Trichromatic Theory of Color Vision, Part II

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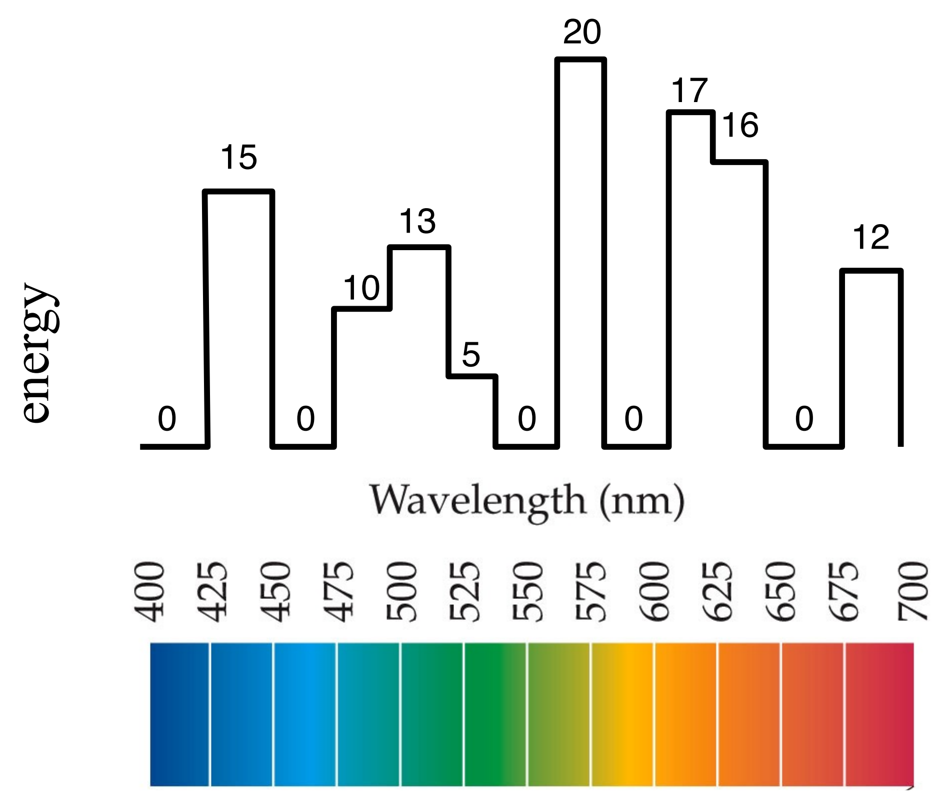
Mathematical Tools for Neuroscience (NEU 314)
Spring, 2016

lecture 5.

Quick review

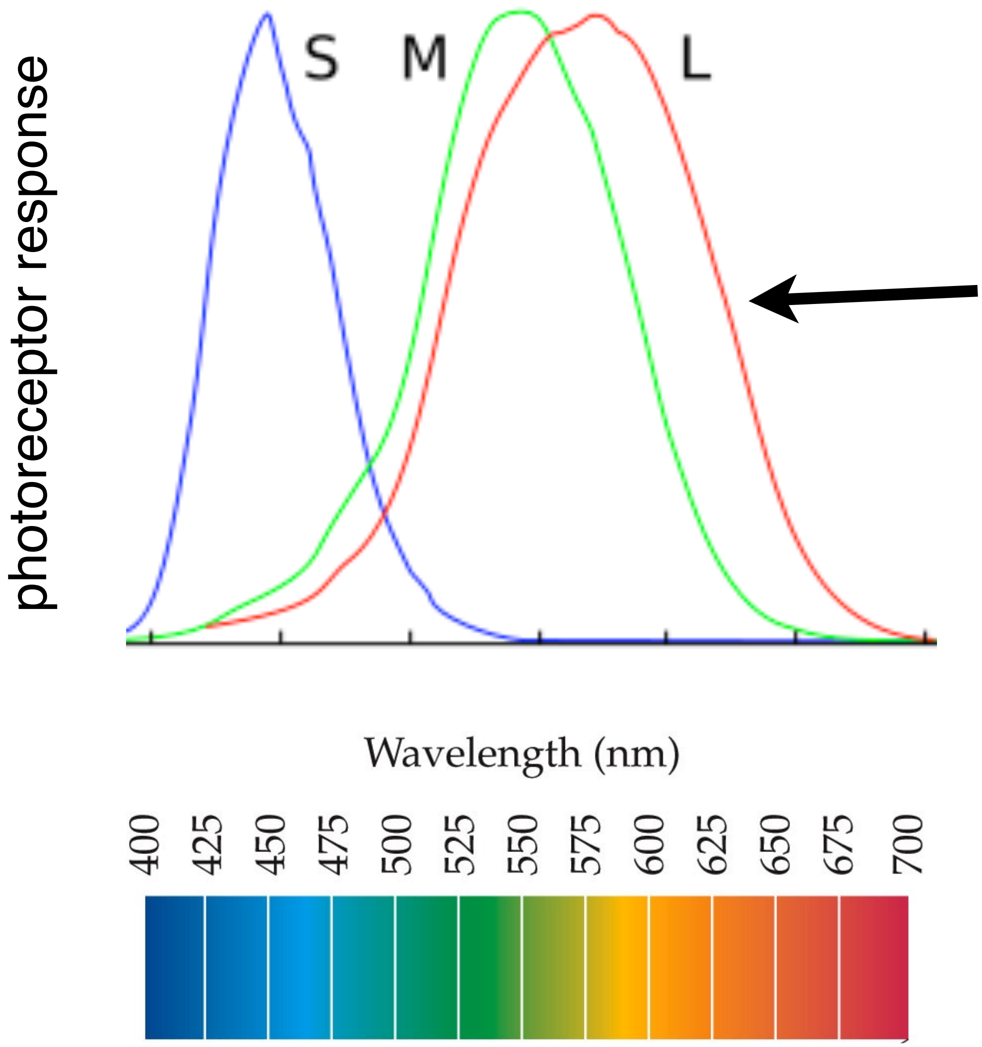
illuminant power spectrum - amount of energy at each freq

(could also call it: *emissions spectrum*)



a vector: one number for each frequency band

absorption spectra - describe response (or “light absorption”) of a photoreceptor as a function of frequency

