Lecture 19:

Introduction to Color Science

Computer Graphics and Imaging
UC Berkeley CS184/284A


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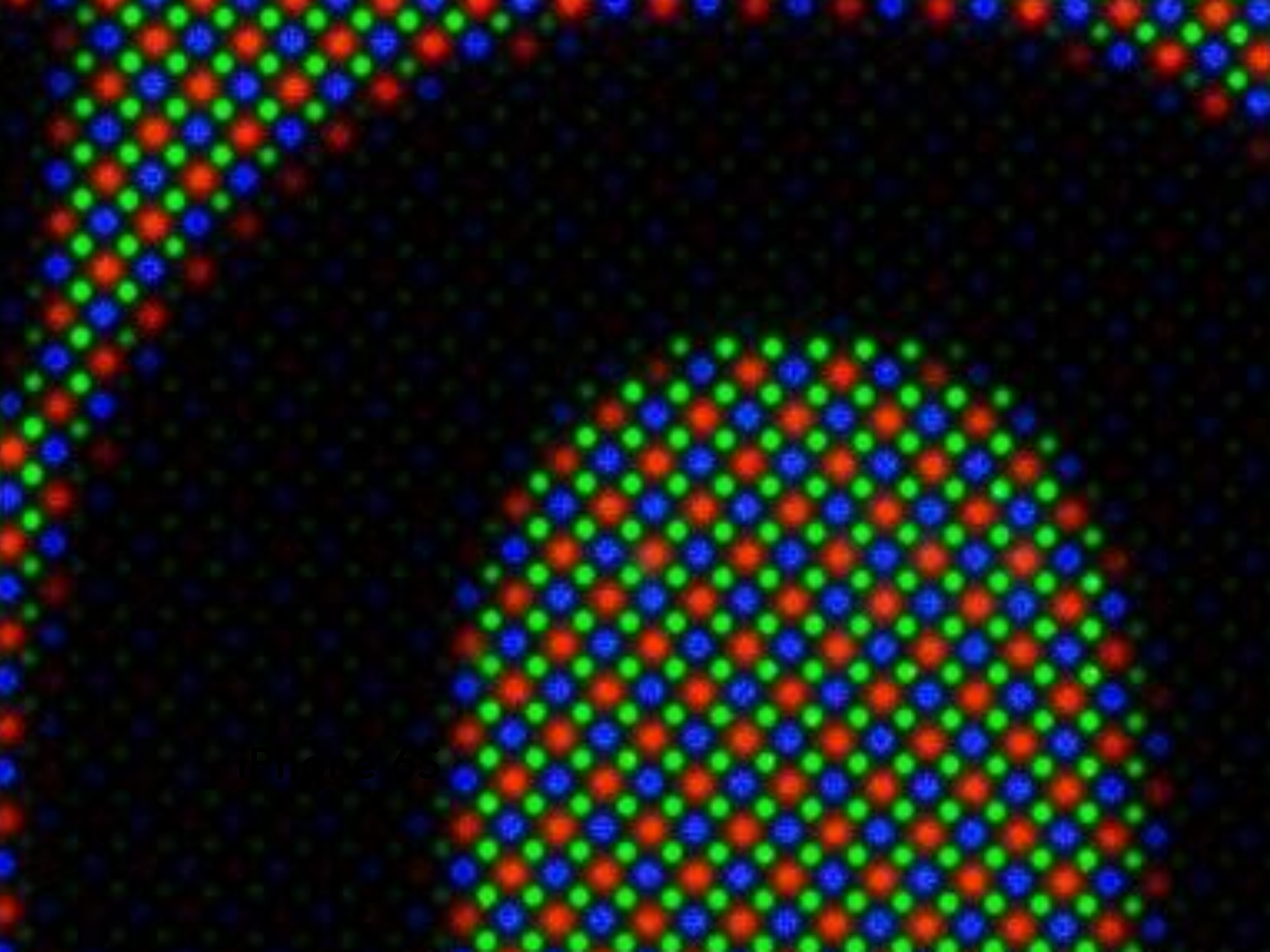
Mark Rothko
No. 61. Rust and Blue
1953,
Museum of Contemporary Art, Los Angeles

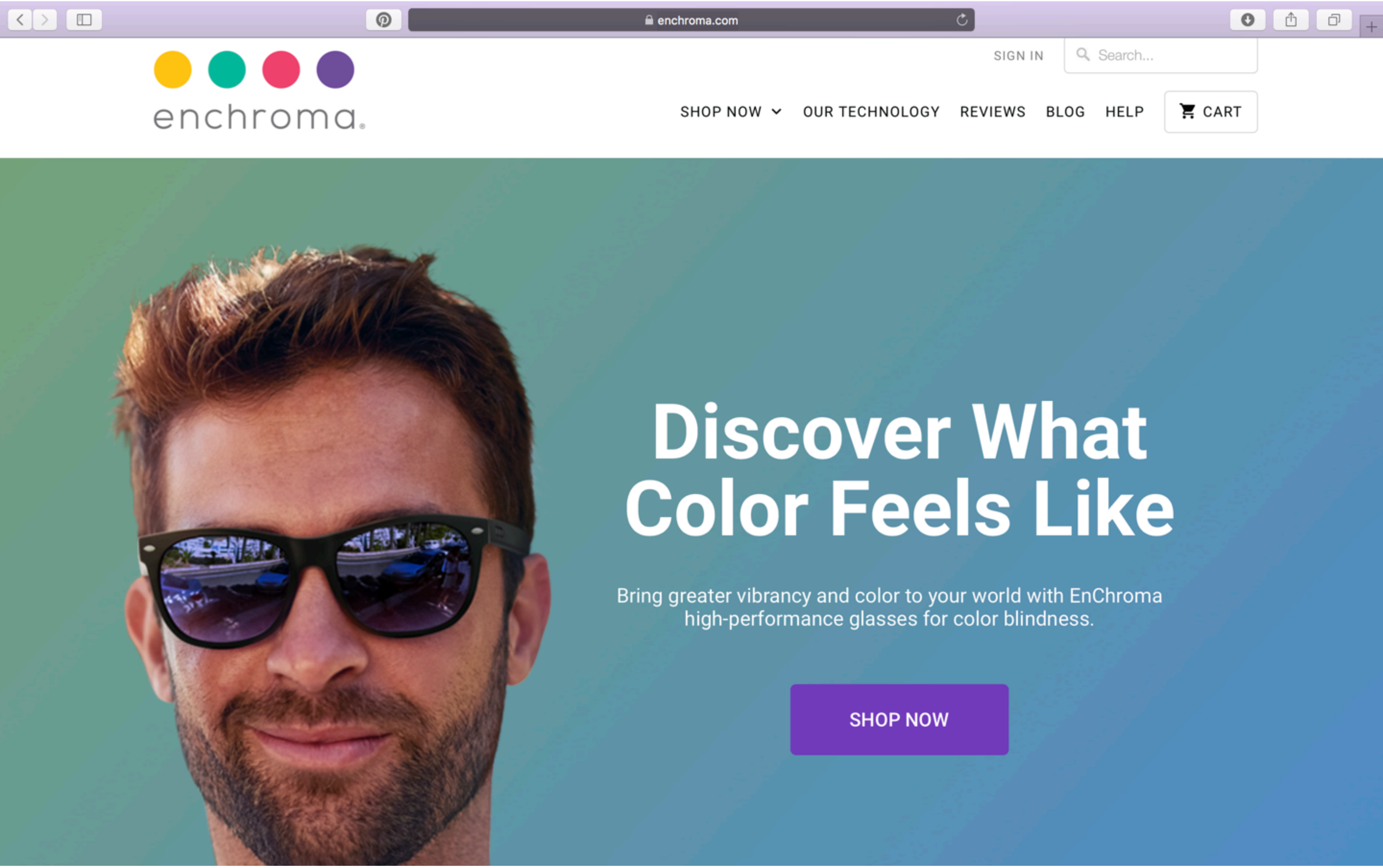
Wassily Kandinsky, Color Study. Squares with Concentric Circles, 1913
Munich, The Städtische Galerie im Lenbachhaus

Ansel Adams, Richard Zhang, Philip Isola, Alyosha Efros


iPhone 6S

11″

12.9″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Color-Blind Reactions to Perceiving New Colors

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

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Discussion: Warm Up

What is a fact you know about color?

- Objects have color that is opposite their shadow
- Mix colors to produce new colors
- Green is perceived as brighter than red, brighter than blue
- Different animals can see different amounts of color
- Human perception of color is non-linear
- Represent as color as RGB
- In printing, it's CMYK
- Colors are determined by electron configurations of material reflecting off
- Magenta is not a wavelength but we can still perceive
- Color of blue does not exist in some languages (hokkien, e.g. mixes blue and green together)
- HCL is better than HSV and HSL
-

Discussion: Learning Goals

What is something you want to learn about color?

- Why people have certain associations with color. E.g. red is both anger and love
- Do animals have different perceptions of color?
- How come people see a white and gold dress??!
- Do different people see the same color in different ways?
- Is it possible to see outside the human color gamut?
- Benham's top -- spin white and black pattern see flecks of color
- Why do shadows and objects have opposite colors?
-

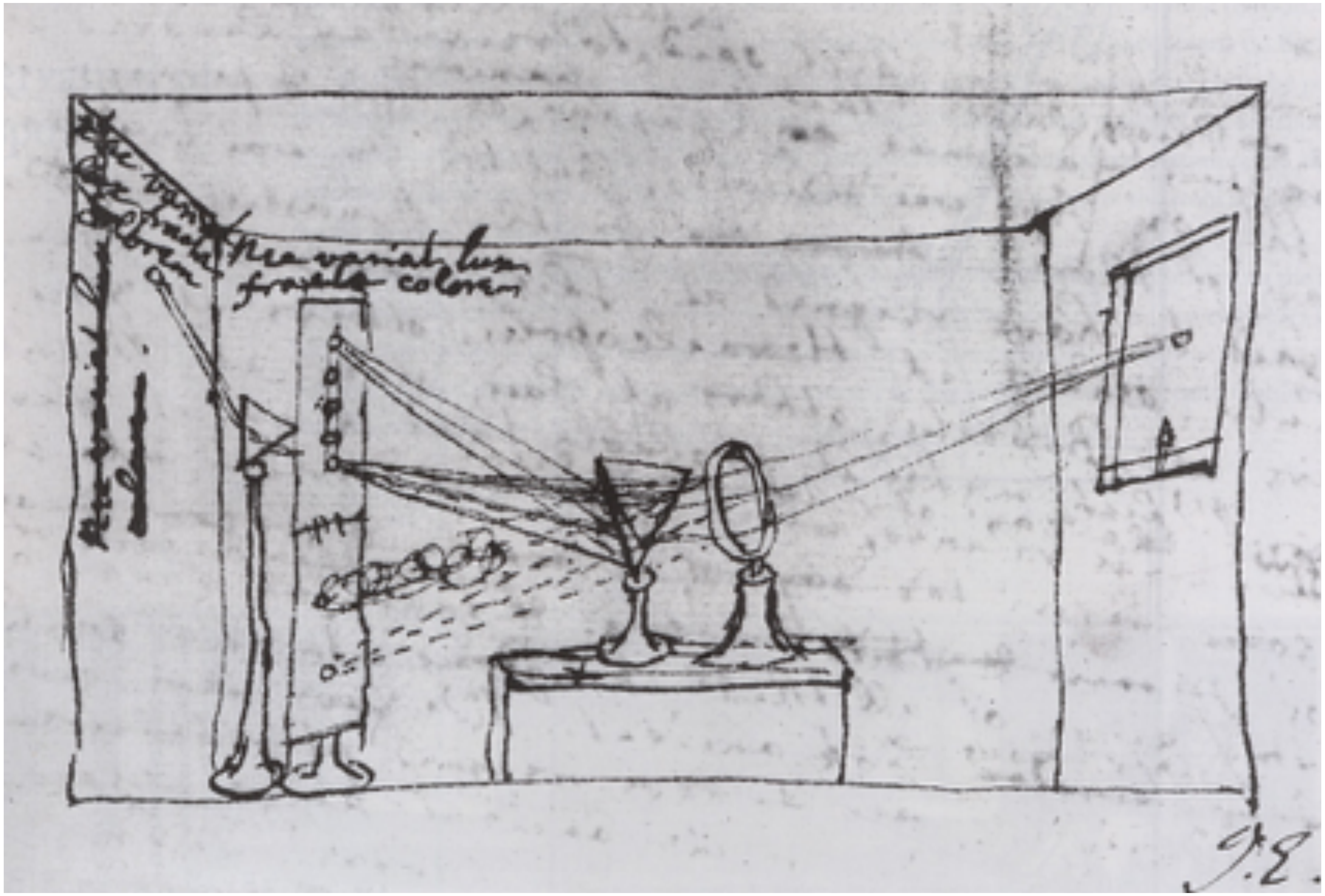
What is Color?

- Color is a phenomenon of human perception; it is not a universal property of light
- Colors are the perceptual sensations that arise from seeing light of different spectral power distributions
- Technically speaking, different wavelengths of light are not “colors”

Physical Basis of Color

credit: Science Media Group.

The Fundamental Components of Light

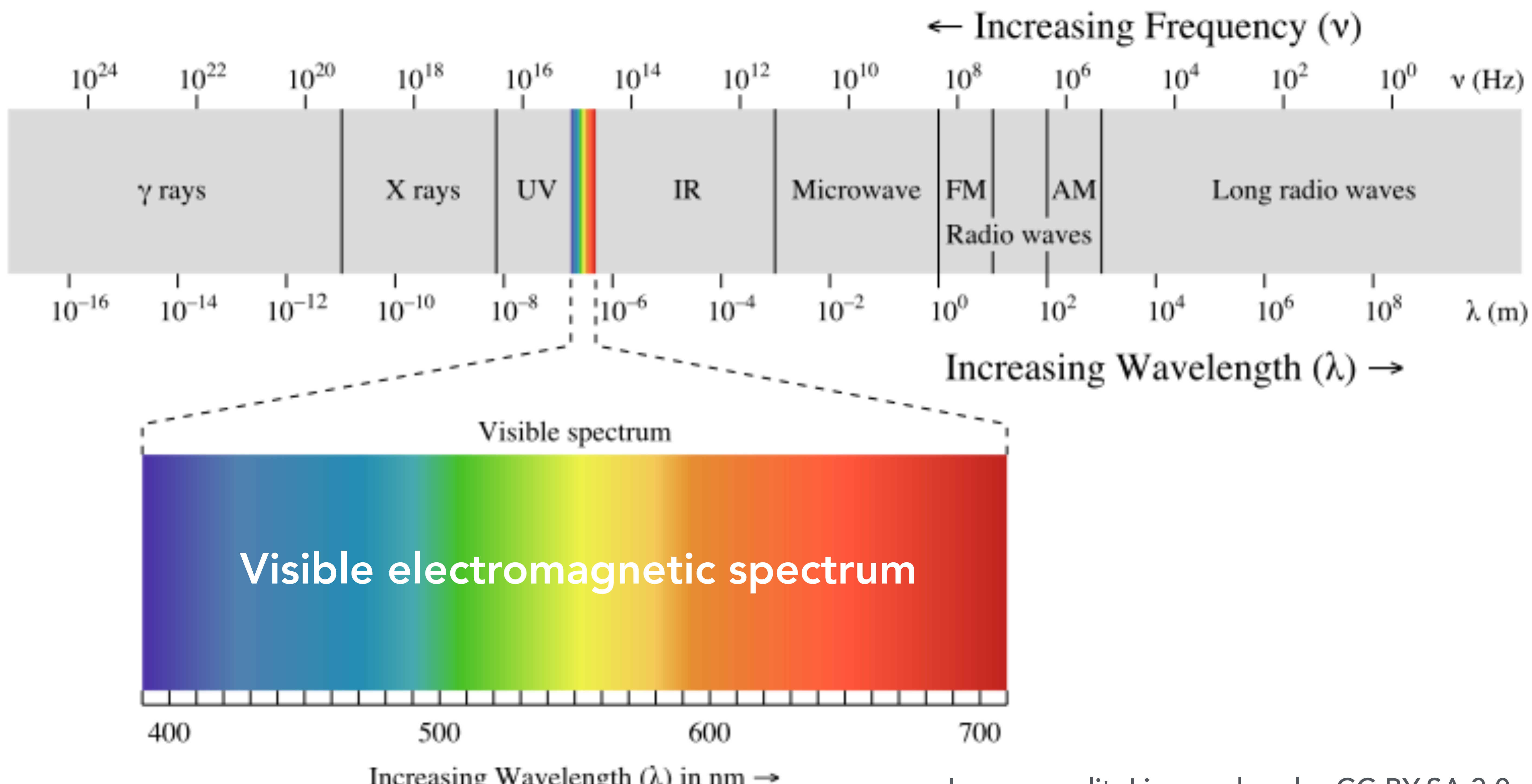


- Newton showed sunlight can be subdivided into a rainbow with a prism
- Resulting light cannot be further subdivided with a second prism

