# Color Vision

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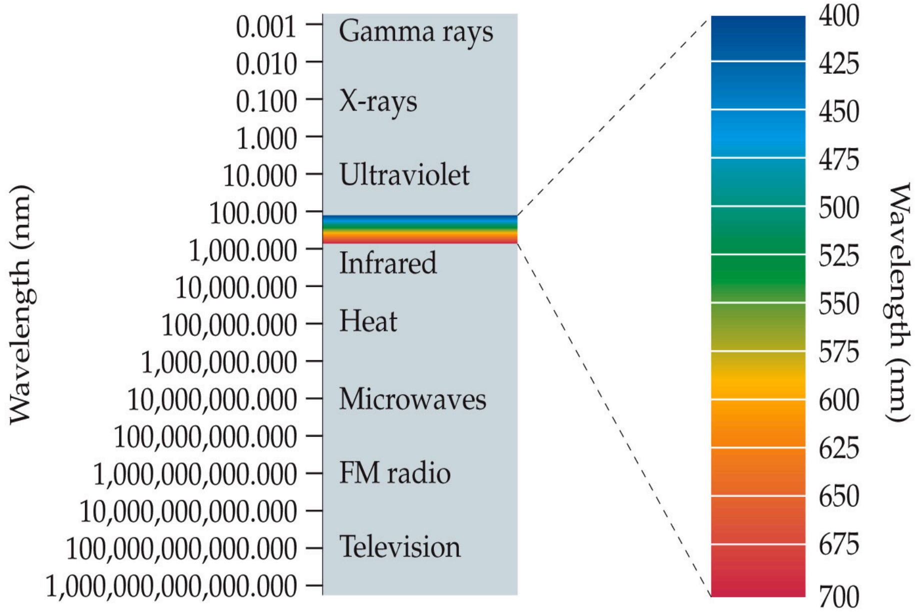
- color vision has evolutionary value
- lack of color vision $\neq$ black & white

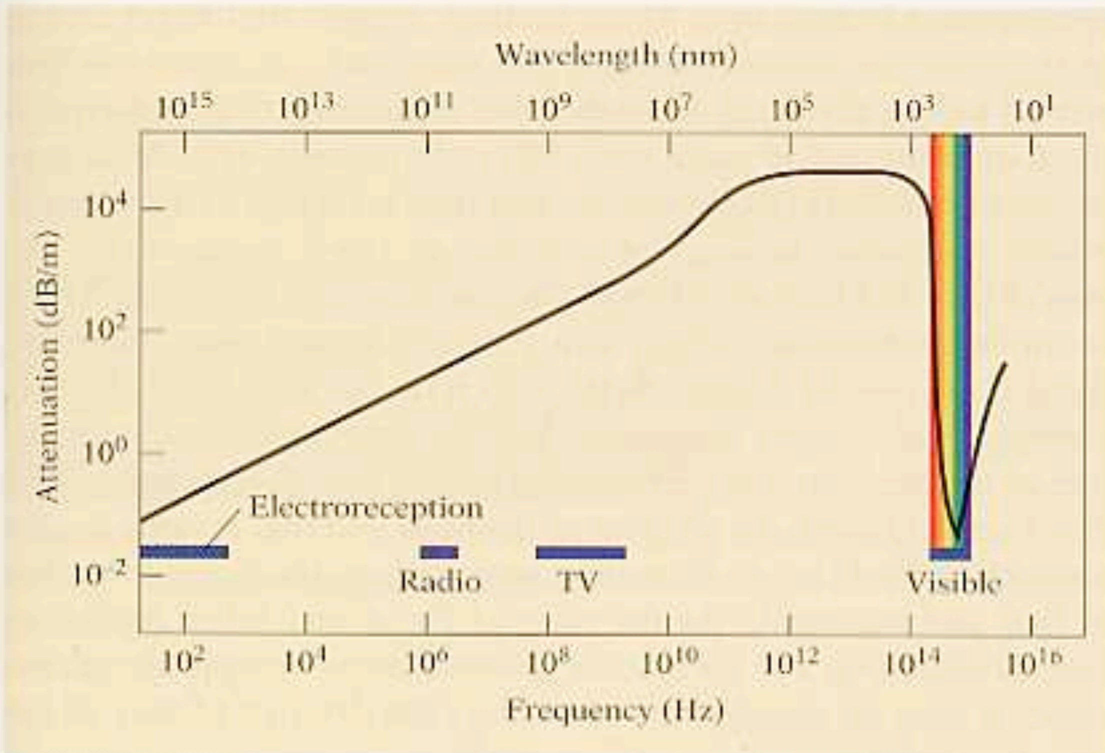
## Basic Principles of Color Perception

- Most of the light we see is reflected
- Typical light sources: Sun, light bulb, fire
- We see only part of the electromagnetic spectrum (between 400 and 700 nm). Why??



# Basic Principles of Color Perception

- Why only 400-700 nm?




The attenuation (measured in decibels per meter) of electromagnetic radiation in seawater as a function of frequency (measured in hertz, cycles per second) and wavelength (measured in nanometers). Russell Fernald has pointed out that this physical limitation constrained the early evolution of photoreceptors in vertebrates because they lived in water. The later evolution of vision in vertebrates appears to have been also constrained by this early adaptation, because photoreceptors in vertebrates living outside water have generally been limited to this range of the electromagnetic spectrum as well.

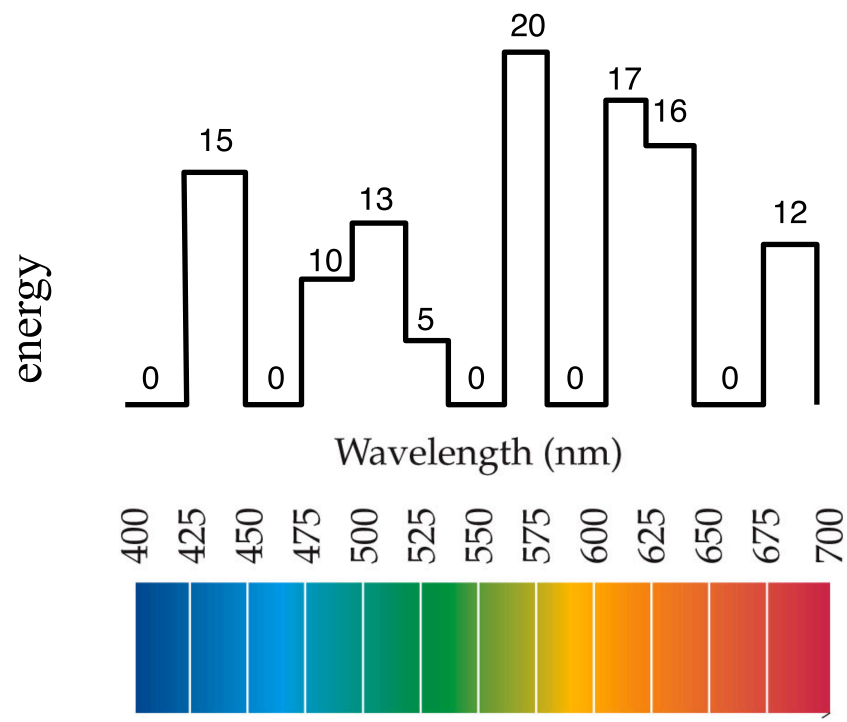
(Pomerantz, Rice U.)

Suggestion: unique ability to penetrate sea water

**Q**: How many numbers would you need to write down to specify the spectral properties of a light source?

**A**: It depends on how you "bin" up the spectrum

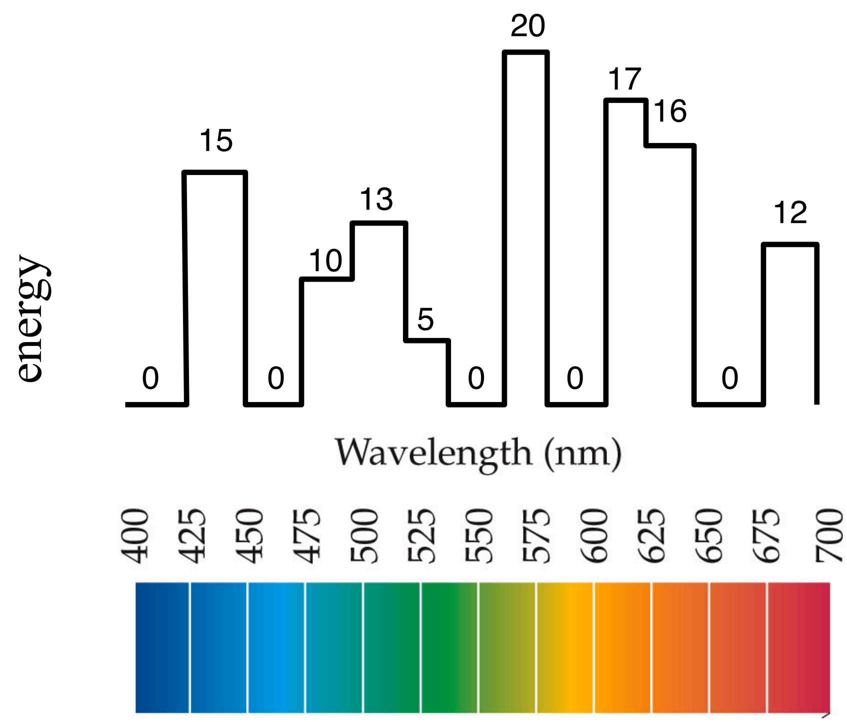
- One number for each spectral "bin":




example: 13 bins

Device: **hyper-spectral camera**

- measures the amount of energy (or number of photons) in each small range of wavelengths
- can use thousands of bins (or “frequency bands”) instead of just the 13 shown here



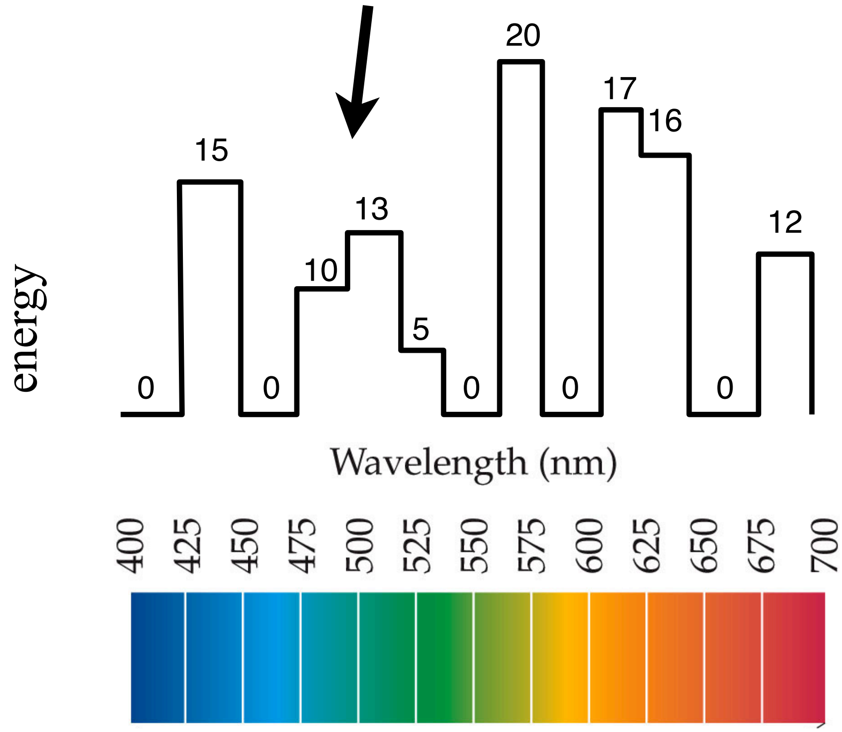
# Basic Principles of Color Perception

Some terminology for colored light:

**spectral** - referring to the wavelength of light

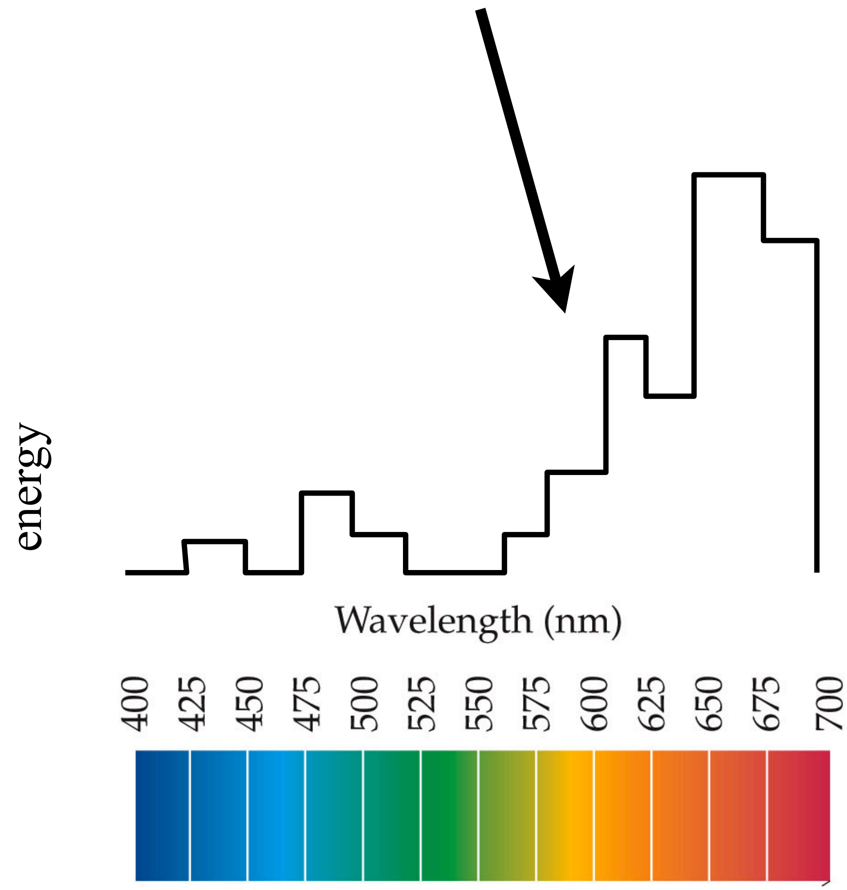
the **illuminant** - light source

**power spectrum** - this curve. Description of the amount of energy (or power) at each frequency



# Basic Principles of Color Perception

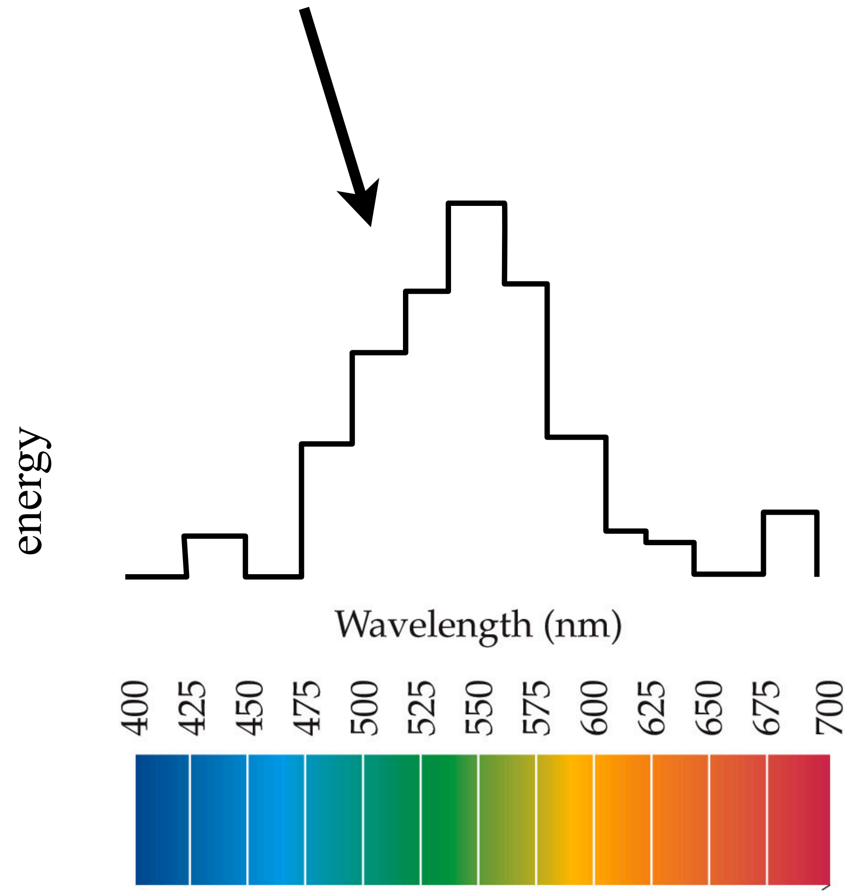
an illuminant with most power at long wavelengths (i.e., a *reddish* light source)




13 measurements of power spectrum (example)

# Basic Principles of Color Perception

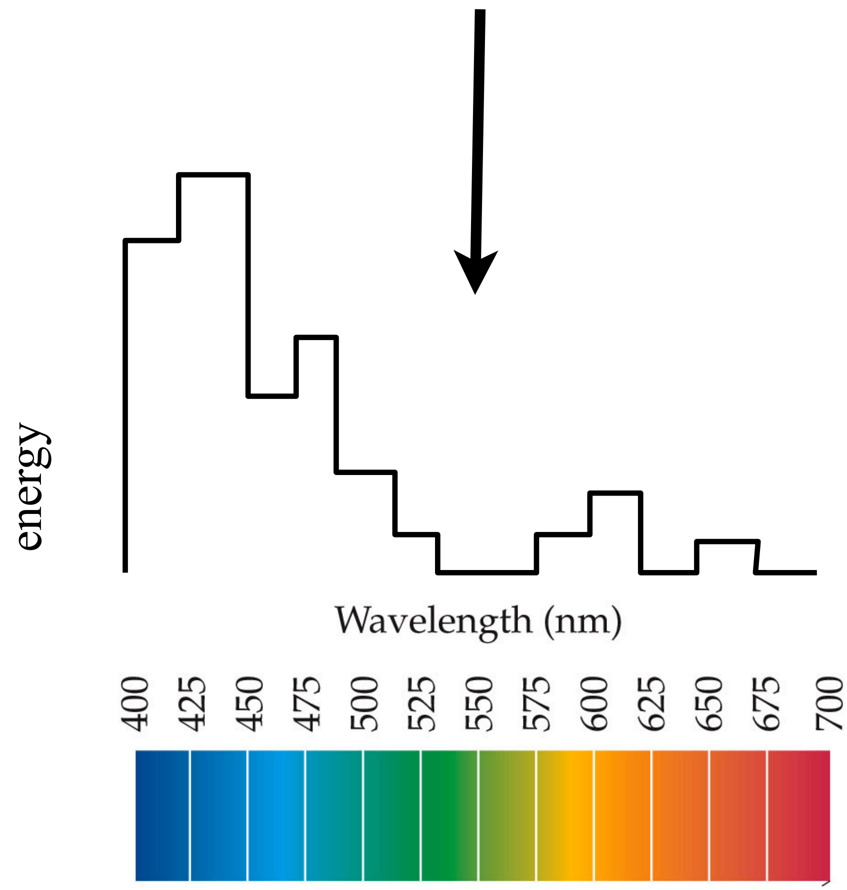
an illuminant with most power at medium wavelengths (i.e., a *greenish* light source)




13 measurements of power spectrum (example)

# Basic Principles of Color Perception

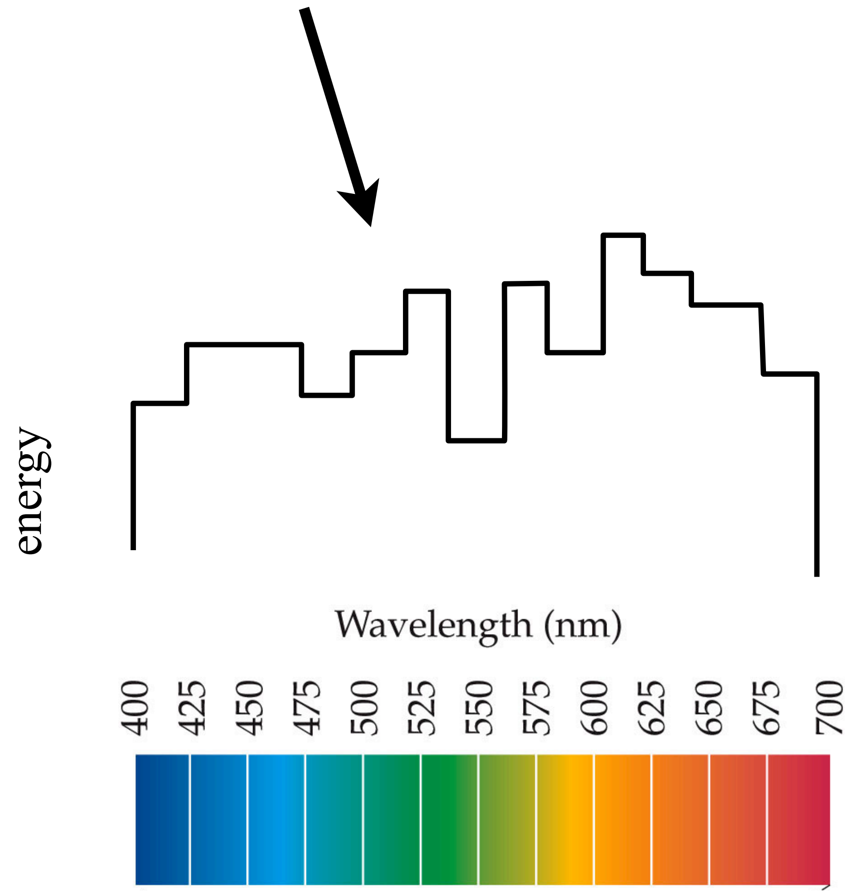
an illuminant with most power at long wavelengths (i.e., a *blueish* light source*)*