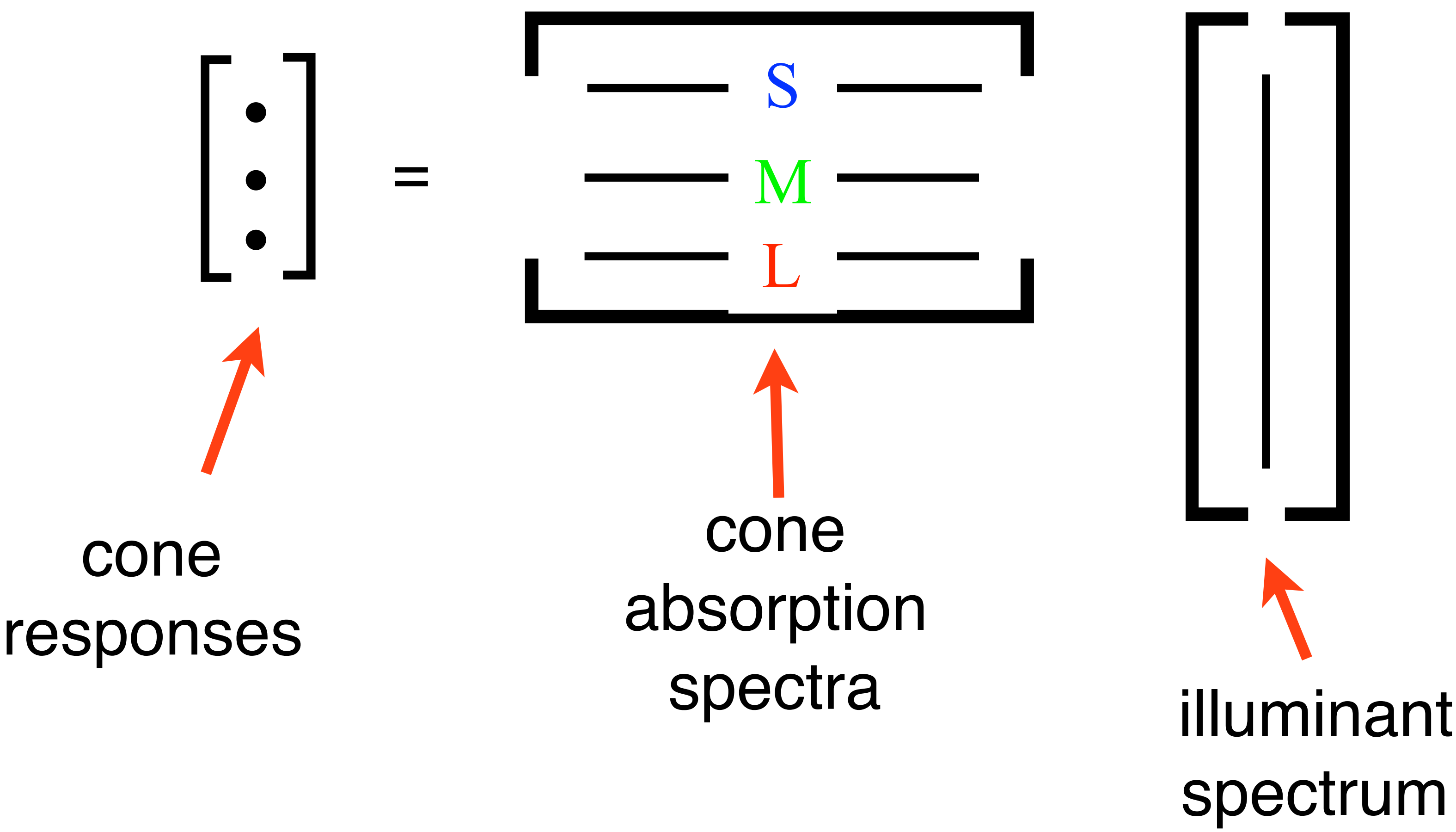


Absorption spectrum for “L” (red) cone

Are **basis vectors** for a 3D **subspace** within the high-D vector space of spectra

Color measurements in the visual system

$$\vec{y} = M\vec{x}$$



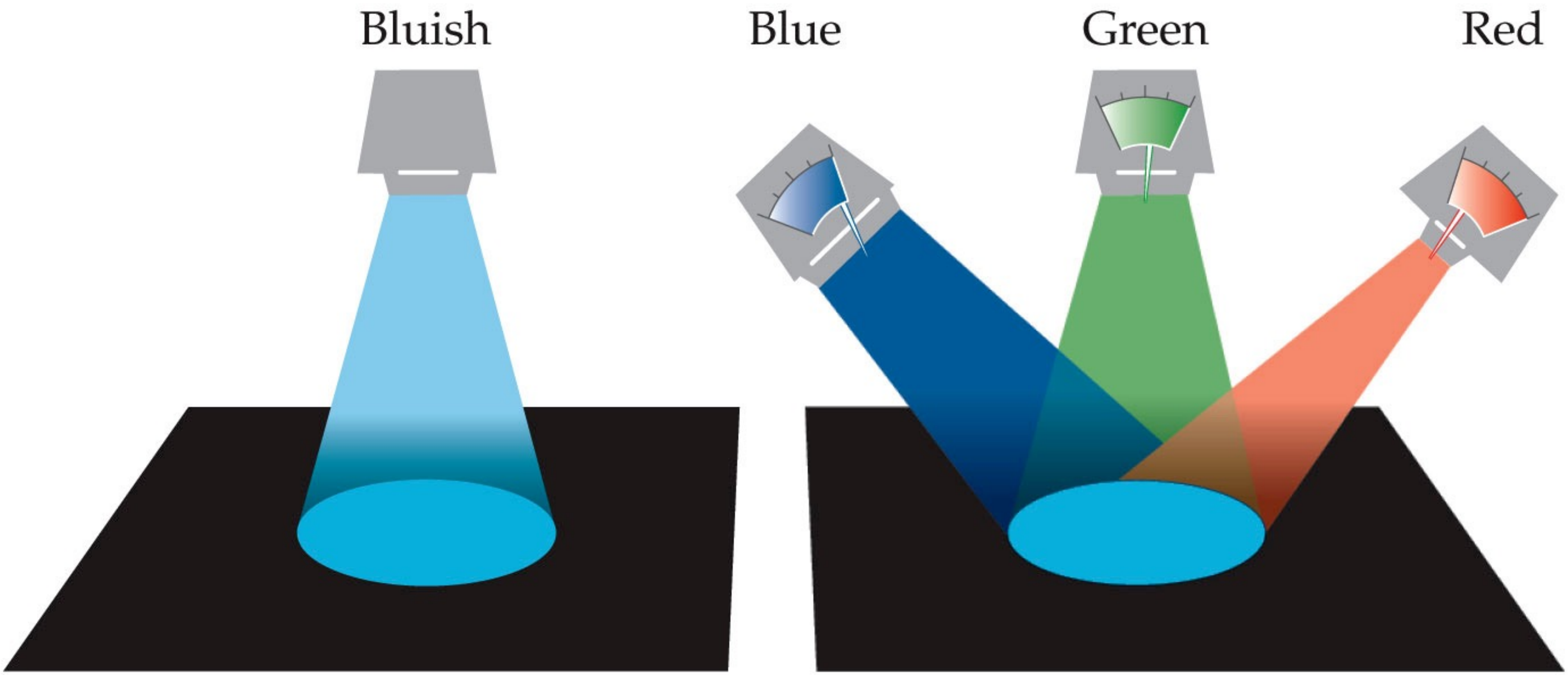
Two lights x_1 and x_2 “match” iff

$$M\vec{x}_1 = M\vec{x}_2$$

(i.e., they evoke the same cone responses)