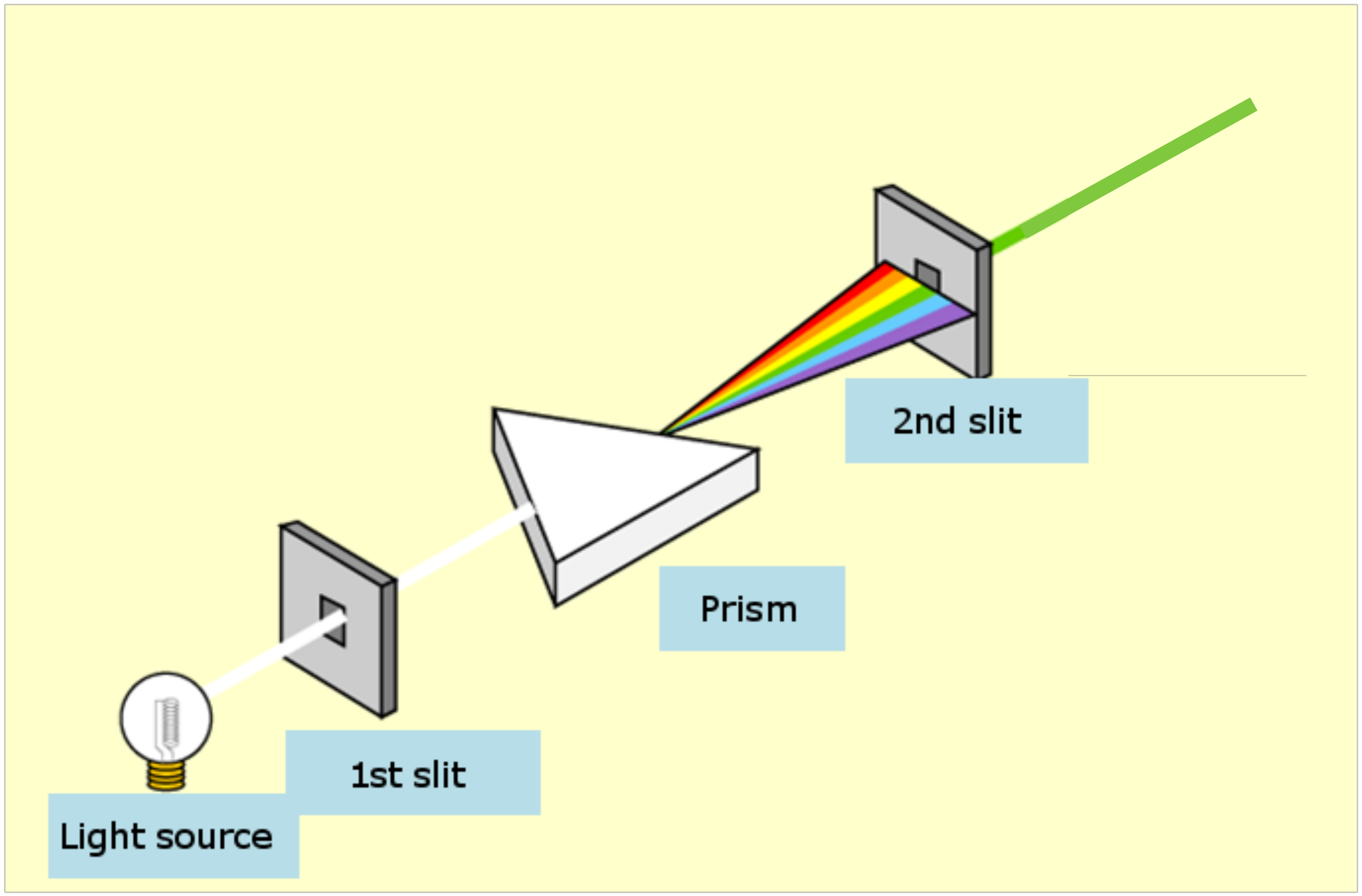
The Visible Spectrum of Light

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.

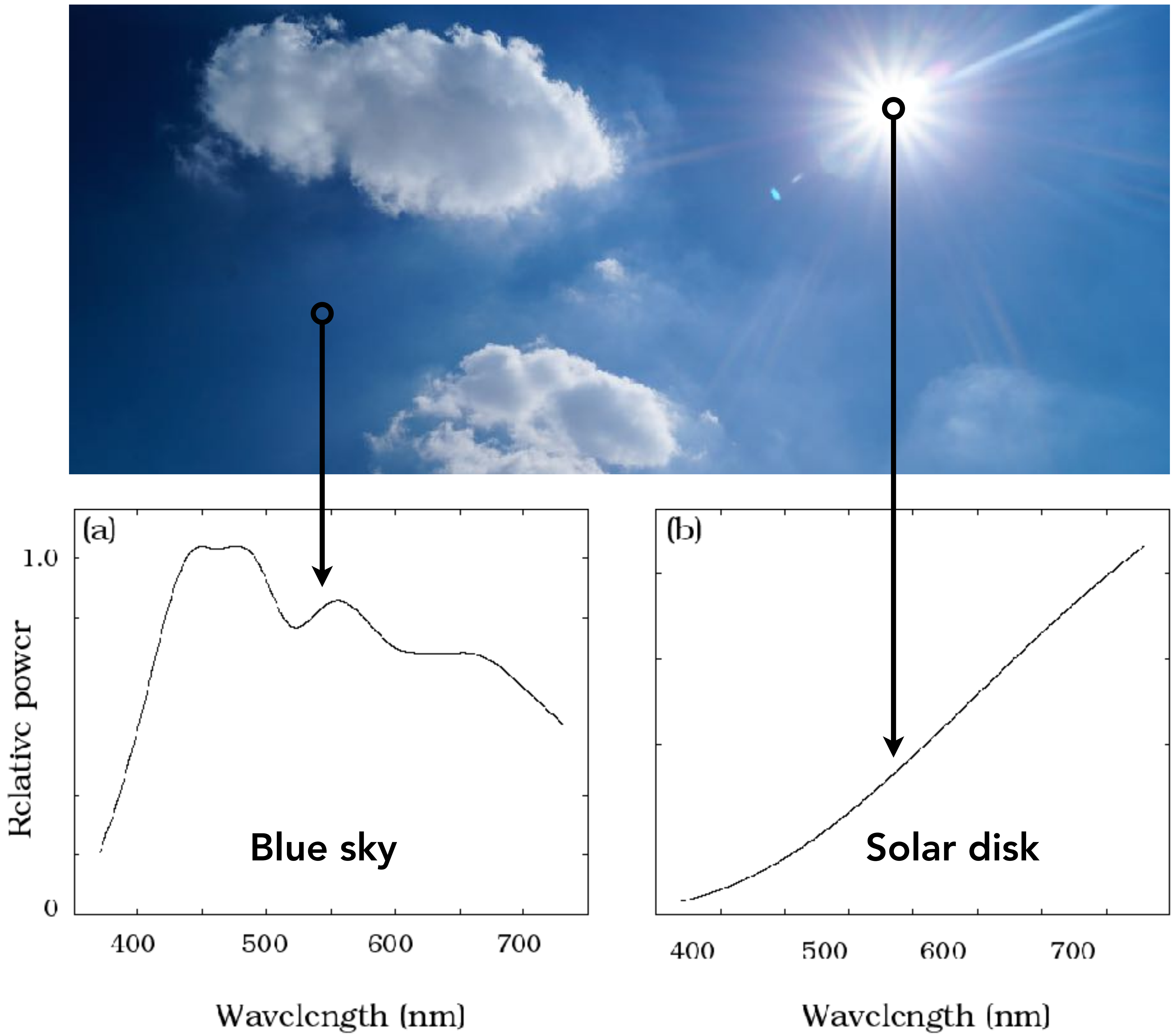
Hegyi et al. "Introduction to Practical Biochemistry"
http://elte.prompt.hu/sites/default/files/tananyagok/IntroductionToPracticalBiochemistry/ch04s07.html

Spectral Power Distribution (SPD)

Salient property in measuring light

- The amount of light present at each wavelength
- Units:
  - radiometric units / nanometer (e.g. watts / nm)
  - Can also be unit-less
- Often use “relative units” scaled to maximum wavelength for comparison across wavelengths when absolute units are not important

Daylight Spectral Power Distributions Vary



[Brian Wandell]

Spectral Power Distribution of Light Sources

Describes distribution of energy by wavelength

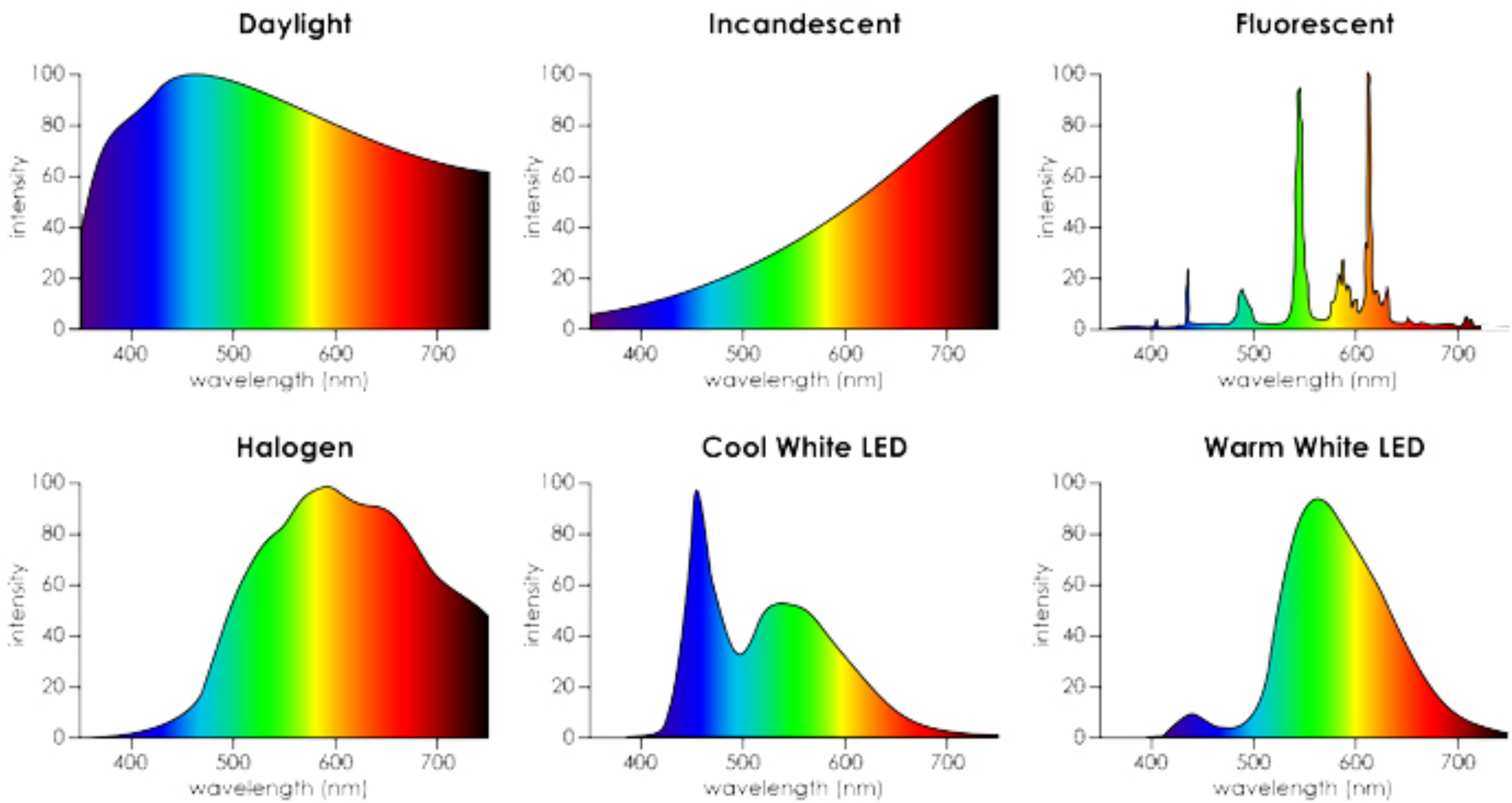
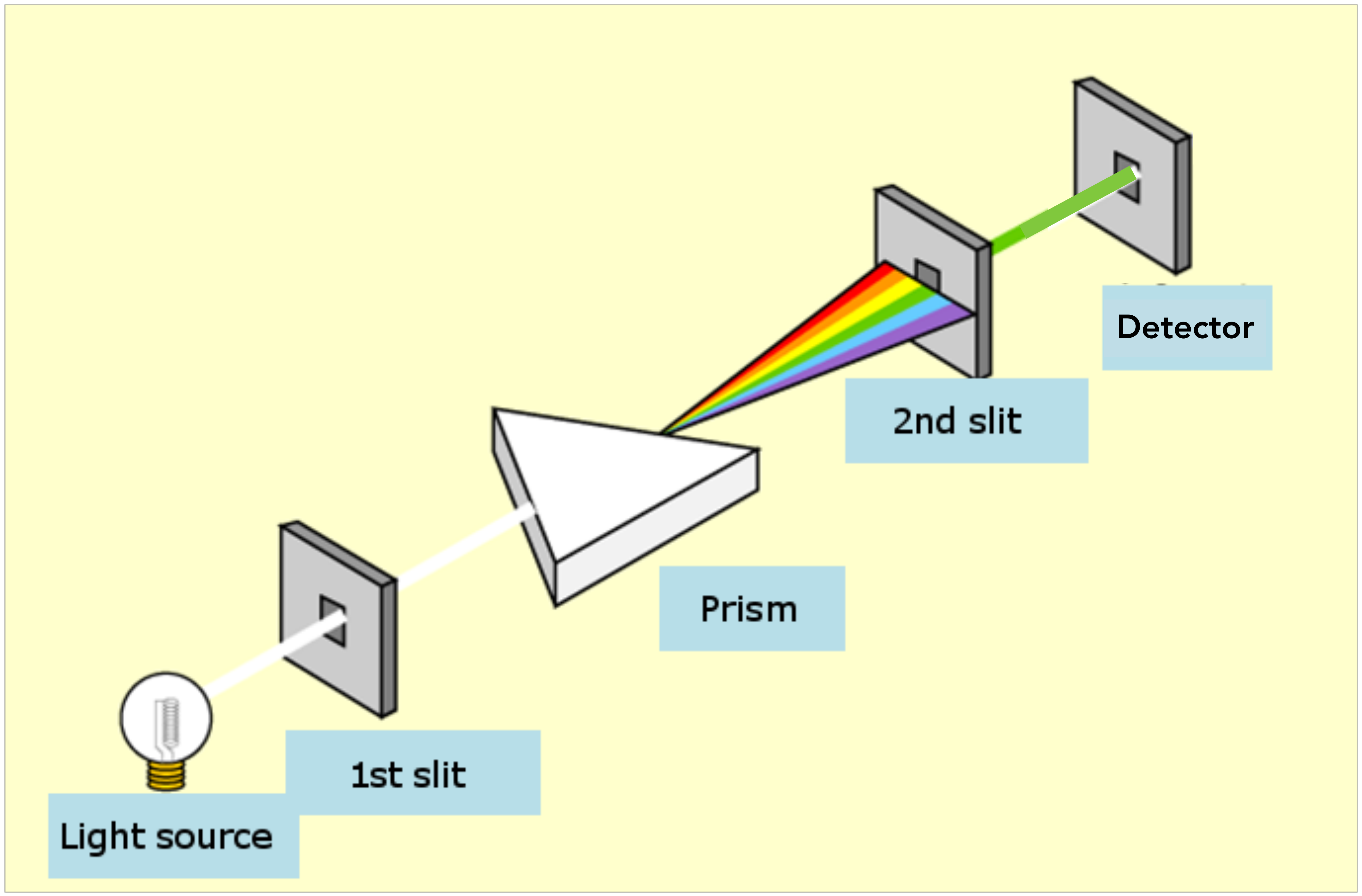