13 measurements of power spectrum (example)

# Basic Principles of Color Perception

an illuminant with power at all visible wavelengths (a *neutral* light source, or “white light”)

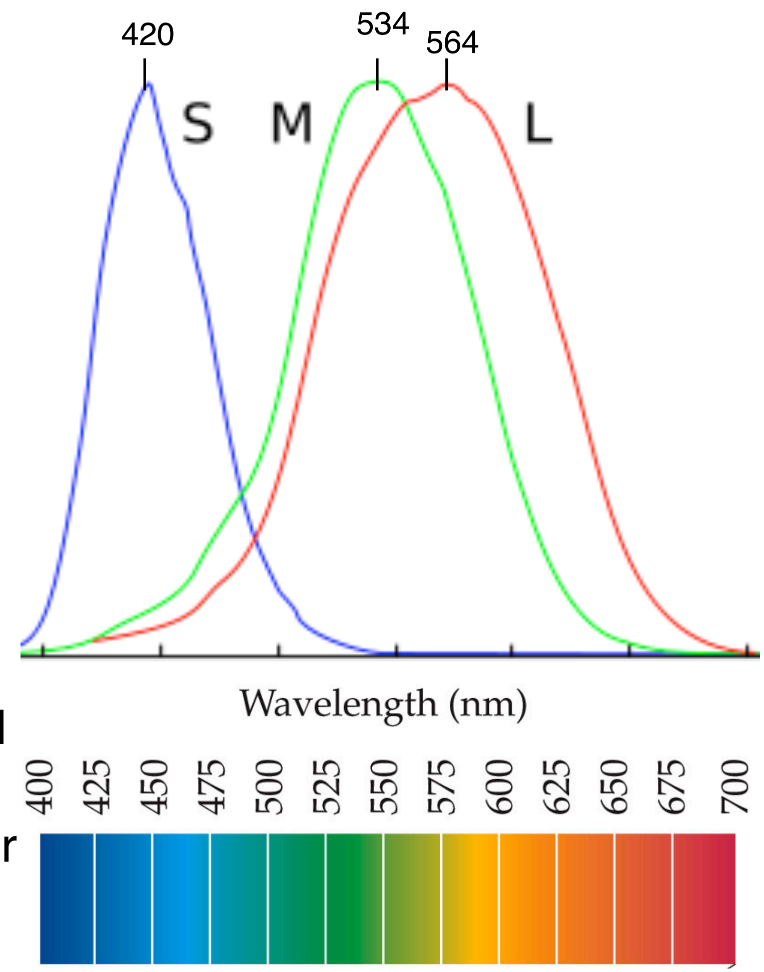



13 measurements of power spectrum (example)

## Basic Principles of Color Perception

**Q:** How many measurements of this same spectrum does the human eye take (in bright conditions?)

photoreceptor response

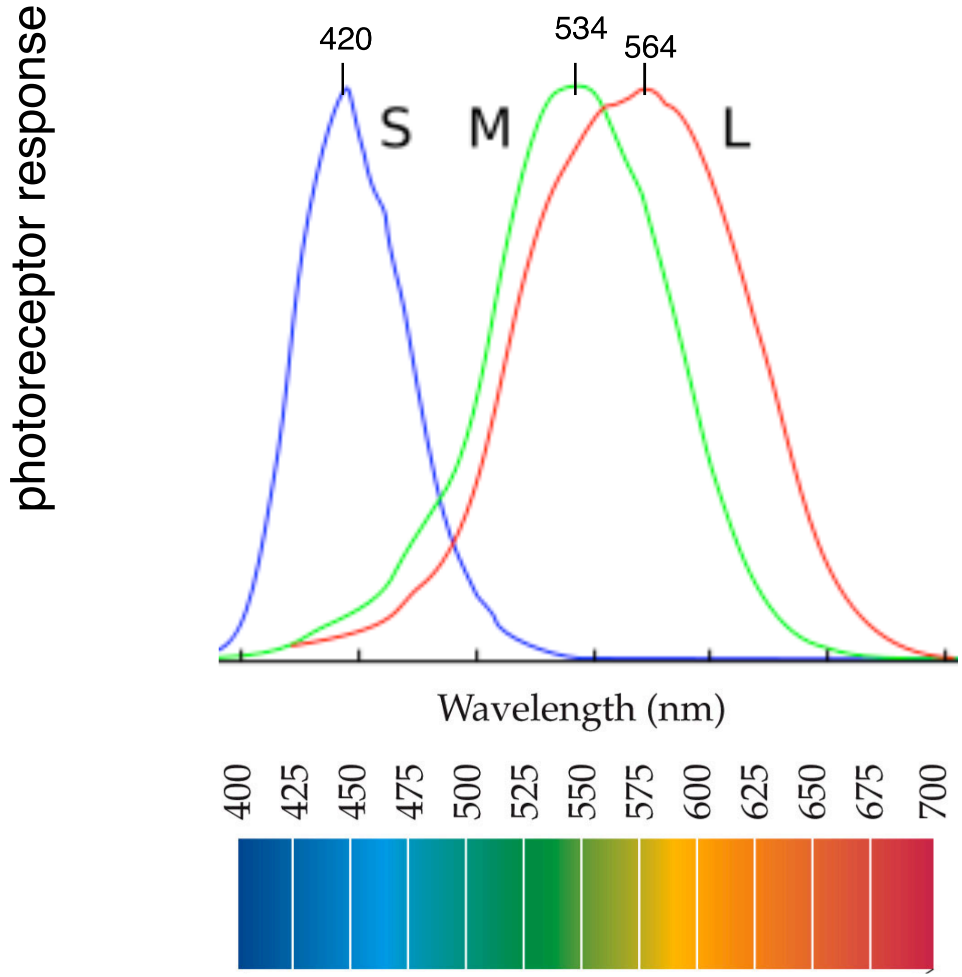



could also call this axis "*absorption*" or "*sensitivity*"

**A:** Only 3! One measurement from each cone class

- tell how to "add up" the energy from different parts of spectrum in order to generate cone response

## Relies on comparing the responses of the three cones!




**cone types**

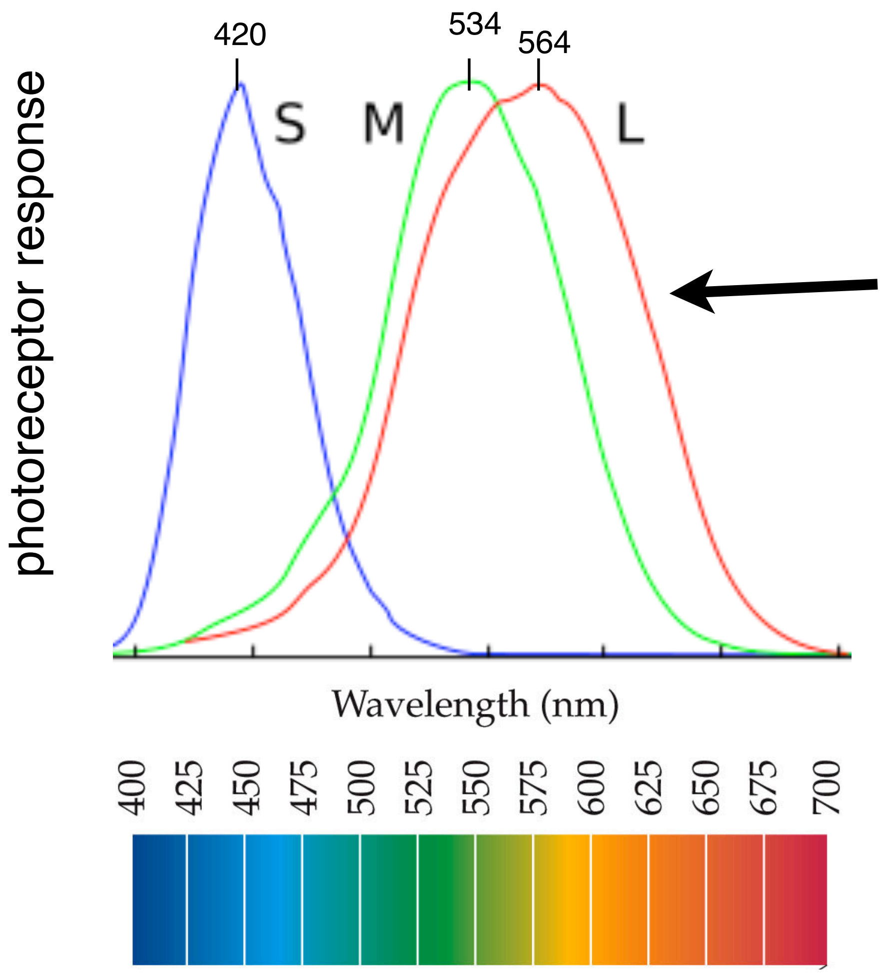
S = short (blue)

M = medium (green)

L = long (red)

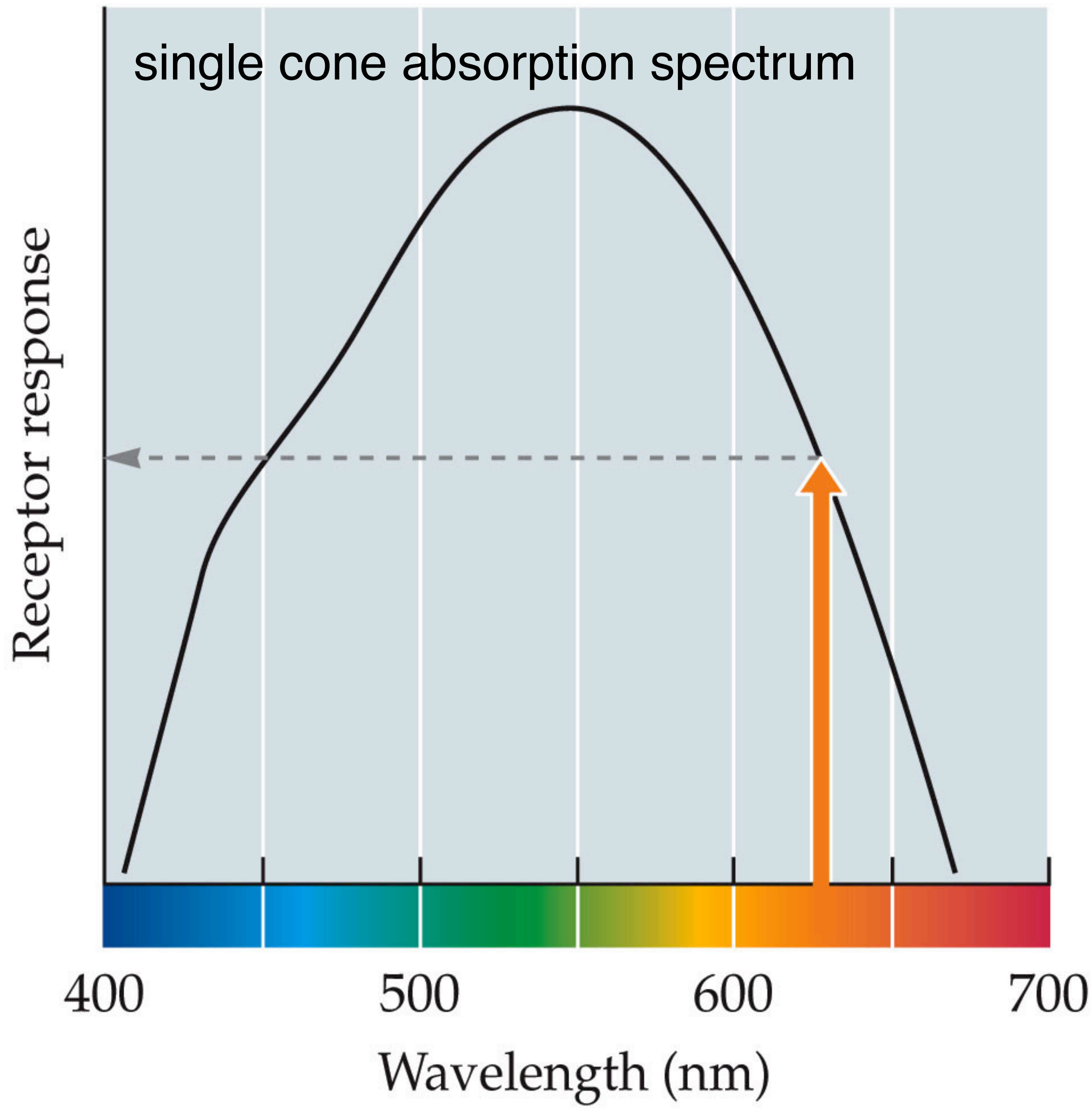
## More terminology:

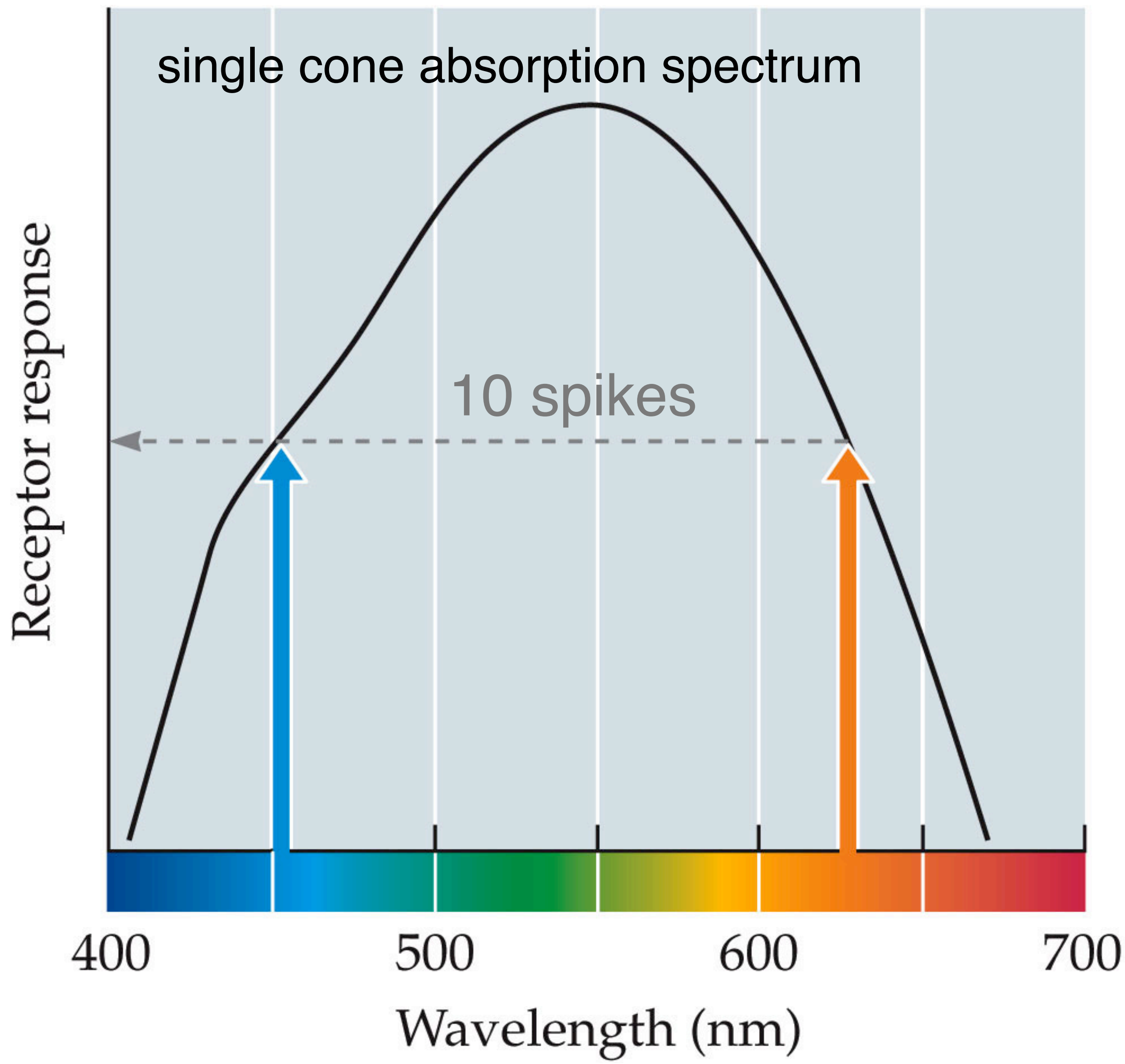
**absorption spectrum** - describes response (or "light absorption") of a photoreceptor as a function of frequency




Absorption spectrum for "L" (red) cone

# A single photoreceptor doesn’t “see” color; it gives greater response to some frequencies than others

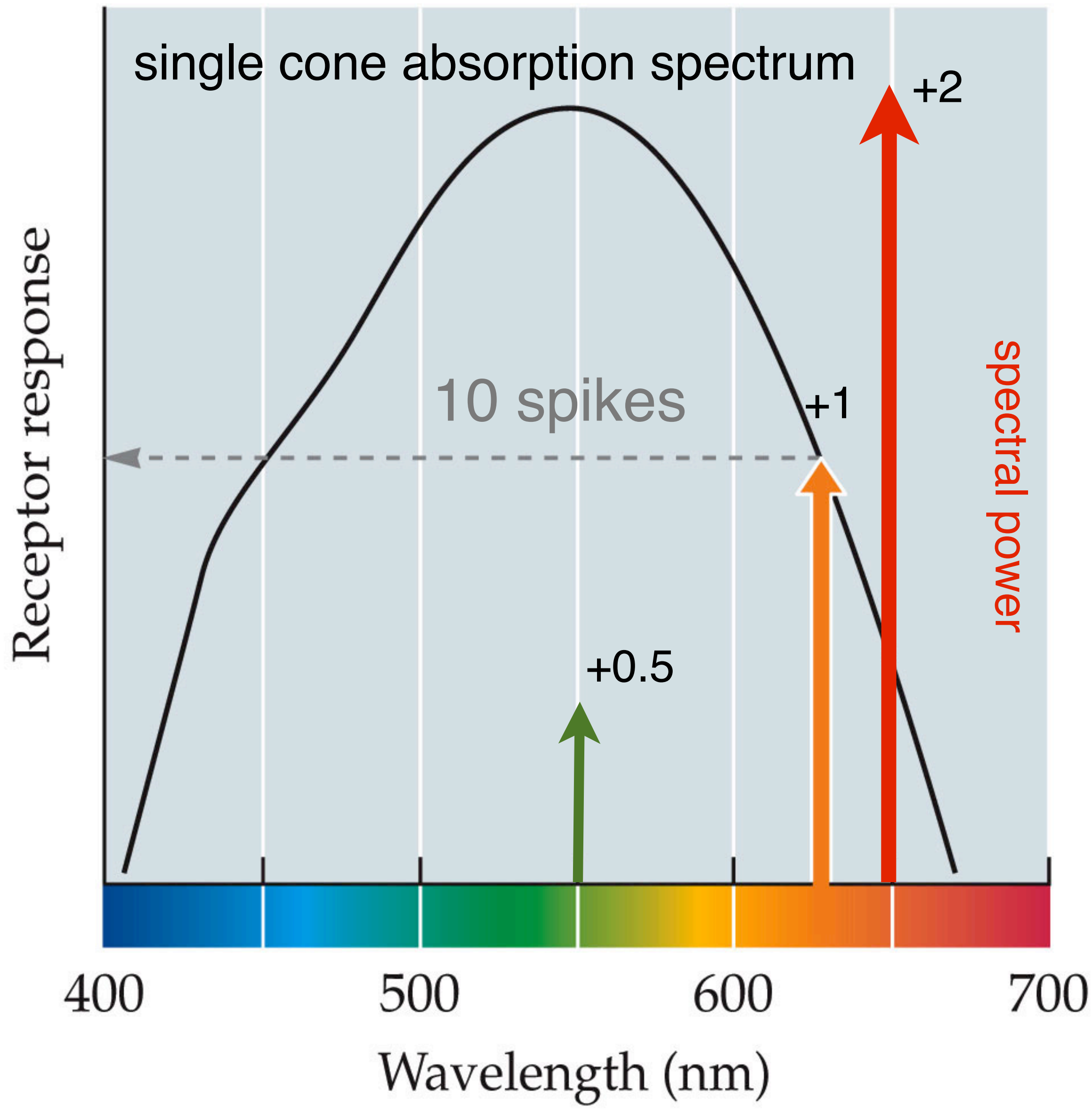





- All the photoreceptor gives you is a “response”

