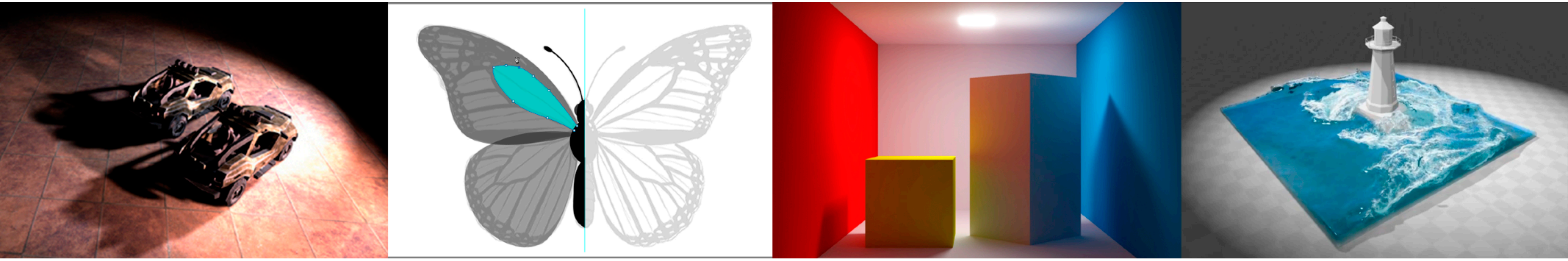
Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 20:
Color and Perception



http://www.cs.ucsb.edu/~lingqi/teaching/games101.html

Announcements

- Homework 6: 239 submissions, still pretty good
- Homework 7: 20 submissions so far
  - Make sure that the indirect ray returns 0 when it hits light sources (already calculated in direct illumination)
- Homework 8: Rope Simulator using Mass-Spring System
- Final project
  - Let us know if you want to do your own project ASAP
  - You need to submit a 2-minute presentation in video format with voice-over (how?)
  - …

Announcements

- Final project
  - …
  - Aesthetics is extremely important (why?)
  - Report (a 1-page write-up) is enough
  - Other questions?
- How to record a video with voice-over?
  - Just record your rehearsal using PowerPoint / Keynote
- How to do screen recording of my demo?
  - In Linux, I recommend SimpleScreenRecorder

Today

Finishing up light field / lumigraph

Color

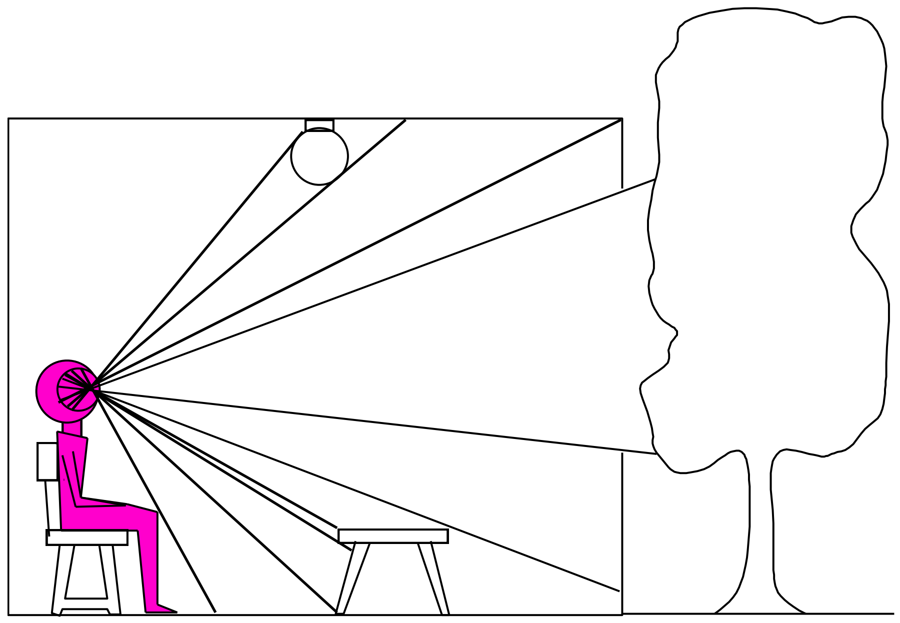
- What is color
- Color perception
- Color reproduction / matching
- Color space

Light Field / Lumigraph

(Credit of the next few slides: SIGGRAPH 2012 course on light fields)

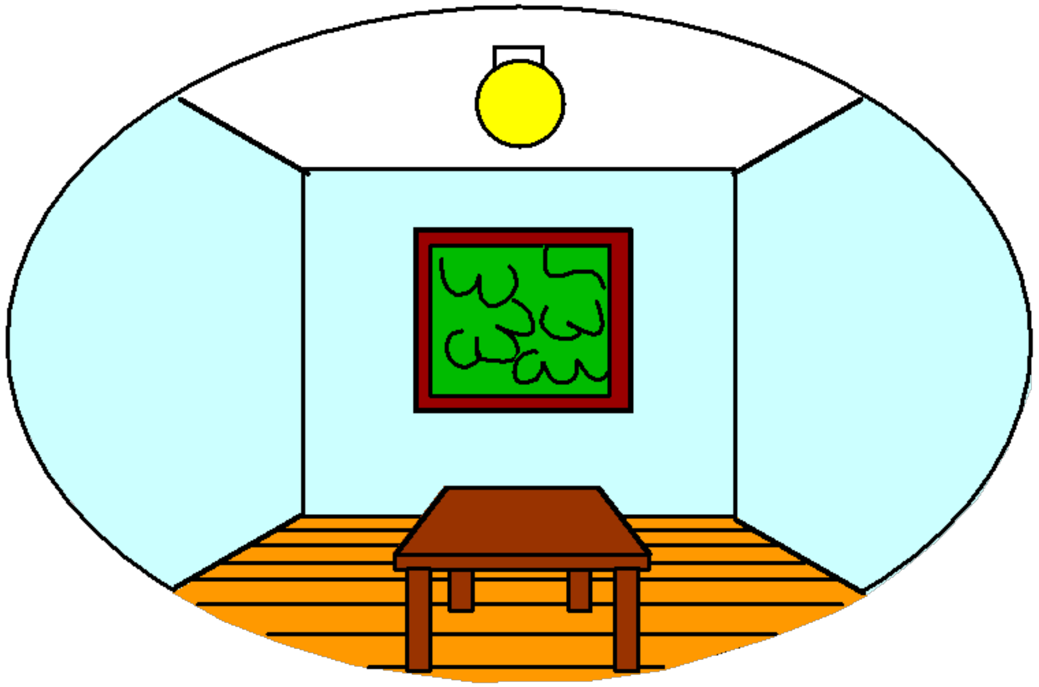
What do we see?

3D world



Point of observation

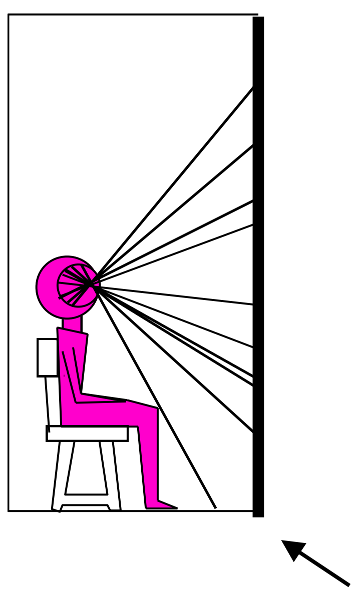
2D image



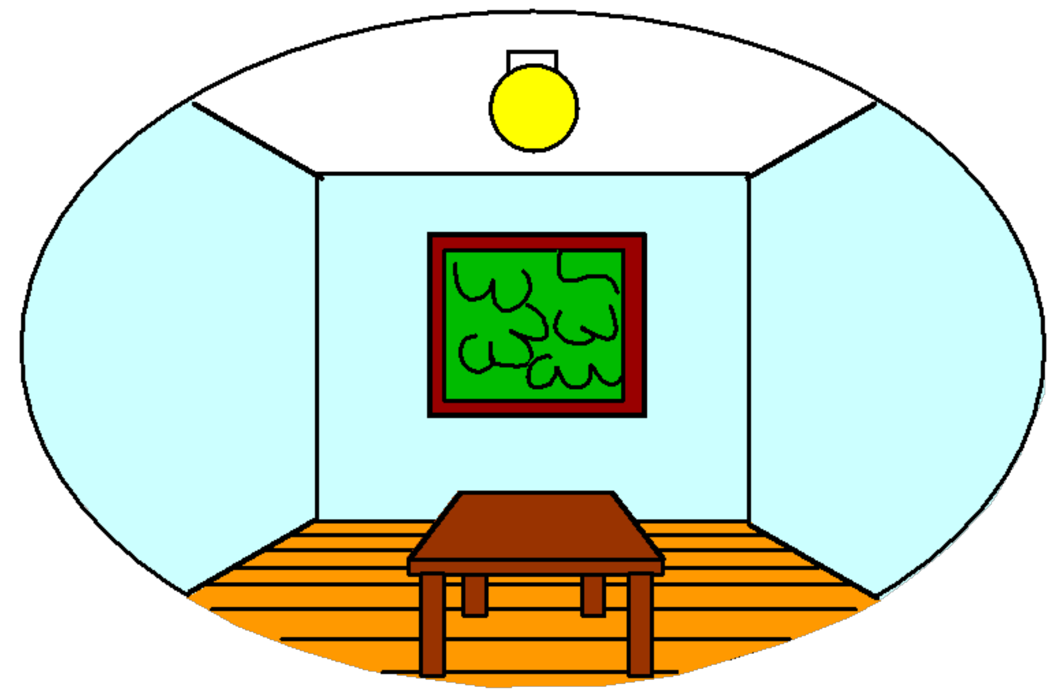
Figures © Stephen E. Palmer, 2002

What do we see?

3D world



2D image



The Plenoptic Function （全光函数）

Figure by Leonard McMillan

Q: What is the set of all things that we can ever see?

A: The Plenoptic Function (Adelson & Bergen)

Let’s start with a stationary person and try to parameterize everything that he can see…

Grayscale snapshot

$$P(\theta,\phi)$$

is intensity of light

- Seen from a single view point
- At a single time
- Averaged over the wavelengths of the visible spectrum

(can also do *P(x,y)*, but spherical coordinate are nicer)

Color snapshot

$$P(\theta,\phi,\lambda)$$

is intensity of light

- Seen from a single view point
- At a single time
- As a function of wavelength

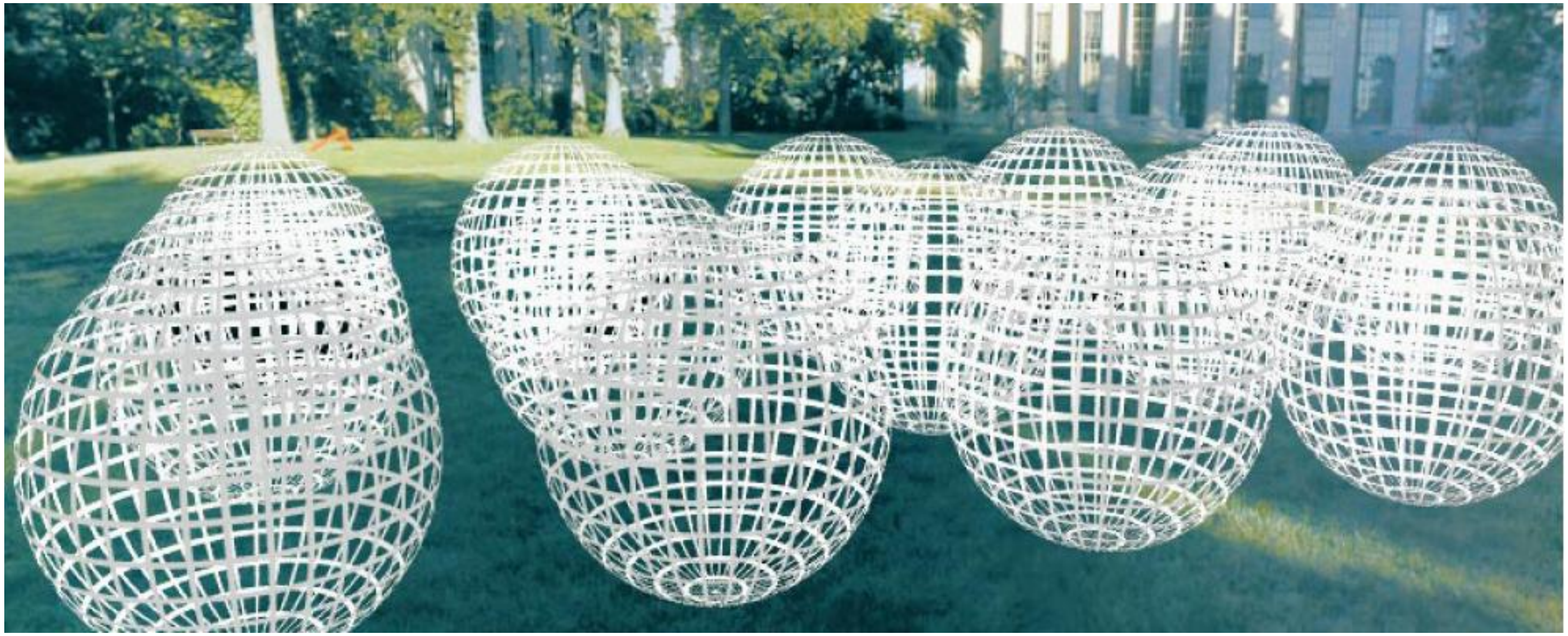
A movie

$$P(\theta,\phi,\lambda,t)$$

is intensity of light

- Seen from a single view point
- Over time
- As a function of wavelength

Holographic movie

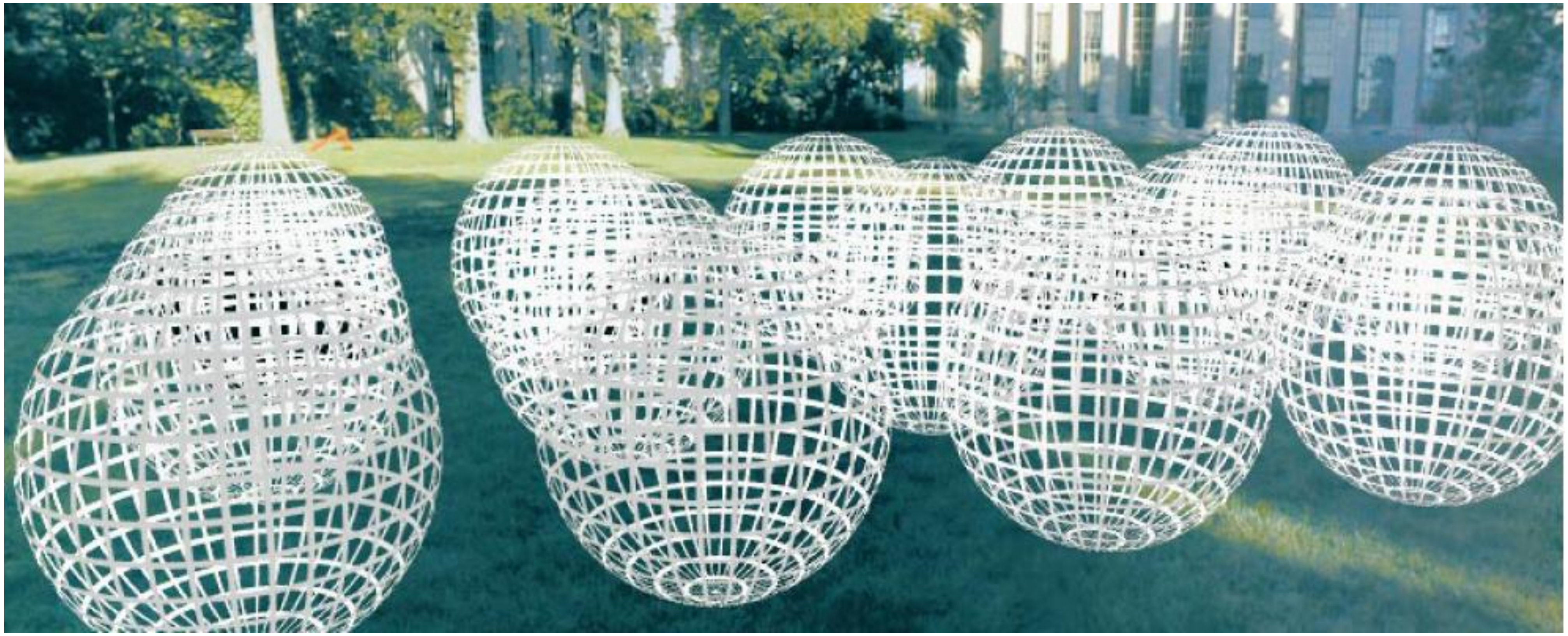


$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

is intensity of light

- Seen from ANY viewpoint
- Over time
- As a function of wavelength

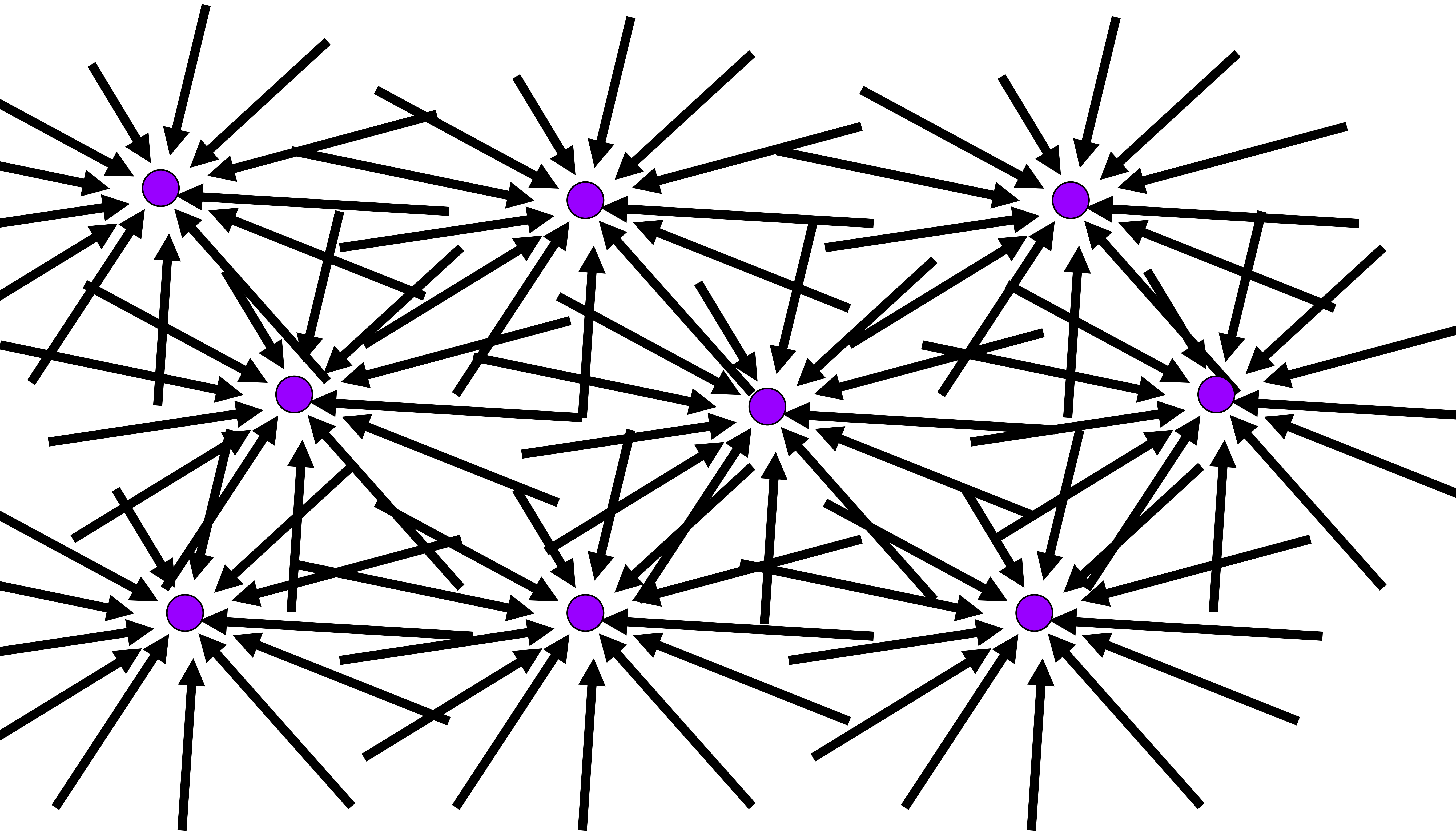
The Plenoptic Function



$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

- Can reconstruct every possible view, at every moment, from every position, at every wavelength
- Contains every photograph, every movie, everything that anyone has ever seen! it completely captures our visual reality! Not bad for a function…

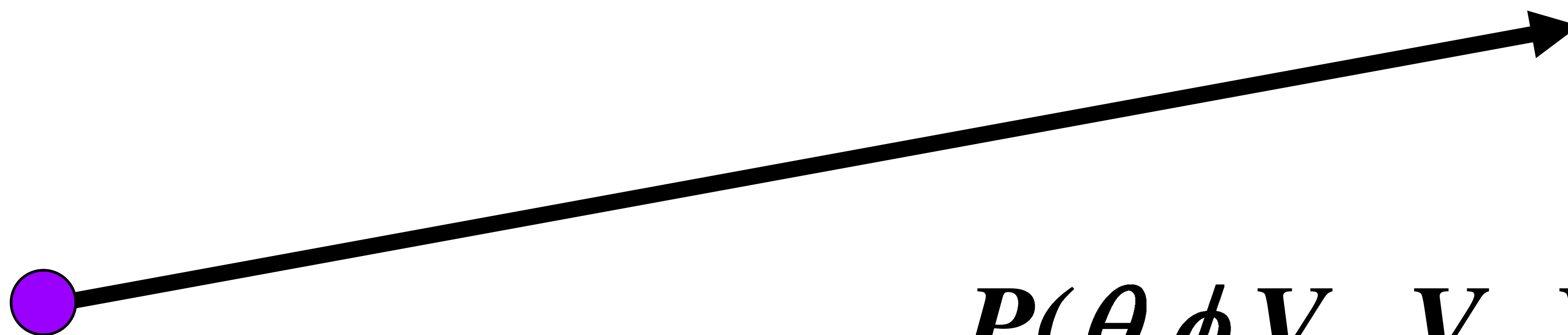
Sampling Plenoptic Function (top view)



Just lookup -- Quicktime VR

Ray

Let's not worry about time and color:



$$P(\theta,\phi,V_X,V_Y,V_Z)$$

5D

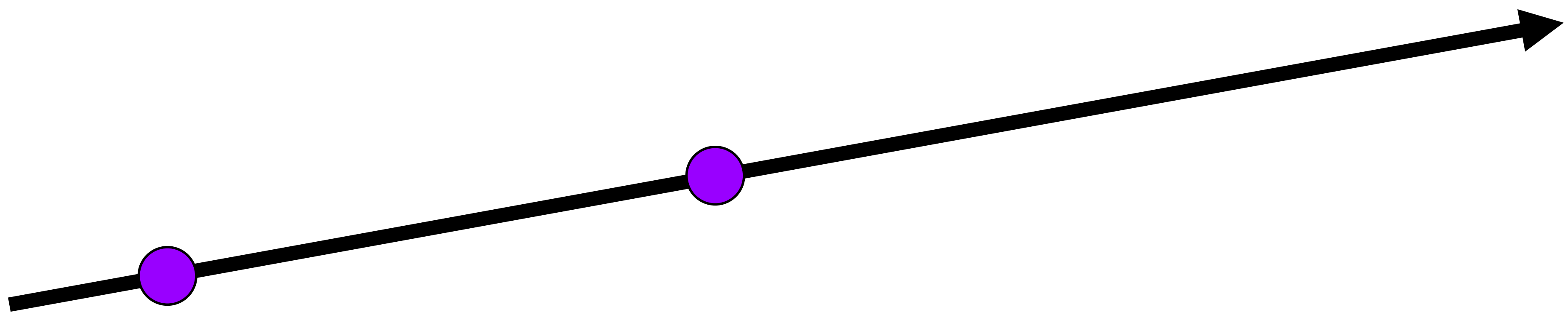
- 3D position
- 2D direction

Slide by Rick Szeliski and Michael Cohen

Ray Reuse

Infinite line

- Assume light is constant (vacuum)



4D

- 2D direction
- 2D position
- non-dispersive medium

Slide by Rick Szeliski and Michael Cohen

Only need plenoptic surface

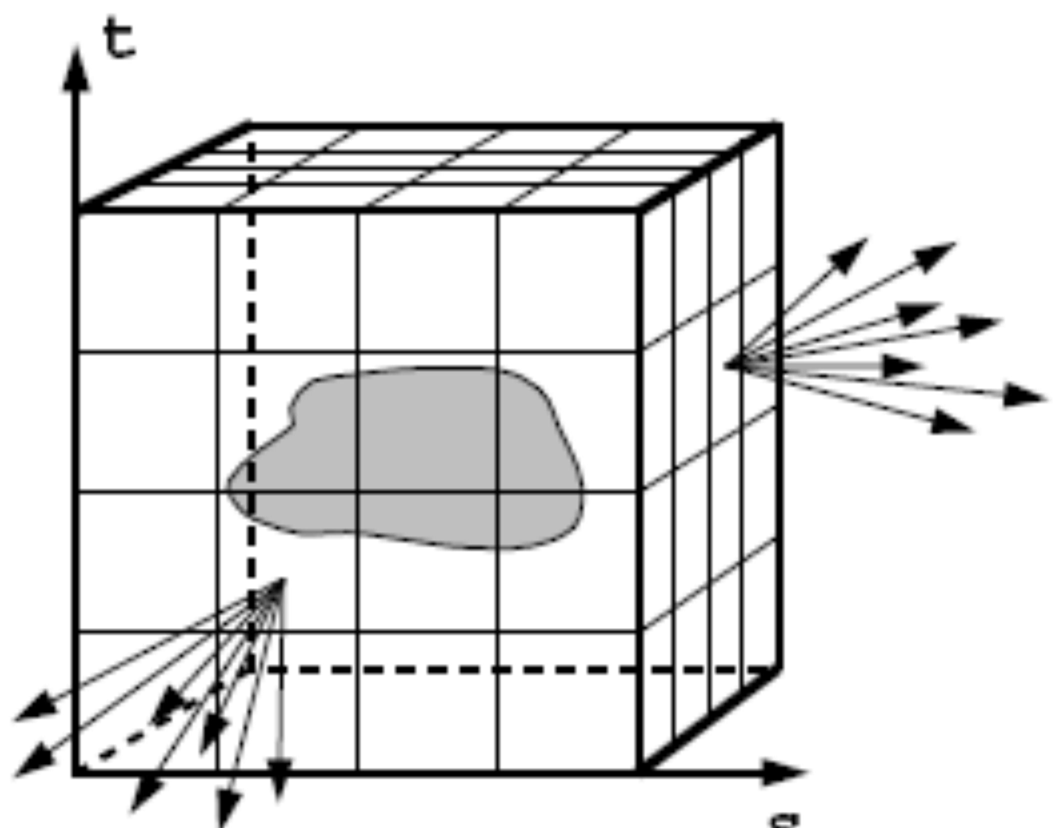
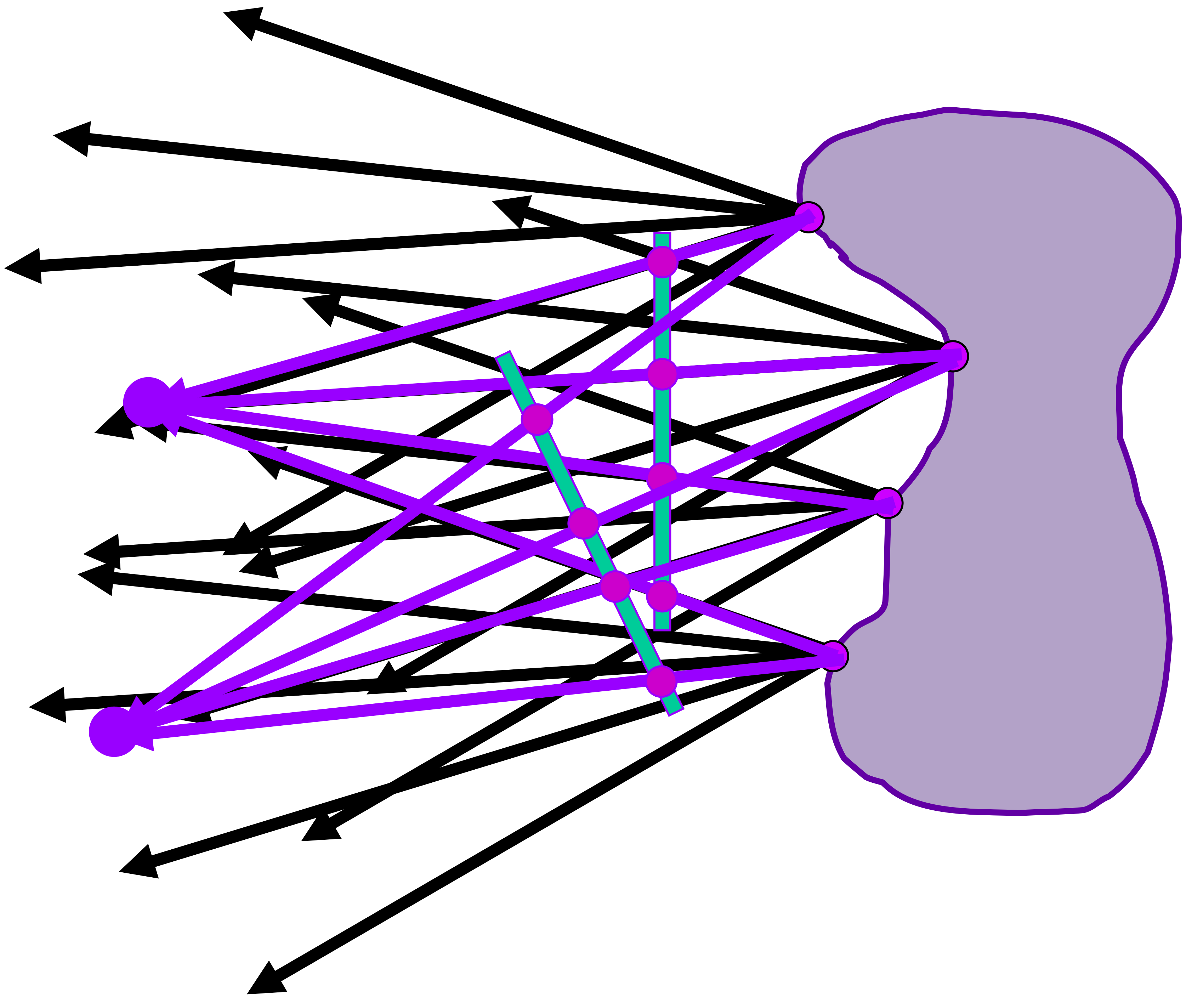


Figure 1: The surface of a cube holds all the radiance information due to the enclosed object.