Figure credit: admesy ADVANCED MEASUREMENT SYSTEMS

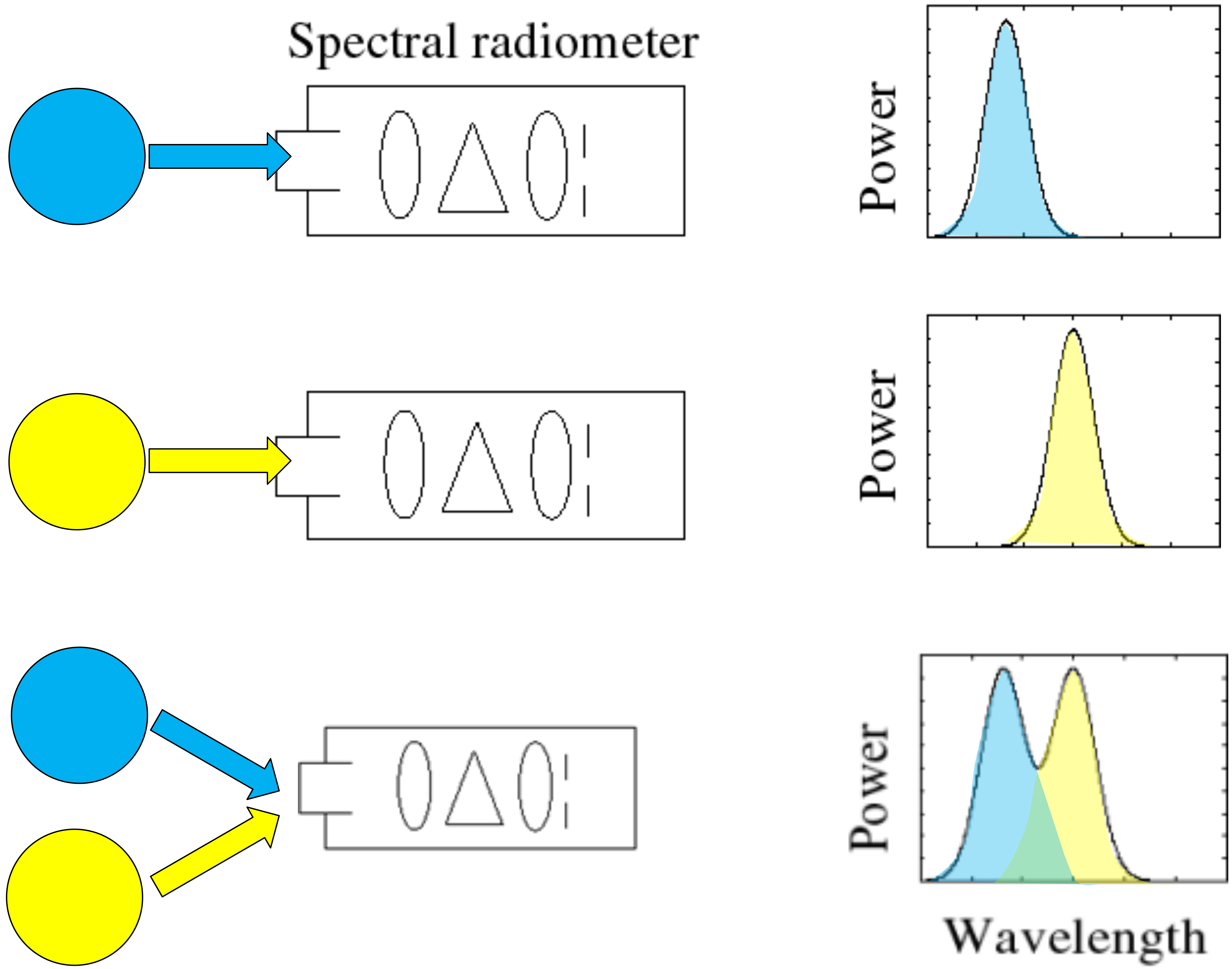
Spectrometer



For 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

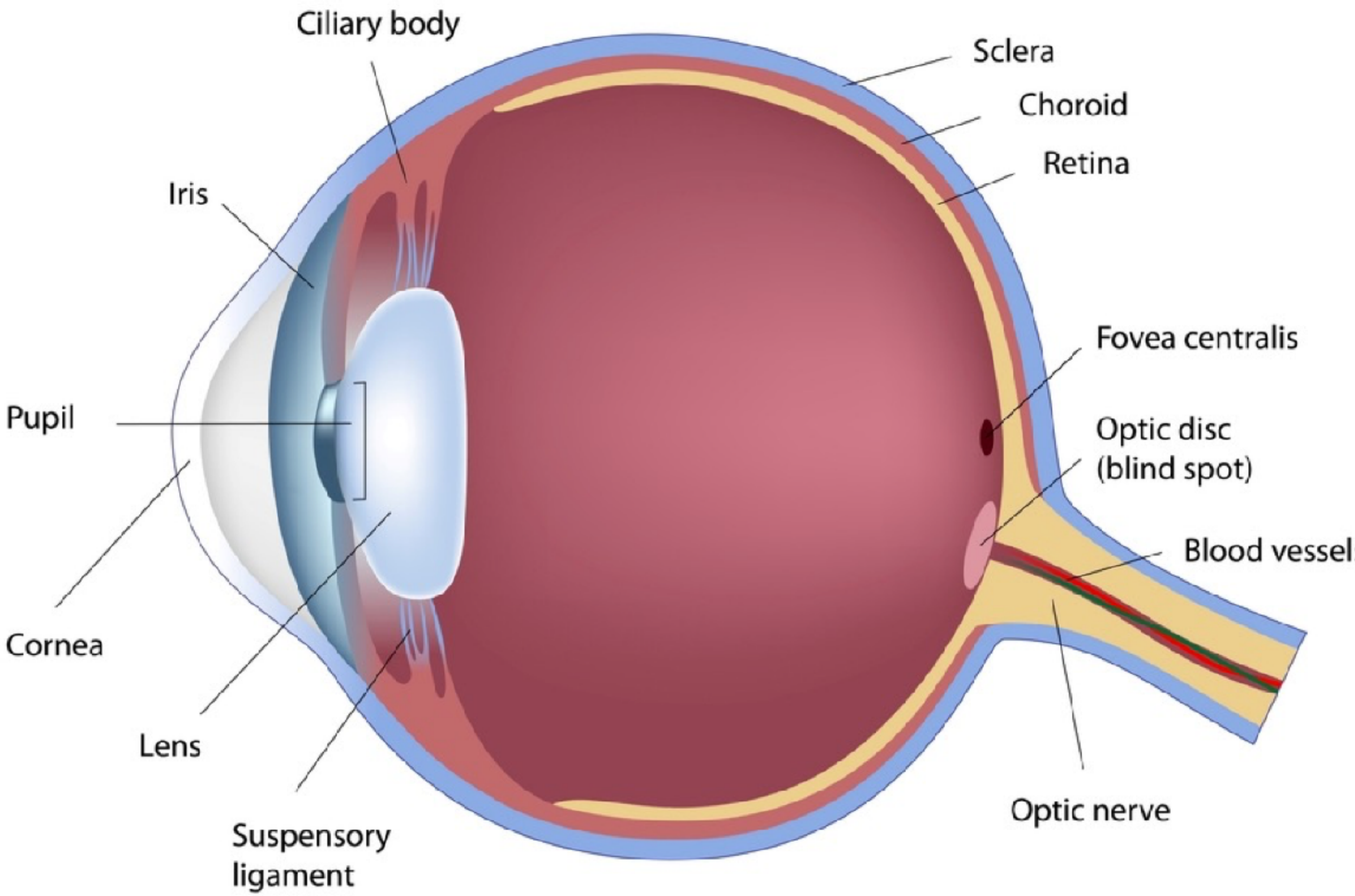
Superposition (Linearity) of Spectral Power Distributions



[Brian Wandell]

Biological Basis of Color

Anatomy of The Human Eye



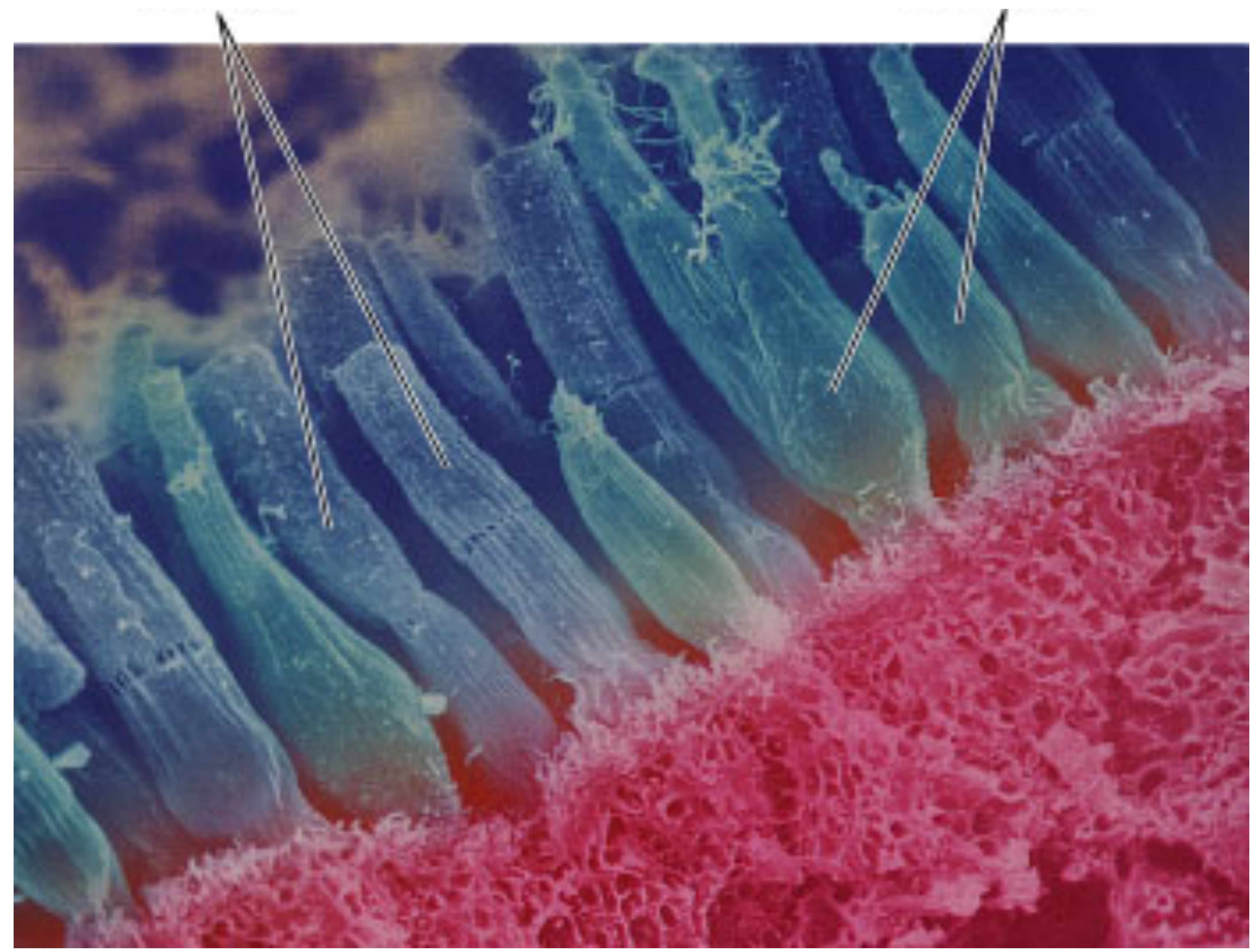
Retinal Photoreceptor Cells: Rods and Cones

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”)

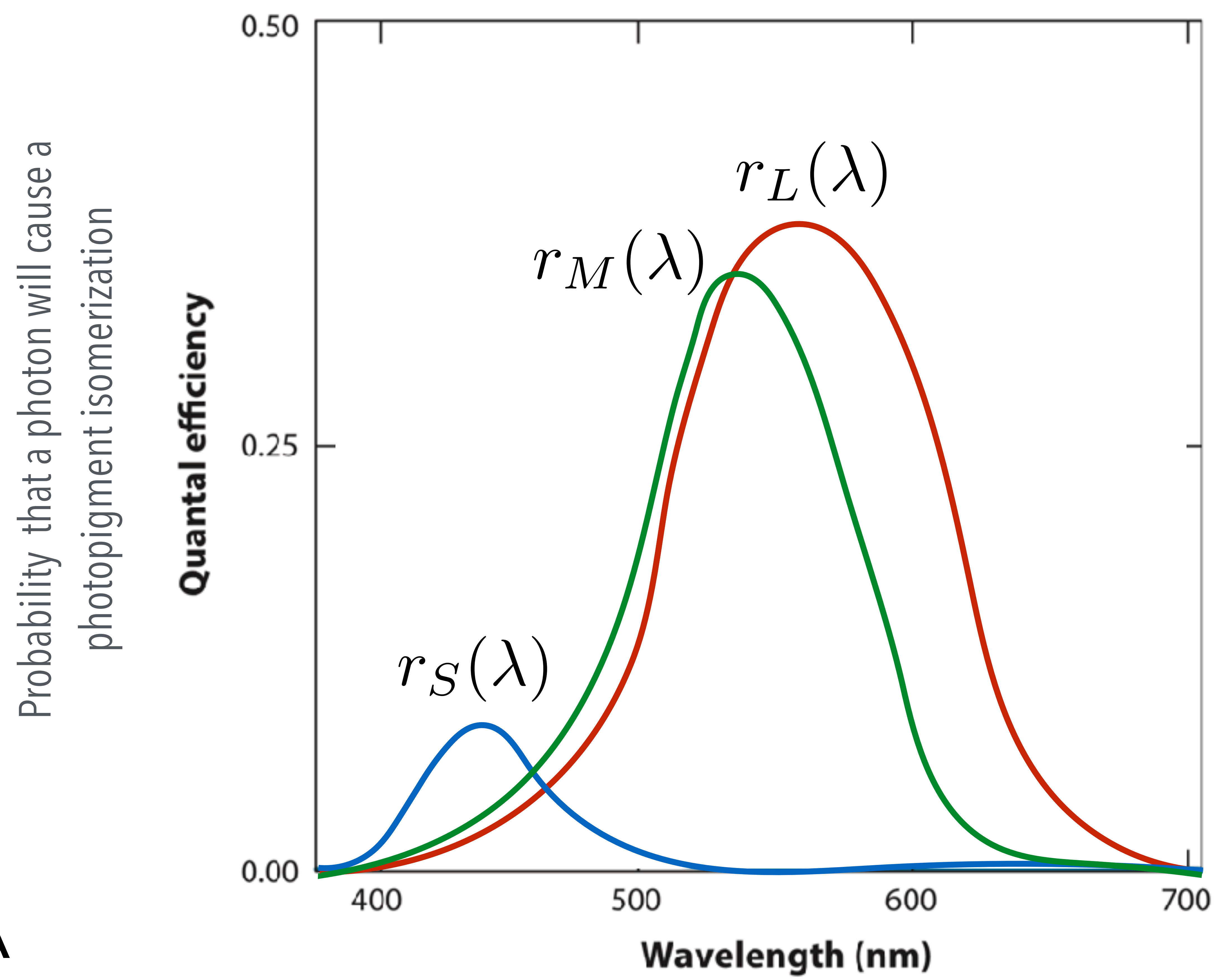
- ~6-7 million cones in eye
- Three types of cones, each with different spectral sensitivity
- Provide sensation of color



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

Human Retinal Cone Cell Response Functions (L, M, S Types)

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



Brainard, Color and the Cone Mosaic, 2015.

