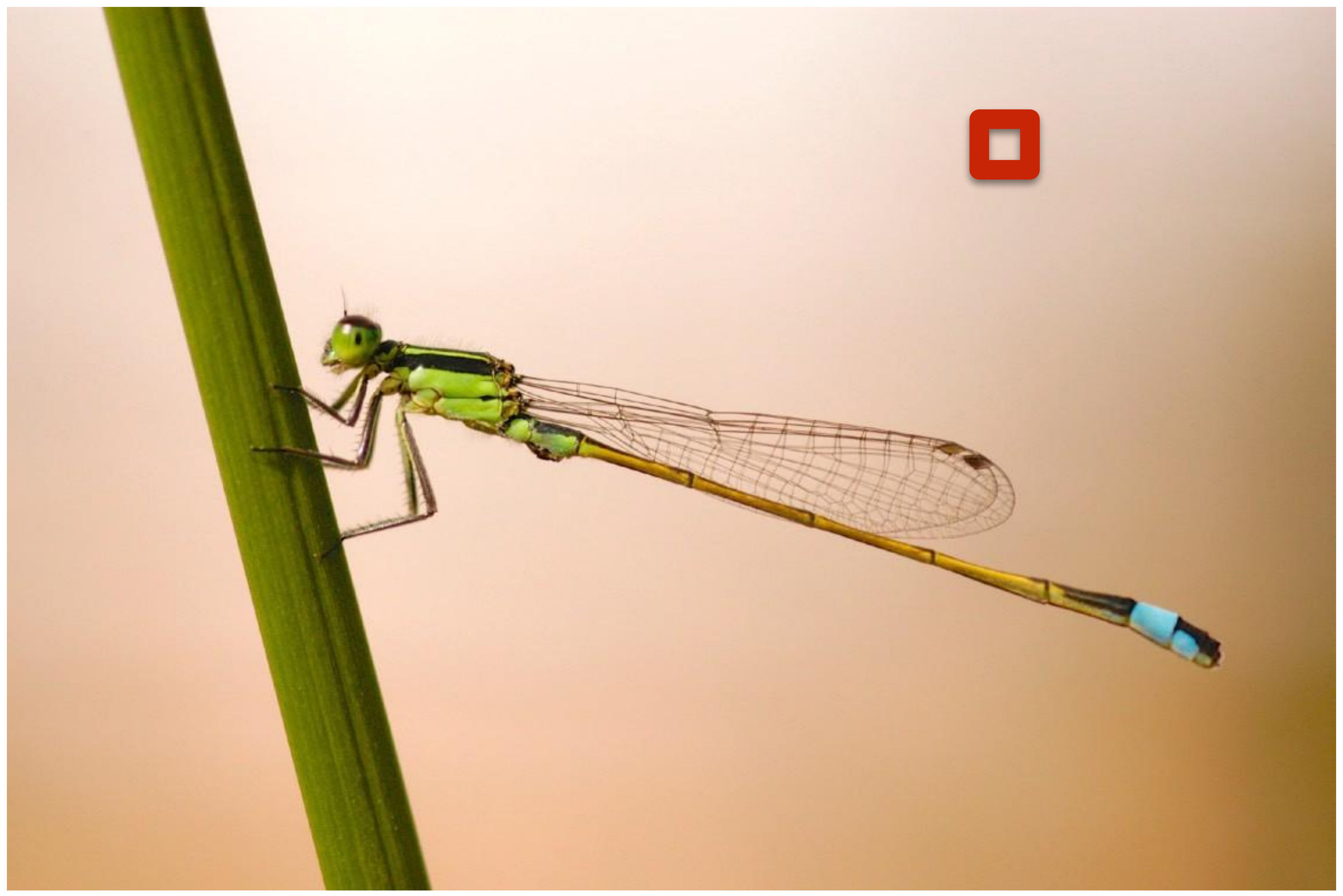


12.9″


iPhone
6S


Cancel
Send to Lightroom
lavender-73_Original-Edit-Edit
56%
30

Color Reproduction Problem



Real world damselfly

Display image of damselfly on computer screen

Lagos

What is Color?

What is Color?

- **Color** is a phenomenon of the human visual perception - it is not a universal property of light (photons).
- **Colors** are the visual sensation that we see from light of different **spectral power distributions**

Color Science

Sources of Optical Radiation: PHYSICS Characterization of Objects: PHYSICS, CHEMISTRY Perception: ANATOMY, PHYSIOLOGY, PSYCHOLOGY

Physical Basis of Color

credit: Science Media Group.

Isaac Newton's Experimentum Crucis

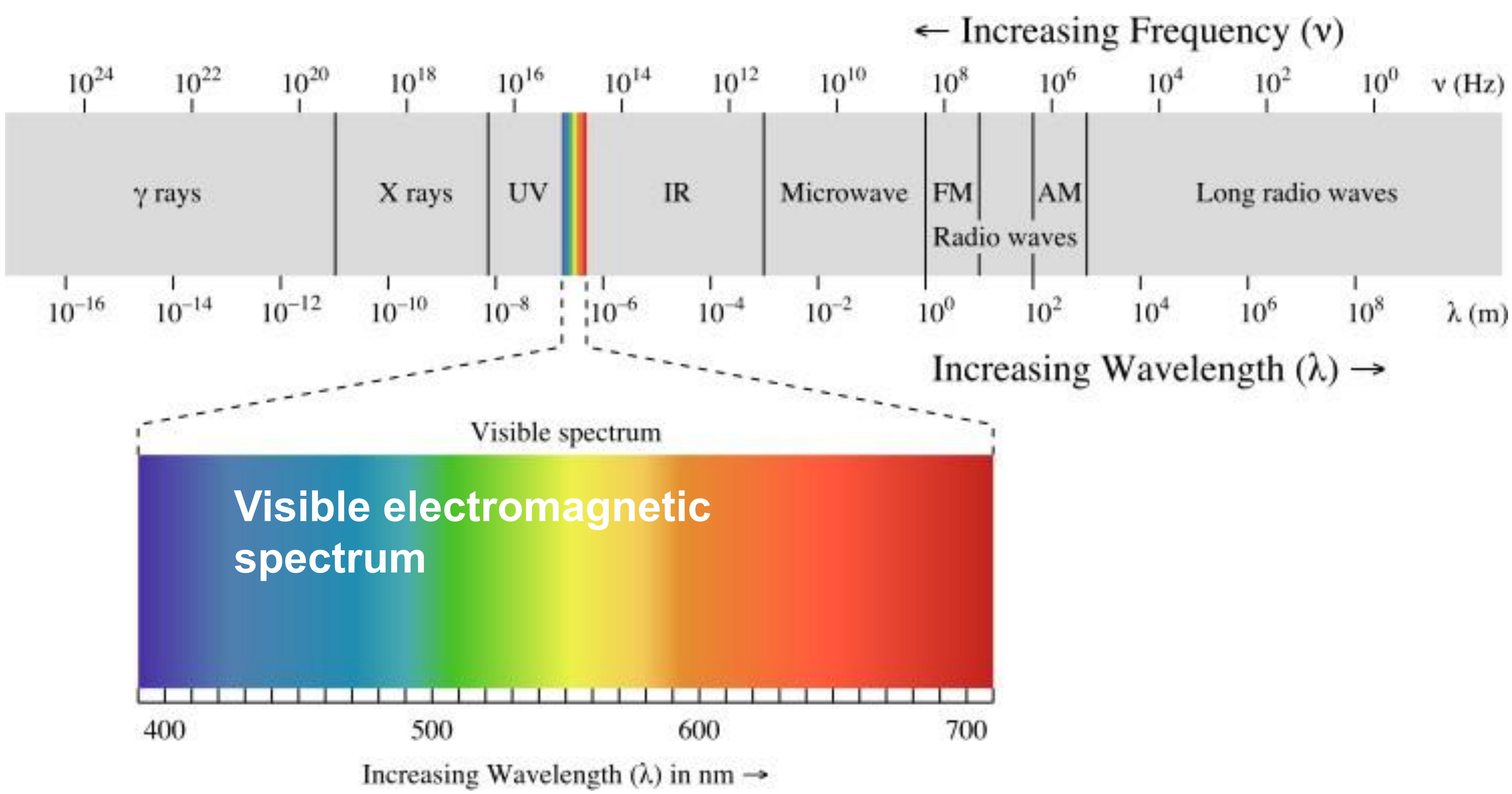
The 'experimentum crucis' – in his Woolsthorpe Manor bedroom. Acrylic painting by Sascha Grusche (17 Dec 2015)

- Newton showed sunlight can be subdivided into a rainbow with a prism
- Resulting light cannot be further subdivided with a second prism

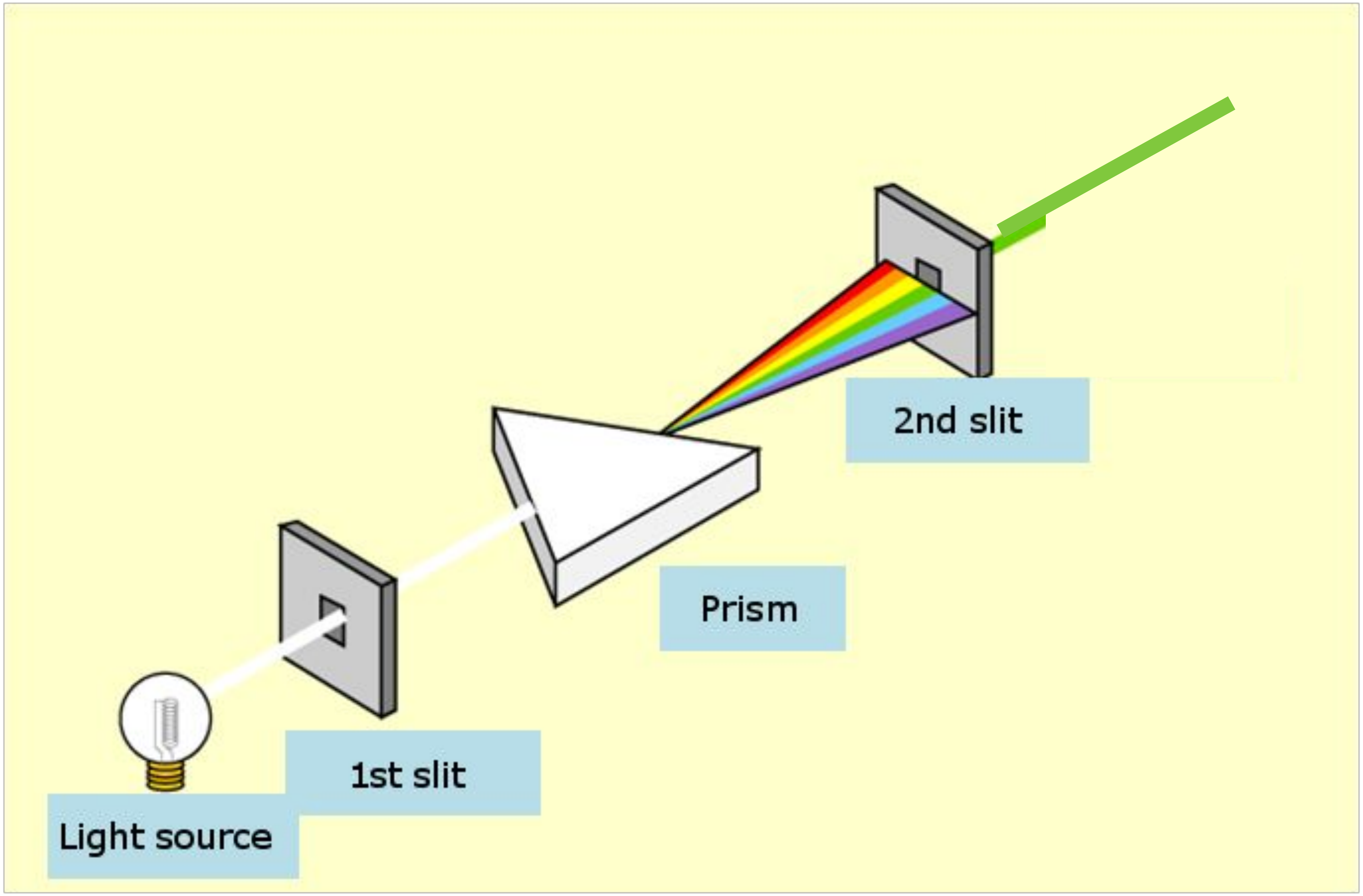
The Visible Spectrum of Light

Electromagnetic radiation

- Oscillations of different frequencies (wavelengths)



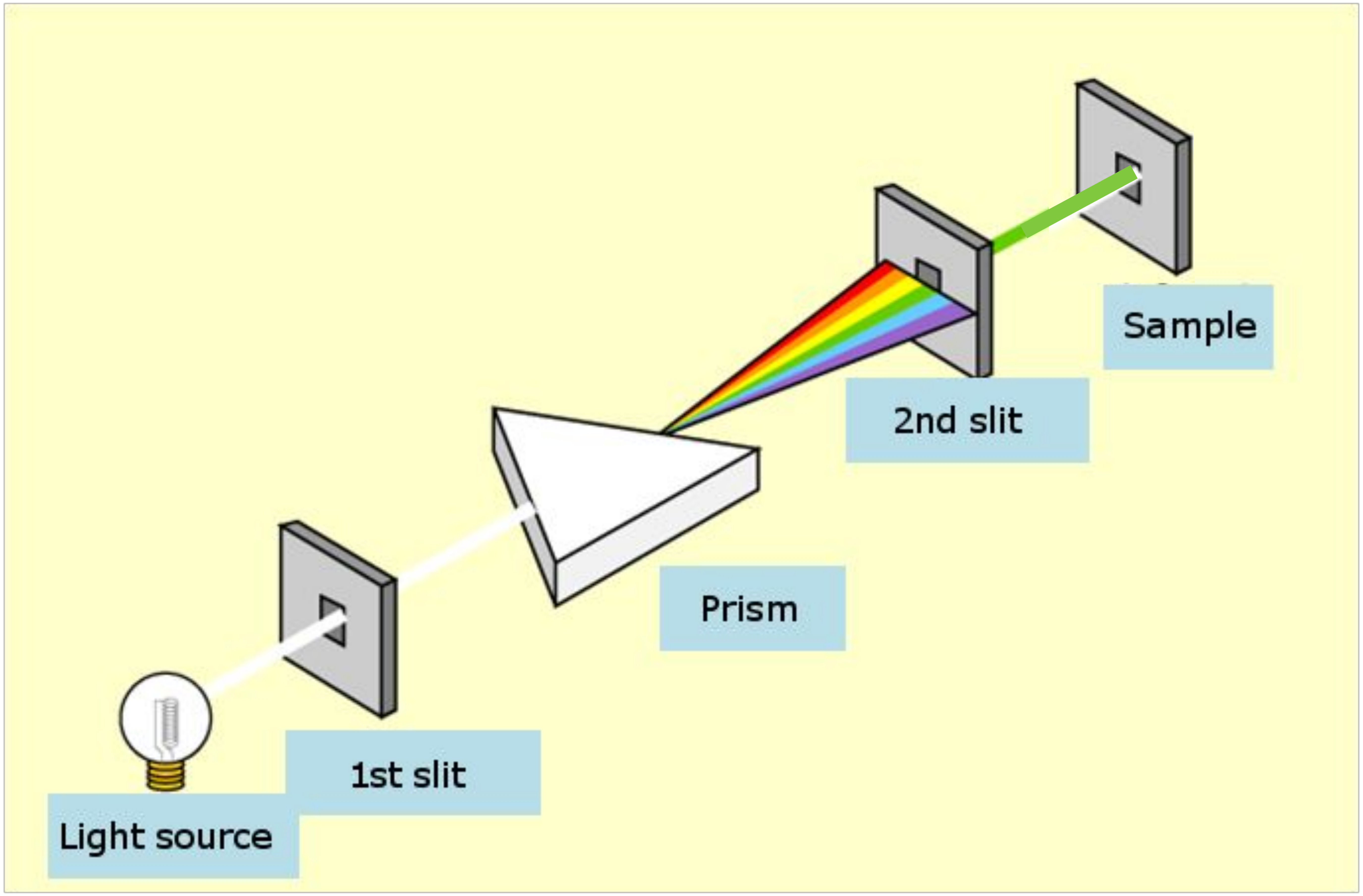
Monochromator



A monochromator delivers light of a single wavelength from a light source with broad spectrum. Control which wavelength by angle of prism.

Hegyi et al. "Introduction to Practical Biochemistry" http://elte.prompt.hu/sites/default/files/tananyagok/IntroductionToPracticalBiochemistry/ch04s07.html

Spectrometer



For an unknown light source, use a monochromator to isolate each wavelength of light for measurement.

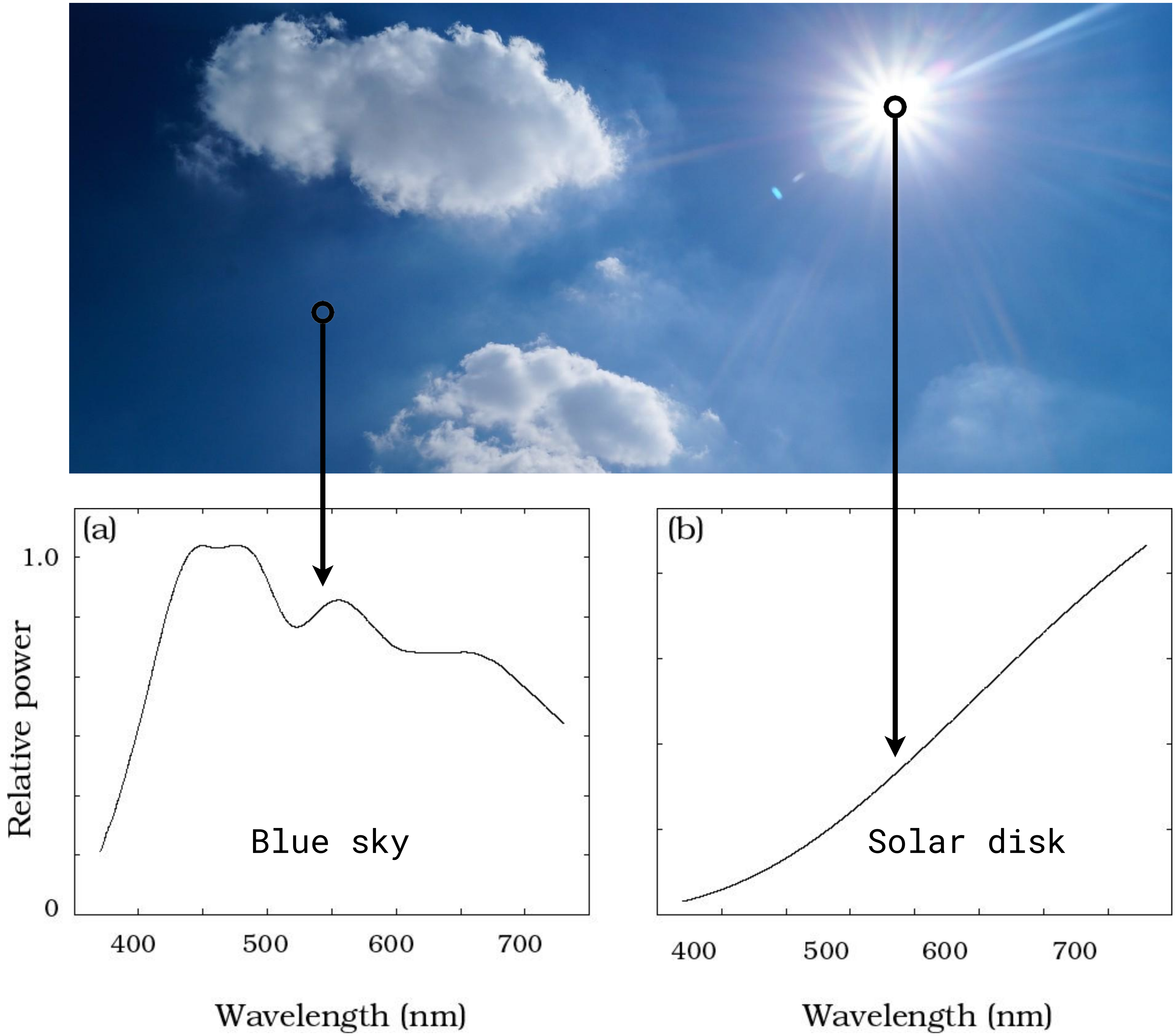
Hegyi et al. "Introduction to Practical Biochemistry" http://elte.prompt.hu/sites/default/files/tananyagok/IntroductionToPracticalBiochemistry/ch04s07.html

Spectral Power Distribution (SPD)

Salient property in measuring light

- The amount of light present at each wavelength

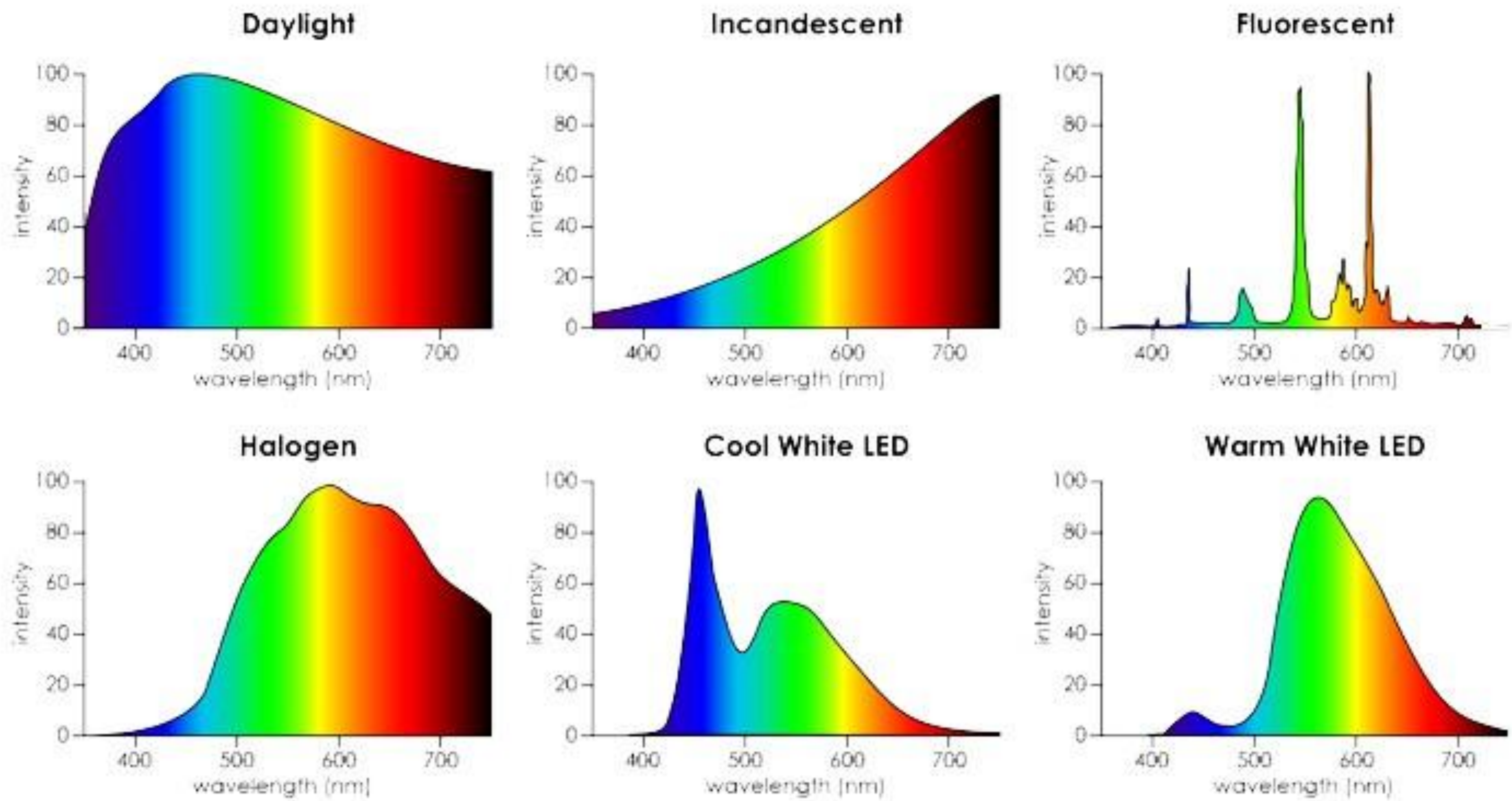
Daylight Spectral Power Distributions



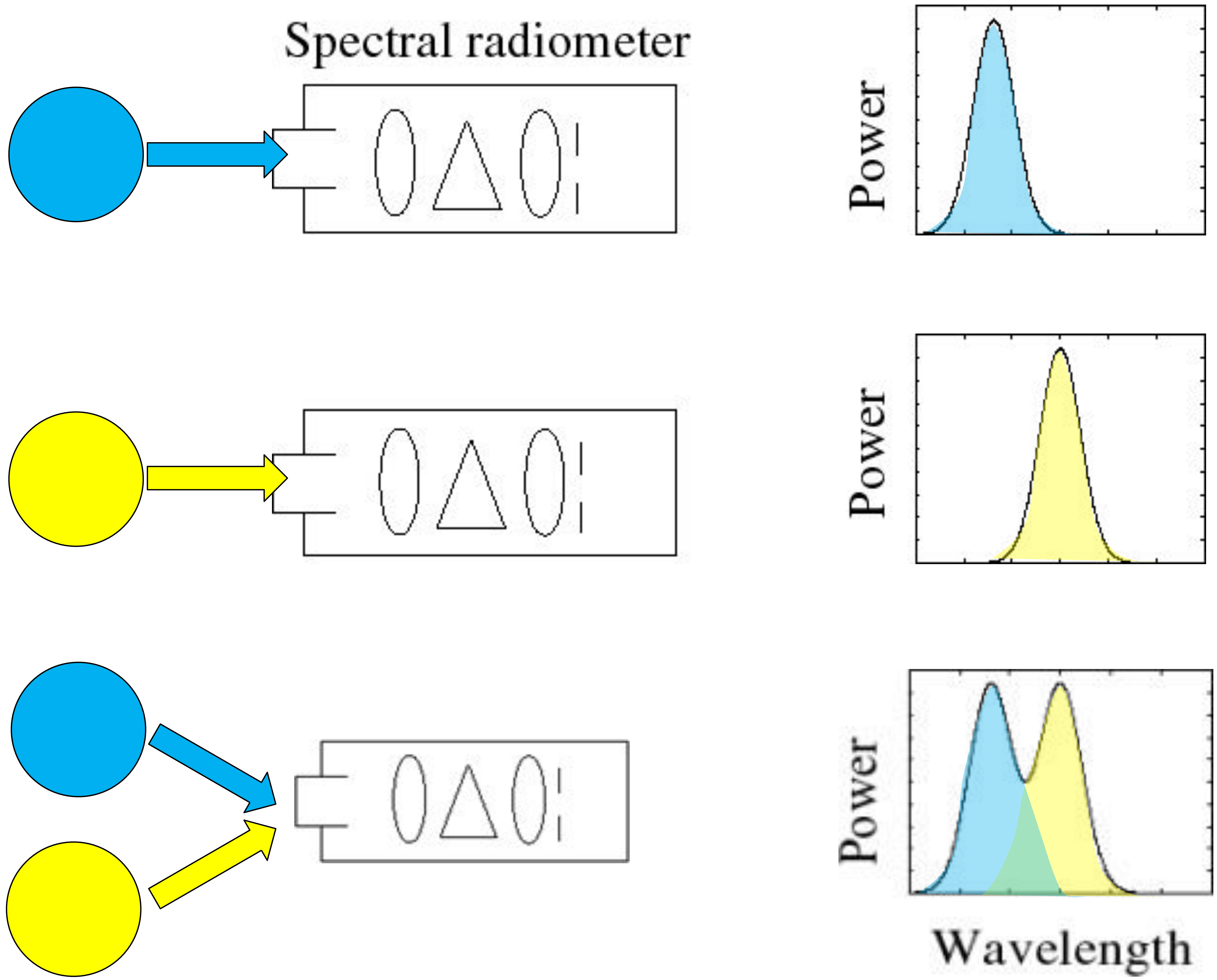
[Brian Wandell]

Spectral Power Distribution of Light Sources

Distribution of energy by wavelength



Superposition (Linearity) of Spectral Power Distributions

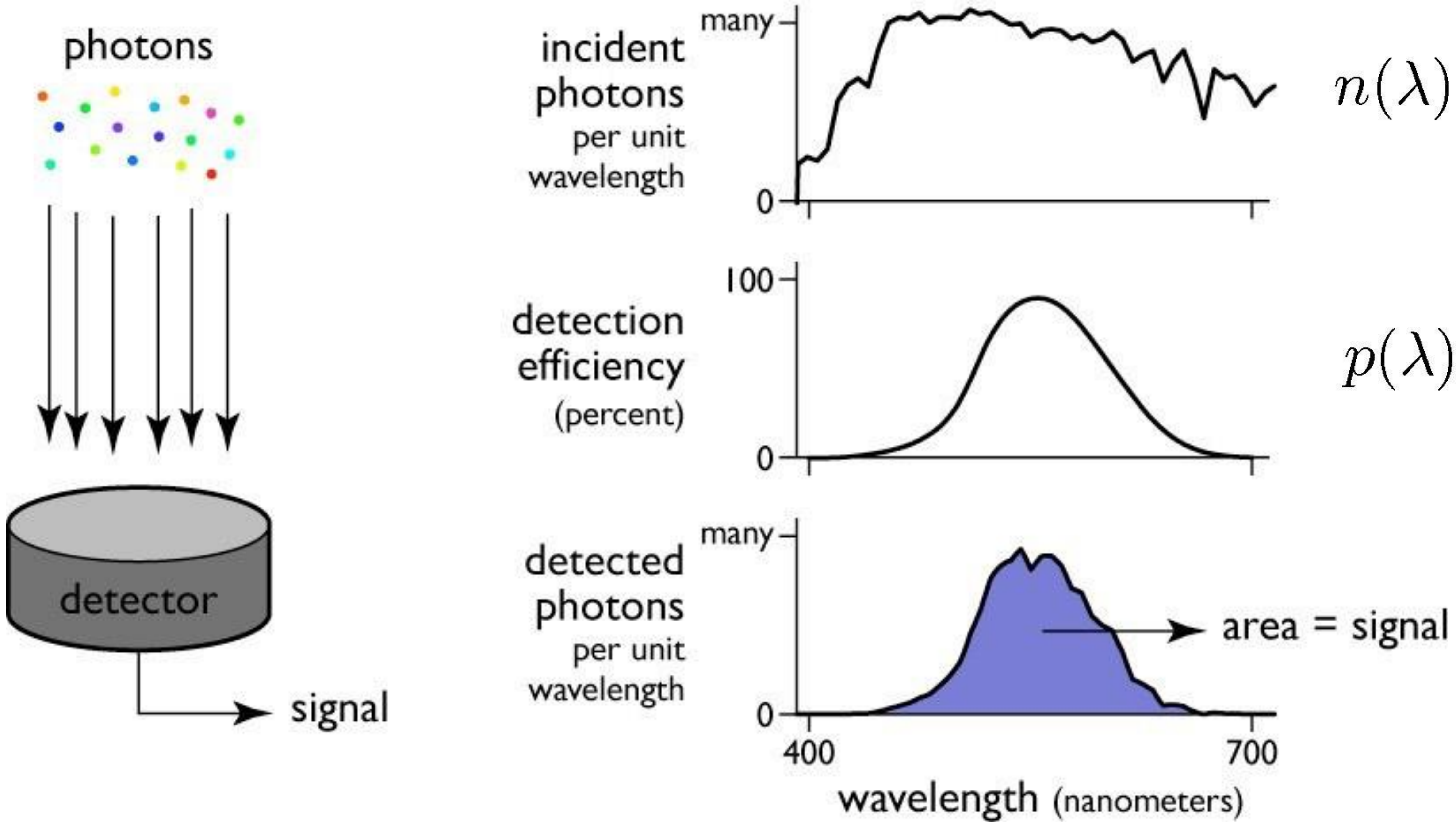


[Brian Wandell]

Measuring Light

A Simple Model of a Light Detector

A Simple Model of a Light Detector



$n(\lambda)$

$p(\lambda)$

Credit: Marschner

$$X = \int n(\lambda)p(\lambda)\, d\lambda$$

Mathematics of Light Detection

Same math carries over to spectral power distributions

- Light entering the detector has its spectral power distribution, s(λ)
- Detector has its spectral sensitivity or spectral response, r(λ)

$$X = \int s(\lambda) r(\lambda) \, d\lambda$$

measured signal

detector's sensitivity

input spectrum

Mathematics of Light Detection

If we think of s and r as discrete, sampled representations (vectors) rather than continuous functions, this integral operation is a dot product:

$$X = s \cdot r$$

We can also write this in matrix form:

$$X = \begin{bmatrix} - & s & - \end{bmatrix} \begin{bmatrix} | \\ r \\ | \end{bmatrix}$$

Dimensionality Reduction From ∞ to 1

At the detector:

- **SPD is a function of wavelength** (∞ dimensional signal)
- **Detector result is a scalar value** (1 dimensional signal)

Tristimulus Theory of Color

Searching for a Linear Systems Basis for Colors:

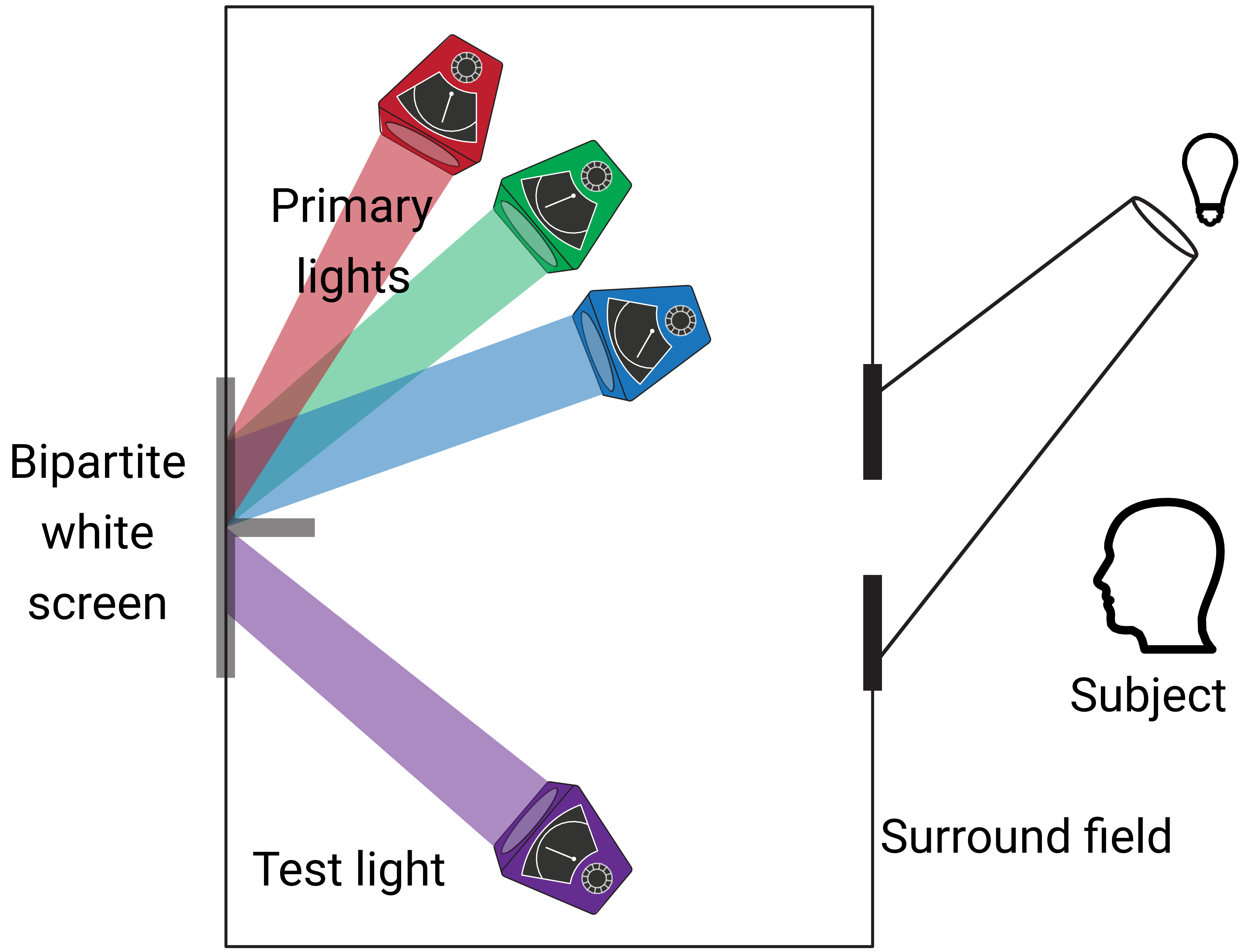
The Color Matching Experiment

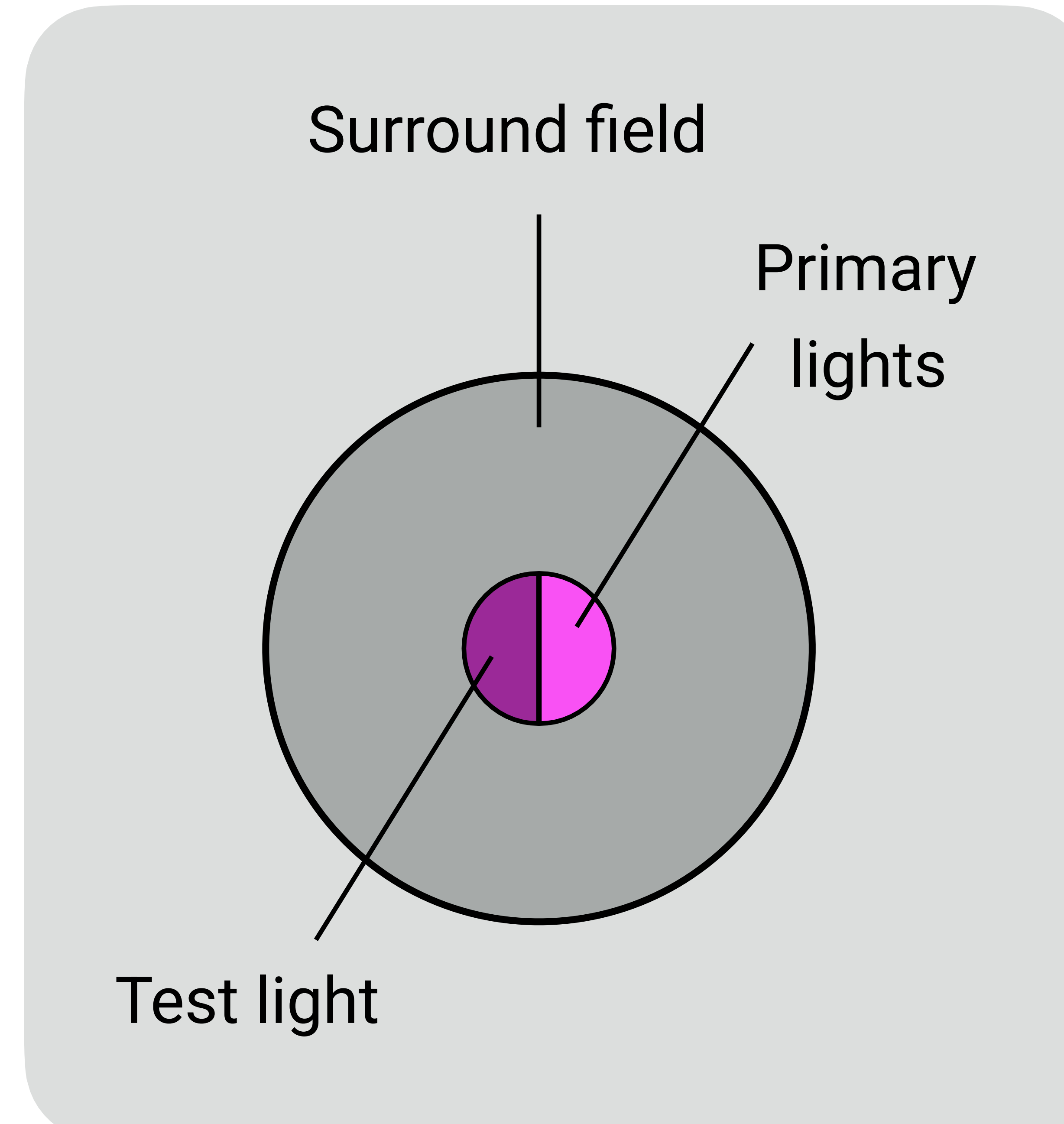
Maxwell's Crucial Color Matching Experiment

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

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

Color Matching Experiment

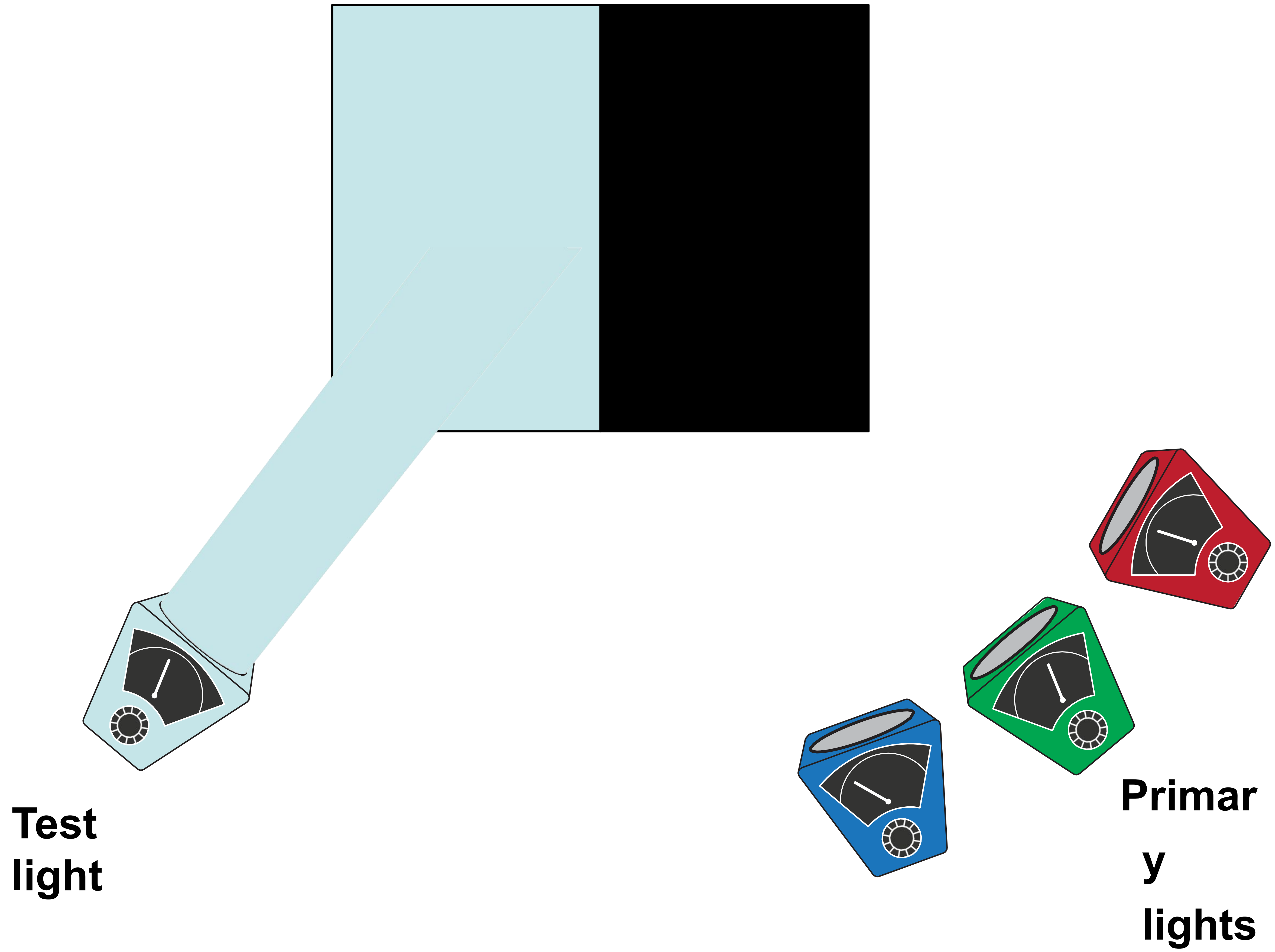




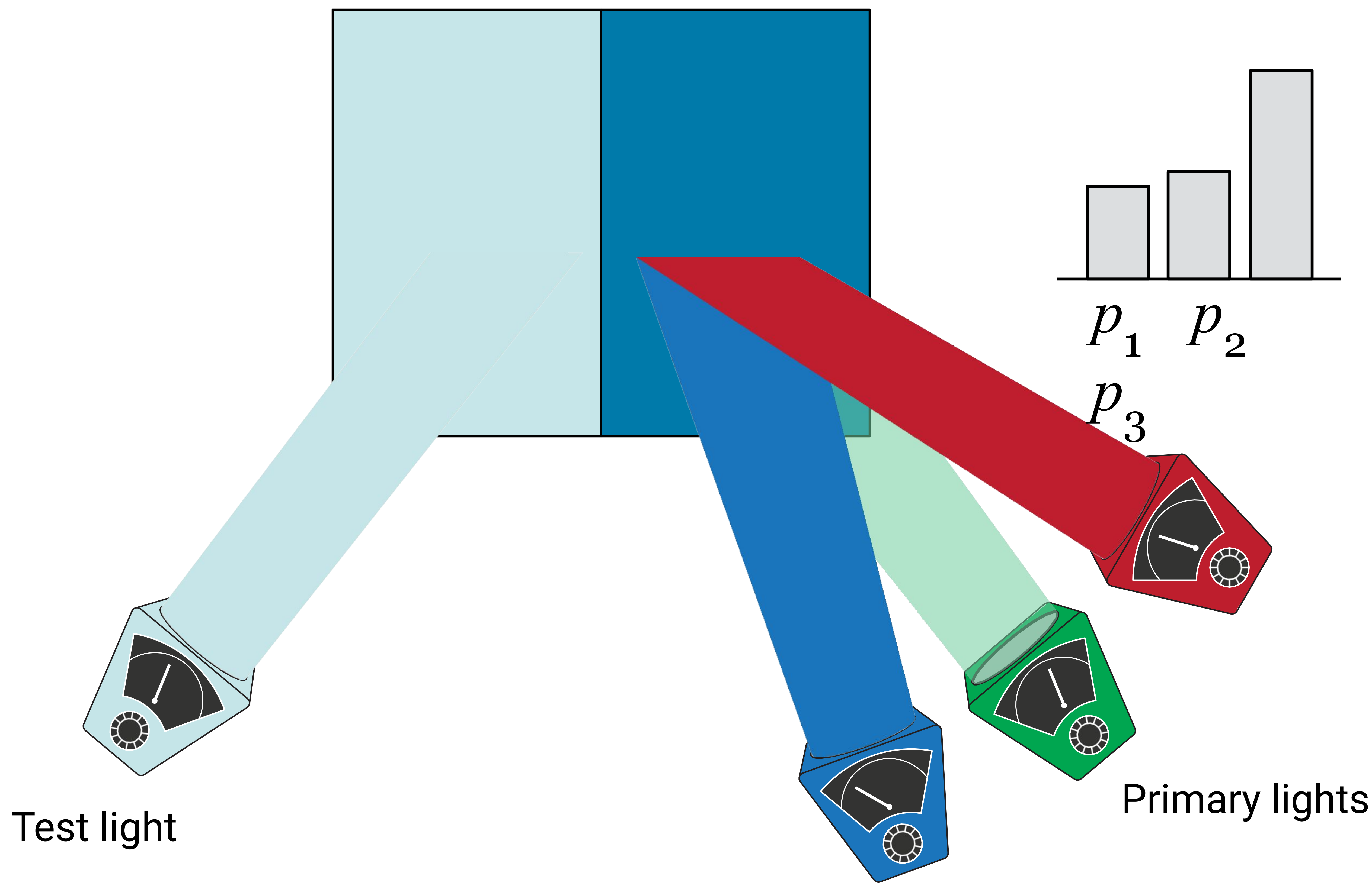
Same idea as spinning top, fancier implementation (Maxwell did this too)

1. Show test light spectrum on left
2. Mix “primaries” on right until they match
3. The primaries need not be RGB

Example Experiment

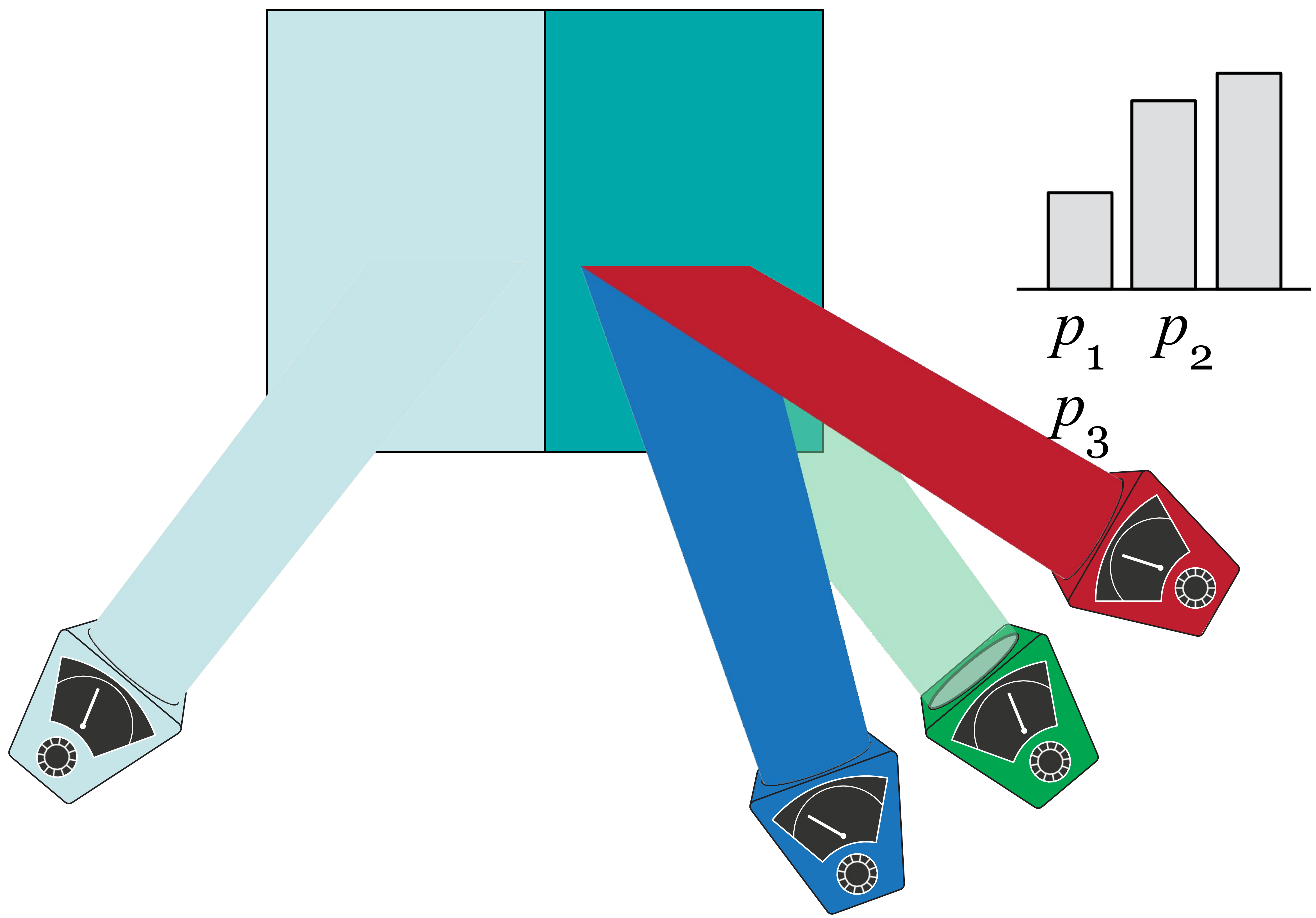


Example Experiment



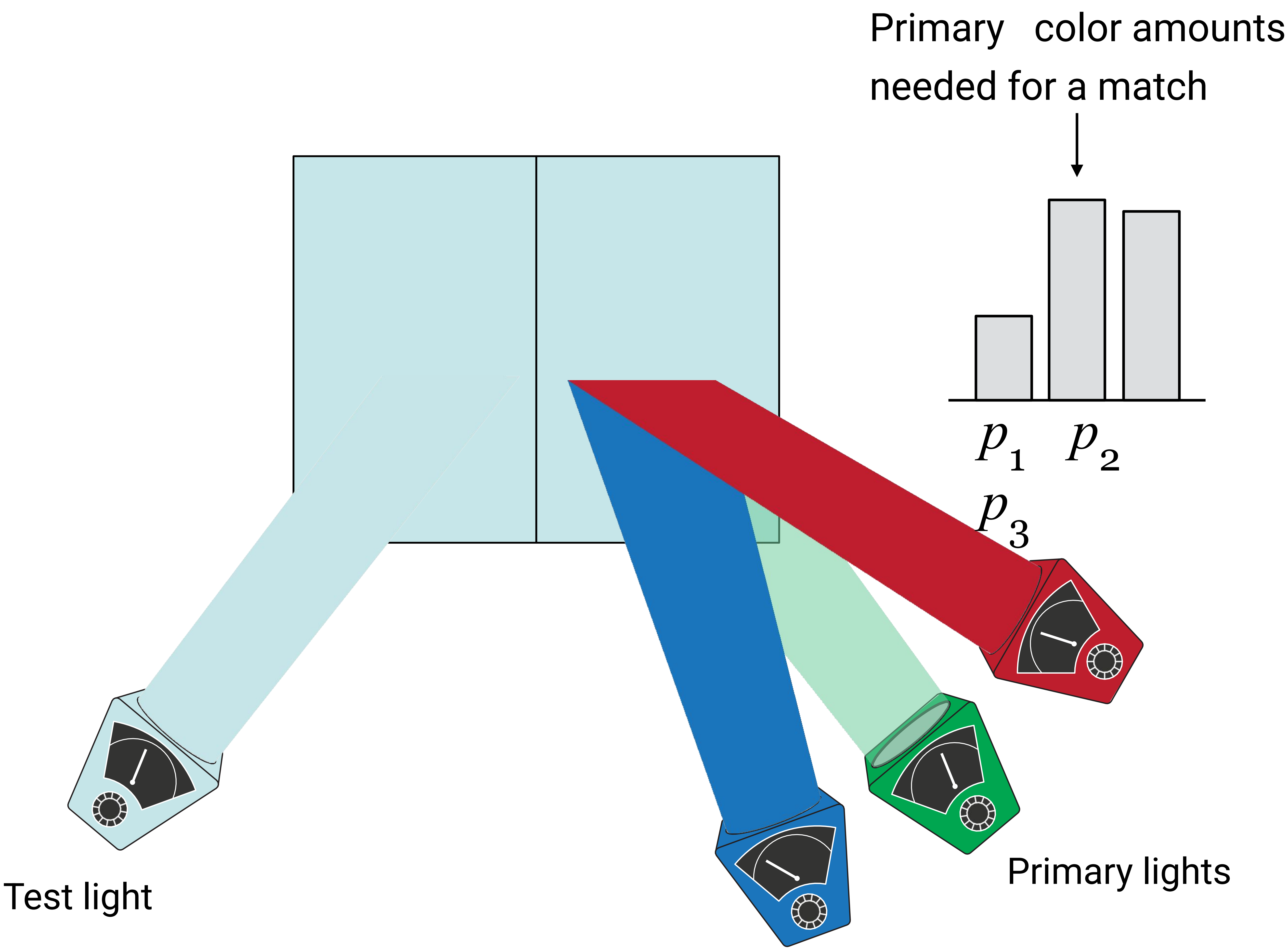
Slide credit: Kotani, Durand, Freeman

Example Experiment



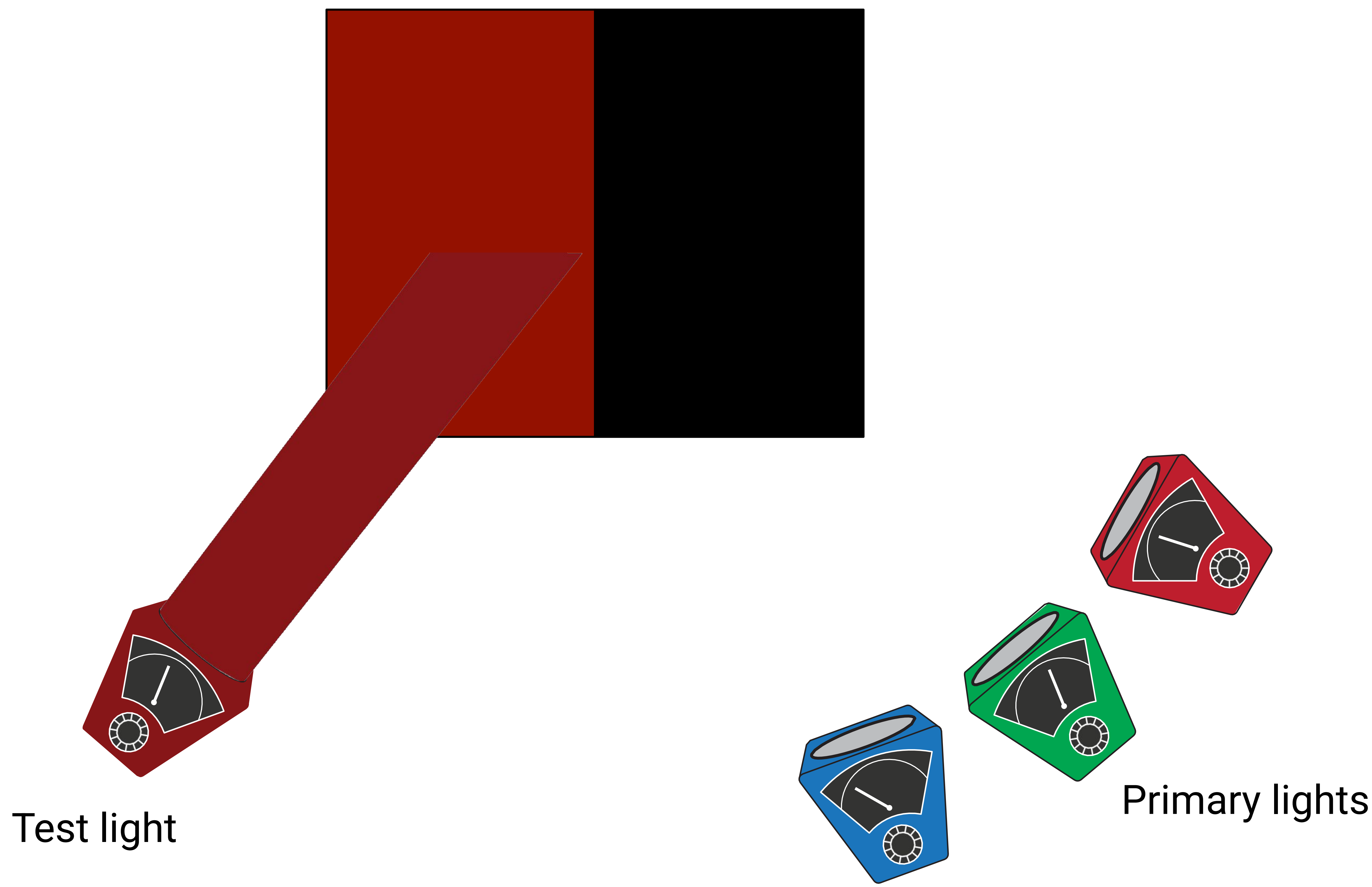
Slide credit: Kotani, Durand, Freeman

Example Experiment



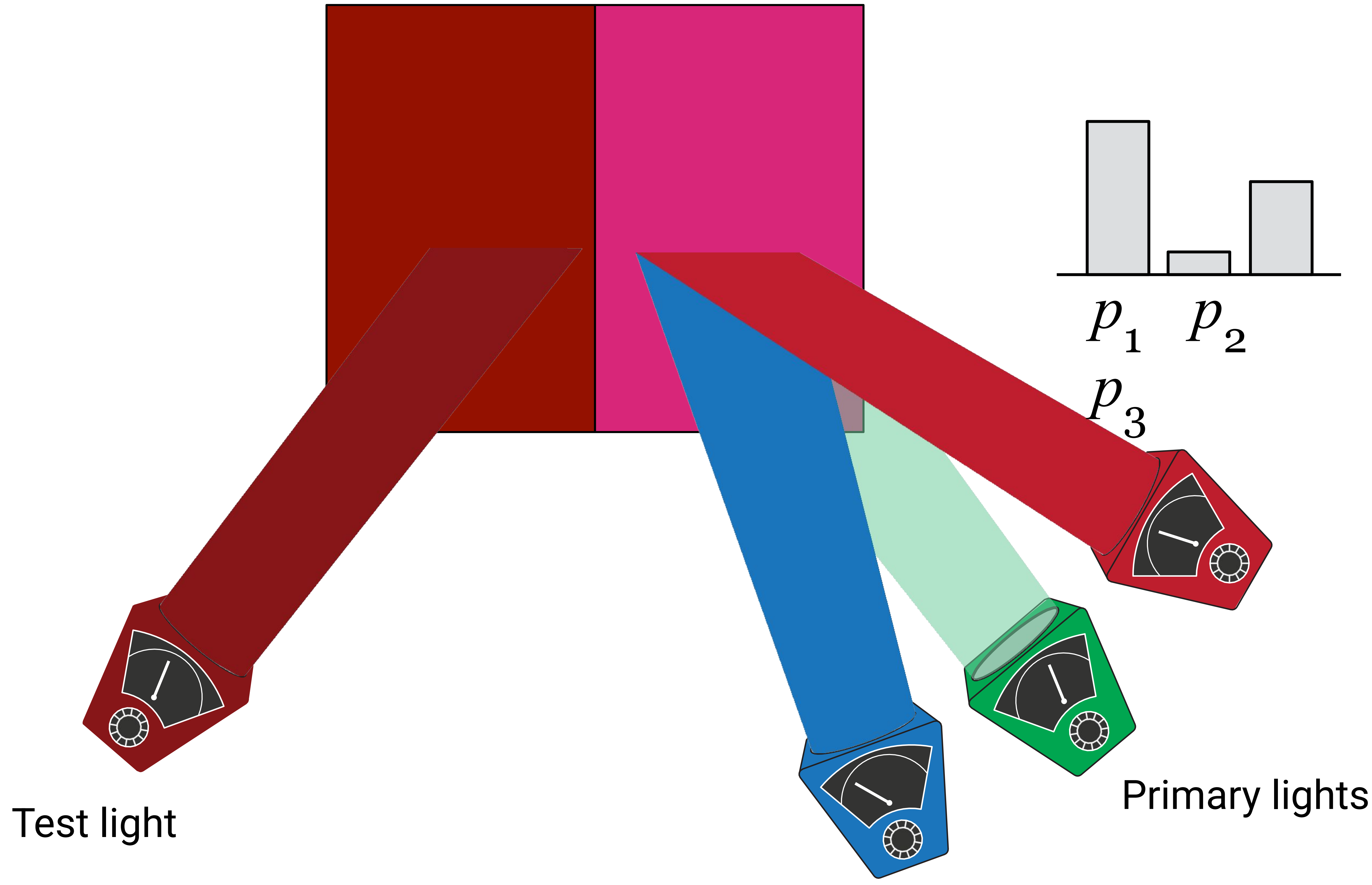
Slide credit: Kotani, Durand, Freeman

Experiment 2: Out of Gamut



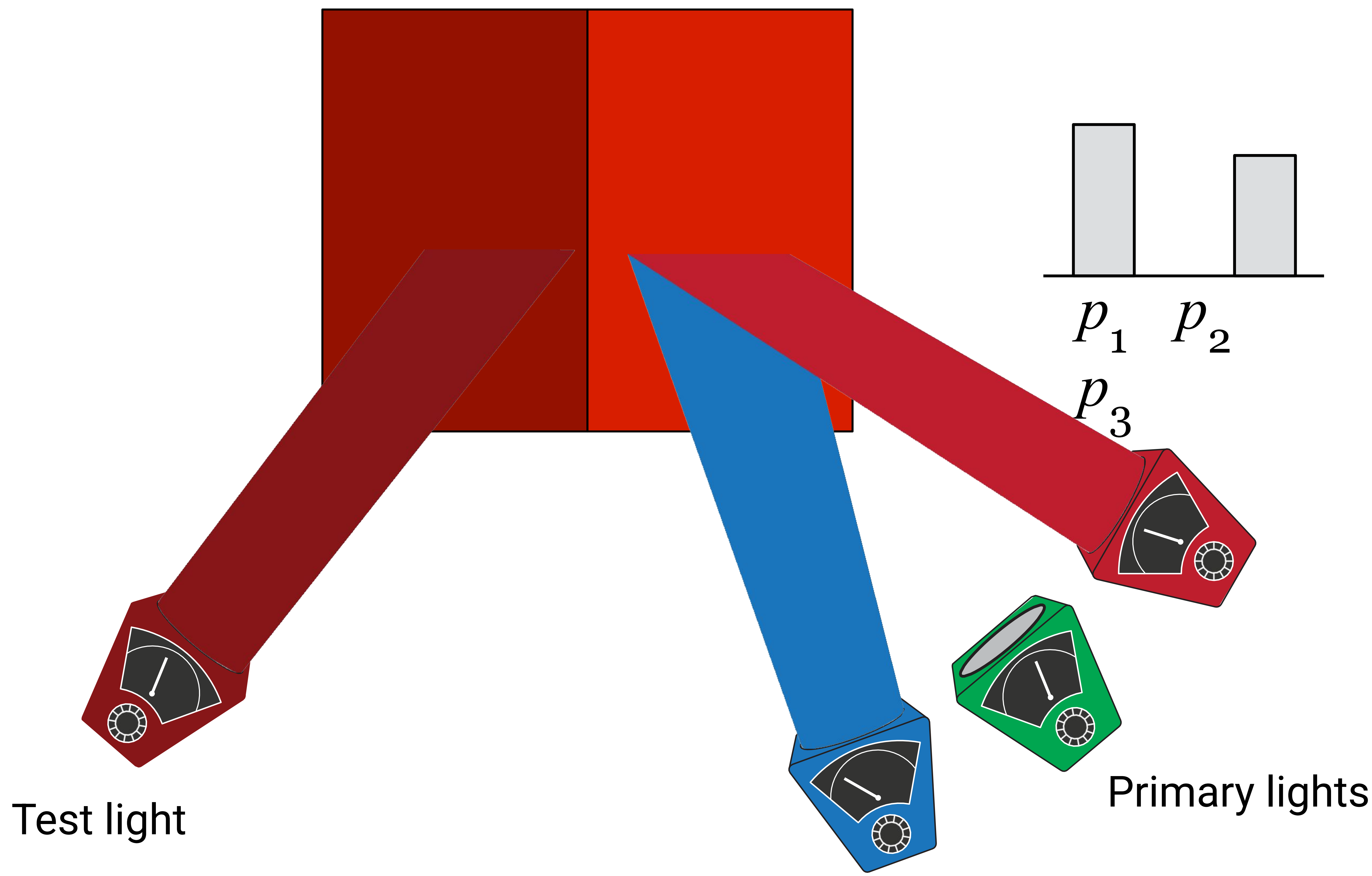
Slide credit: Kotani, Durand, Freeman

Experiment 2: Out of Gamut



Slide credit: Kotani, Durand, Freeman

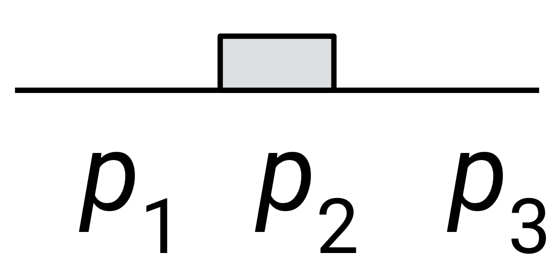
Experiment 2: Out of Gamut

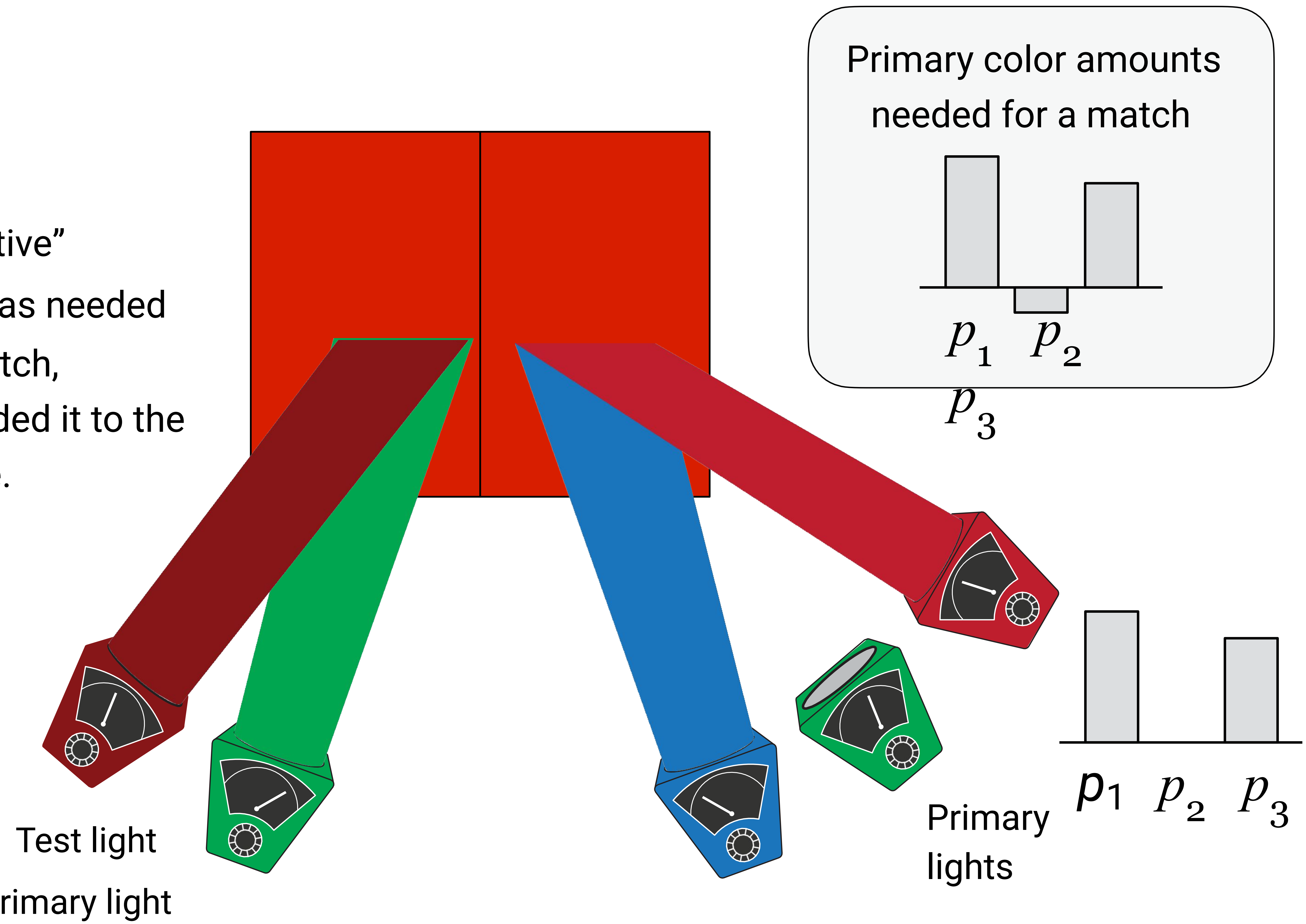


Slide credit: Kotani, Durand, Freeman

Experiment 2: Out of Gamut

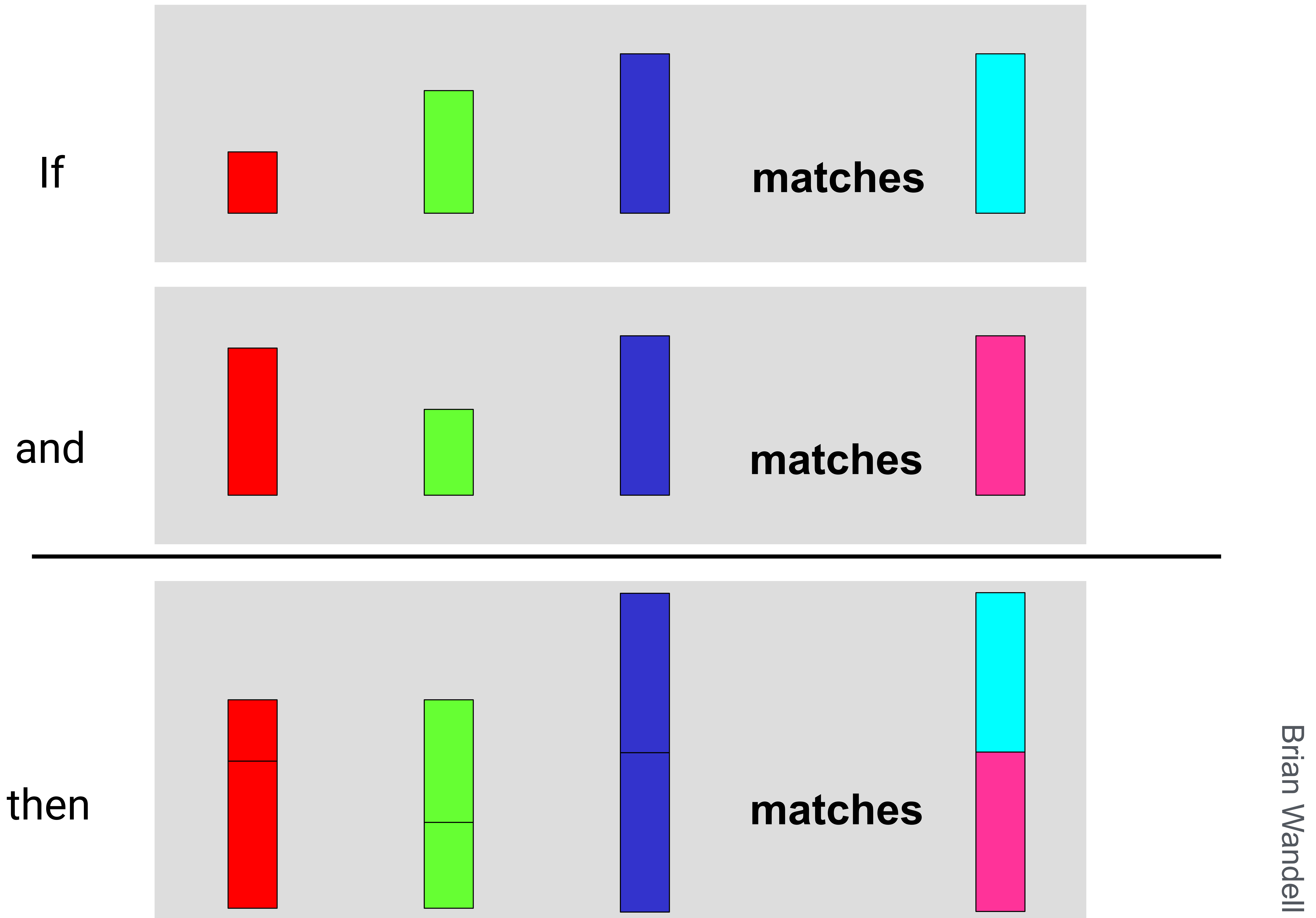
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.