If not equal, x_1 and x_2 are *metamers*

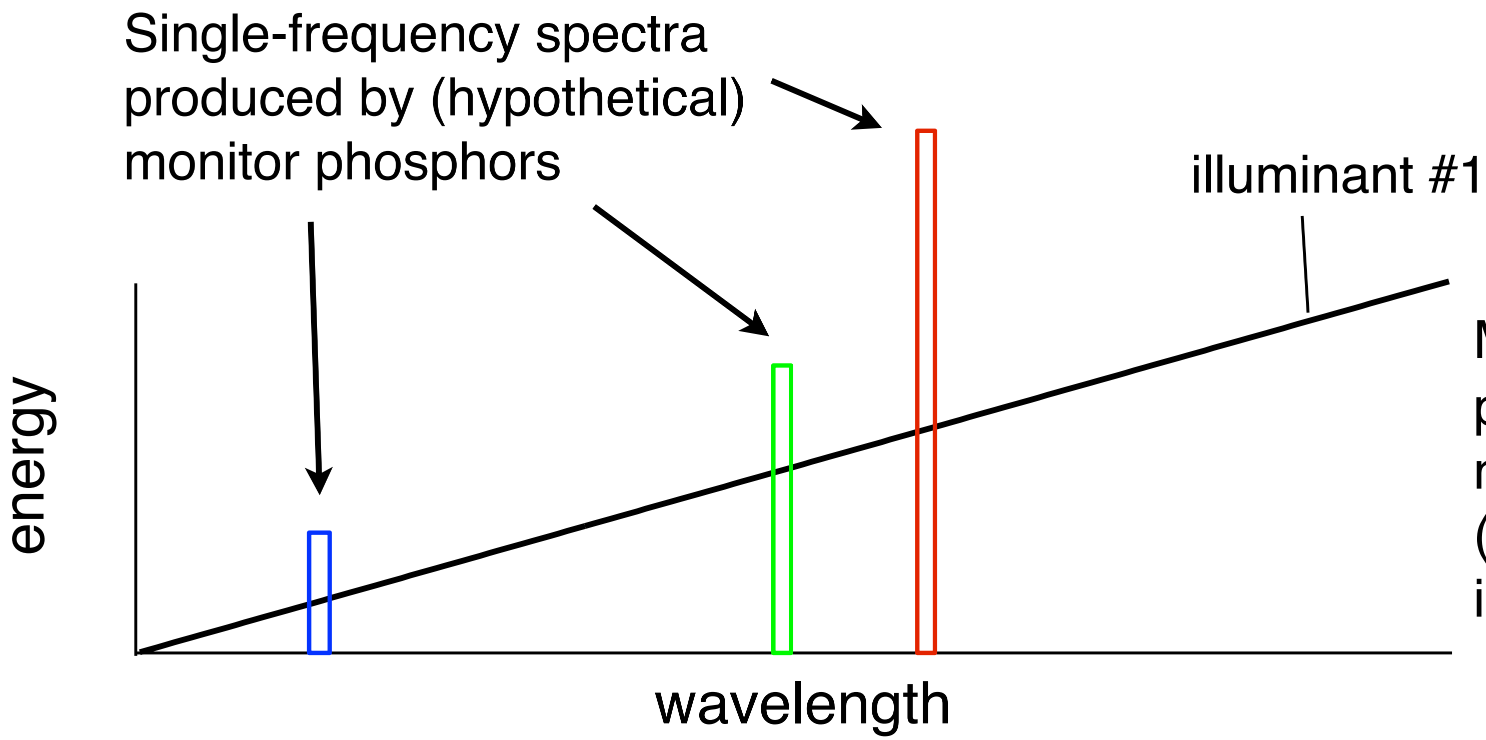
James Maxwell (1831–1879): color-matching experiment



• Any “test” light (“vector”), can be matched by adjusting the intensities of any three other lights (“basis vectors”)
• 2 is not enough; 4 is more than enough

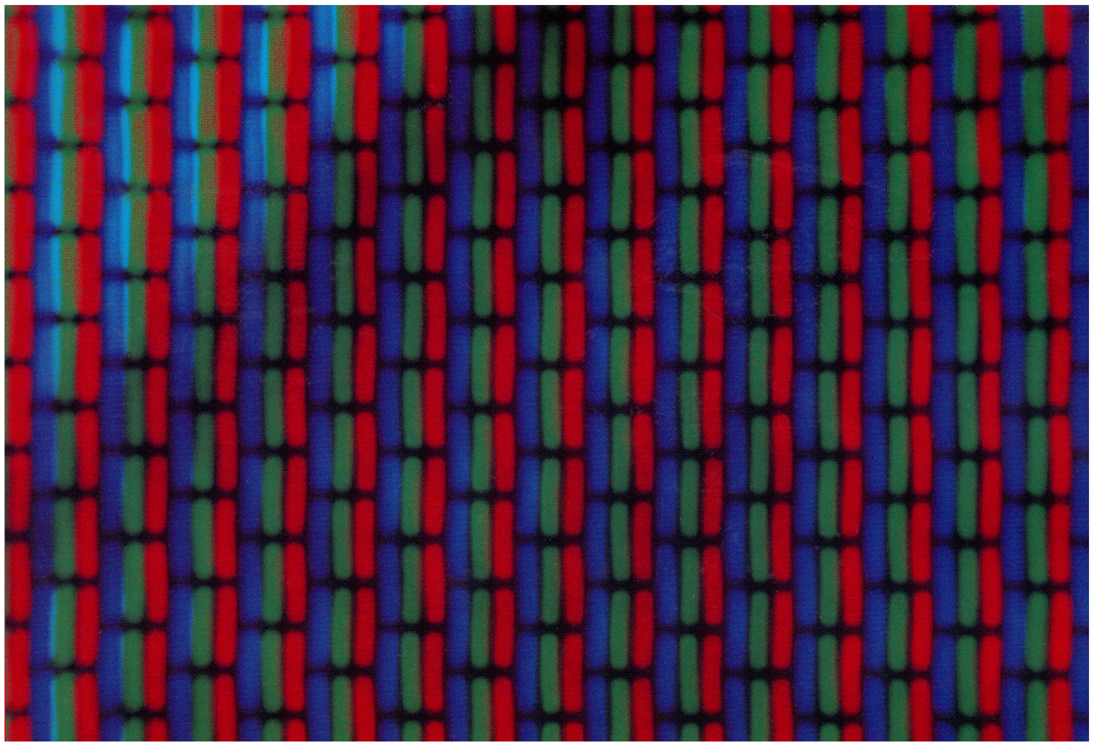
Implication: tons of things in the natural world have different spectral properties, but look the same to us.

But, great news for the makers of TVs and Monitors: any three lights can be combined to approximate any color.



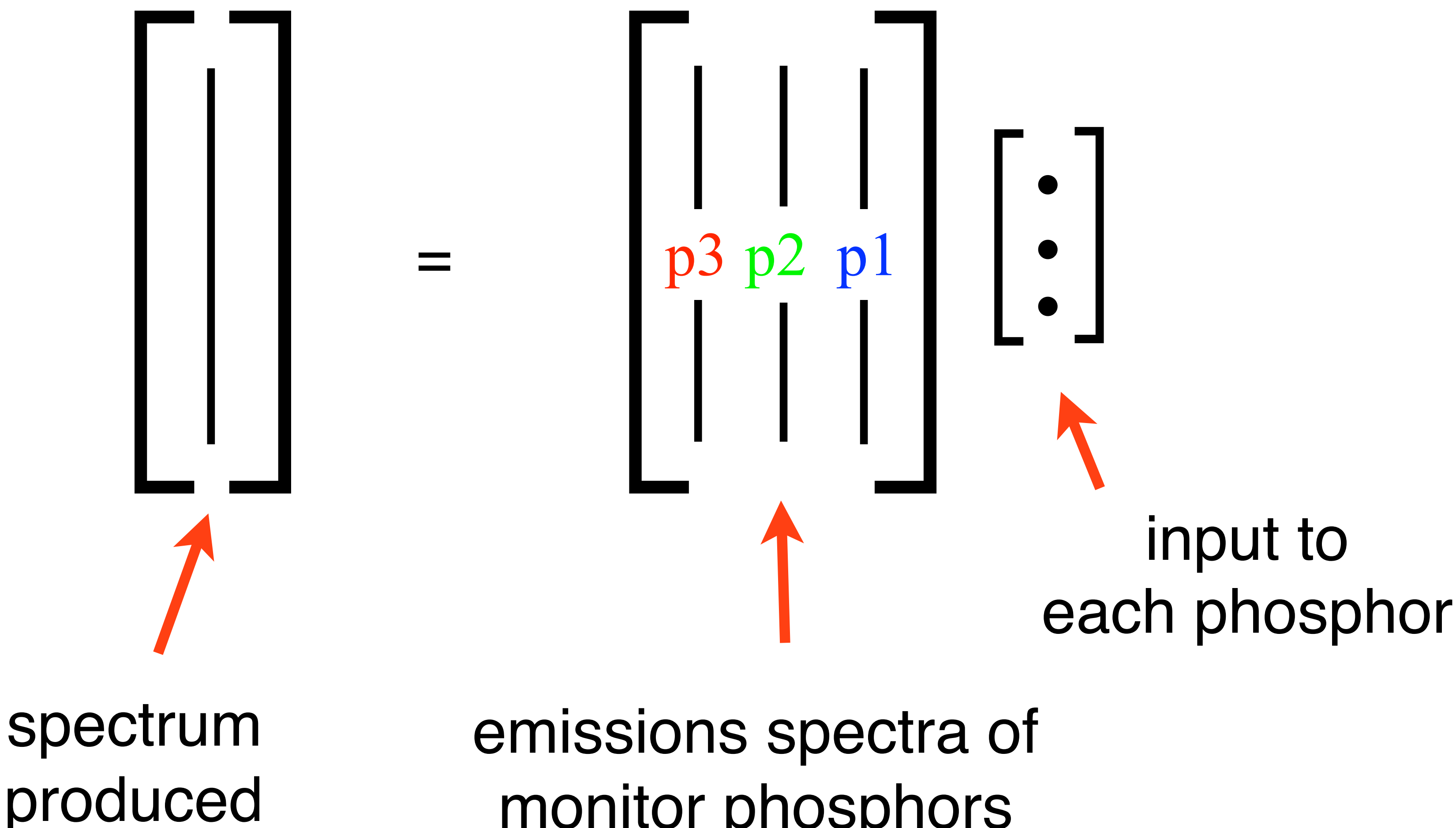
Monitor phosphors produce “metameric match” to illuminant #1 (or any other possible illuminant).