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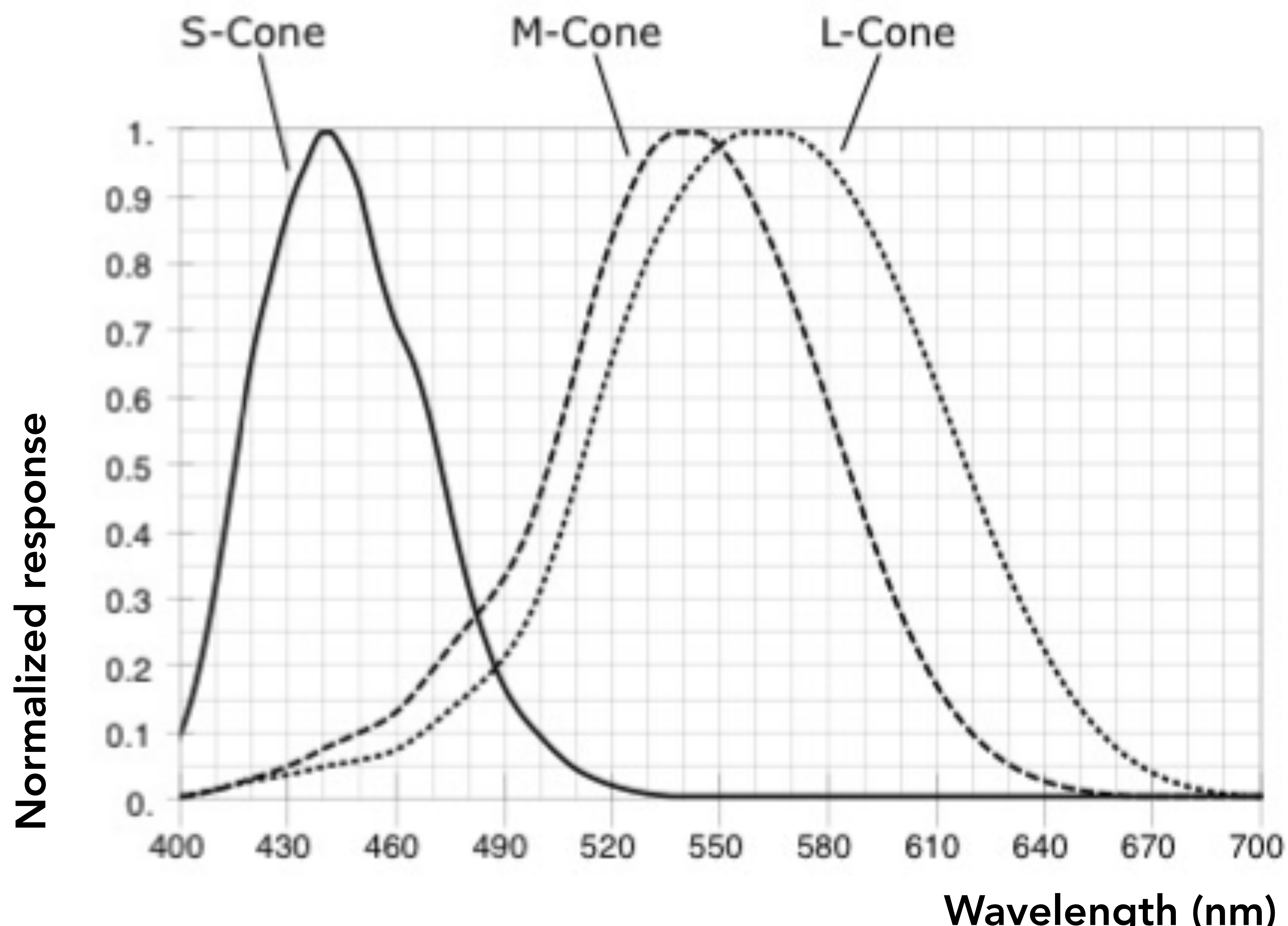
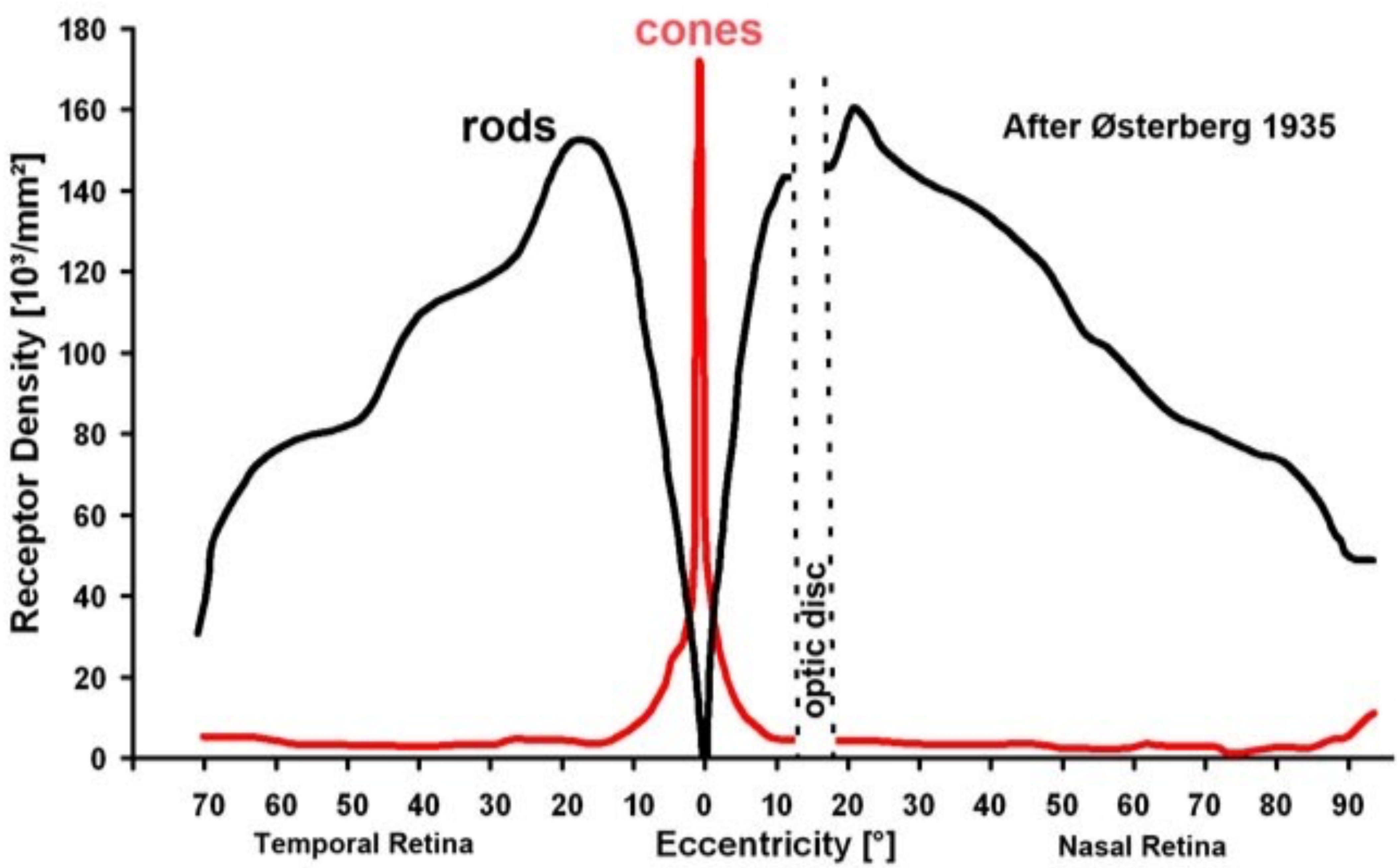
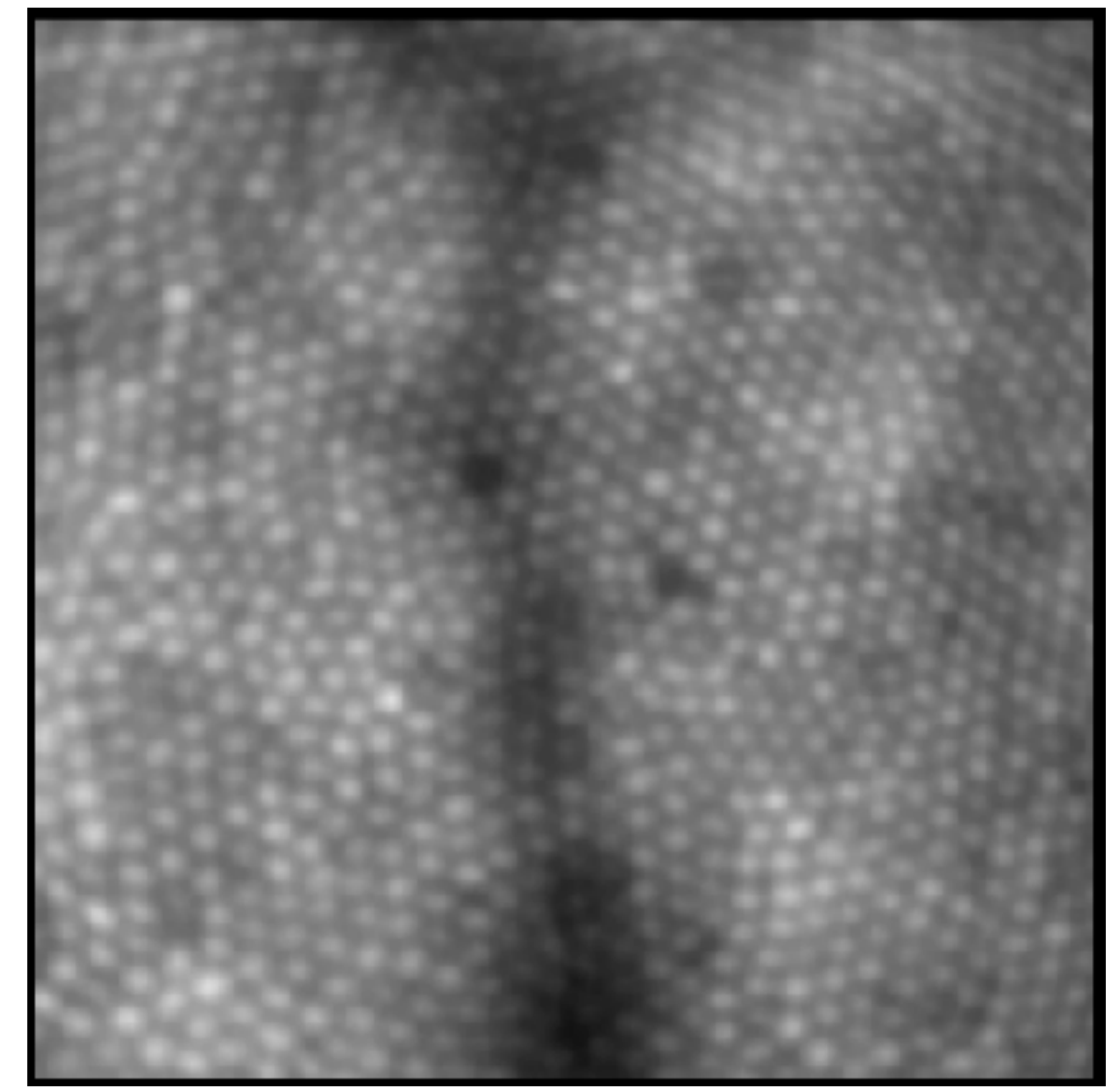


An Aside: Spatial Resolution of Rods and Cones in the Retina

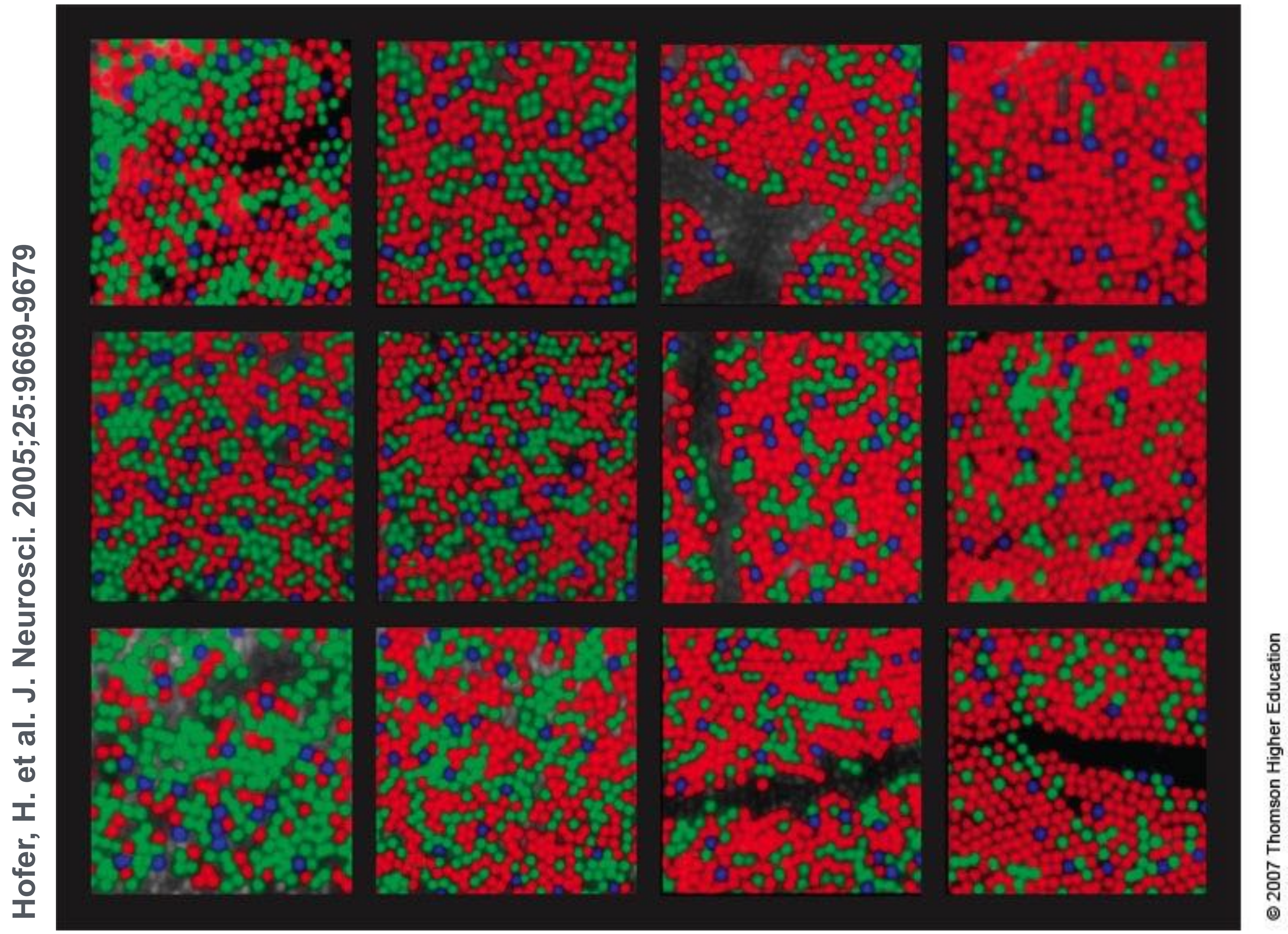




[Roorda 1999]

- Highest density of cones is in fovea (and no rods there)
- "Blind spot" at the optic disc, where optic nerve exits eye