- Can’t tell which light frequency gave rise to this response (blue or orange)

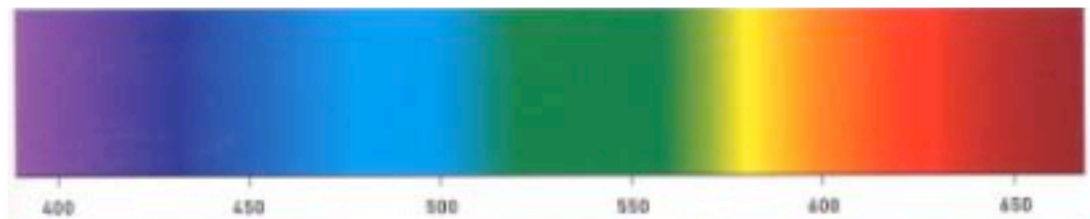
Problem of **univariance**: An infinite set of different wavelength–intensity combinations can elicit exactly the same response from a single type of photoreceptor



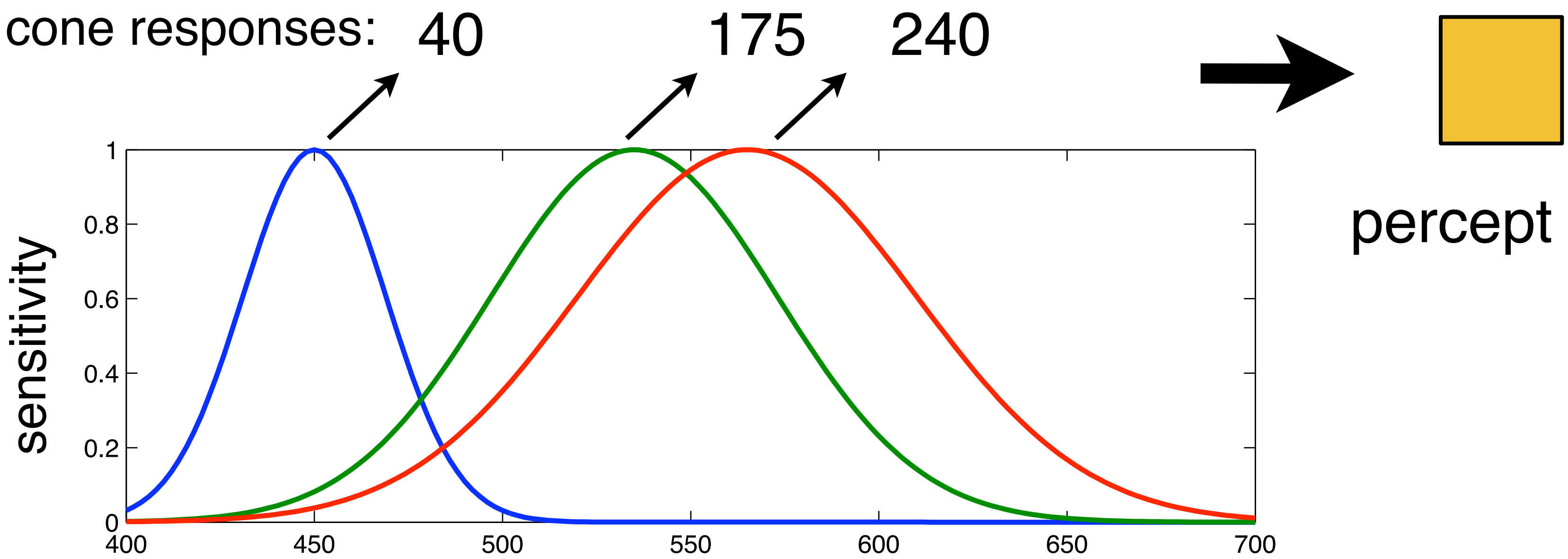

- Therefore, one type of photoreceptor cannot make color discriminations based on wavelength

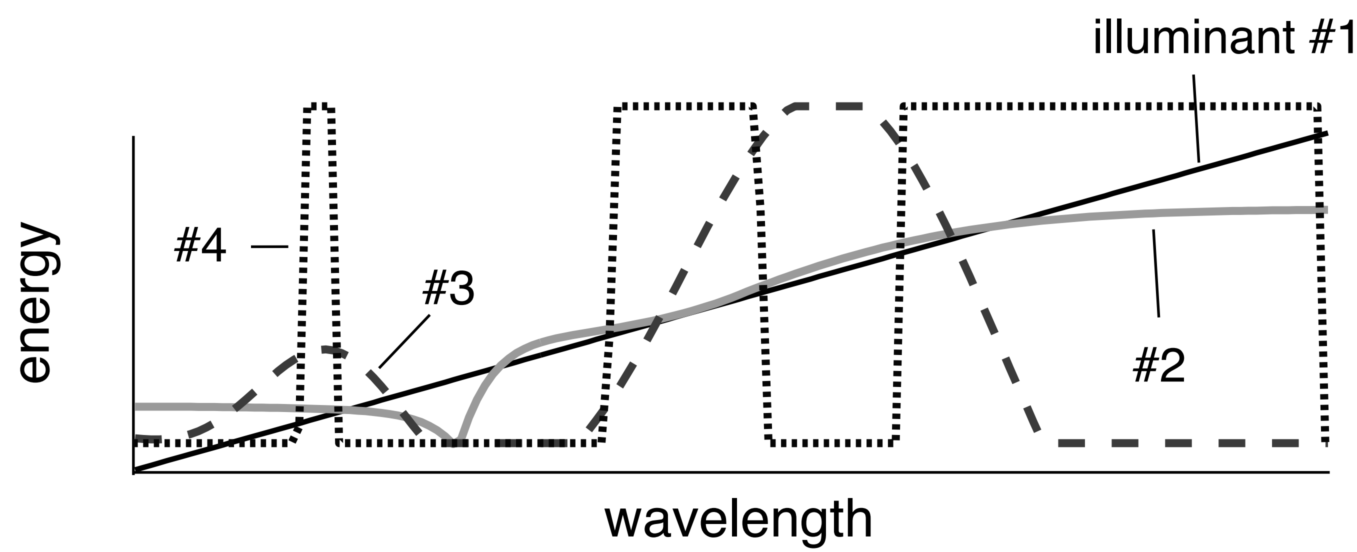
So a single cone can’t tell you anything about the color of light!

Colored stimulus




Response of your
“S” cones



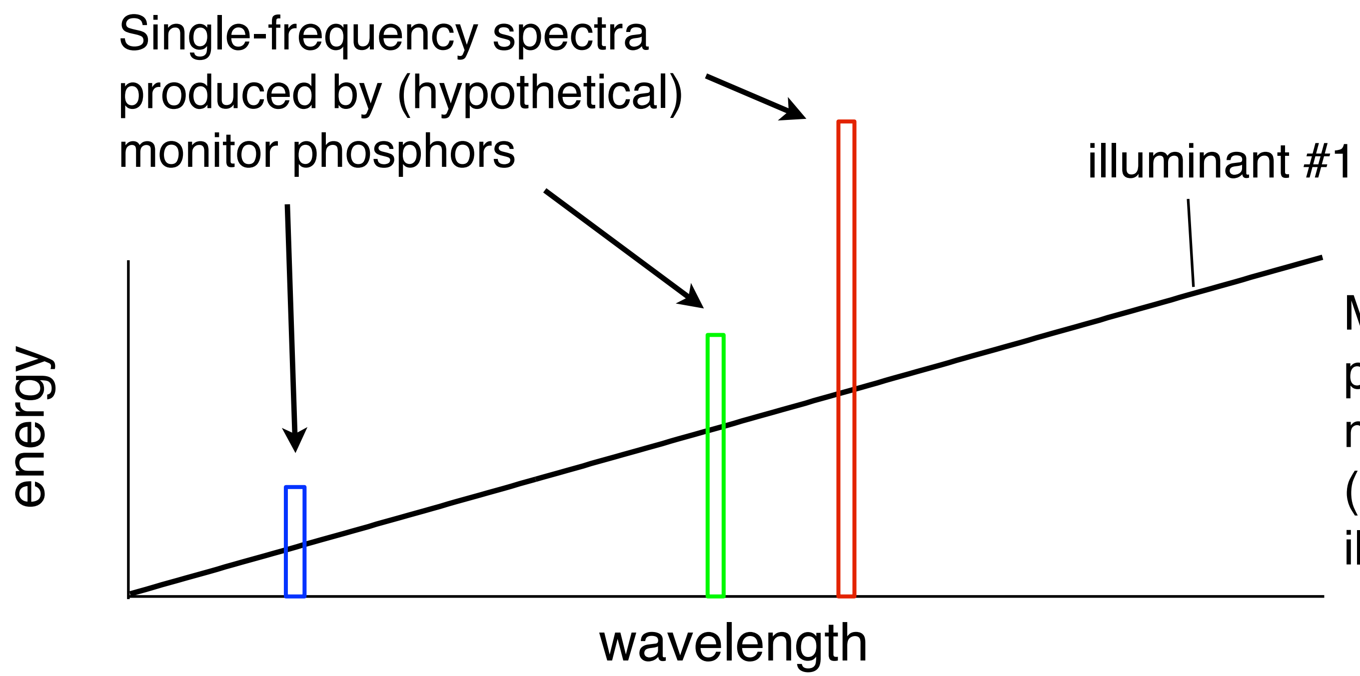




## Metamers

- Illuminants that are physically distinct but perceptually indistinguishable

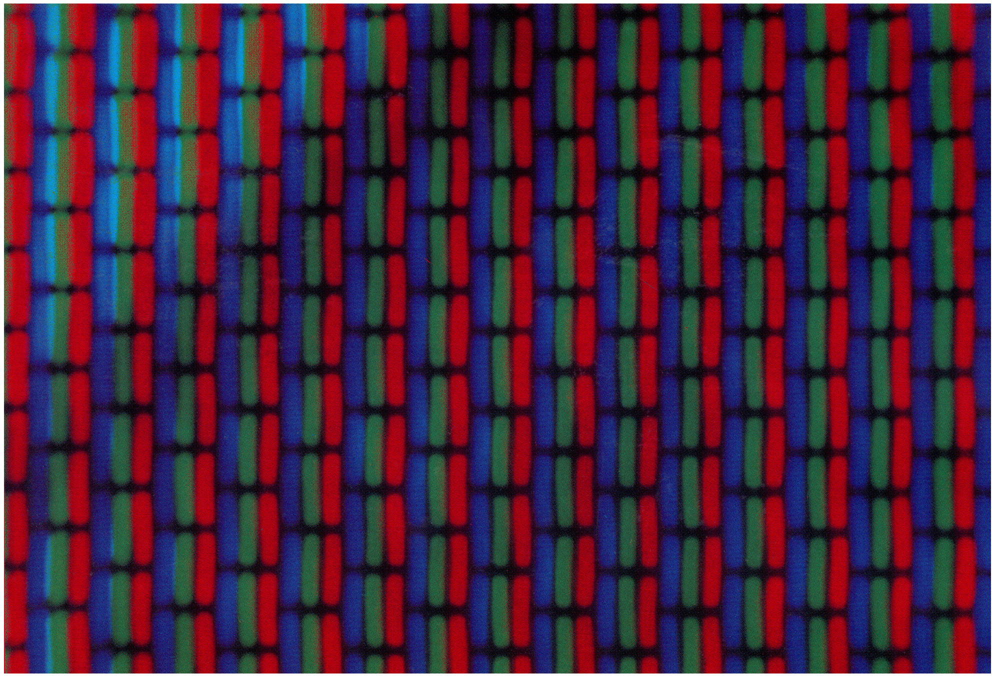
Implication: tons of things in the natural world have different spectral properties, but look the same to us.

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

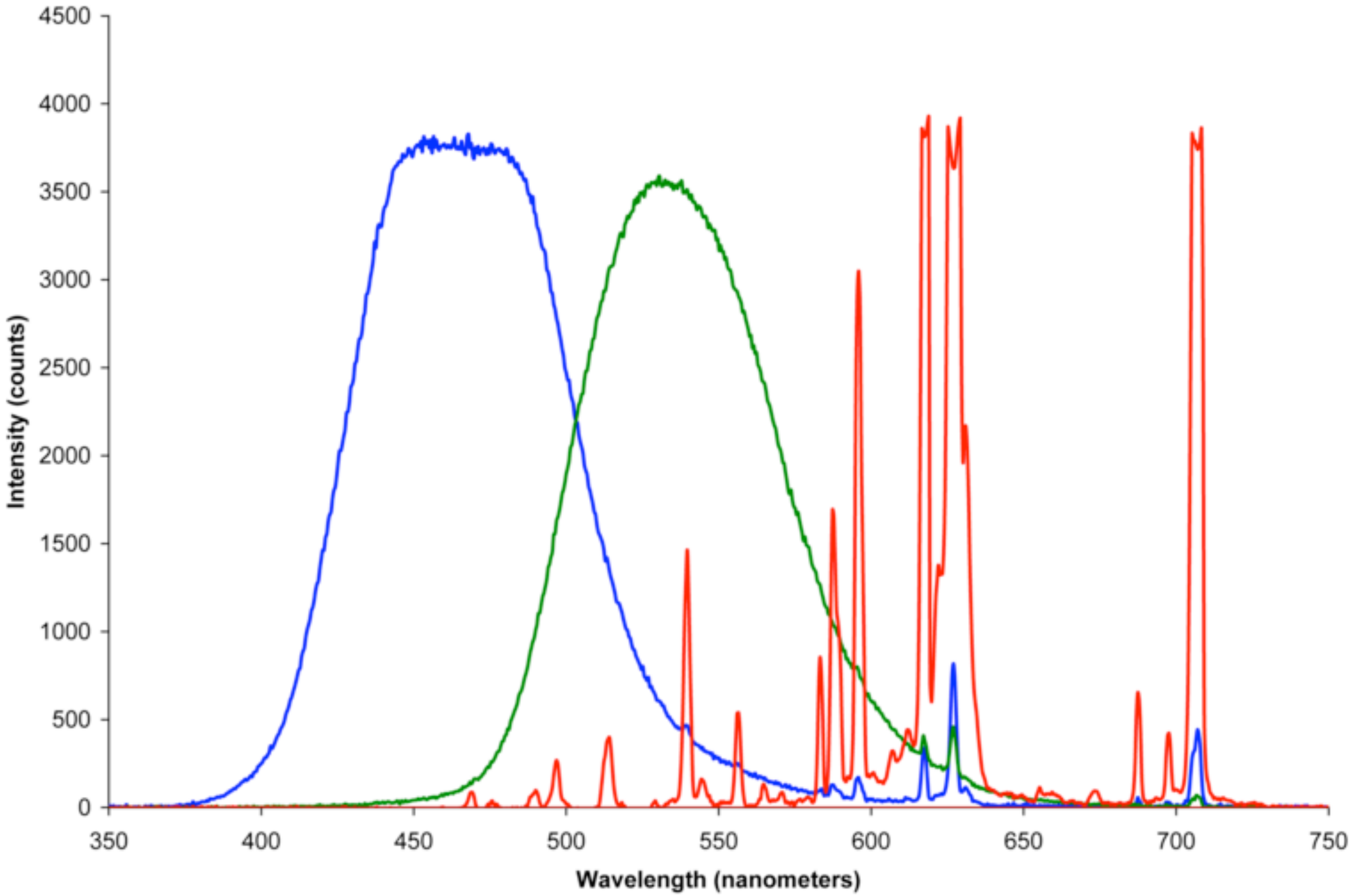



Monitor phosphors produce “metameric match” to illuminant #1 (or any other possible illuminant).

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



# Spectra of typical CRT monitor phosphors

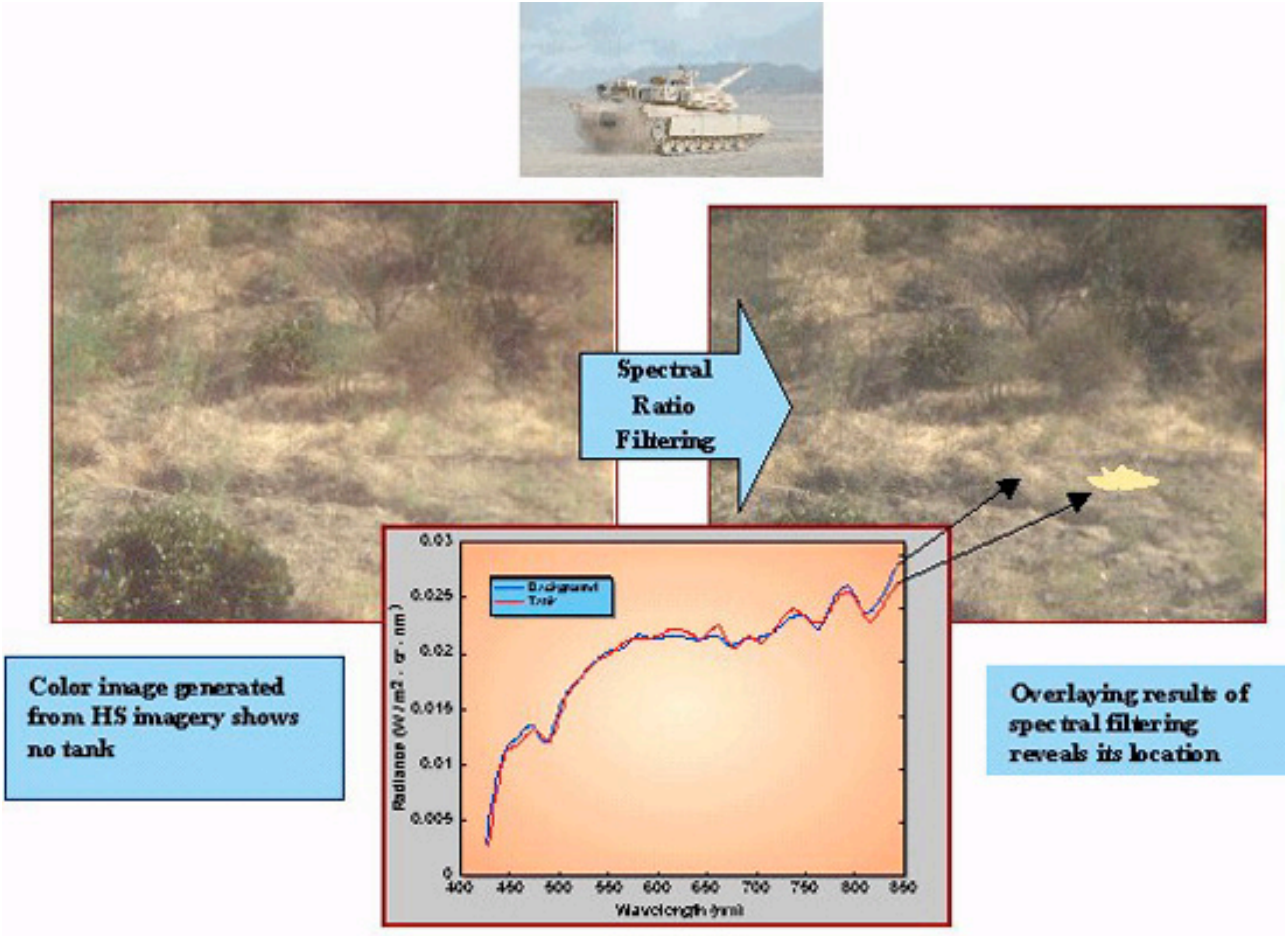


This wouldn't be the case if we had more cone classes.

hyperspectral marvel:
*mantis shrimp*
*(stomatopod)*

- 12 different cone classes
- sensitivity extending into UV range

- No surprise that they never invented color TV!