Close-up of computer monitor, showing three phosphors, (which can approximate any light color)



Producing color on a color monitor

$$\vec{x} = P\vec{z}$$



This wouldn't be the case if we had more cone classes.

hyperspectral marvel:
mantis shrimp
(stomatopod)

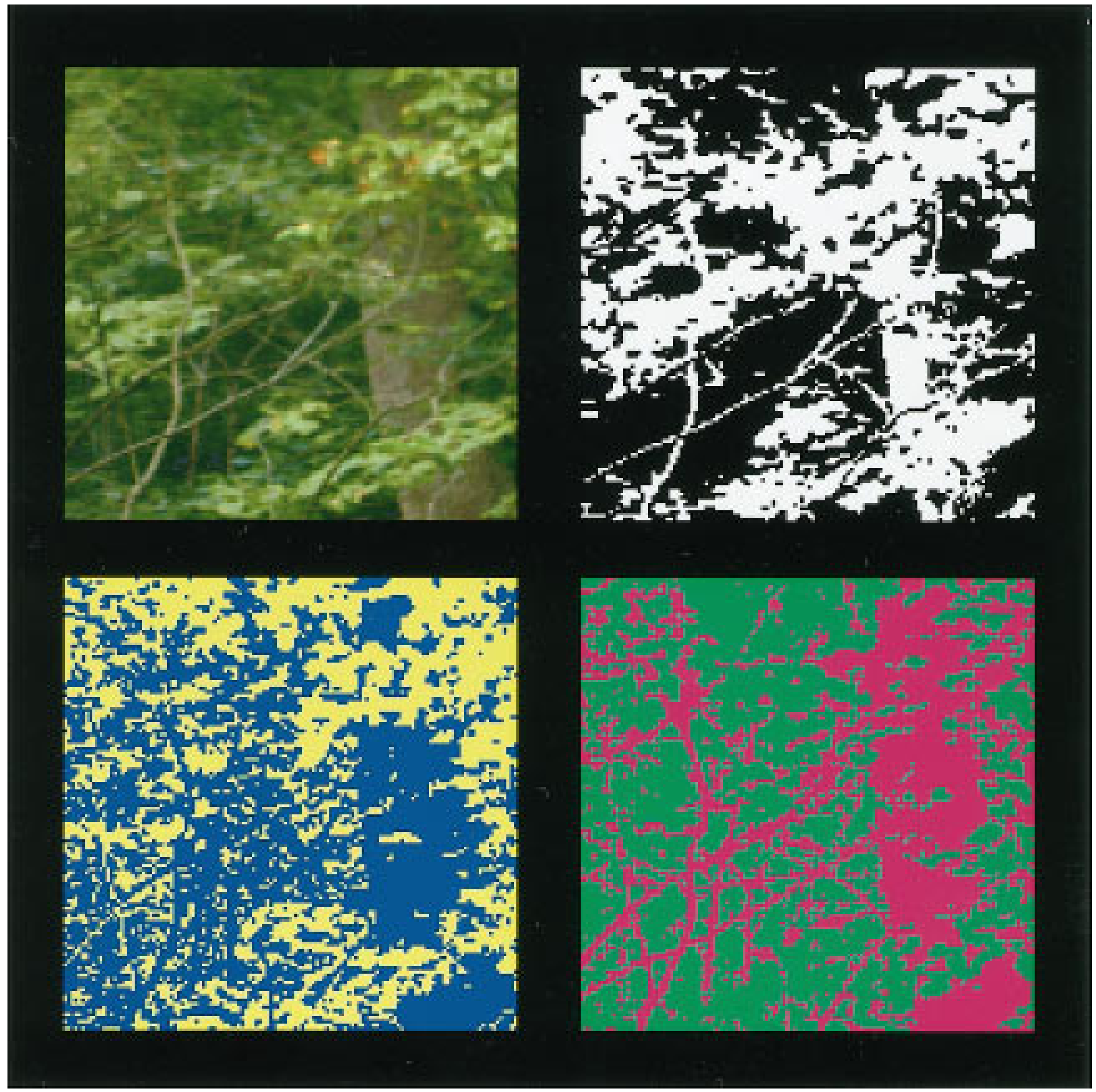
- 12 different cone classes
- sensitivity extending into UV range
- 12-dimensional color vision space

Why these three cone classes?

- "efficient coding" of natural spectra: preserve most of the variability present in hyper-spectral images