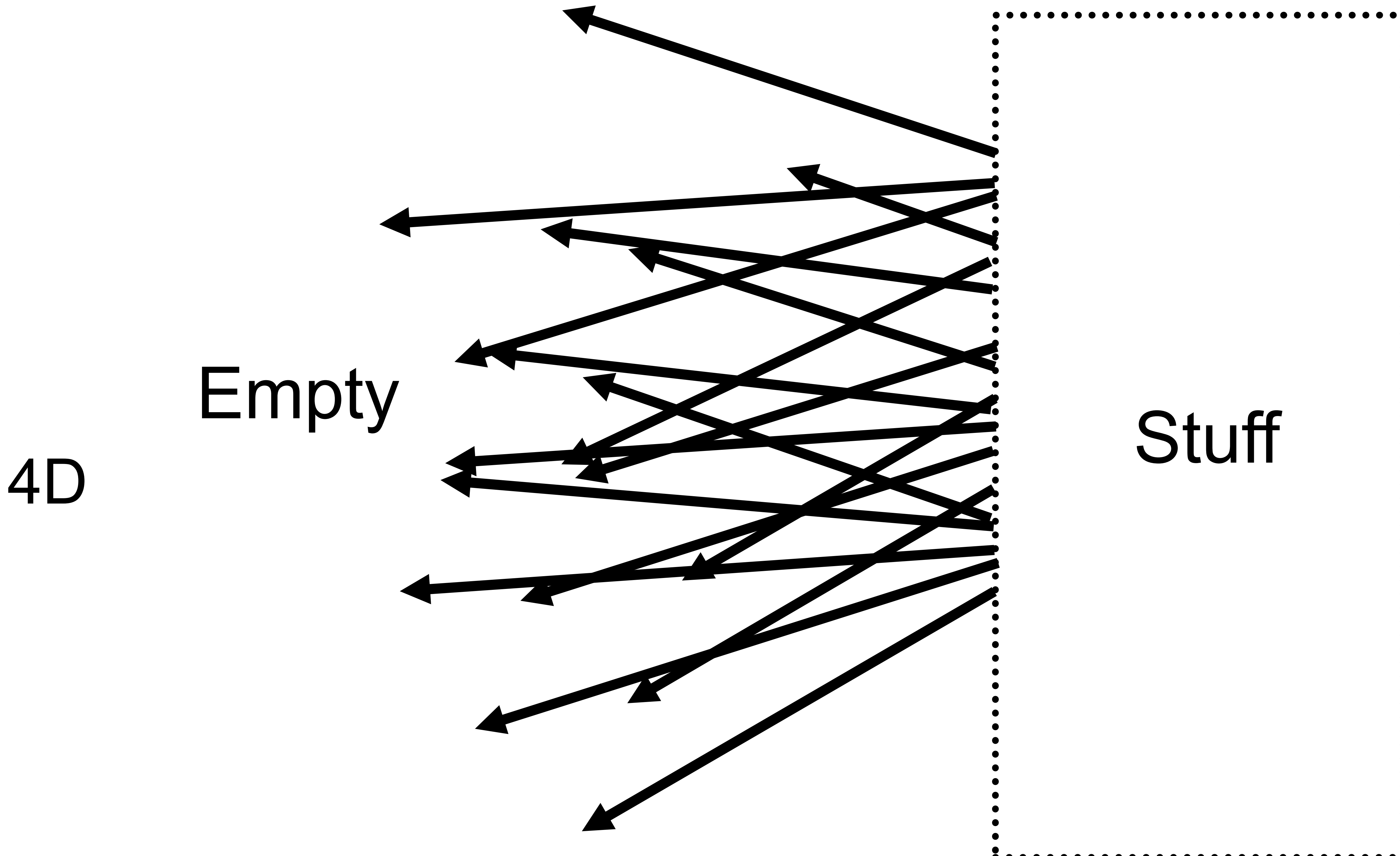
Synthesizing novel views



Slide by Rick Szeliski and Michael Cohen

Lumigraph / Lightfield

Outside convex space

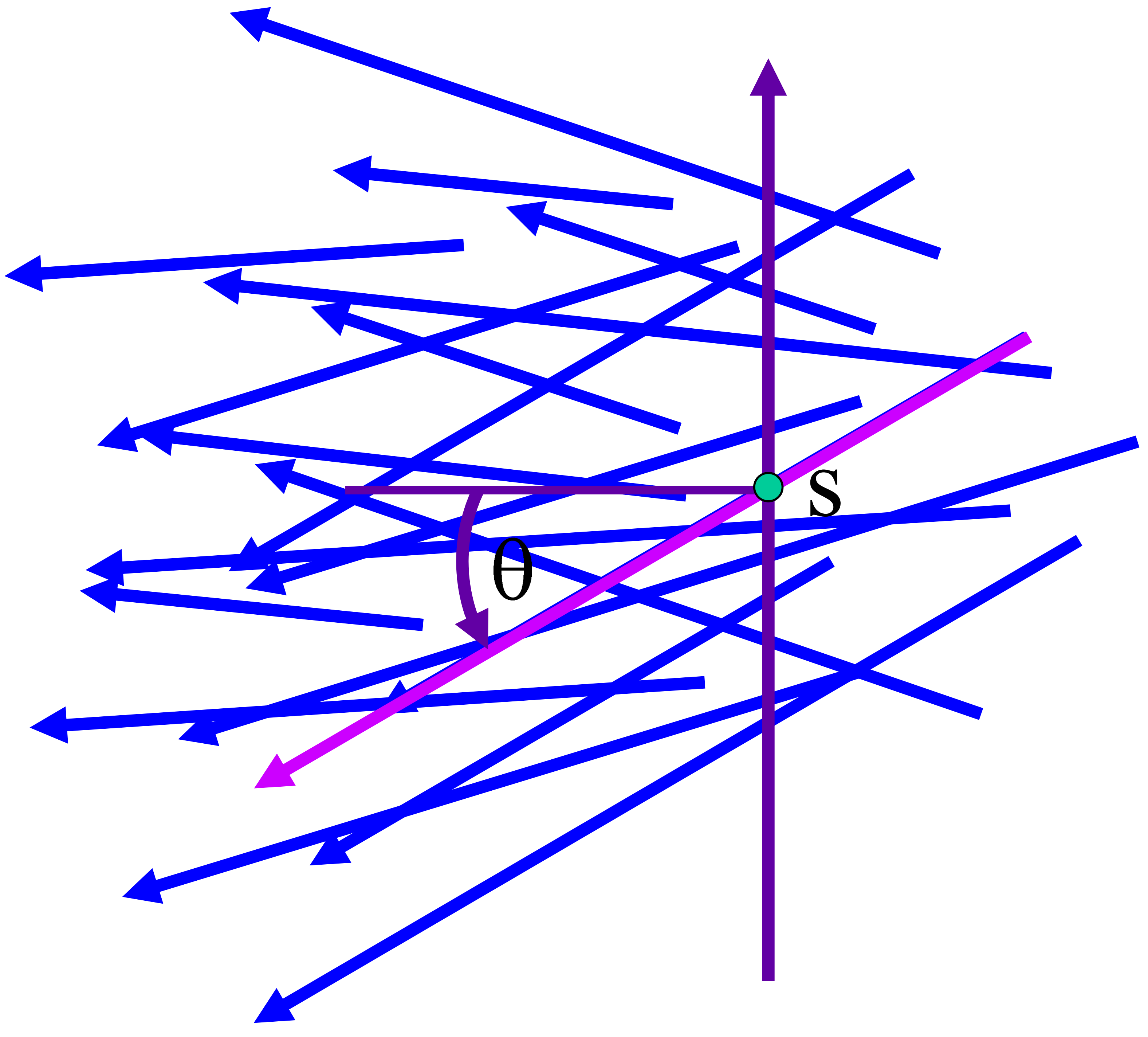


Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D direction



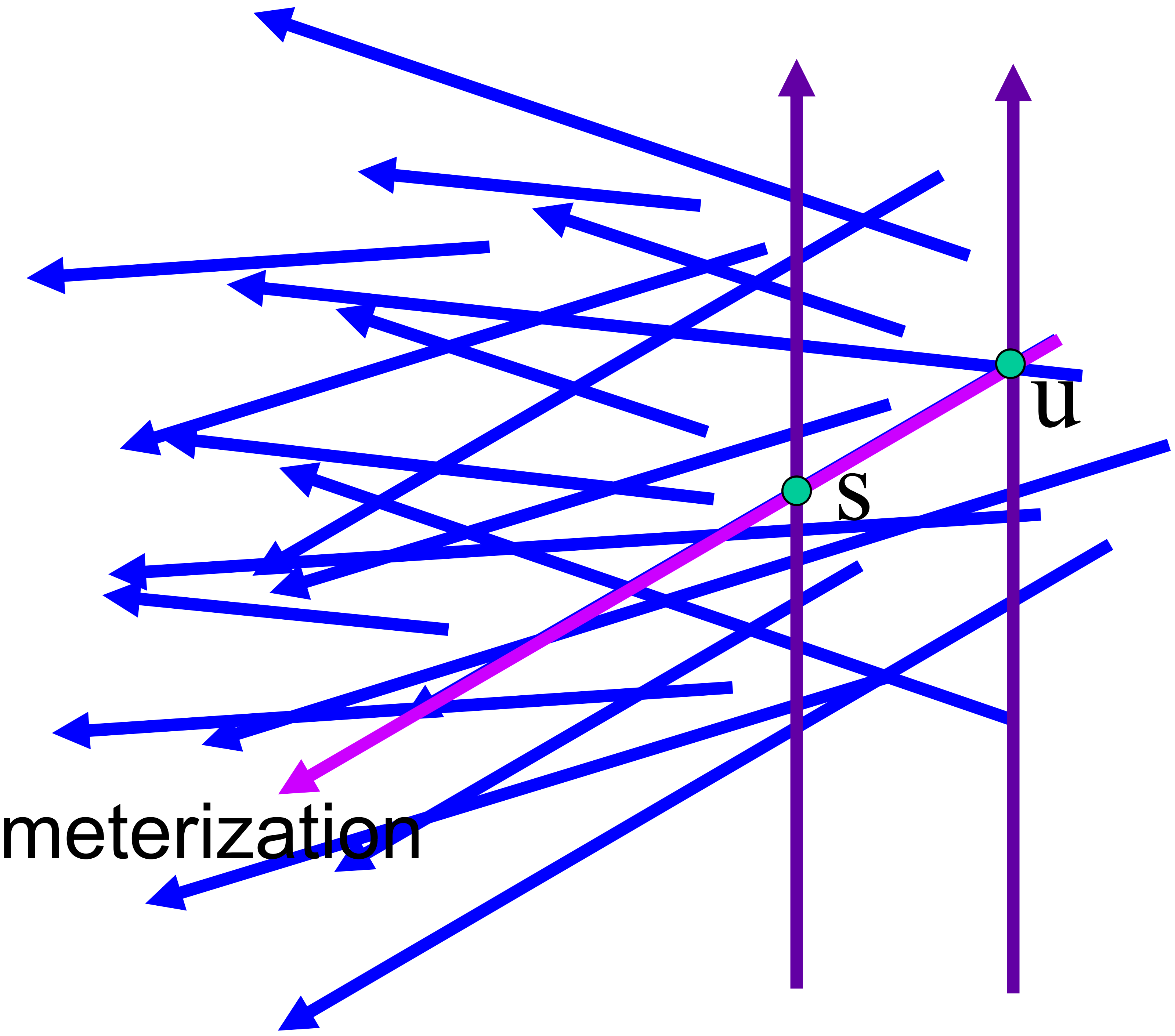
Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D position

2 plane parameterization



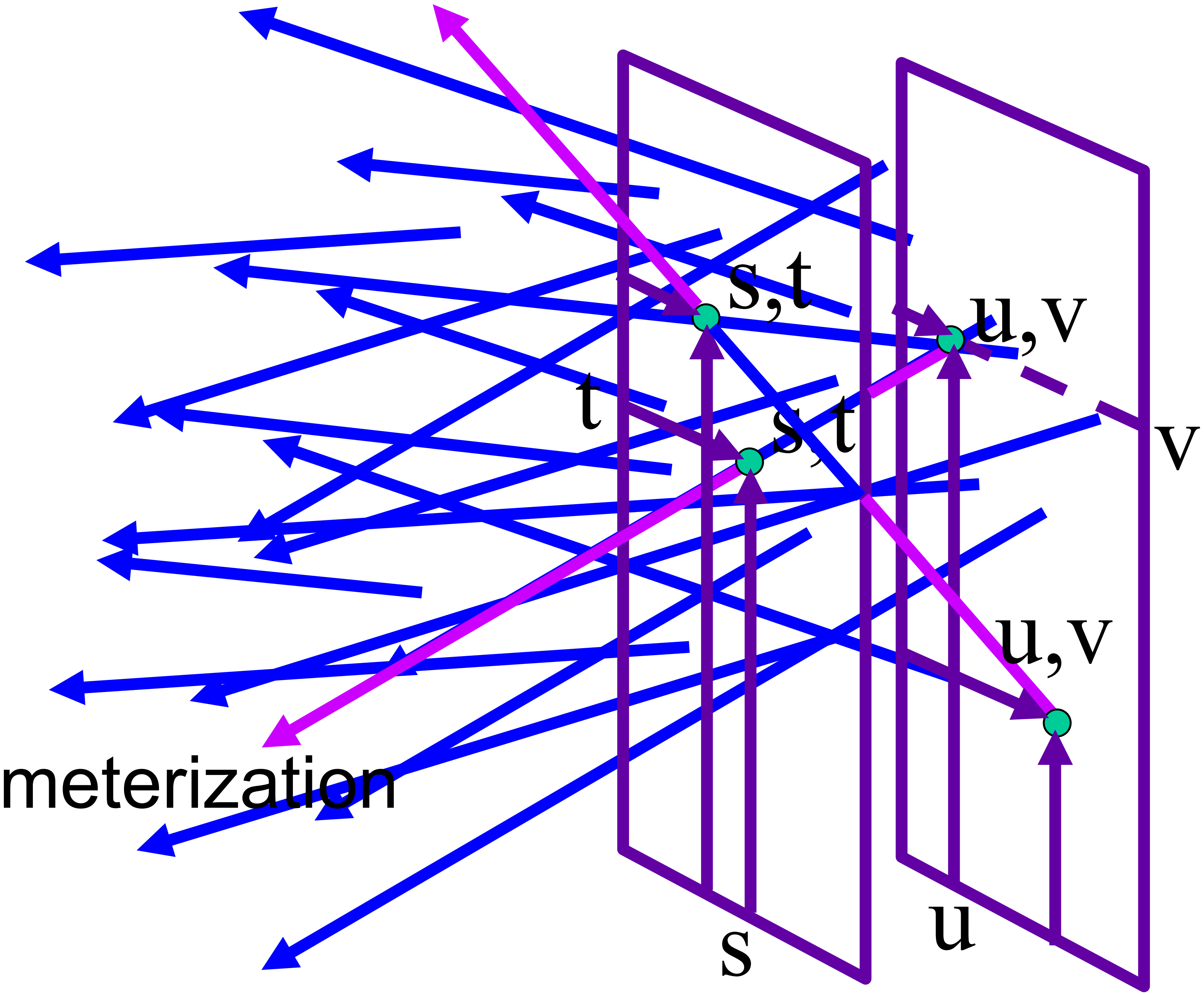
Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D position

2 plane parameterization



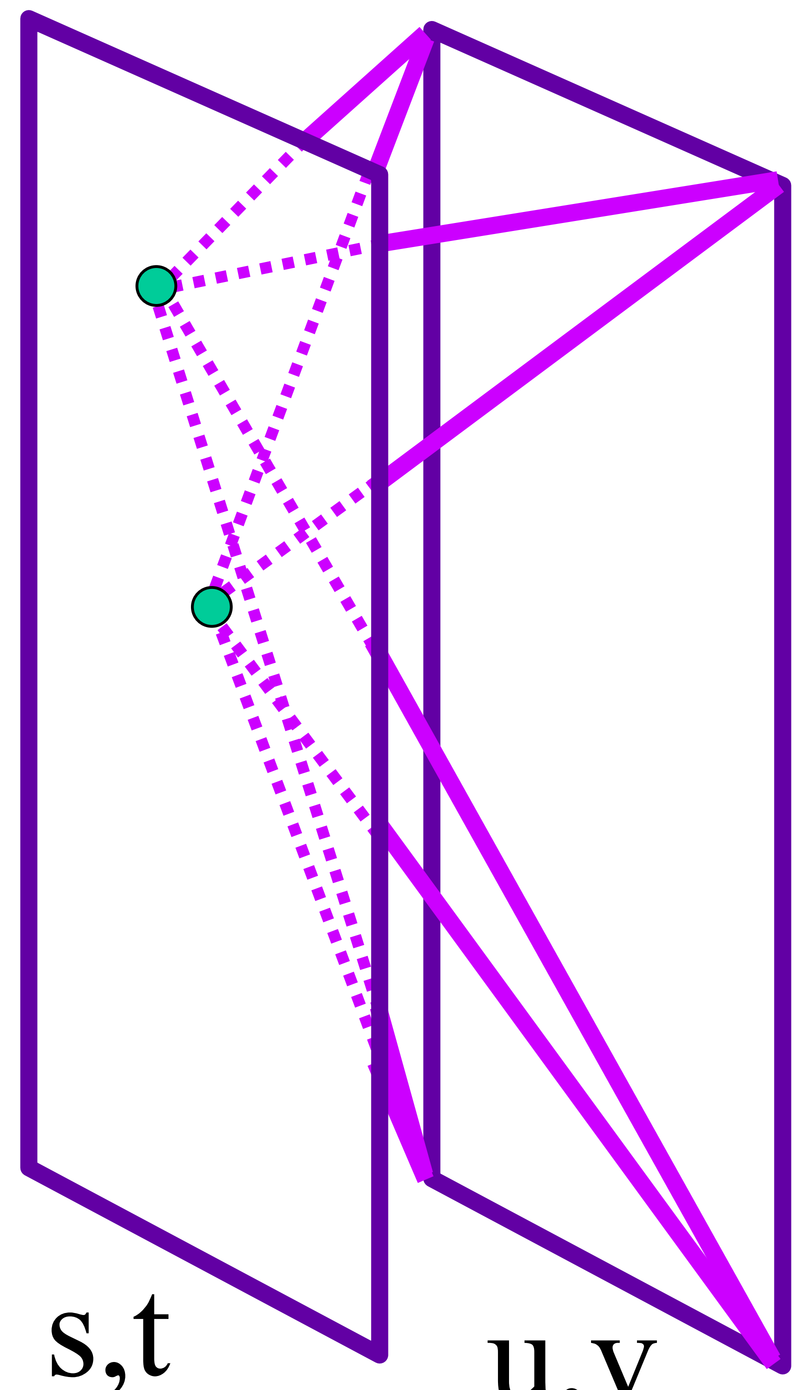
Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

Hold s,t constant

Let u,v vary

An image



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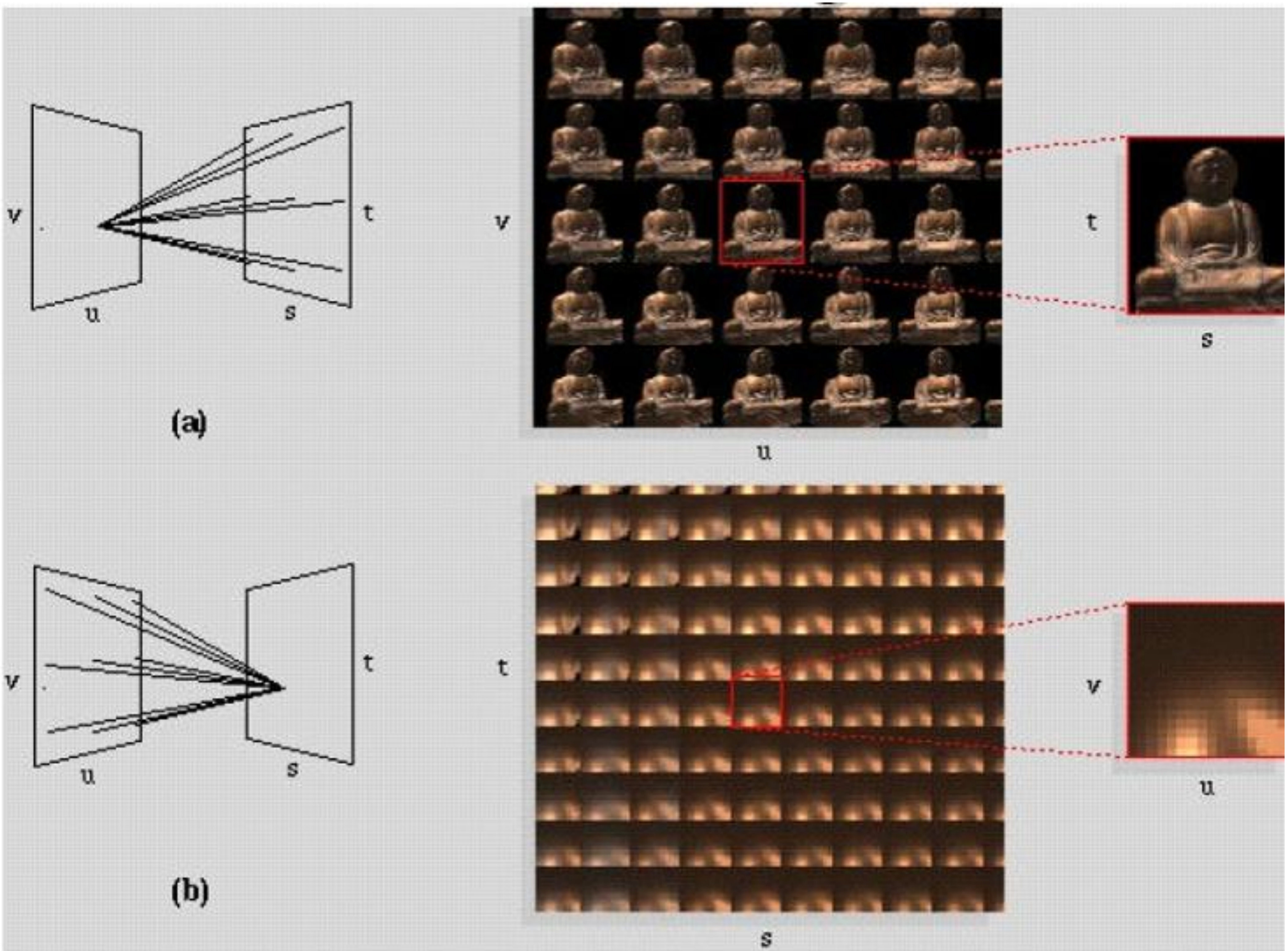
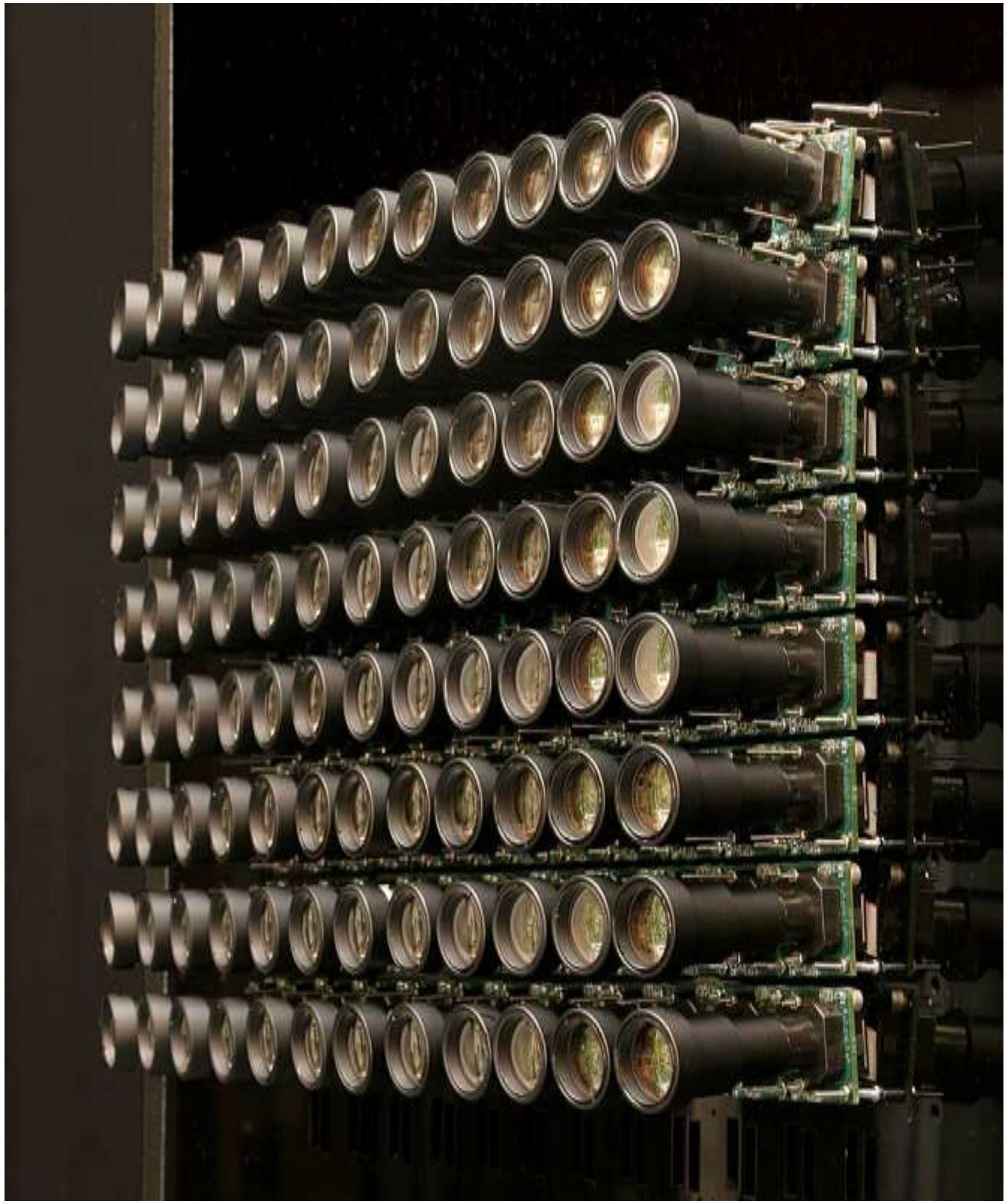
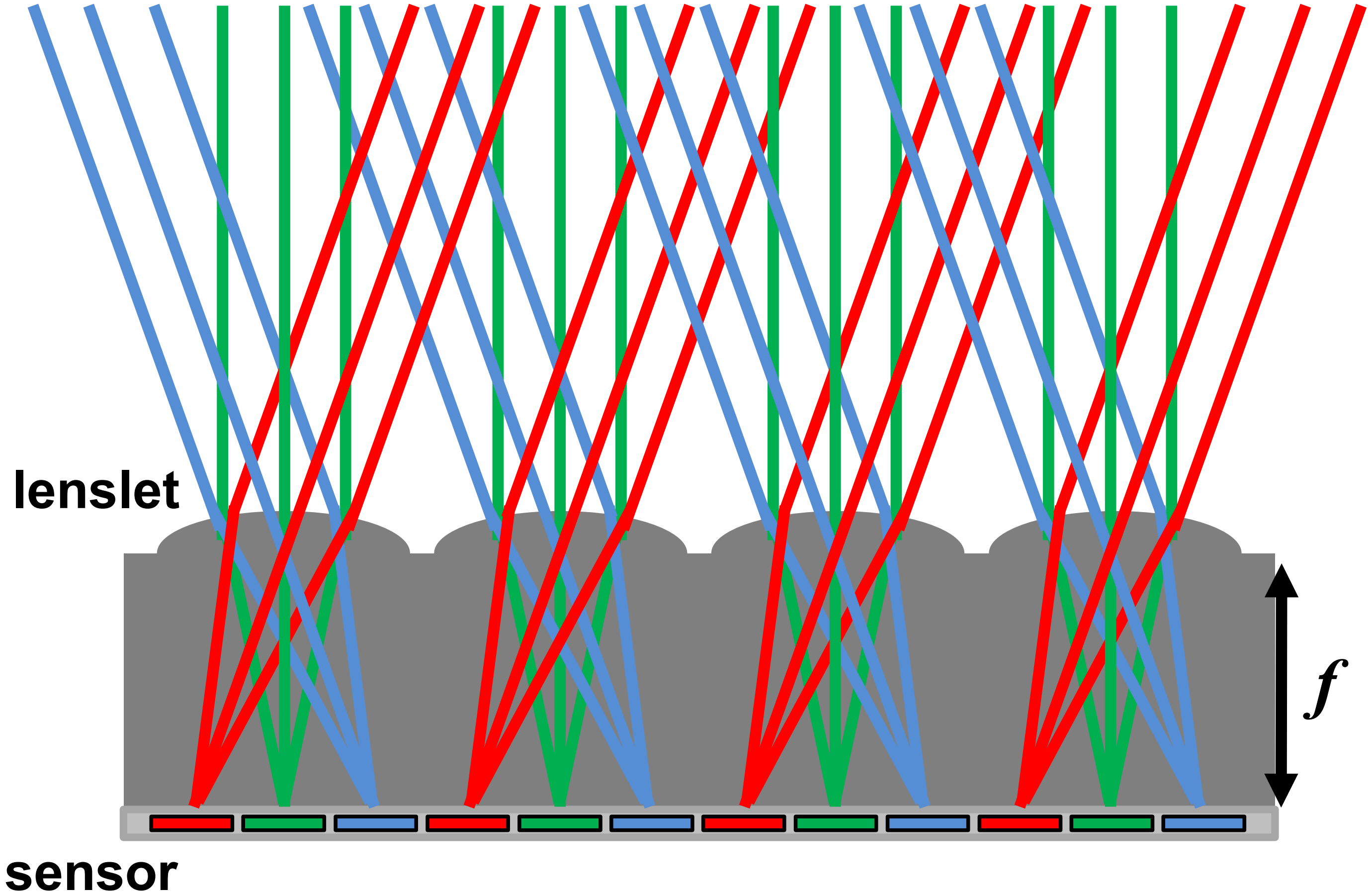
Lumigraph / Lightfield



