Color Vision

Chapter 5
(Lecture 9)

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Sensation & Perception (PSY 345 / NEU 325)
Princeton University, Spring 2019

- color vision has evolutionary value
- lack of color vision ≠ black & white

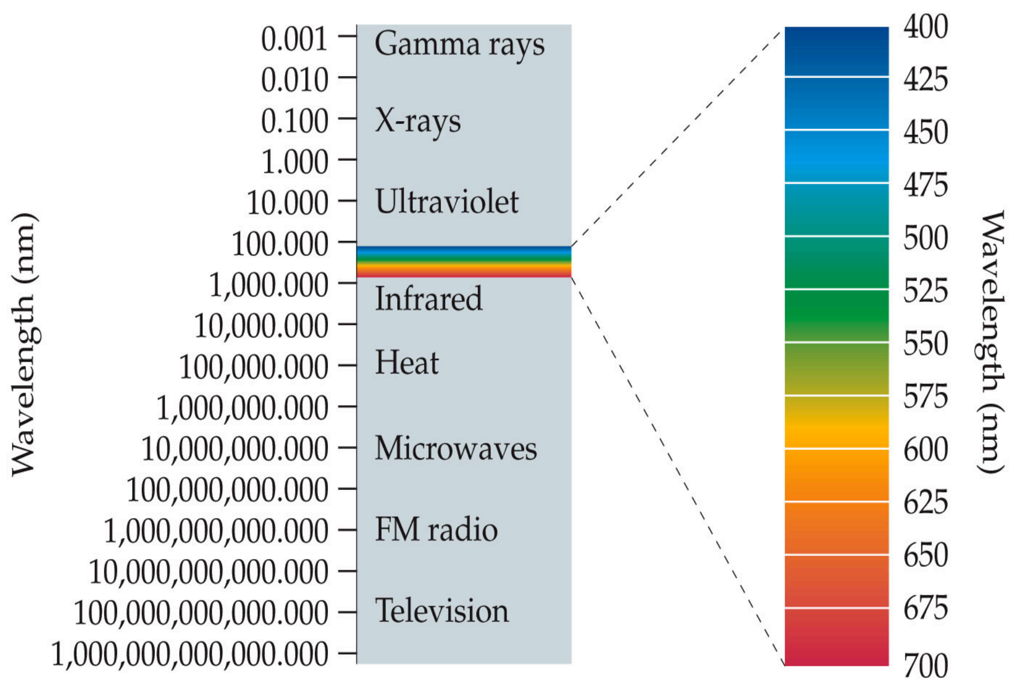
Basic Principles of Color Perception

The book says:

“Color is not a physical property but a psychophysical property”