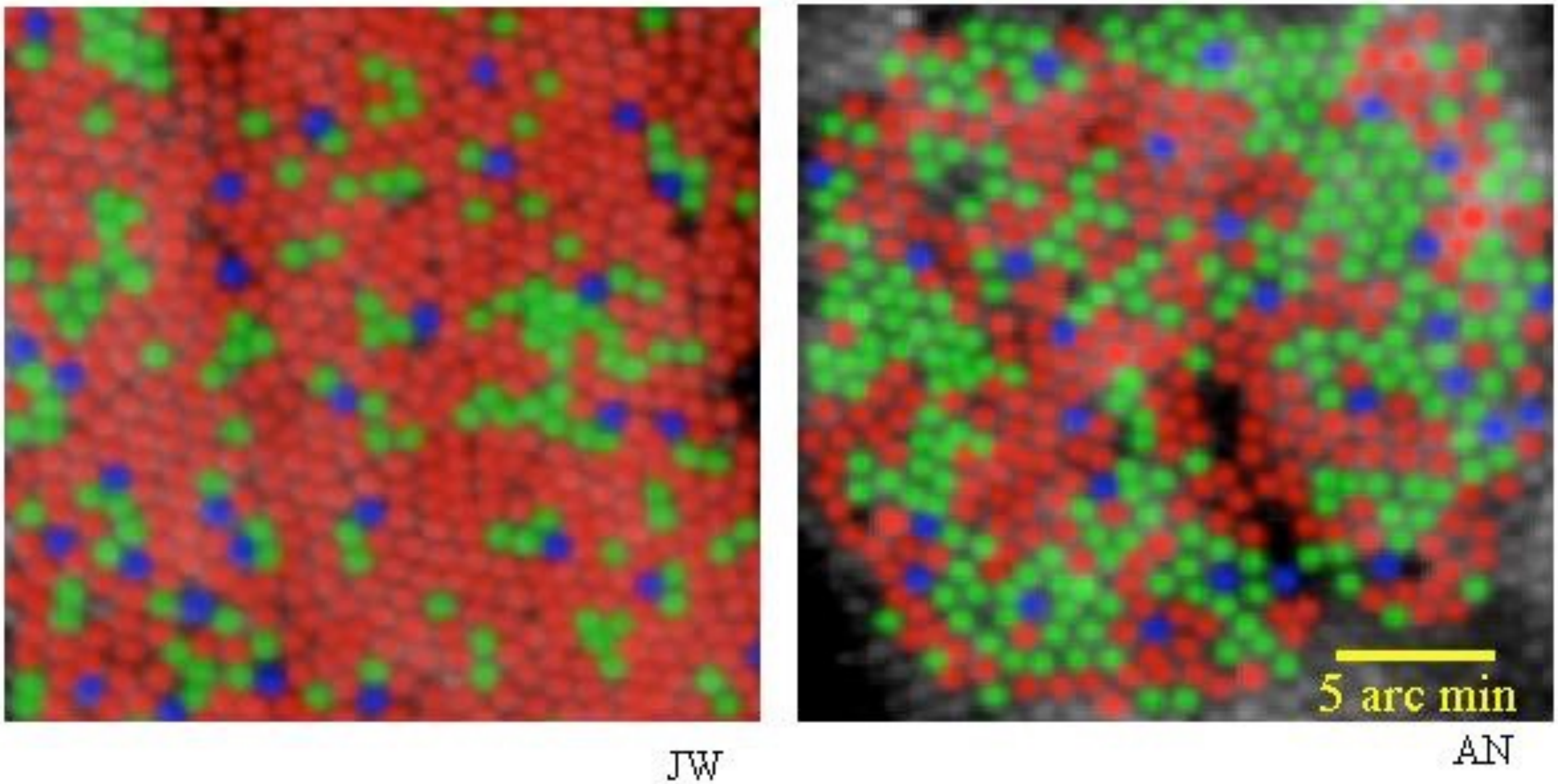
projection of a natural image onto first 3 principal components

Ruderman et al 1998



(let's revisit this when we discuss PCA)

First Images of the Human Trichromatic Cone Mosaic
(Roorda, A. and Williams, D.R. *Nature*, Feb.,1999)



- Large variability across individuals!
- But, doesn't have (strong) effects on color space

color blindness

- About 8% of male population, 0.5% of female population has some form of color vision deficiency: Color blindness
- Mostly due to missing M or L cones (sex-linked; both cones coded on the X chromosome)

Types of color-blindness:

dichromat - only 2 channels of color available
(i.e., color vision defined by a 2D subspace)
(contrast with “trichromat” = 3 color channels).

Three types, depending on missing cone:	Frequency: M / F
• **Protanopia**: absence of L-cones	2% / 0.02%
• **Deuteranopia**: absence of M-cones	6% / 0.4%
• **Tritanopia**: absence of S-cones	0.01% / 0.01%

↑ includes true dichromats and color-anomalous trichromats


Scene Viewed by
Protanope
Same Scene Viewed by
Normal Trichromat


Scene Viewed by
Deuteranope
Same Scene Viewed by
Normal Trichromat


Scene Viewed by Tritanope
Same Scene Viewed by Normal Trichromat

So don’t call it color *blindness*.

Say: “Hey man, I’m just living in a 2D subspace.”

Other types of color-blindness:

- **Color-anomalous**: Have two cone types (typically L- and M-cones) that are so similar they can't make discriminations based on them
- not *missing* cones, but the peak frequency is shifted so that certain colors are hard to distinguish
- in linear algebra terms: cone absorption spectra close to linearly dependent

Other types of color-blindness:

- **Monochromat:** true “color-blindness”; world is black-and-white
- **cone monochromat** - only have one cone type (vision is truly b/w)
- **rod monochromat** - visual in b/w AND severely visually impaired in bright light

Rod monochromacy

Scene Viewed by Rod Monochromat

Same Scene Viewed by Normal Trichromat

Color Vision in Animals

- most mammals (dogs, cats, horses): dichromats
- old world primates (including us): trichromats
- marine mammals: monochromats
- bees: trichromats (but lack "L" cone; ultraviolet instead)
- some birds, reptiles & amphibians: tetrachromats!

Opponent Processes

Afterimages: A visual image seen after a stimulus has been removed

Negative afterimage: An afterimage whose polarity is the opposite of the original stimulus

- Light stimuli produce dark negative afterimages
- Colors are complementary: Red produces green afterimages, blue produces yellow afterimages (and vice-versa)

color after-effects:

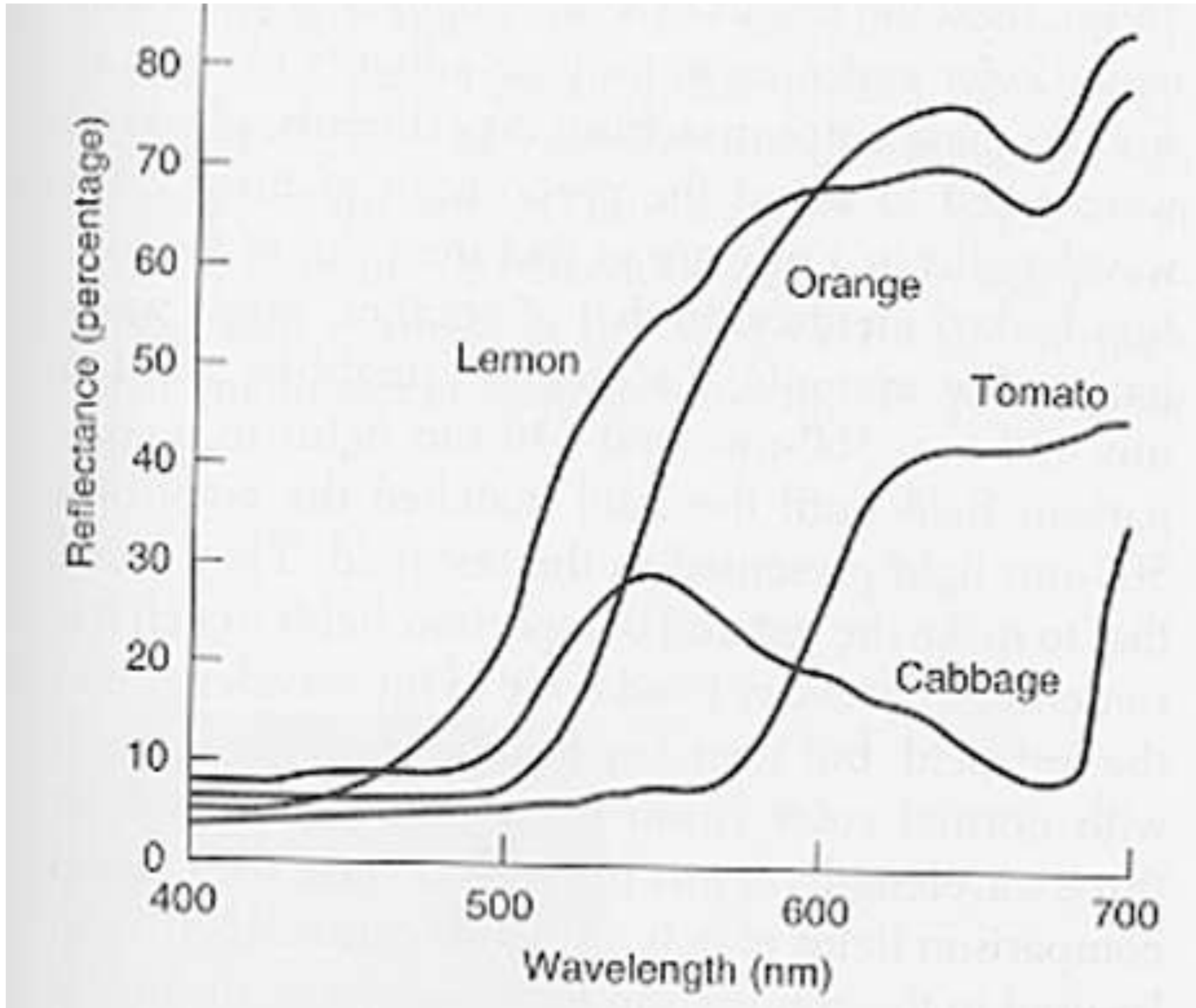
lilac chaser:

http://www.michaelbach.de/ot/col-lilacChaser/index.html

last piece: *surface reflectance function*

Describes how much light an object reflects, as a function of wavelength

Think of this as the *fraction* of the incoming light that is reflected back



By now we have a complete picture of how color vision works:

Illinant

Illuminant — defined by its power or “intensity” spectrum

amount of light energy at each wavelength

↓

Object — defined by its reflectance function

certain percentage of light at each wavelength is reflected

↓

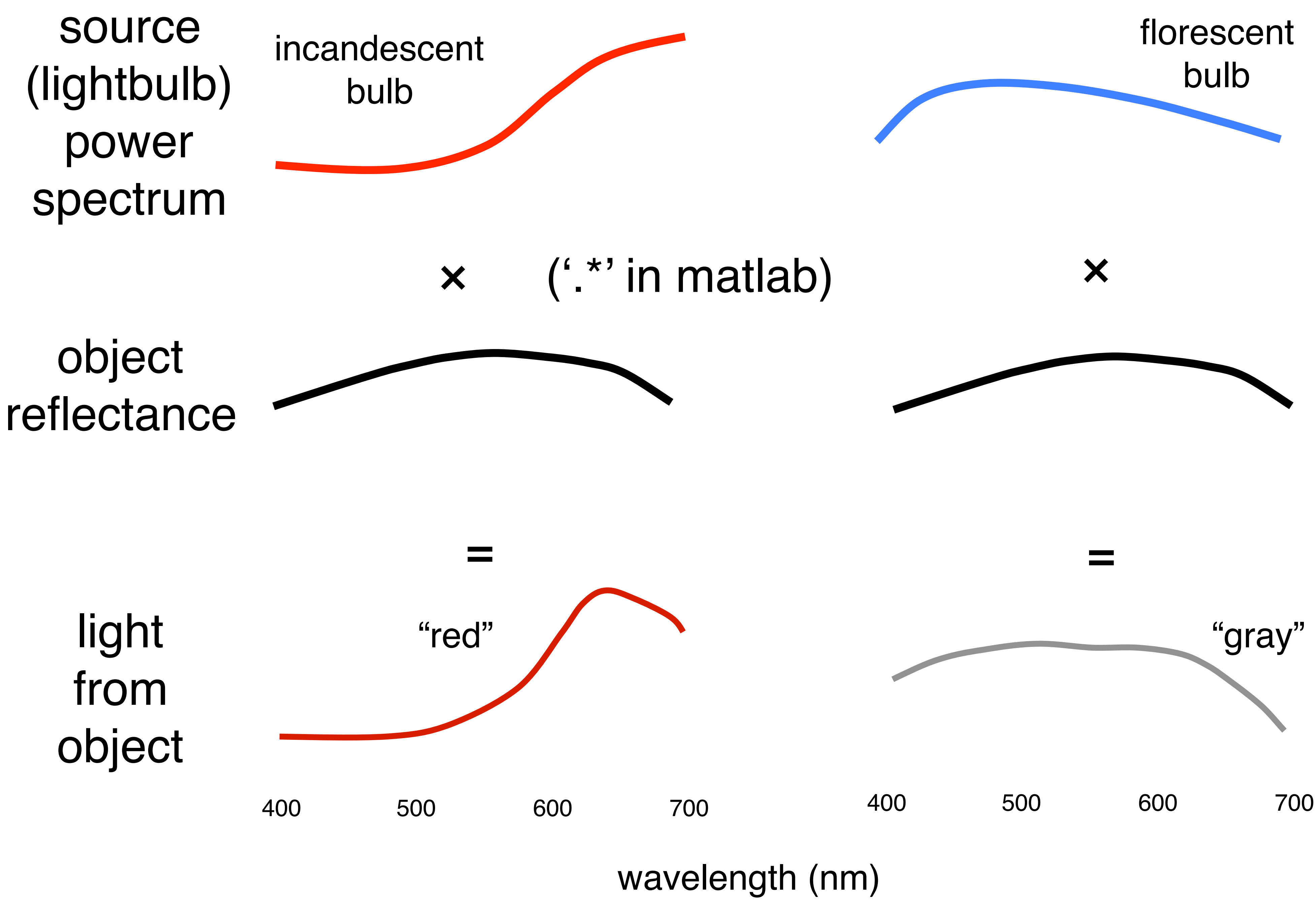
Cones — defined by absorption spectra

each cone class adds up light energy according to its absorption spectrum

↓

cone responses — three spectral measurements

convey all color information to brain via opponent channels

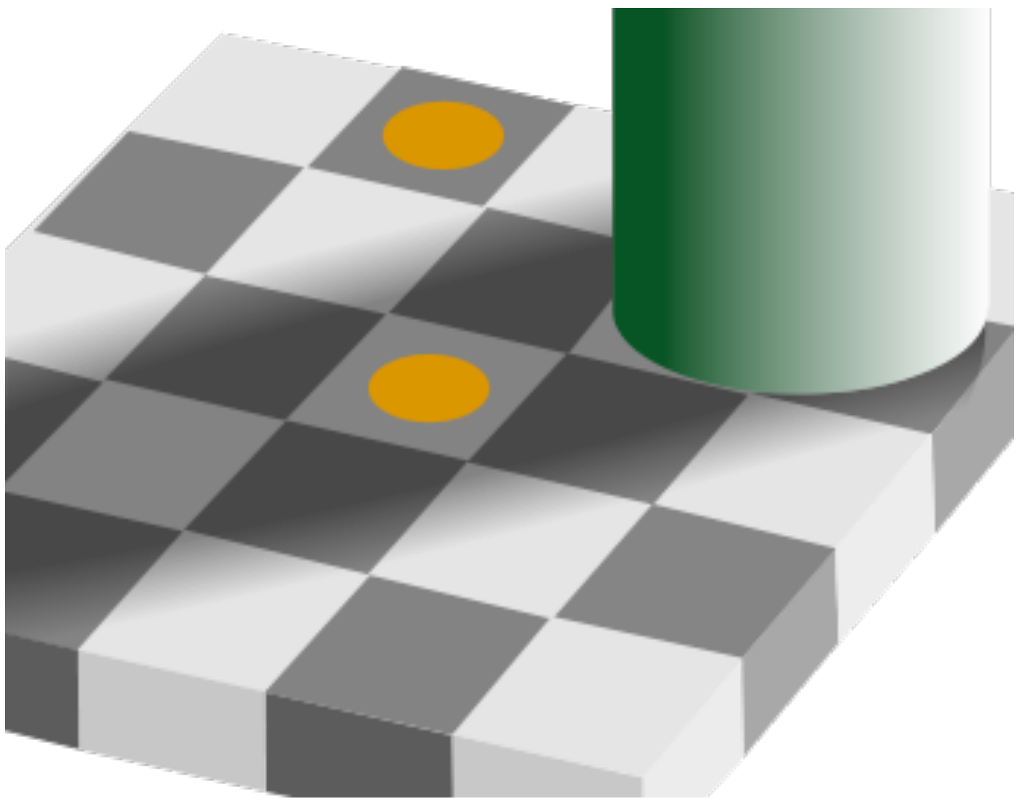

source (lightbulb) power spectrum
incandescent bulb
florescent bulb
×
('.*' in matlab)
×
object reflectance
=
=
light from object
"red"
"gray"
400
500
600
700
400
500
600
700
wavelength (nm)

But in general, this doesn't happen!
We *don't* see a white sheet of paper as reddish under a tungsten light and blueish under a halogen light.