Stanford camera array



Integral Imaging ("Fly's Eye" Lenslets)



Credit: JJ Harrison

Spatially-multiplexed light field capture using lenslets:

- Impose fixed trade-off between spatial and angular resolution

[Lippmann 1908]

Light Field Camera

The Lytro Light Field Camera

Lytro: founded by Prof. Ren Ng (UC Berkeley)

Microlens design

Most significant function

- Computational Refocusing
  (virtually changing focal length & aperture size, etc. **after** taking the photo)

Ren at Lingqi's graduation ceremony

Prof. Ren Ng

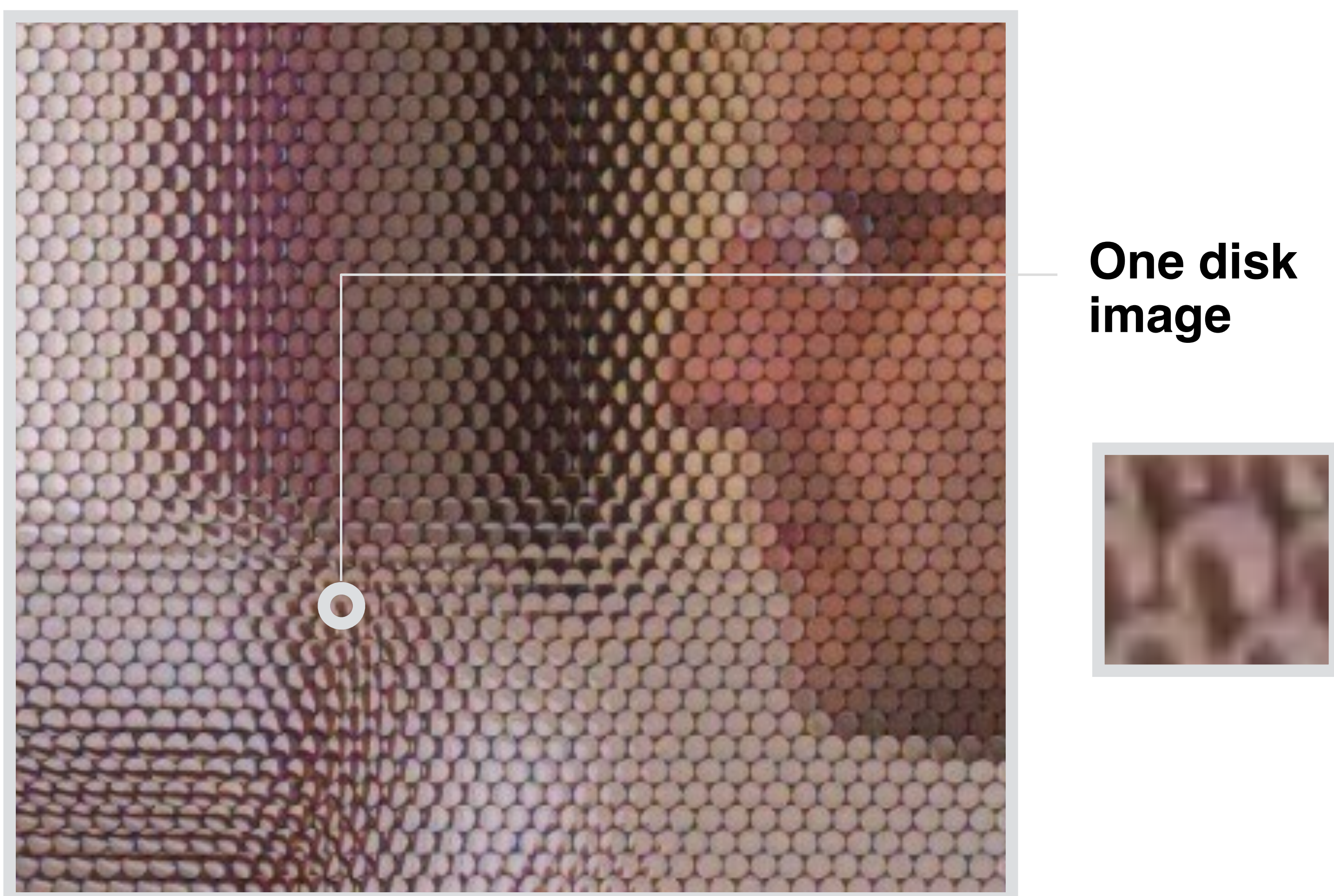
The riginal Lytro light field camera

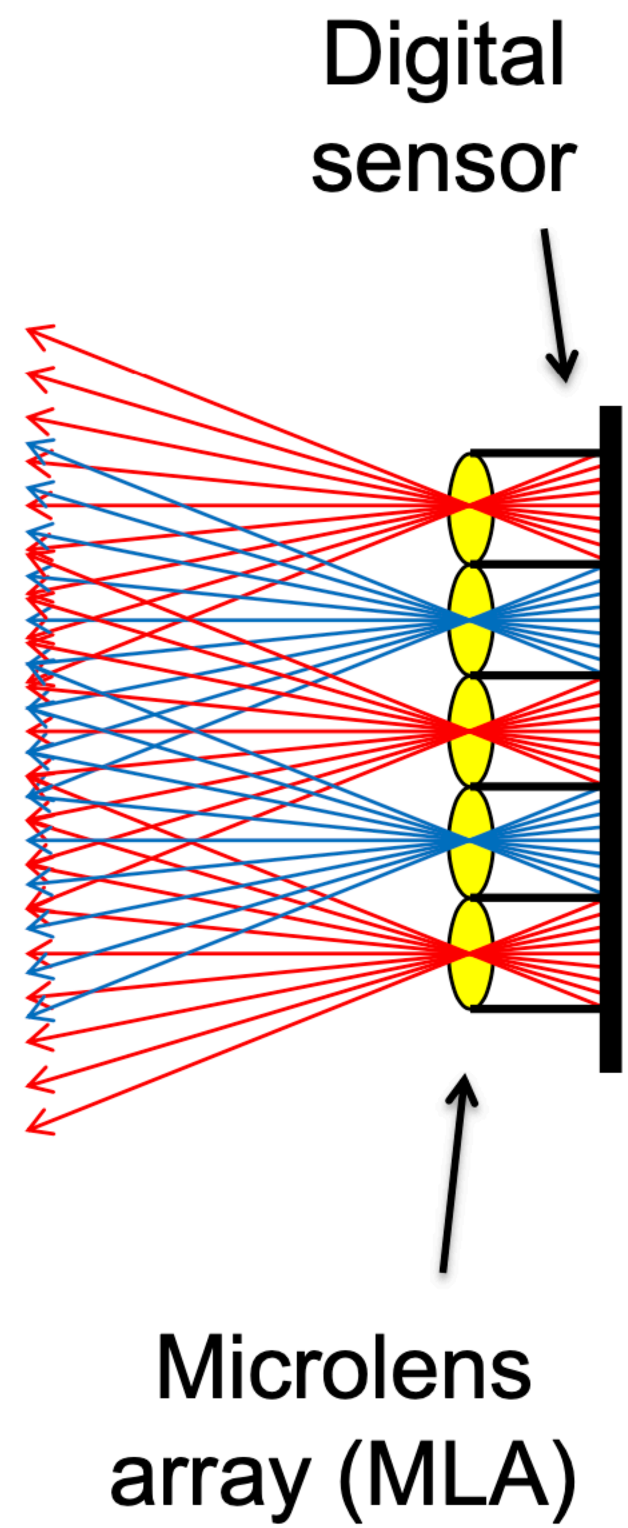
Lytro Illum

Light Field Camera

Understanding

- Each pixel (irradiance) is now stored as a block of pixels (radiance)
- A close-up view of a picture taken





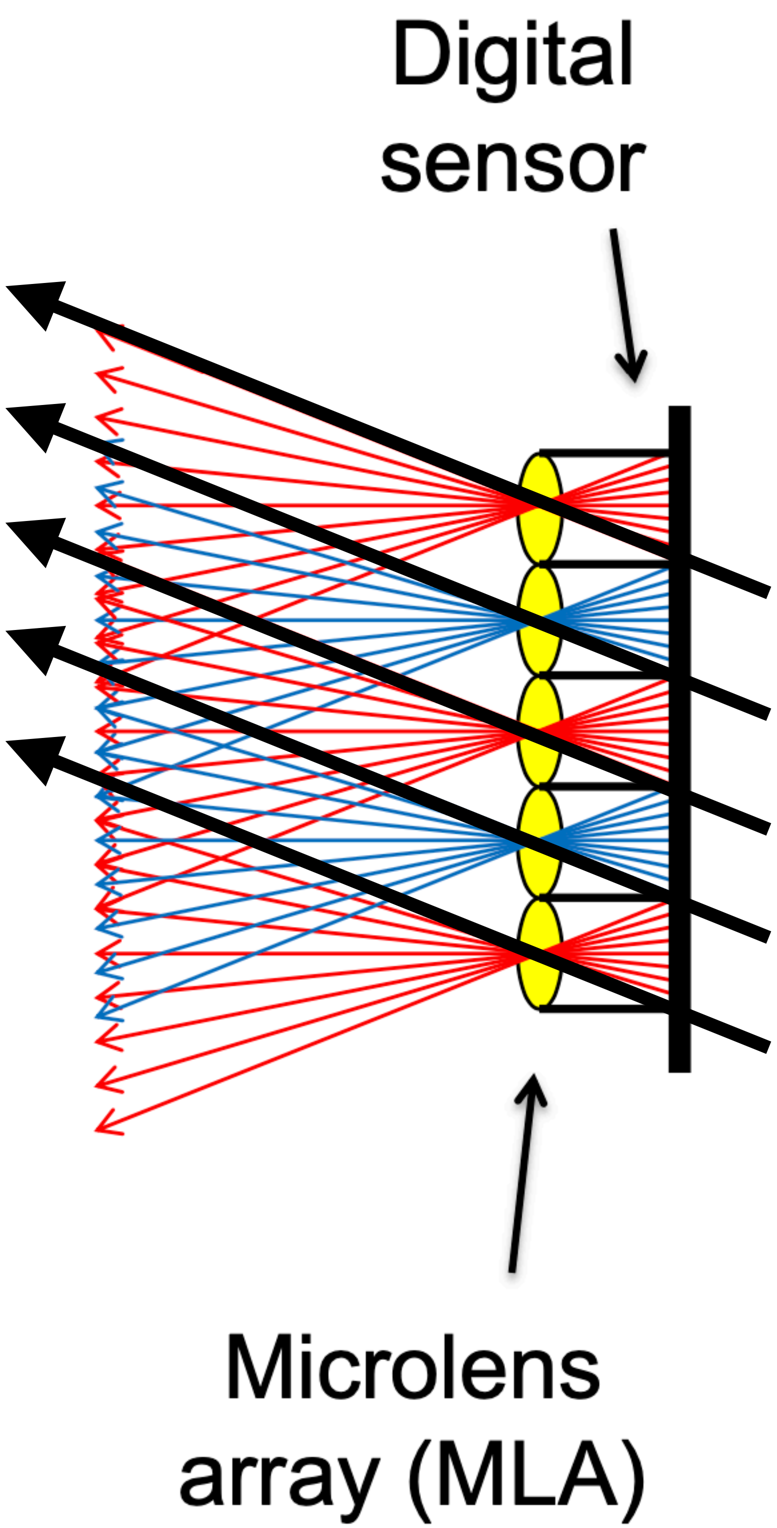
Light Field Camera

How to get a "regular" photo from the light field photo?

- A simple case — always choose the pixel at the bottom of each block
- Then the central ones & the top ones
- Essentially "moving the camera around"

Computational / digital refocusing

- Same idea: visually changing focal length, picking the refocused ray directions accordingly



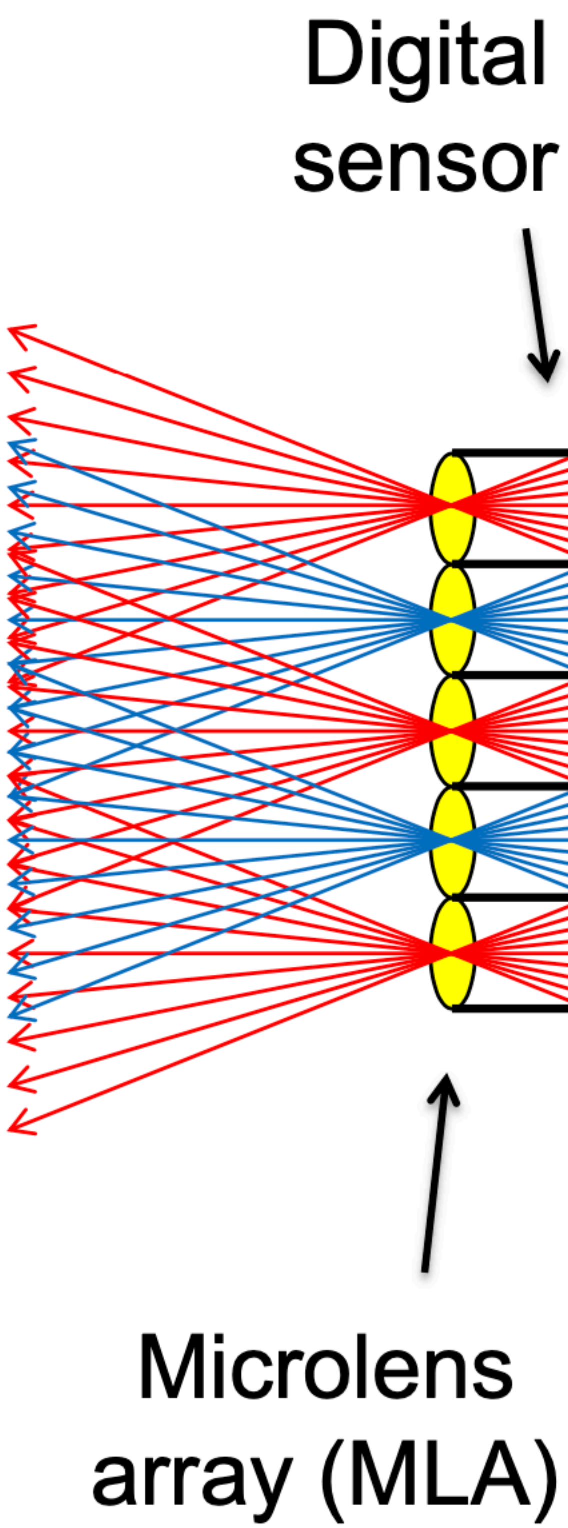
Light Field Camera

In all, all these functionalities are available because

- The light field contains everything

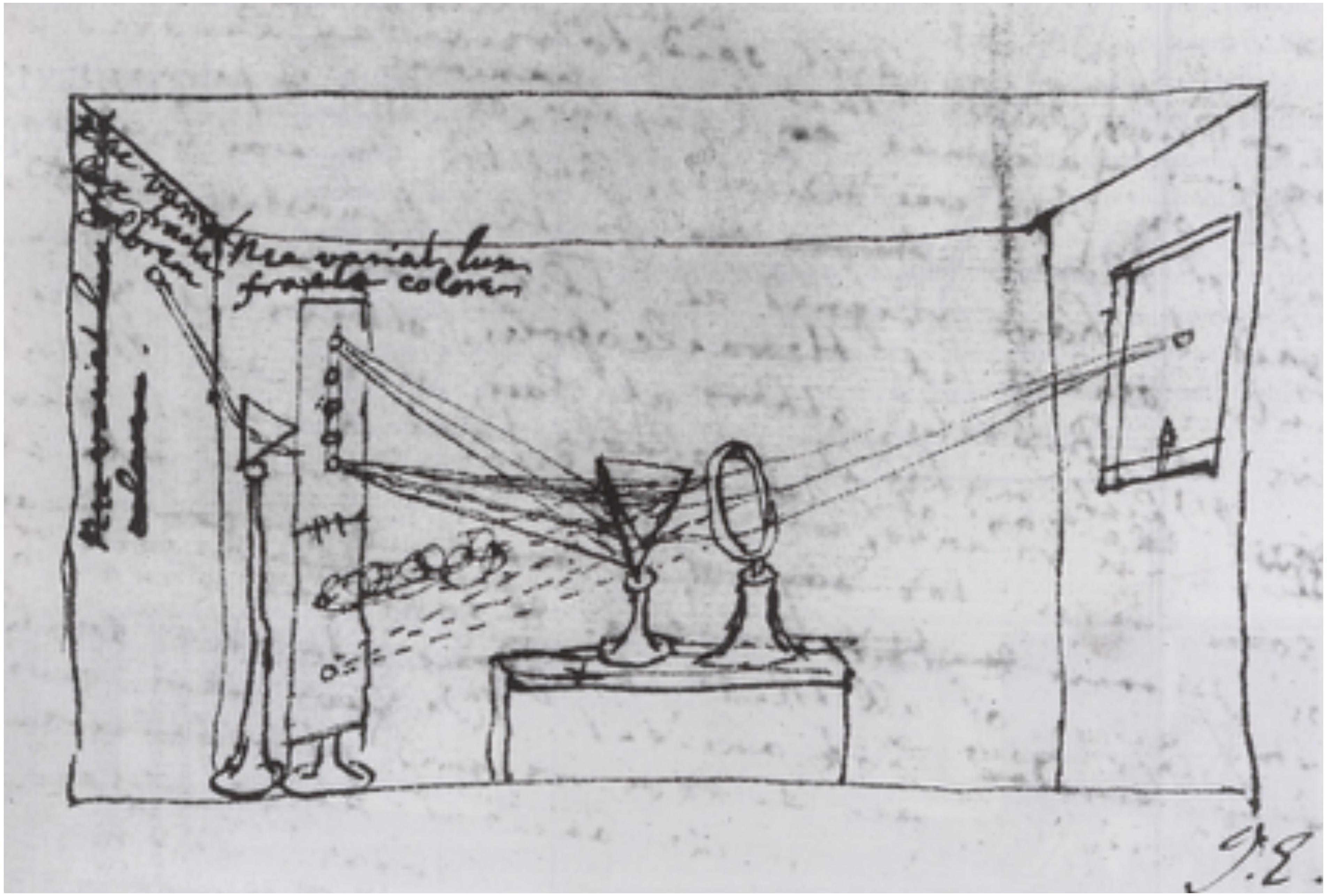
Any problems to light field cameras?

- Insufficient spatial resolution (same film used for both spatial and directional information)
- High cost (intricate designation of microlenses)
- Computer Graphics is about trade-offs



Physical Basis of Color

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
(光谱)

Electromagnetic radiation

- Oscillations of different frequencies (wavelengths)

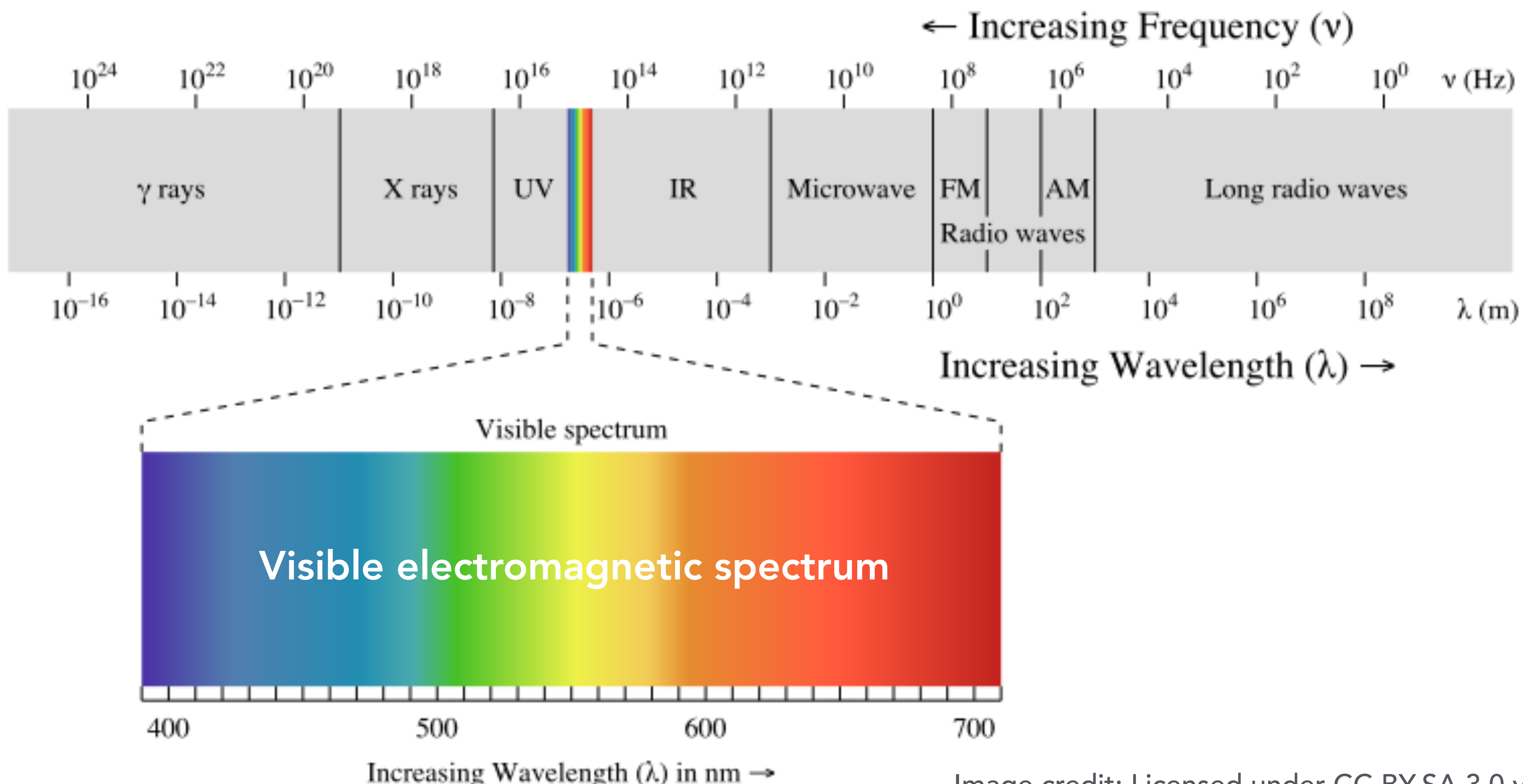


Image credit: Licensed under CC BY-SA 3.0 via Commons
https://commons.wikimedia.org/wiki/File:EM_spectrum.svg#/media/File:EM_spectrum.svg

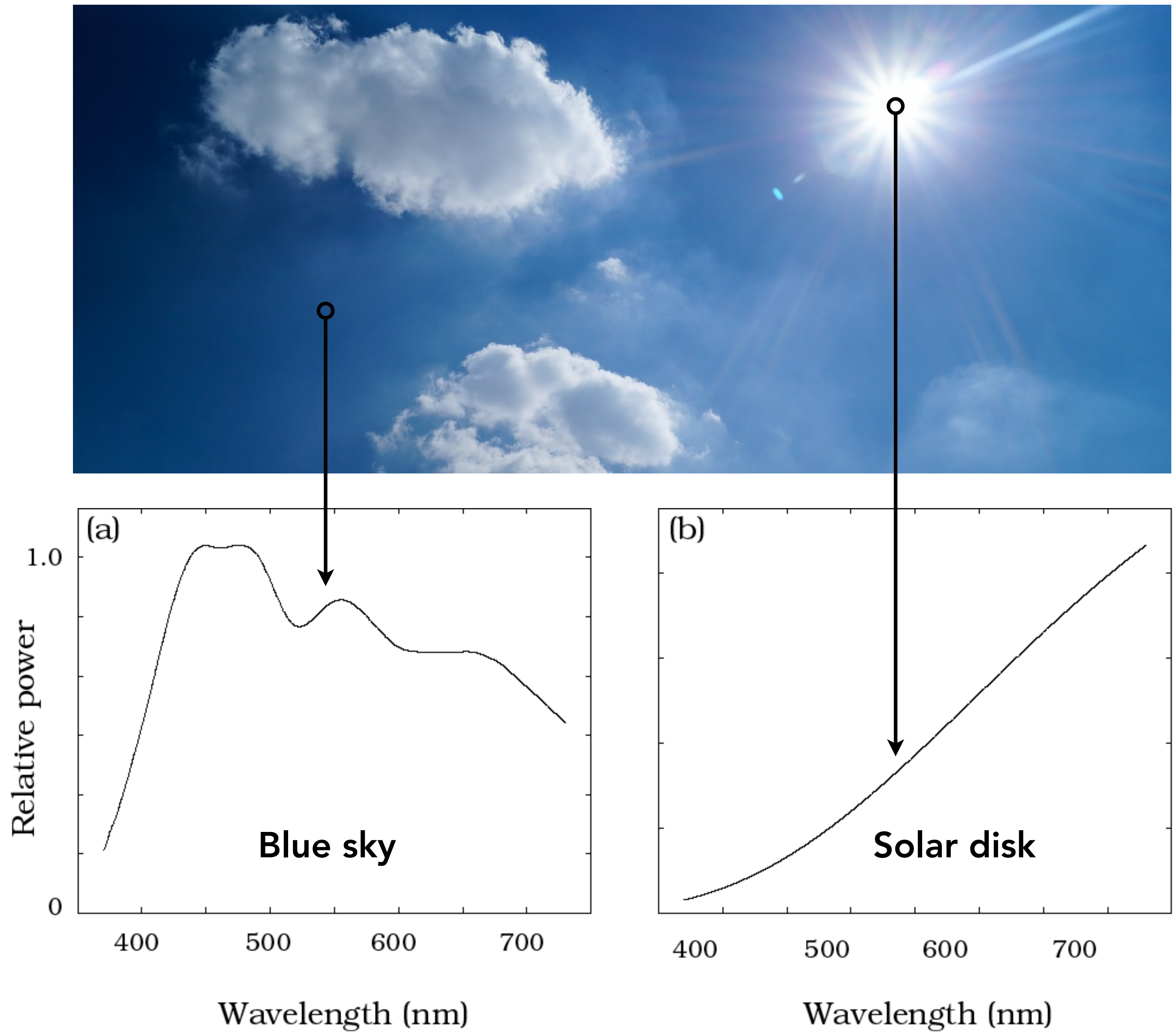
Spectral Power Distribution (SPD)