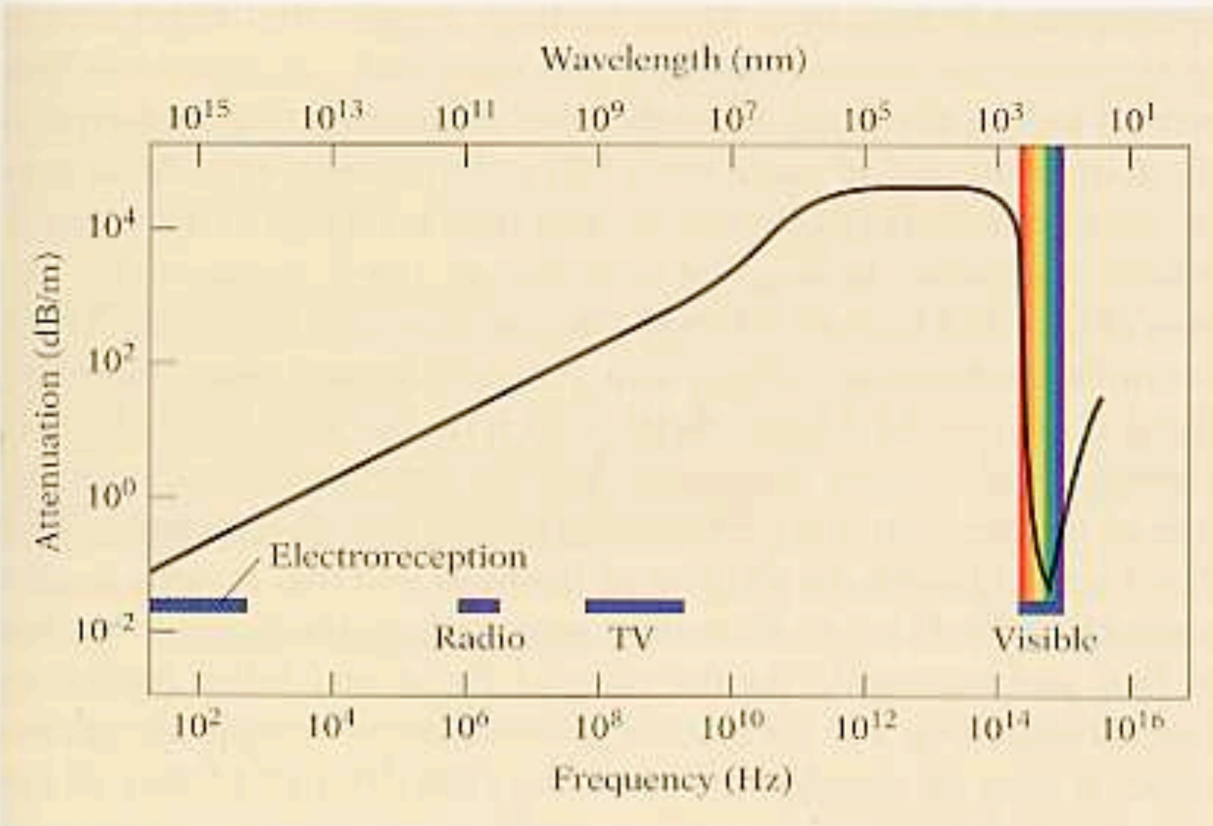
Basic Principles of Color Perception

- Most of the light we see is reflected
- Typical light sources: Sun, light bulb, LED screen
- 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.)

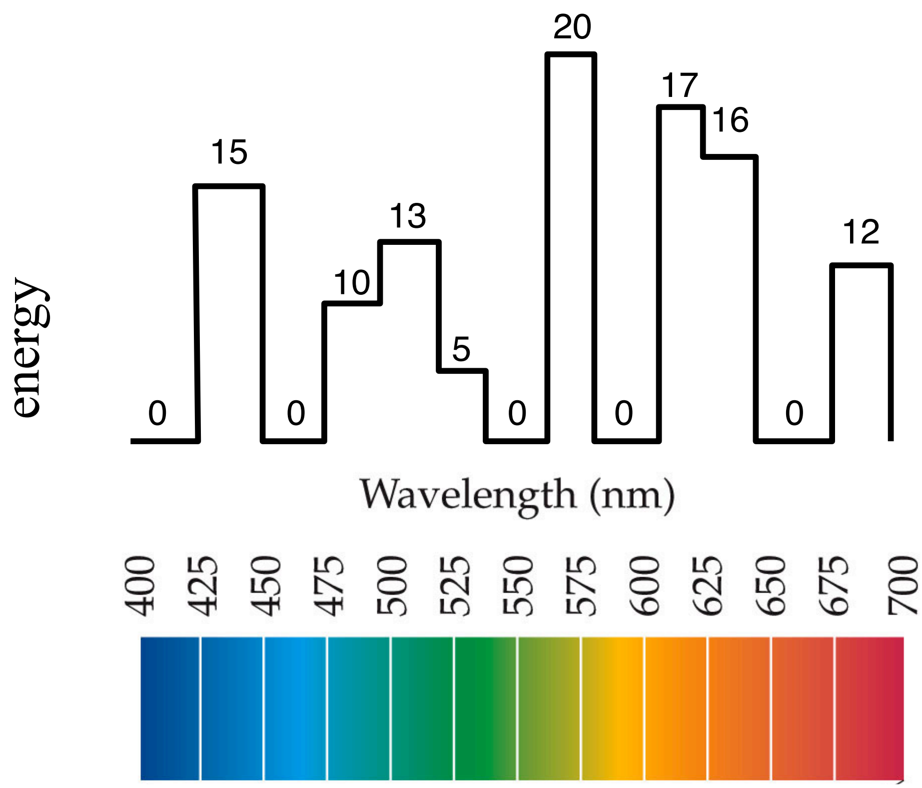
Suggestion: unique ability to penetrate sea water