Fraction of Three Cone Cell Types Varies Widely



Distribution of cone cells at edge of fovea in 12 different humans with normal color vision. Note high variability of percentage of different cone cell types. (false color image)

Measuring Light

A Simple Model of a Light Detector

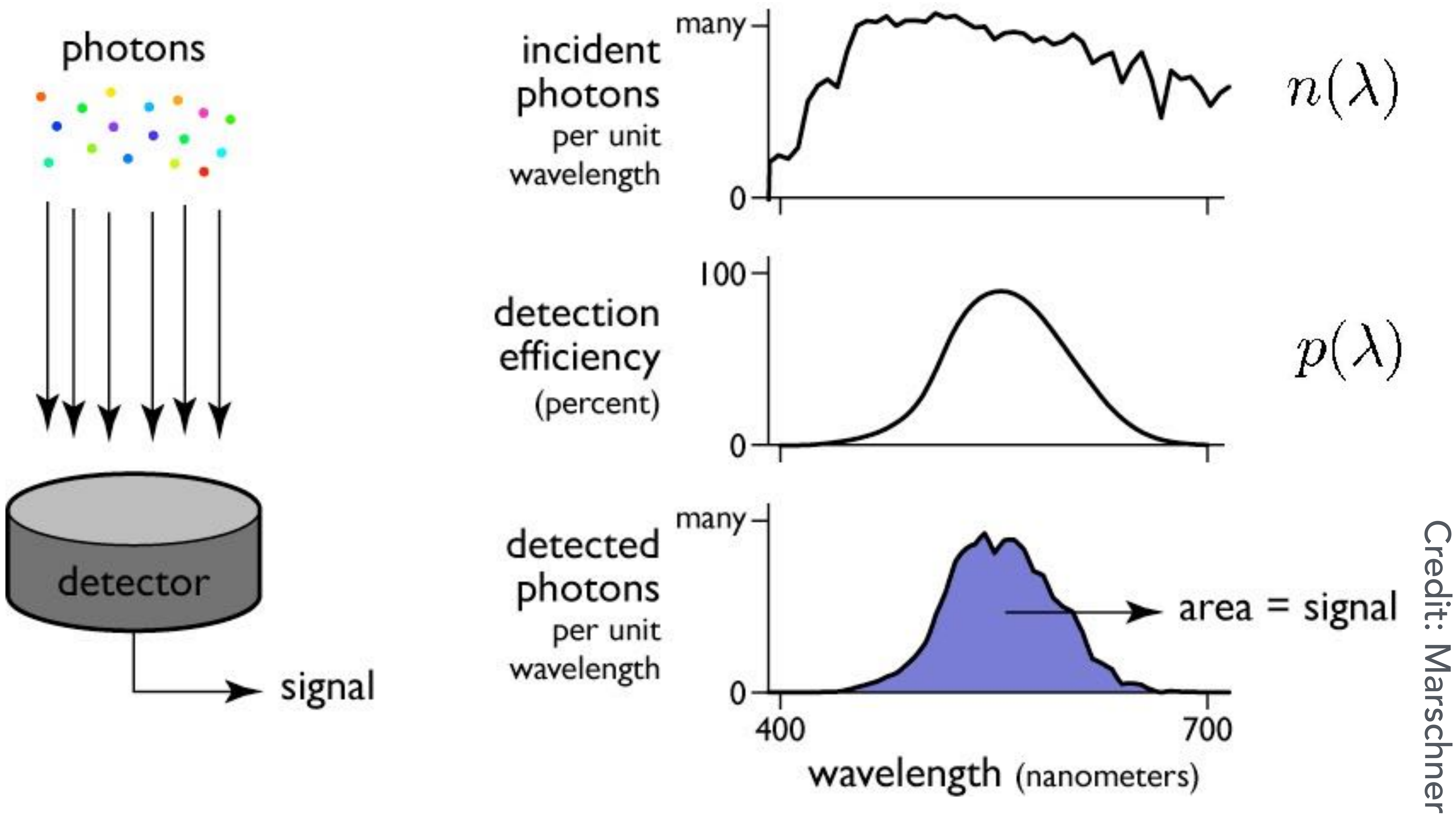
Produces a scalar value (a number) when photons land on it

- Value depends only on the number of photons detected
- Each photon has a probability of being detected that depends on the wavelength
- No way to distinguish between signals caused by light of different wavelengths: there is just a number

This model works for many detectors:

- based on semiconductors (such as in a digital camera)
- based on visual photopigments (such as in human eyes)

A Simple Model of a Light Detector



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

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

Discussion: What is The Dimensionality of Color?

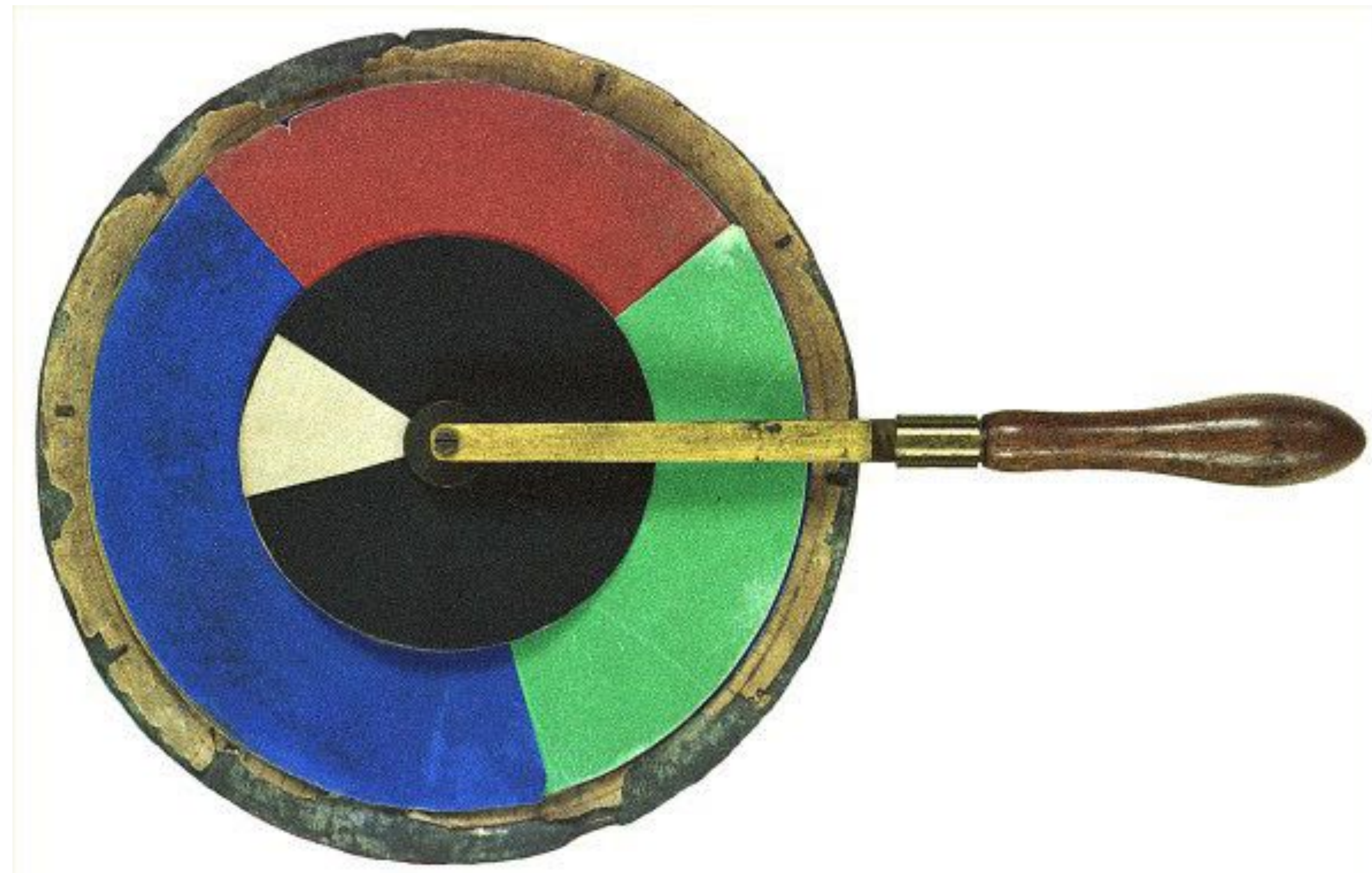
How do we know?

- 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

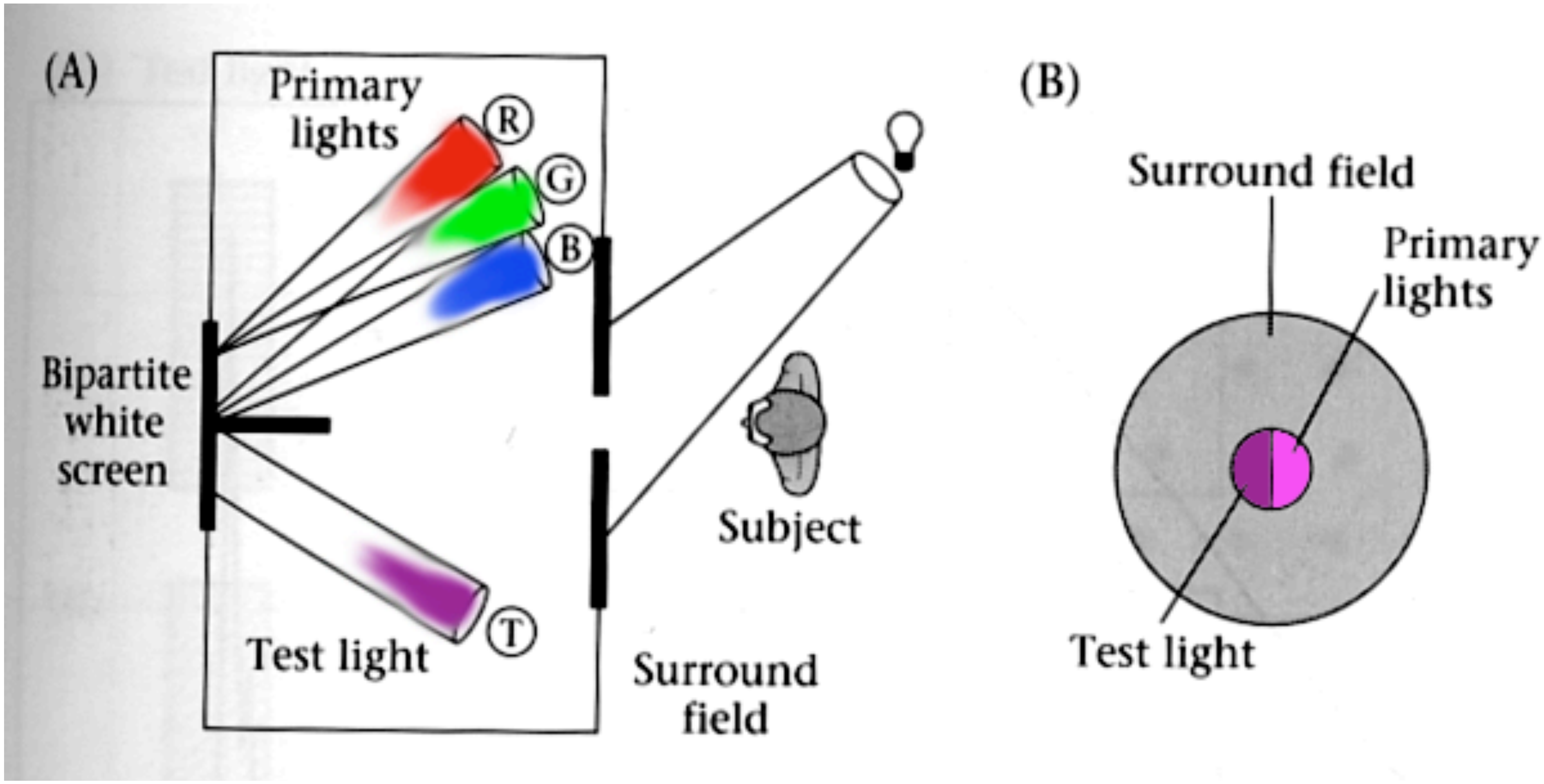
Maxwell's Crucial Color Matching Experiment



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

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

Color Matching Experiment



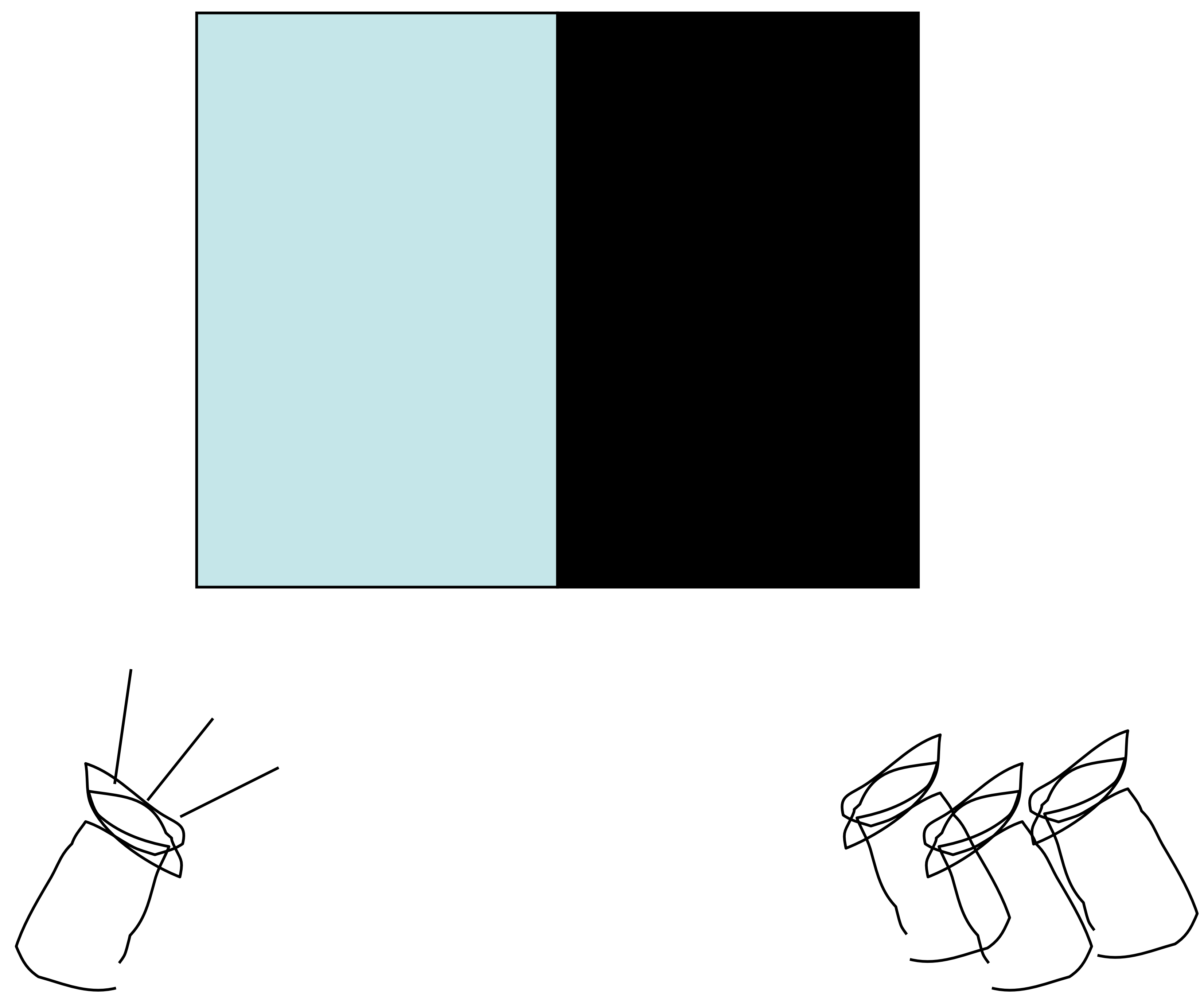
Same idea as spinning top, fancier implementation (Maxwell did this too)