（谱功率密度）

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

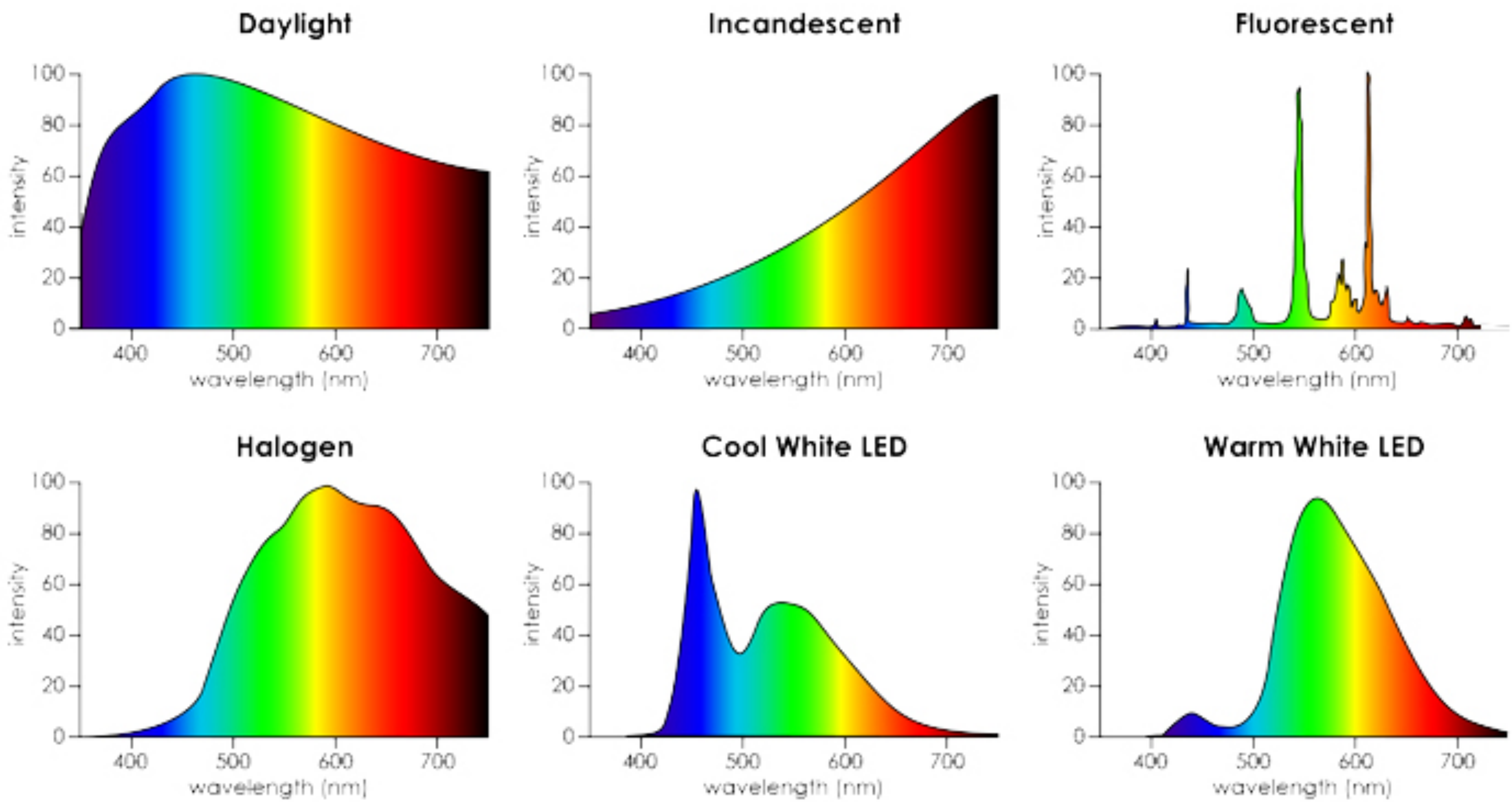
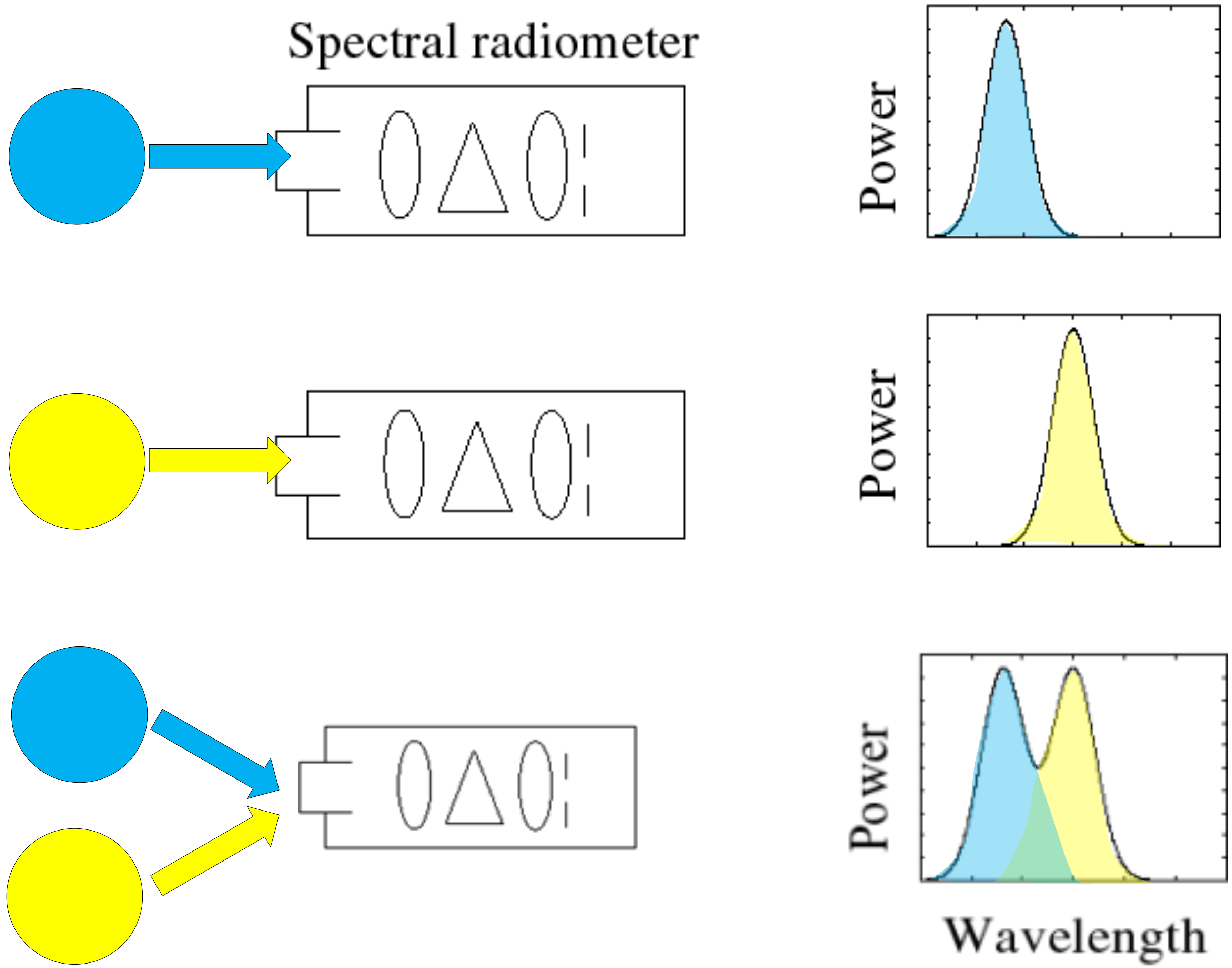


Figure credit: admesy ADVANCED MEASUREMENT SYSTEMS

Linearity of Spectral Power Distributions



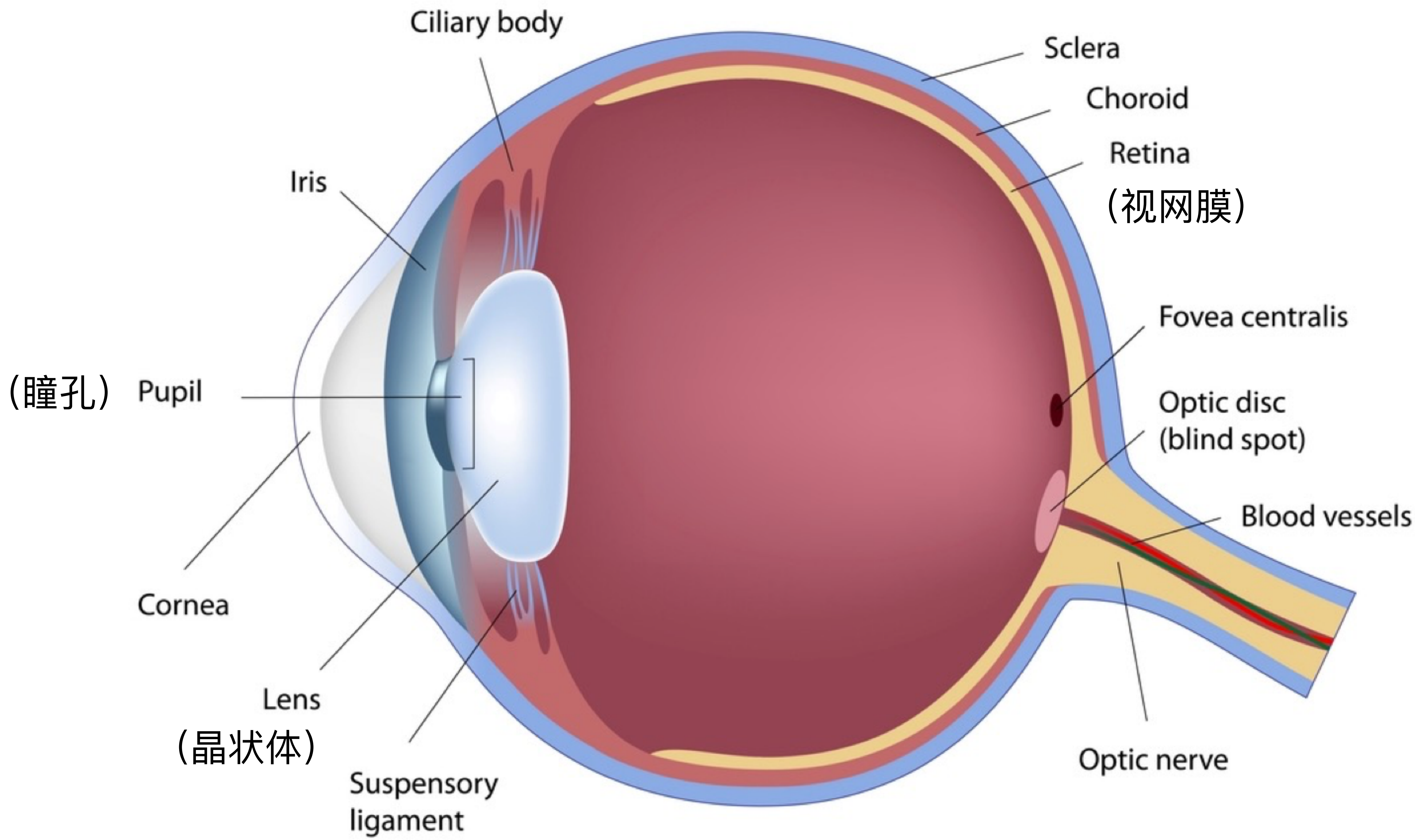
[Brian Wandell]

What is Color?

- Color is a phenomenon of human perception; it is not a universal property of light
- Different wavelengths of light are not “colors”

Biological Basis of Color

Anatomy of The Human Eye



Retinal Photoreceptor Cells: Rods and Cones

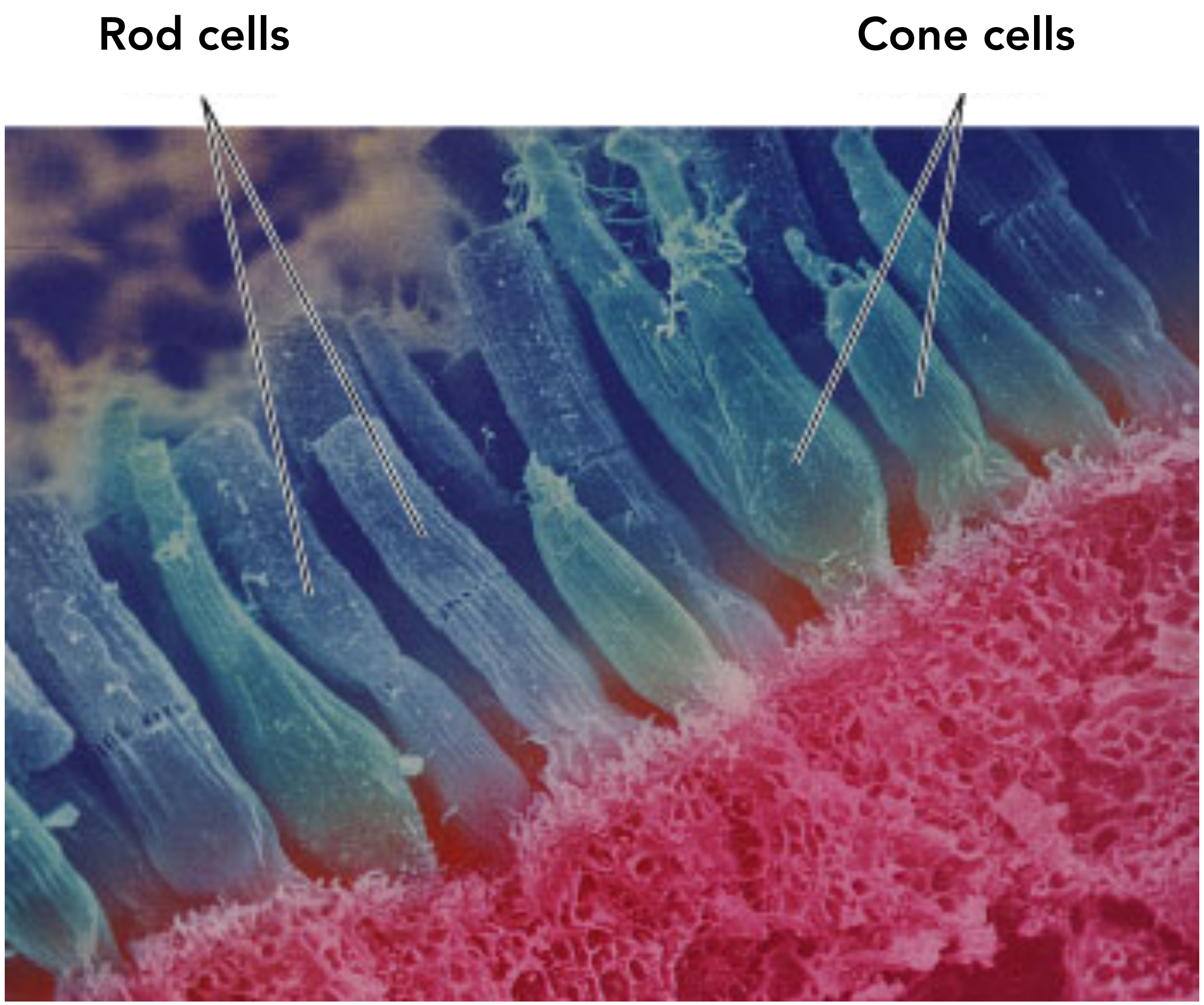
(感光细胞)

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”)

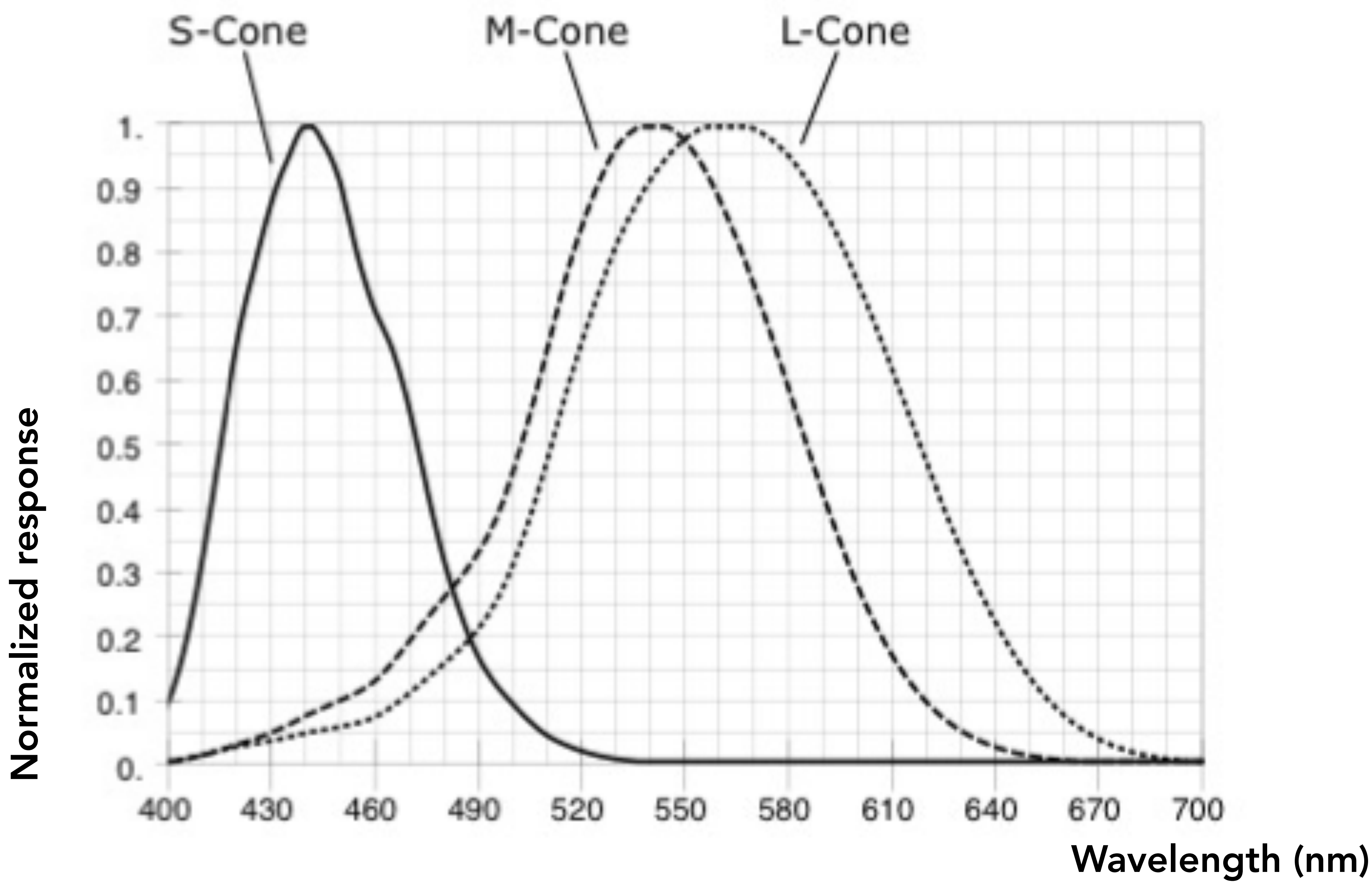
- ~6-7 million cones in eye
- Three types of cones, each with different spectral sensitivity
- Provide sensation of **color**



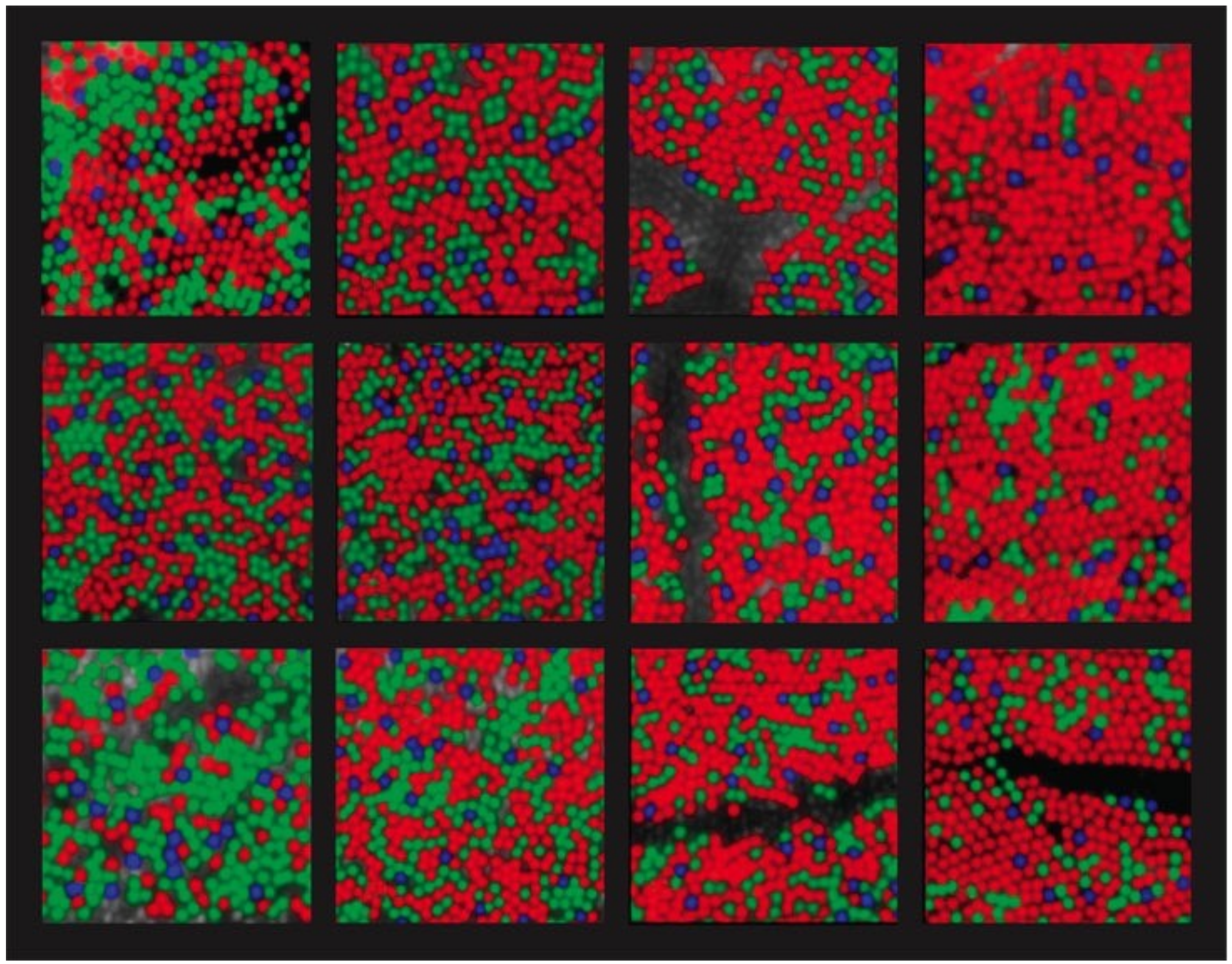
http://ebooks.bfwpub.com/life.php Figure 45.18

Spectral Response of Human Cone Cells

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



Fraction of Three Cone Cell Types Varies Widely



Hofer, H. et al. J. Neurosci. 2005;25:9669-9679

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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)

Tristimulus Theory of Color

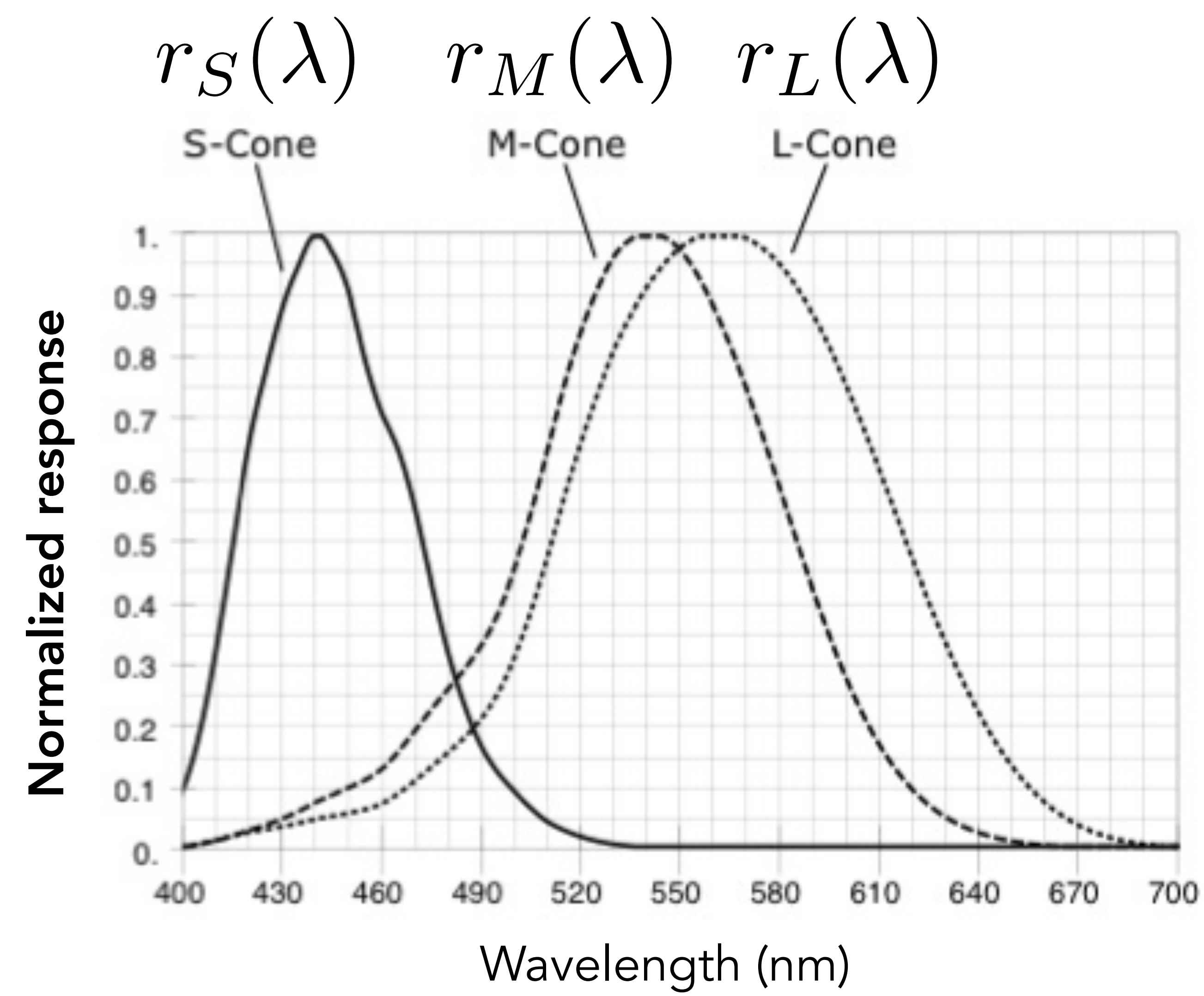
Spectral Response of Human Cone Cells

Now we have three detectors (S, M, L cone cells), each with a different spectral response curve

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

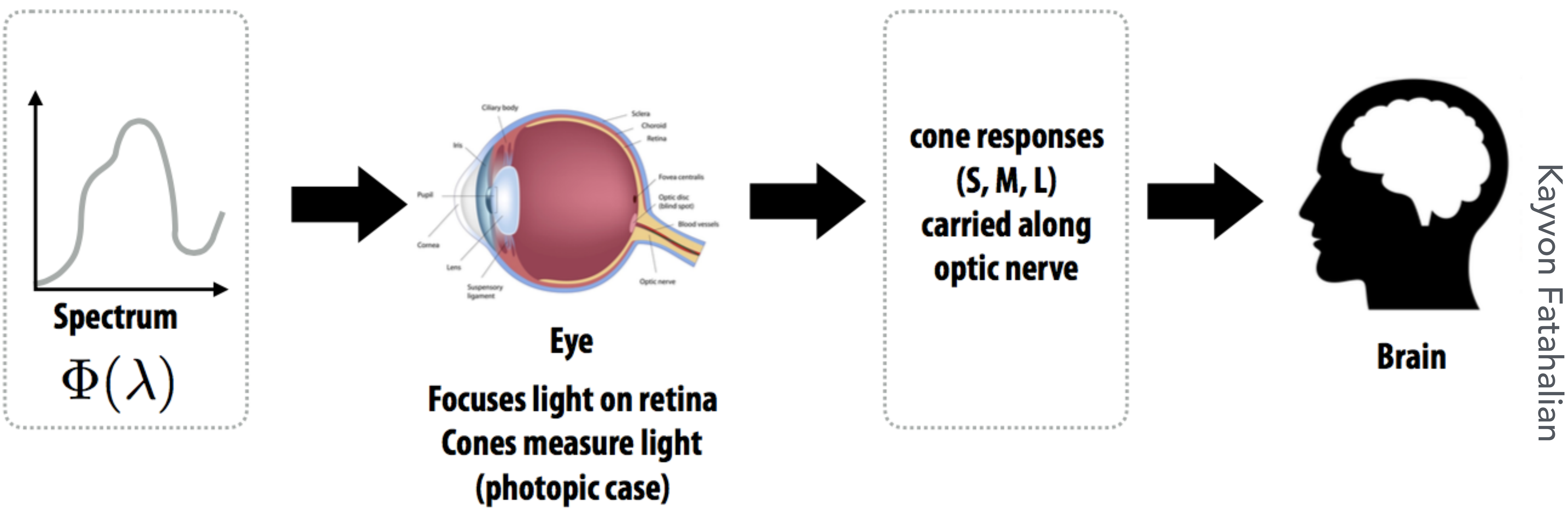
$$M = \int r_M(\lambda) s(\lambda)\, d\lambda$$

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



The Human Visual System

- Human eye does not measure and
  brain does not receive information about each wavelength of light
- Rather, **the eye "sees" only three response values (S, M, L)**, and this is only info available to brain



Metamerism

(同色异谱)

Metamers

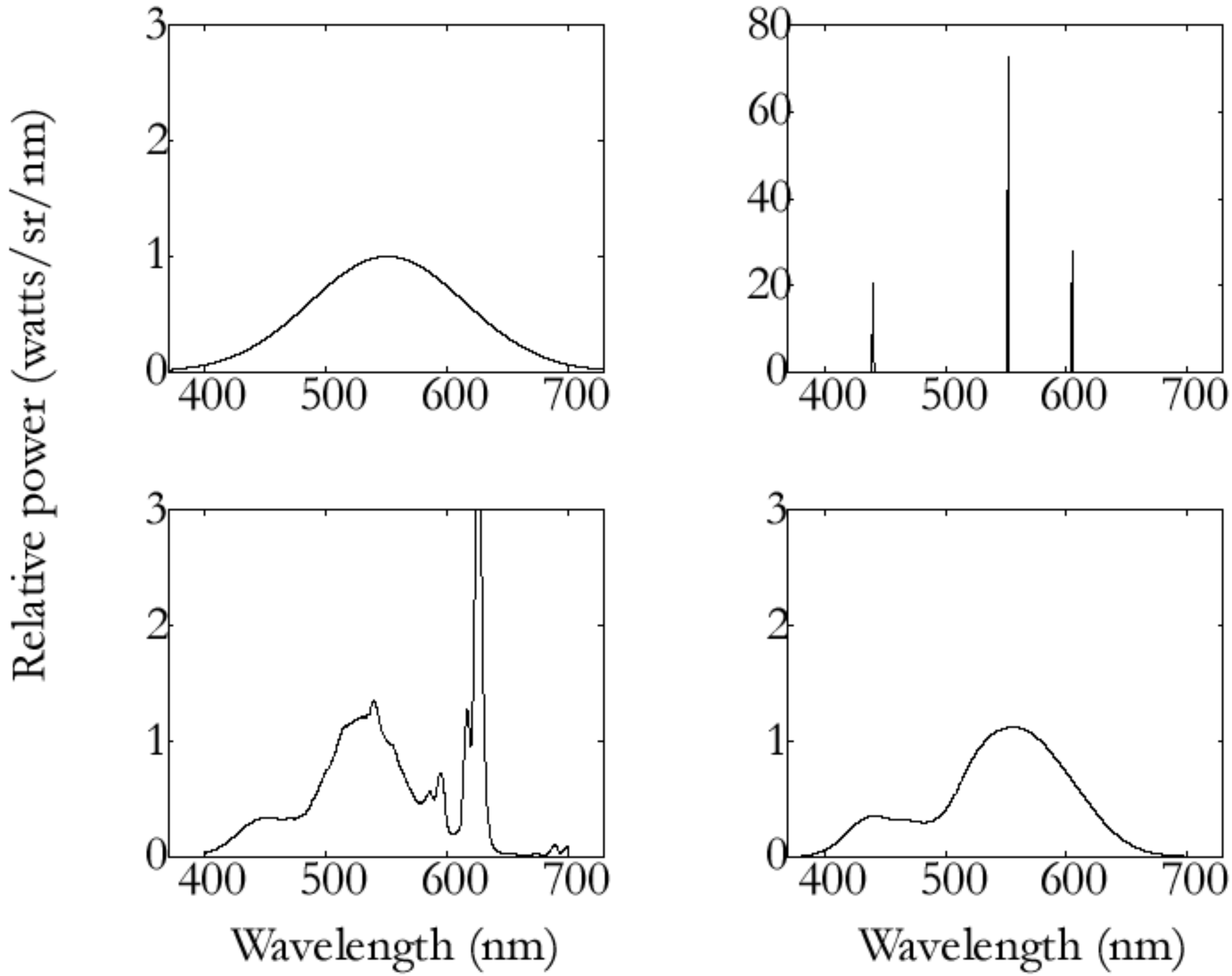
Metamers are two different spectra (∞-dim) that project to the same (S,M,L) (3-dim) response.