Basic Principles of Color Perception

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”:

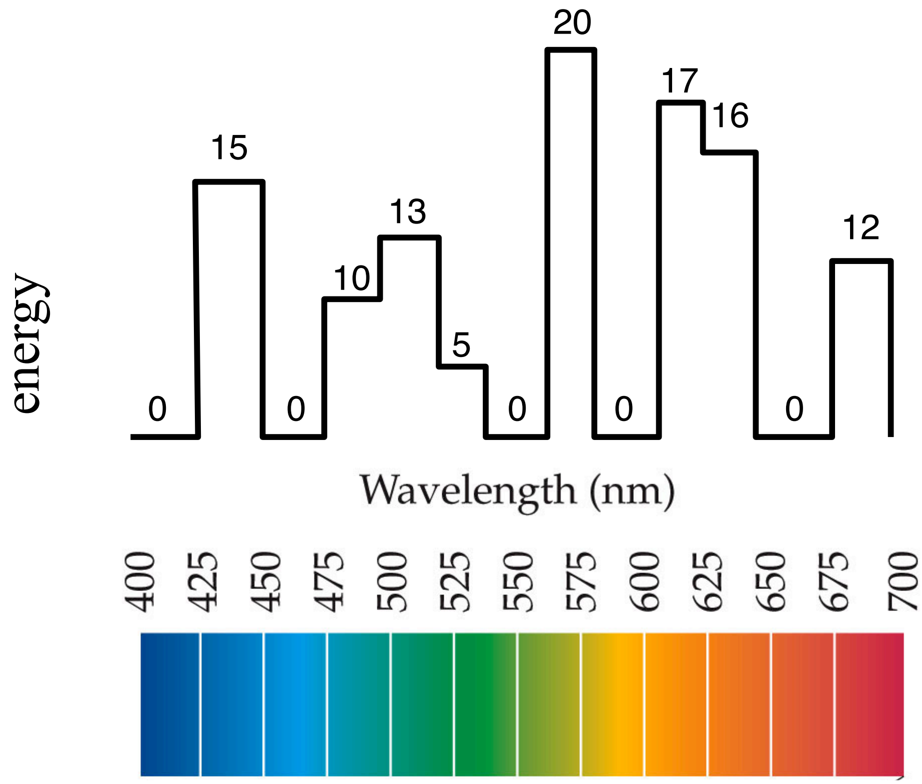


example: 13 bins

Basic Principles of Color Perception

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



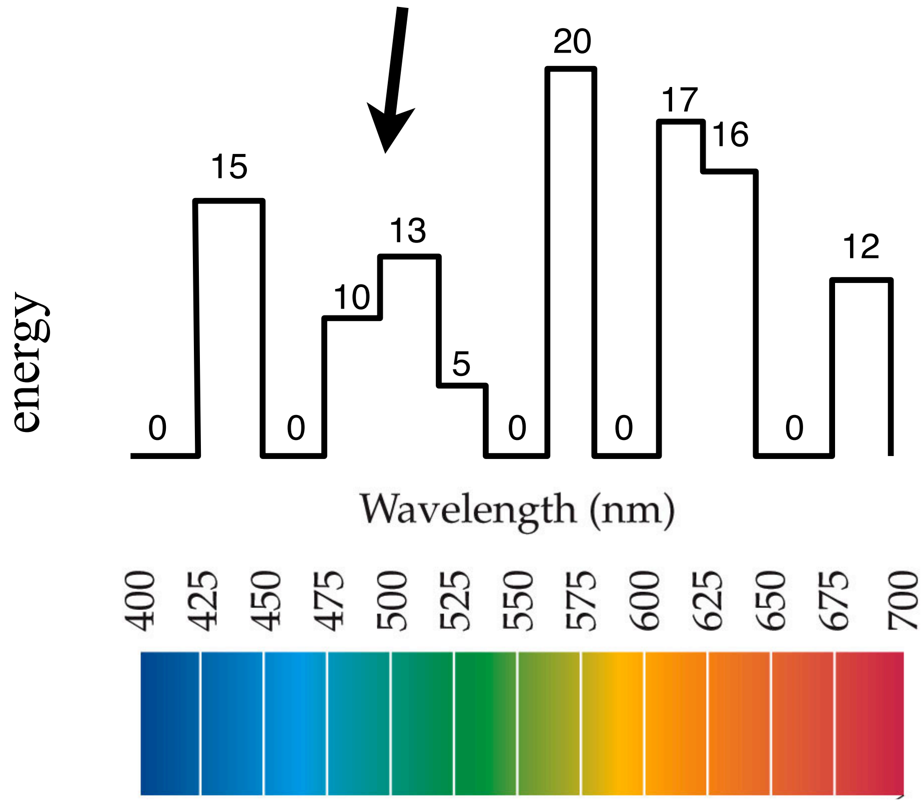
Basic Principles of Color Perception

Some terminology for colored light:

spectral - referring to the wavelength of light

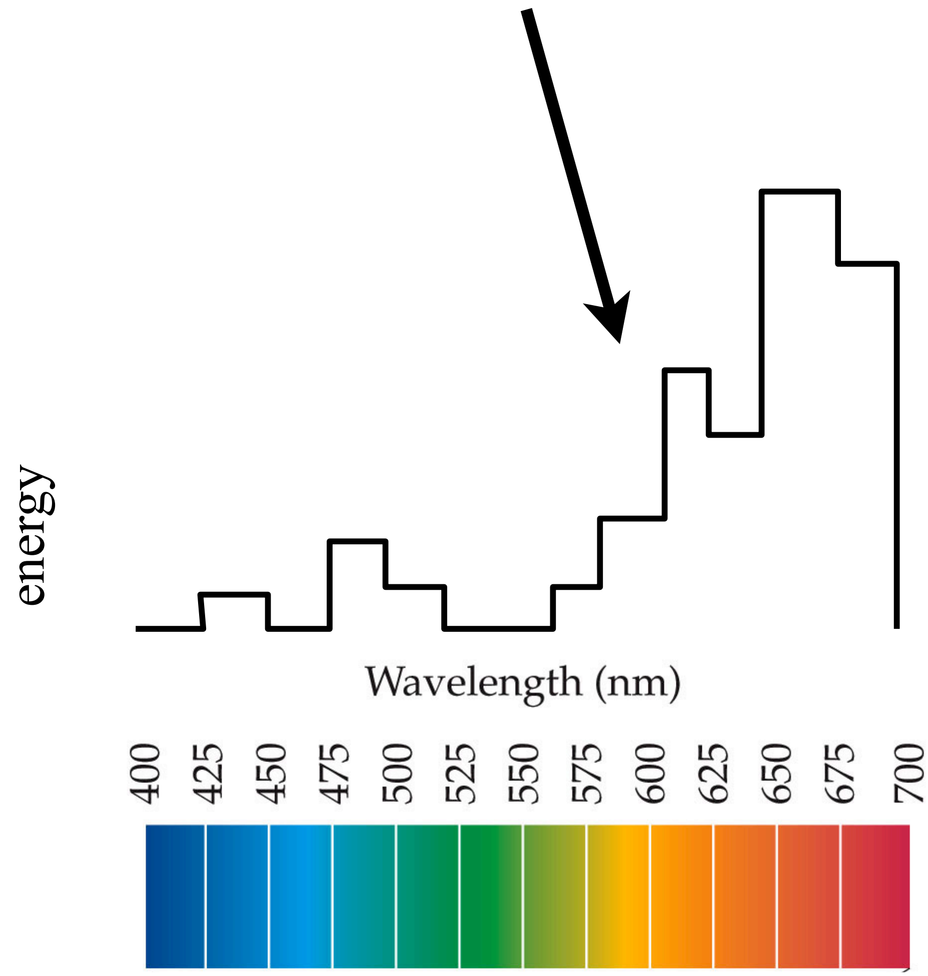
the **illuminant** - light source

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



Basic Principles of Color Perception

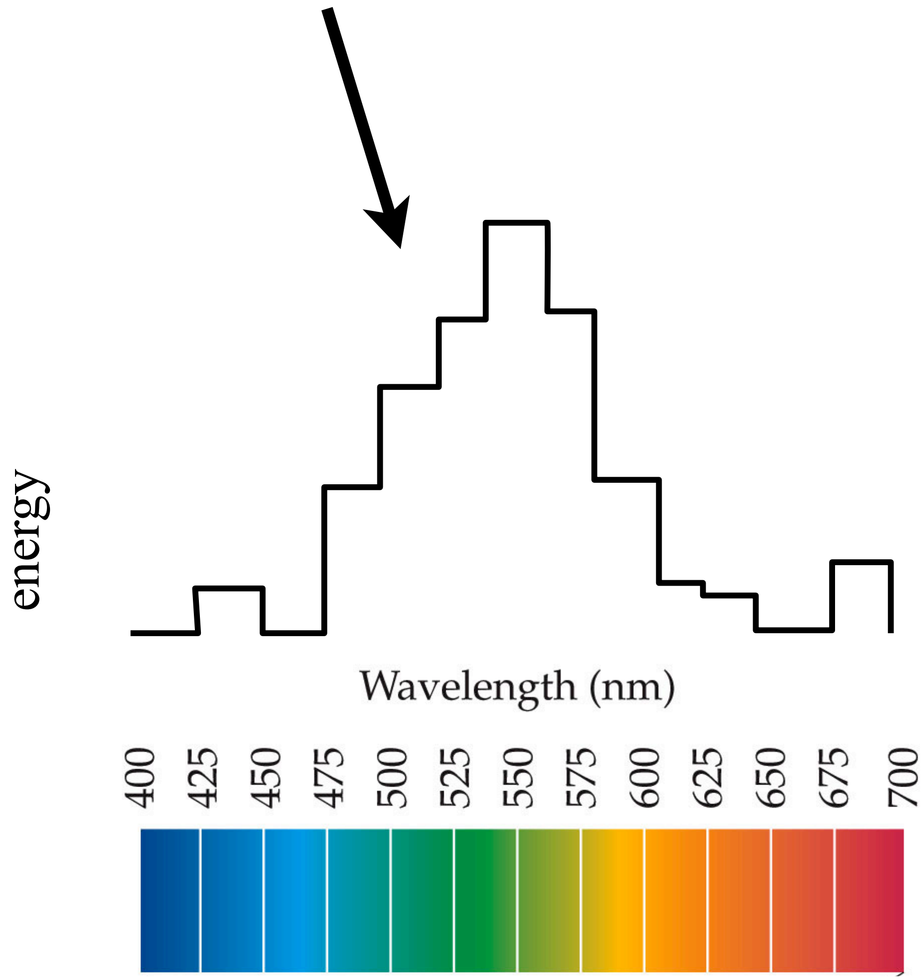
an illuminant with most power at long wavelengths (i.e., a *reddish* light source)



13 measurements of power spectrum (example)