Slide credit: Kotani, Durand, Freeman

The Color Matching Experiment is Linear



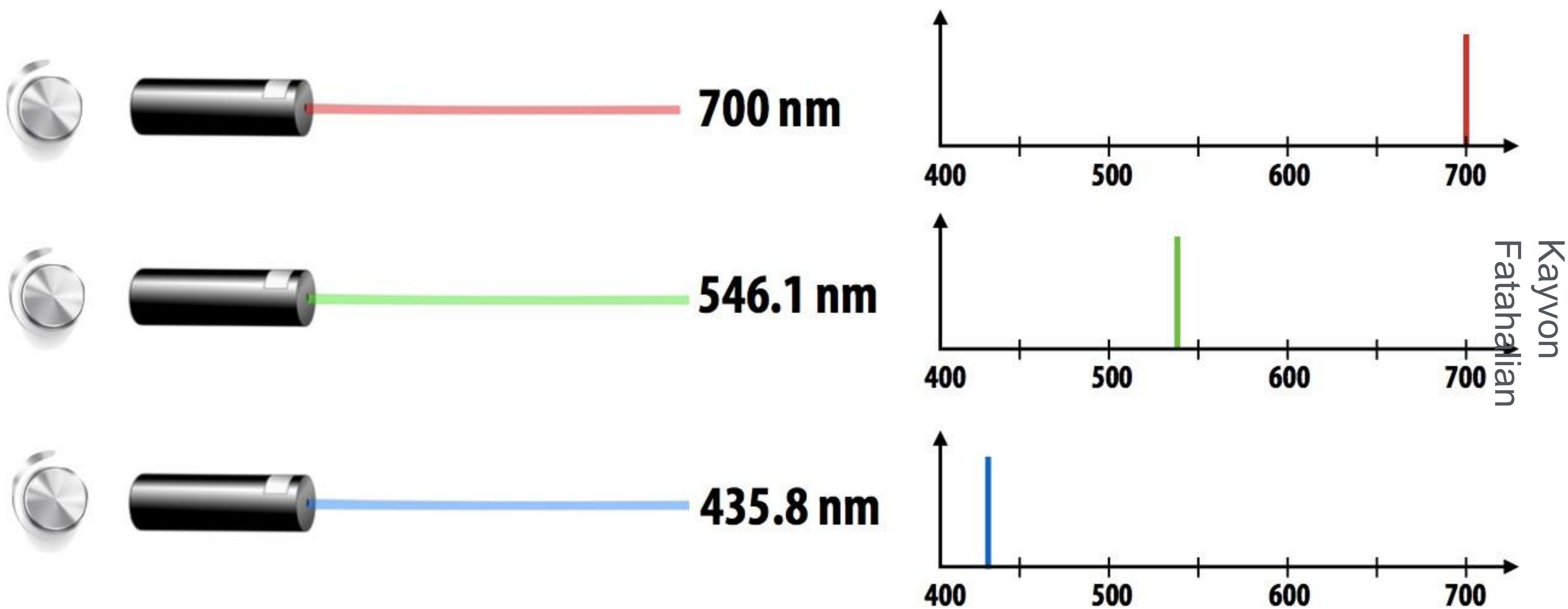
What is the Dimensionality of Human Color Perception?

What is the definition of “dimension” here?

- We can appeal to linear systems theory, where “dimension” equals the rank of a basis for the linear space.

CIE RGB Color Matching Experiment

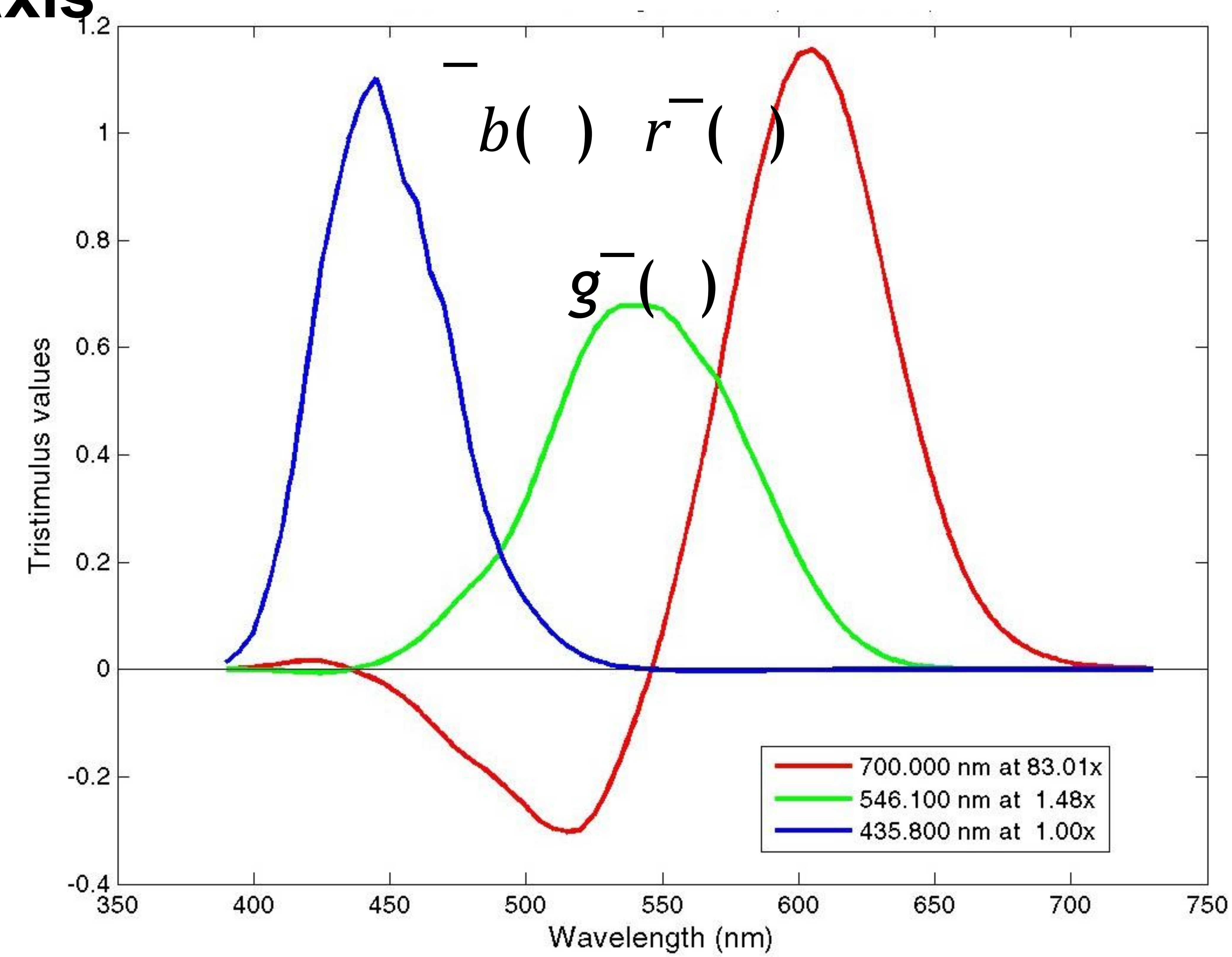
Same setup as additive color matching before, but primaries are monochromatic light (single wavelength) of the following wavelengths defined by CIE RGB standard



The test light is also a monochromatic light

CIE RGB Color Matching Functions

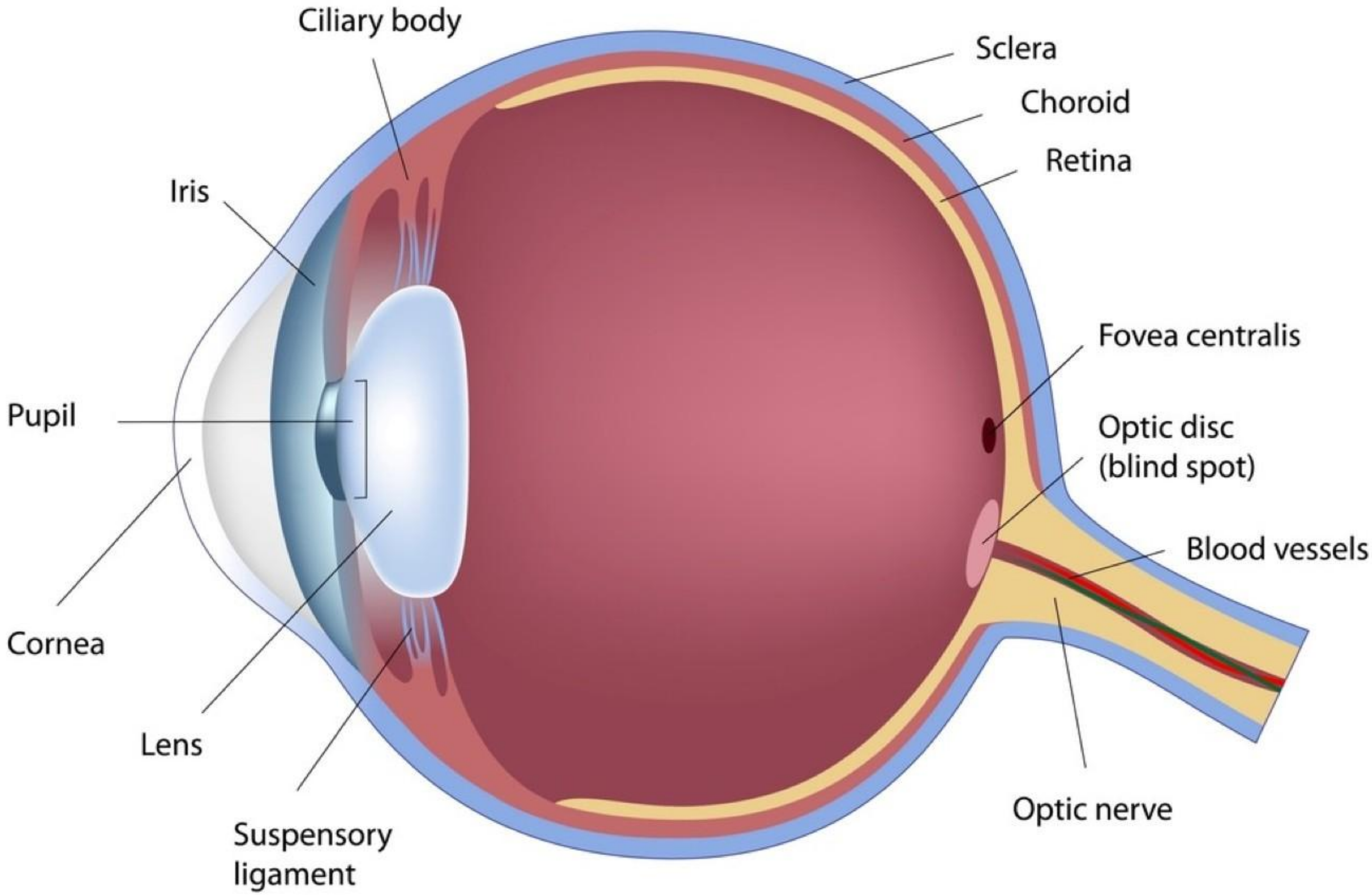
Graph plots how much of each CIE RGB primary light must be combined to match a monochromatic light of wavelength given on x-axis



Careful: these are not response curves or primary spectra!

Biological Basis of Color

Anatomy of The Human Eye



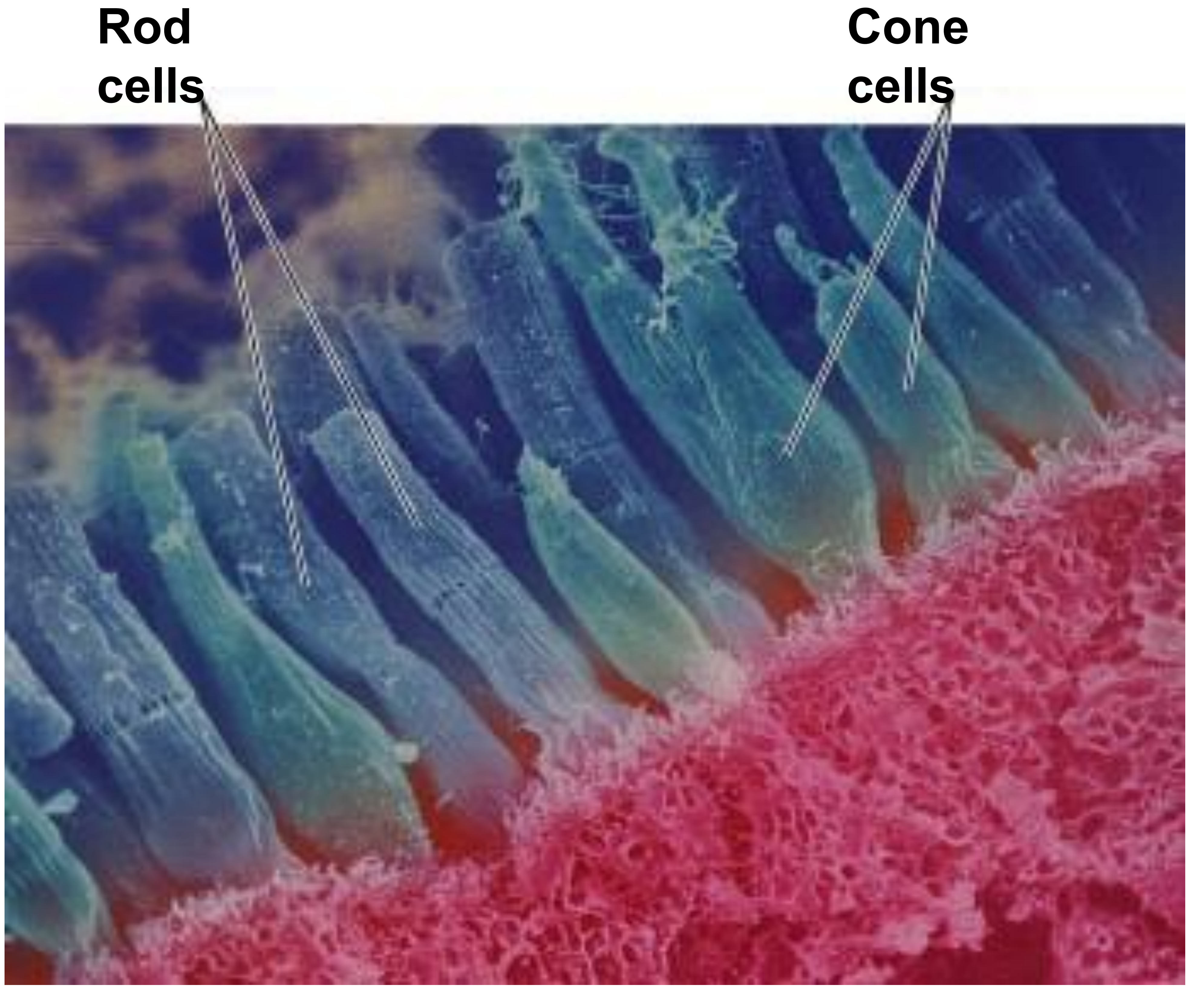
Retinal Photoreceptor Cells: Rods and Cones

Rods are primary receptors in very low light ("scotopic" conditions), e.g. dim moonlight

- **~120 million rods in eye**
- **Perceive only shades of gray, no color**

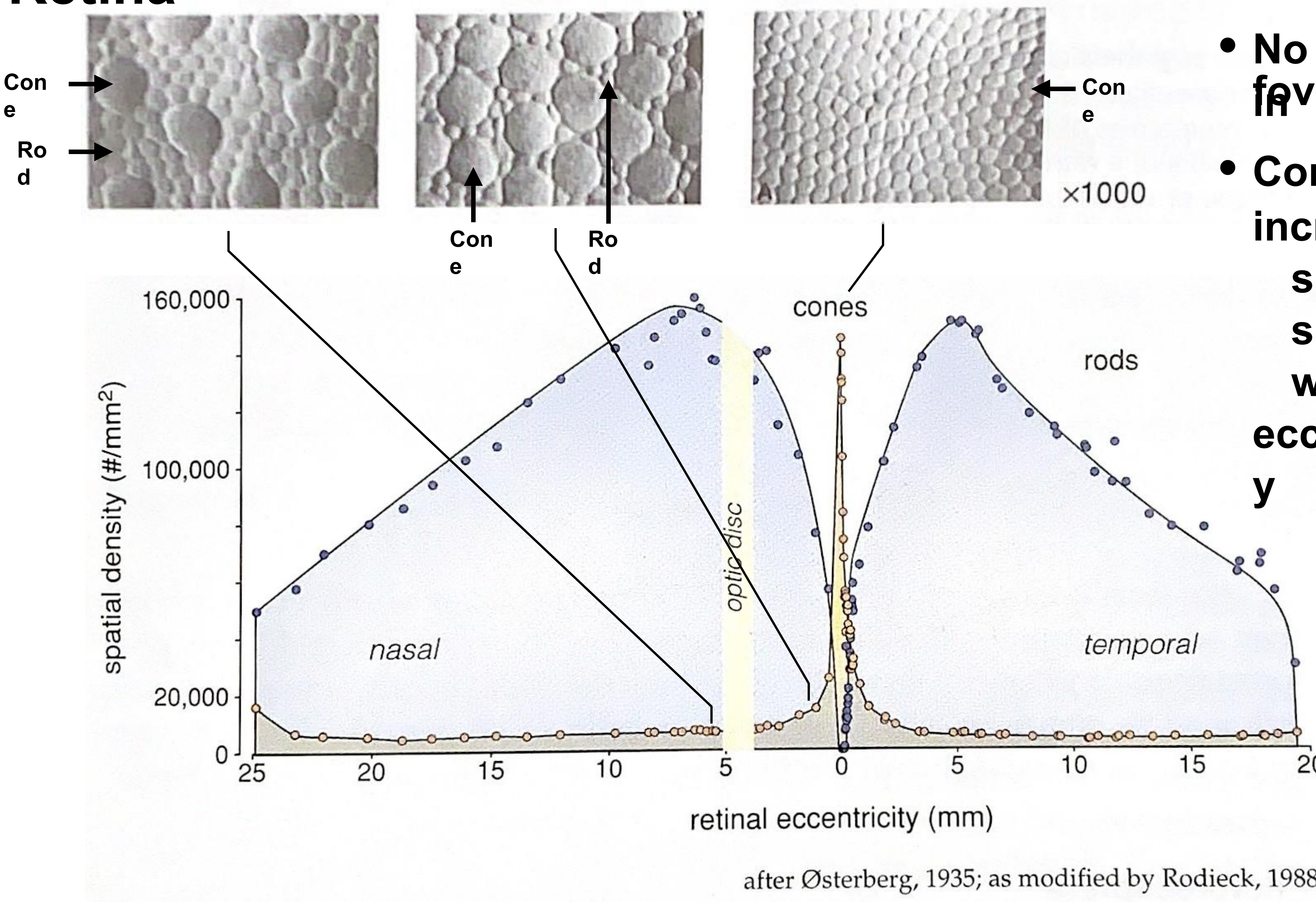
Cones are primary receptors in typical light levels ("photopic")

- **~6-7 million cones in eye**
- **Three types of cones, each with different spectral sensitivity**



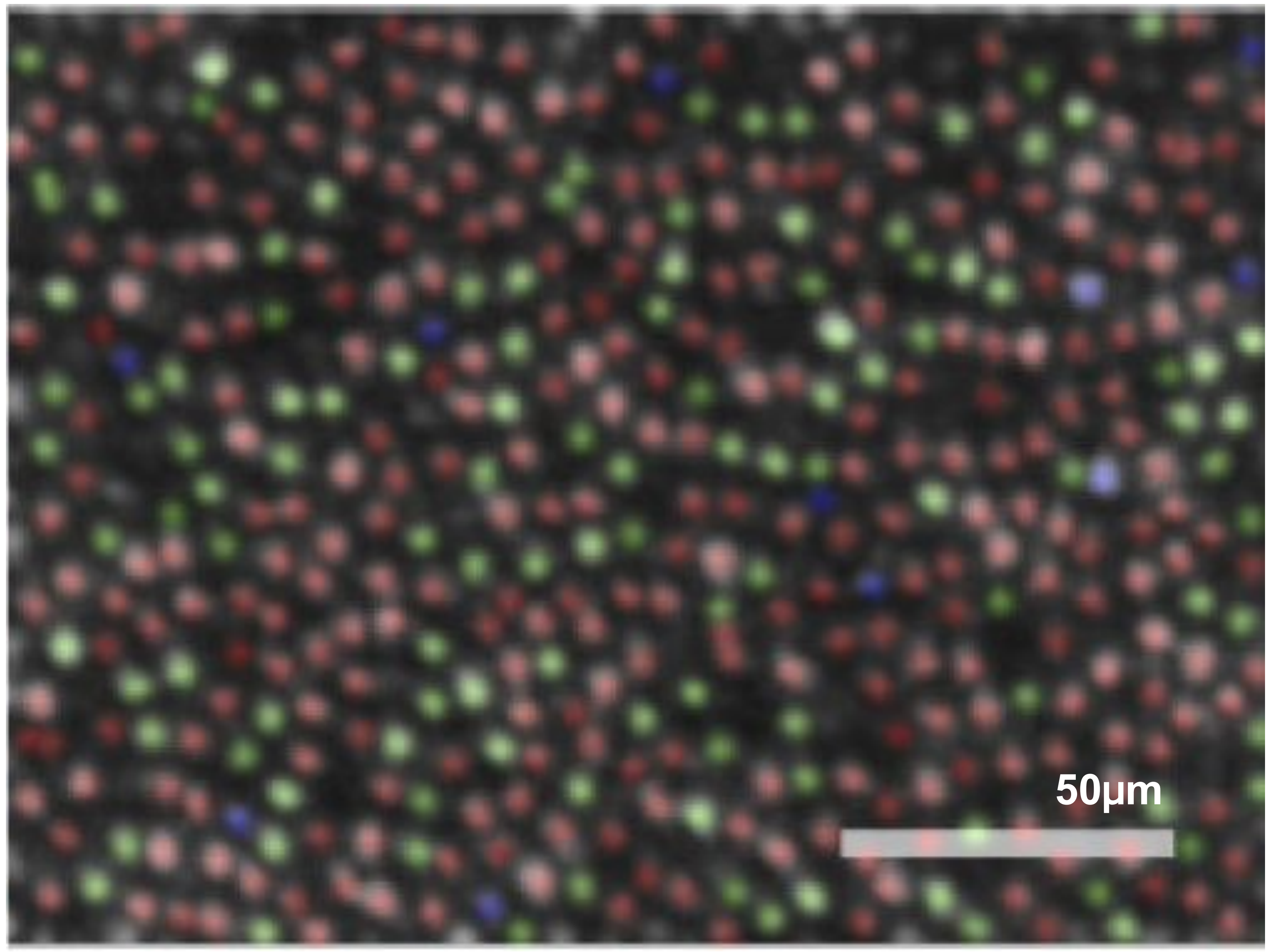
http://ebooks.bfwpub.com/life.php Figure 45.18

Photoreceptor Size and Distribution Vary Across Retina



- No rods in fovea
- Cones increase in size and spacing with eccentricity

On the Retina, Three Types of Cone Cells



Sabesan Lab, UW. Pandiyan et al. 2020.

Three types of cone cells: S, M, and L (corresponding to peak response at short, medium, and long wavelengths)

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

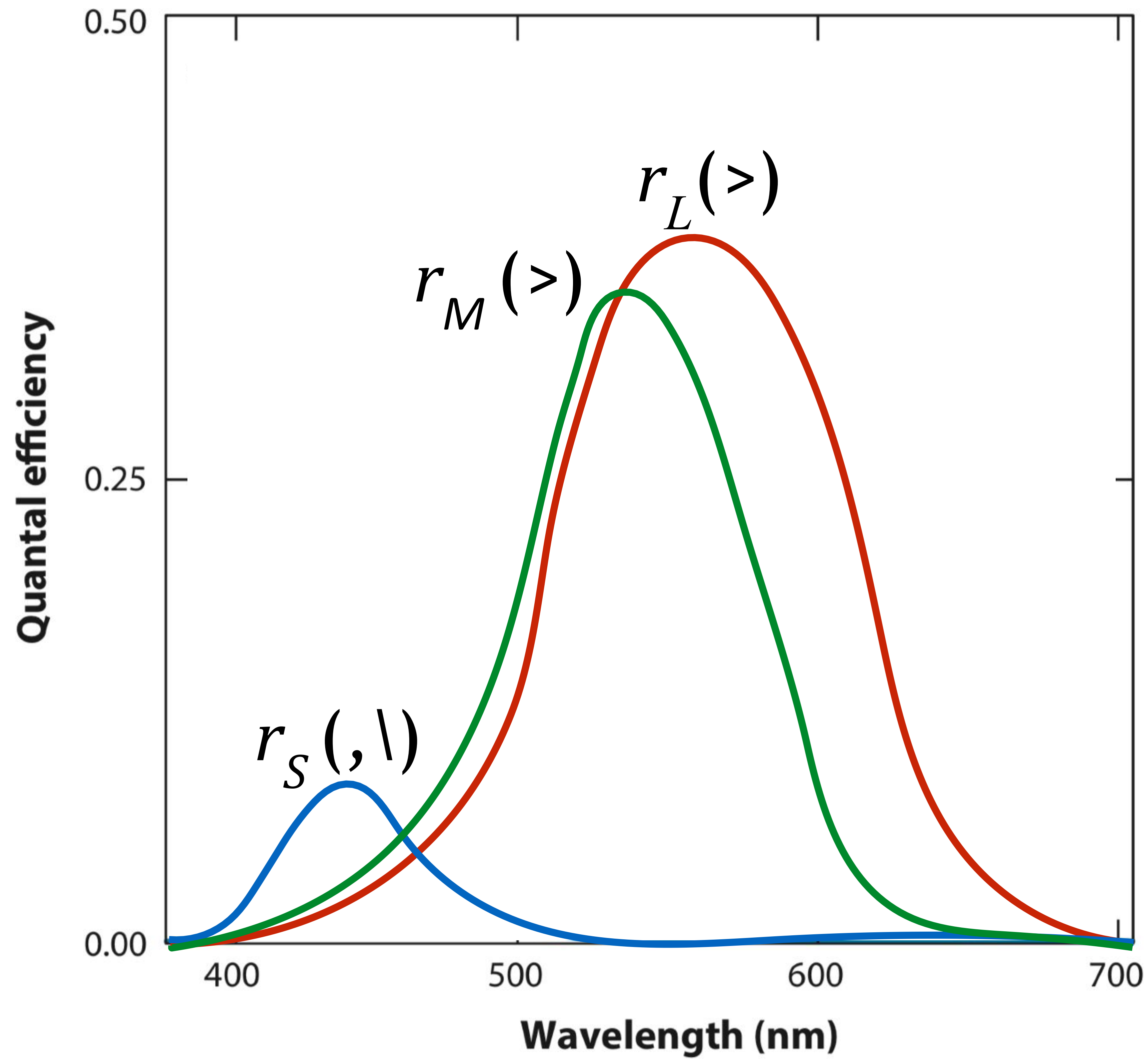
Spectral Response of Human Cone Cells

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

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

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

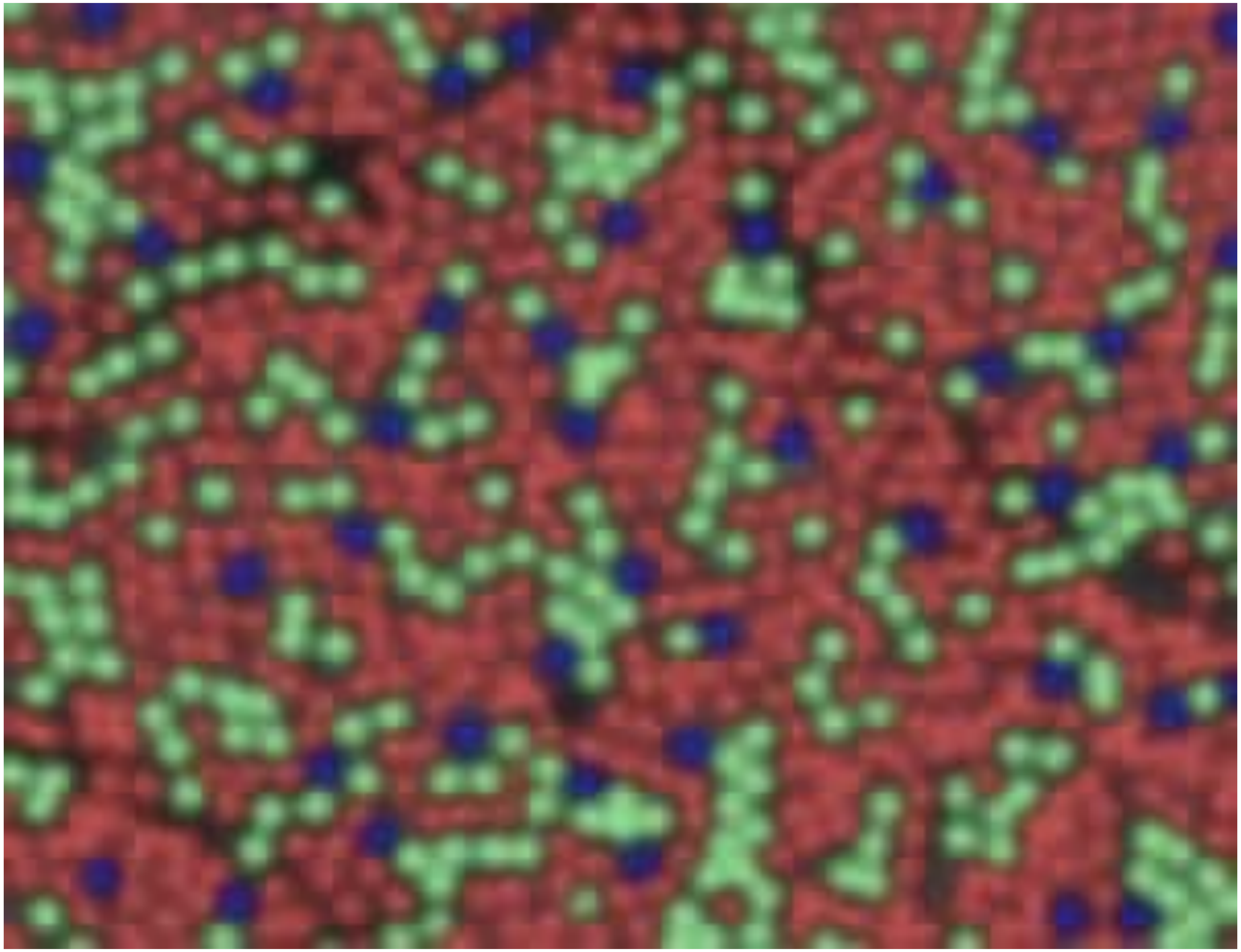
$$L = \int r_L(\lambda) s(\lambda)\, d\lambda$$



Brainard, Color and the Cone Mosaic, 2015.