- 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

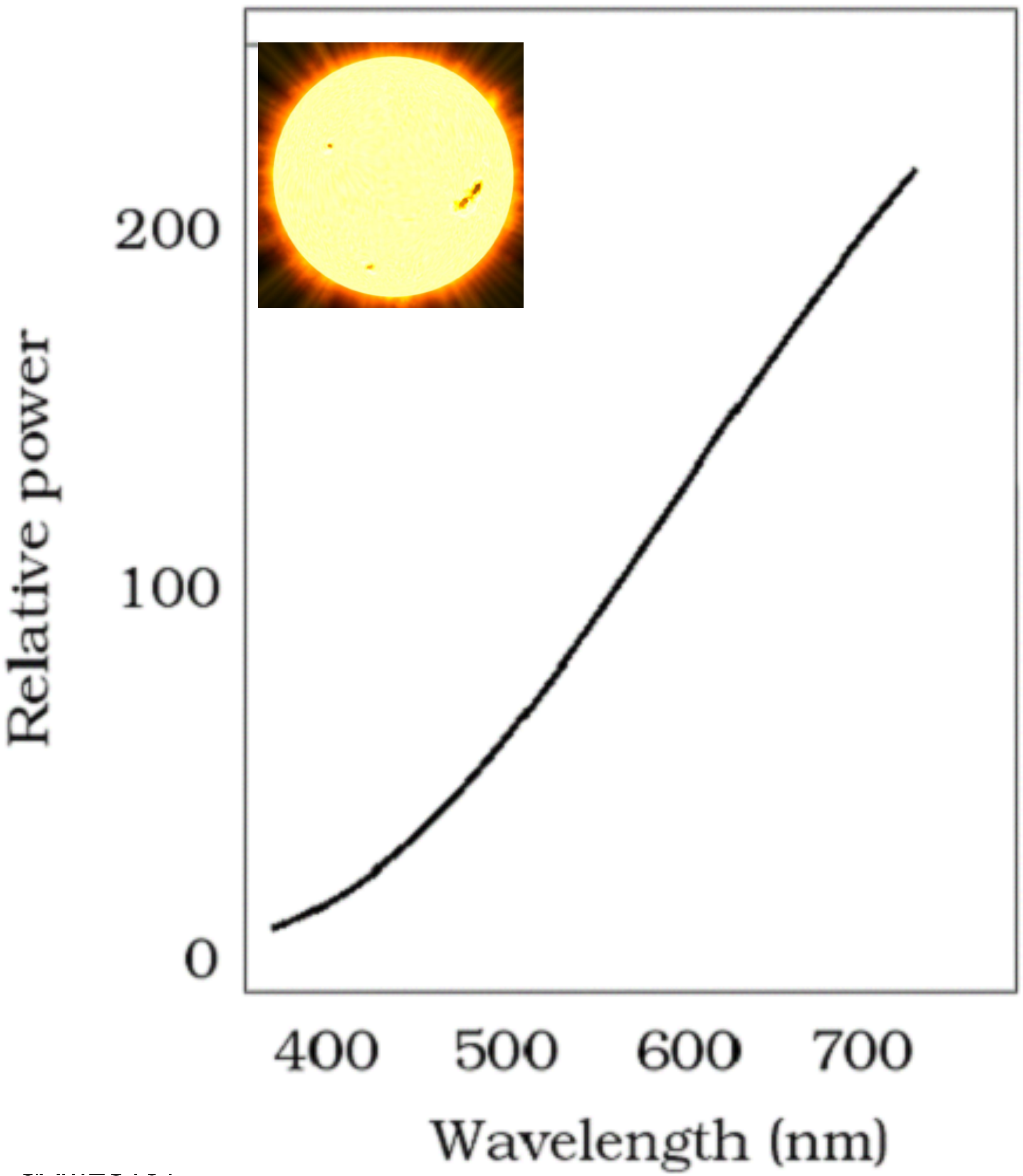
Metamerism is a Big Effect

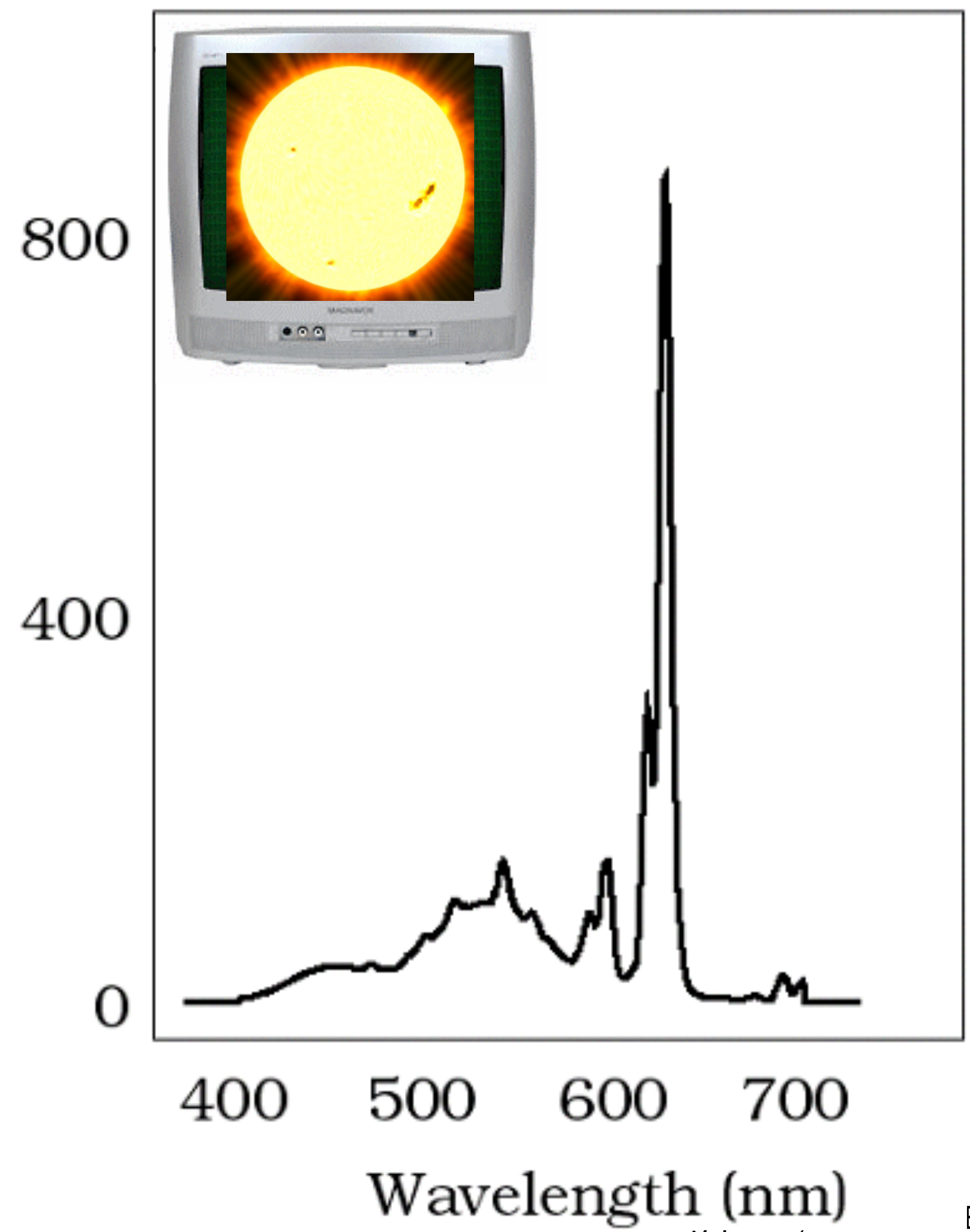


Brian Wandell

Metamerism

The theory behind color matching





Brian Wandell

Barbara

Color Reproduction / Matching

Additive Color

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

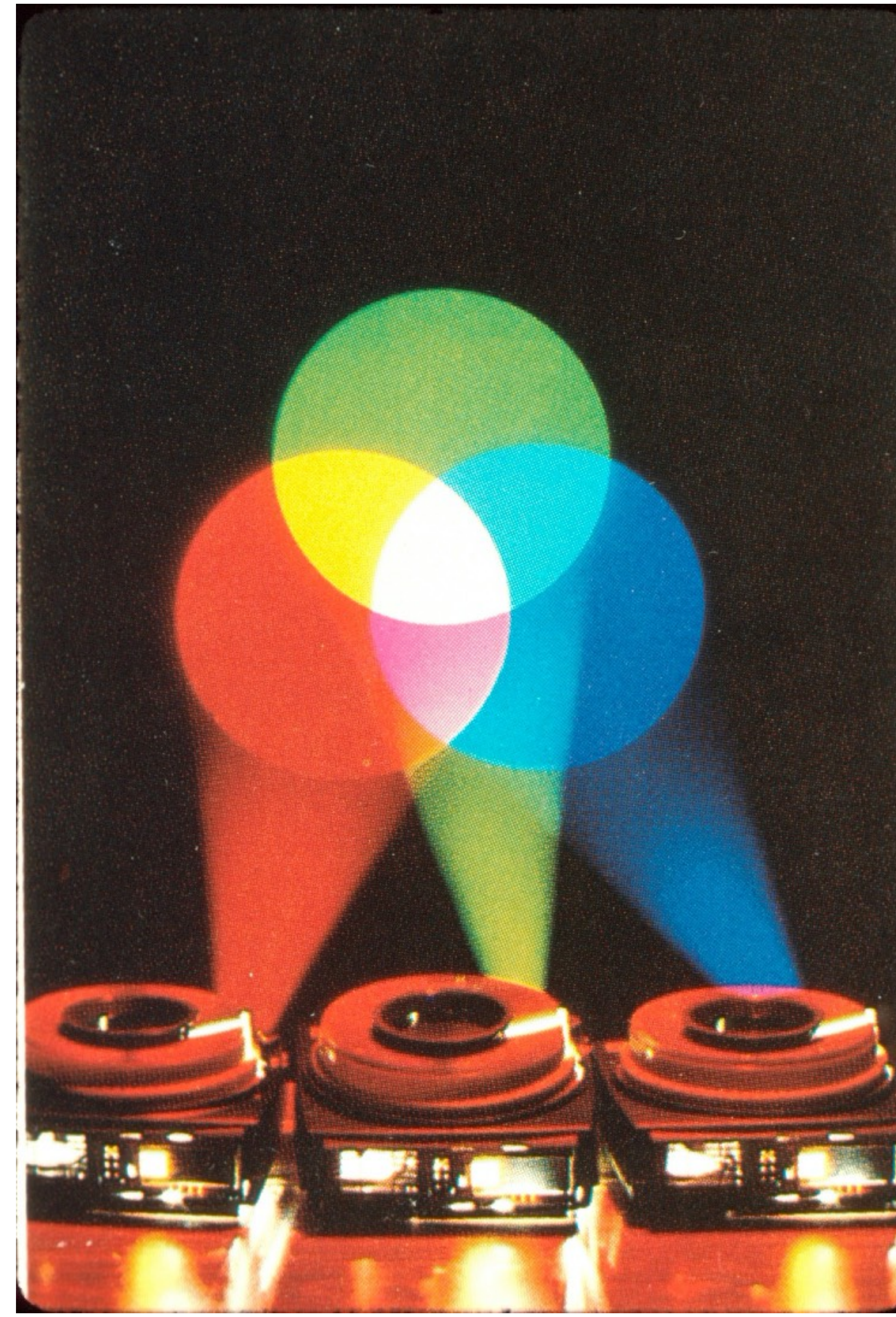
$$s_R(\lambda),\ s_G(\lambda),\ s_B(\lambda)$$

- Adjust the brightness of these lights and add them together:

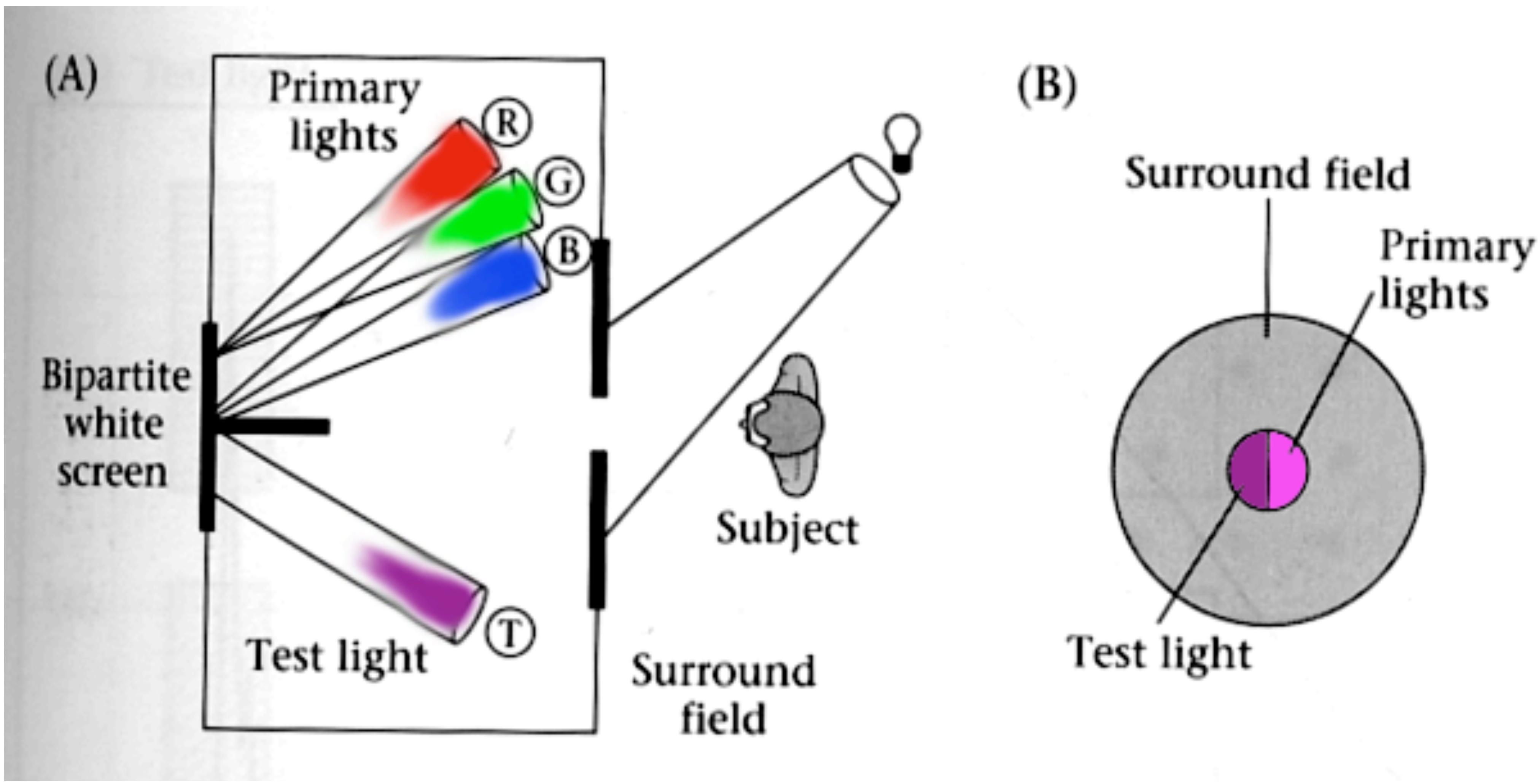
$$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

- The color is now described by the scalar values:

$$R,\ G,\ B$$

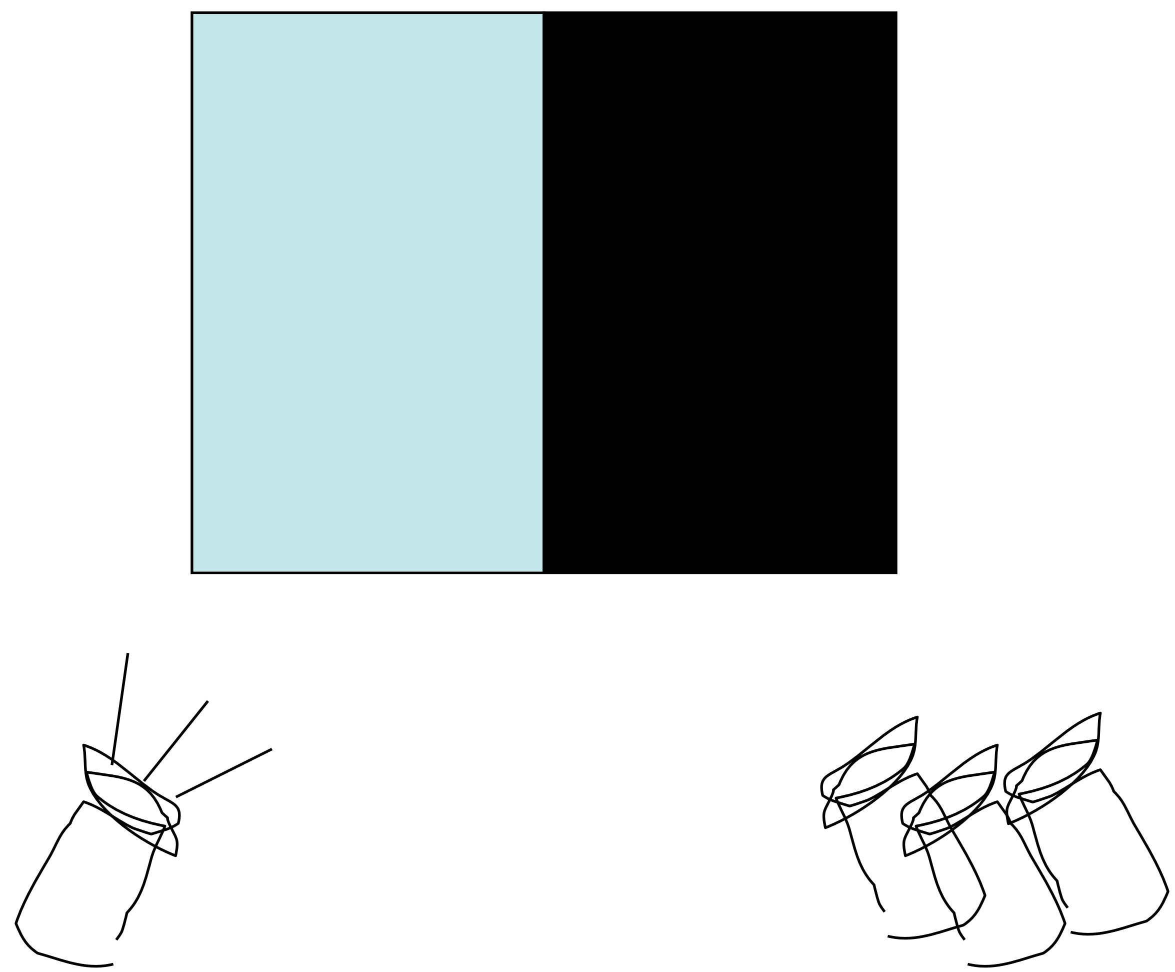


Additive Color Matching Experiment



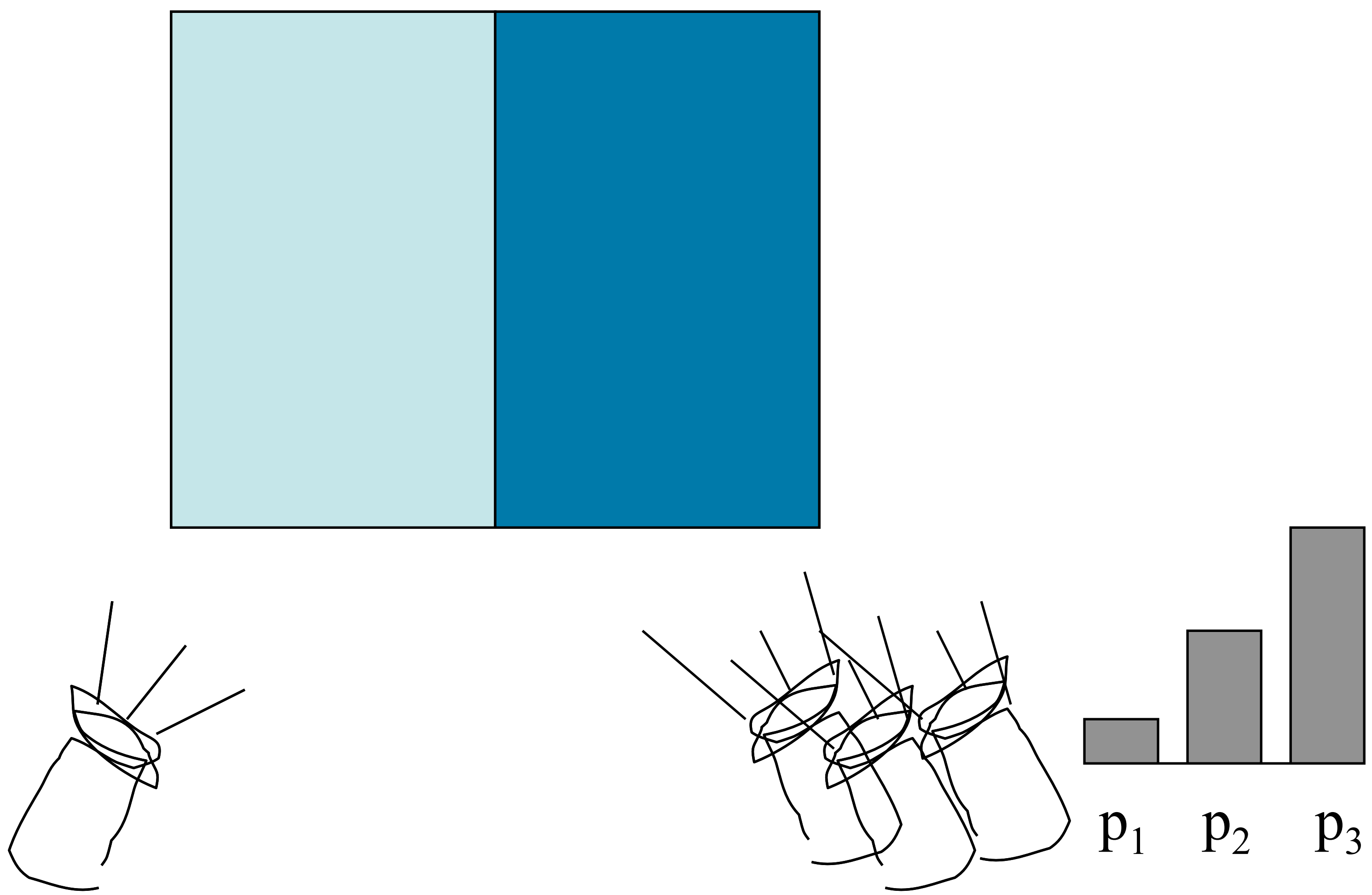
Slide courtesy of Prof. Ren Ng, UC Berkeley