Basic Principles of Color Perception

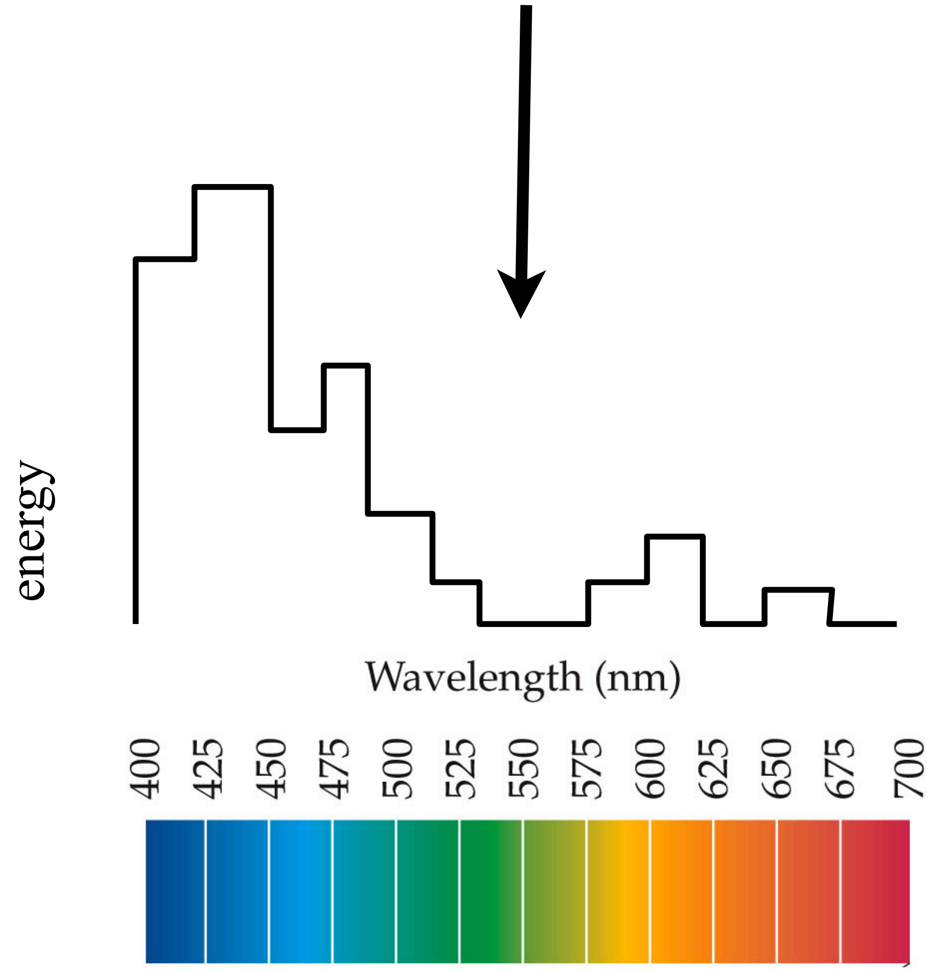
an illuminant with most power at medium wavelengths (i.e., a *greenish* light source)



13 measurements of power spectrum (example)