Spectral
Ratio
Filtering
Color image generated from HS imagery shows no tank
Overlaying results of spectral filtering reveals its location
Background
Tank
Radiance (W/m2 · sr · nm)
Wavelength (nm)
0.03
0.025
0.02
0.015
0.01
0.005
0
400
450
500
550
600
650
700
750
800
850

RGB Image

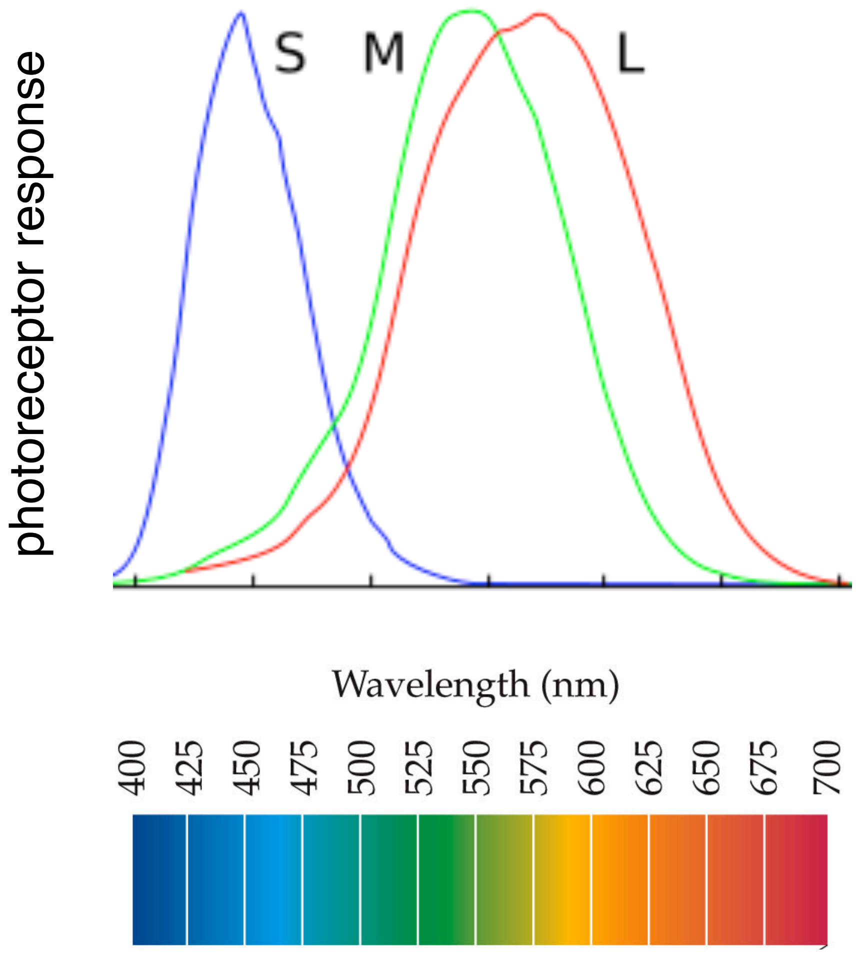
RGB Image Processed With Spectral Filter

Worth knowing about if you end up seeking employment in the “informal” sector following graduation.

(or law enforcement)

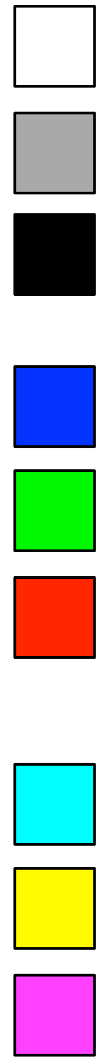
# Color vision

**Our color vision relies on comparing the responses of three cone classes**



## Cone responses entirely determine our color percepts:

| S | M | L |
|---|---|---|
| 100 | 100 | 100 |
| 50 | 50 | 50 |
| 0 | 0 | 0 |
| 100 | 0 | 0 |
| 0 | 100 | 0 |
| 0 | 0 | 100 |
| 100 | 100 | 0 |
| 0 | 100 | 100 |
| 100 | 0 | 100 |

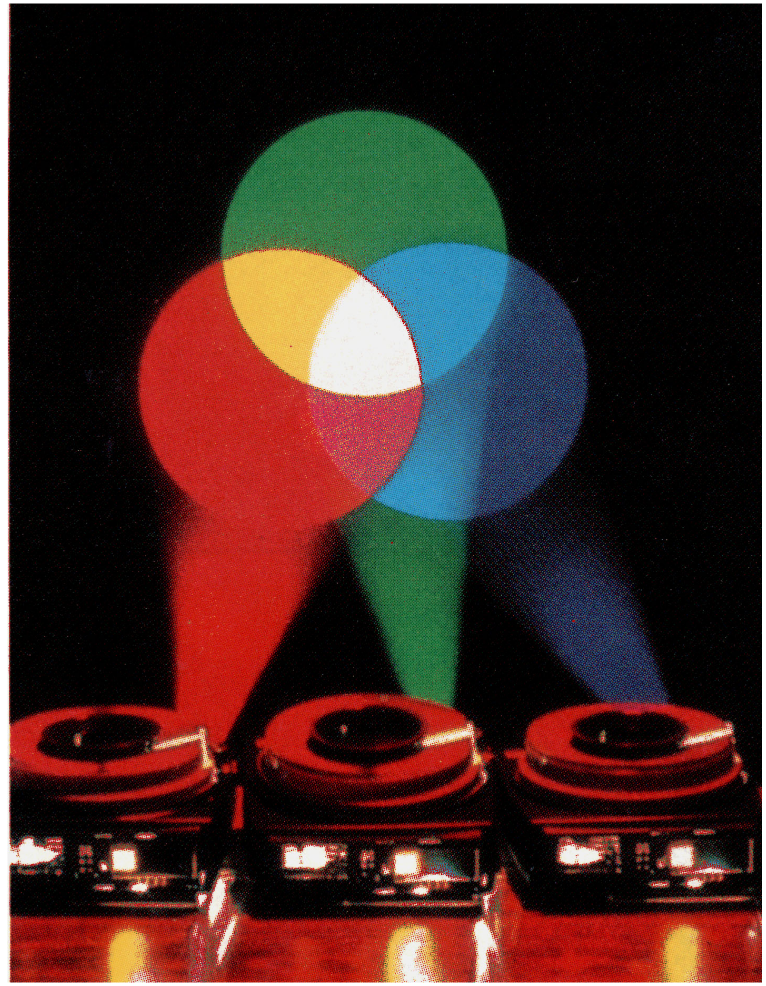


"non-spectral hues"

- percept couldn't be produced by any single-wavelength light

3 “primary” lights

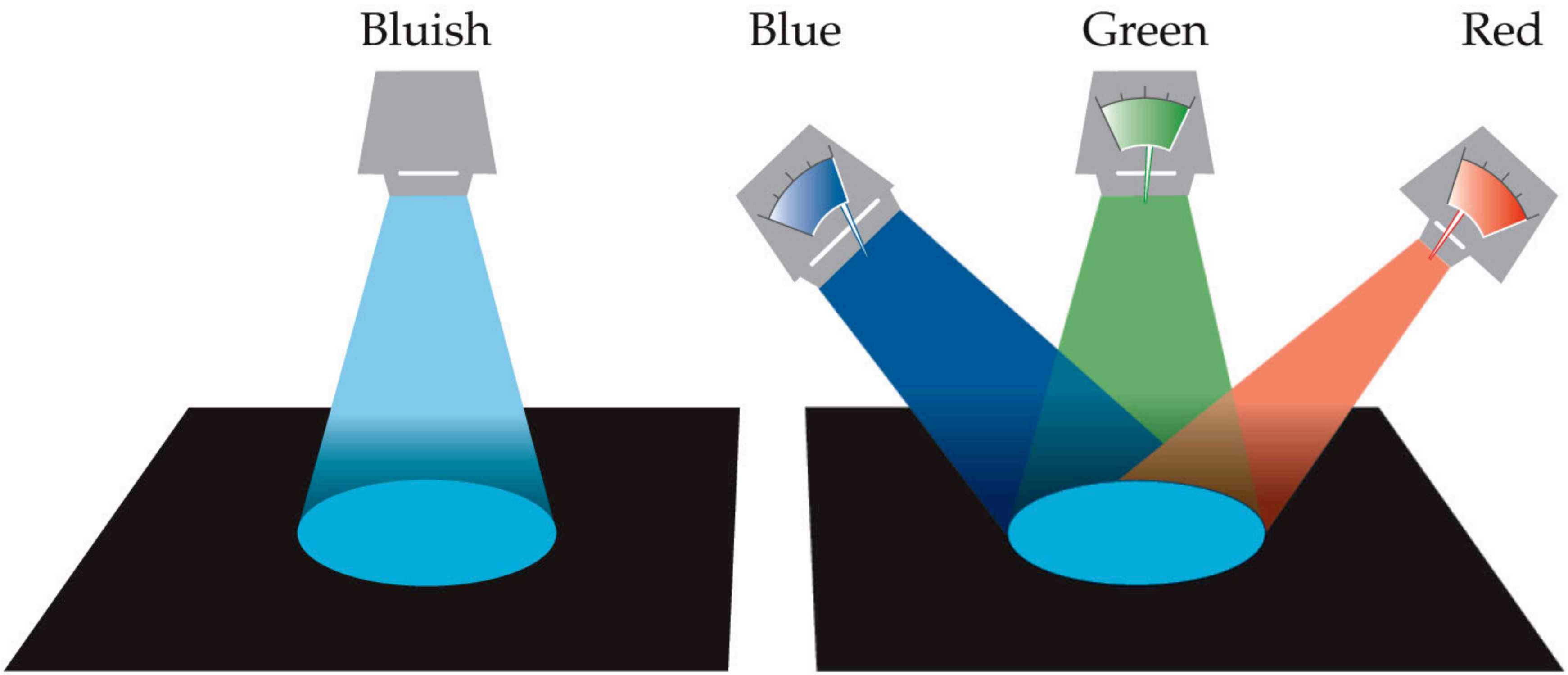
<u>any</u> color can be made by combining three suitable lights...



R G B

How did they figure this out?

# James Maxwell: color-matching experiment



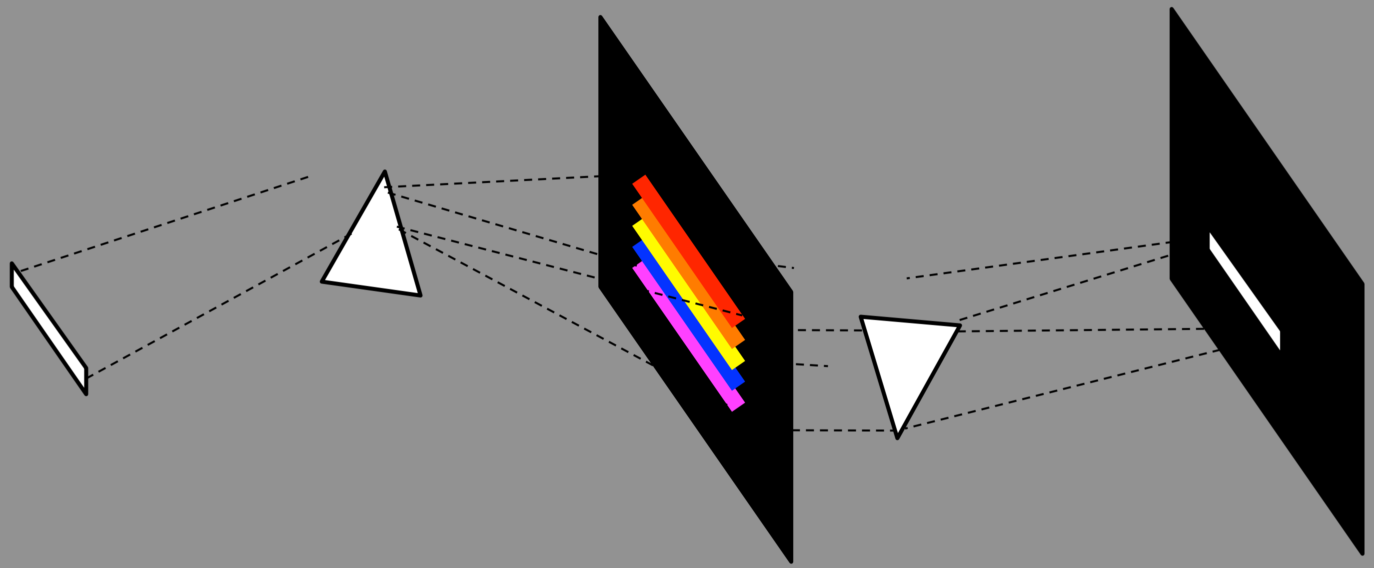

Given any “test” light, you can match it by adjusting the intensities of any three other lights
(2 is not enough; 4 is more than enough)

**Trichromatic color vision**: (Young & Helmholtz theory)

- "three" lights needed to make a specific color percept

- due to having 3 distinct cones with different sensitivities

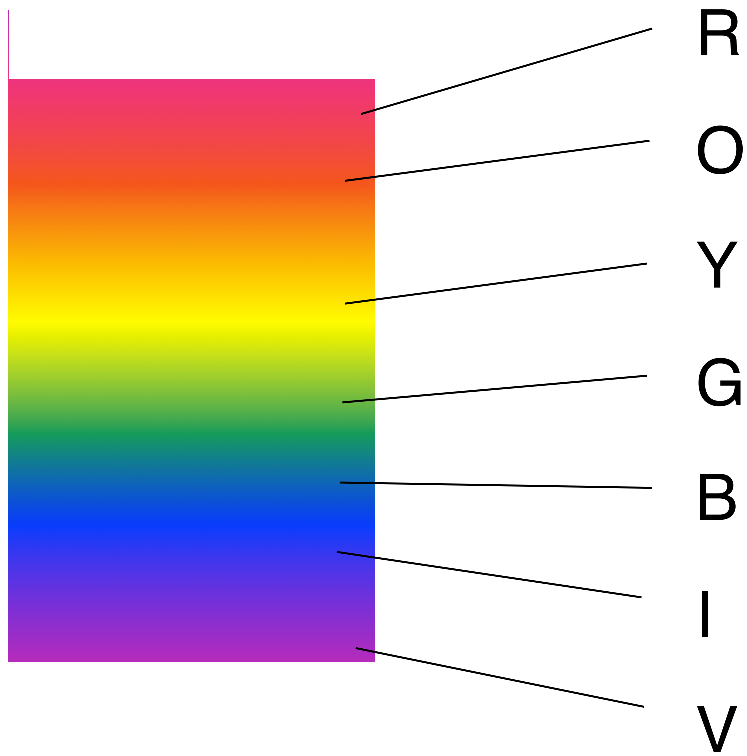
- colors are uniquely defined by combinations of cone activations



Late 17th Century: Isaac Newton

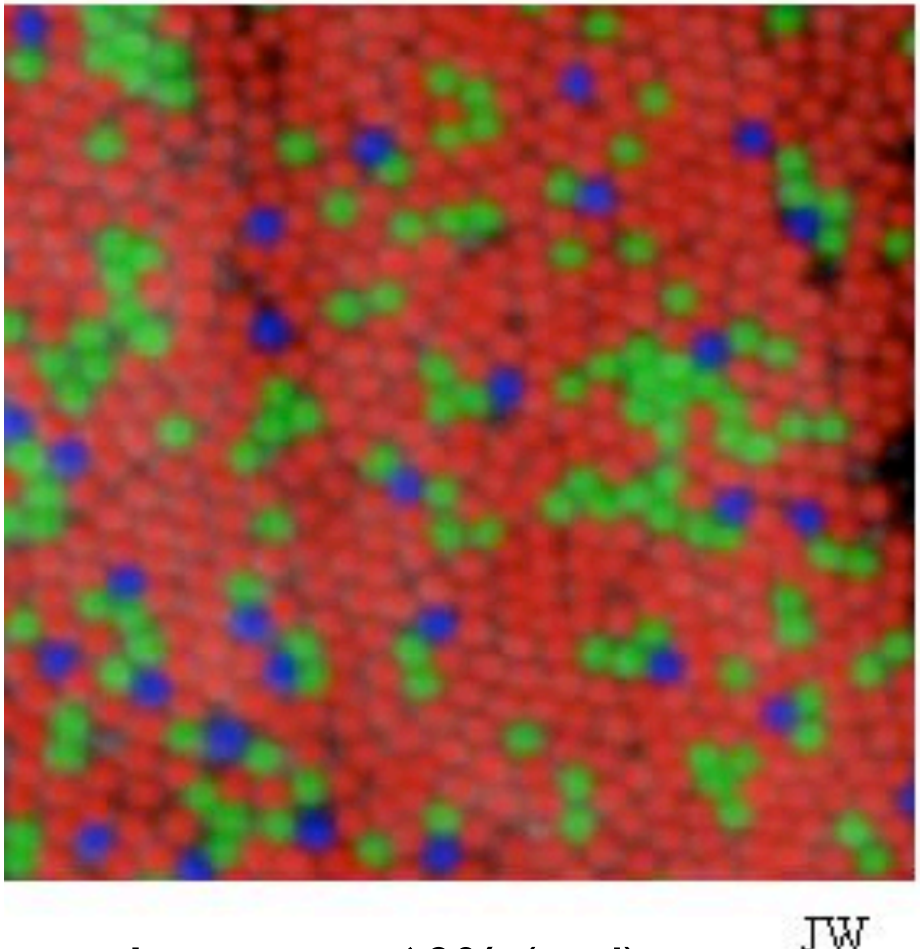
“The rays themselves, to speak properly, are not coloured”

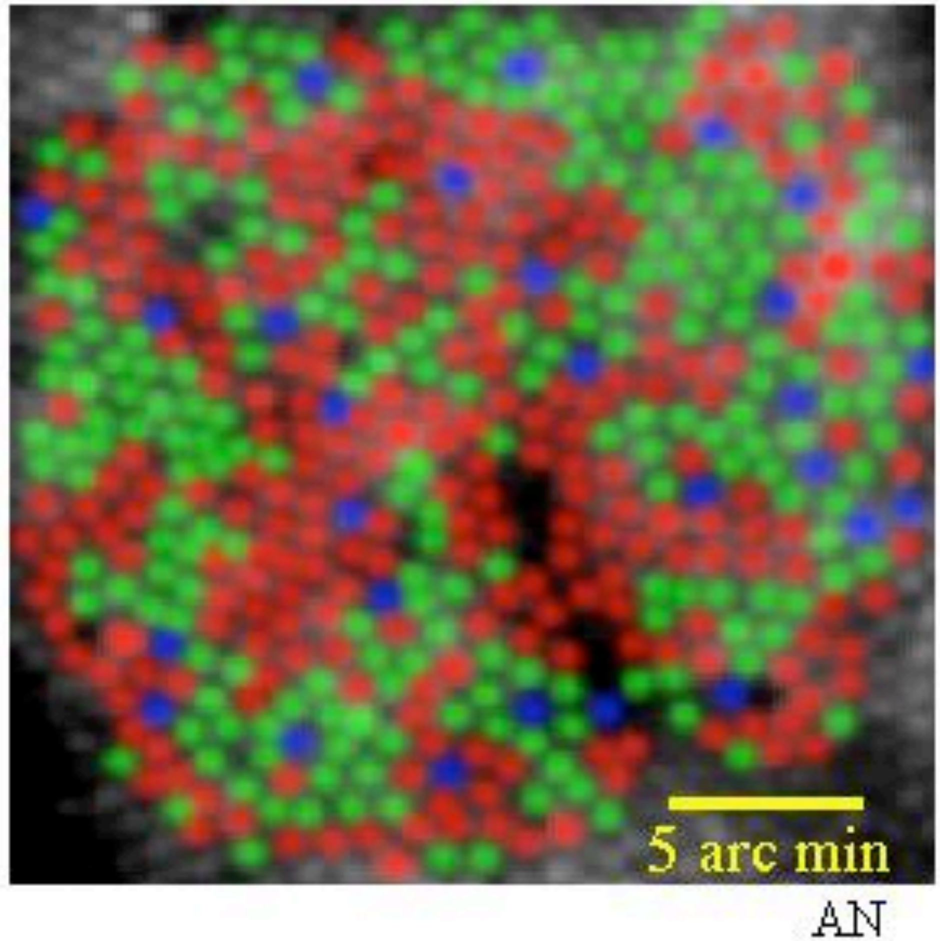
Newton’s Spectrum:




Newton’s Theory:
seven kinds of light -> seven kinds of photoreceptor

# First images of human trichromatic cone mosaic
(Roordra & Wililams, Nature 1999)




L cones: ~60% (red)
M cones: ~30% (green)
S cones ~10% (blue)

Notice the variability between individuals!

# However, this doesn't quite explain everything

Why does staring at red produce the green after-image?