Example Experiment



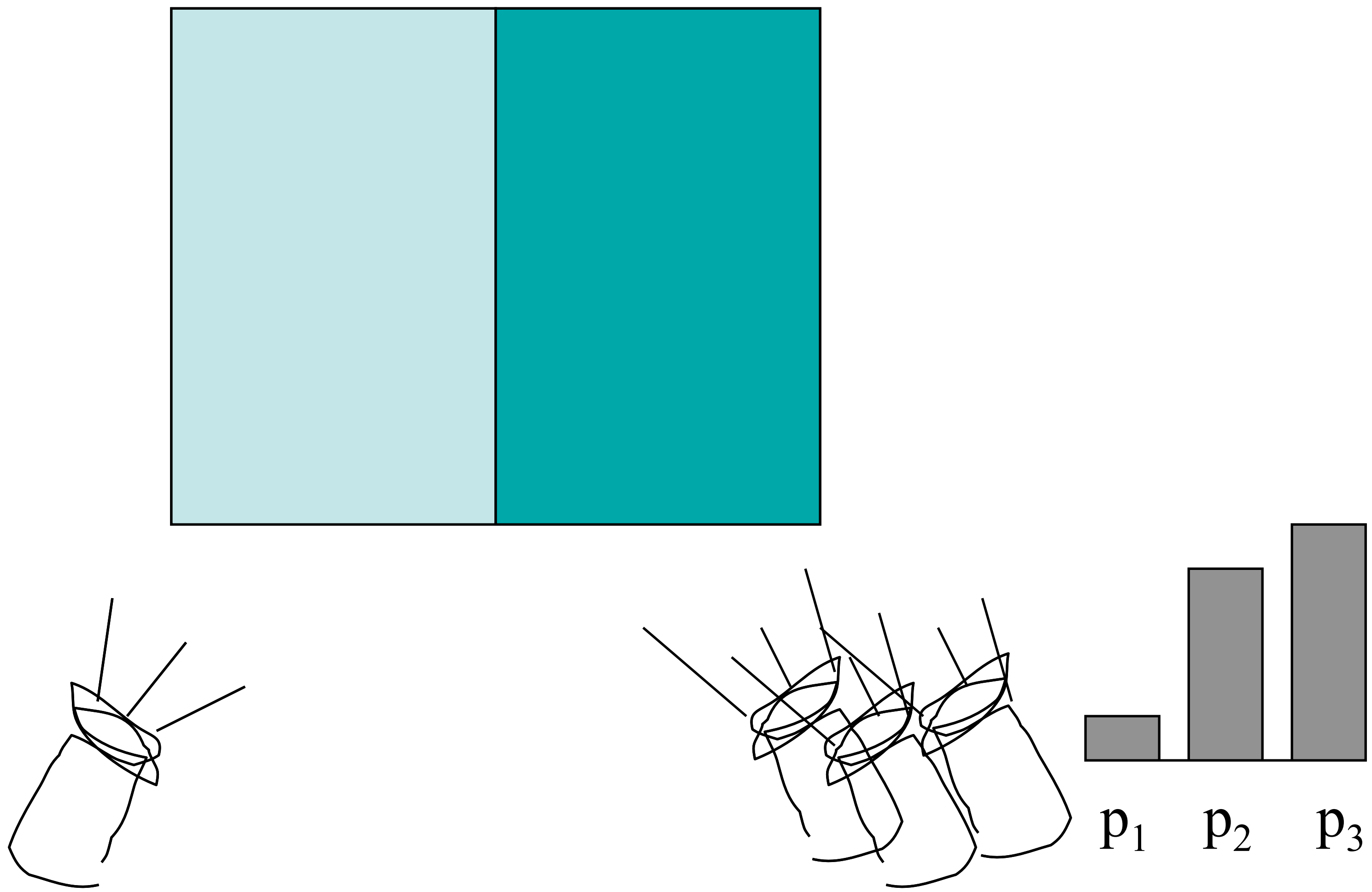
Slide from Durand
and Freeman 06

Example Experiment



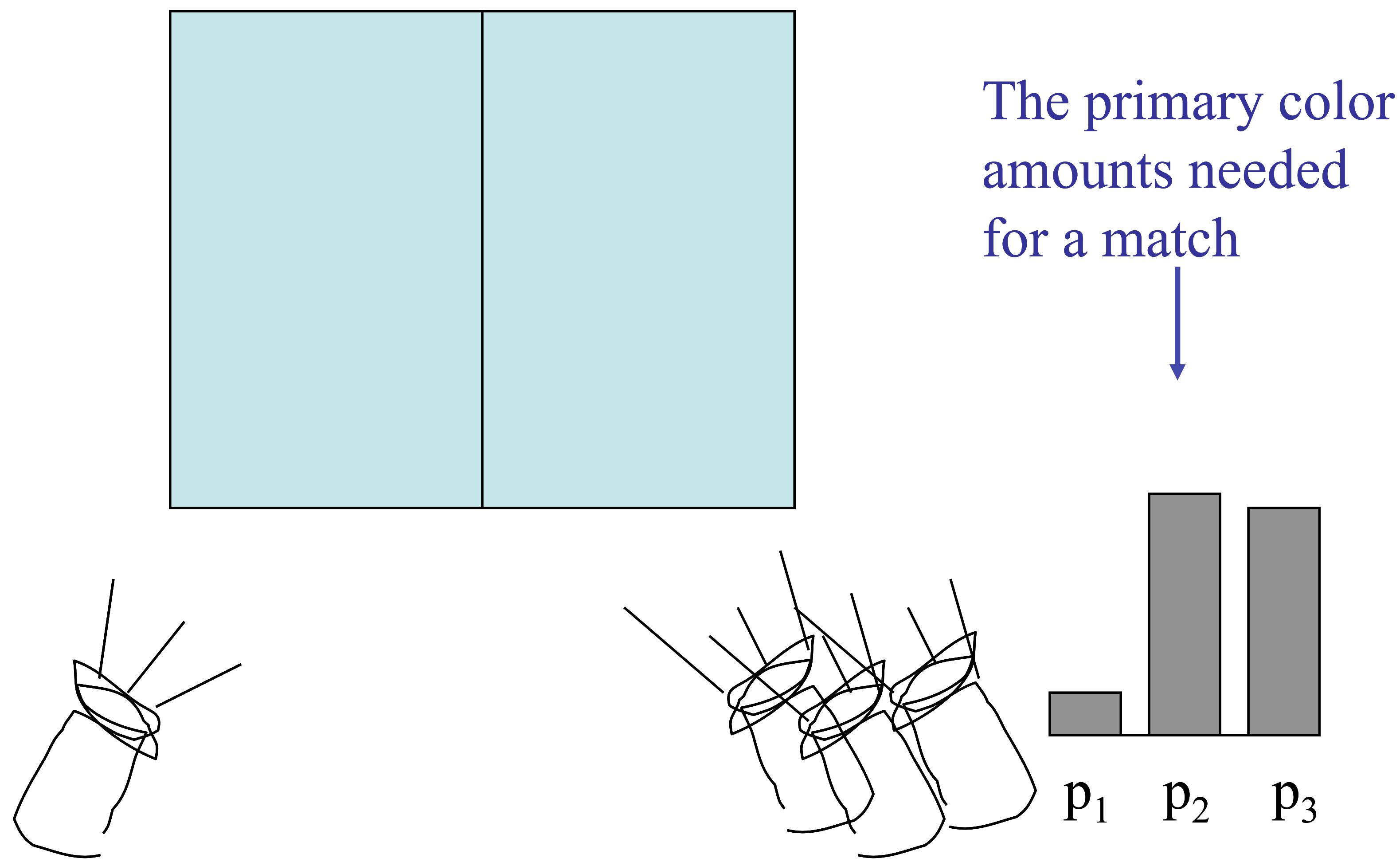
Slide from Durand and Freeman 06

Example Experiment



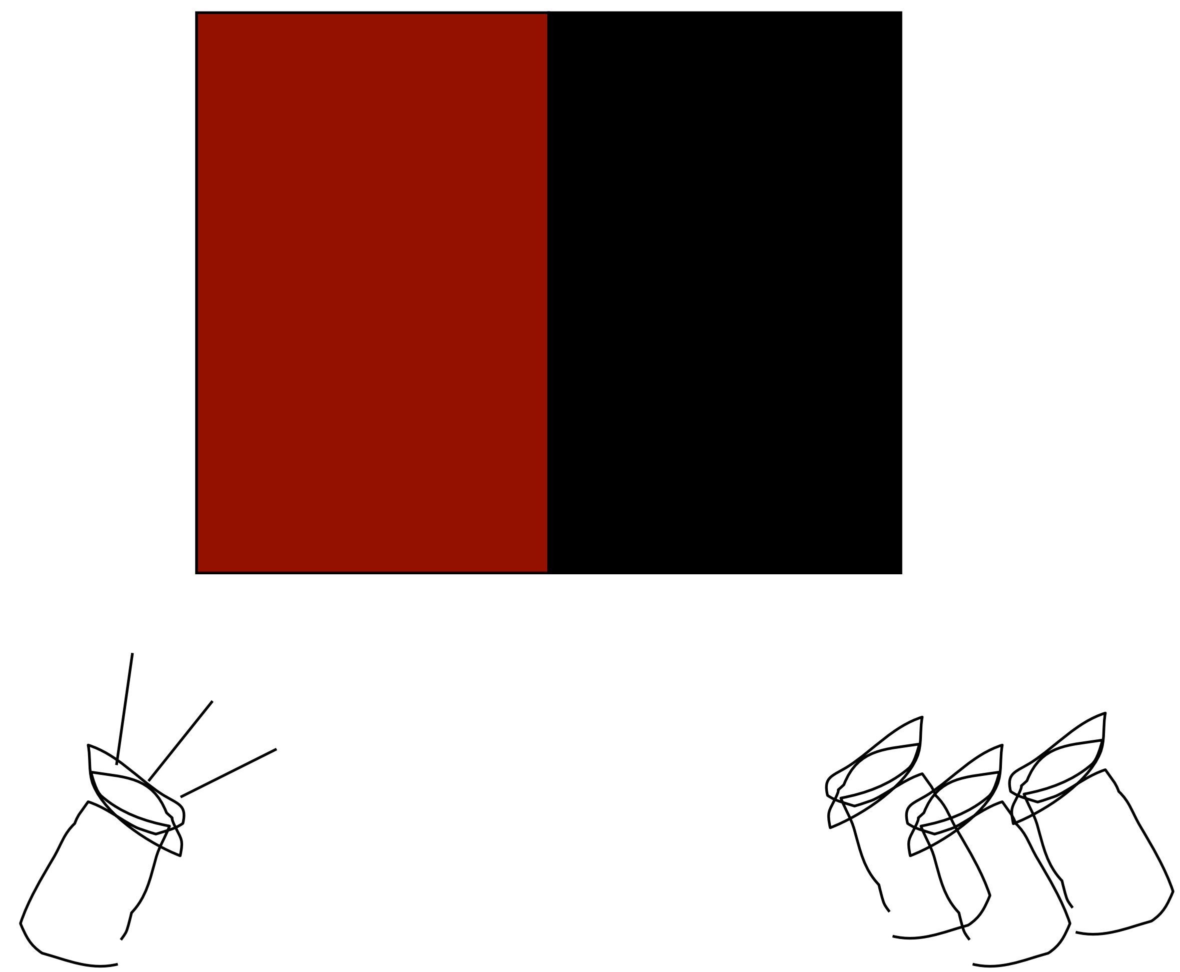
Slide from Durand and Freeman 06

Example Experiment



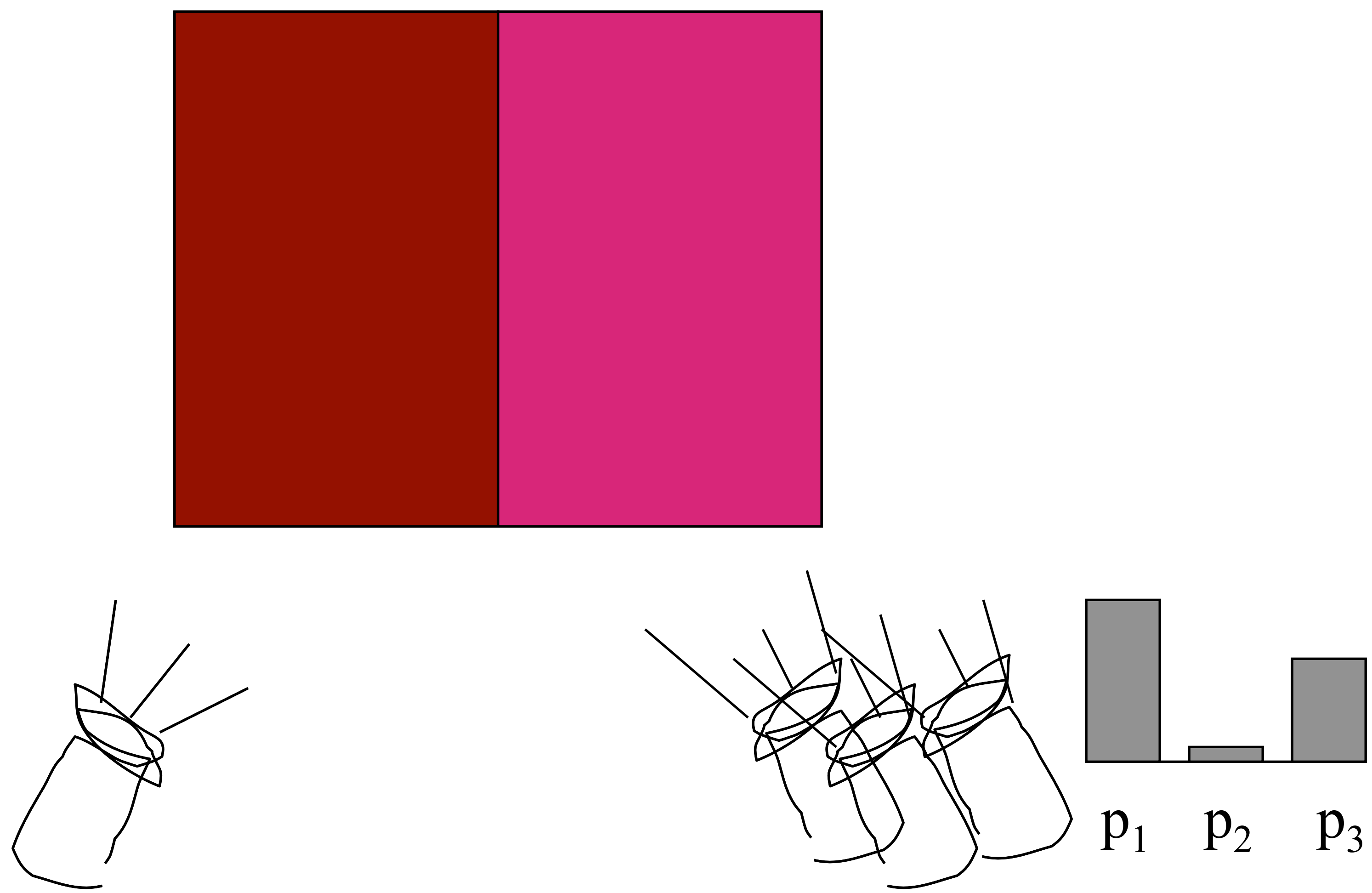
Slide from Durand and Freeman 06

Experiment 2



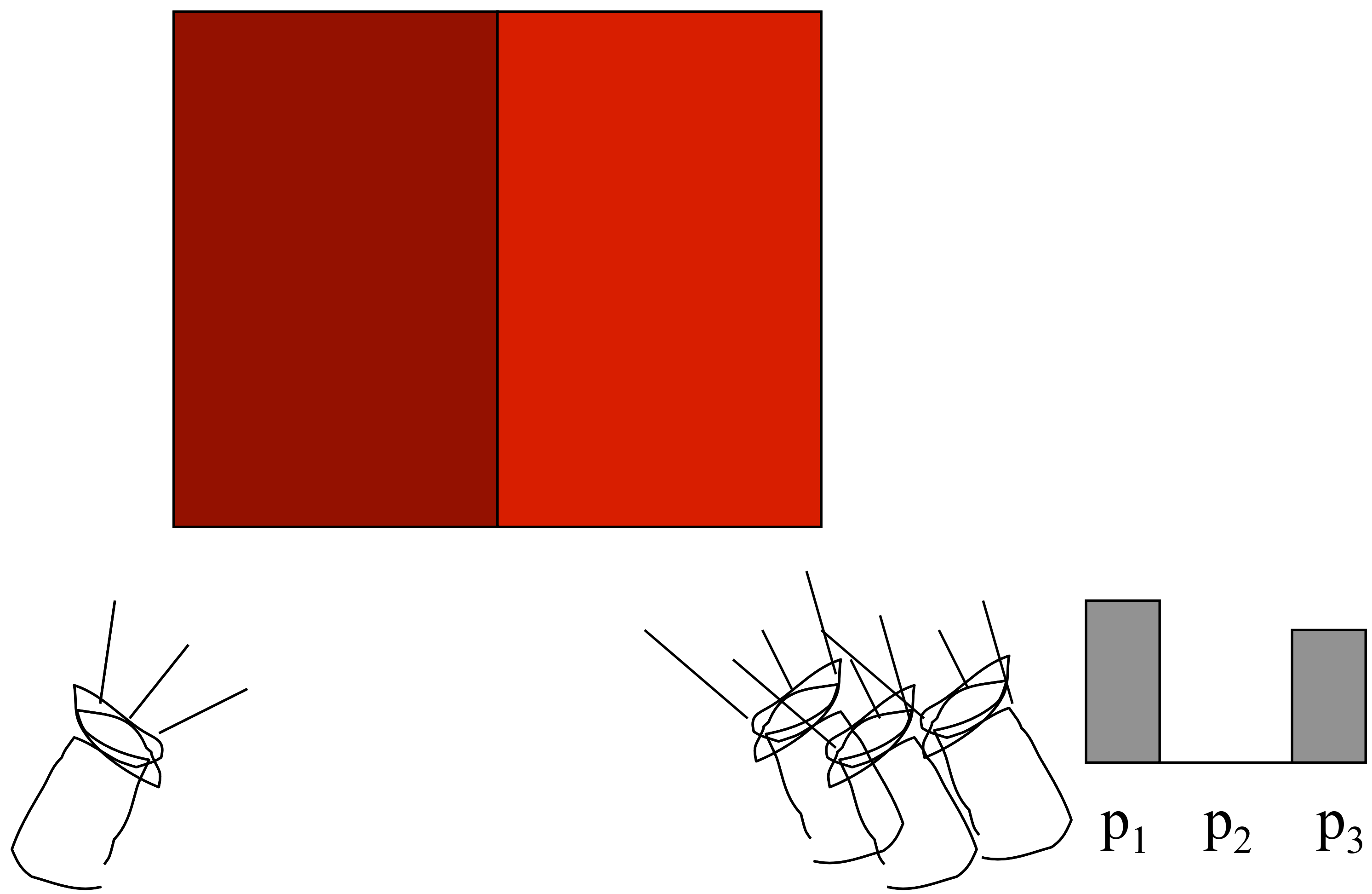
Slide from Durand and Freeman 06

Experiment 2



Slide from Durand and Freeman 06

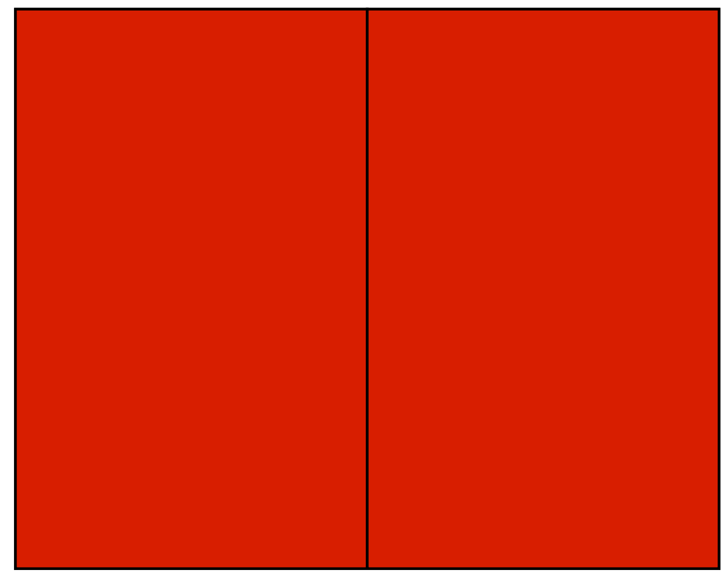
Experiment 2



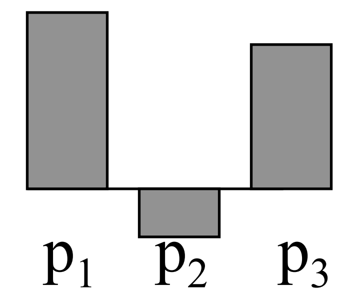
Slide from Durand and Freeman 06

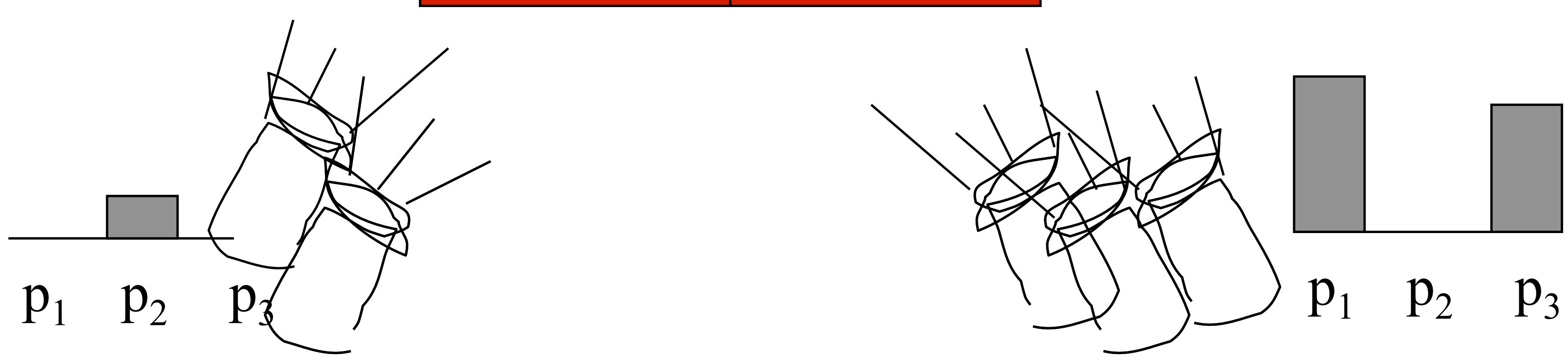
Experiment 2

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:

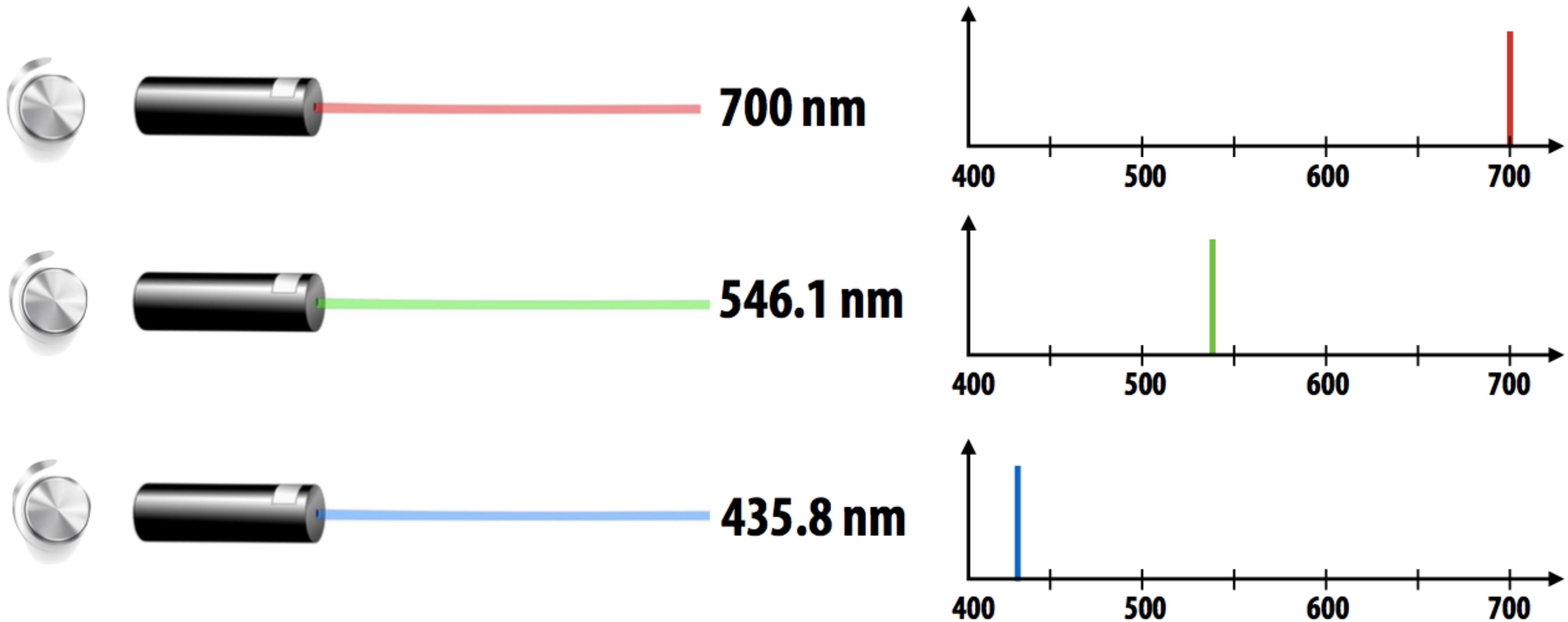




Slide from Durand and Freeman 06

CIE RGB Color Matching Experiment

Same setup as additive color matching before,
but primaries are monochromatic light (single wavelength)



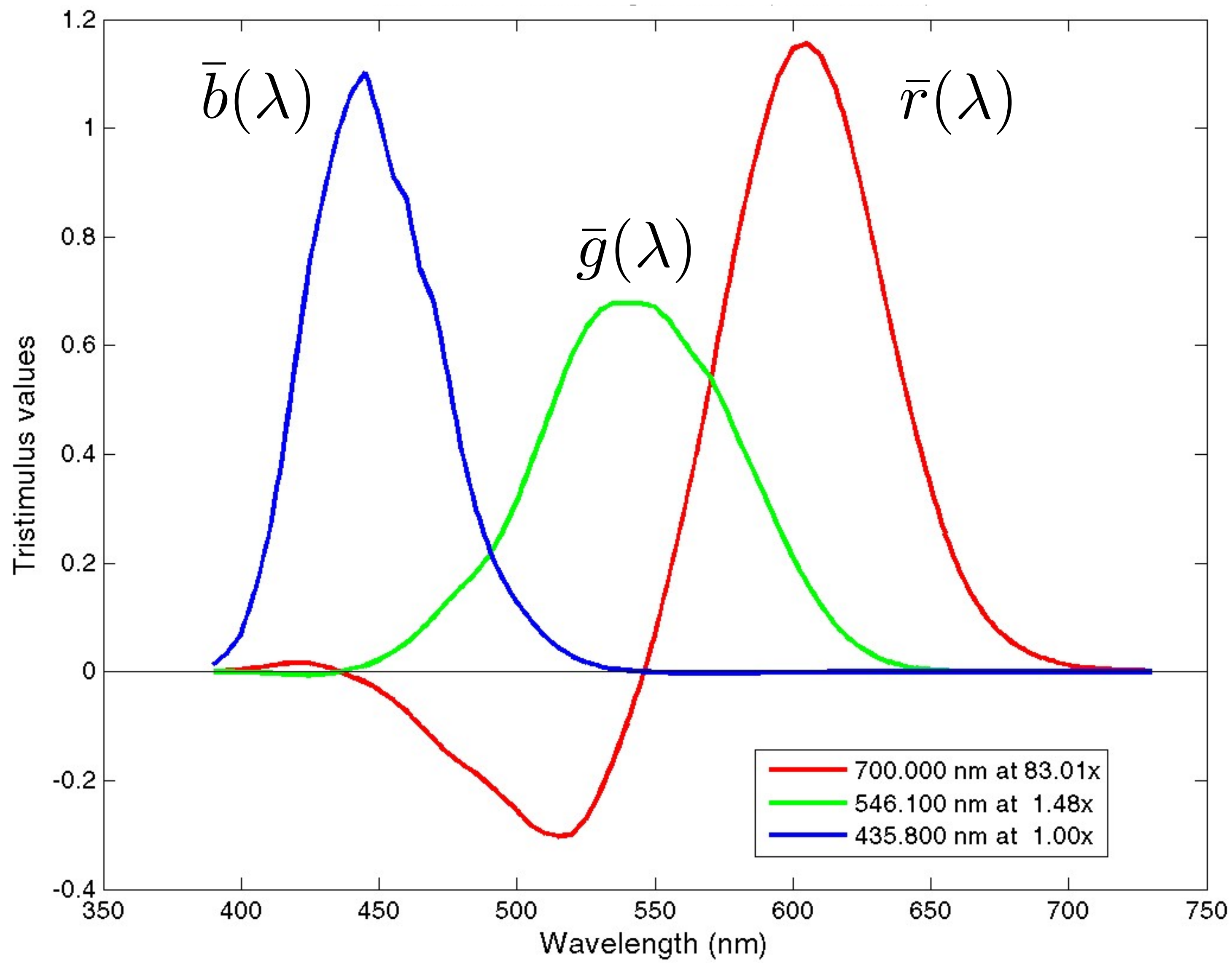
Kayvon Fatahalian

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 spectra!



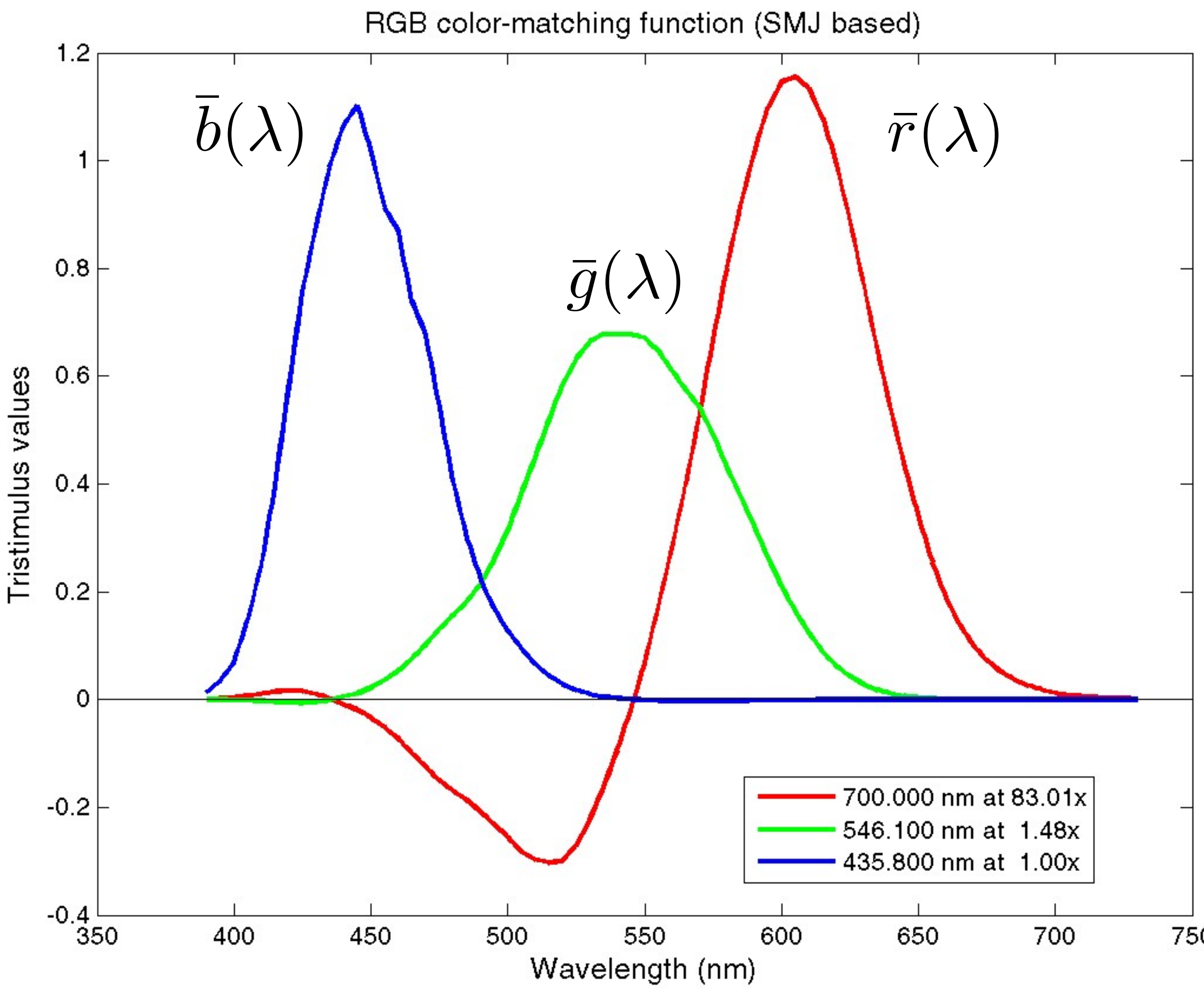
Color Reproduction with Matching Functions

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

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

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

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



Careful: these are not response curves or primary spectra!