Example: Spectral Response of Human Cone Cells

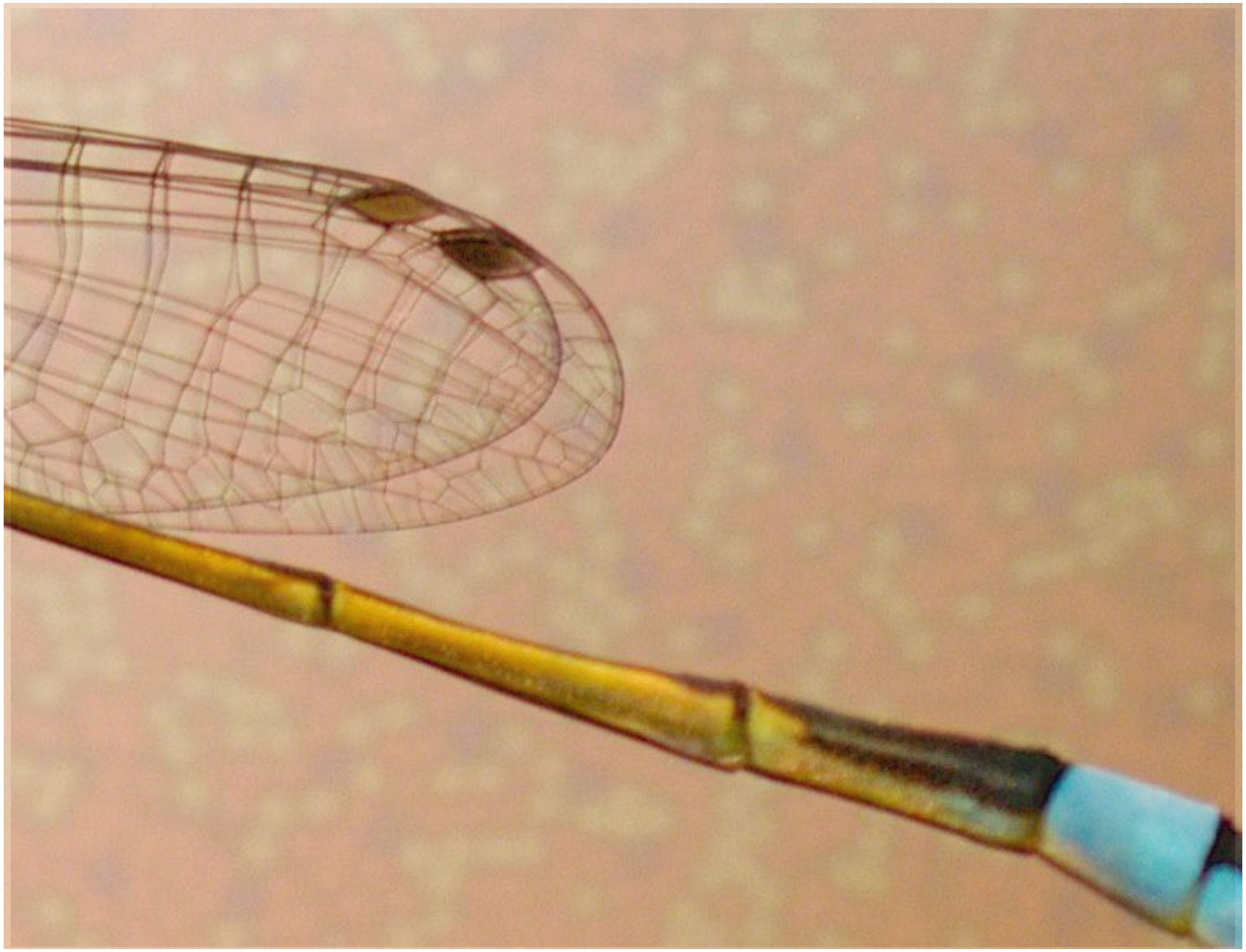
Example: Spectral Response of Human Cone Cells



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

Scene projected onto retina

Example: Spectral Response of Human Cone Cells



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

Scene projected onto retina

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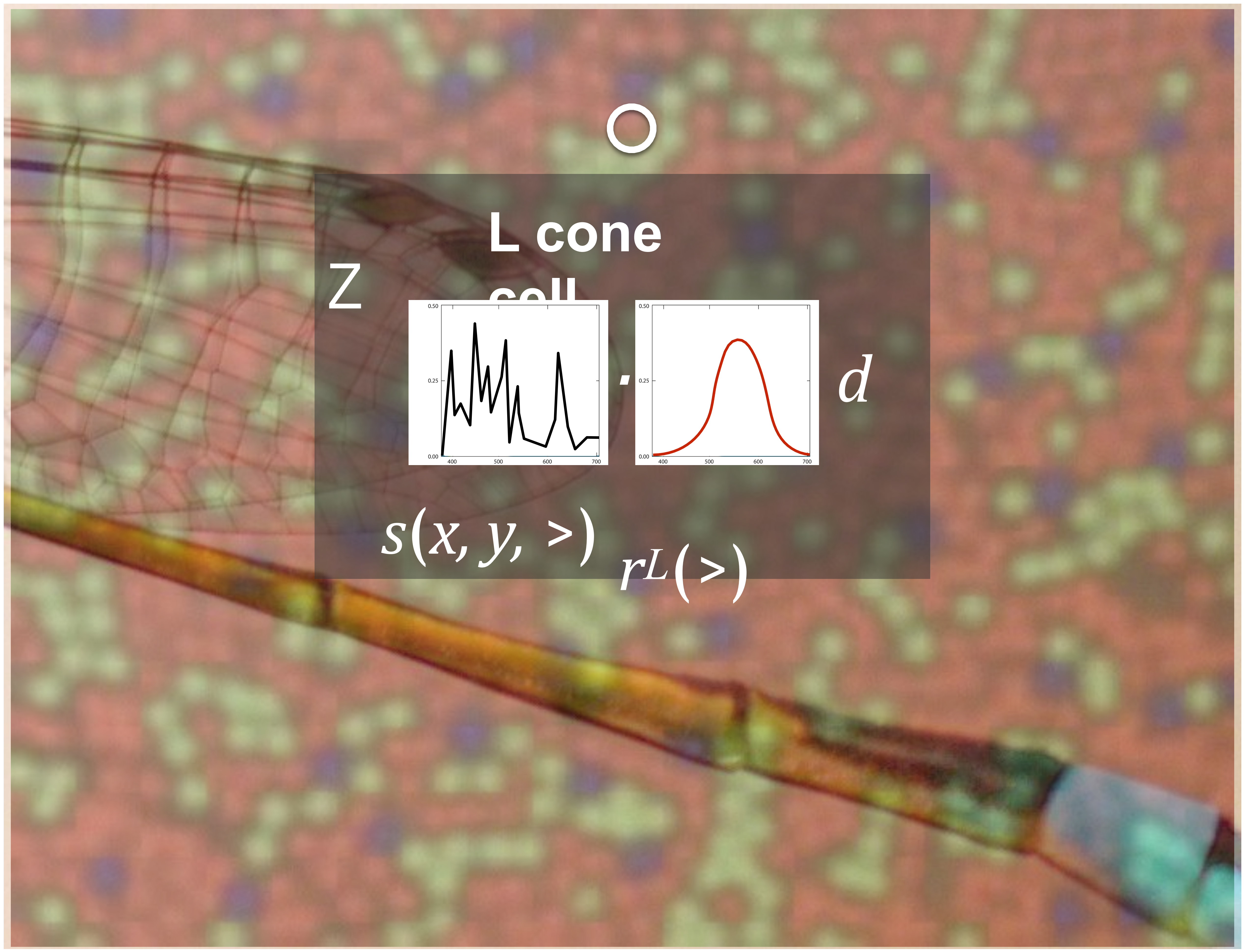
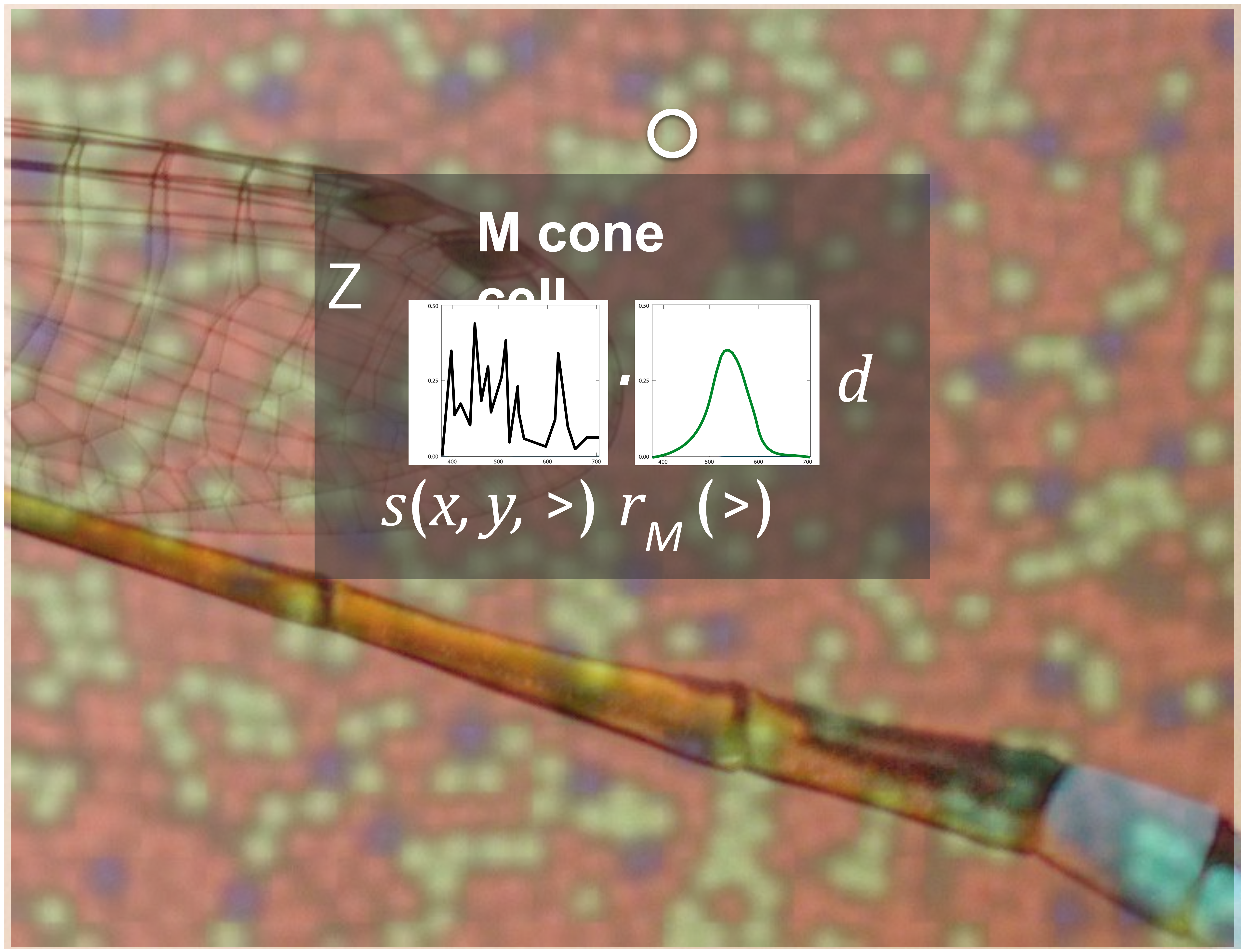


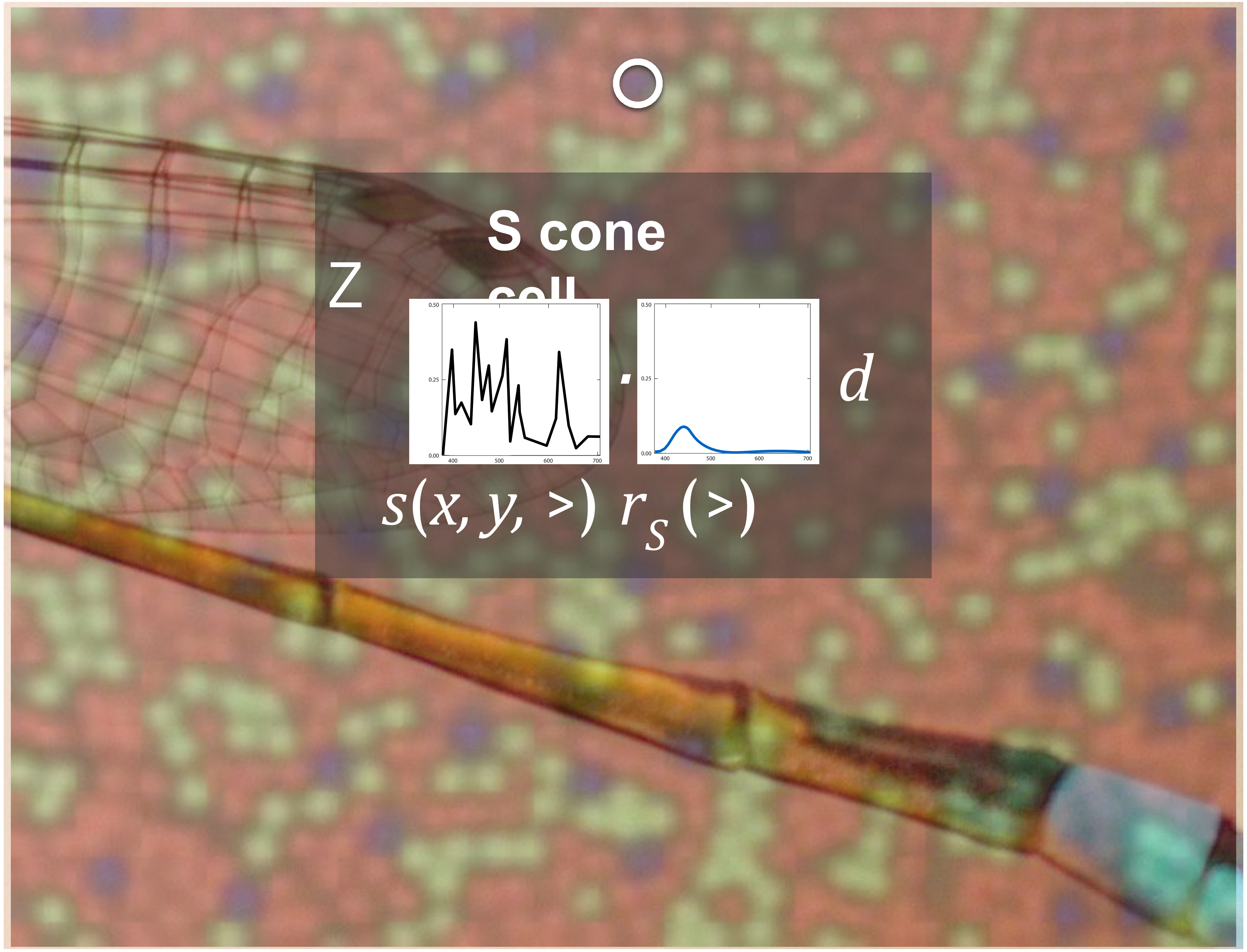
Credit: Sabesan, http://depts.washington.edu/sabaolab/

Example: Spectral Response of Human Cone Cells



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

Example: Spectral Response of Human Cone Cells



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

Spectral Response of Human Cone Cells

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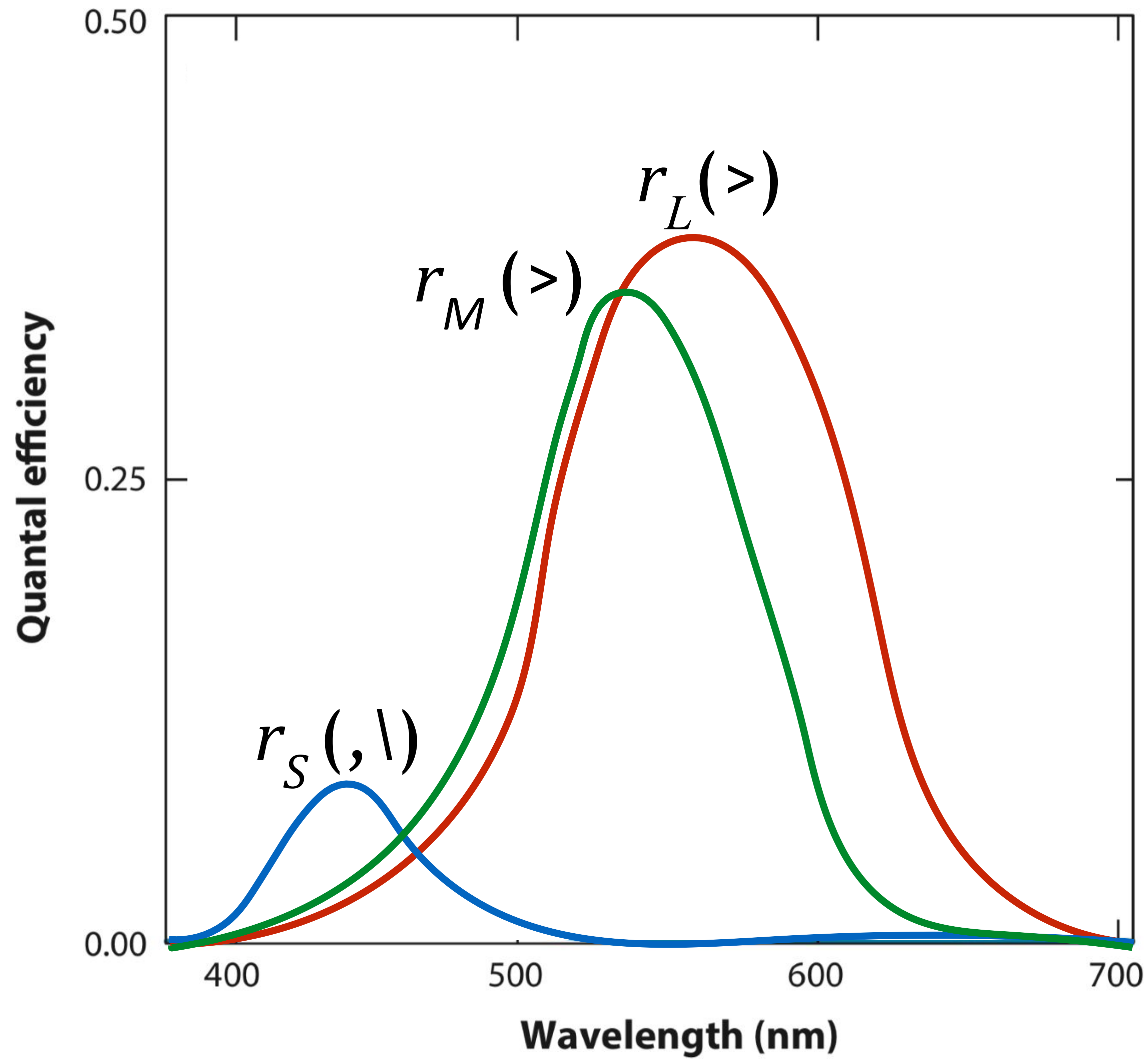


Brainard, Color and the Cone Mosaic, 2015.

Spectral Response of Human Cone Cells

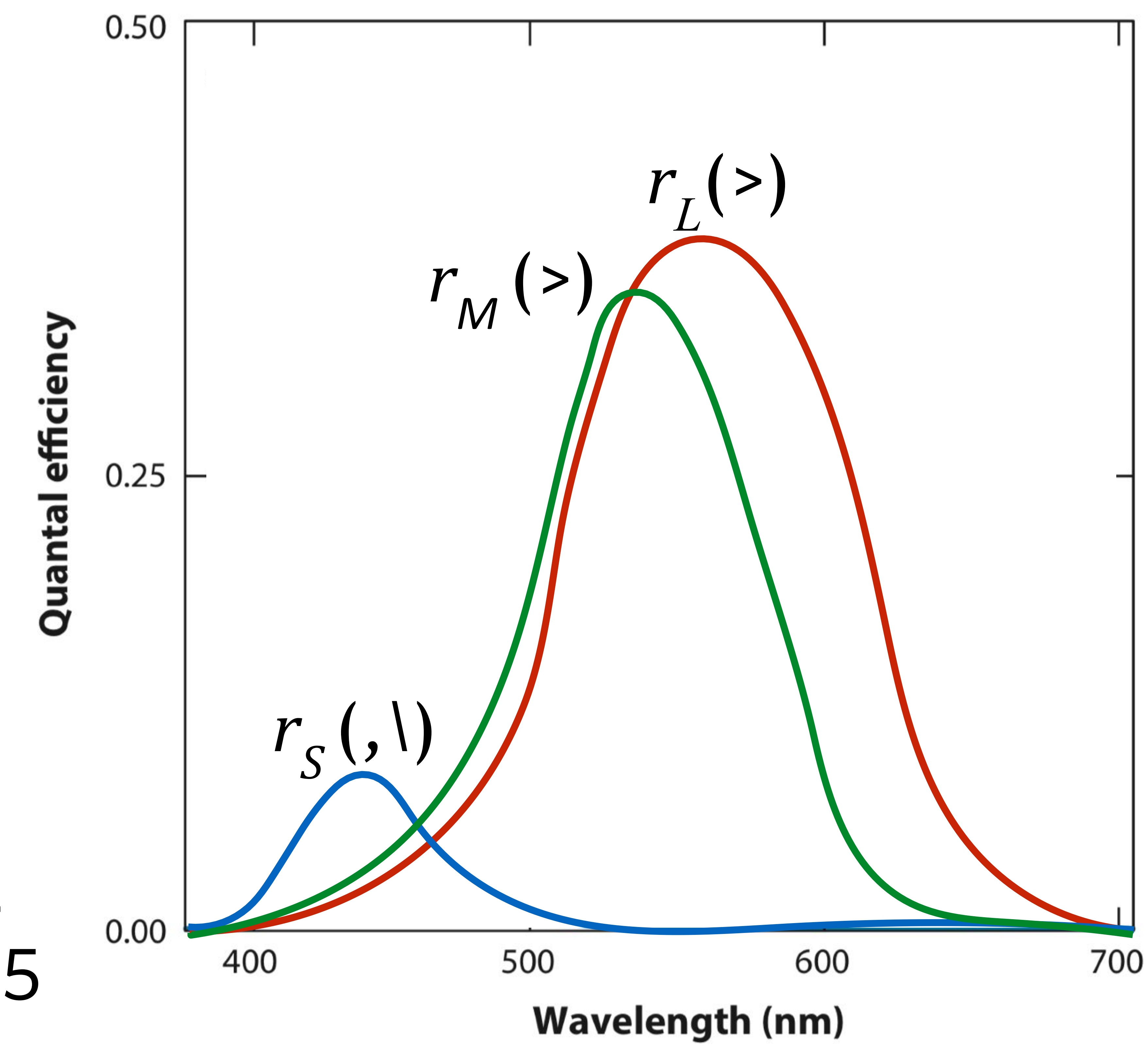
Instead of one detector as before, now we have three detectors (S, M, L cone cells), each with a different spectral response curve

Written as vector dot products:

$$S = r_S \cdot s$$
$$M = r_M \cdot s$$
$$L = r_L \cdot s$$

Matrix formulation:

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



Brainard, Color and the Cone Mosaic, 2015.

Dimensionality Reduction From ∞ to 3

At each position on the human retina:

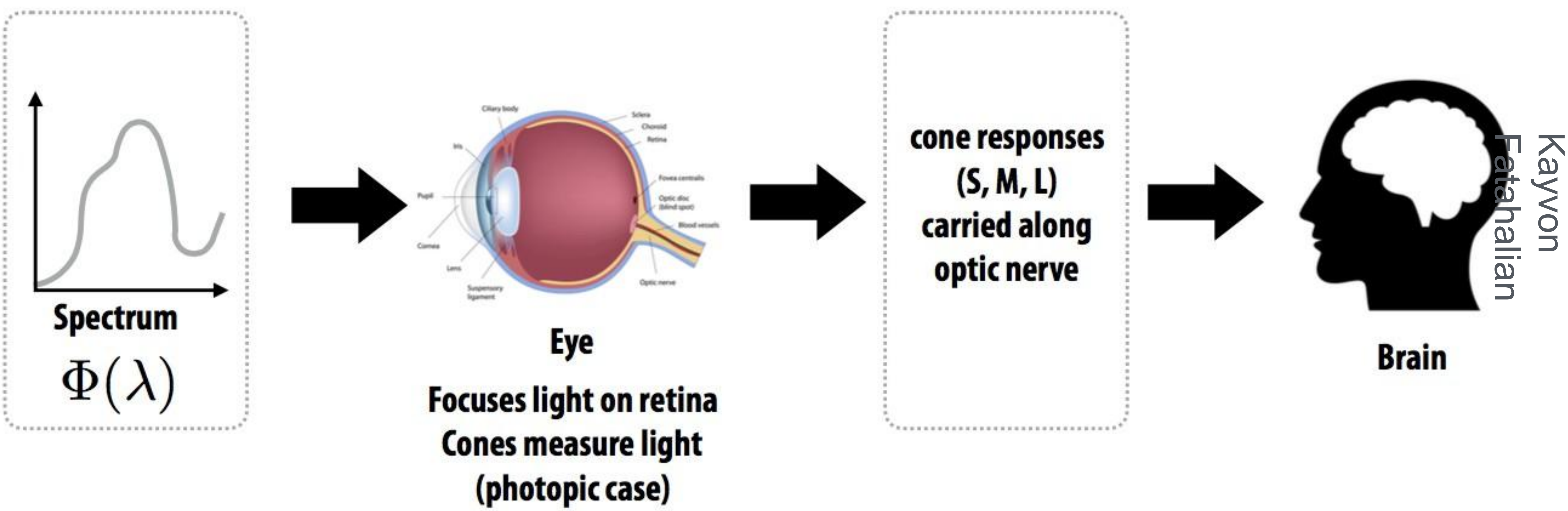
- SPD is a function of wavelength (∞ - dimensional signal)
- 3 types of cones near that position produce three scalar values (3 - dimensional signal)

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**



Metamerism

Metamers

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

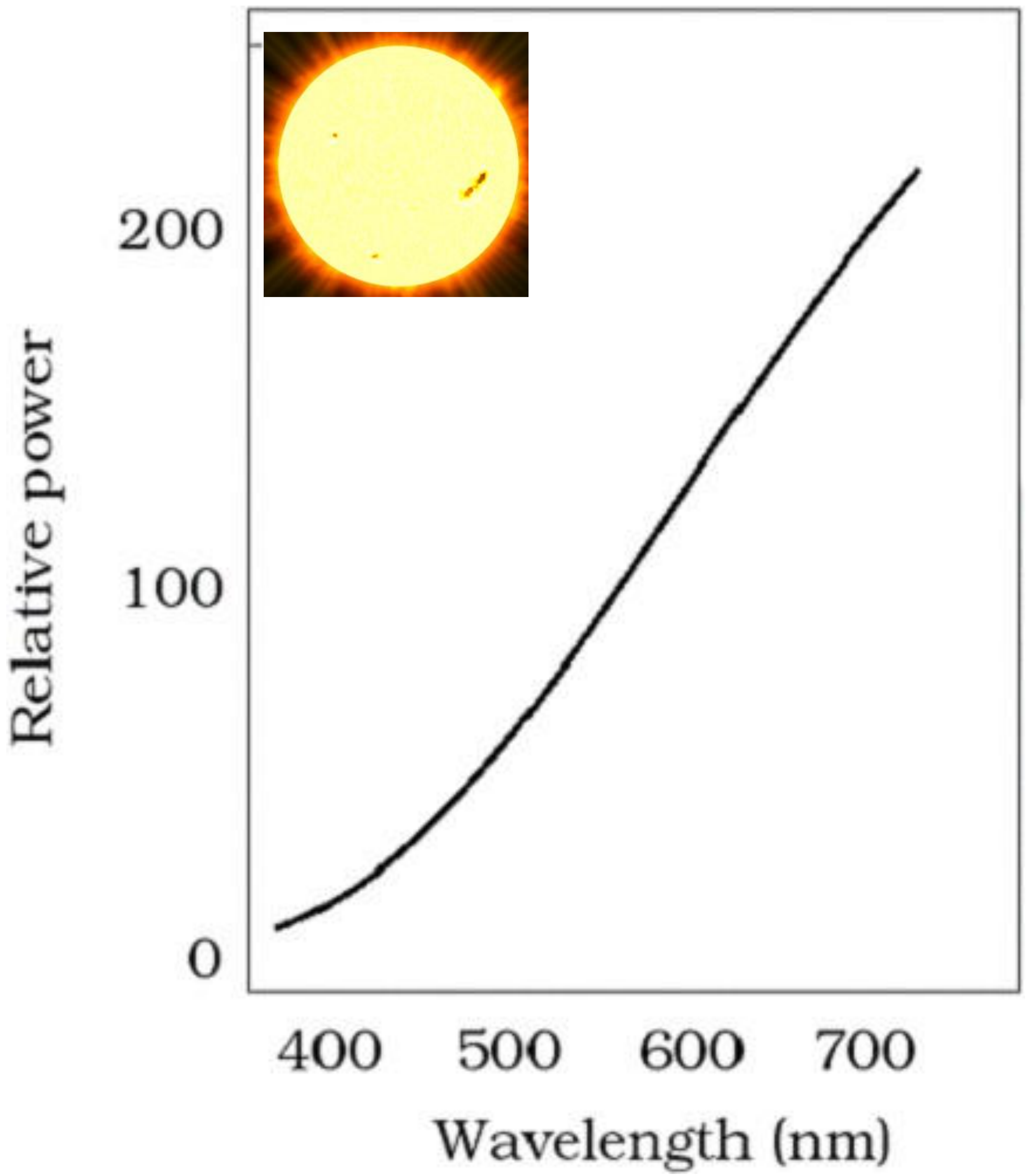
- These will appear to have the same color to a human

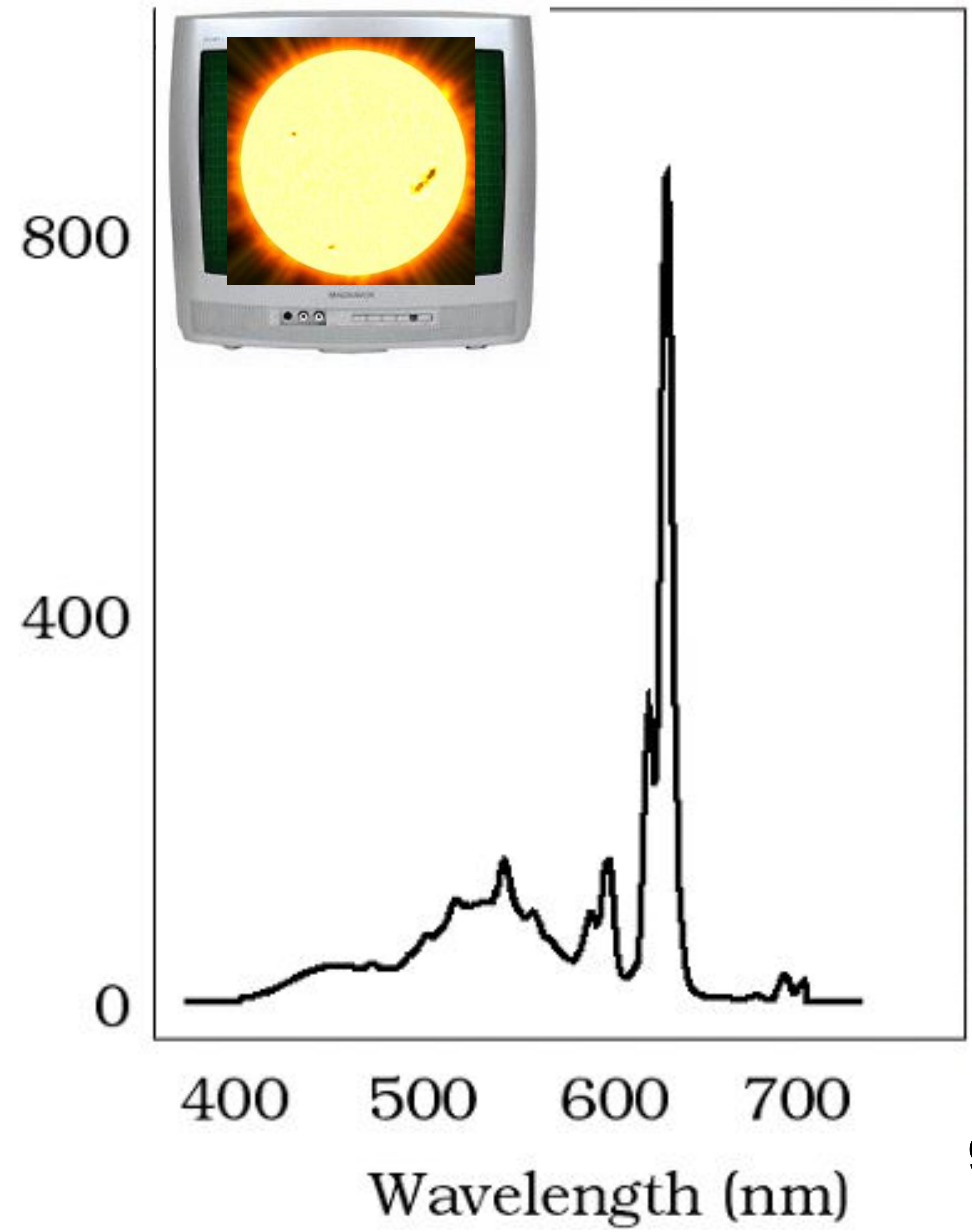
The existence of metamers is critical to color reproduction

- 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

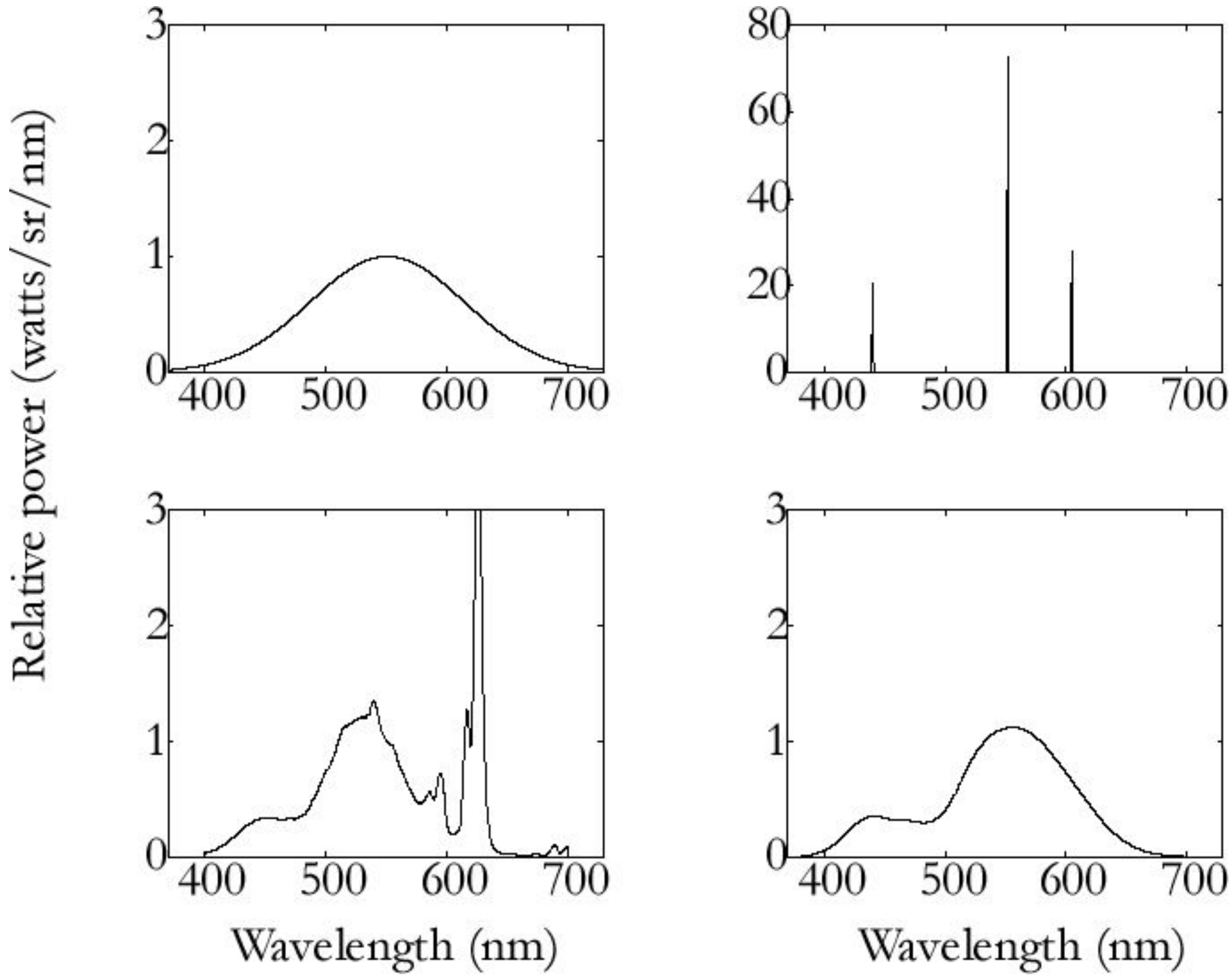




Brian Wandell

g

Metamerism is a Big Effect



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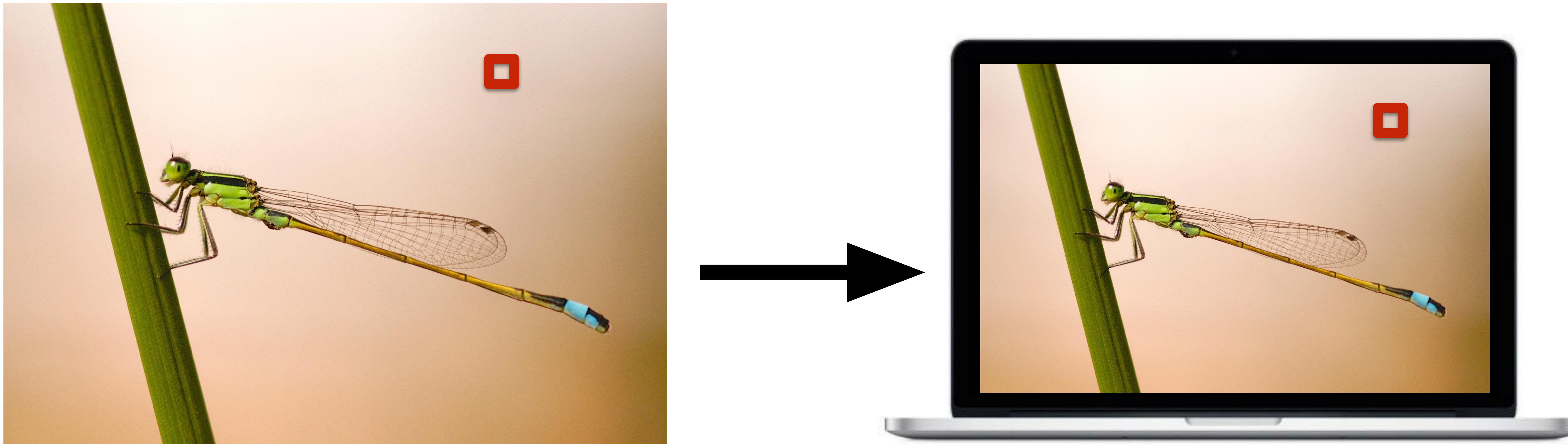
Color Reproduction

Color Reproduction Problem



Target real spectrum
$s(,\backslash)$

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

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.