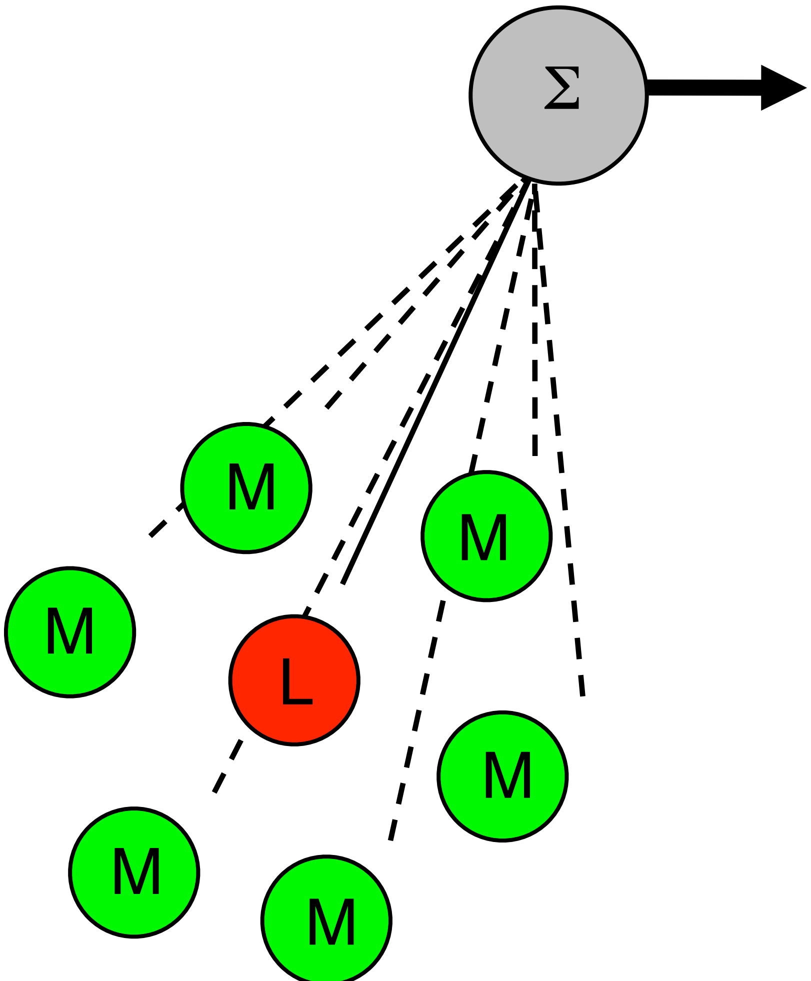
# **Opponent color theory**:

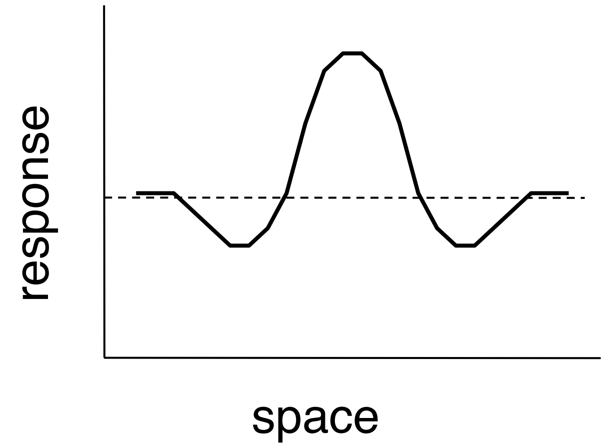
- perception of color is based on the output of three mechanisms, each based on an opponency between two colors

## Opponent Channels:

- L-M (red - green)
- S - (L+M) (blue -yellow)
- L+M - (L+M) (black - white )

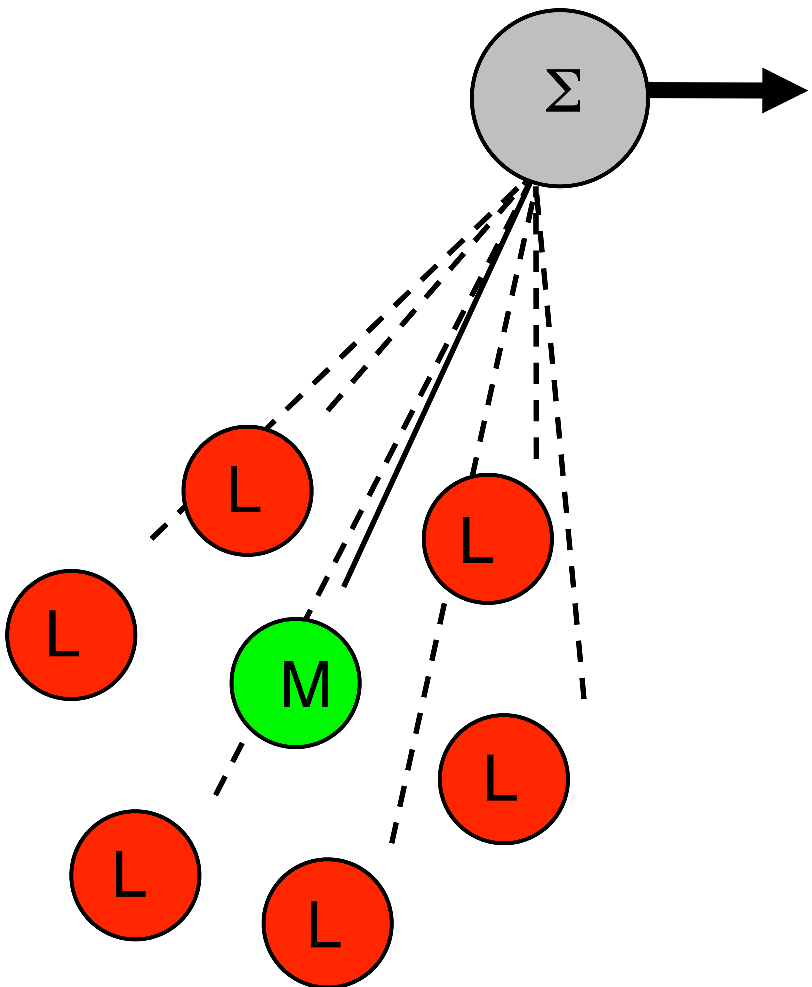
# Some Retinal Ganglion Cells have center-surround receptive fields with "color-opponency"

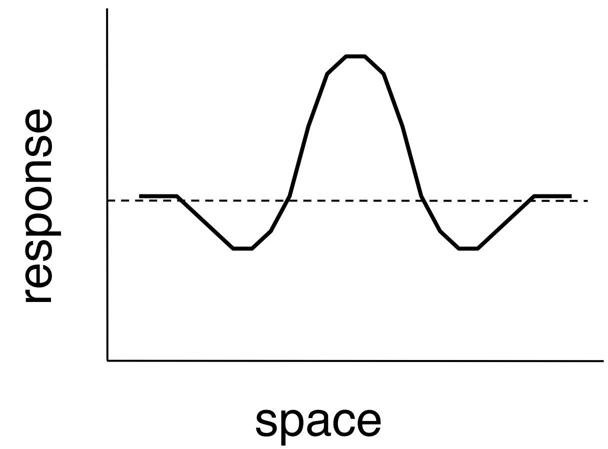



- Red-Green (L - M) Color-Opponent cell
- Carries info about red vs. green

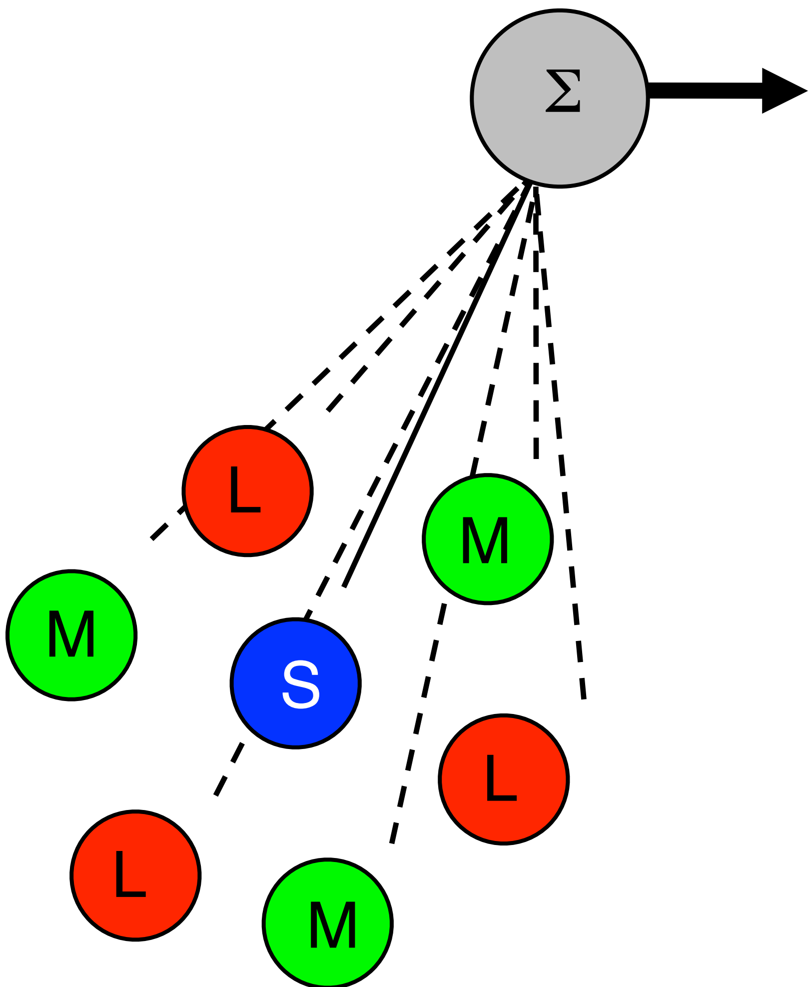
Some Retinal Ganglion Cells have center-surround receptive fields with "color-opponency"

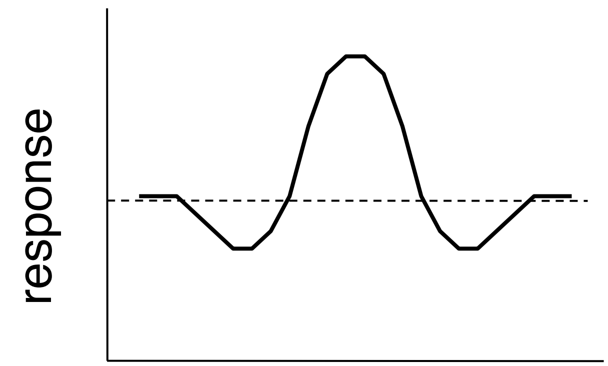



- Red-Green (M-L) Color-Opponent cell
- Carries info about red vs. green

Some Retinal Ganglion Cells have center-surround receptive fields with “color-opponency”




- Blue-Yellow (S-(M+L)) Opponent cell
- Carries info about blue vs. yellow

# 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)
- This is a way to see opponent colors in action

examine color after-effects

lilac chaser:

http://www.michaelbach.de/ot/col_lilacChaser/index.html

So far we've addressed:

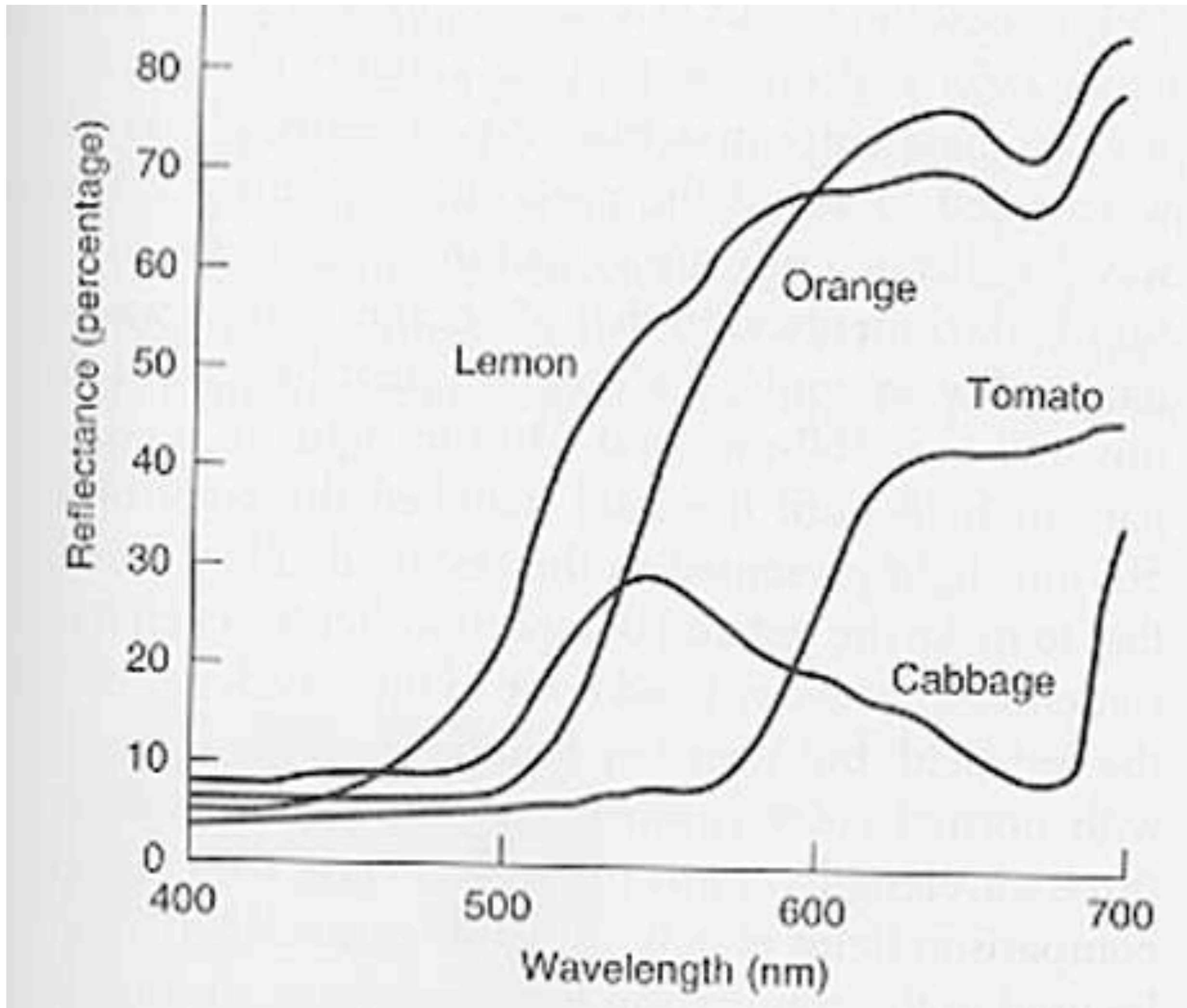
1) The illuminant ("light source")
2) Cones & opponent ganglion cells
("detecting & processing the light")

Q: what's missing?

A: how does the "color" of objects determine the light hitting our eyes?

# 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:

Illuminant

defined by 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 spectrum

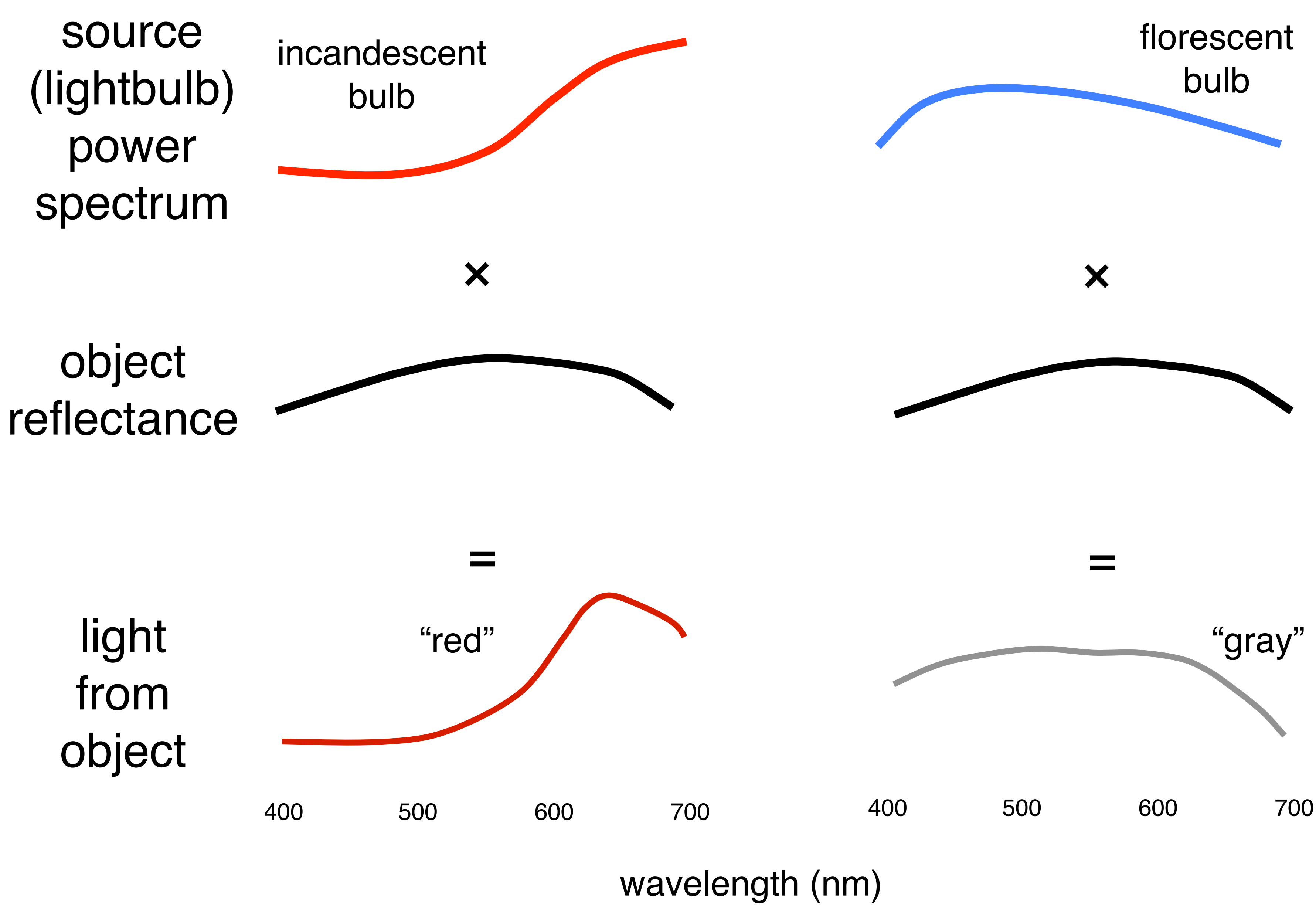
*each cone class adds up light energy according to its absorption spectrum*

↓

cone responses

three spectral measurements

*convey all color information to brain via opponent channels*


source
(lightbulb)
power
spectrum
incandescent
bulb
florescent
bulb
×
×
object
reflectance
=
=
light
from
object
“red”
“gray”
400
500
600
700
400
500
600
700
wavelength (nm)

But in general, this doesn't happen:

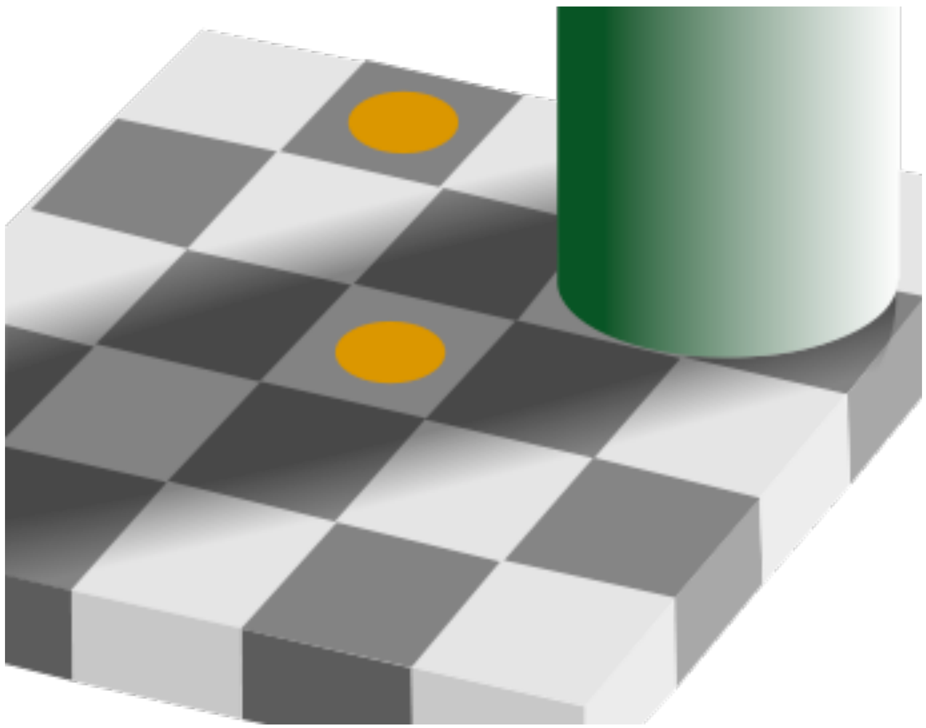
We don't perceive a white sheet of paper as looking reddish under a tungsten light and blueish/grayish under a halogen light.