Show test light spectrum on left

Mix "primaries" on right until they match

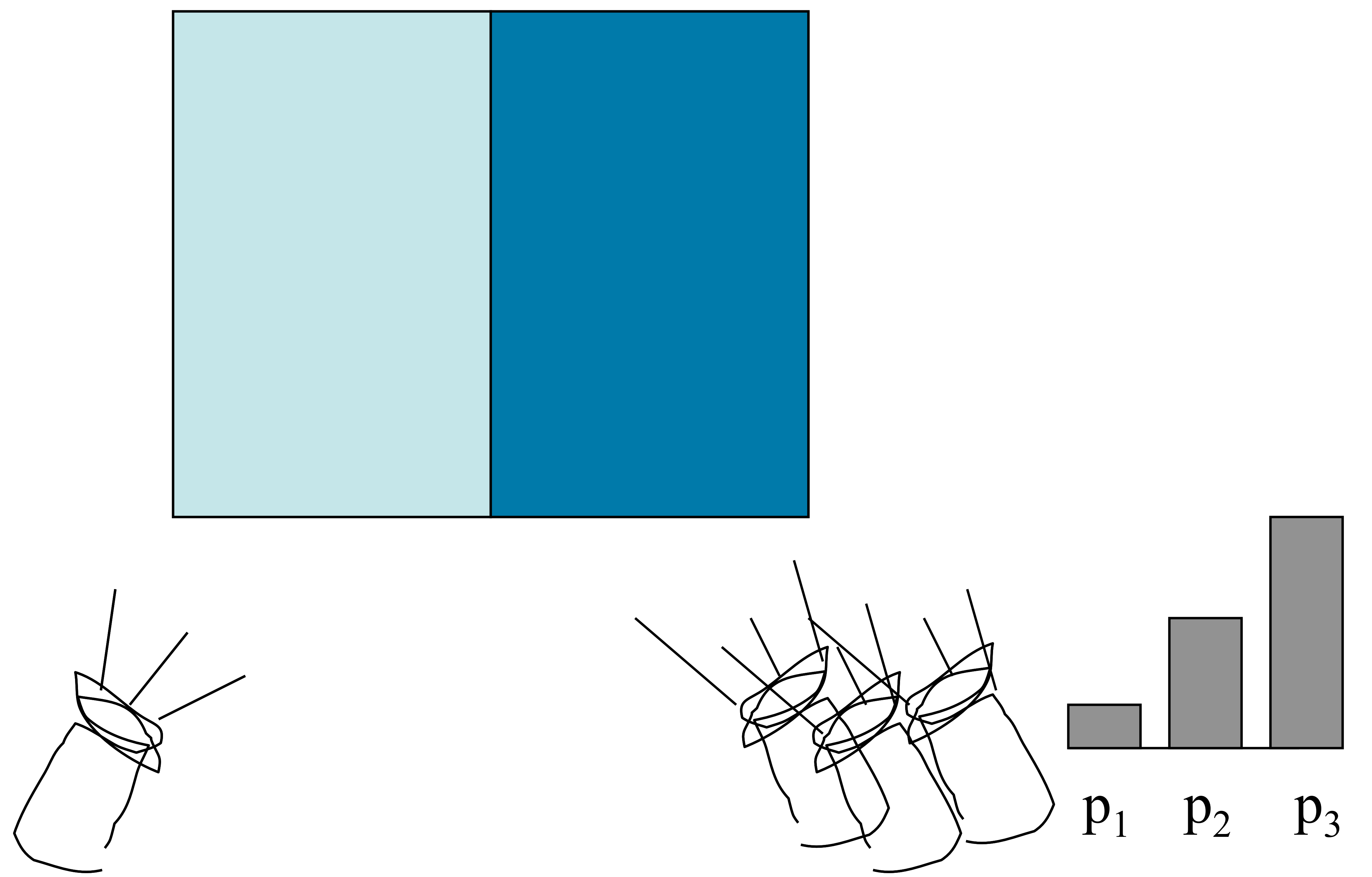
The primaries need not be RGB

Example Experiment



Slide from Durand and Freeman 06

Example Experiment



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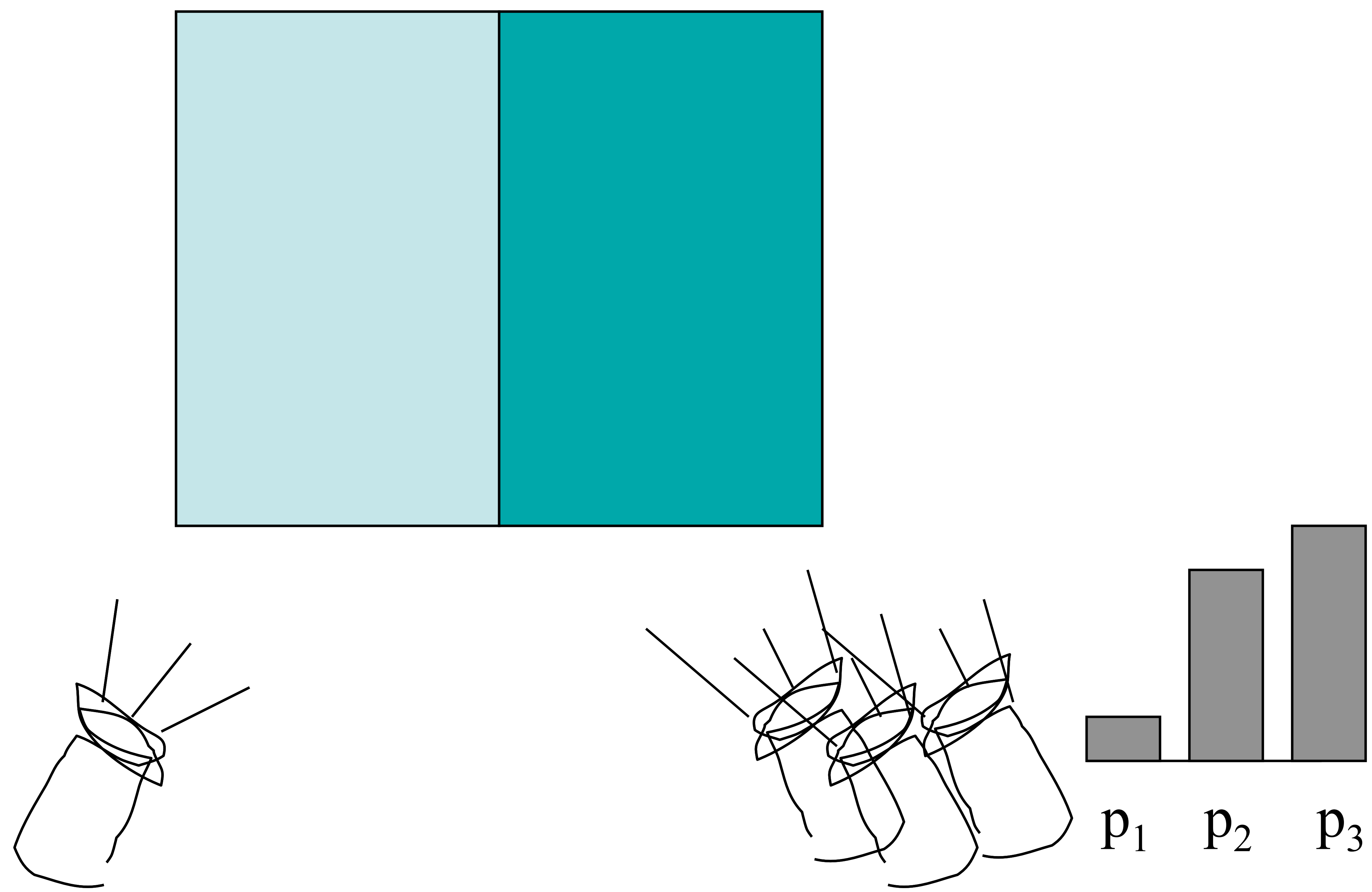
Example Experiment



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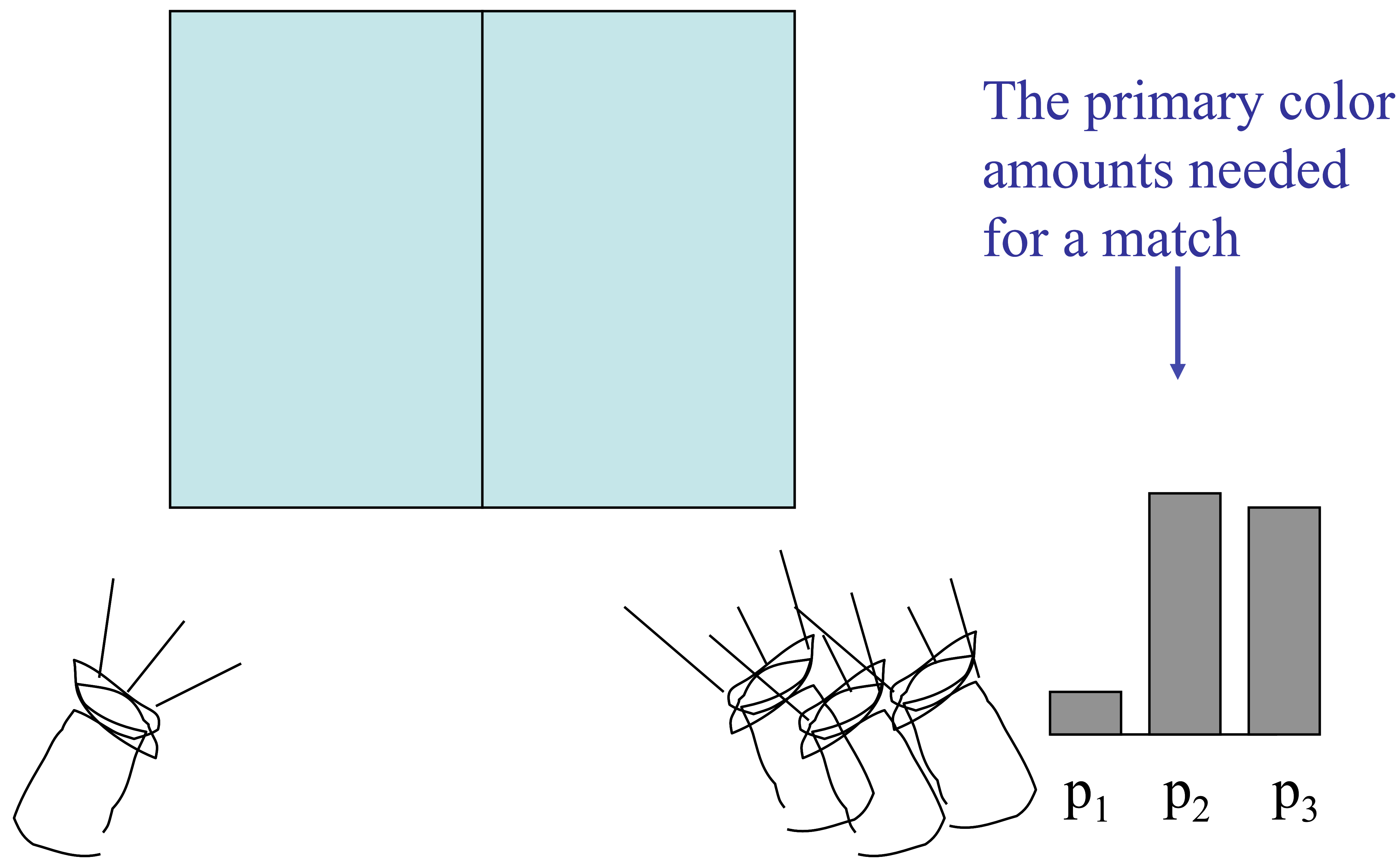
Example Experiment



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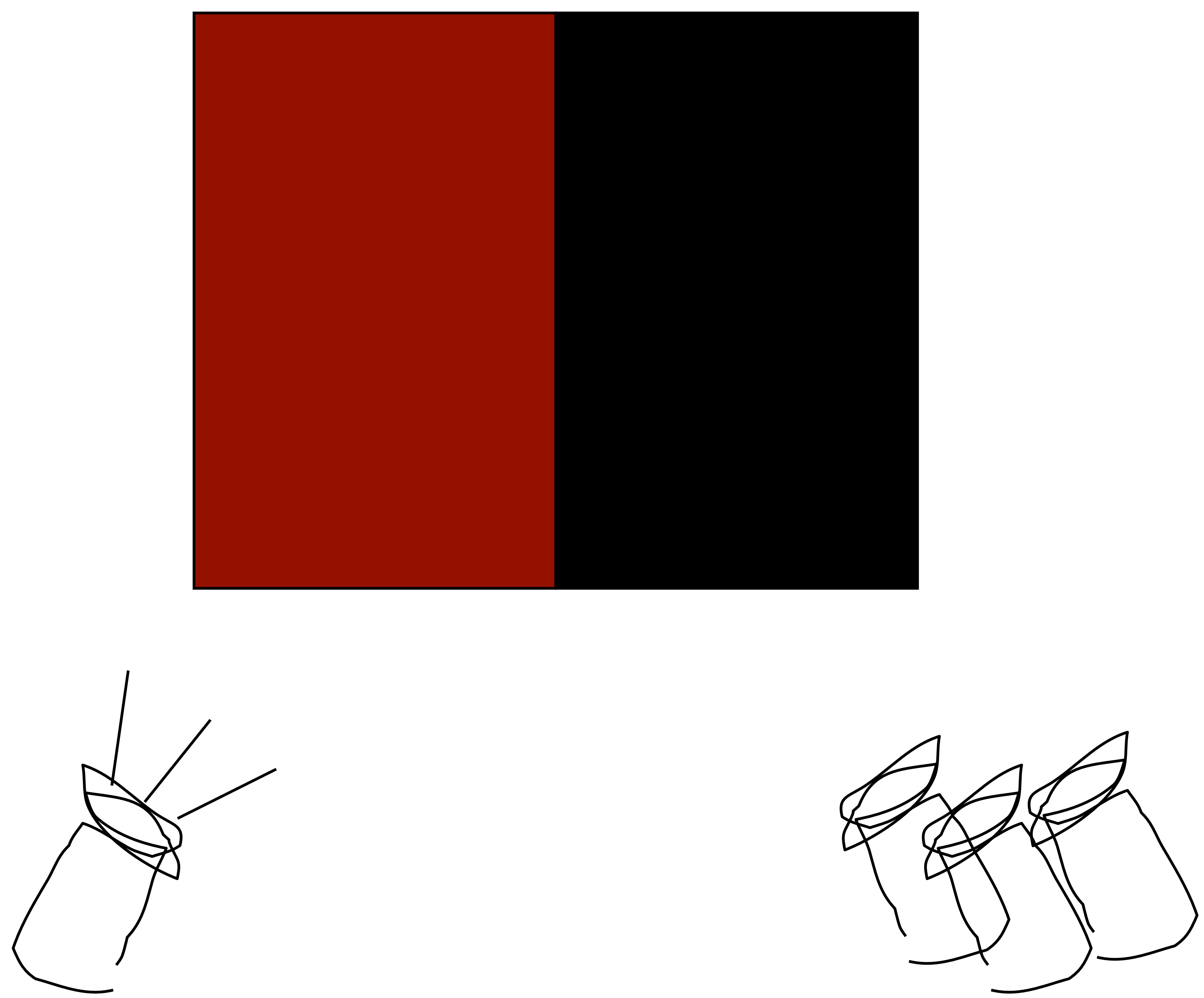
Experiment 2: Out of Gamut