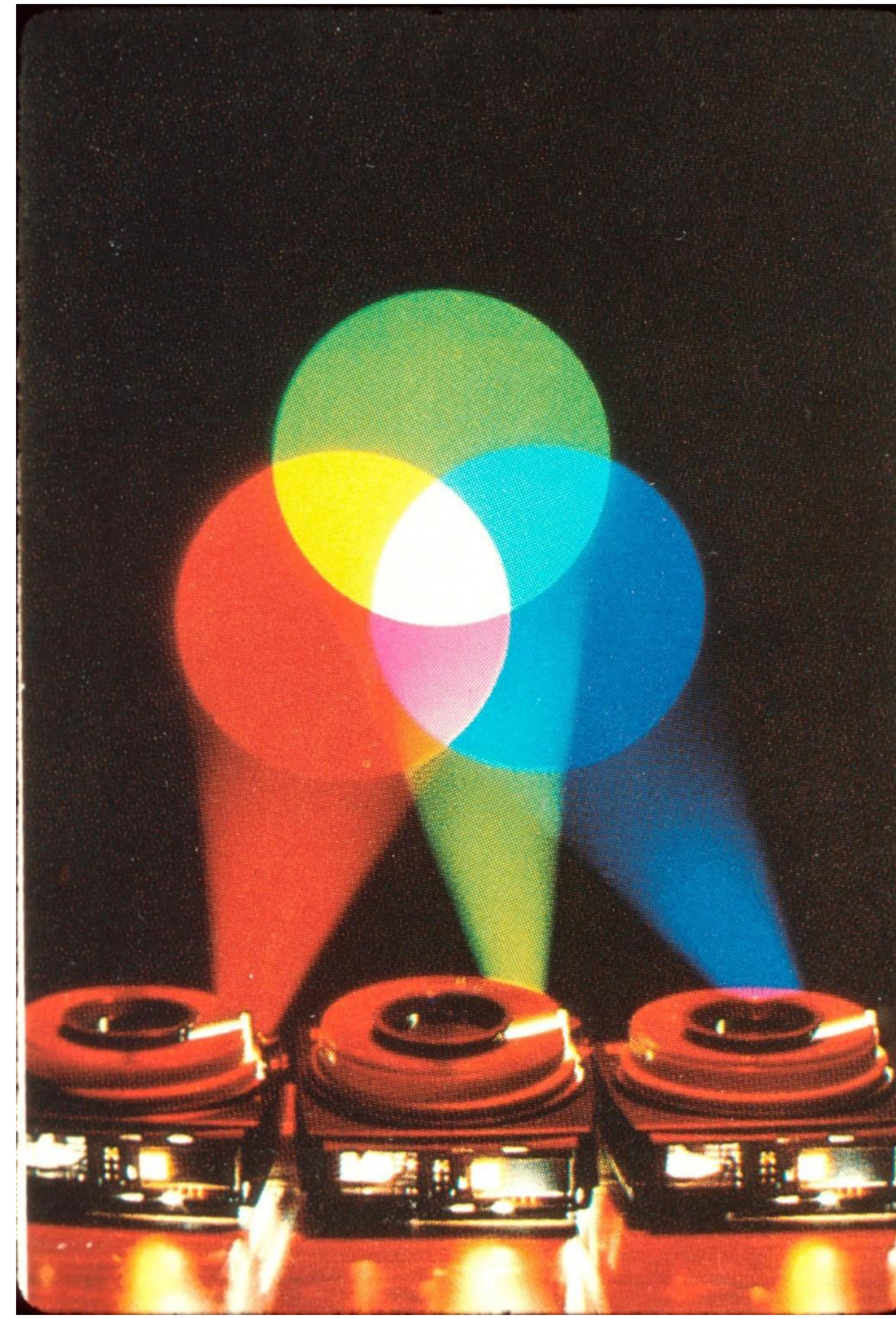
Additive Color

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

$$s_R(>),\quad s_G(>),\quad s_B(>)$$

- **We can adjust the brightness of these lights and add them together to produce a linear subspace of spectral distribution:** $R\, s_R(>) + G s_G(>) + B\, s_B(>)$
- **The color is now described by the scalar values:**

$$R,\quad G,\quad B$$

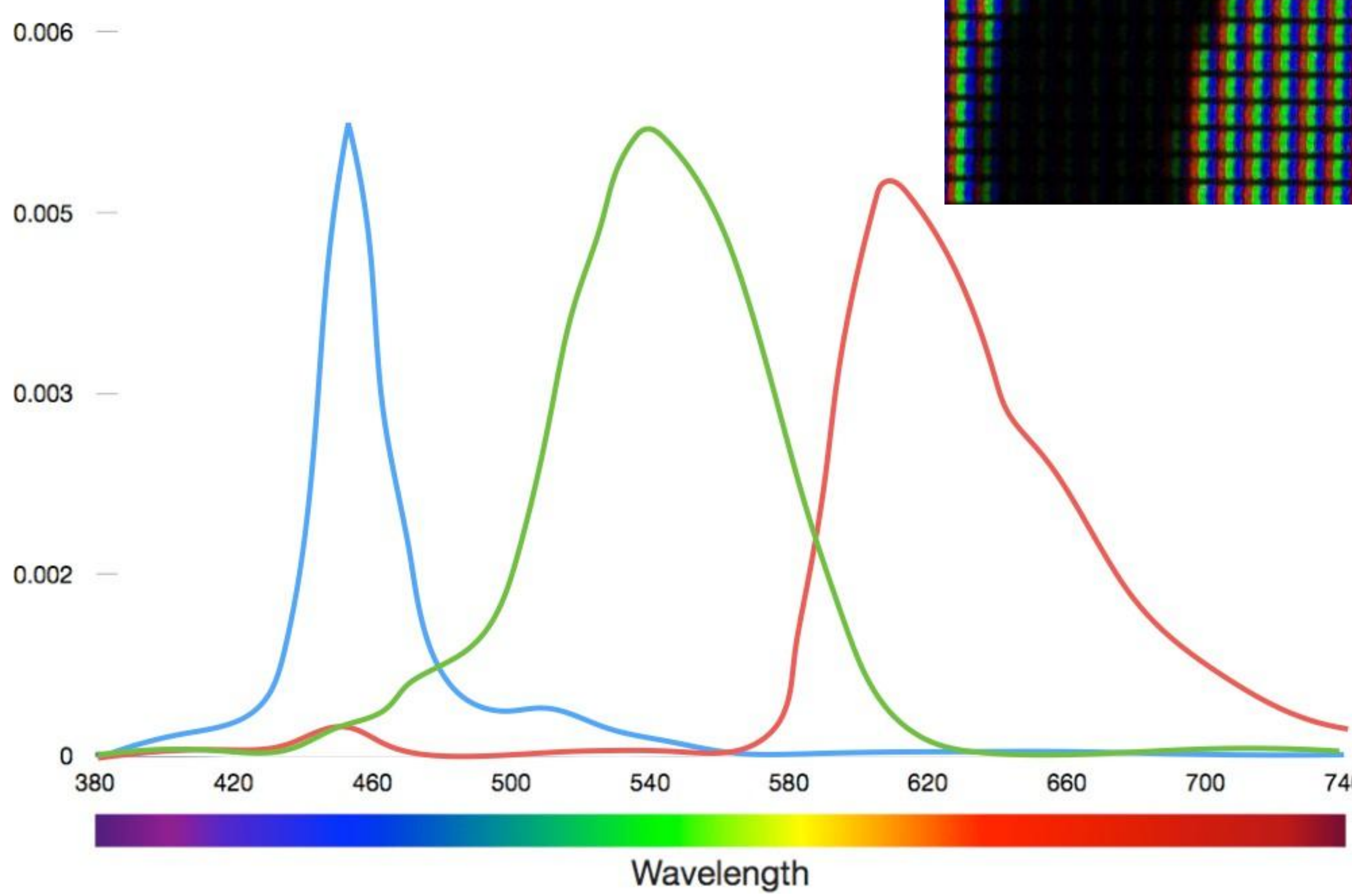


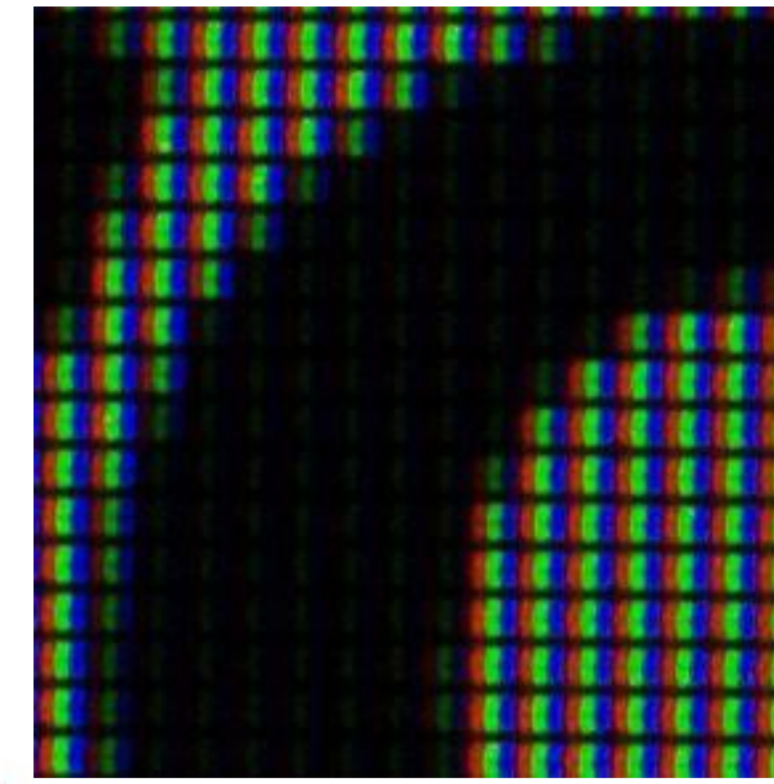
Example RGB Emission Spectra ("Color Primaries") for Phone Display

https://www.macrumors.com/roundup/iphone-5s/

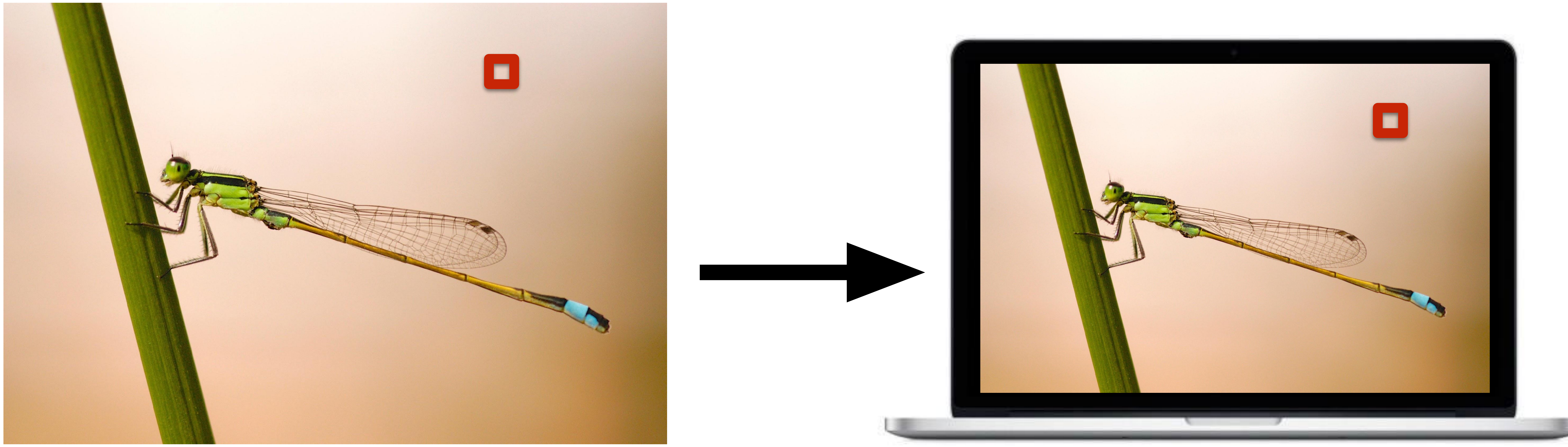
RGB pixel spectra (iPhone 5)

Credit: Yurek, https://dot-color.com/tag/color-2/page/2/





Color Reproduction Problem



Target real spectrum

$s(\lambda)$

Display outputs spectrum

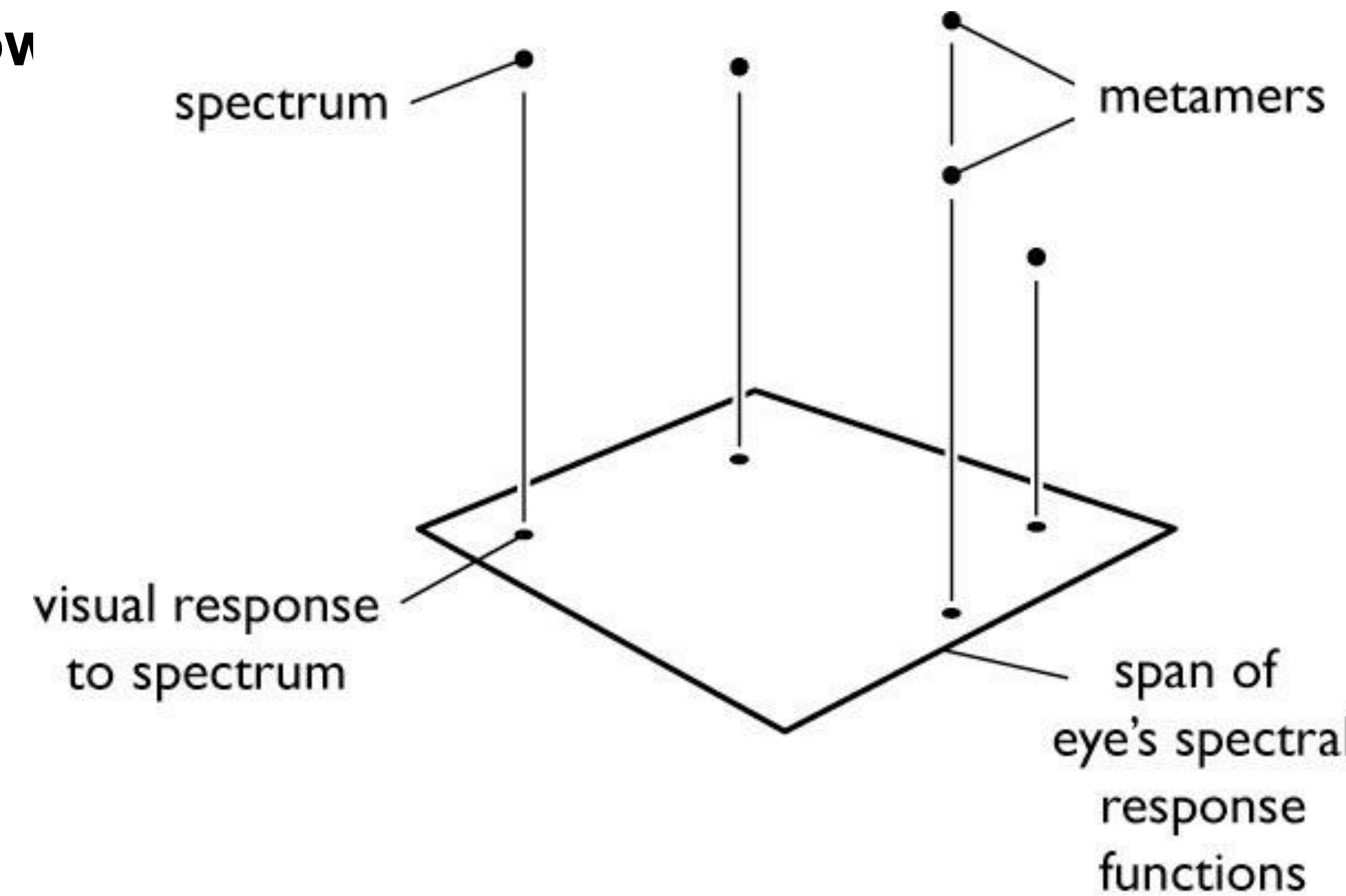
$R\, s_R(\lambda) + G s_G(\lambda) + B\, s_B(\lambda)$

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

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

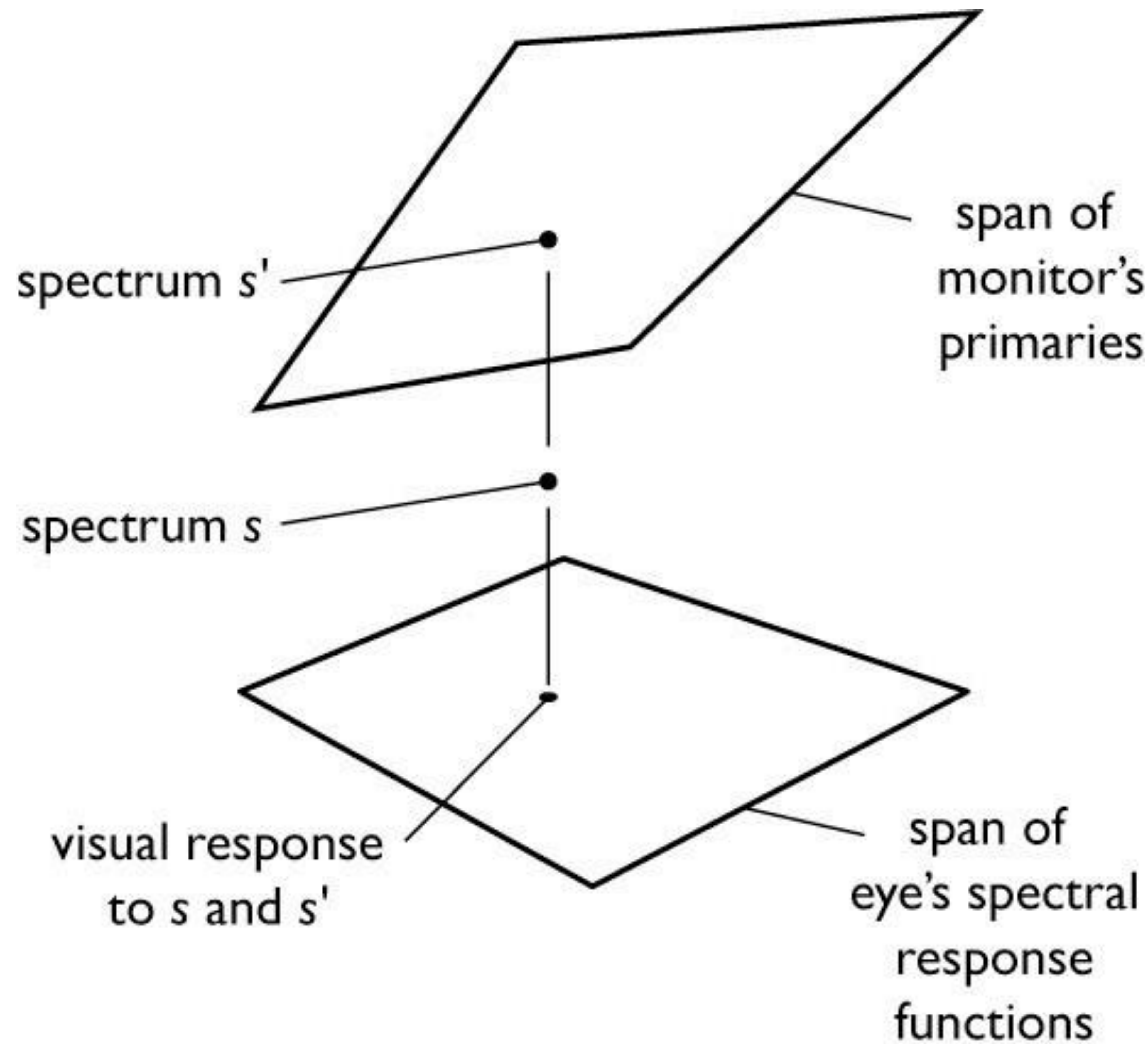
- **Differences that are perpendicular to the basis vectors of the low**



Slide credit: Steve Marschner

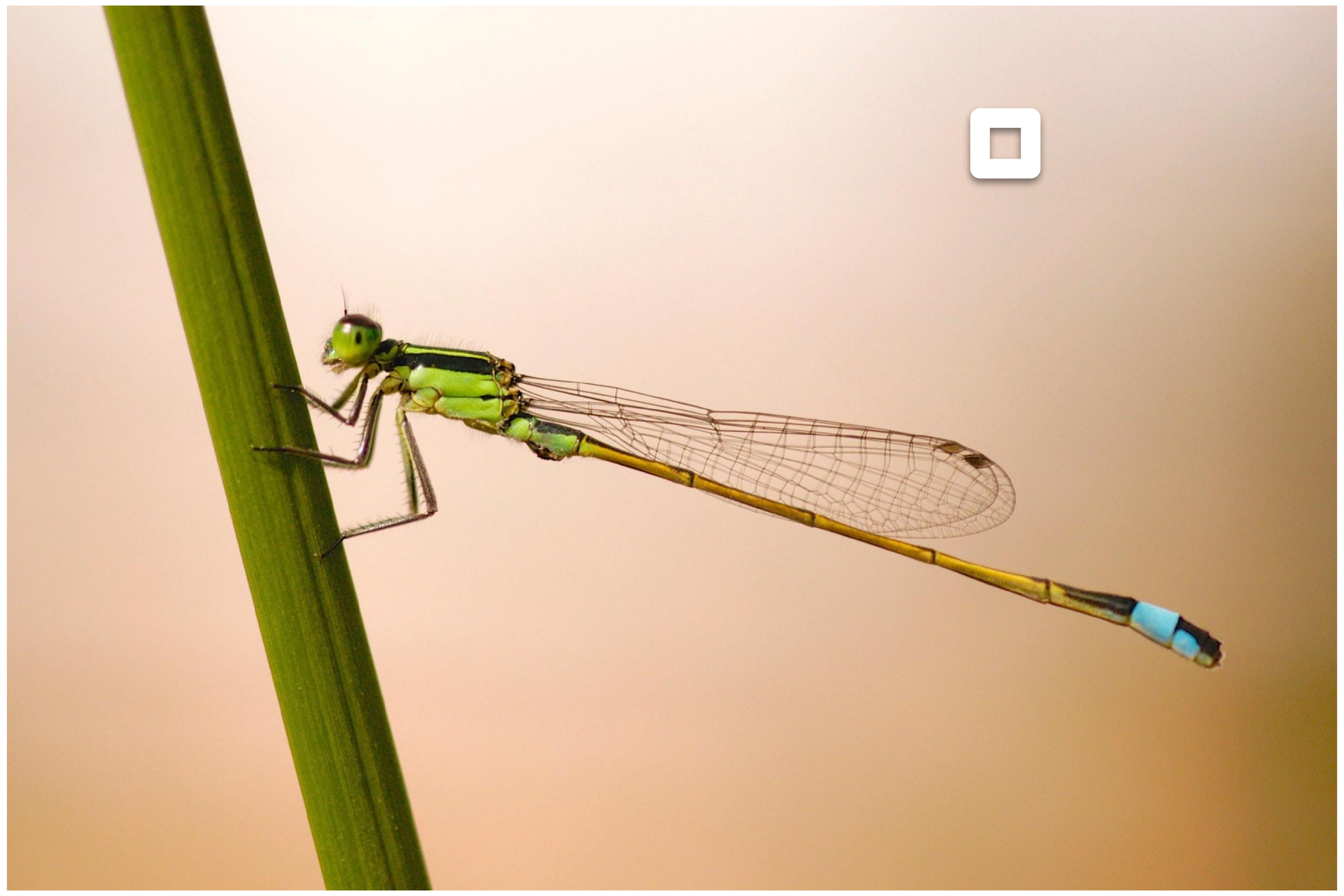
Pseudo-Geometric Interpretation of Color Reproduction

- The display can only produce a low-dimensional subspace of all possible spectra (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

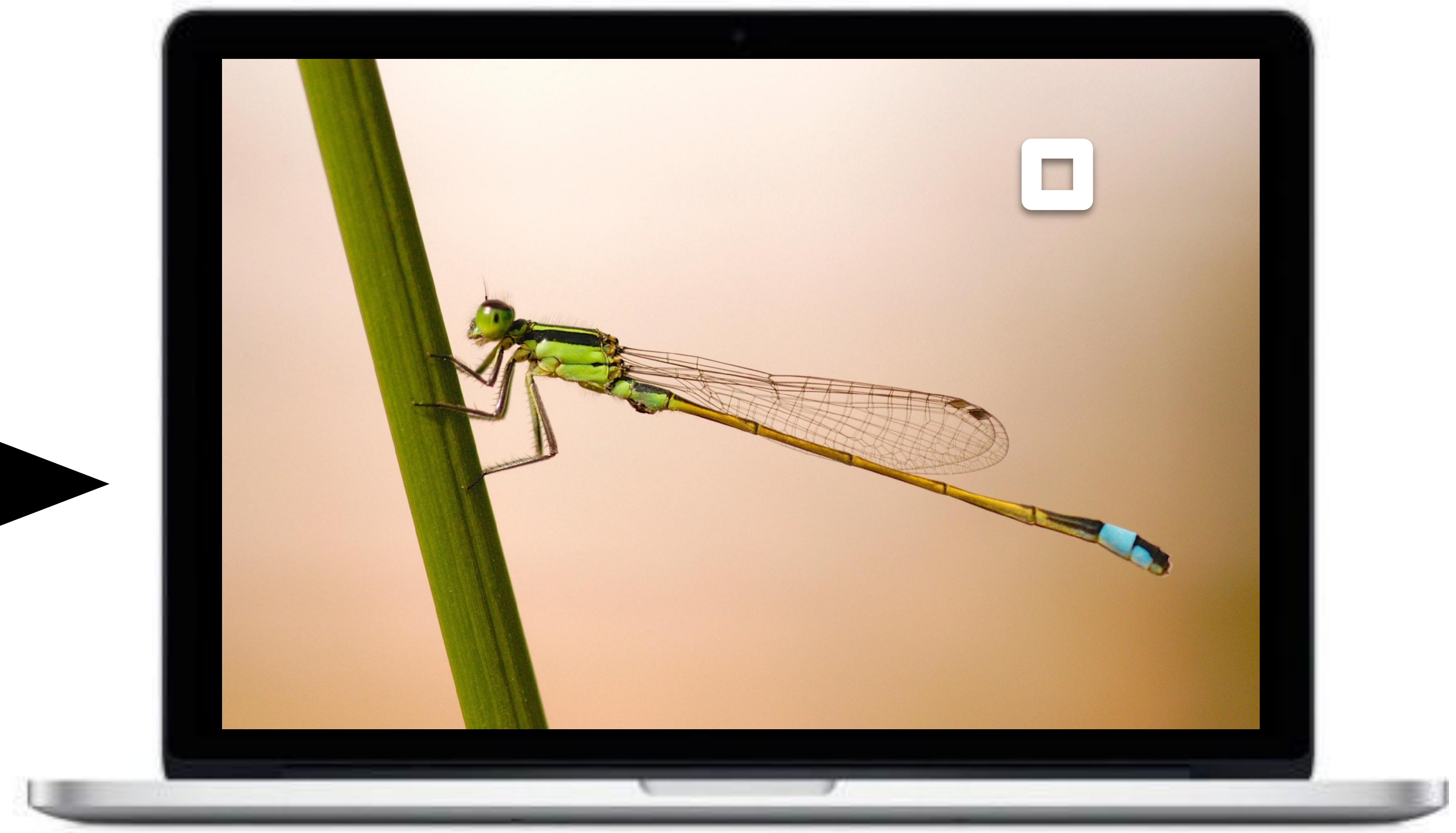


Slide credit: Steve Marschner

Color Reproduction as Linear Algebra



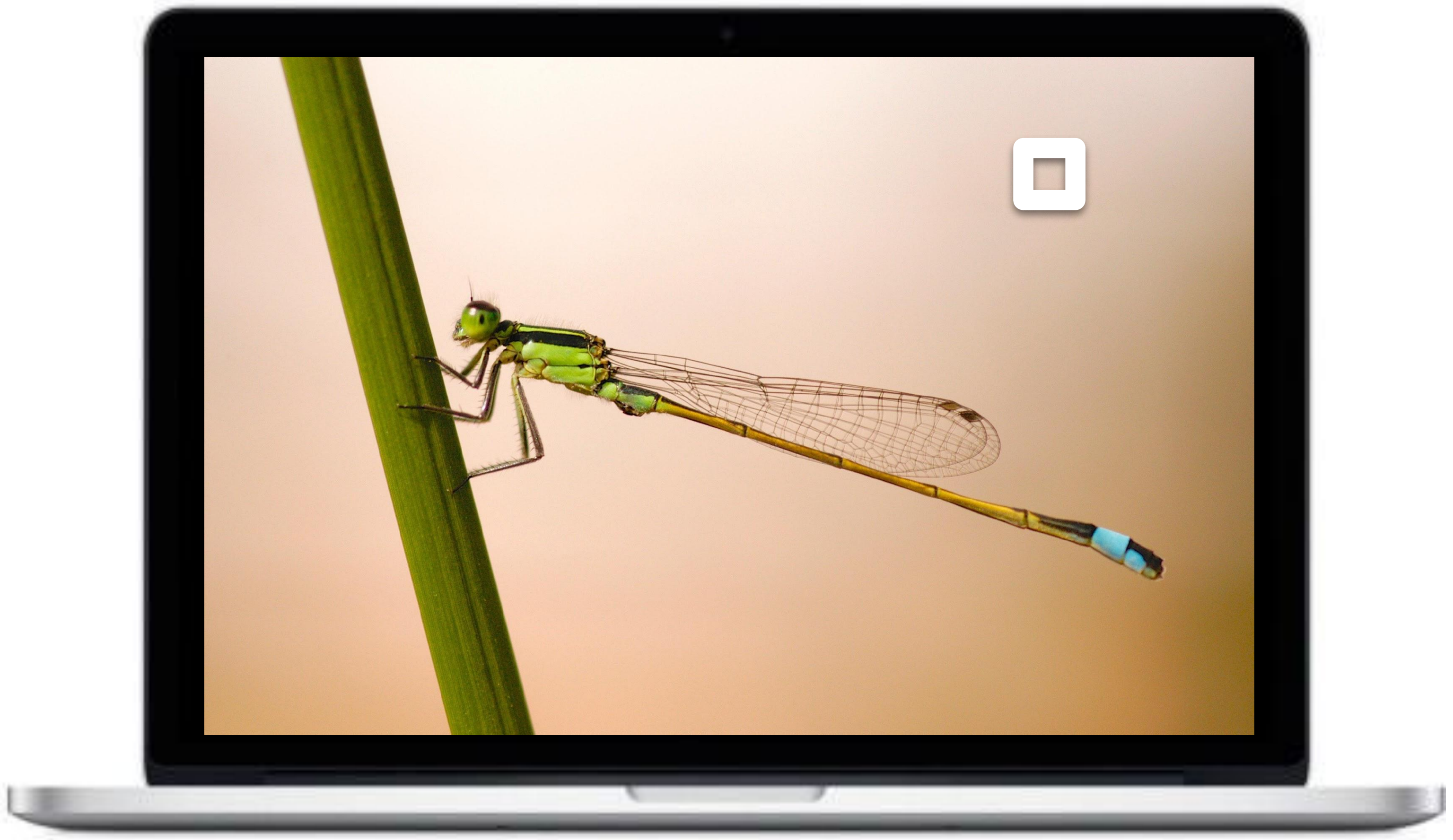
Input spectrum *s*



What R, G, B values?