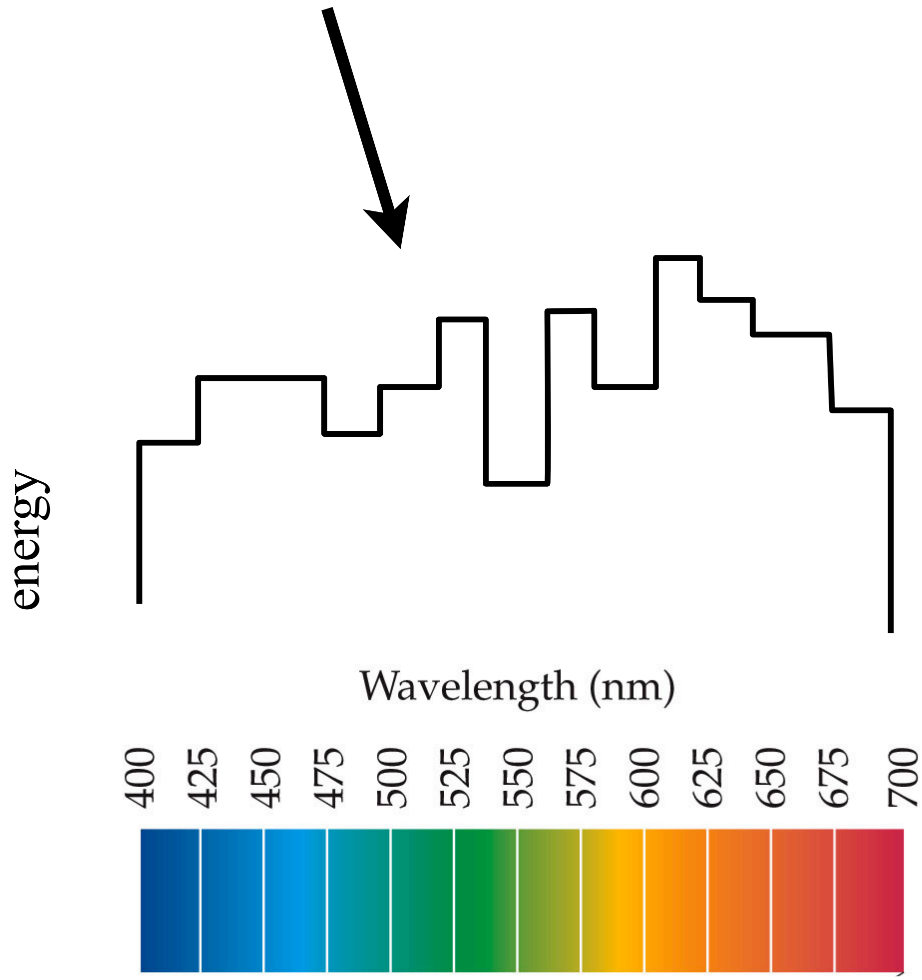
Basic Principles of Color Perception

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



13 measurements of power spectrum (example)