# Color Constancy

The visual system uses a variety of tricks to make sure things look the same color, regardless of the illuminant (light source)

- **Color constancy** - tendency of a surface to appear the same color under a wide range of illuminants
- To achieve color constancy, we must discount the illuminant and determine the surface color, regardless of how it appears

# Illusion illustrating Color Constancy

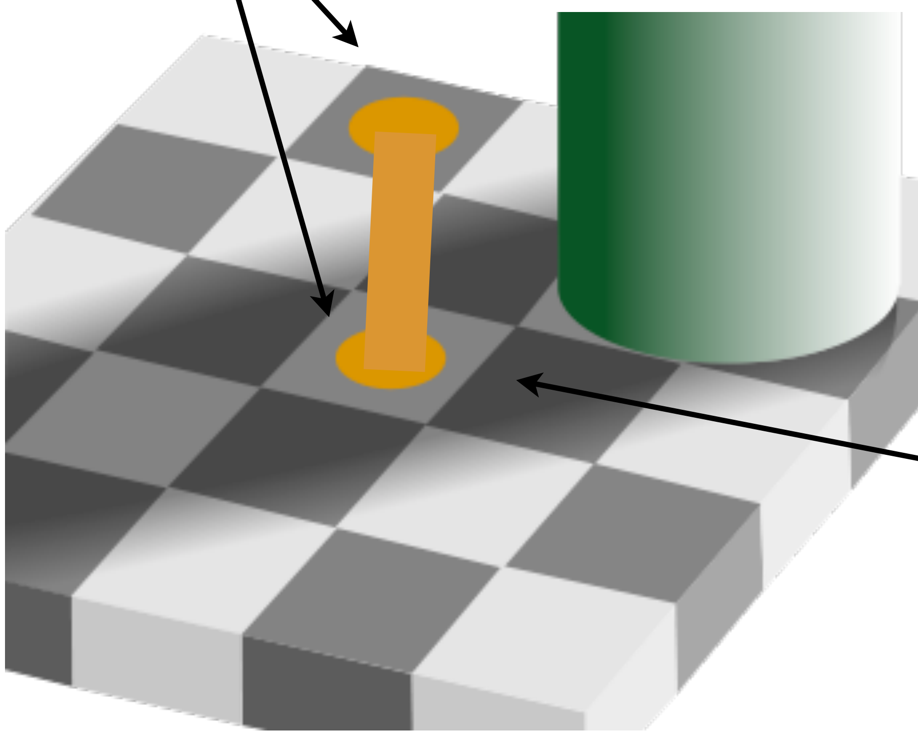


Same yellow in both patches

Same gray around yellow in both patches

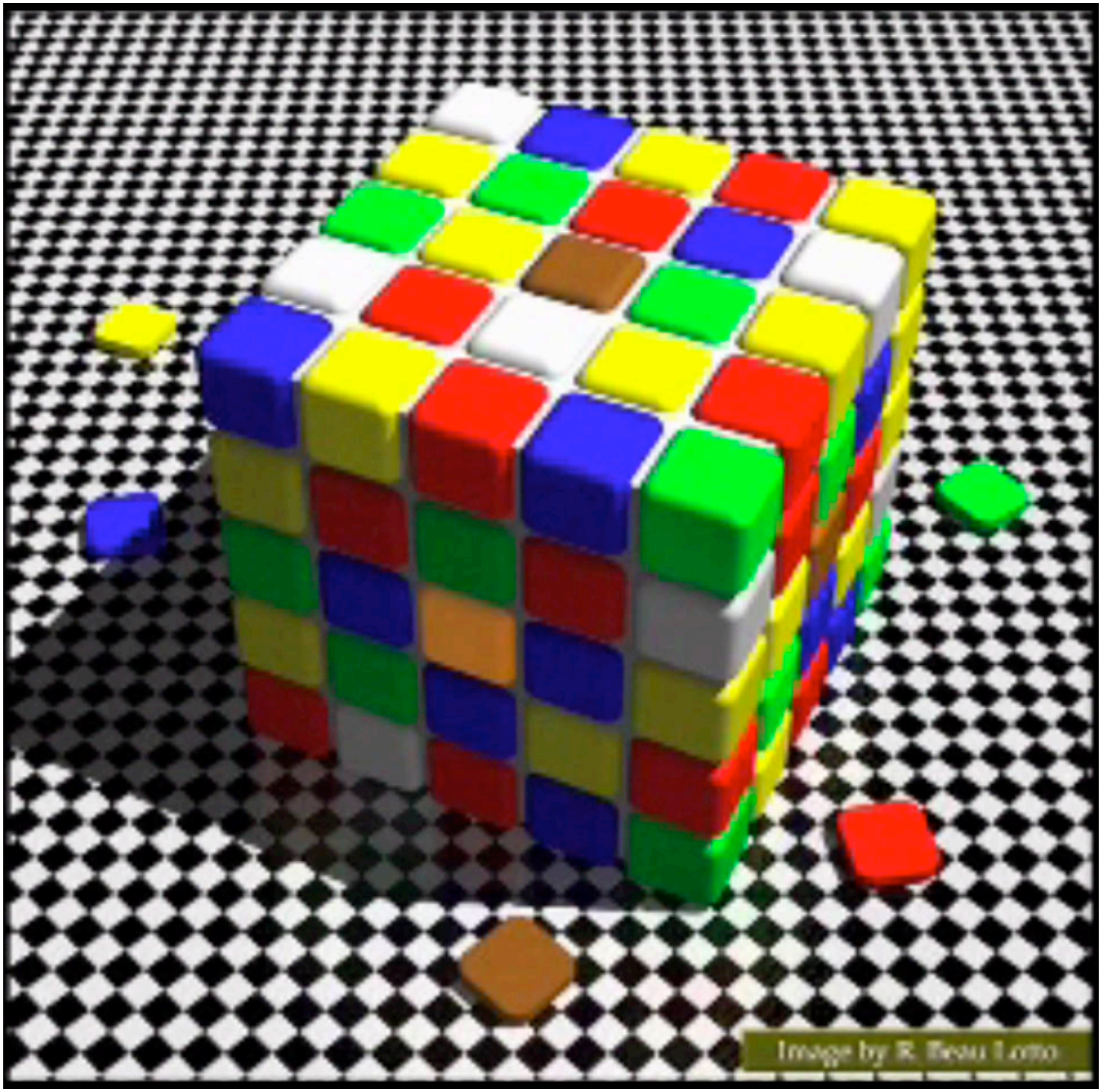
(the effects of lighting/shadow can make colors look different that are actually the same!)

Exact same light coming
to your eye from these
two patches

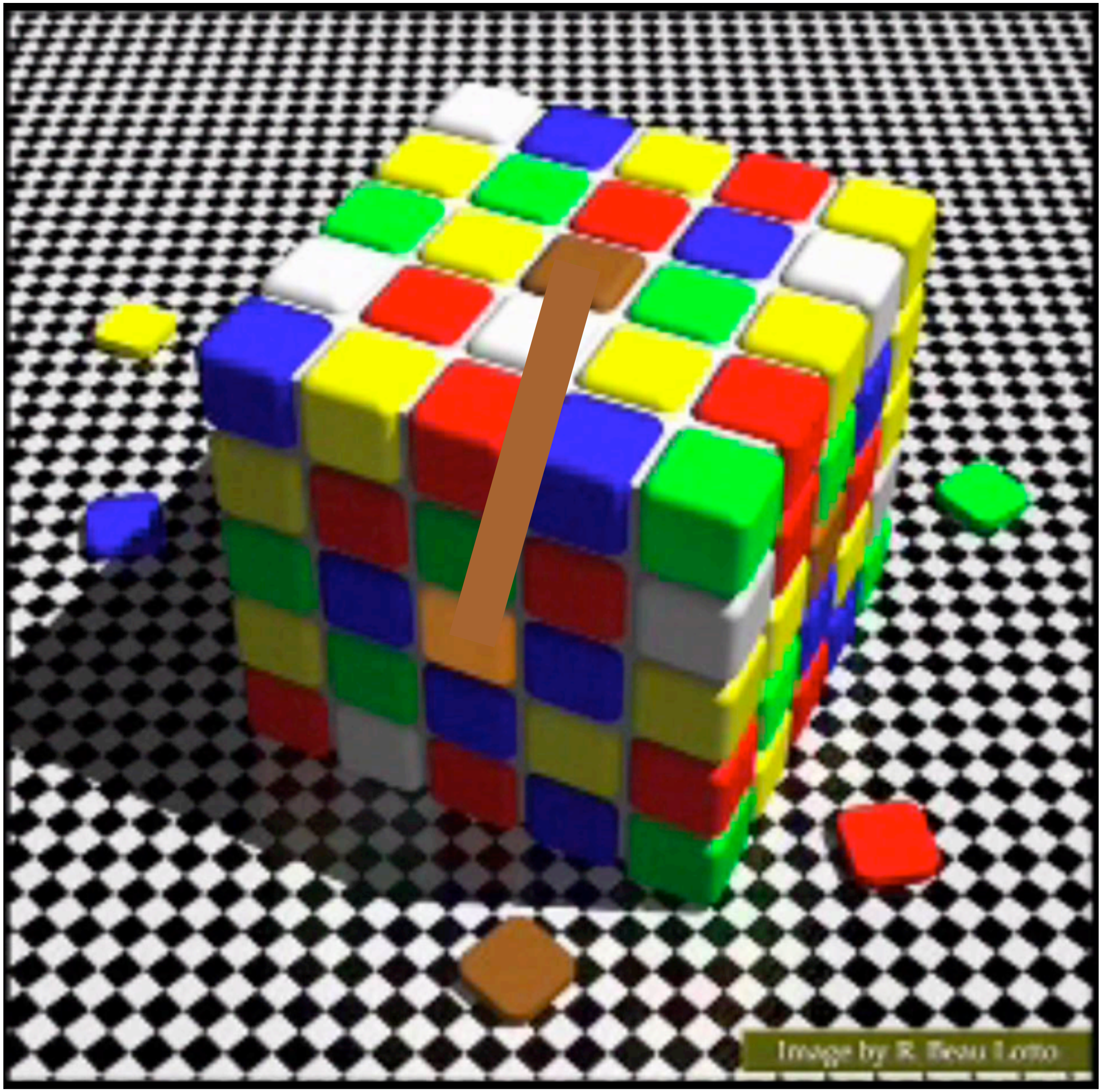


But the brain infers
that less light is hitting
this patch, due to
shadow

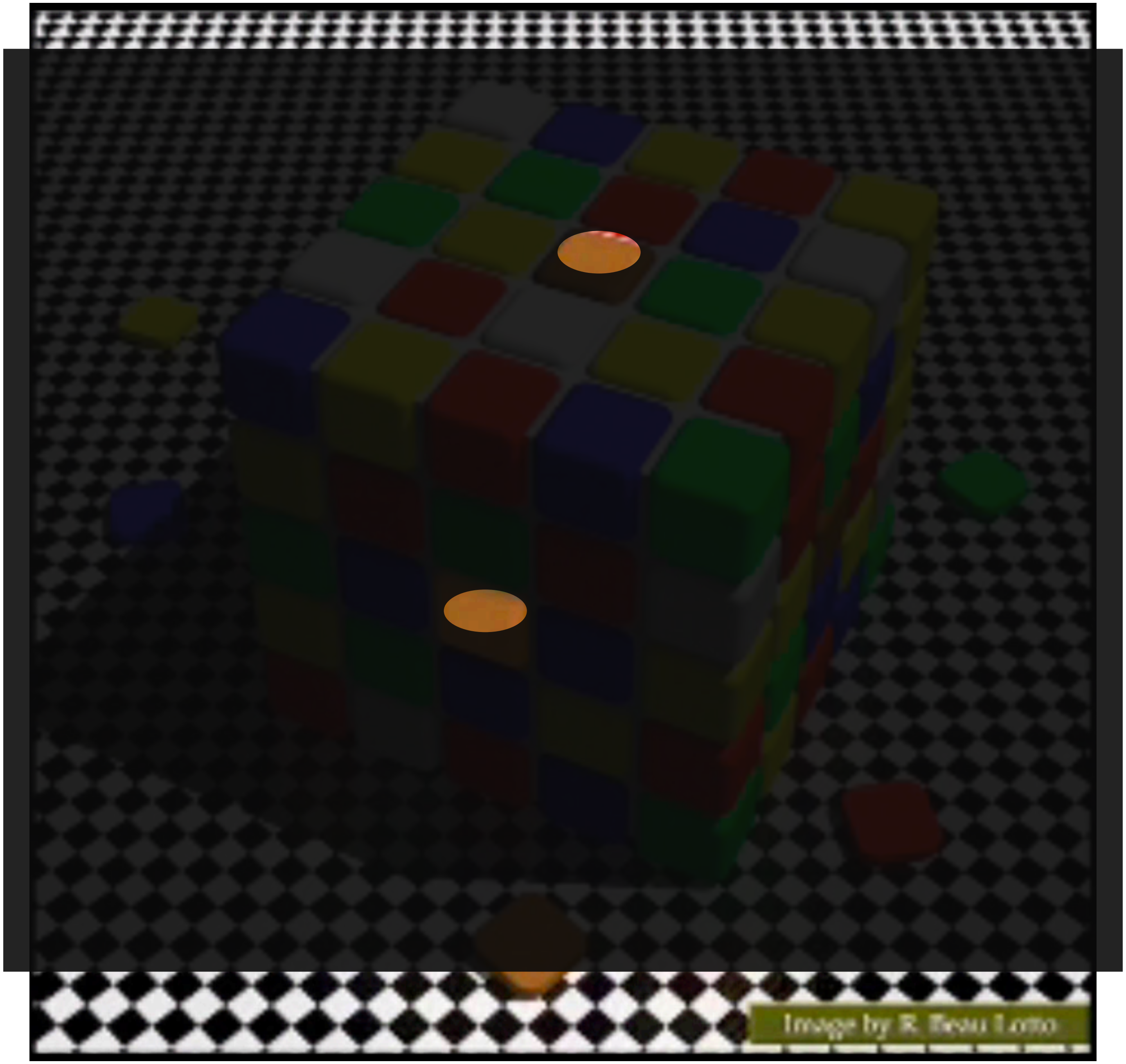
CONCLUSION: the lower patch must be reflecting a higher
fraction of the incoming light (i.e., it’s brighter)