Color Reproduction as Linear Algebra

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



Color Reproduction as Linear Algebra

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

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

Color perceived for real scene spectra, s

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

Color Reproduction as Linear Algebra

Color Reproduction as Linear Algebra

Color Matching Functions

Recall the color matching functions from the matching experiment

Color Reproduction Issue: No Negative Light

R,G,B values must be positive

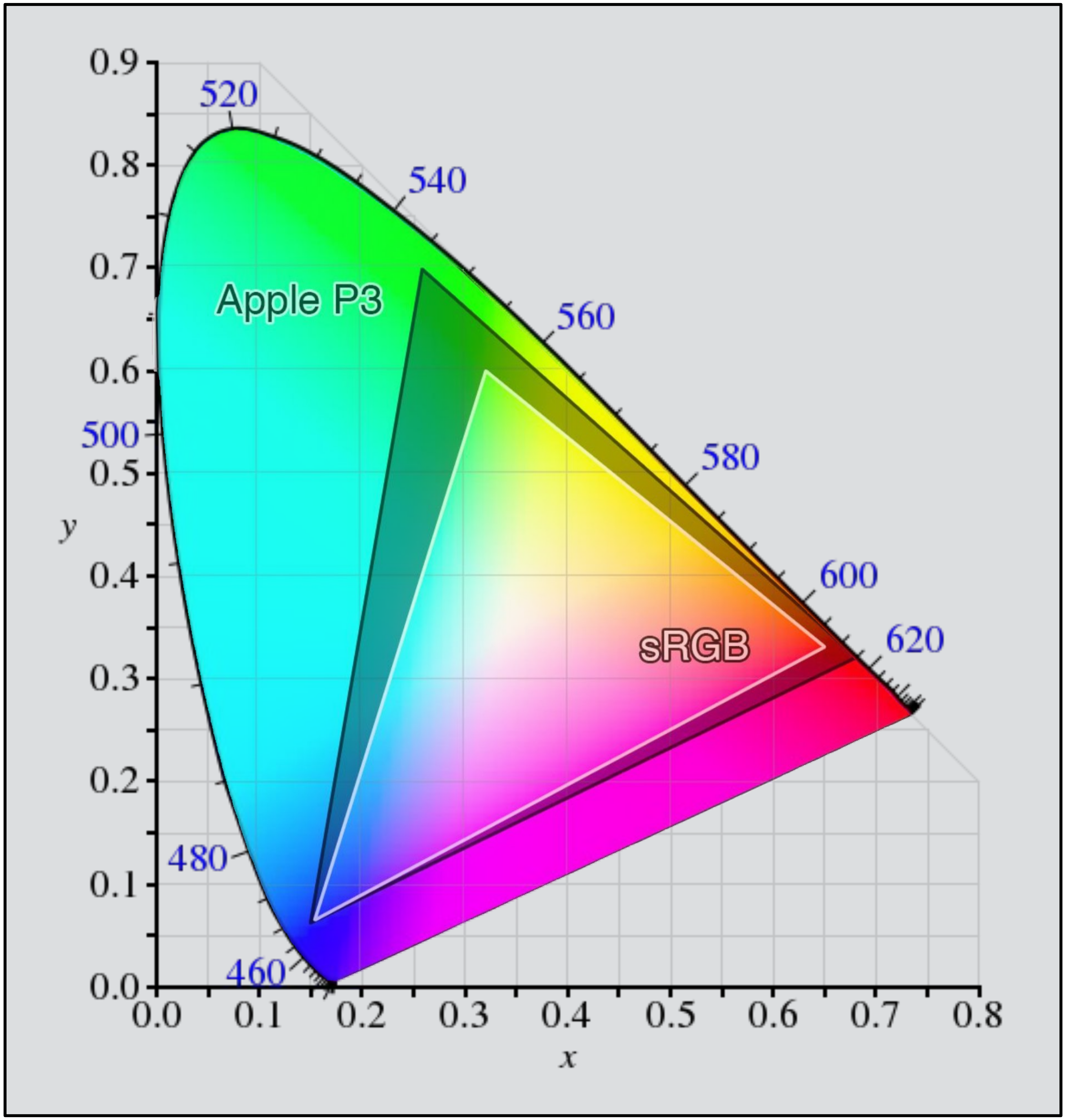
- Display primaries can't emit negative light
- But solution formulas can certainly produce negative R,G,B values

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

Color Gamut

Example: Color Gamut for sRGB and Apple P3



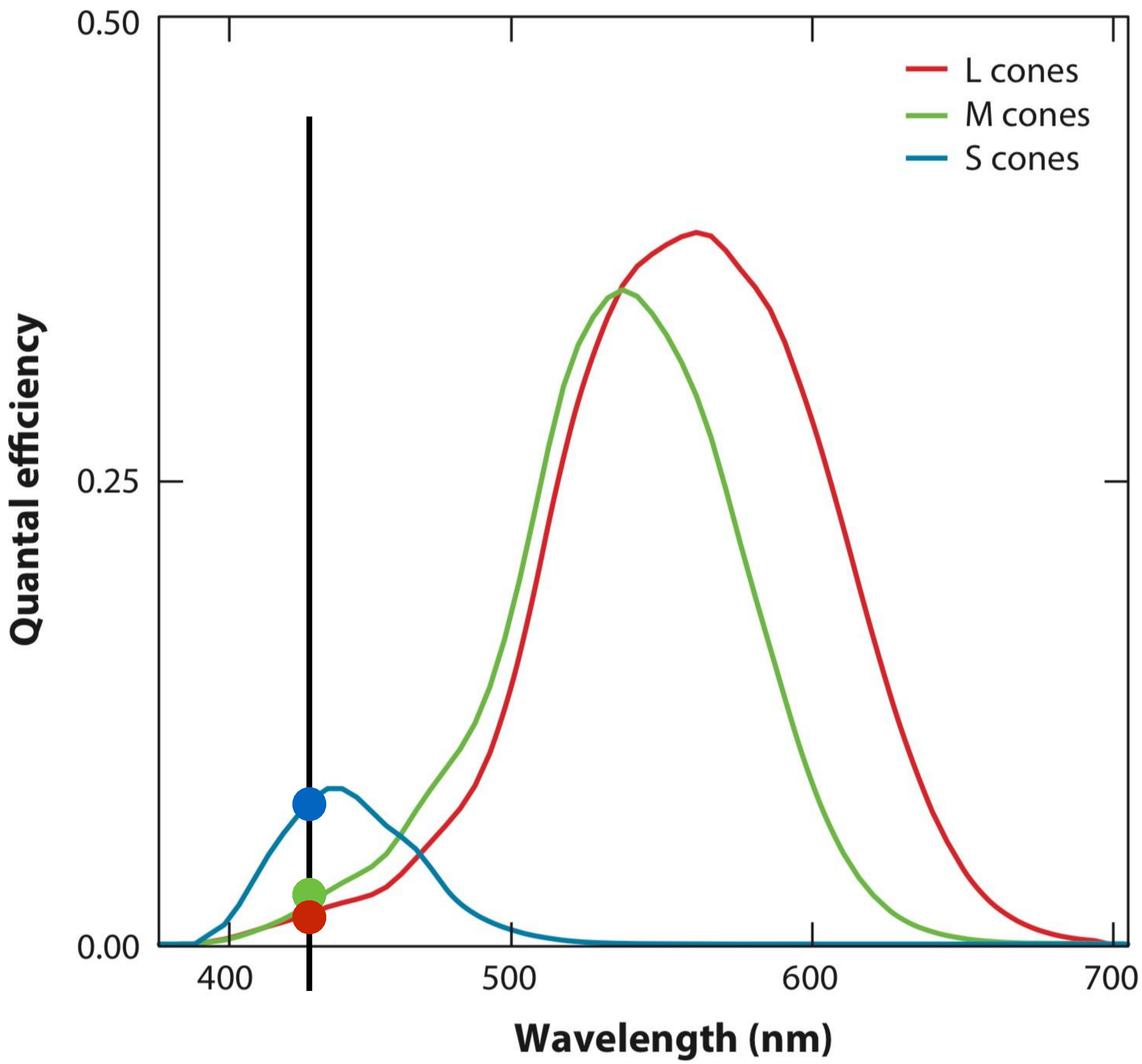
Comparing sRGB and Wide Gamut P3 Color Spaces

Interactive Color Space Comparison:

- Needs a wide-gamut physical display
- I can see differences clearly on my MacBook Pro, less so on LG display
- https://webkit.org/blog-files/color-gamut/comparison.html

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

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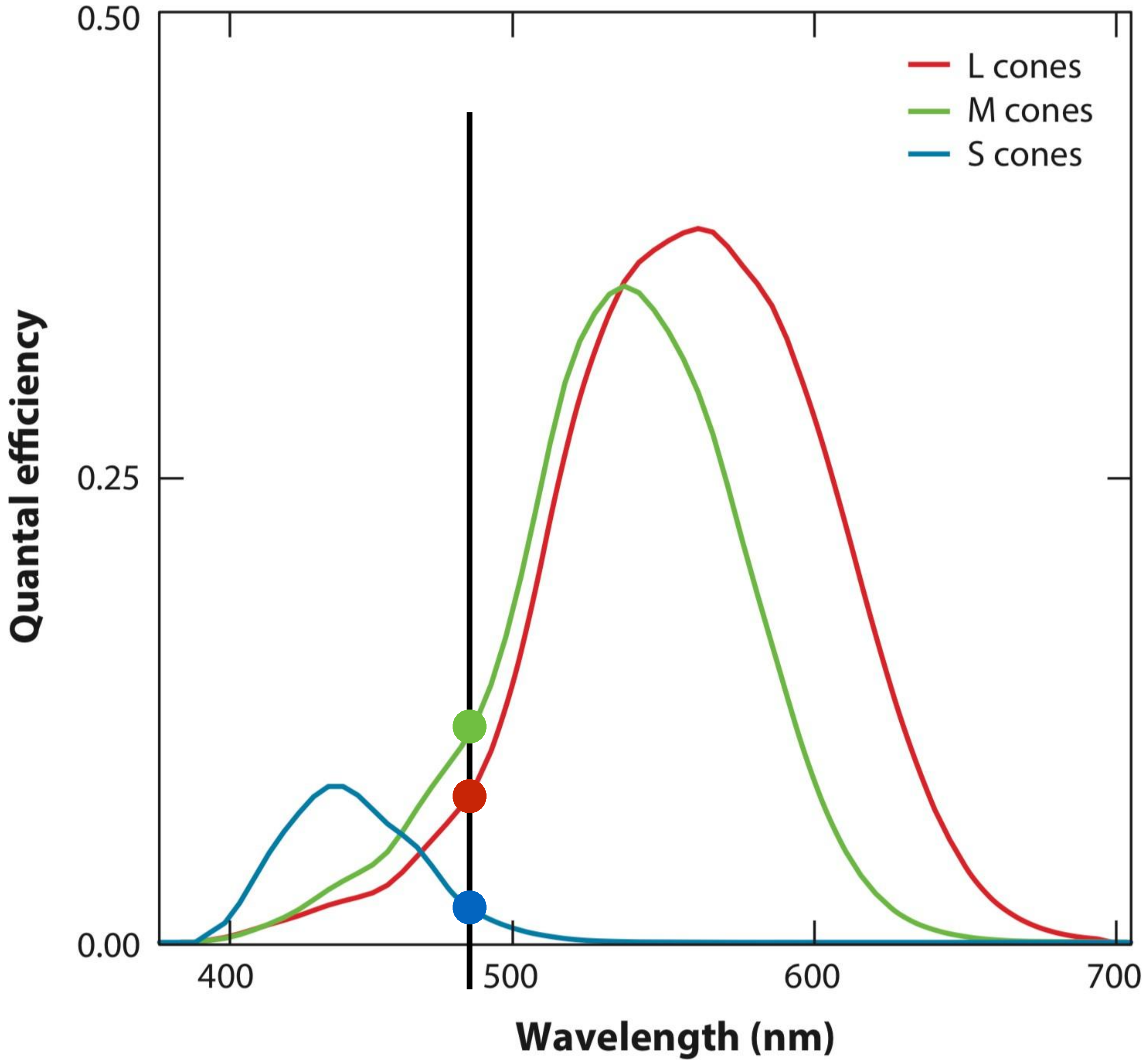

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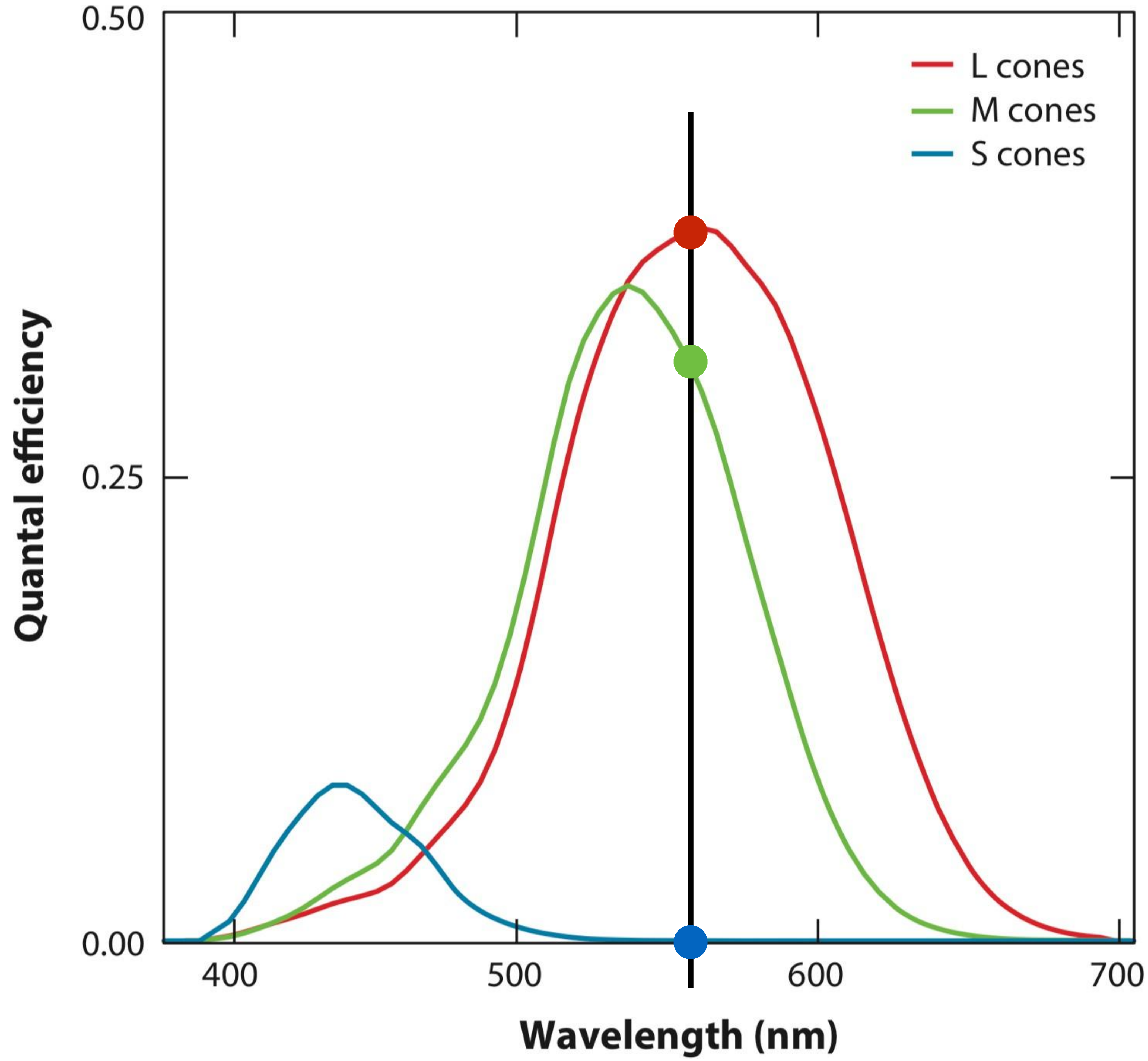
LMS Response Values for Each Wavelength



Probability that a photon will cause a photopigment isomerization

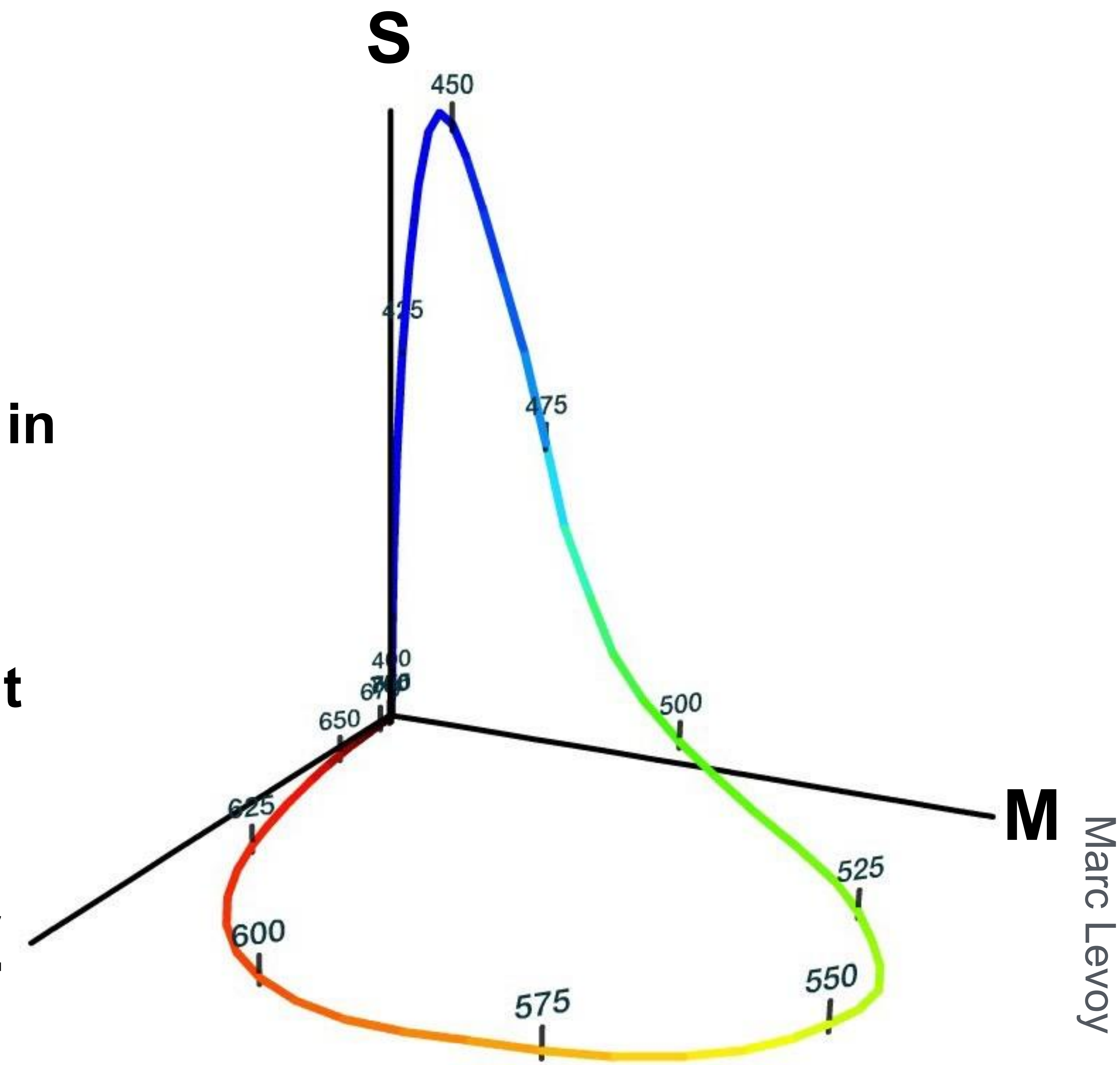
Brainard, Color and the Cone Mosaic, 2015.

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.

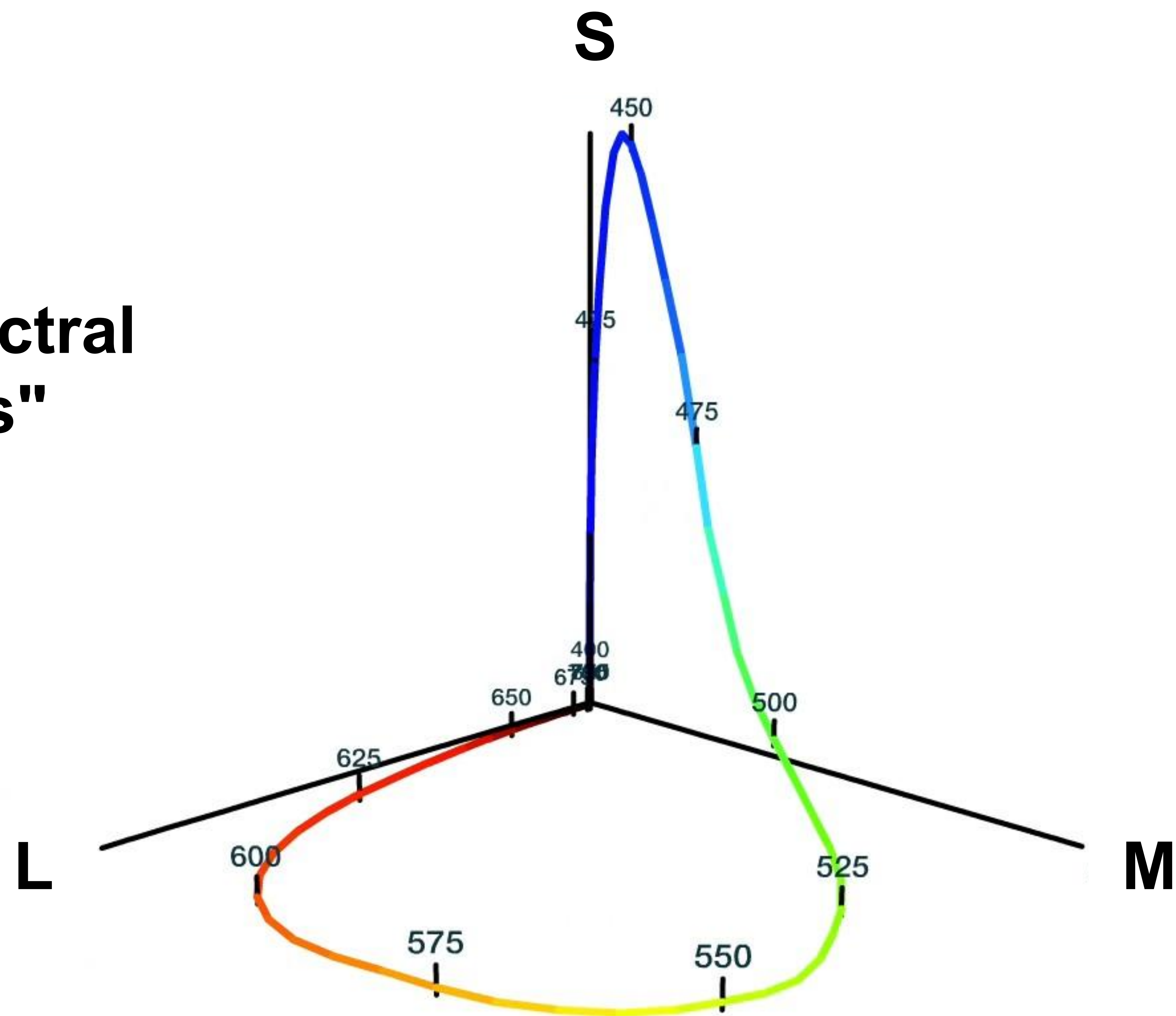
This is a plot of the S, M, L response functions as a point in 3D space.

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



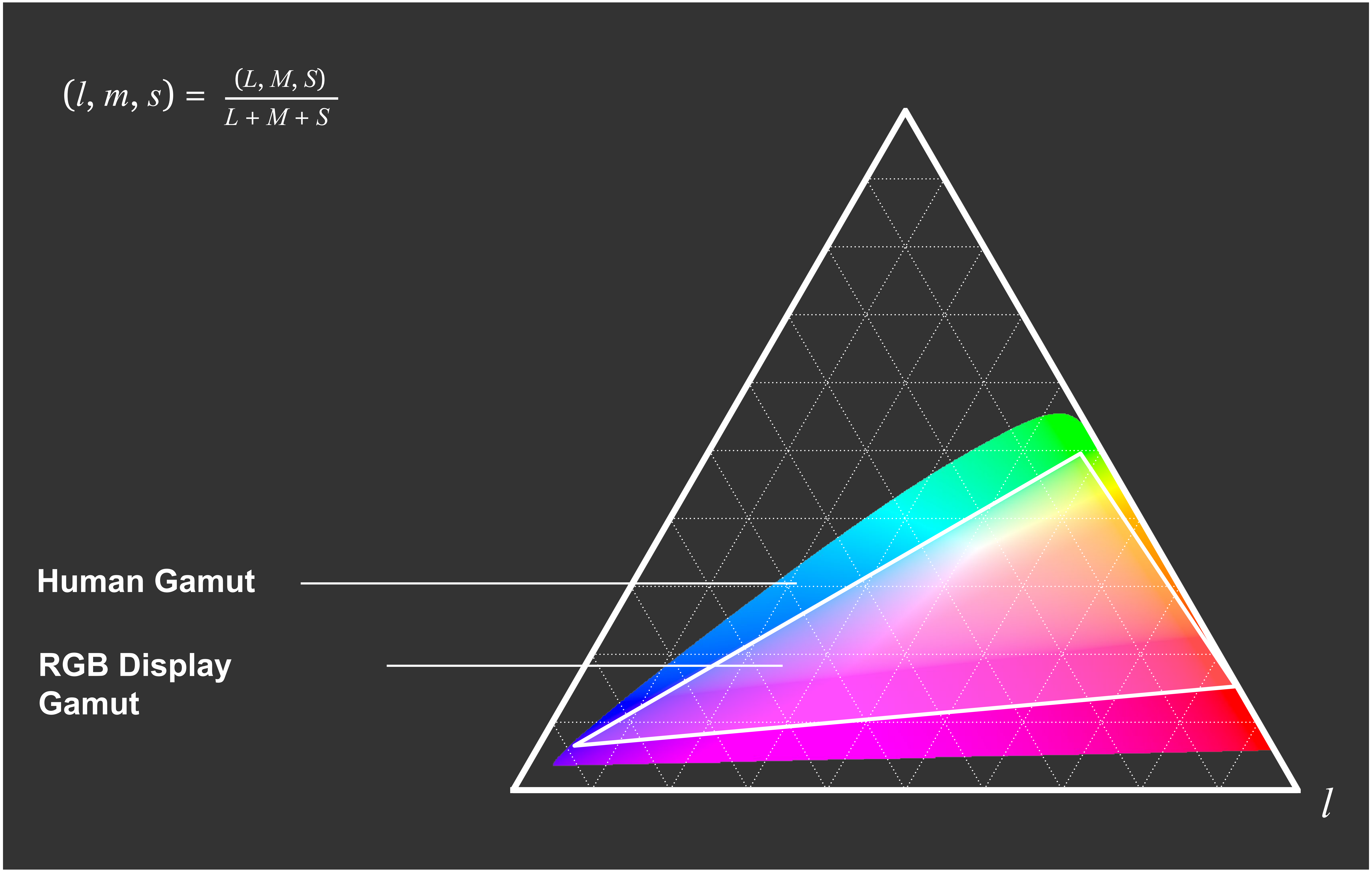
LMS Responses Plotted as 3D Color Space

"Spectral locus"

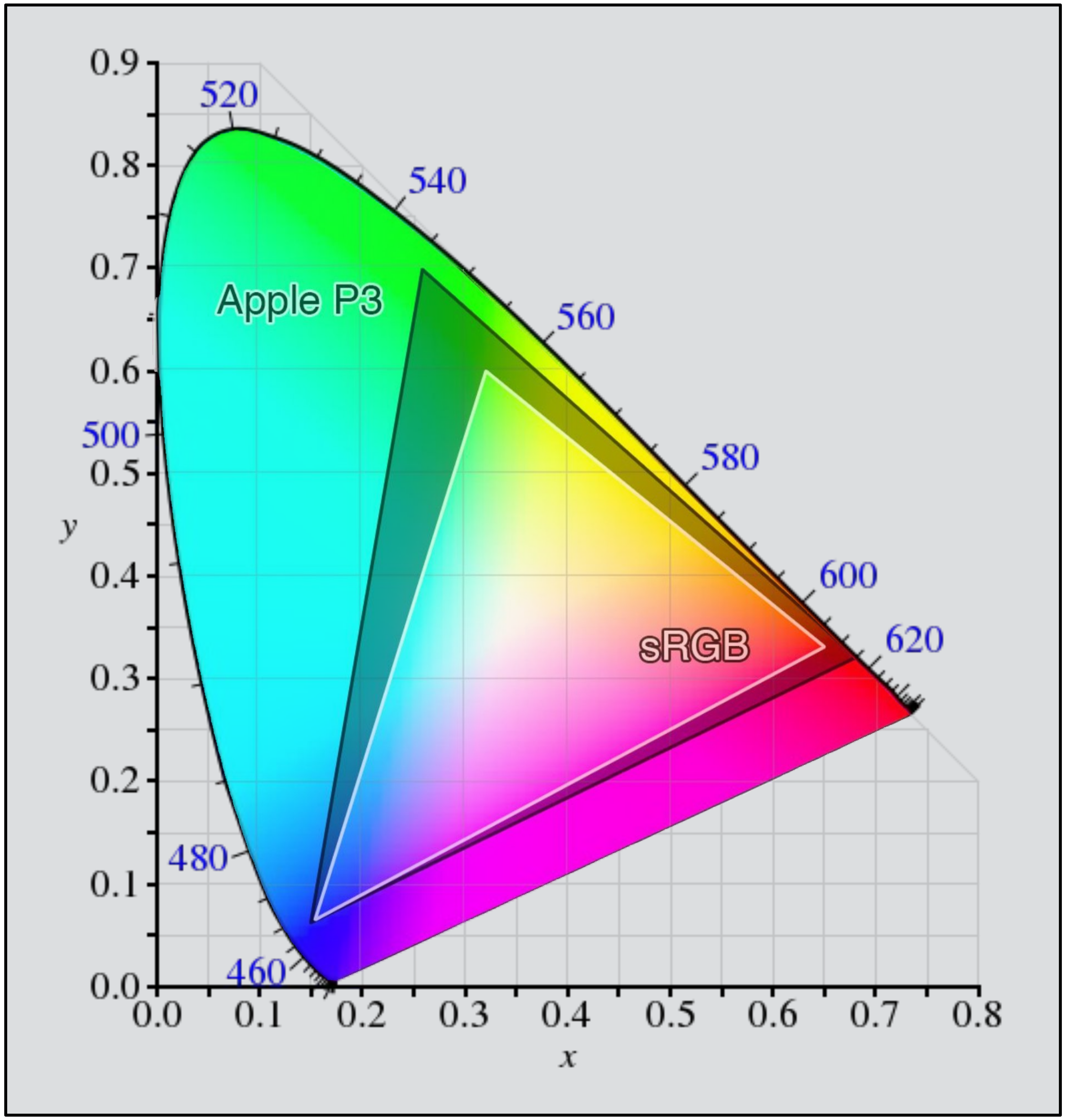


Dektar, Adams, Levoy
https://graphics.stanford.edu/courses/cs178-10/applets/locus.html

Color Gamut on Chromaticity Diagram (Maxwellian)



Color Gamut on Chromaticity Diagram (CIE 1931 xy)



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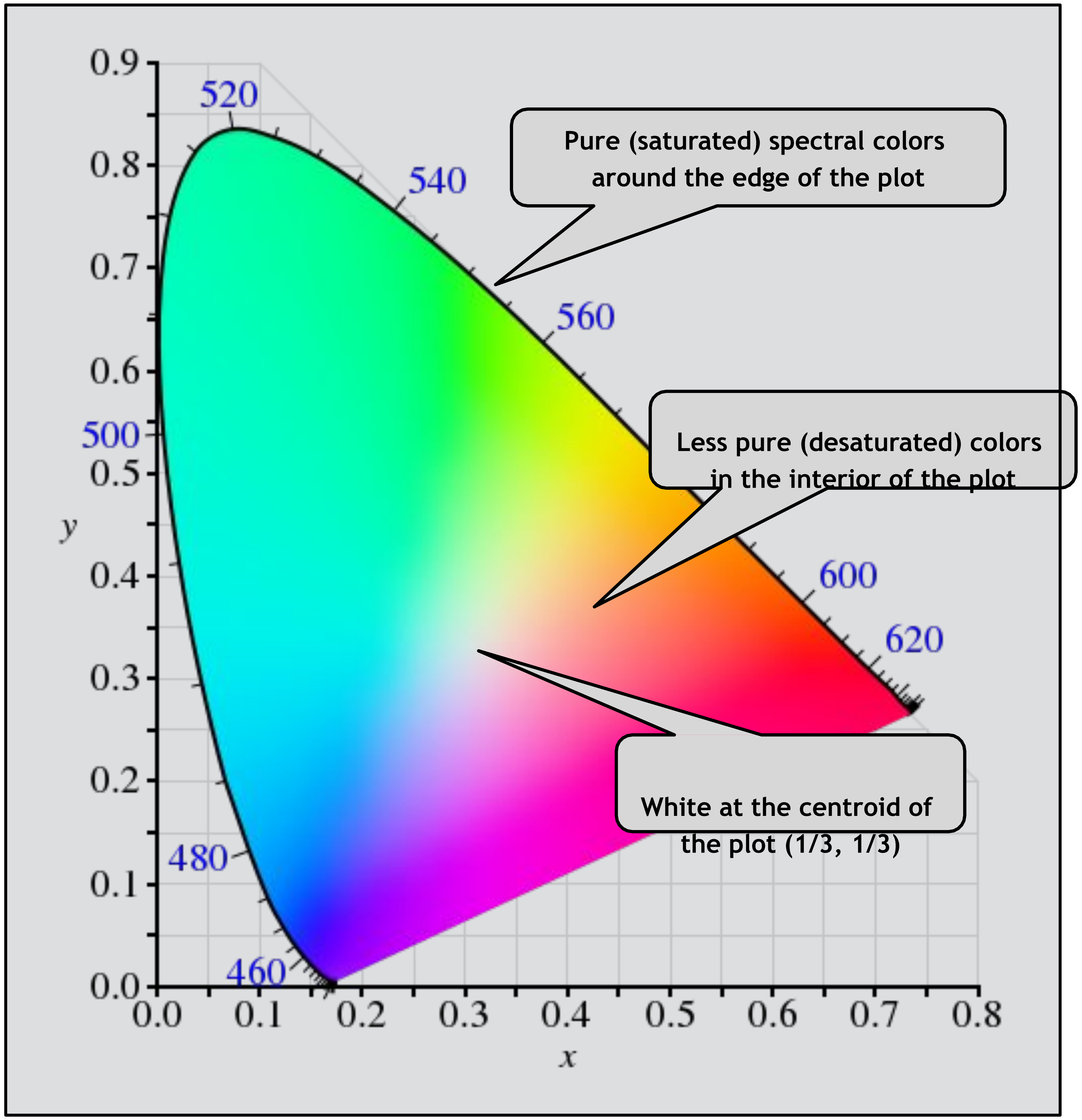