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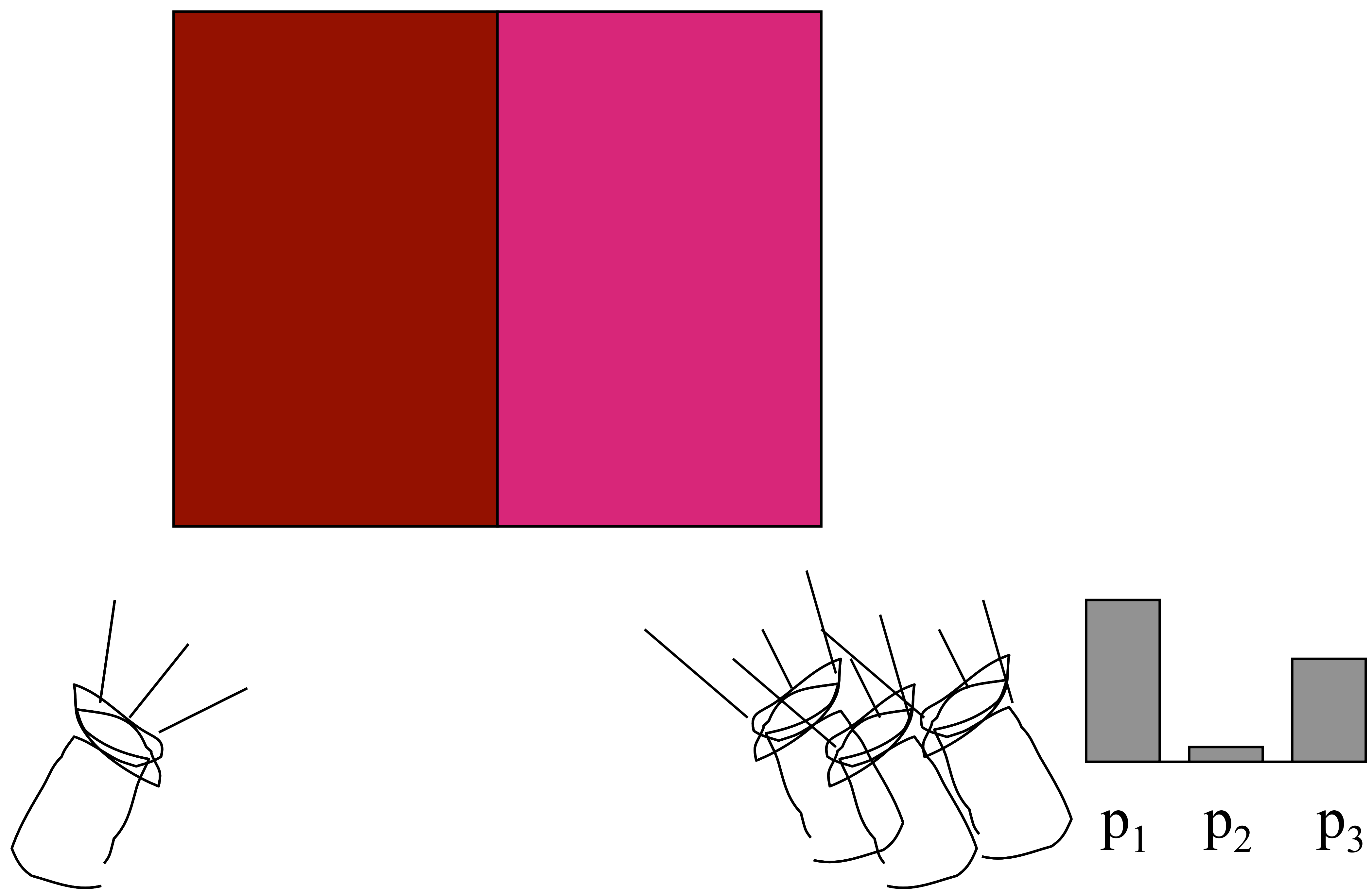
Experiment 2: Out of Gamut



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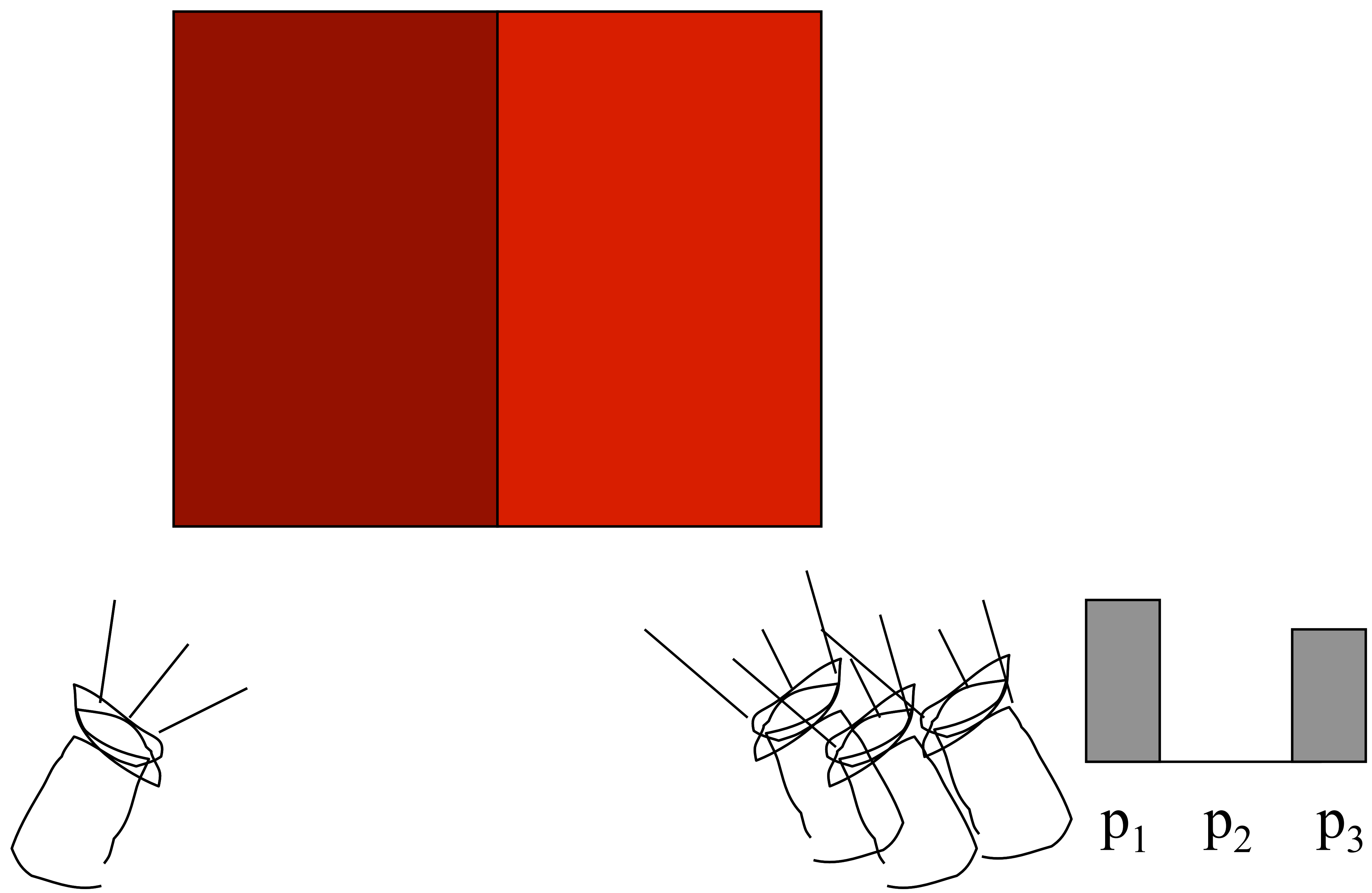

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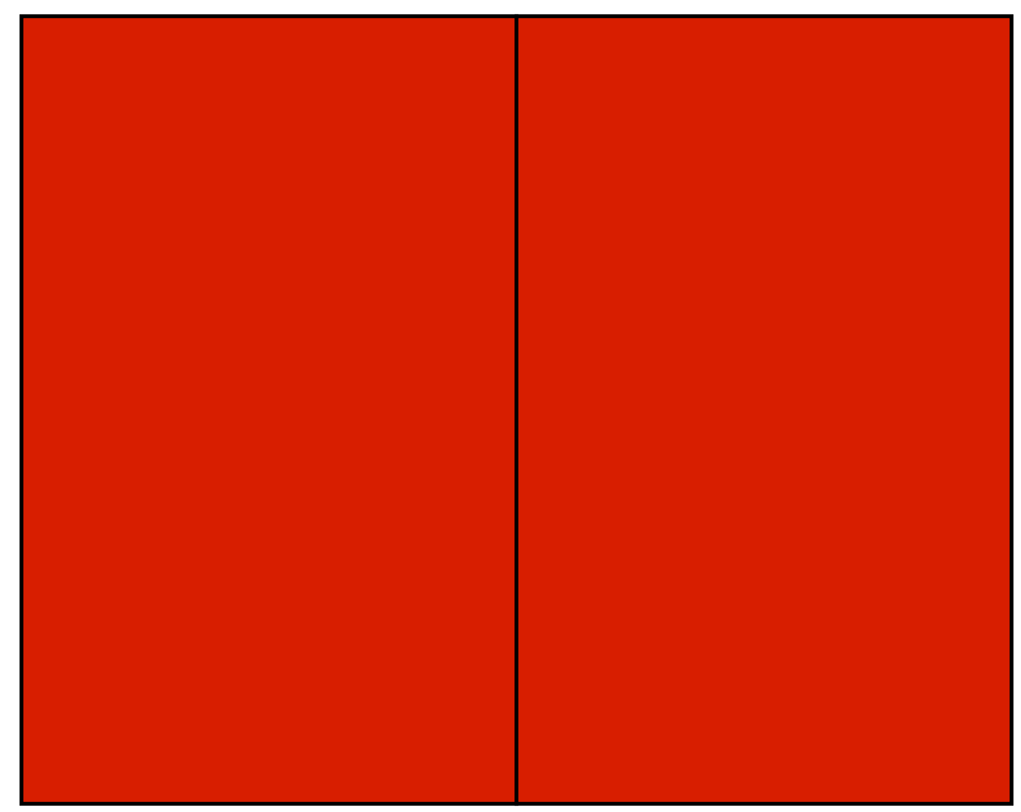
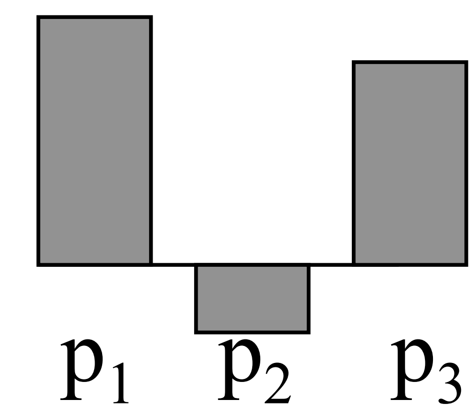
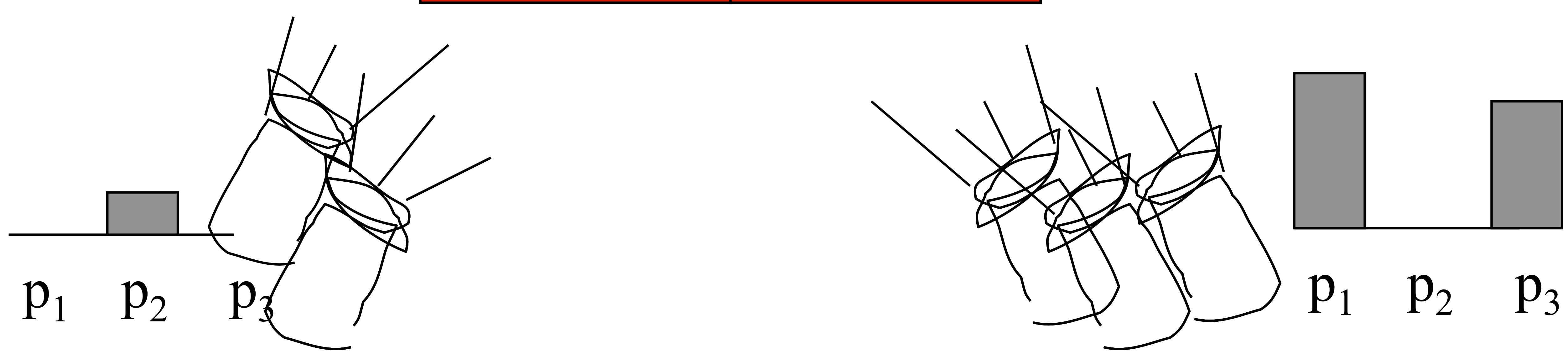
Experiment 2: Out of Gamut

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



The primary color amounts needed for a match:





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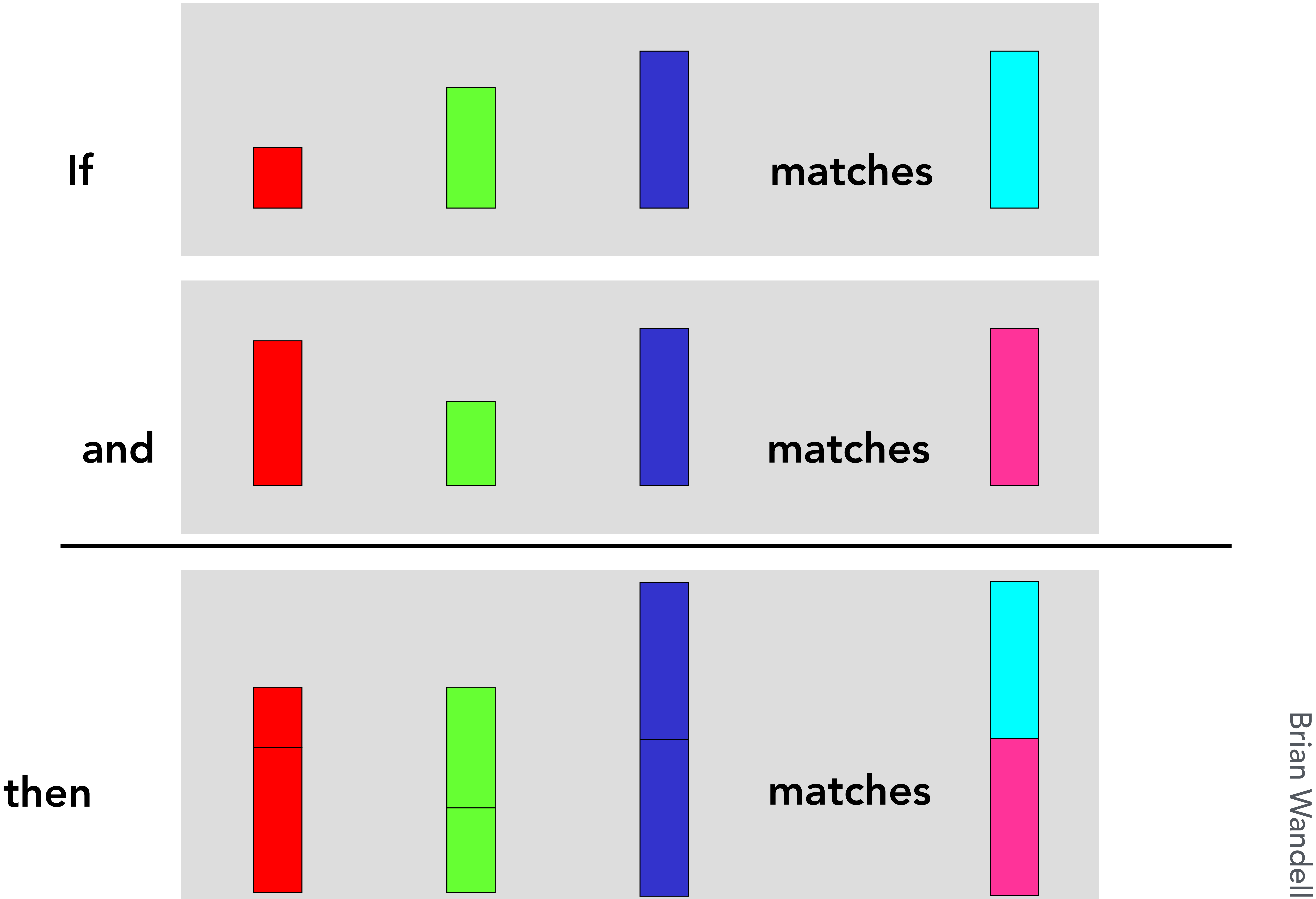
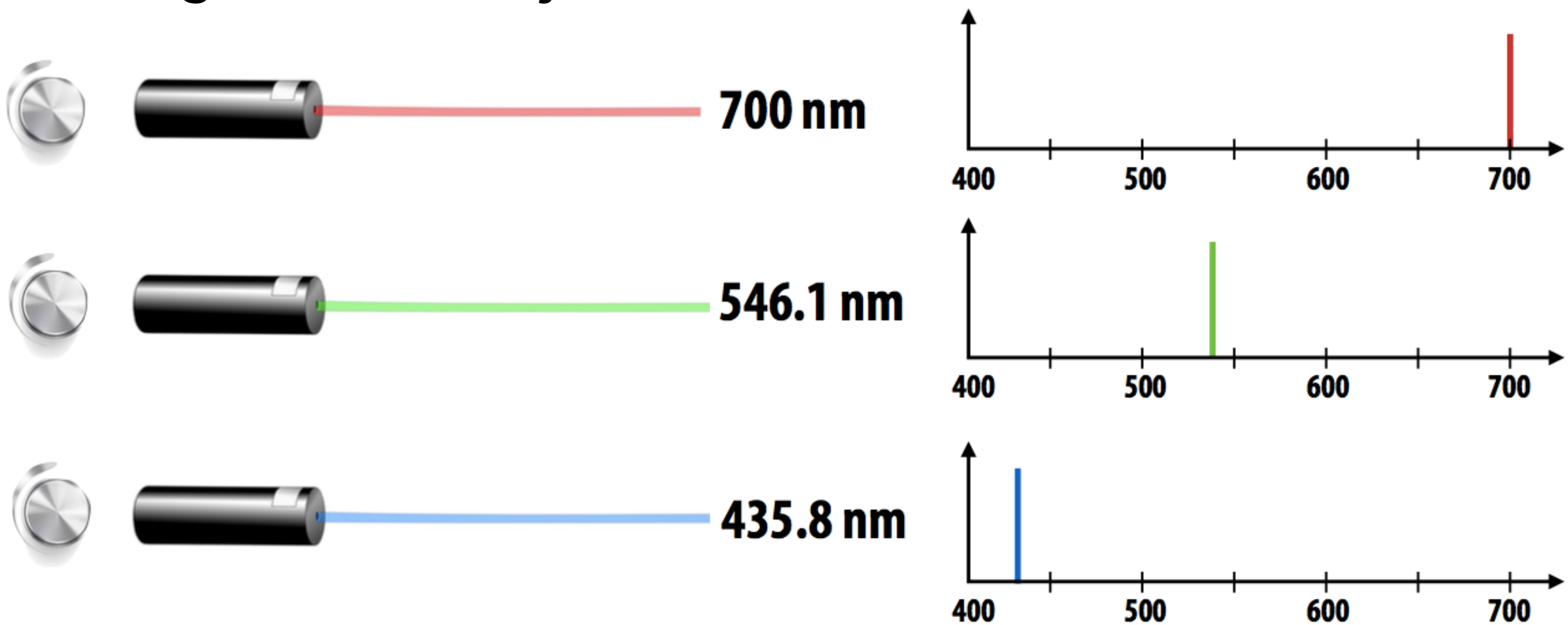
The Color Matching Experiment is Linear