Why?

- **Color constancy**: the tendency of a surface to appear the same color under a wide range of illuminants
- to achieve this, brain tries to "discount" the effects of the illuminant using a variety of tricks (e.g., inferences about shadows, the light source, etc).

Illusion illustrating Color Constancy



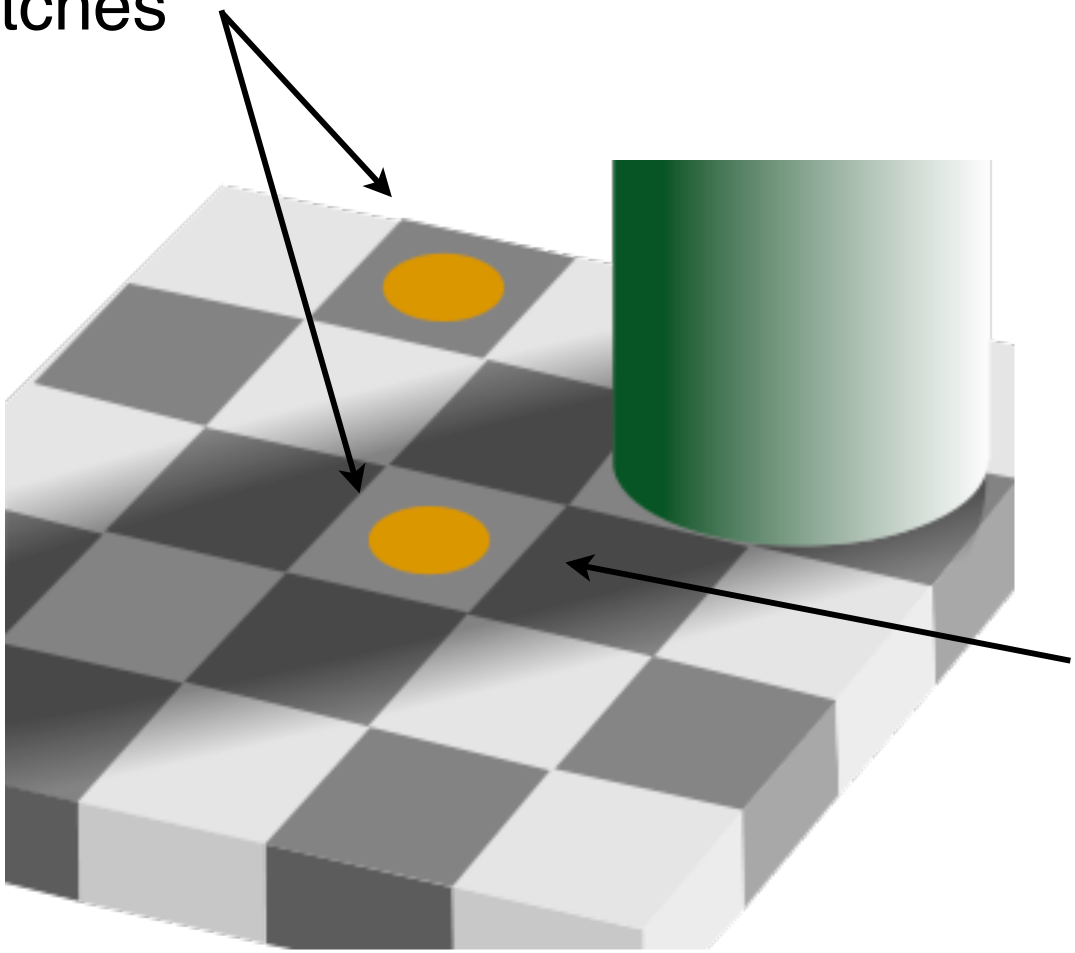
Same yellow in both patches

Same gray around yellow in both patches

(the effects of lighting/shadow can make colors look different that are actually the same!)

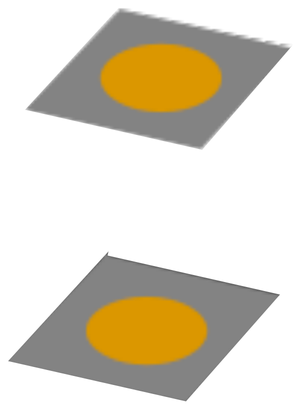
Bayesian Explanation

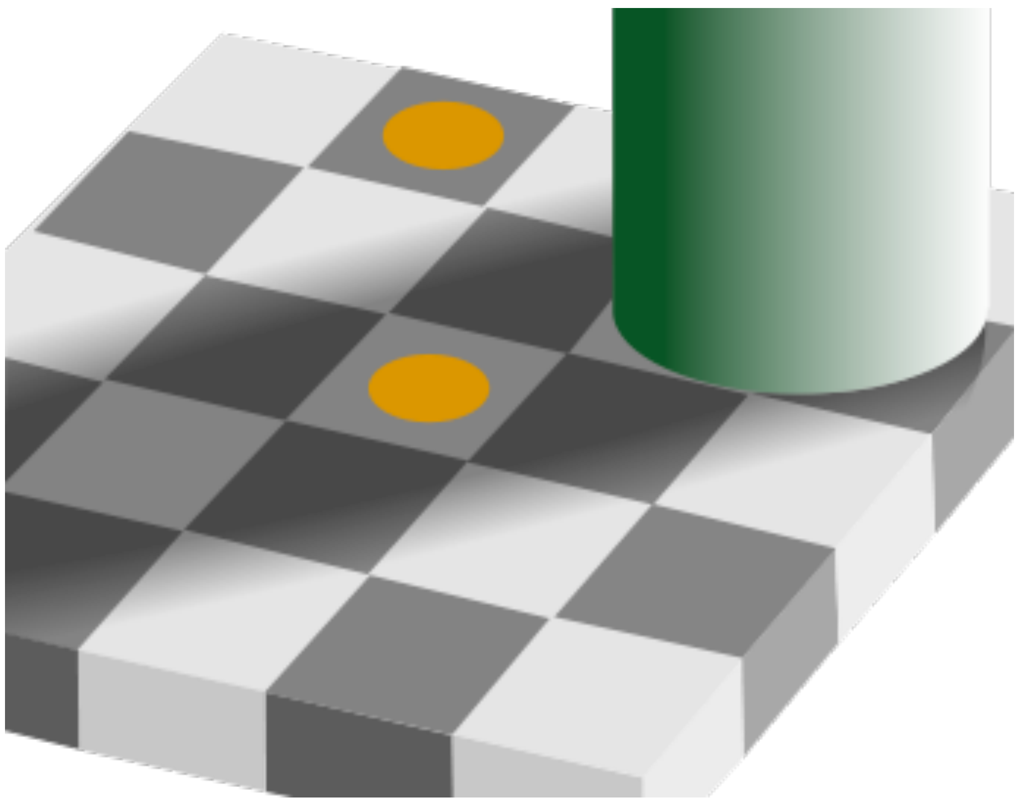
Exact same light hitting emanating from these two patches