Color Representation

Color Spaces

Need three numbers to specify a color

- But what three numbers?
- A color space is an answer to this question
- Same color has different coordinates in different color spaces. E.g. RGB, XYZ, Lab, HSV, …

Common example: display color space

- Define a color by what R, G, B scalar values will produce it on your display
  - As before, $s(\lambda) = r(\lambda)R + g(\lambda)G + b(\lambda)B$ for some spectra r, g, b
- Device dependent (depends on primary spectra, gamma, …)
  - 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
  - Because in file formats R, G, B usually constrained to be non-negative

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; still widely used today, though other standards common now
- gamut is still limited

The Historical "Standard" Color Space: CIE XYZ

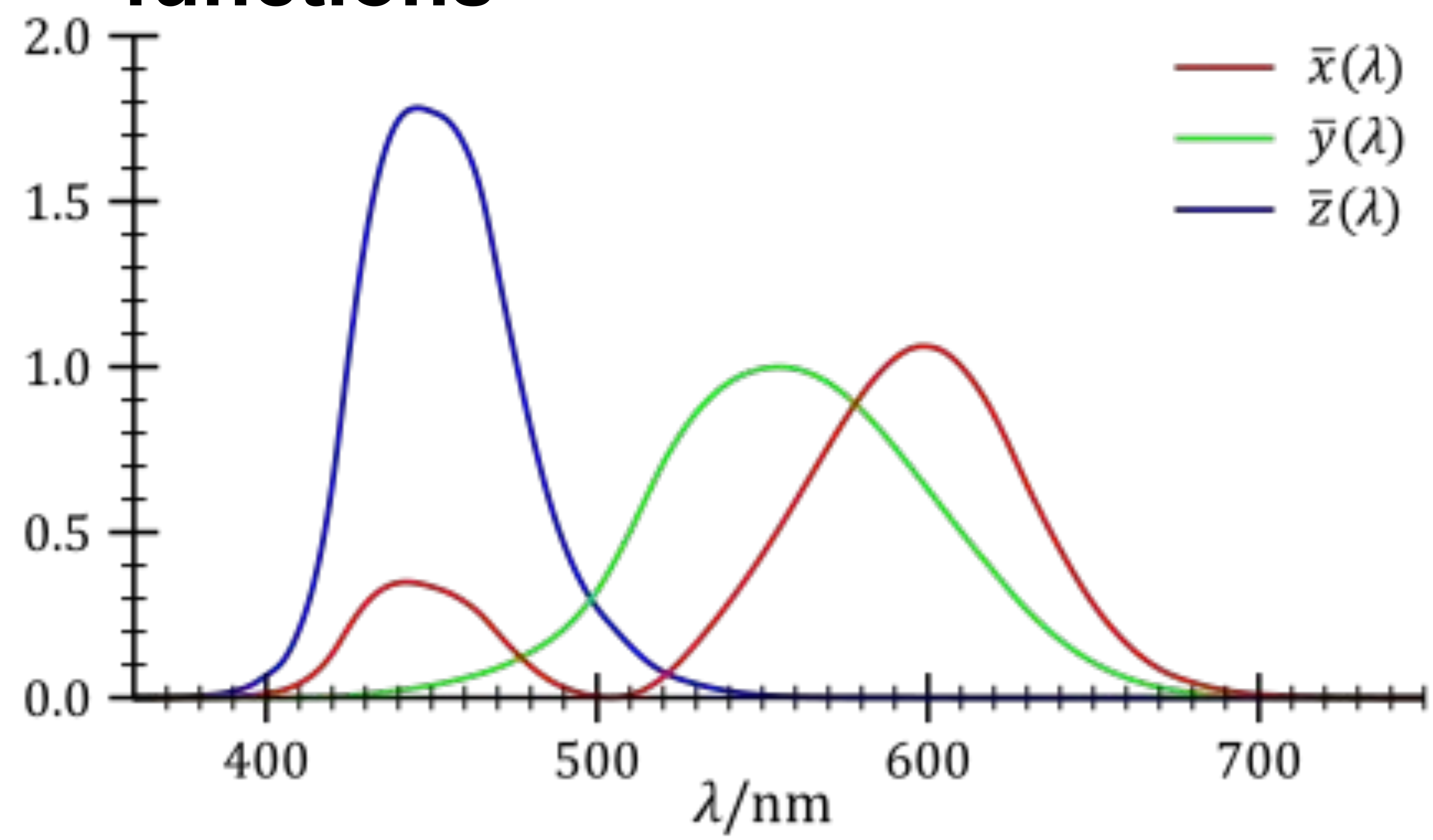
Imaginary set of standard color primaries X, Y, Z

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

CIE XYZ color matching functions

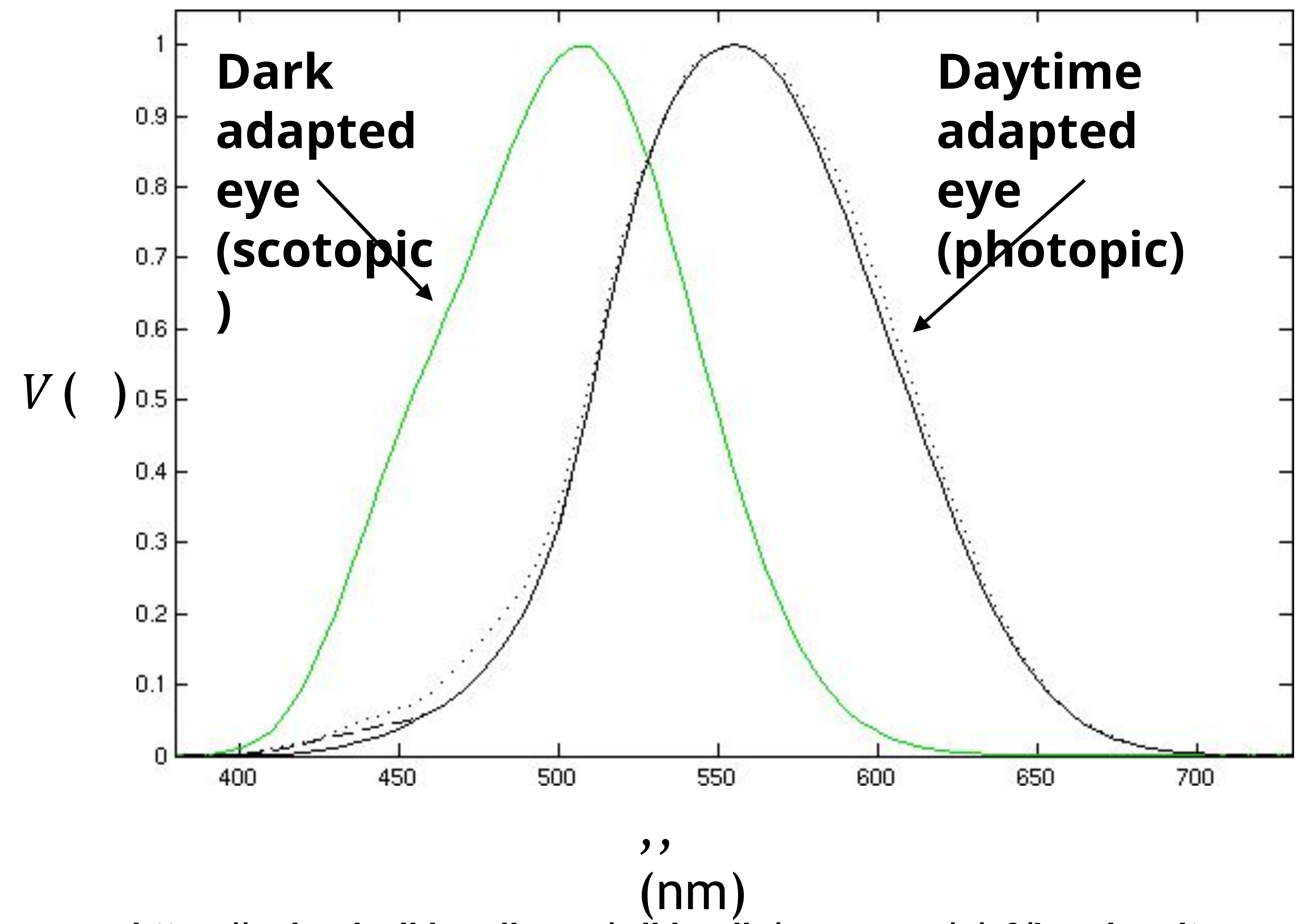


Luminance (Lightness)

Integral of radiance scaled by the visual luminous efficiency

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

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



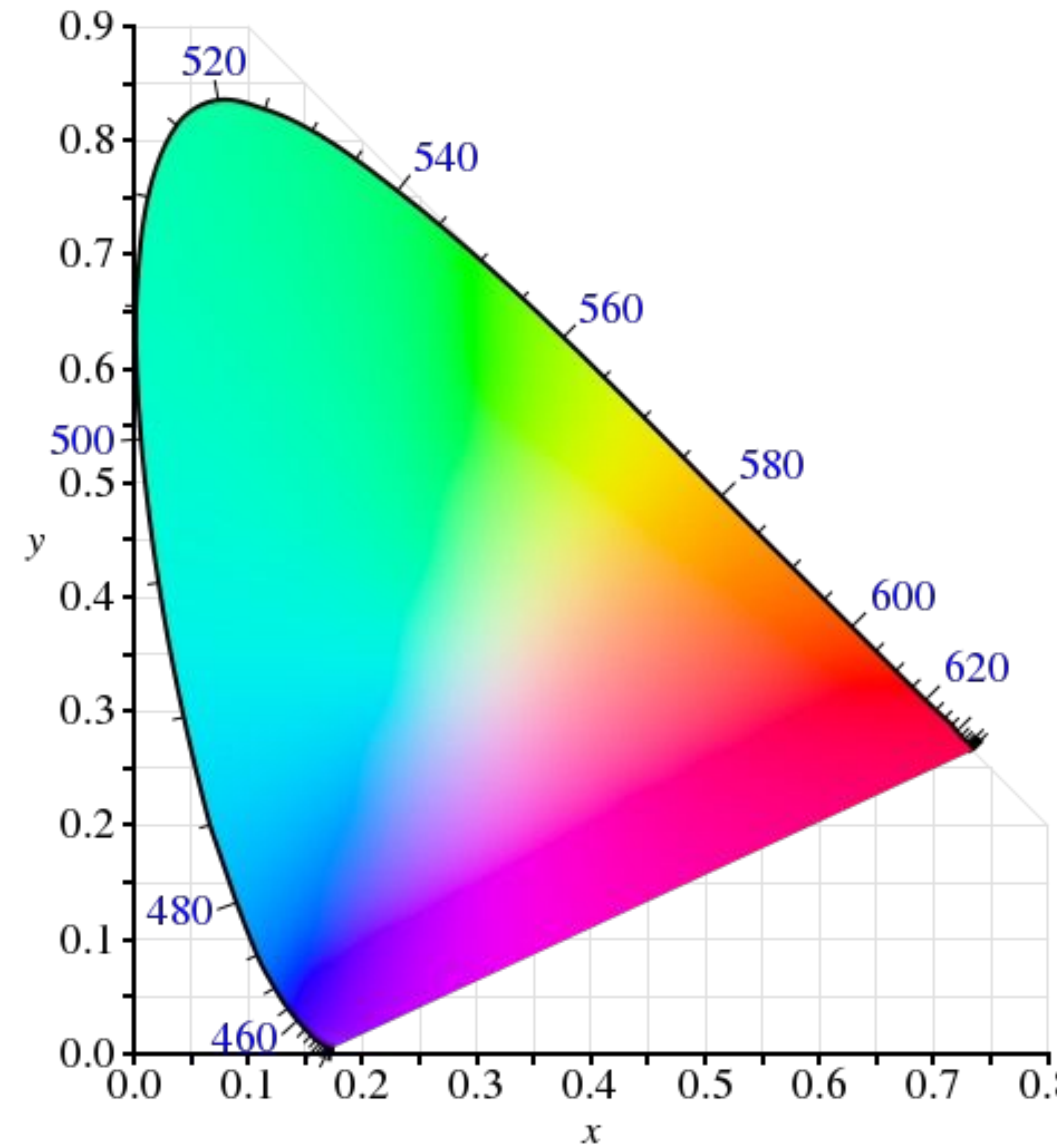
https://upload.wikimedia.org/wikipedia/commons/a/a0/Luminosity.png

Separating Luminance, Chromaticity

Luminance: ***Y***

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

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

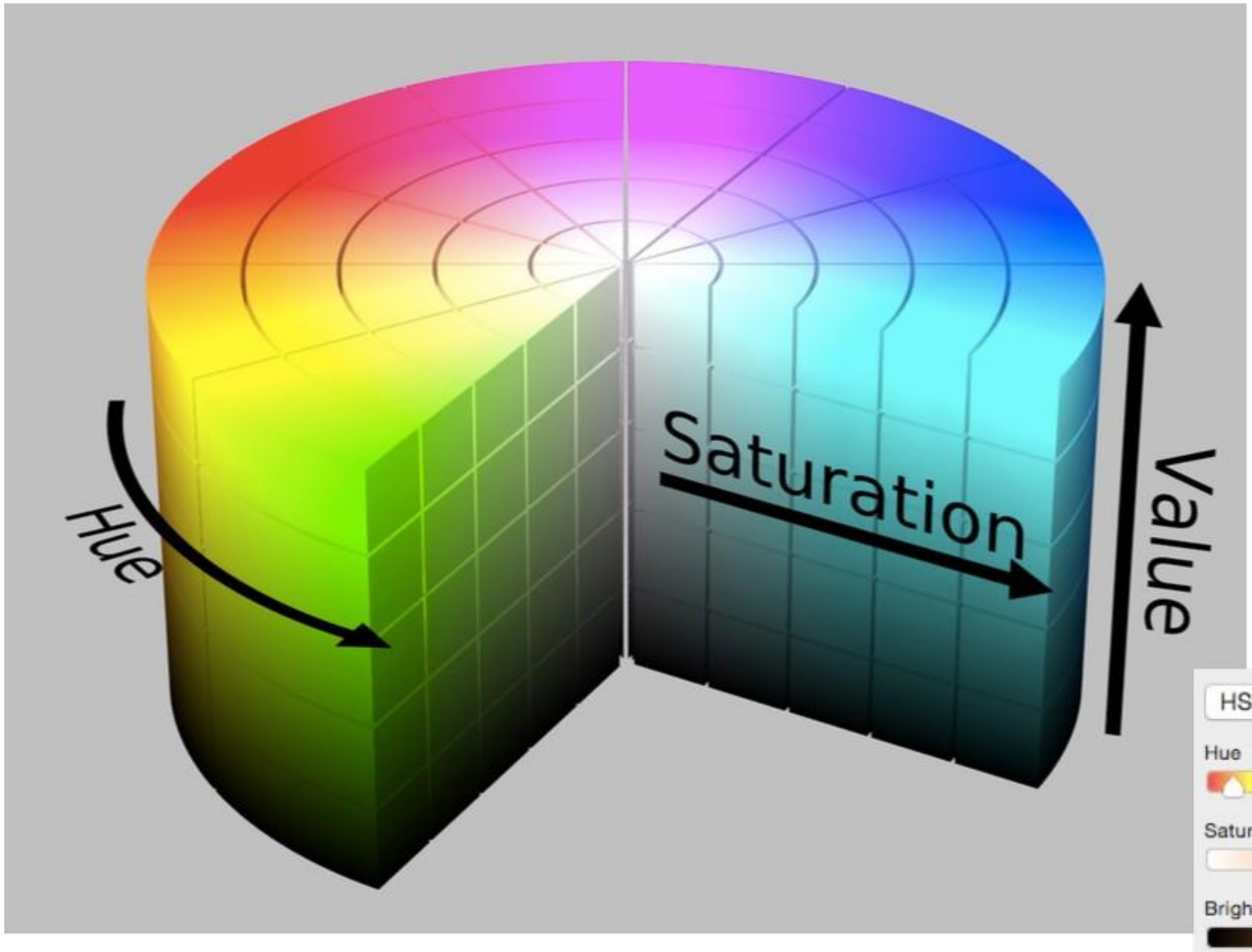


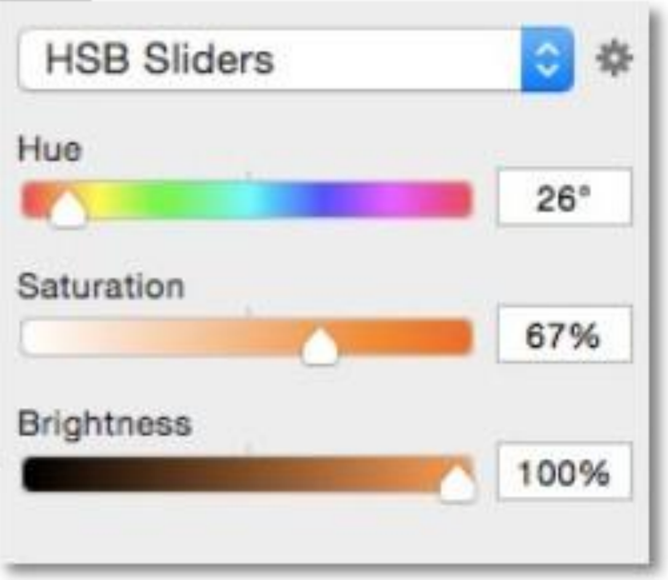
- **since** ***x*** **+** ***y*** **+** ***z*** **= 1, we only need to record two of the three**
  - **usually choose** ***x*** **and** ***y*****, leading to (*****x, y, Y*****) coords**

Perceptually Organized Color Spaces

HSV Color Space (Hue-Saturation-Value)

Axes correspond to artistic characteristics of color





HSV Color Space (Hue-Saturation-Value)

Perceptual dimensions of

color Hue

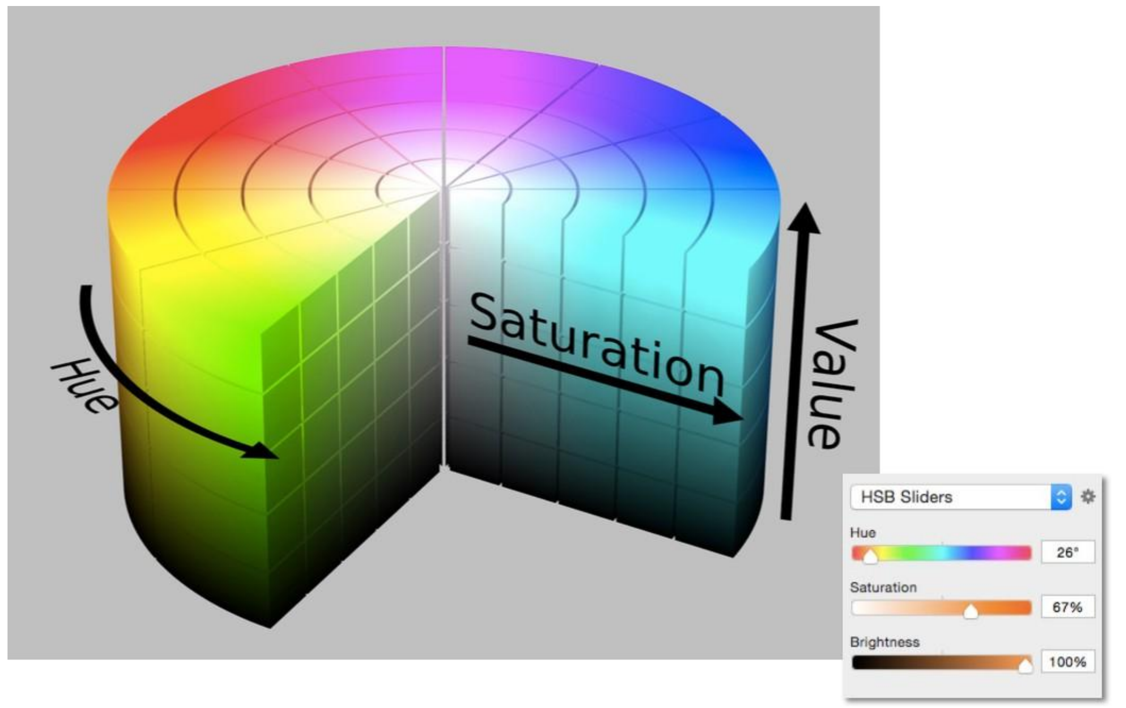
- the “kind” of color, regardless of attributes
- colorimetric correlate: dominant wavelength
- artist’s correlate: the chosen pigment

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



CIELAB (AKA L*a*b*)

A perceptually-organized color space that acts as a simple and useful color appearance model

Features

- Chromatic adaptation (white balance)
- Predicts color appearance
  - Opponent color encoding
  - Formulas for hue, chroma, lightness
- Perceptual uniformity (non-linear warping)

CIELAB Definition

CIEXYZ --> CIELAB

$$L^\star = 116\, f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^\star = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

$$b^\star = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$

$$\delta = \frac{6}{29}$$

CIELAB --> CIEXYZ

$$X = X_n f^{-1}\left(\frac{L^\star + 16}{116} + \frac{a^\star}{500}\right)$$

$$Y = Y_n f^{-1}\left(\frac{L^\star + 16}{116}\right)$$

$$Z = Z_n f^{-1}\left(\frac{L^\star + 16}{116} - \frac{b^\star}{200}\right)$$

where

$$f^{-1}(t) = \begin{cases} t^3 & \text{if } t > \delta \\ 3\delta^2\left(t - \frac{4}{29}\right) & \text{otherwise} \end{cases}$$

and where $\delta = 6/29$.

X_n, Y_n and Z_n **are the CIEXYZ coordinates of the reference white point**

Wikipedia

CIELAB Has Chromatic Adaptation (Reference White)

CIEXYZ --> CIELAB

$$L^\star = 116\, f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^\star = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

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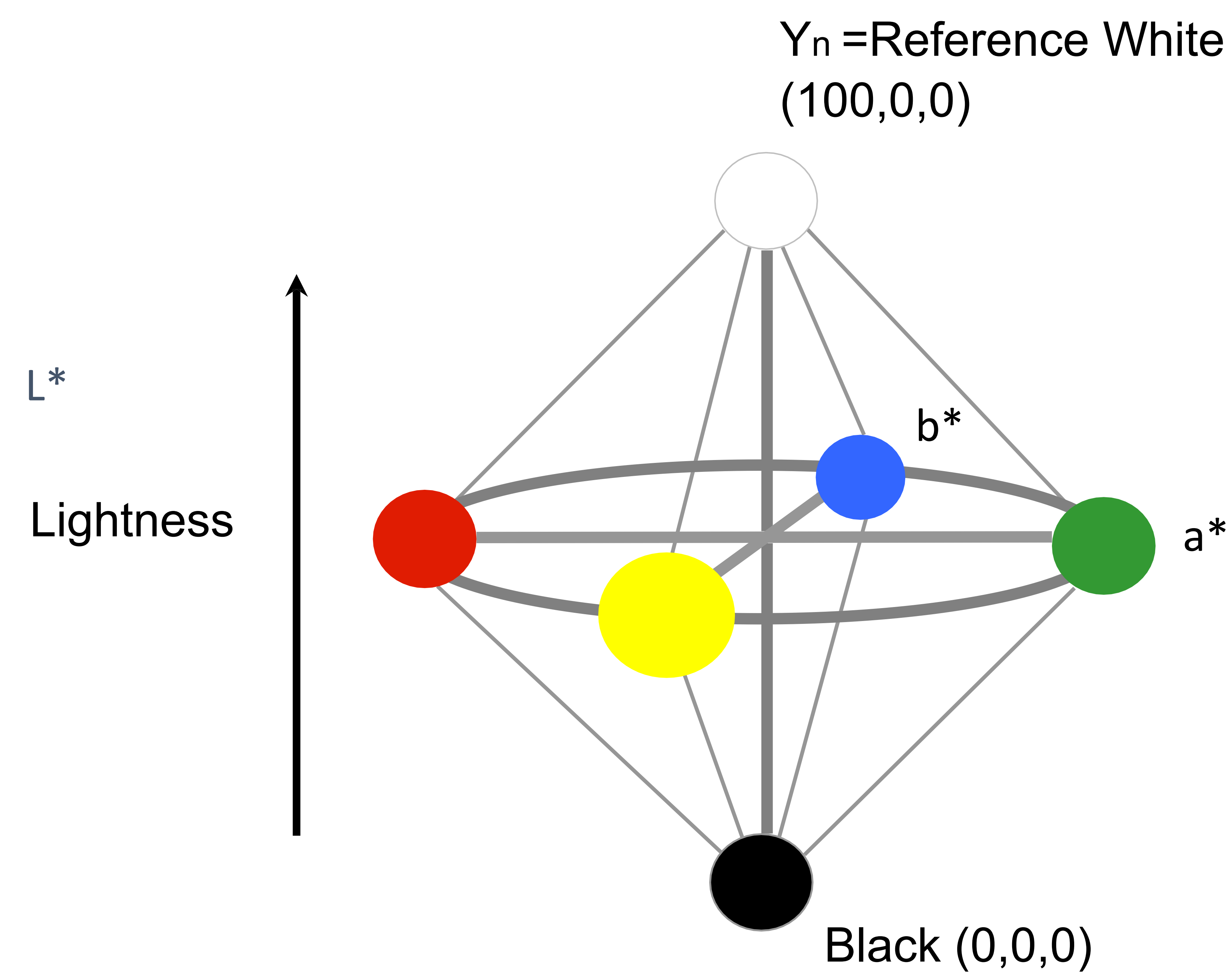
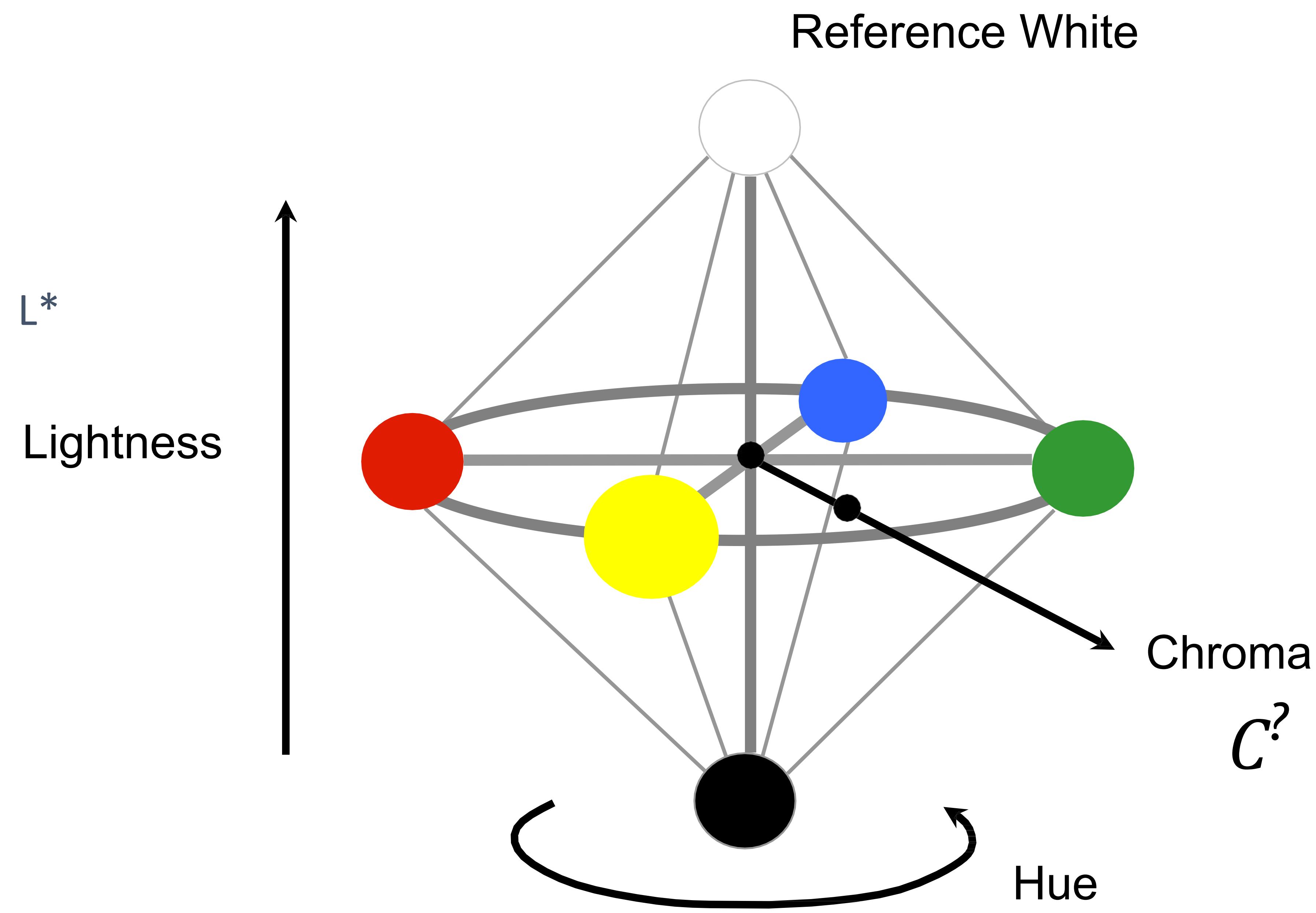


X_n, Y_n and Z_n **are the CIEXYZ coordinates of the reference white point**

CIELAB As a Color Appearance Model

Hue,
lightness, chroma
s

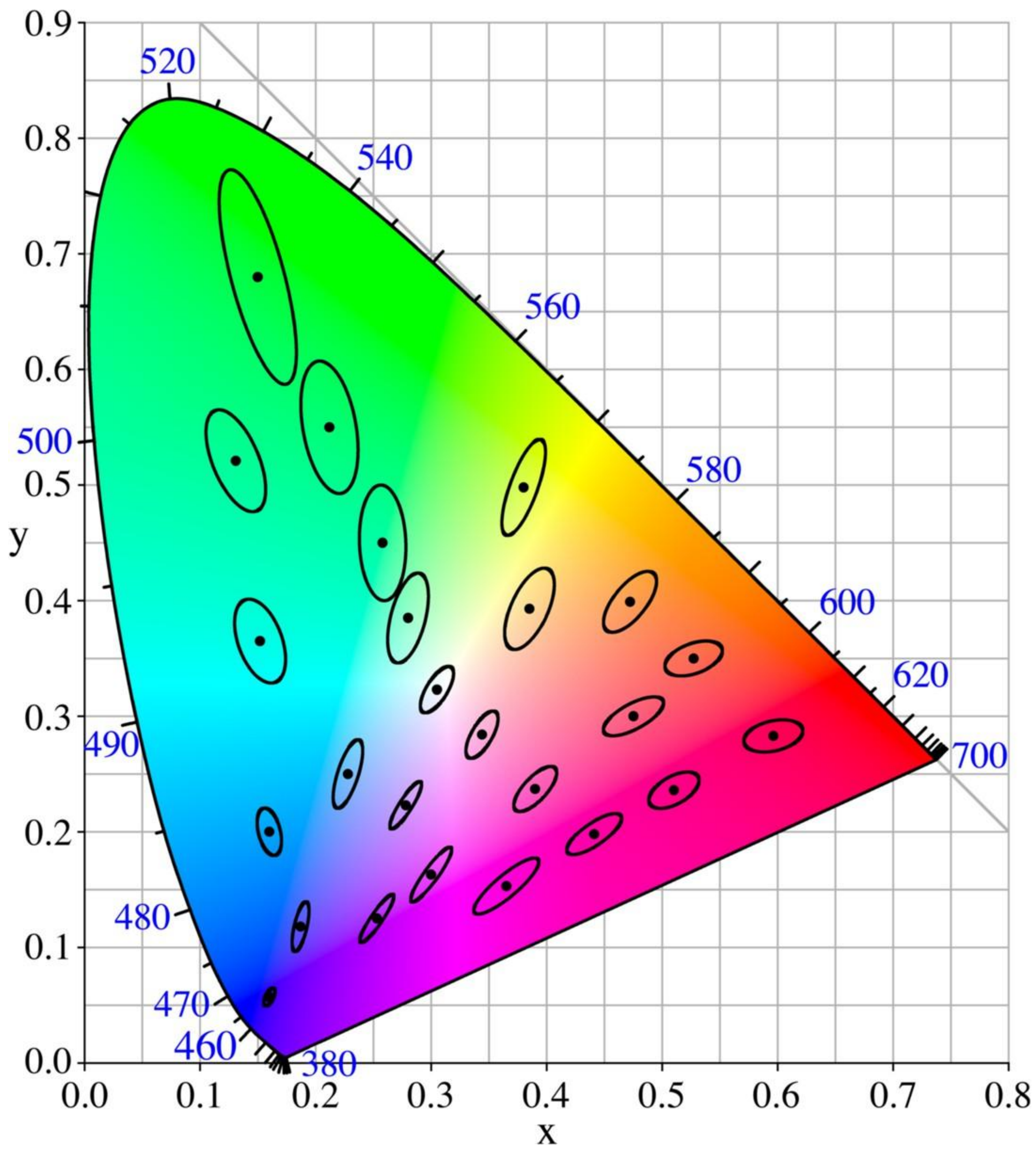
Not L*, a*, b*



$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h = \arctan\left(\frac{b^*}{a^*}\right)$$