Color Spaces

Standard Color Spaces

Standardized RGB (sRGB)

- makes a particular monitor RGB standard
- other color devices simulate that monitor by calibration
- widely adopted today
- gamut (?) is limited
  (色域)

A Universal Color Space: CIE XYZ

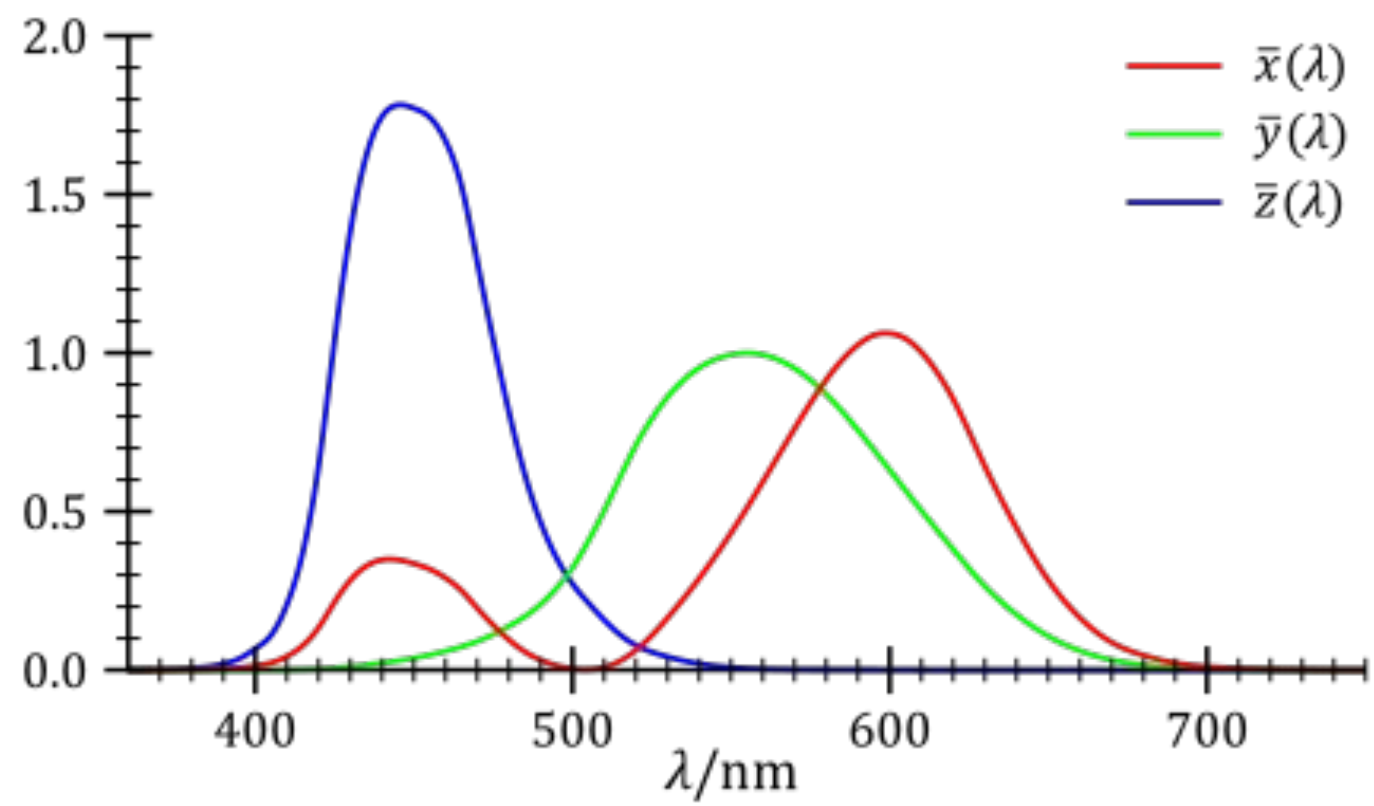
Imaginary set of standard color primaries X, Y, Z

- Primary colors with these matching functions do not exist
- Y is luminance (brightness regardless of color) (亮度)

Designed such that

- Matching functions are strictly positive
- Span all observable colors

CIE XYZ color matching functions

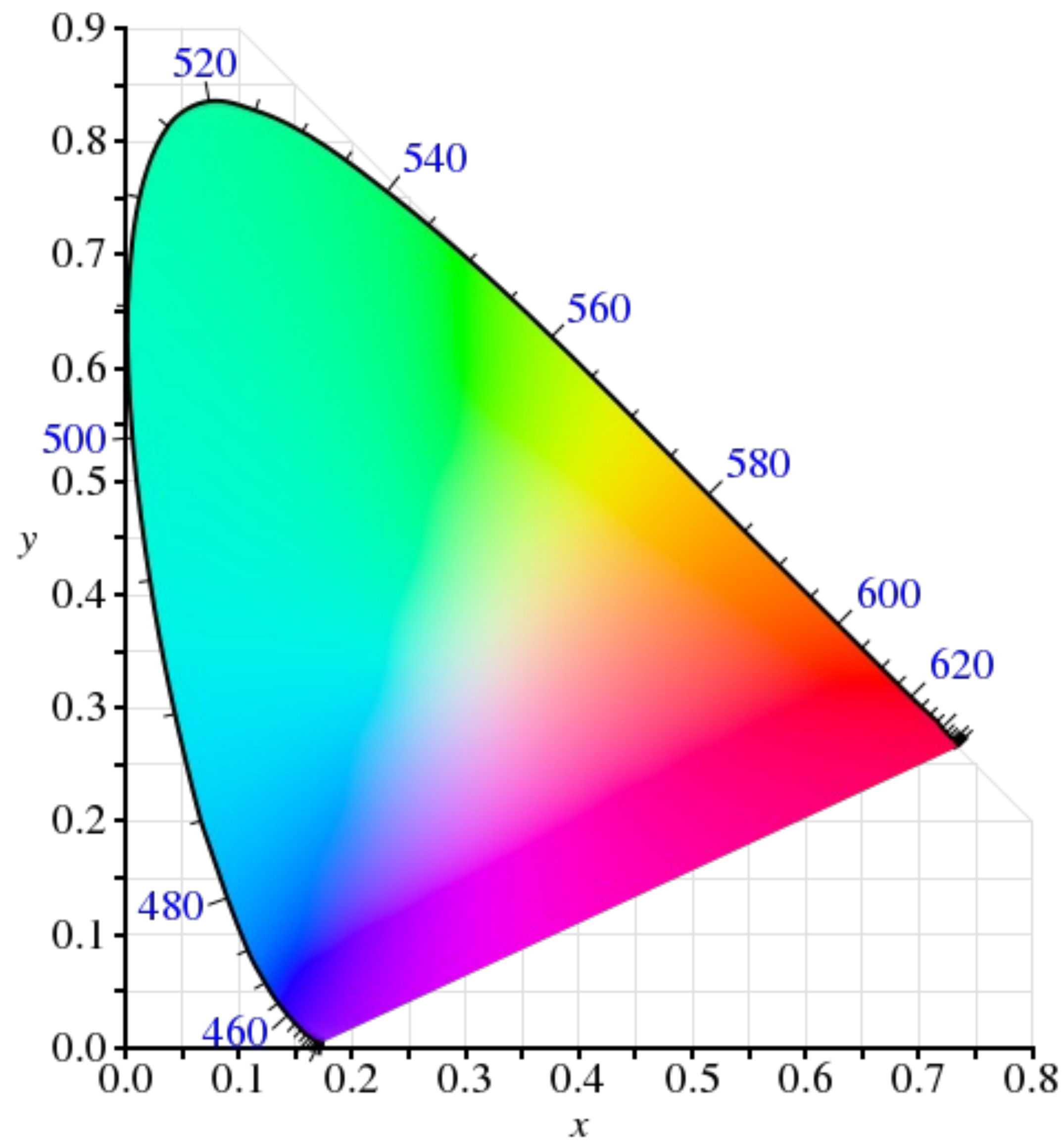


Separating Luminance, Chromaticity

Luminance: *Y*

Chromaticity: *x*, *y*, *z*, defined as
(色度)

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



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

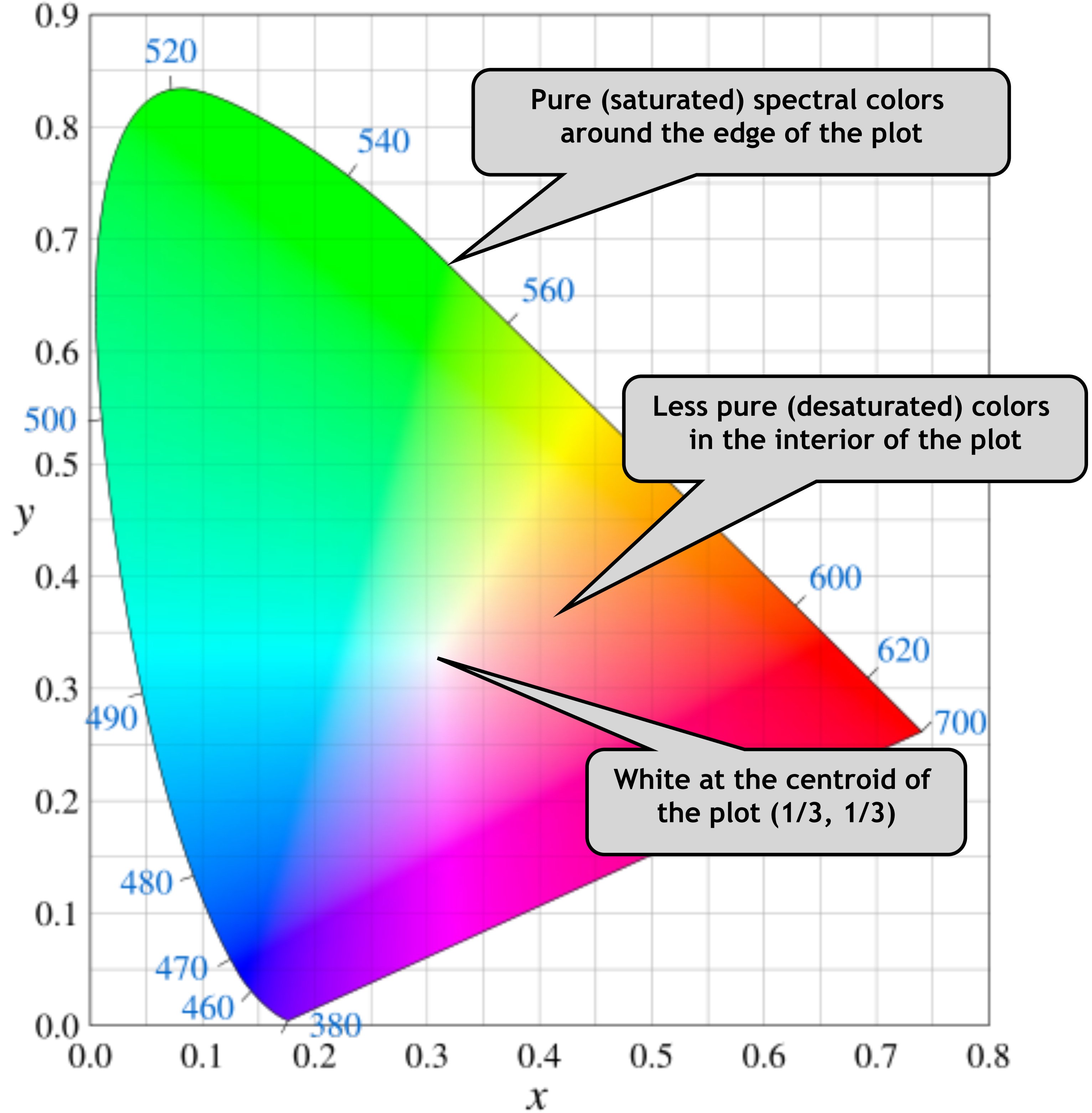
CIE Chromaticity Diagram

The curved boundary

- named spectral locus
- corresponds to monochromatic light (each point representing a pure color of a single wavelength)

Any color inside is less pure

- i.e. mixed



Gamut (色域)

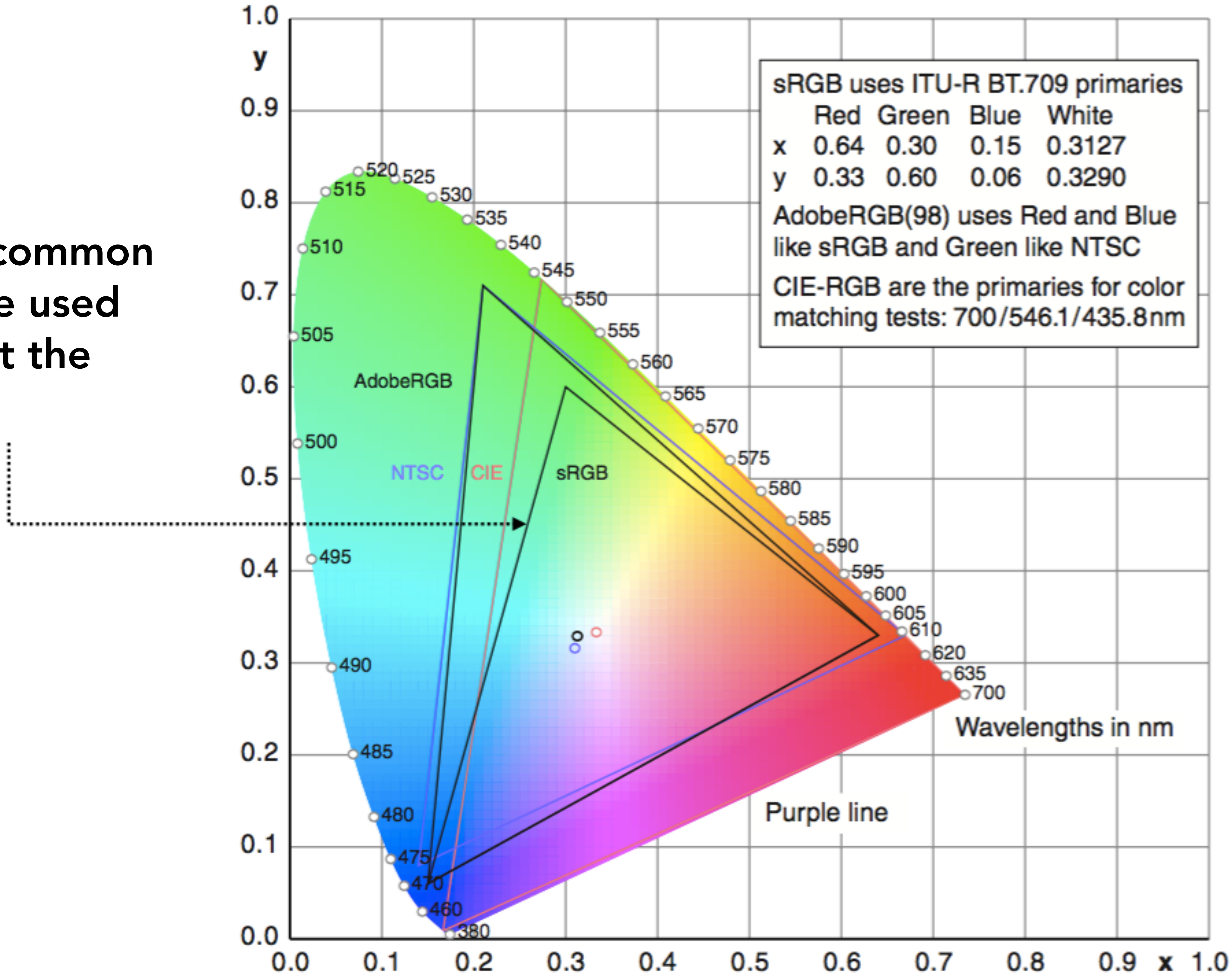
Gamut is the set of chromaticities generated by a set of color primaries

Different color spaces represent different ranges of colors

So they have different gamuts, i.e.
they cover different regions on the chromaticity diagram

Gamut

sRGB is a common color space used throughout the internet

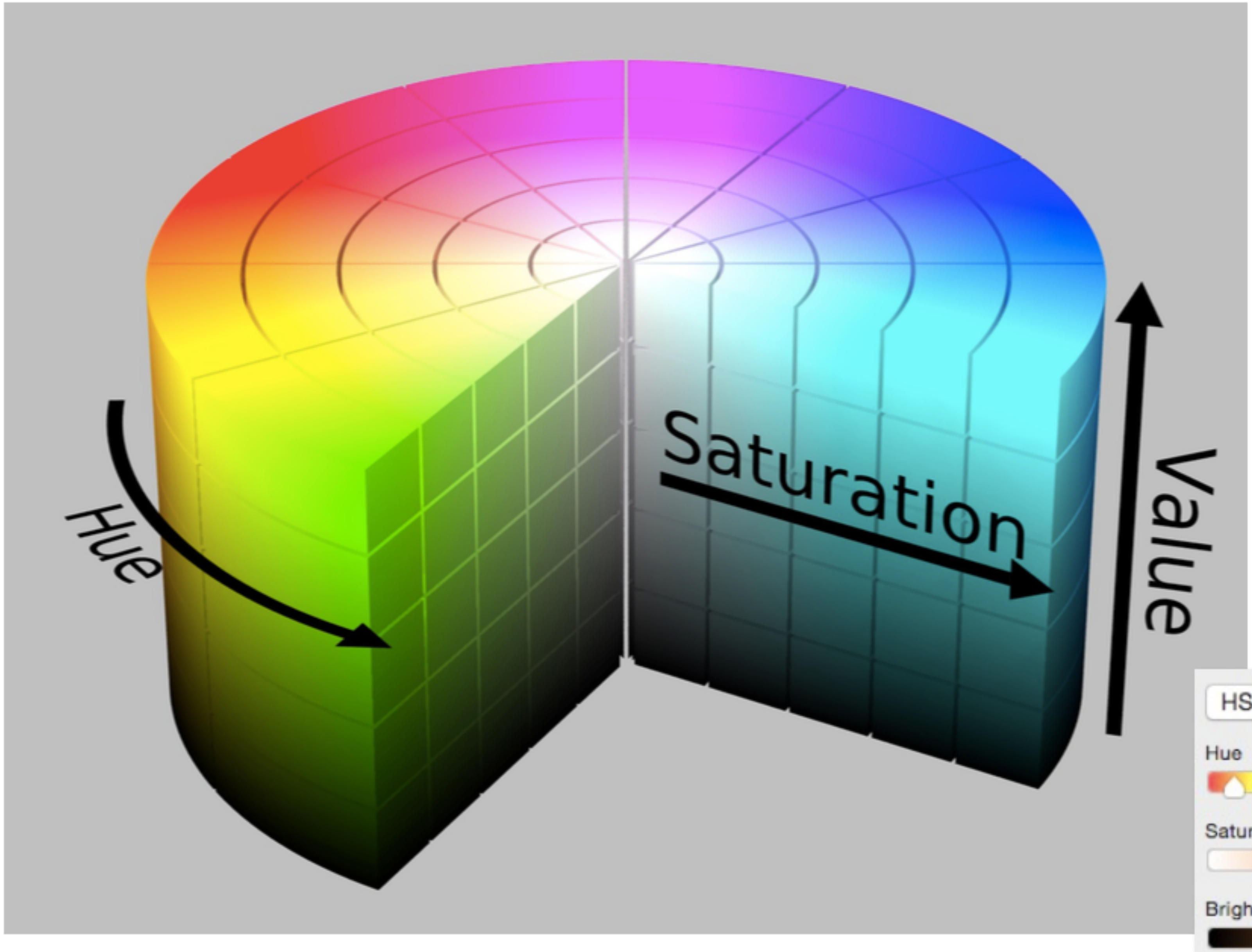


Perceptually Organized Color Spaces

HSV Color Space (Hue-Saturation-Value)

Axes correspond to artistic characteristics of color

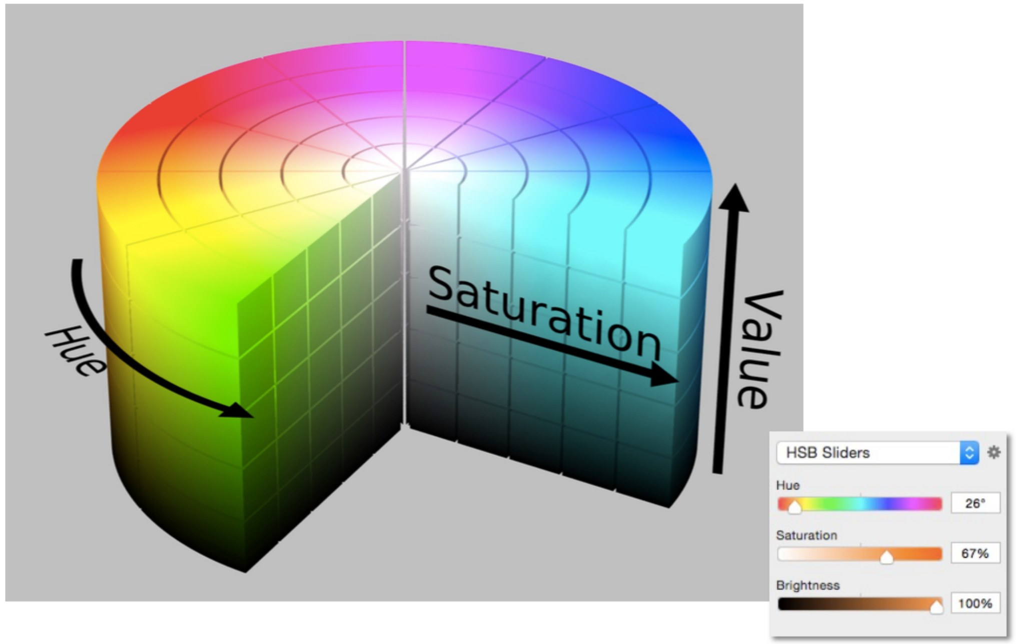
Widely used in a "color picker"



Perceptual Dimensions of Color

Hue (色调)

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



Saturation (饱和度)

- the “colorfulness”
- colorimetric correlate: purity
- artist’s correlate: fraction of paint from the colored tube

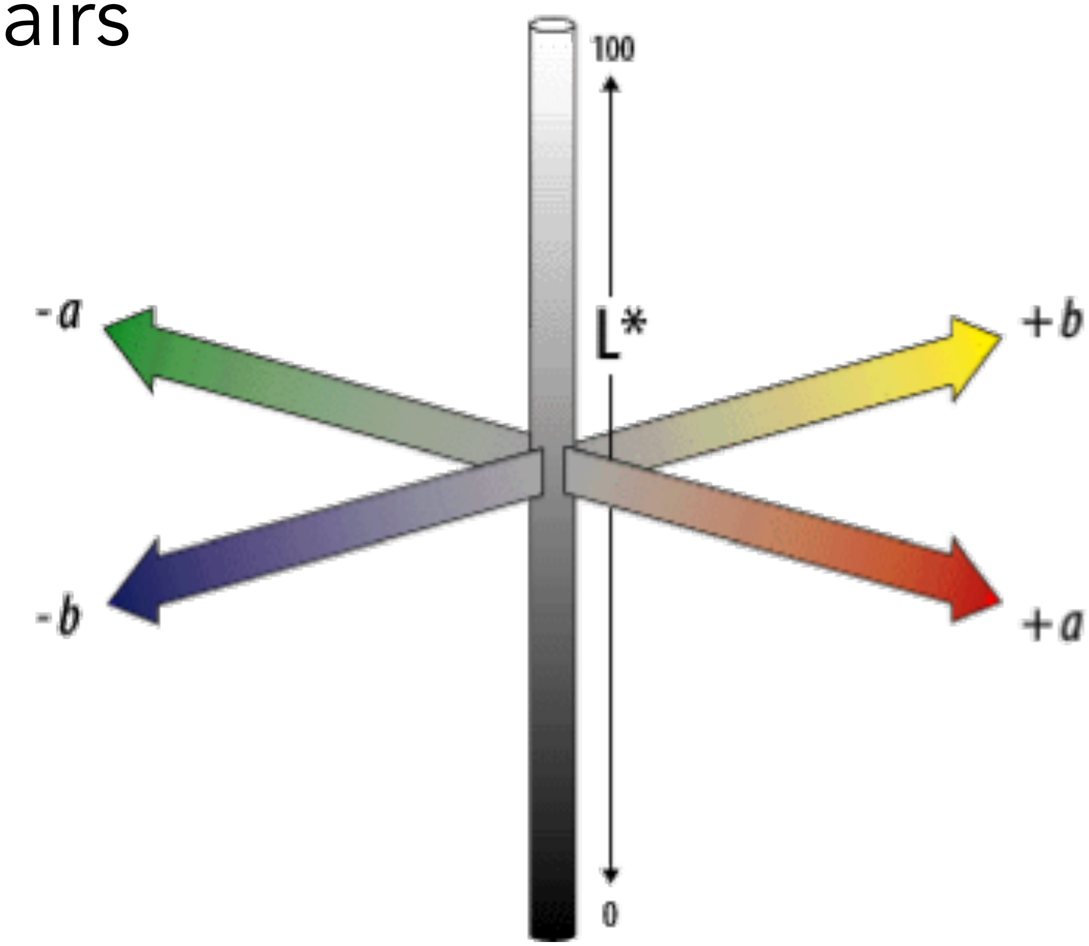
Lightness (or value) (亮度)

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

CIELAB Space (AKA L*a*b*)

A commonly used color space that strives for perceptual uniformity

- L* is lightness (brightness)
- a* and b* are color-opponent pairs
  - a* is red-green
  - b* is blue-yellow



Opponent Color Theory

(互补色)

There's a good neurological basis for the color space dimensions in CIE LAB

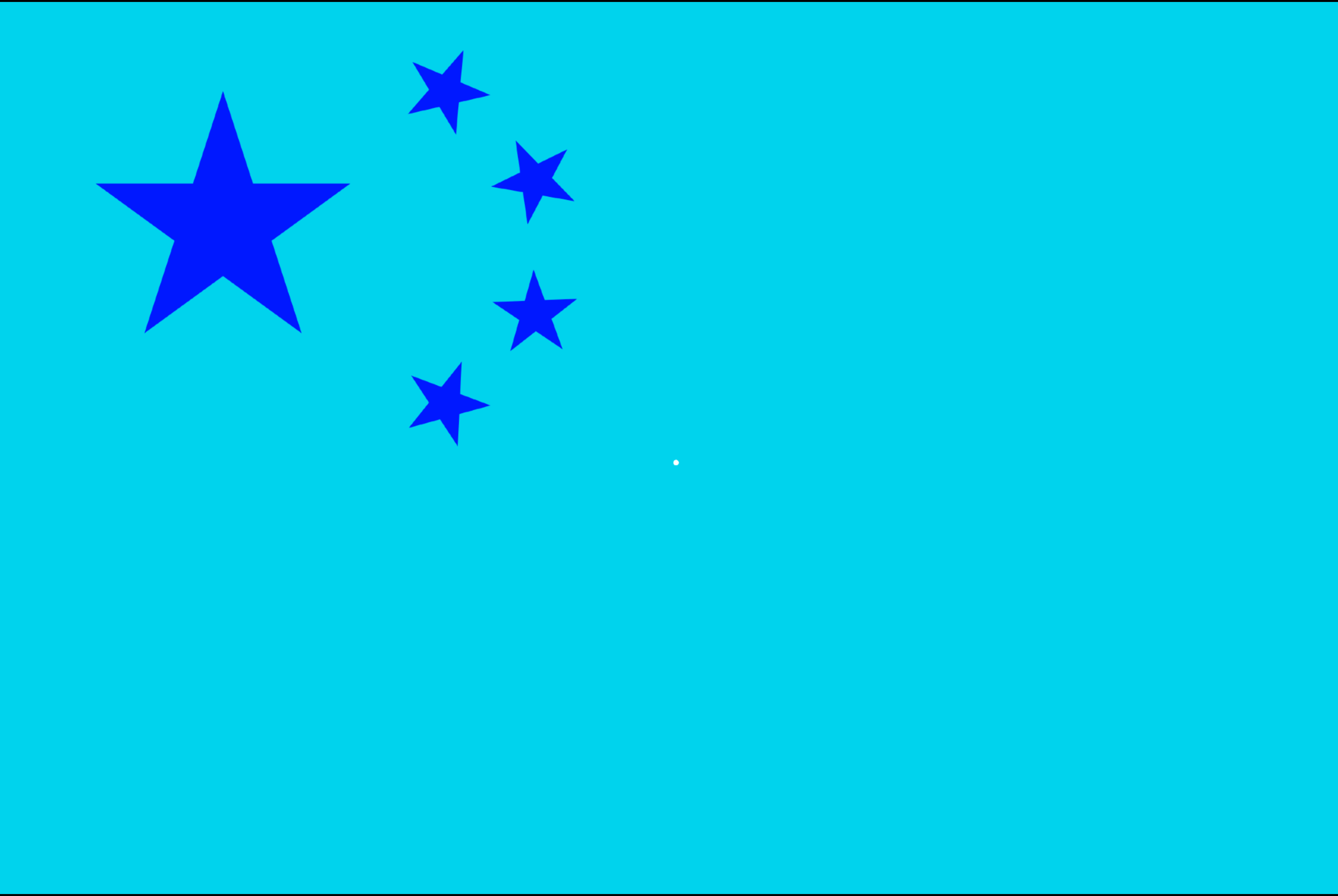
- the brain seems to encode color early on using three axes:
  - white — black,   red — green,   yellow — blue
- the white — black axis is lightness; the others determine hue and saturation