Beau Lotto

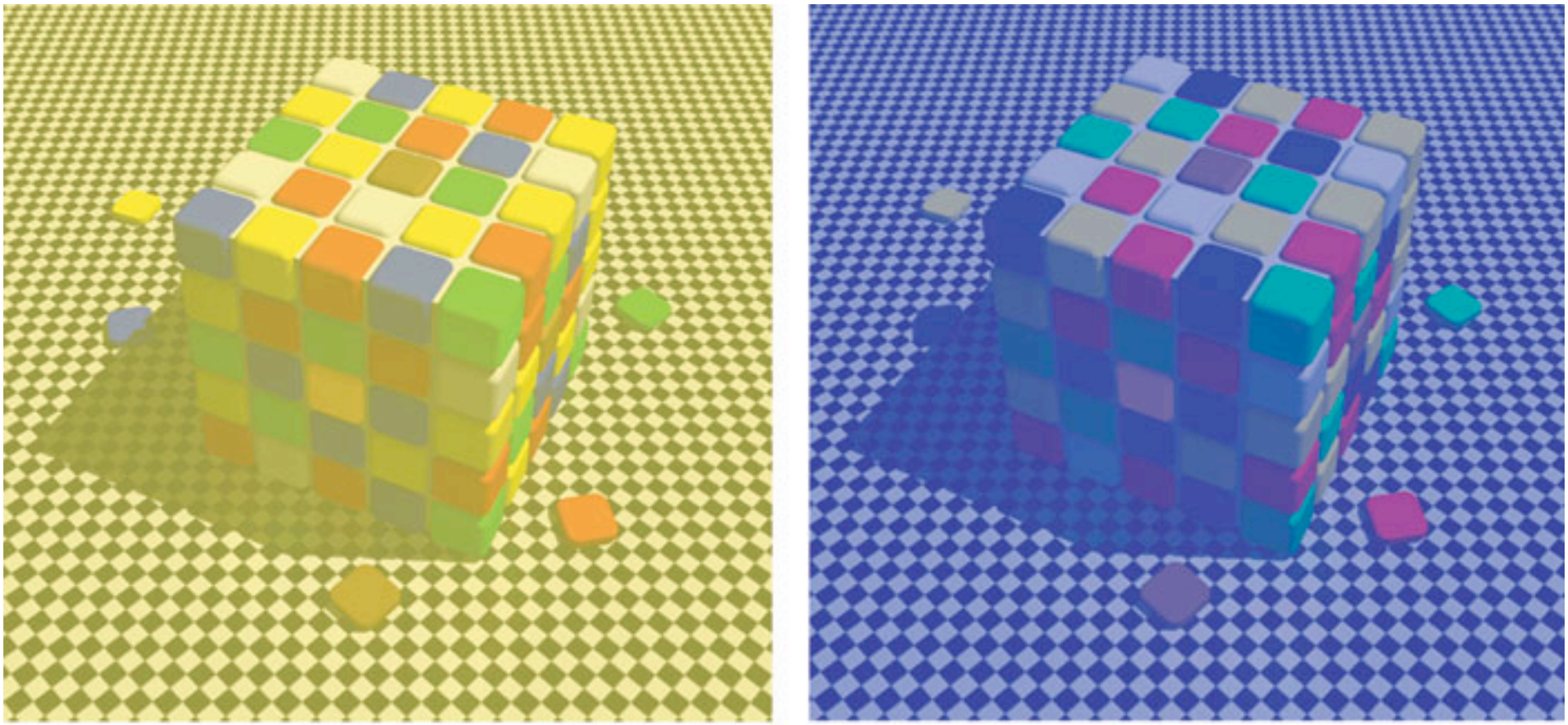



Beau Lotto



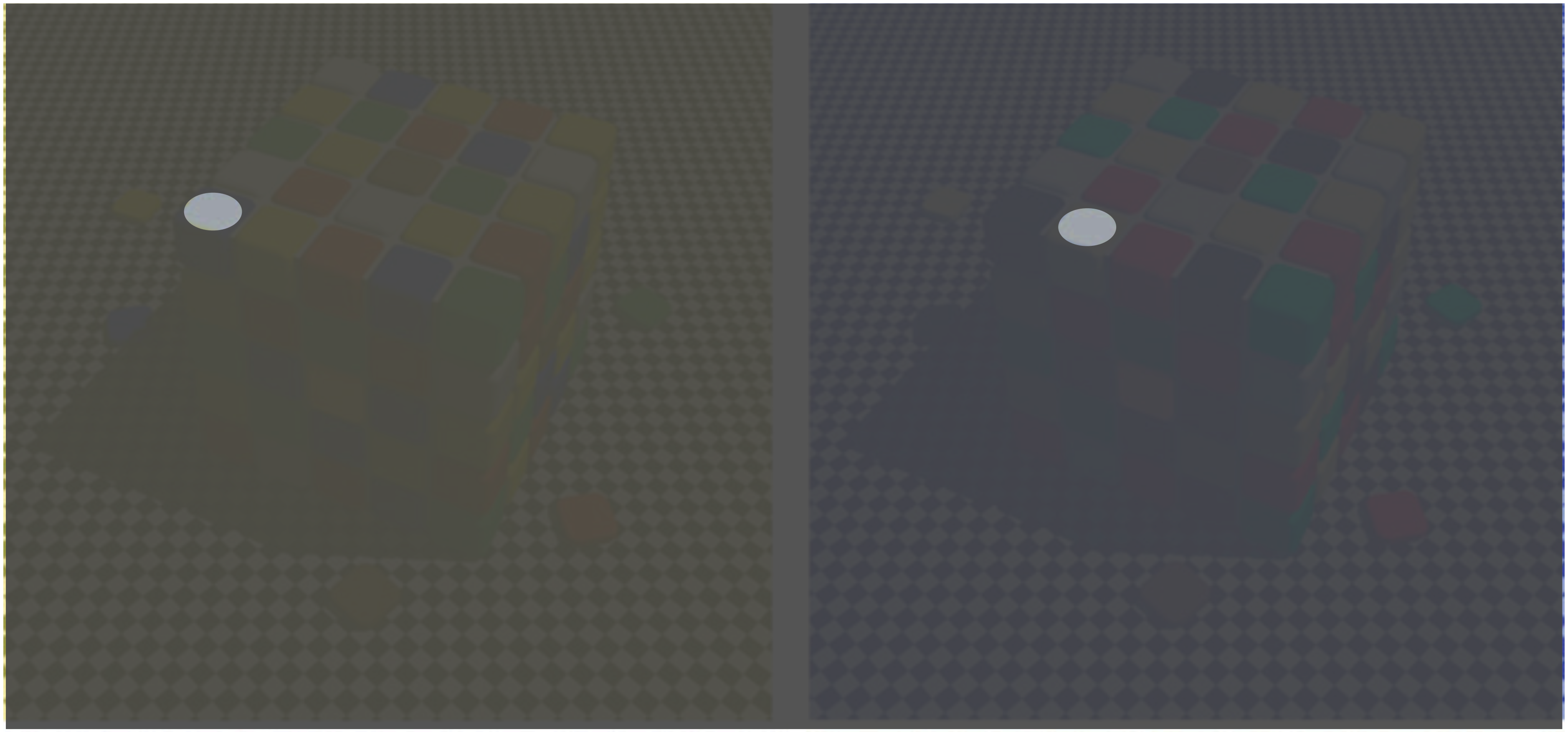

Beau Lotto

# Color Constancy



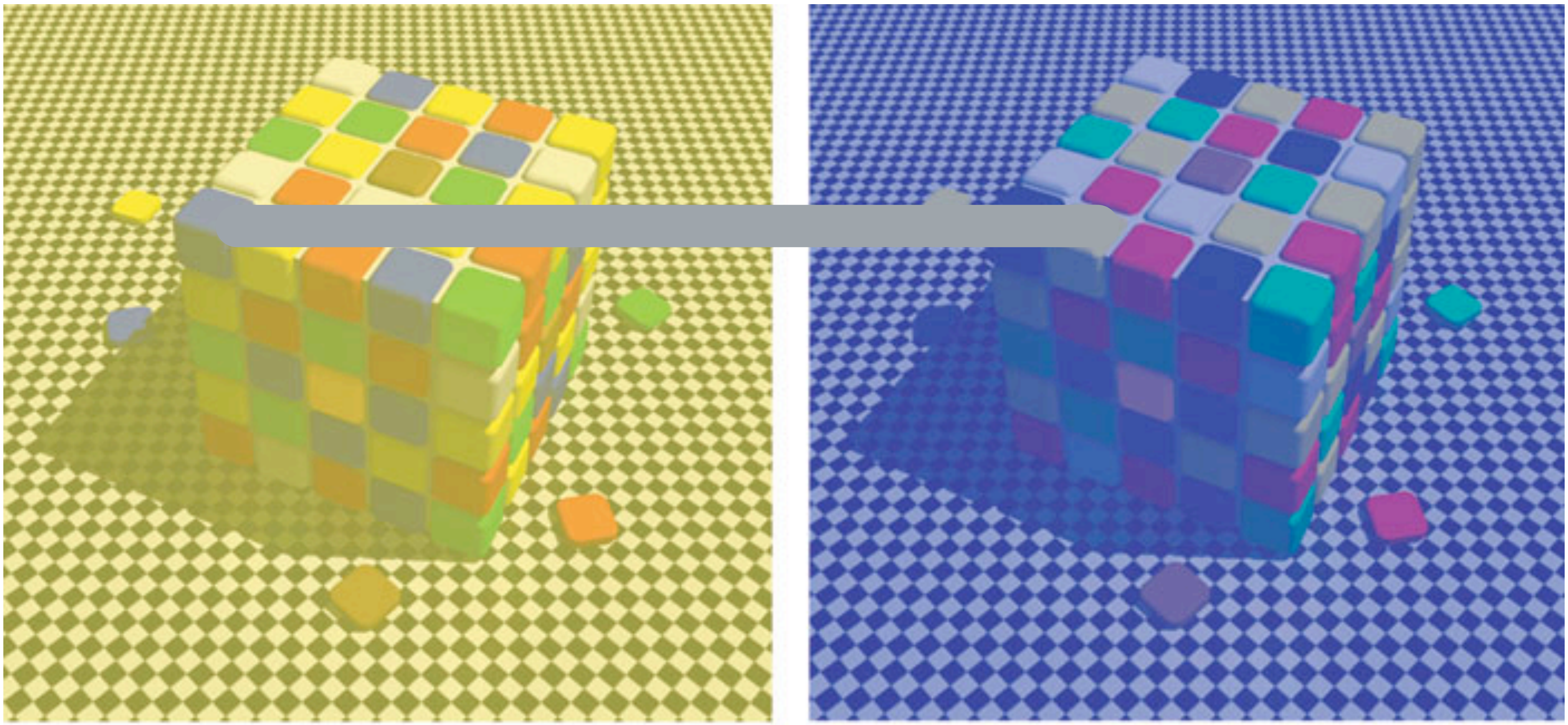
Beau Lotto

# Color Constancy



Beau Lotto

# Color Constancy



Beau Lotto

# Color Constancy

Beau Lotto

- In general, visual system tries to discount the effects of the illuminant: it cares about the properties of the *surface*, not the *illuminant*.

- last slide example: brain discounts the cone responses by taking into account information about much light is hitting different surfaces

- still unknown how the brain does this: believed to be in cortex (V1 and beyond).

- *but*: color-constancy is not perfect
- possible to fool the visual system by:
  - using a light source with unusual spectrum
    (most light sources are broad-band;
    narrow-band lights will make things look very unusual)
  - showing an image in which there is little spectral variation (e.g., a blank red wall).

# Aside #1: 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)

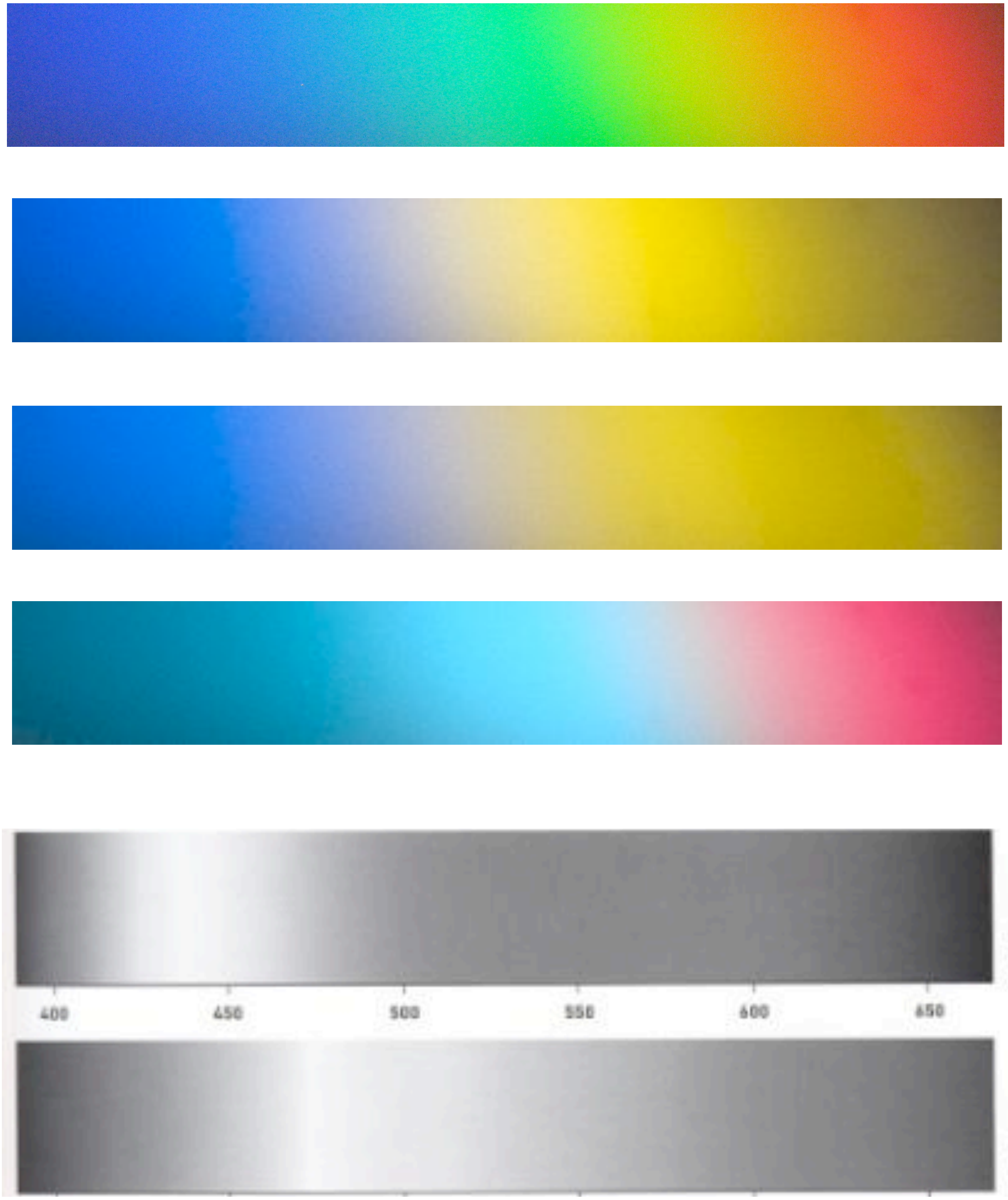
# Types of color-blindness:

**dichromat** - only 2 channels of color available (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




normal trichromat

protanope

deuteranope

tritanope

monochromat

“scotopic” light levels

# Color Vision in Animals

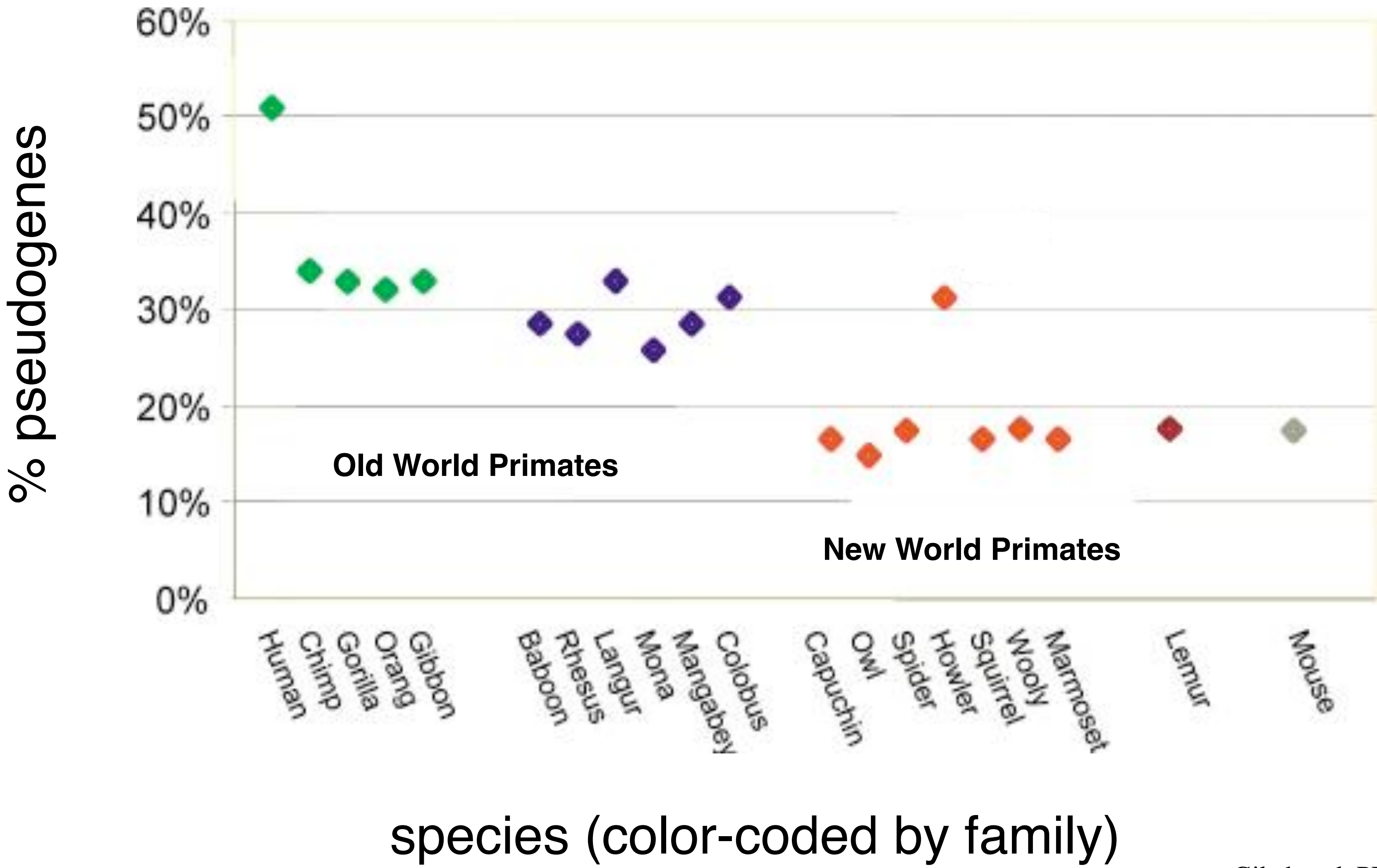
- most mammals (dogs, cats, horses): dichromats
- old world primates (including us): trichromats
- marine mammals: monochromats
- bees: trichromats (but lack "L" cone; ultraviolet instead)
- some birds, reptiles & amphibians: tetrachromats!

# Aside #2: Evolutionary tradeoff between Olfaction vs. Color vision

- Buck and Axel (1991): genome contains about 1000 different olfactory receptor genes

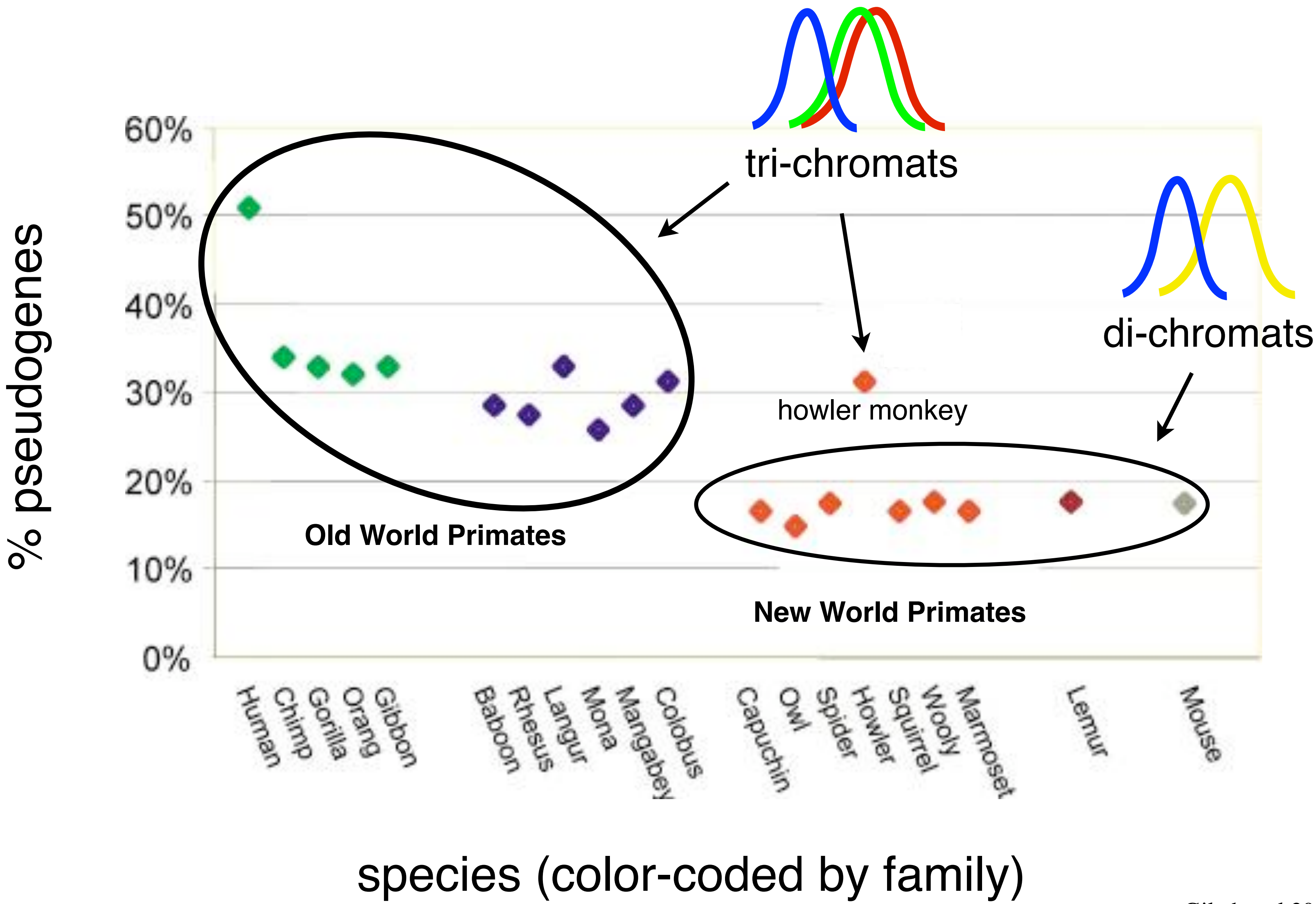
- All mammals have pretty much the same 1000 genes.
- However, some genes are non-functional "**pseudogenes**"
  - Dogs and mice: About 20% are pseudogenes
  - Humans: Between 60% and 70% are pseudogenes

# Evolutionary trade-off between vision and olfaction

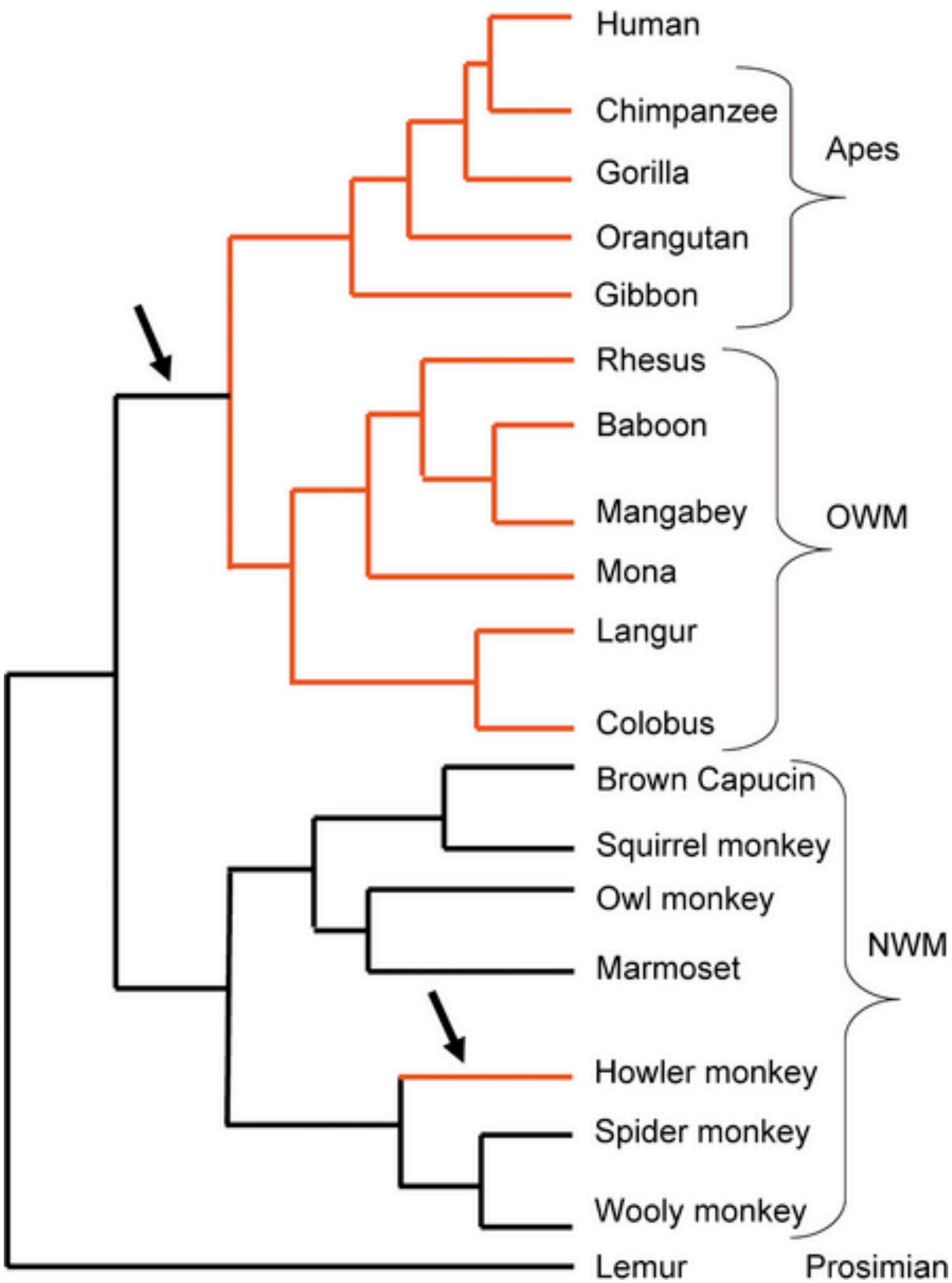



Gilad et al, PLoS 2004

# Evolutionary trade-off between vision and olfaction




Gilad et al 2004




Arrows indicate on which lineages the acquisition of full trichromatic color vision occurred. The red color highlights lineages with a high proportion of OR pseudogenes