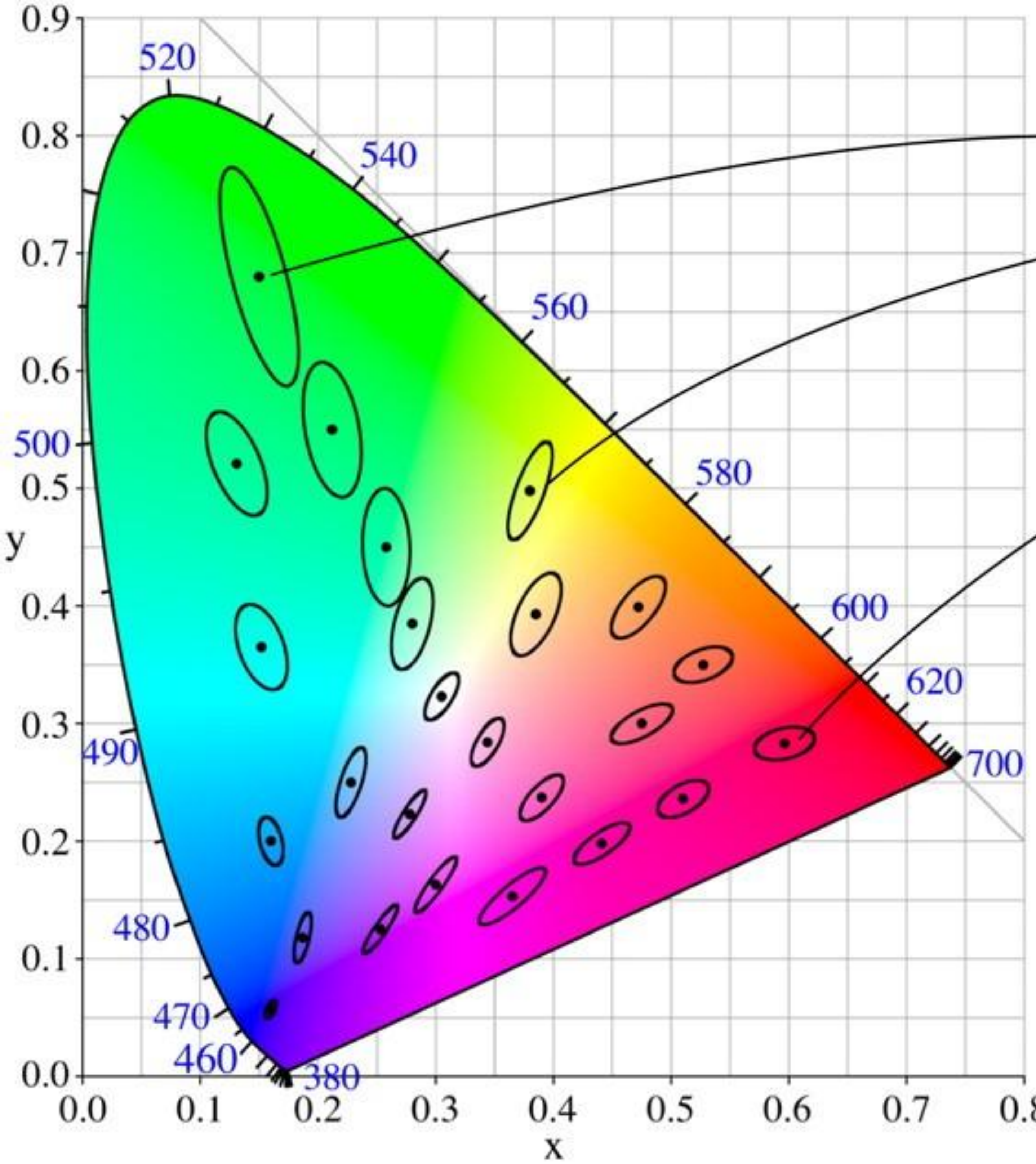
CIEXYZ is Not Perceptually Uniform



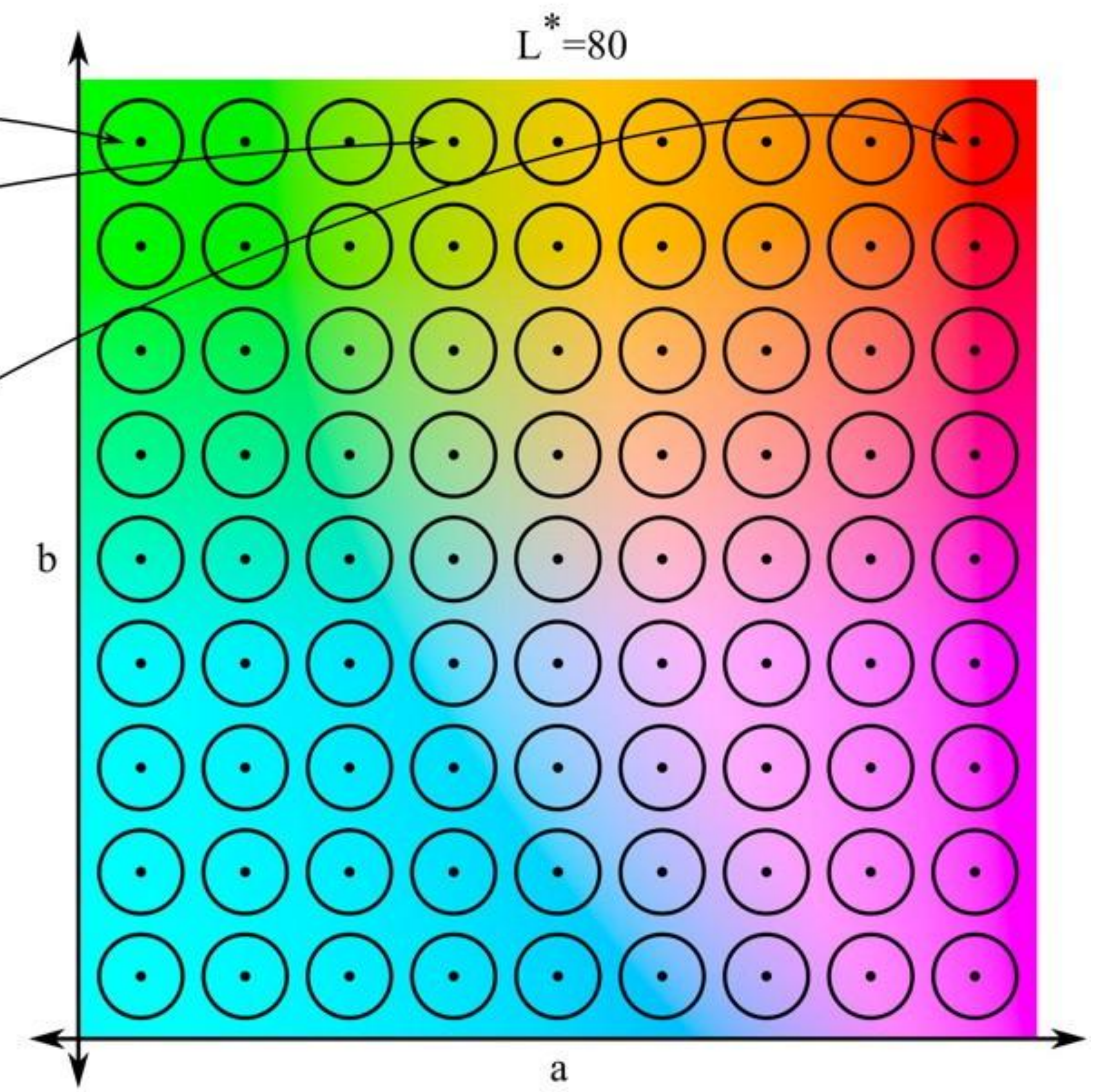
Wikipedia

- In the xy chromaticity diagram at left, MacAdam ellipses show regions of perceptually equivalent color (ellipses enlarged 10x)

CIELAB Aims for Perceptual Uniformity



CIE 1931



CIELAB (CIE 1976 L*,a*,b*)

From Henrich et al. 2011

https://iovs.arvojournals.org/article.aspx?articleid=2187751

Perceptual Normalization Function Applies to L*, a*, b*

CIEXYZ --> CIELAB

$$L^\star = 116\, f\left(\frac{Y}{Y_n}\right) - 16$$

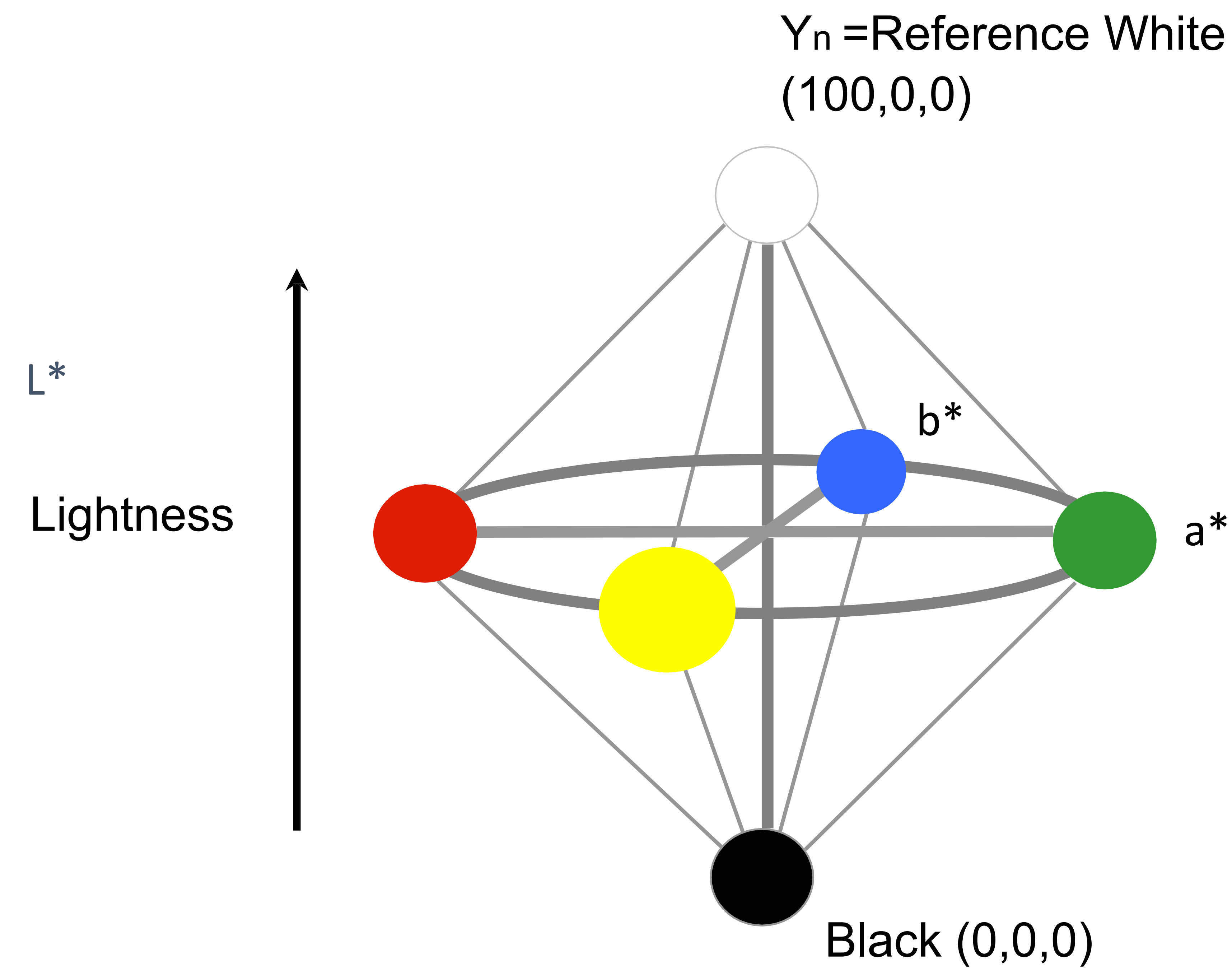
$$a^\star = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

$$b^\star = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$

$$\delta = \frac{6}{29}$$



X_n, Y_n and Z_n **are the CIEXYZ coordinates of the reference white point**

CIELAB Gives a Recommended Color Difference Metric

Other color spaces we looked at (RGB, CIEXYZ, HSV) are not perceptually uniform and are not recommended for color difference calculations

- E.g. a pair of colors that look similar to a human observer may have R,G,B coordinates further apart than another pair of colors that look quite different
- Try converting colors to CIELAB coordinates for applications that need to quantify differences in color appearance

Distance between (L*, a*, b*) coordinates for two colors is a recommended color difference metric that is approximately perceptually uniform

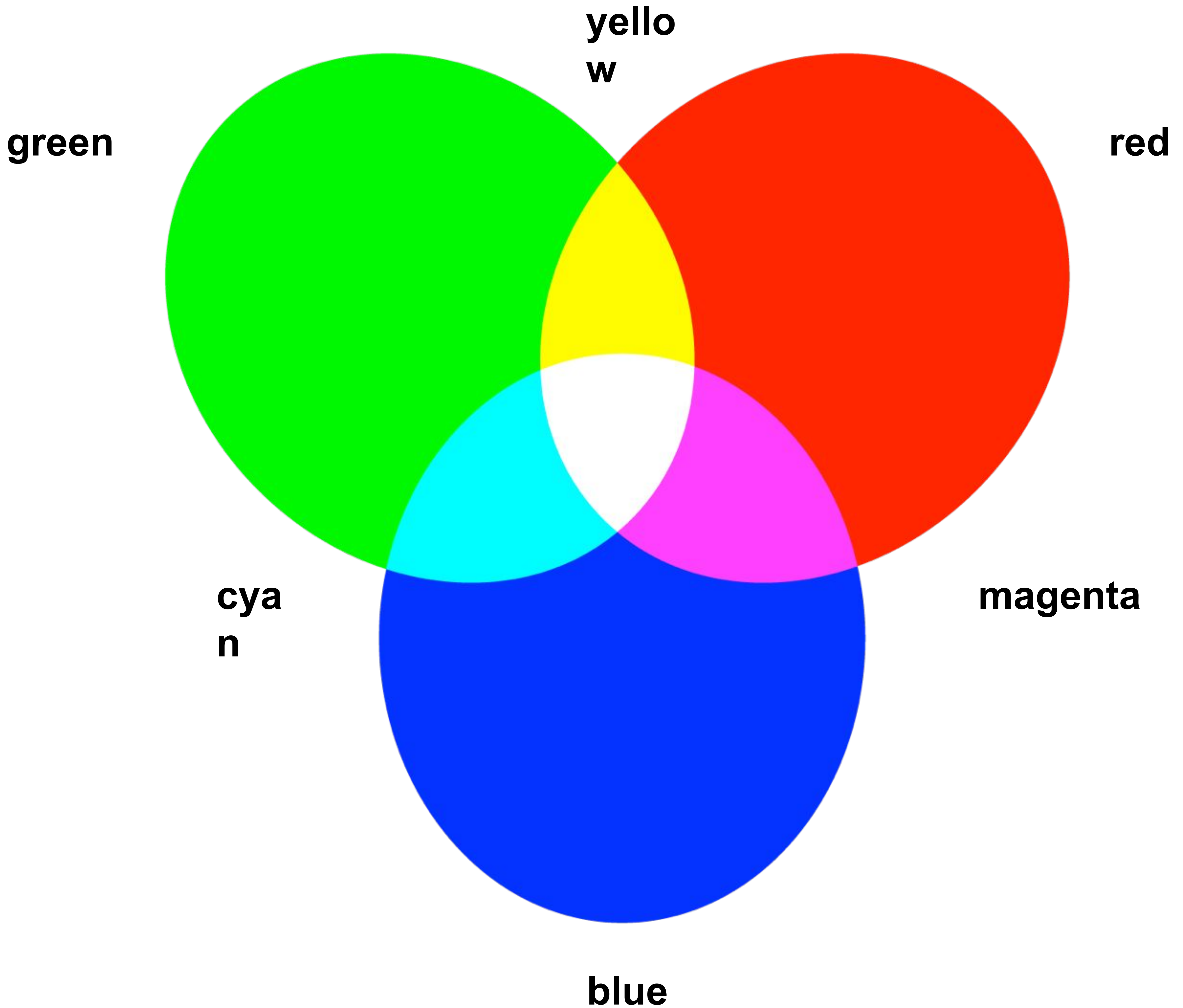
- $\Delta E^*_{ab} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$ ("Delta E")
- Caveat: ΔE^*_{ab} is not perfect (e.g. large differences, and differences between highly saturated colors are inaccurate). CIEDE2000 is a more complex/accurate metric based on color appearance models

Additive vs Subtractive Color

or

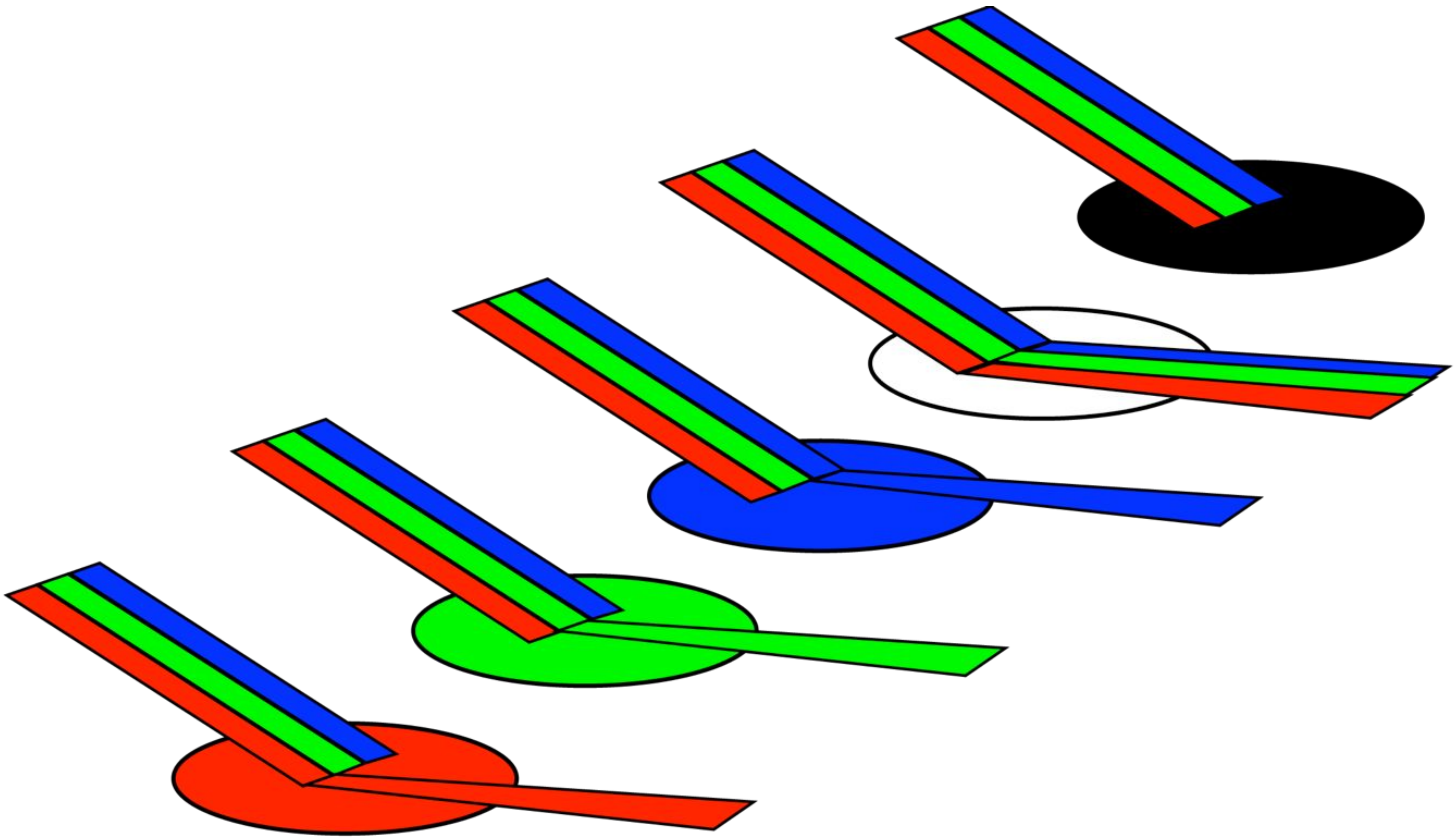
Beam Colors vs Object Colors

Additive Color



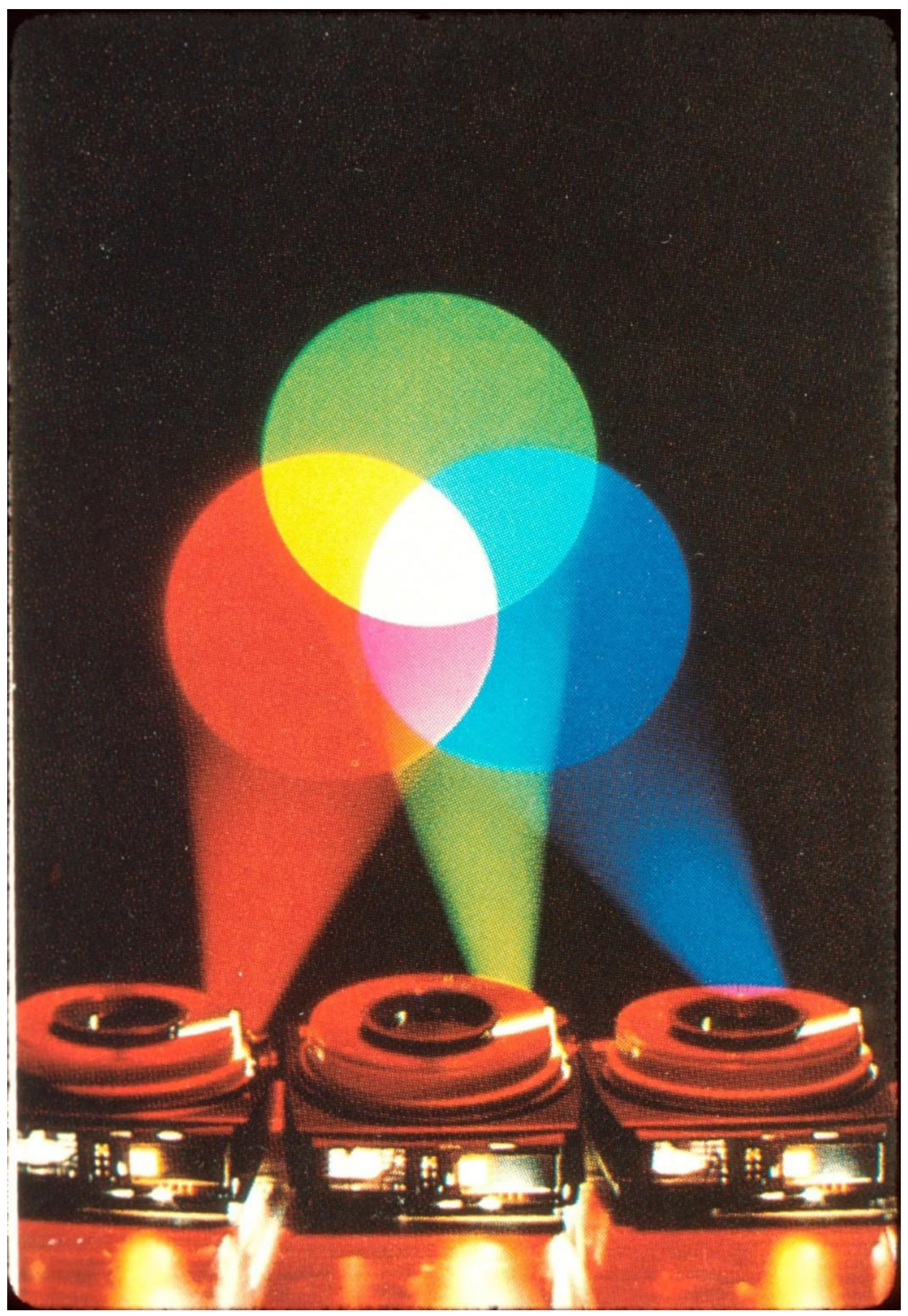
Slide courtesy K. Breeden

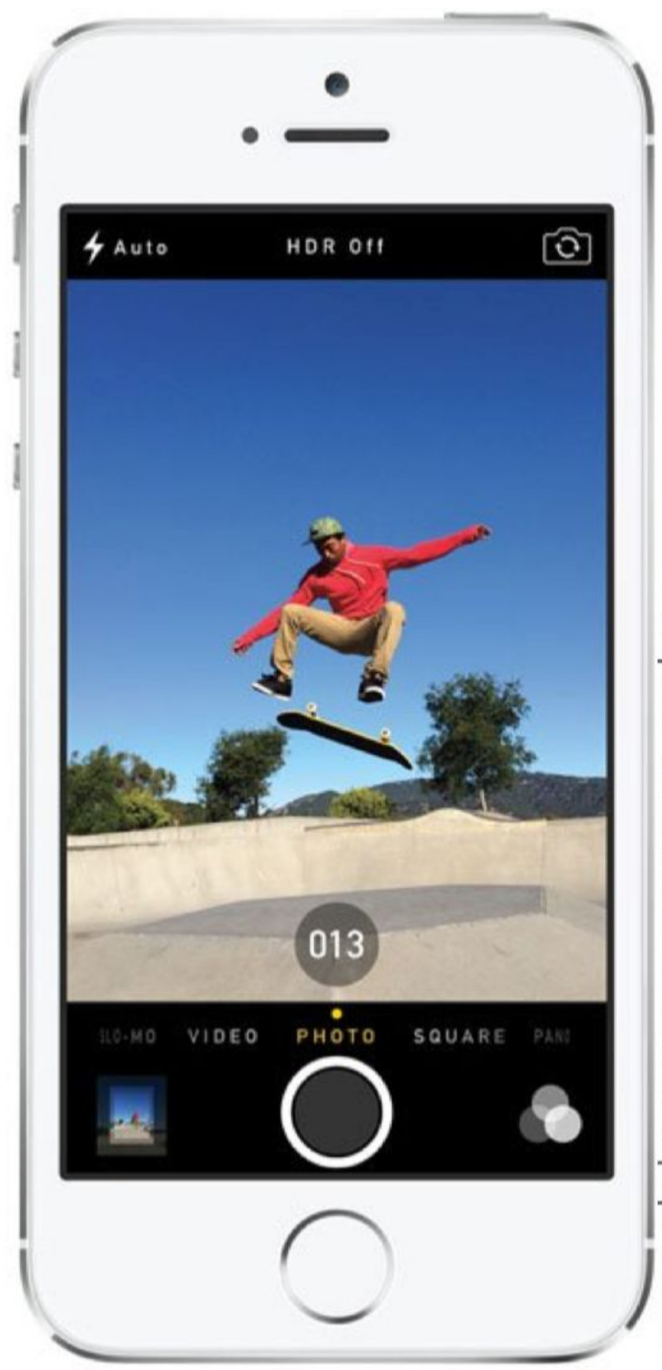
Subtractive (Actually Multiplicative) Color



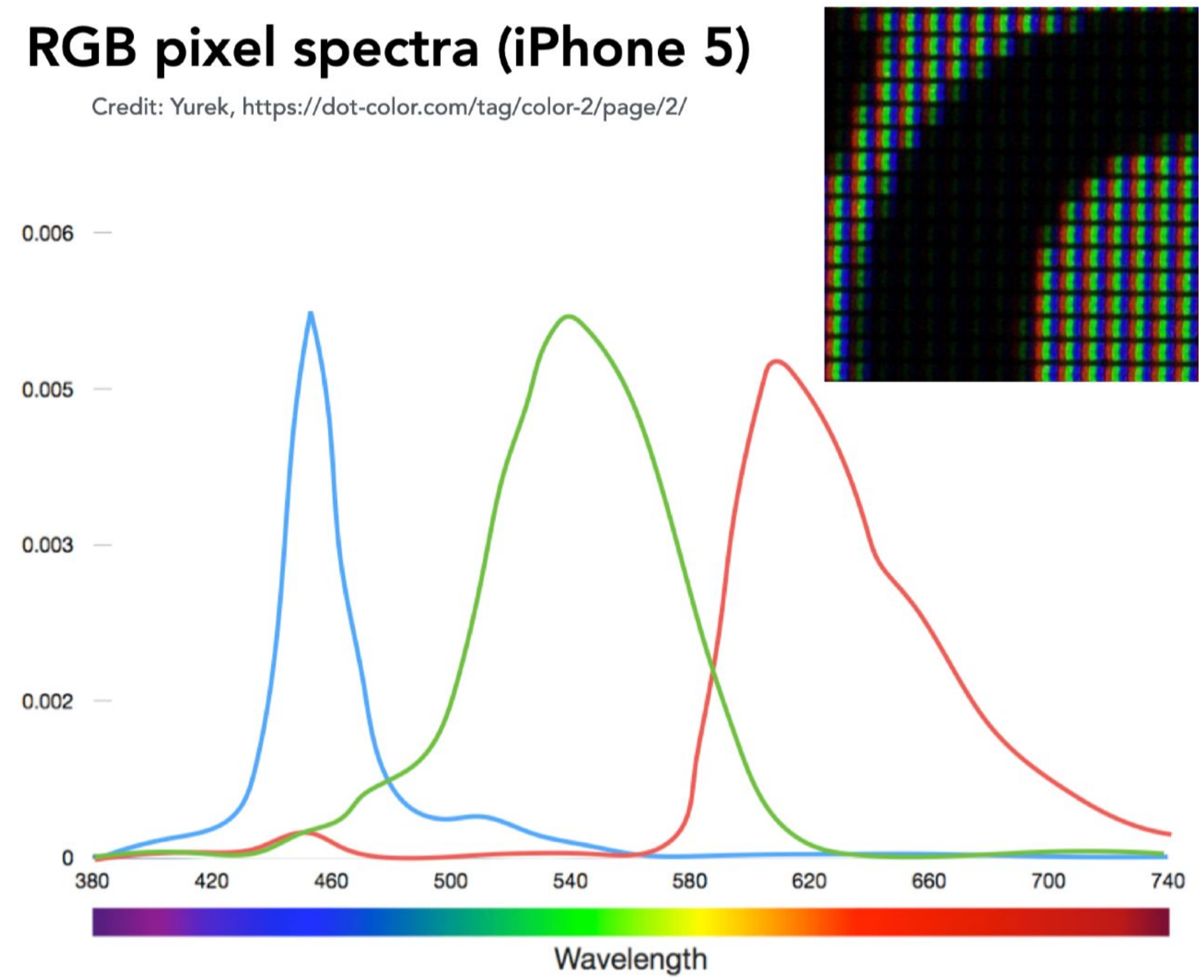
Shining white light on various colored pigments

Beam Colors and Additive Color



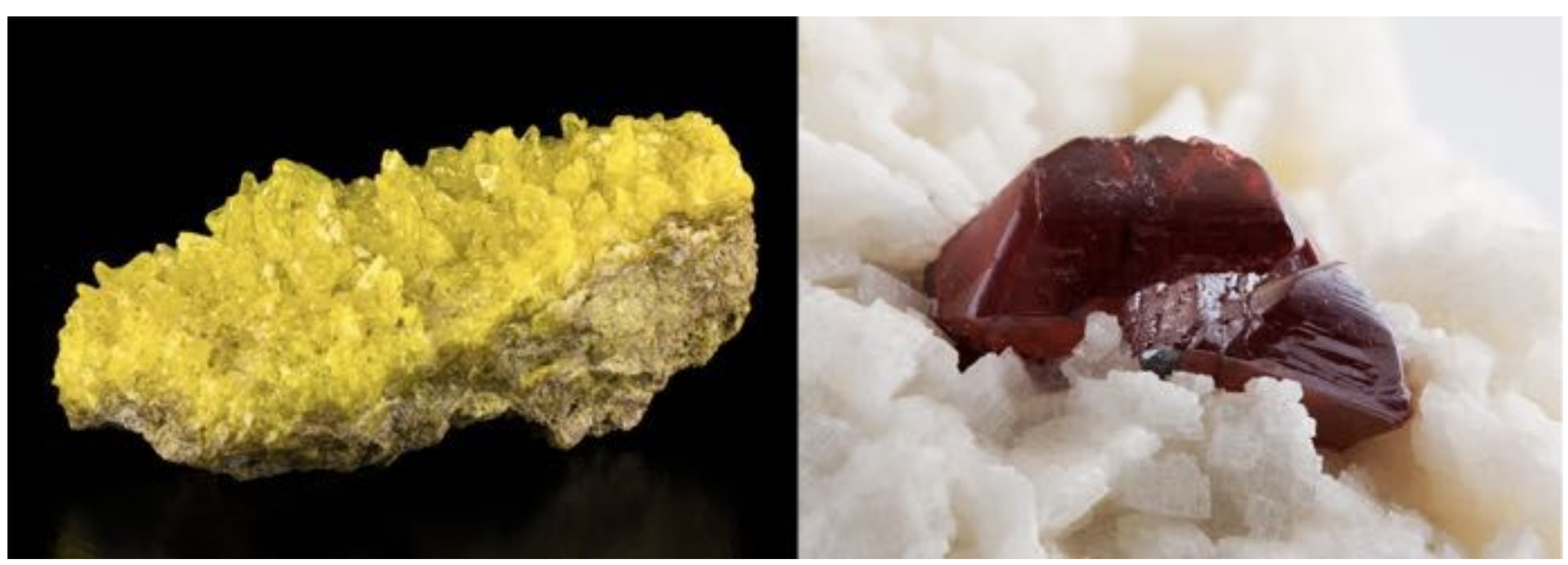


https://www.macrumors.com/roundup/iphone-5s/

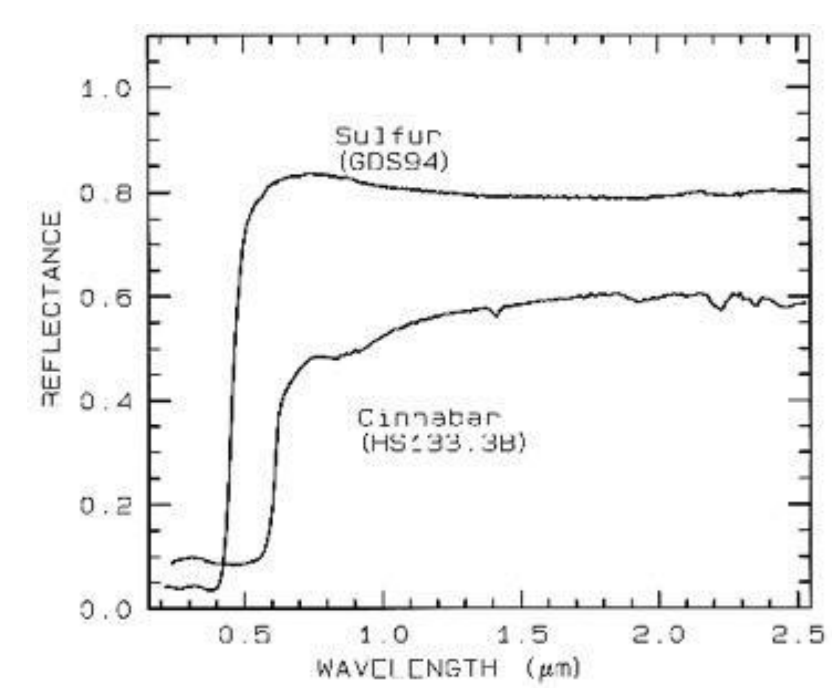


Object Colors - Multiplicative Color

The "Seven Sisters", Sussex. Such white chalk cliffs are the primordial objects.



Sulphur crystals (the element, bright yellow) and cinnabar (a deep red mer- cury(II) sulphide) on Dolomite.



Reflection (range 0–100%) spectra of sulphur and cinnabar. The wavelength range involves the infrared, the visual range is about 0.4– 0.75μm. Notice that these spectra are roughly of an all-or-none type. There are no signs of anything spe- cial at some "yellow or red wave- length" as many naive persons are wont to think.

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 (and DeltaE), HSV

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Credit to

Michael S. Brown, "Understanding the In-Camera Image Processing Pipeline for Computer Vision", IEEE Computer Vision and Pattern Recognition - Tutorial, June 26, 2016.

Mark D. Fairchild, "Color appearance, color order, & other color systems," ISCC-AIC Munsell Centennial Color Symposium, Boston (2018).


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.