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

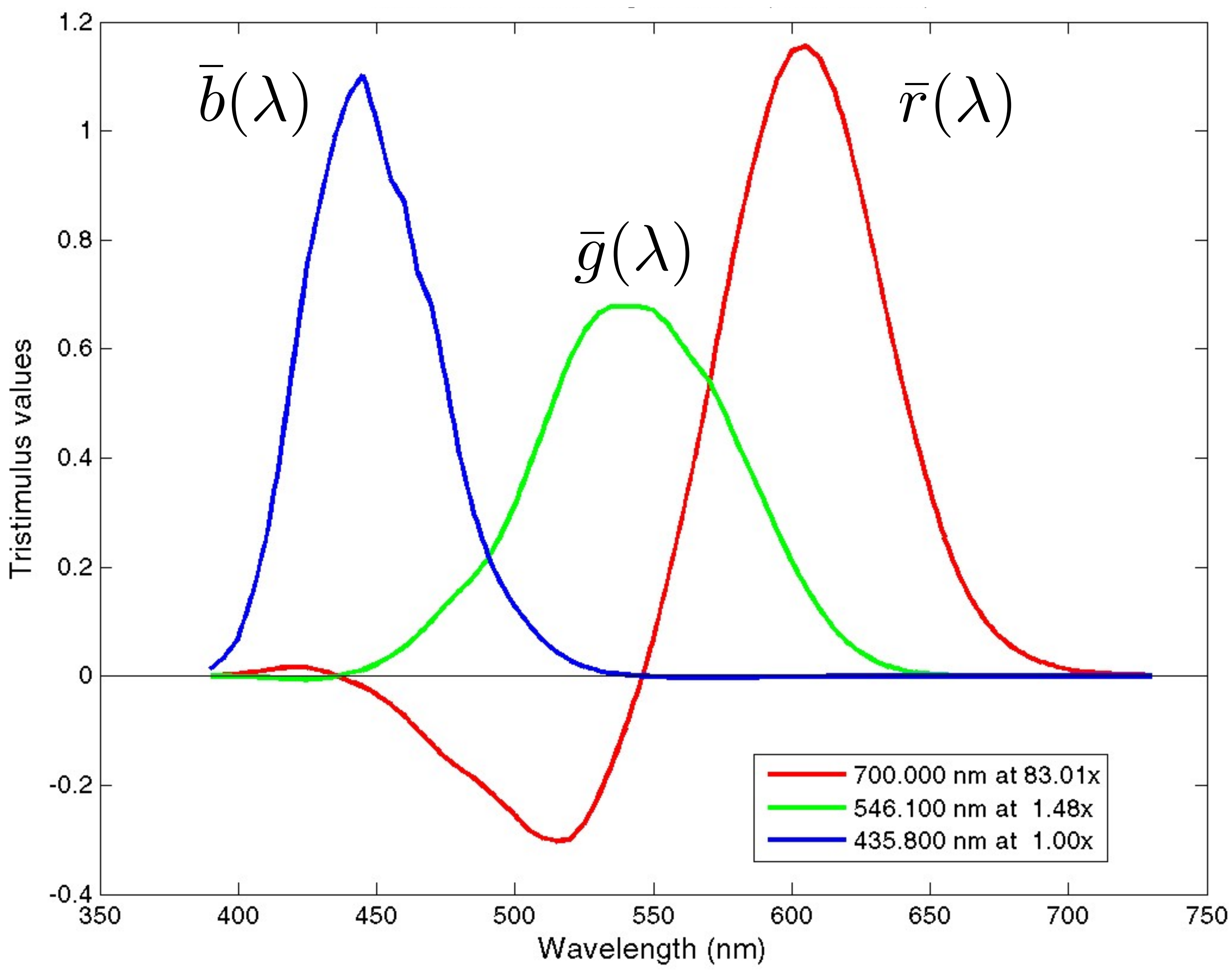


Kayvon Fatahalian

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!

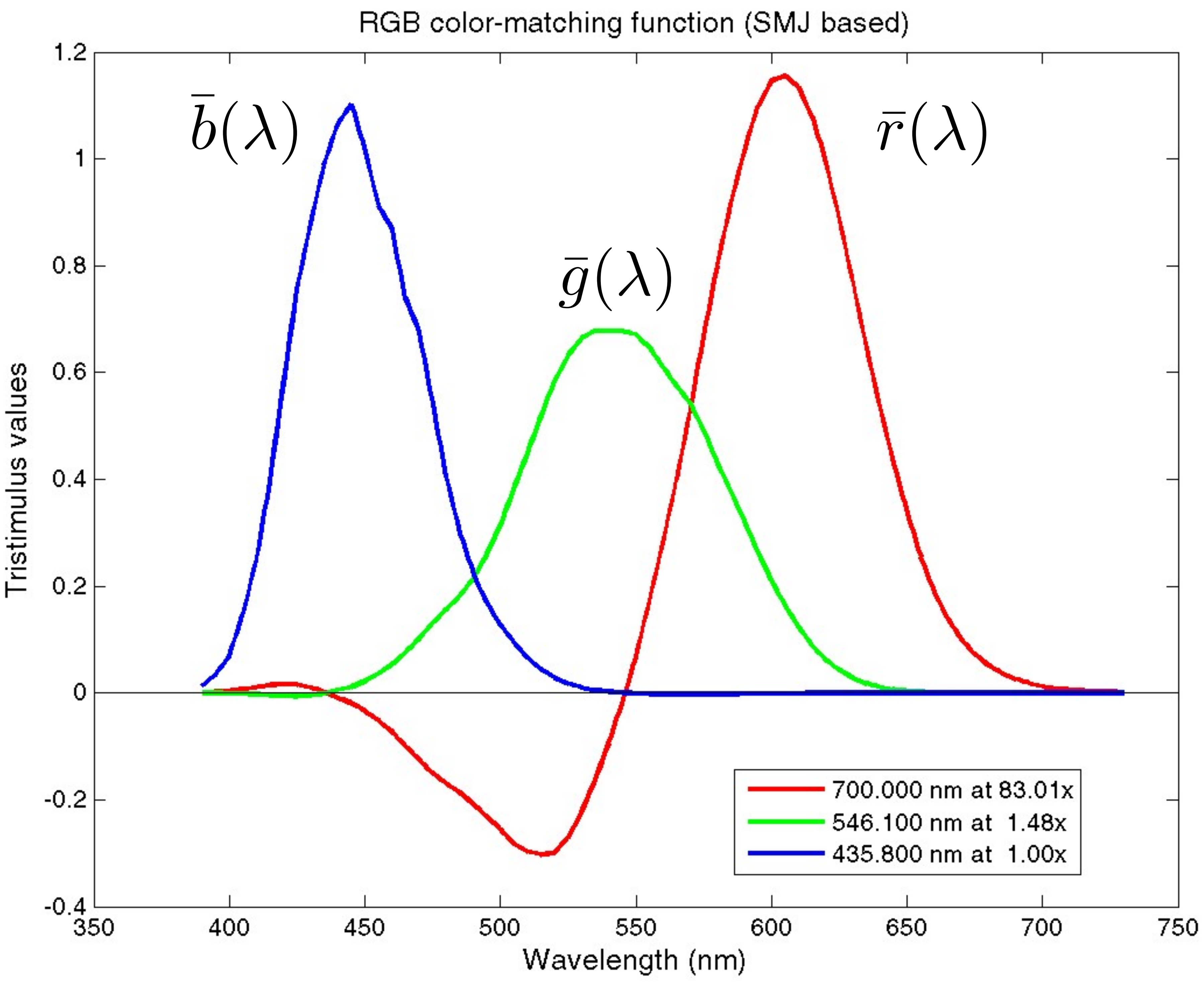
Color Reproduction with Matching Functions

For any spectrum *s*, the perceived color is matched by the following formulas for scaling the CIE RGB primaries

$$R_{\mathrm{CIE\,RGB}} = \int_\lambda s(\lambda)\bar{r}(\lambda)\,d\lambda$$

$$G_{\mathrm{CIE\,RGB}} = \int_\lambda s(\lambda)\bar{g}(\lambda)\,d\lambda$$

$$B_{\mathrm{CIE\,RGB}} = \int_\lambda s(\lambda)\bar{b}(\lambda)\,d\lambda$$



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Color Reproduction with Matching Functions

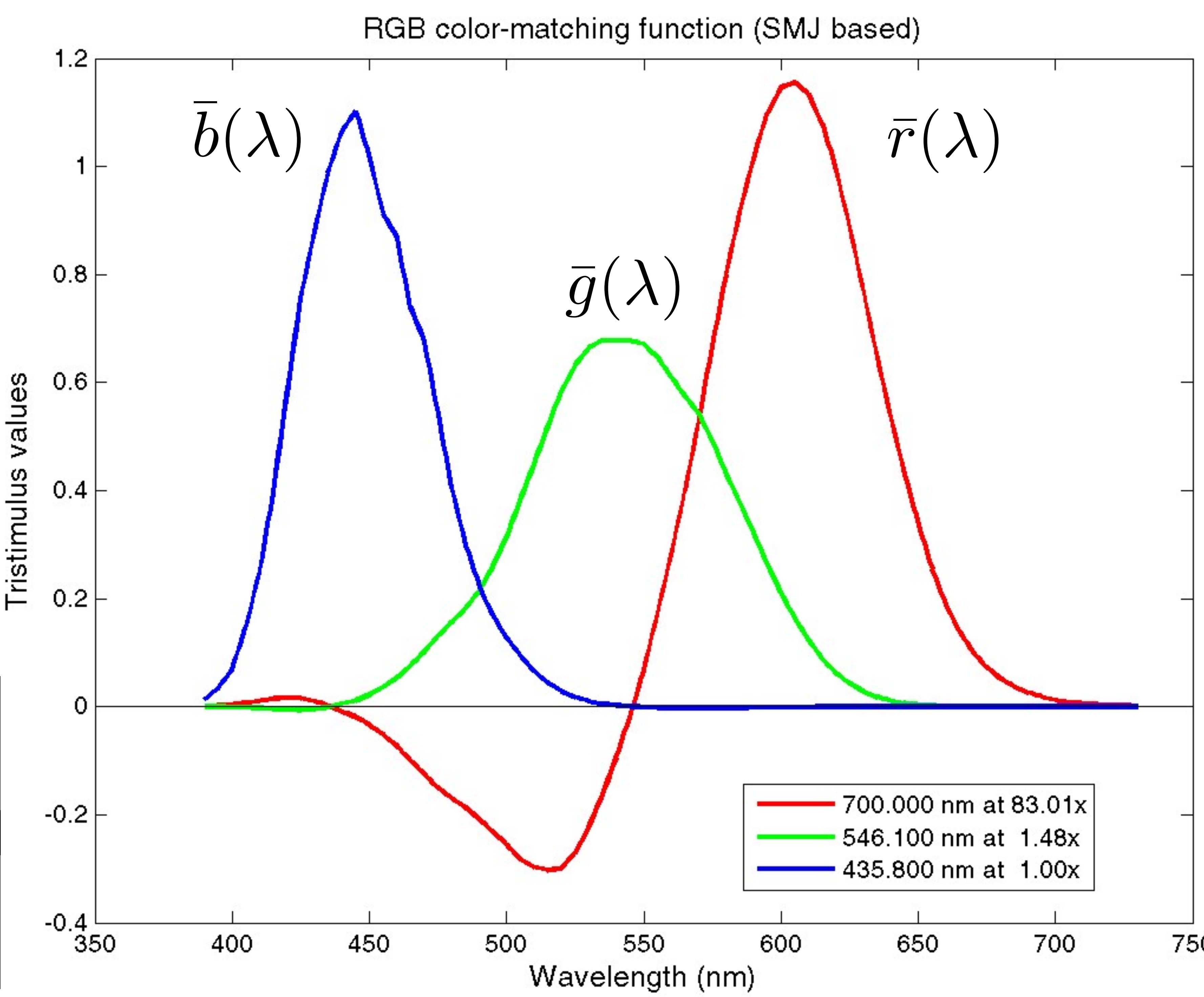
For any spectrum *s*, the perceived color is matched by the following formulas for scaling the CIE RGB primaries

Written as vector dot products:

$$R_{\mathrm{CIE\,RGB}} = s \cdot \bar{r}$$
$$G_{\mathrm{CIE\,RGB}} = s \cdot \bar{g}$$
$$B_{\mathrm{CIE\,RGB}} = s \cdot \bar{b}$$

Matrix formulation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\mathrm{CIE\,RGB}} = \begin{bmatrix} — & \bar{r} & — \\ — & \bar{g} & — \\ — & \bar{b} & — \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$



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To Be Continued

Acknowledgments

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