slide credit: Steve Marschner

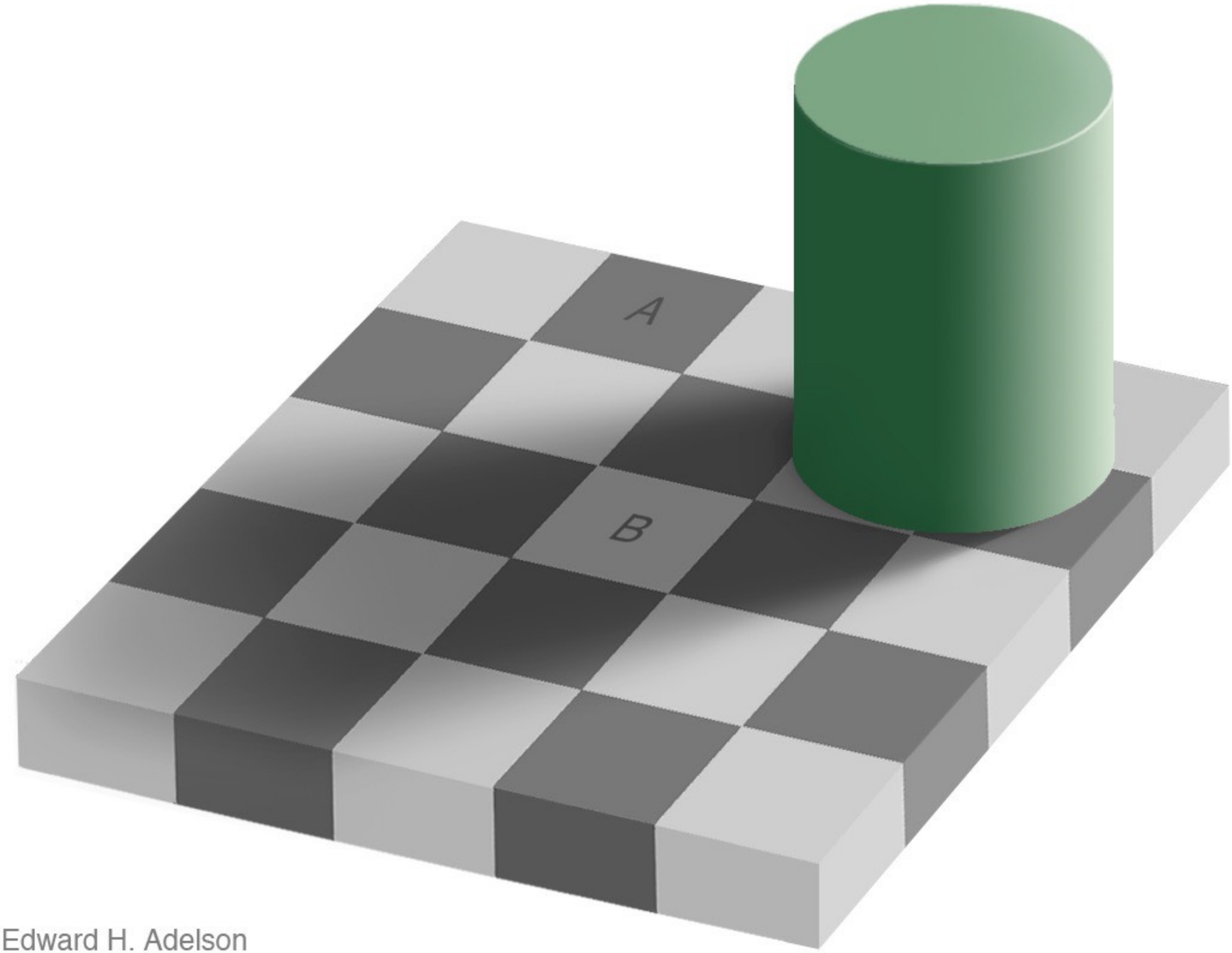
Opponent Color Theory

- 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

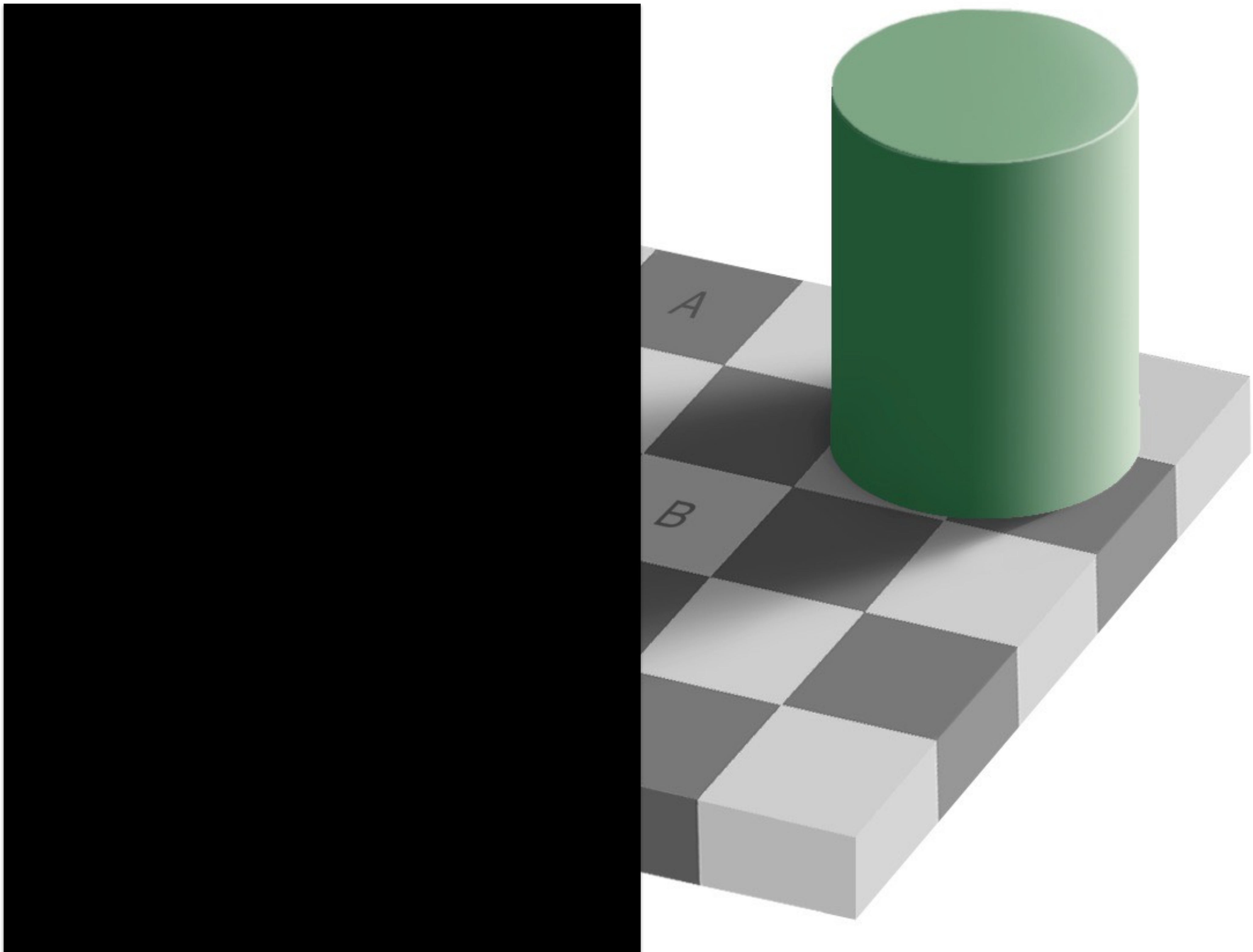


Everything is Relative

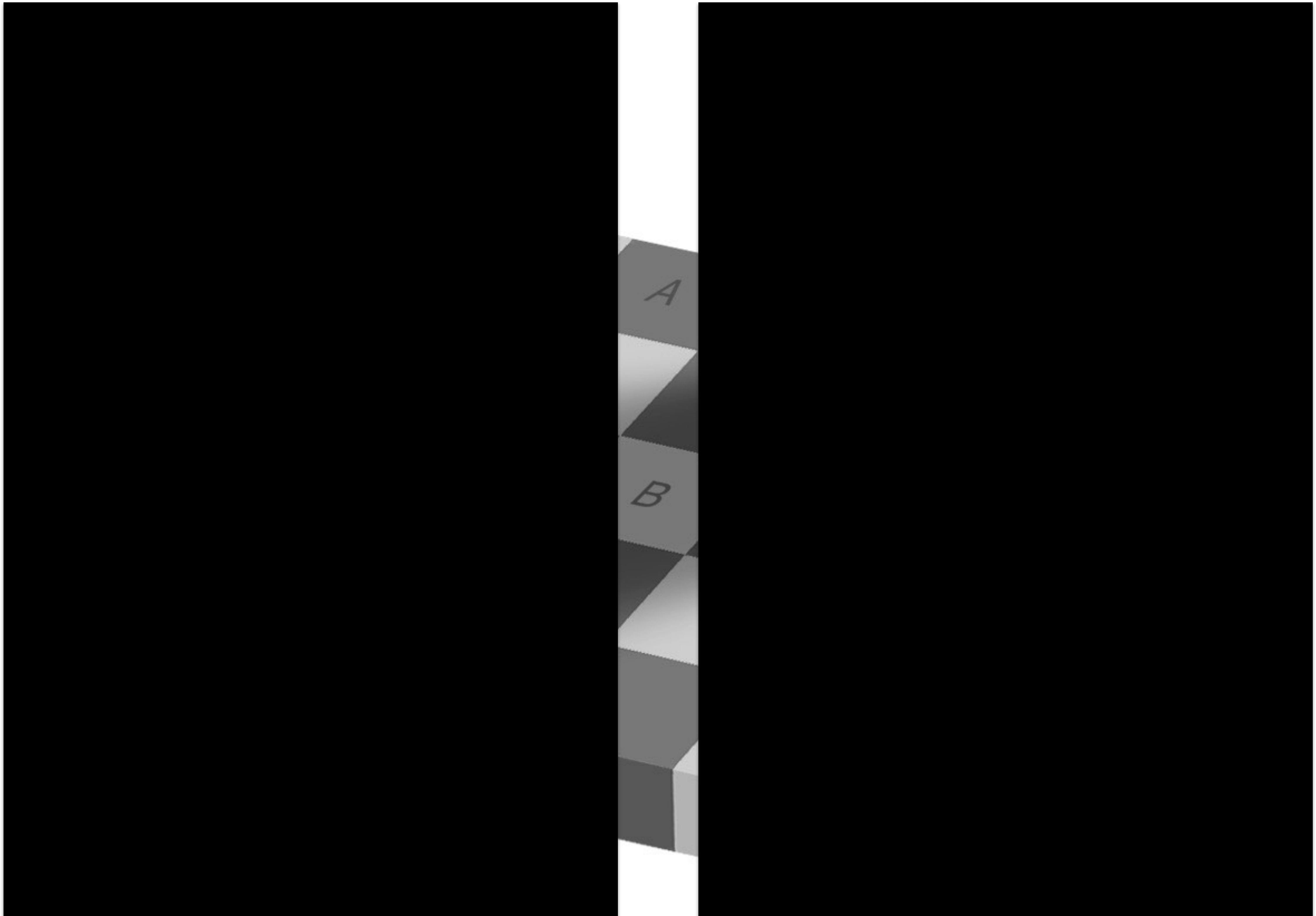


Edward H. Adelson

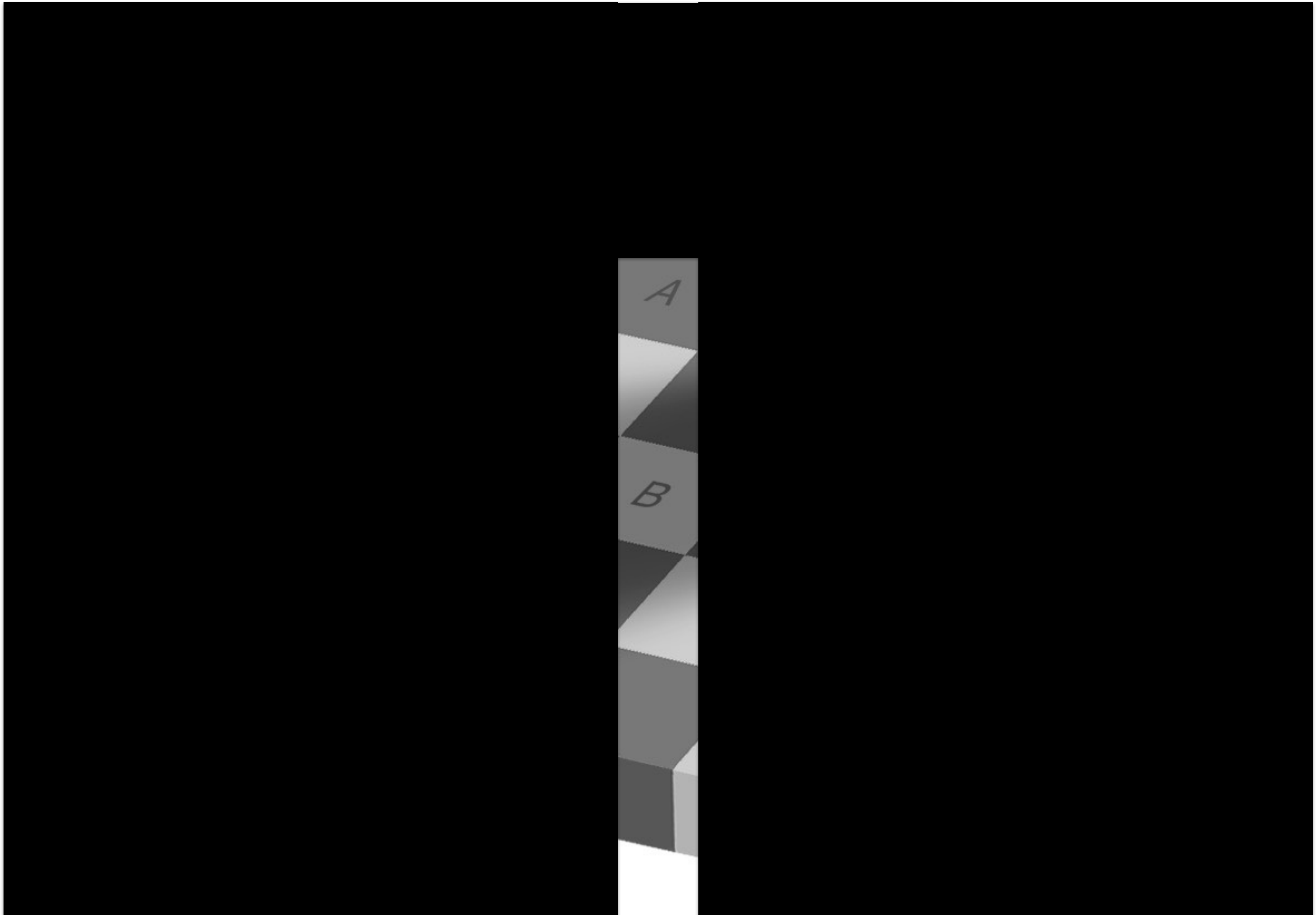
Everything is Relative



Everything is Relative



Everything is Relative



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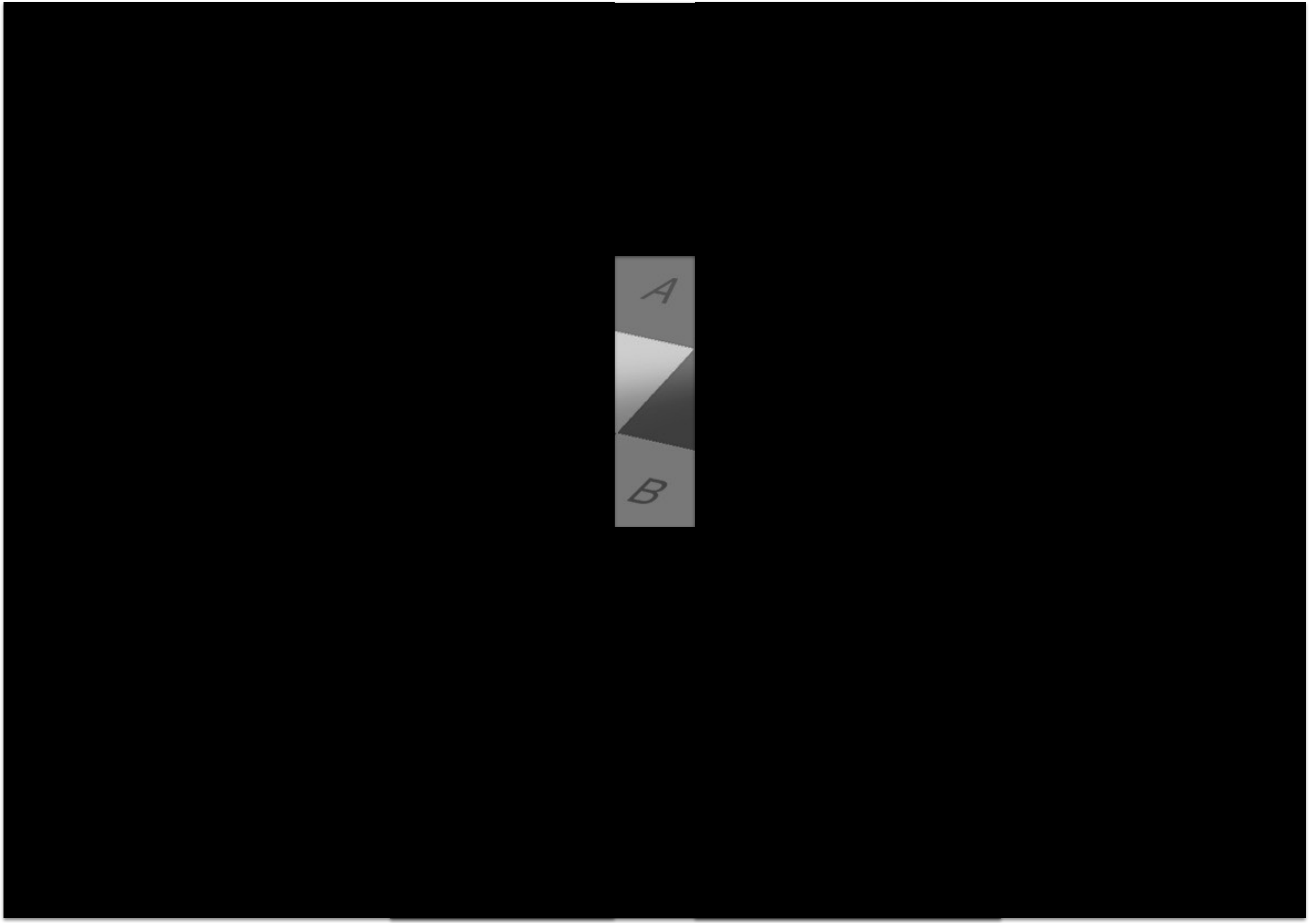

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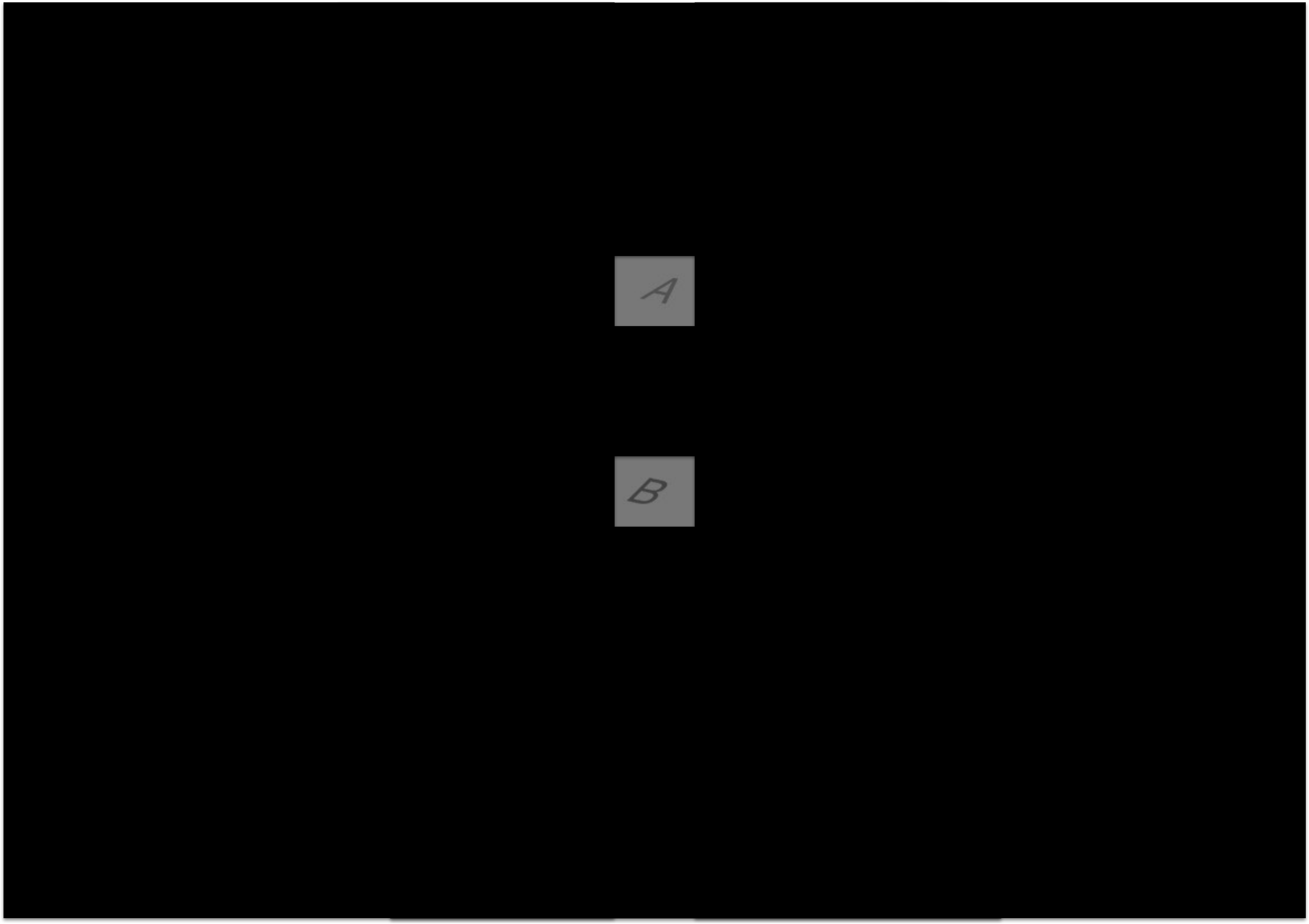

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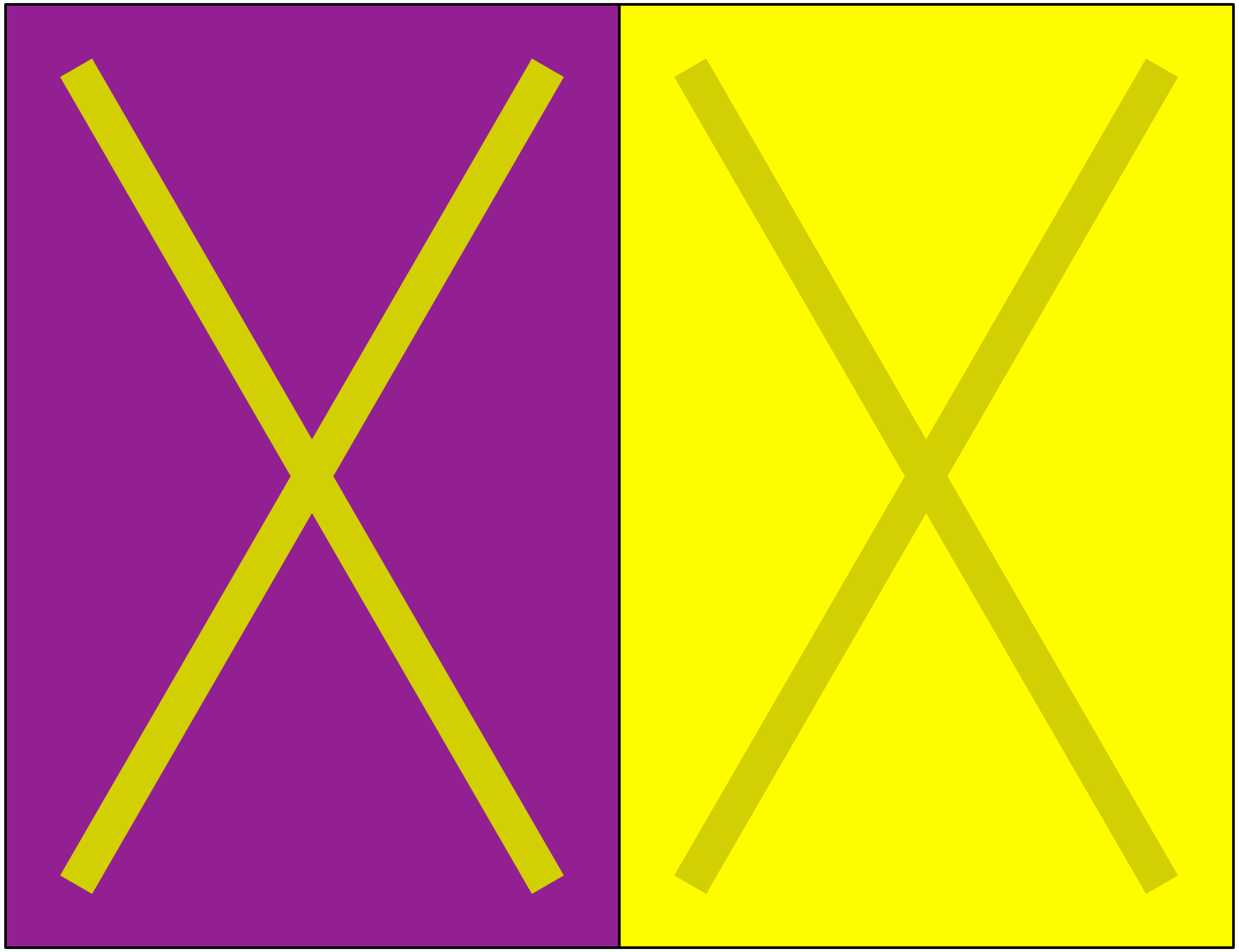

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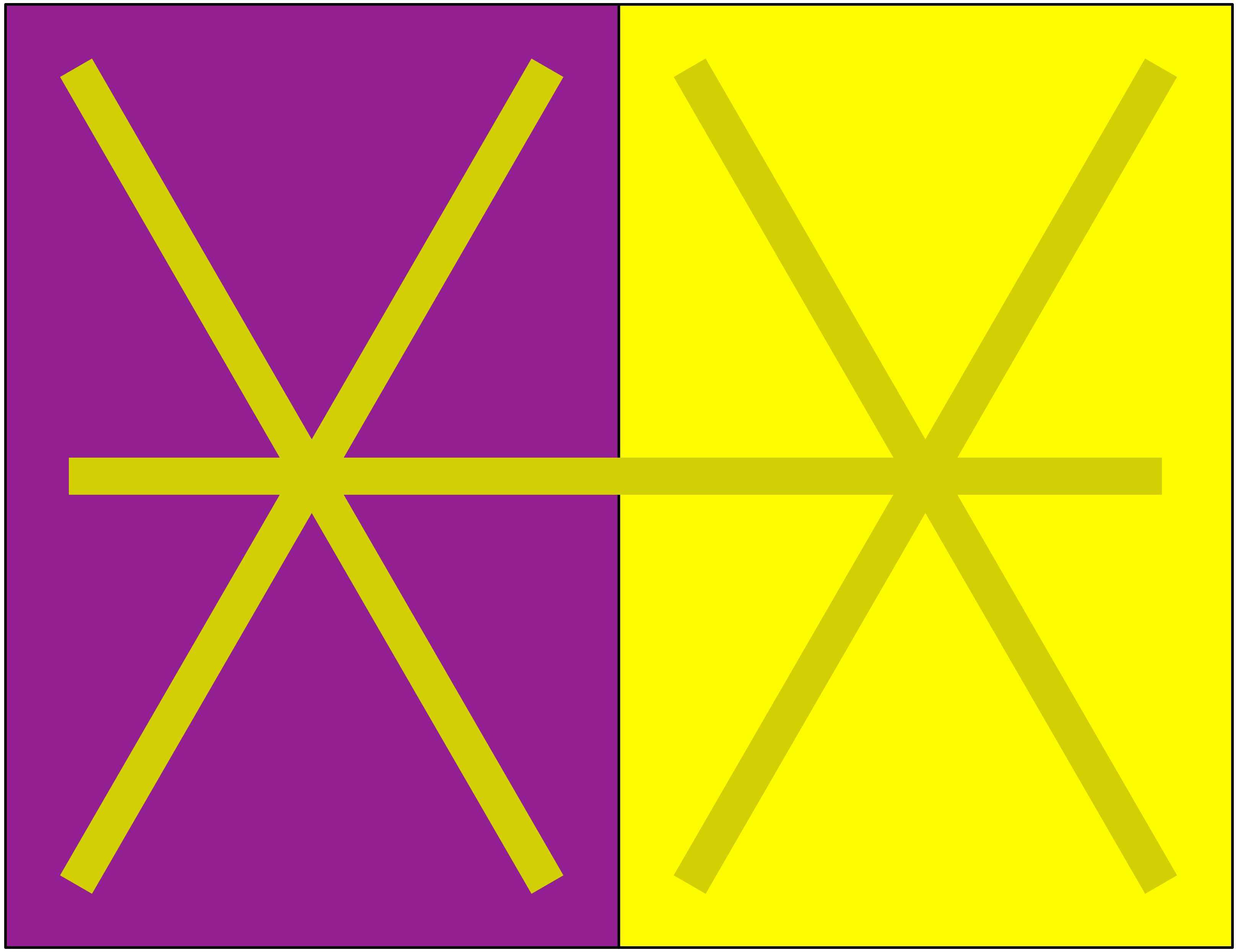


CMYK: A Subtractive Color Space

Subtractive color model

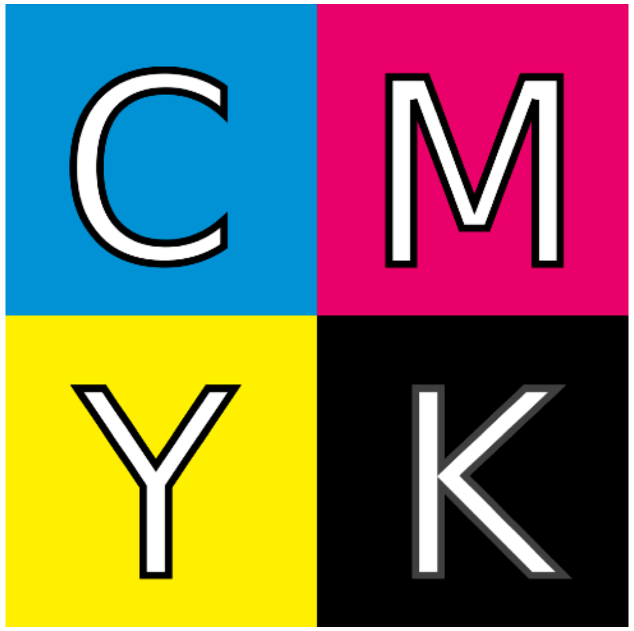
- The more you mix,
  the darker it will be

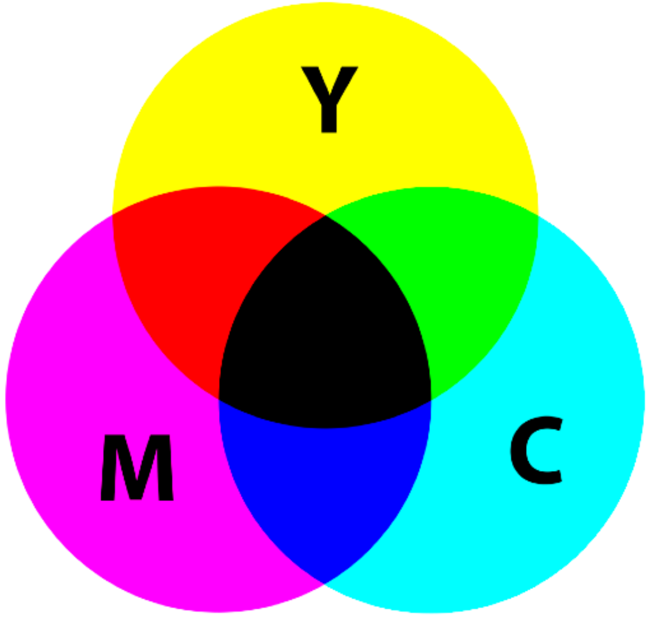
Cyan, Magenta, Yellow, and Key

Widely used in printing

Question:

- If mixing C, M and Y gives K,
  why do you need K?





Thank you!

(And thank Prof. Ren Ng for many of the slides!)