Gilad et al 2004

# Aside #3: Color vision doesn't work at low light levels!

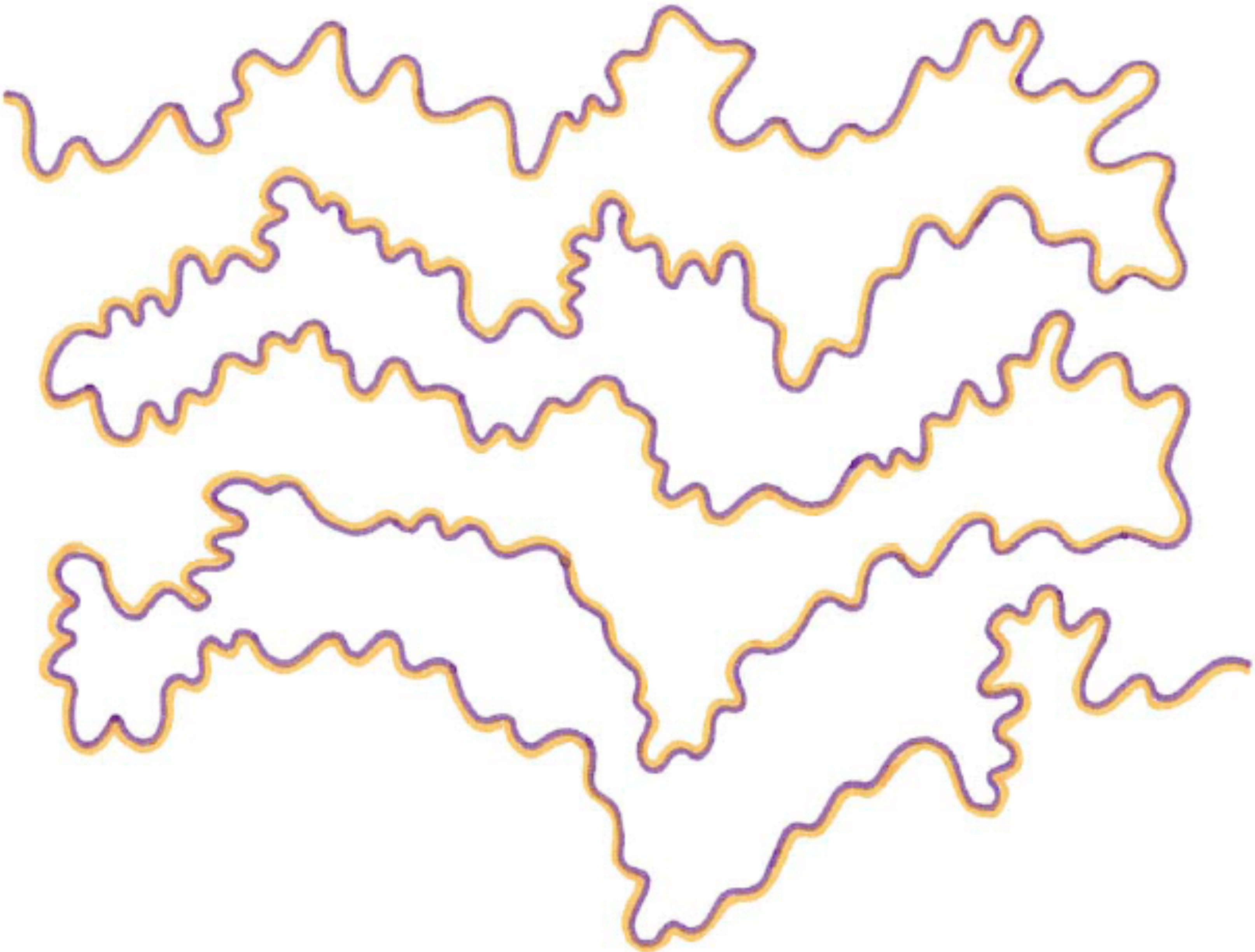
# Two Regimes of Light Sensitivity

- **Photopic**: Light intensities that are bright enough to stimulate the cone receptors and bright enough to "saturate" the rod receptors
    - Sunlight and bright indoor lighting

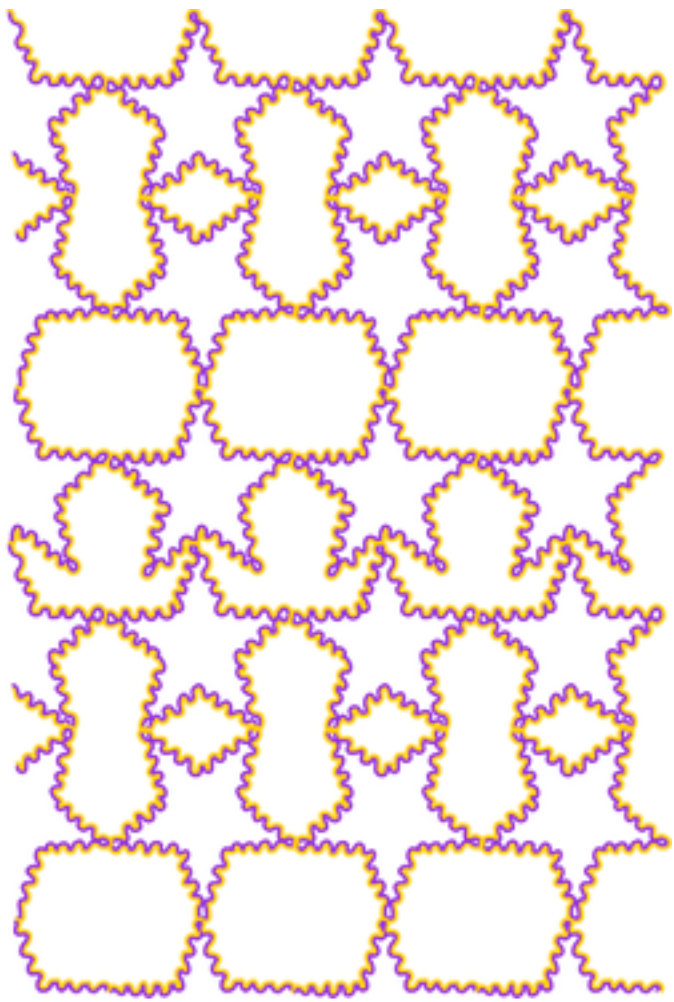
- **Scotopic**: Light intensities that are bright enough to stimulate the rod receptors but too dim to stimulate the cone receptors
    - Moonlight and extremely dim indoor lighting

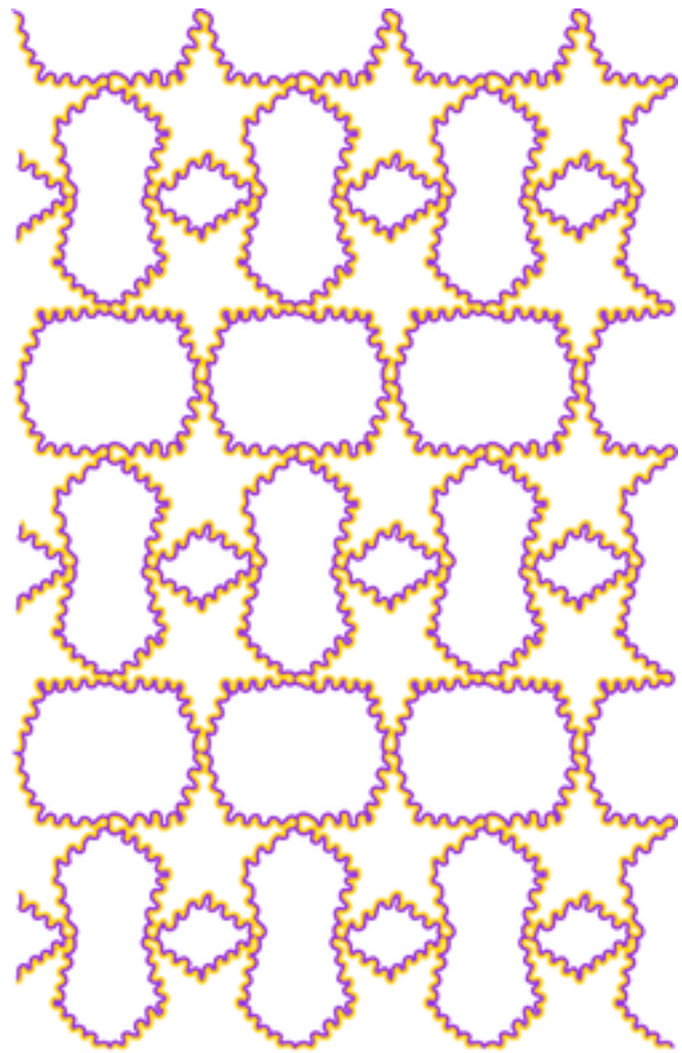
# Other (unexplained) color phenomenon:

- watercolor illusion
- neon color spreading
- motion-induced color: *Benham’s top*

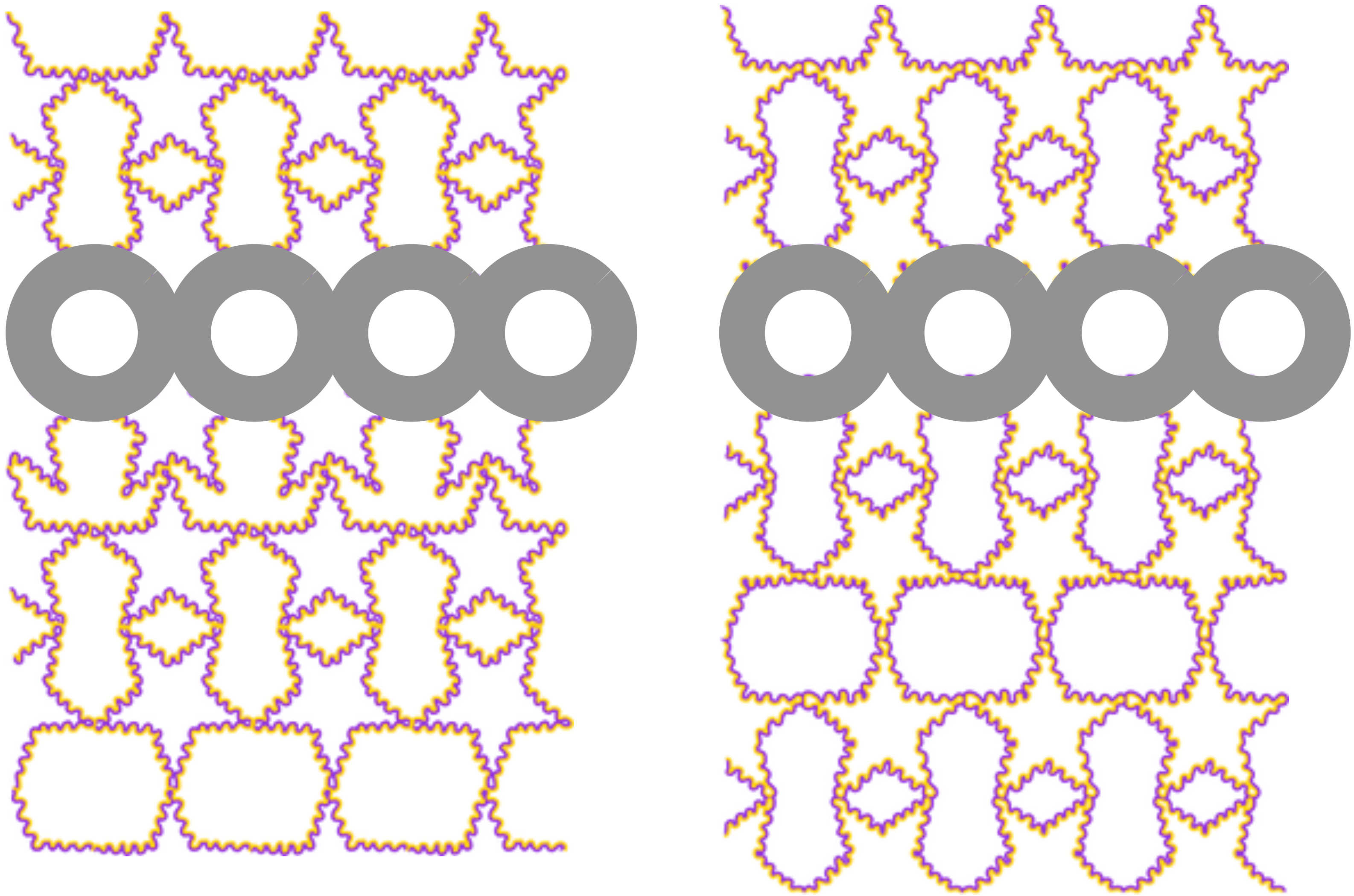


Watercolor illusion

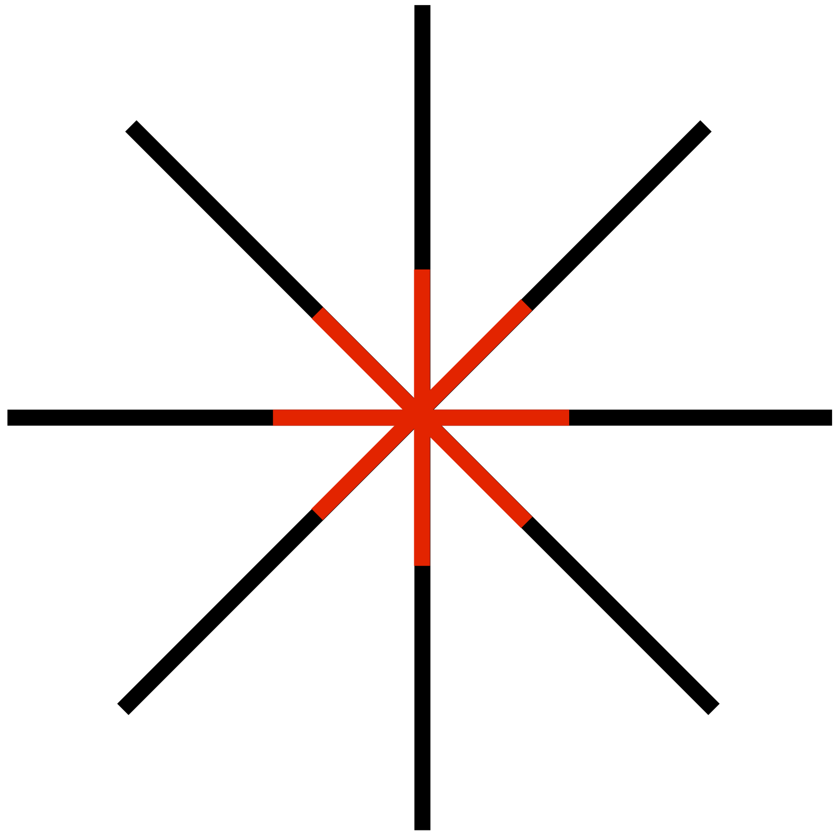




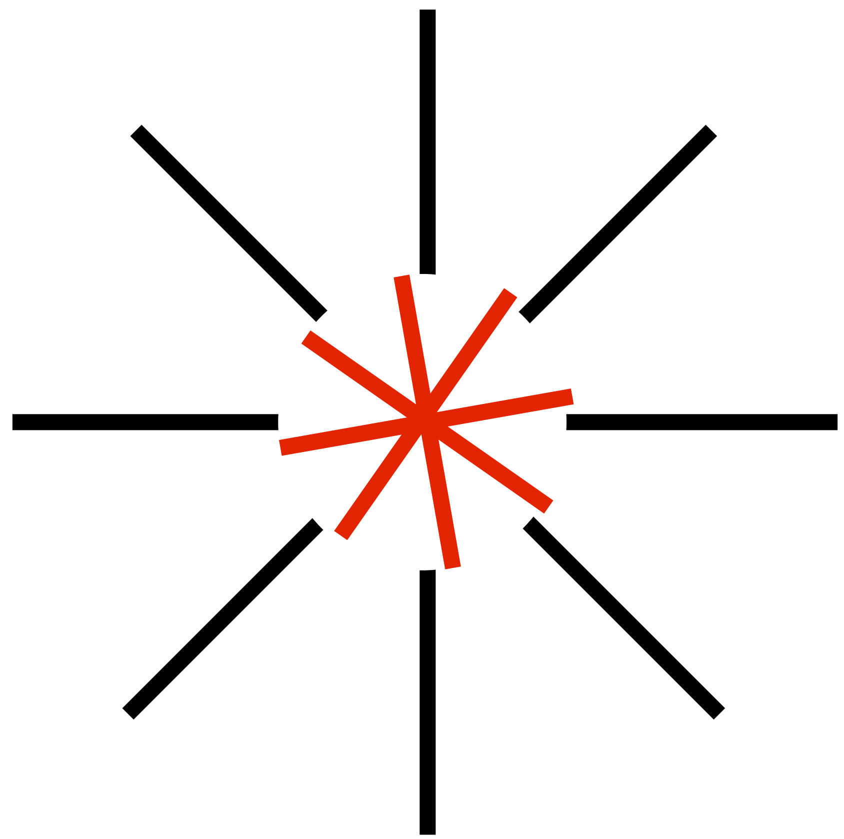
Watercolor illusion



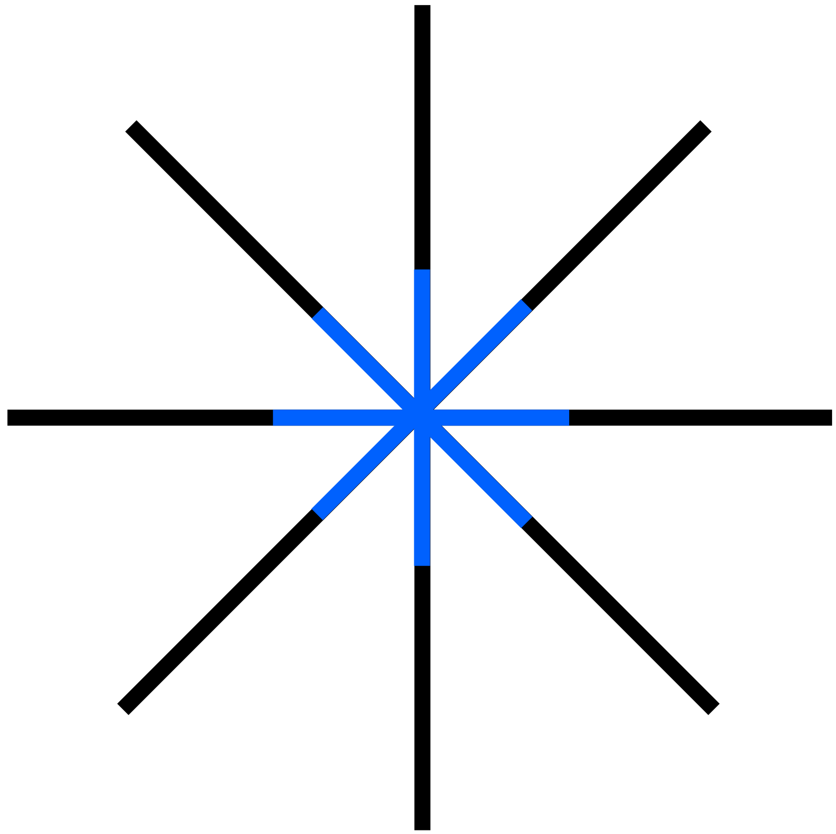
Watercolor illusion



Neon Color-Spreading



Neon Color-Spreading



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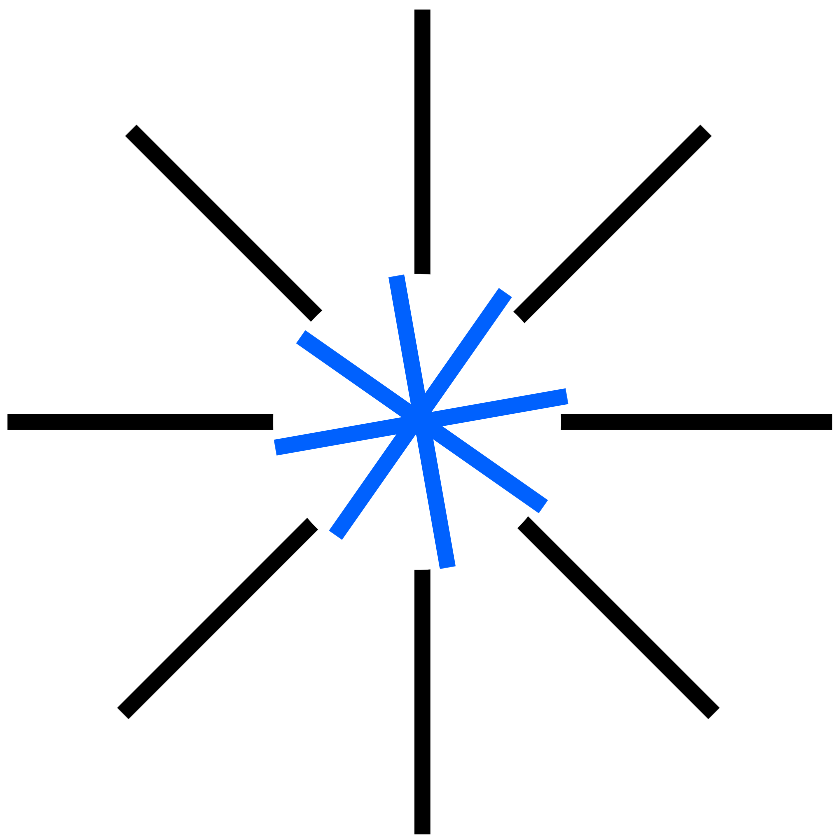

Neon Color-Spreading

# Benham's top:

## motion-induced color perception

http://www.michaelbach.de/ot/col_benham/index.html

- not well-understood; believed to arise from different color-opponent retinal ganglion cells having different temporal latencies.
- the flickering pattern stimulates the different color channels differently (although this is admittedly a crude theory)

# Summary

- trichromacy: 3-dimensional color vision (vs. hyper-spectral cameras!)
- metamers
- color-matching experiment
- opponent channels, negatives & after-images
- photopic / scotopic light levels
- color-opponent channels
- surface reflectance functions
- color constancy
- additive / subtractive color mixing
- color blindness