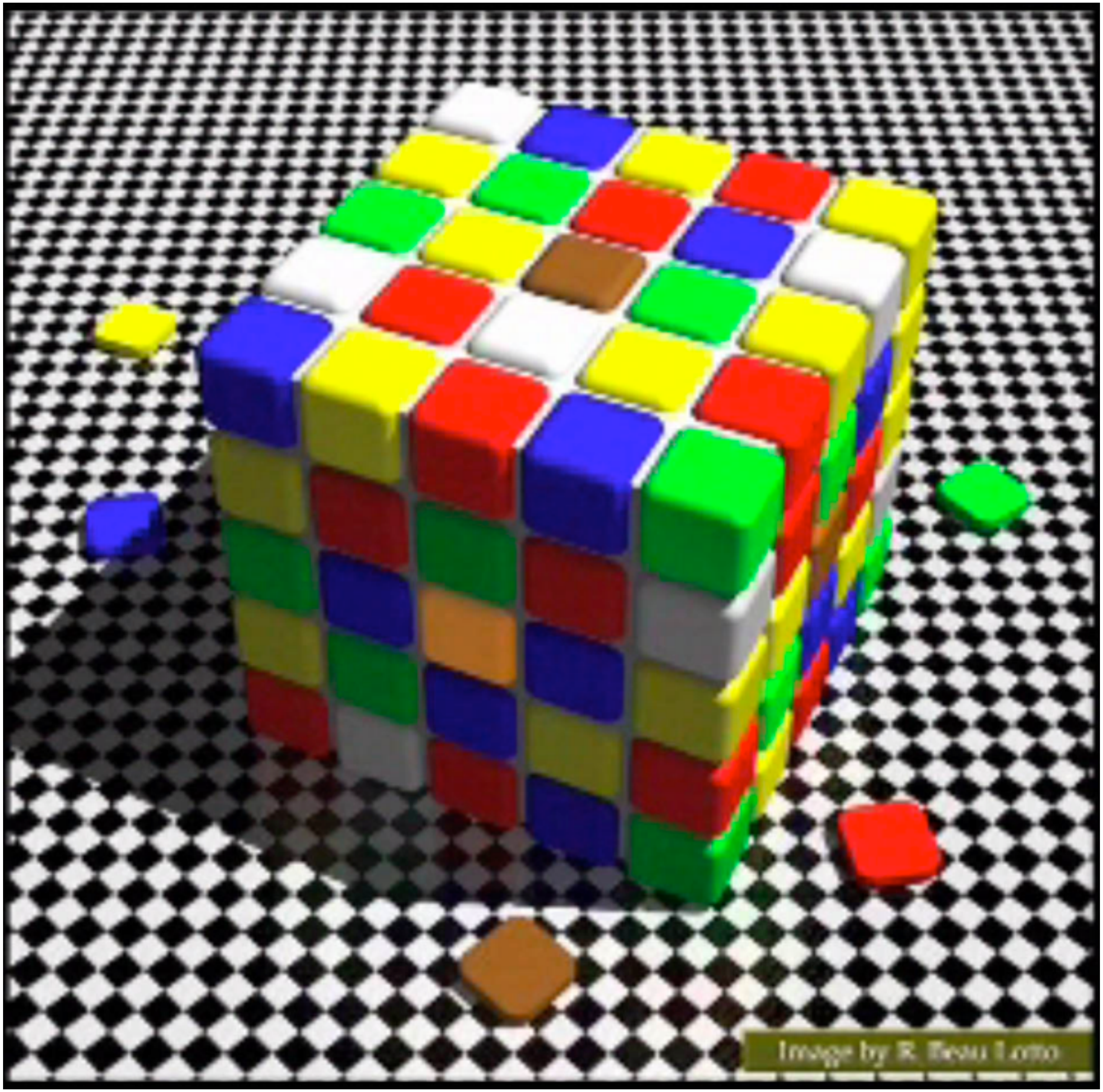


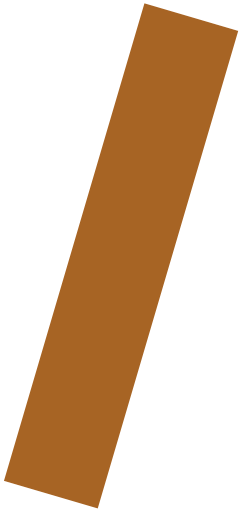
But the brain infers that less light is hitting this patch, due to shadow

CONCLUSION: the lower patch must be reflecting a higher fraction of the incoming light (i.e., it’s brighter)





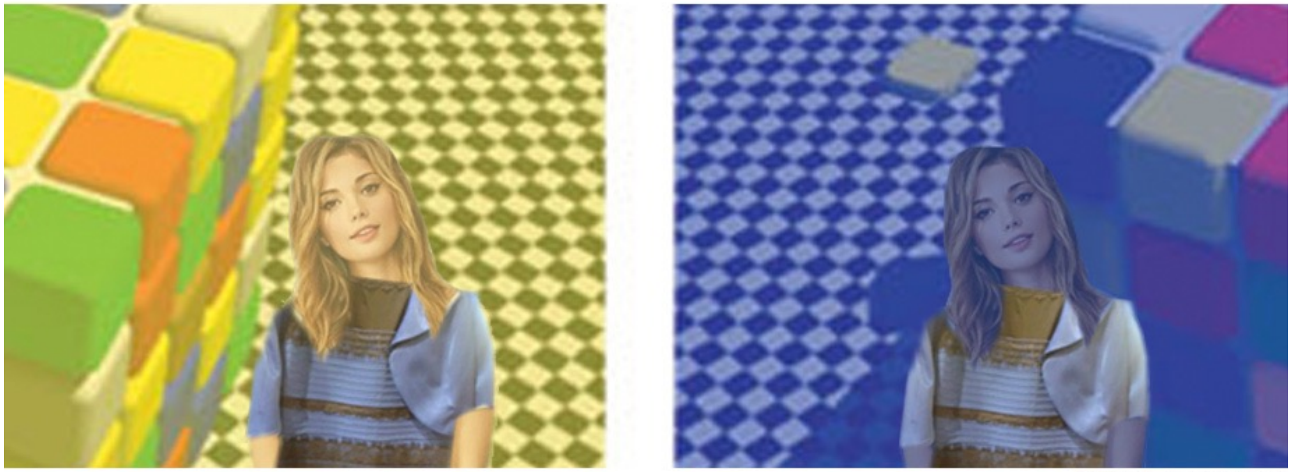




Beau Lotto

- Visual system tries to estimate the qualities of the illuminant so it can discount them

- still unknown how the brain does this (believed to be in cortex)



Rosa Lafer-Sousa

Color vision summary

- light source: defined by *illuminant power spectrum*

•Trichromatic color vision relies on 3 cones: characterized by *absorpotion spectra* ("basis vectors" for color perception)

- Color matching: any 3 lights that span the vector space of the cone absorption spectra can match any color percept

- *metamer*: two lights that are physically distinct (have different spectra) but give same color percept (have same projection)
    - this is a very important and general concept in perception!

- *surface reflectance function*: determines reflected light by pointwise multiplication of spectrum of the light source

- adaptation in color space ("after-images")

- color constancy - full theory of color vision (unfortunately) needs more than linear algebra!