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



13 measurements of power spectrum (example)

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

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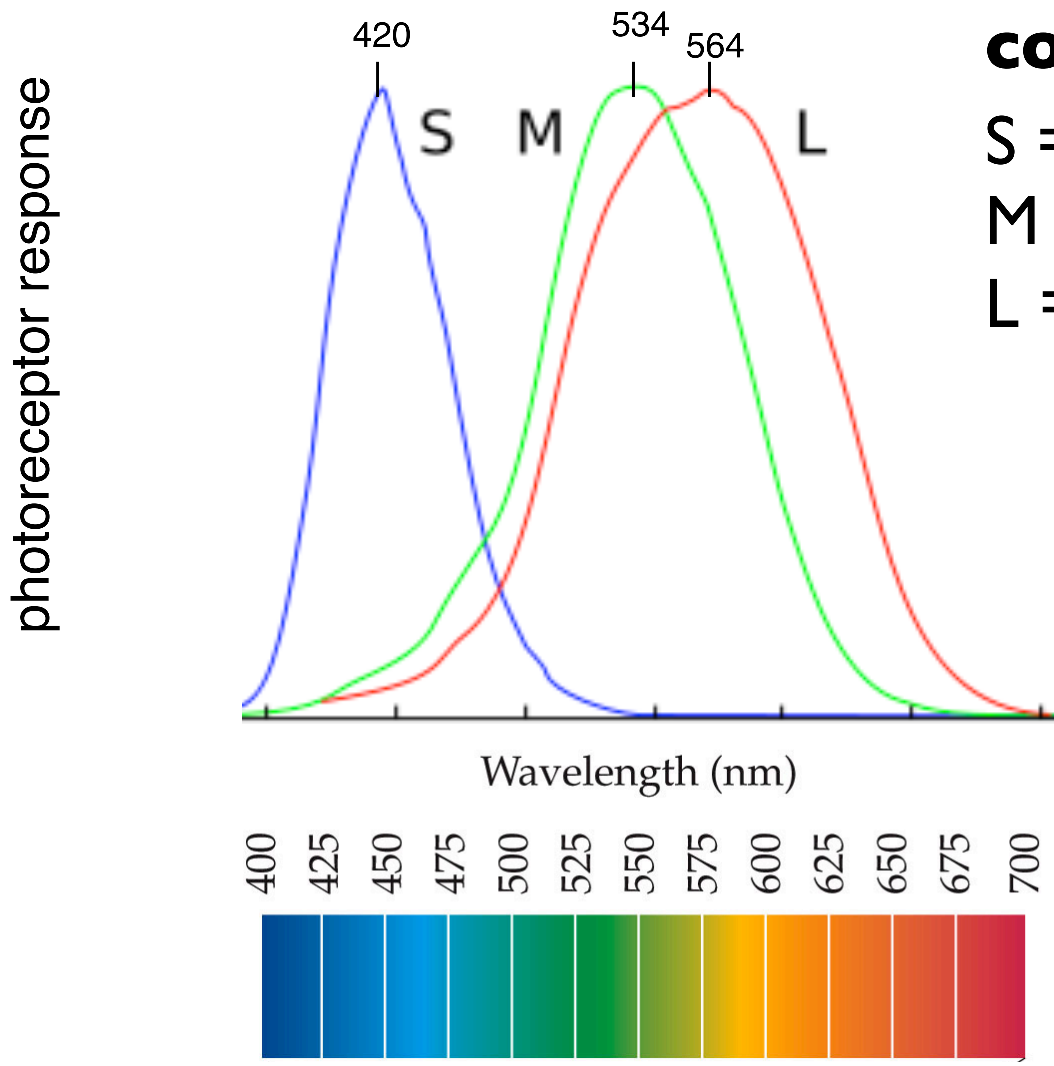
A: Only 3! One from each cone class



cone types

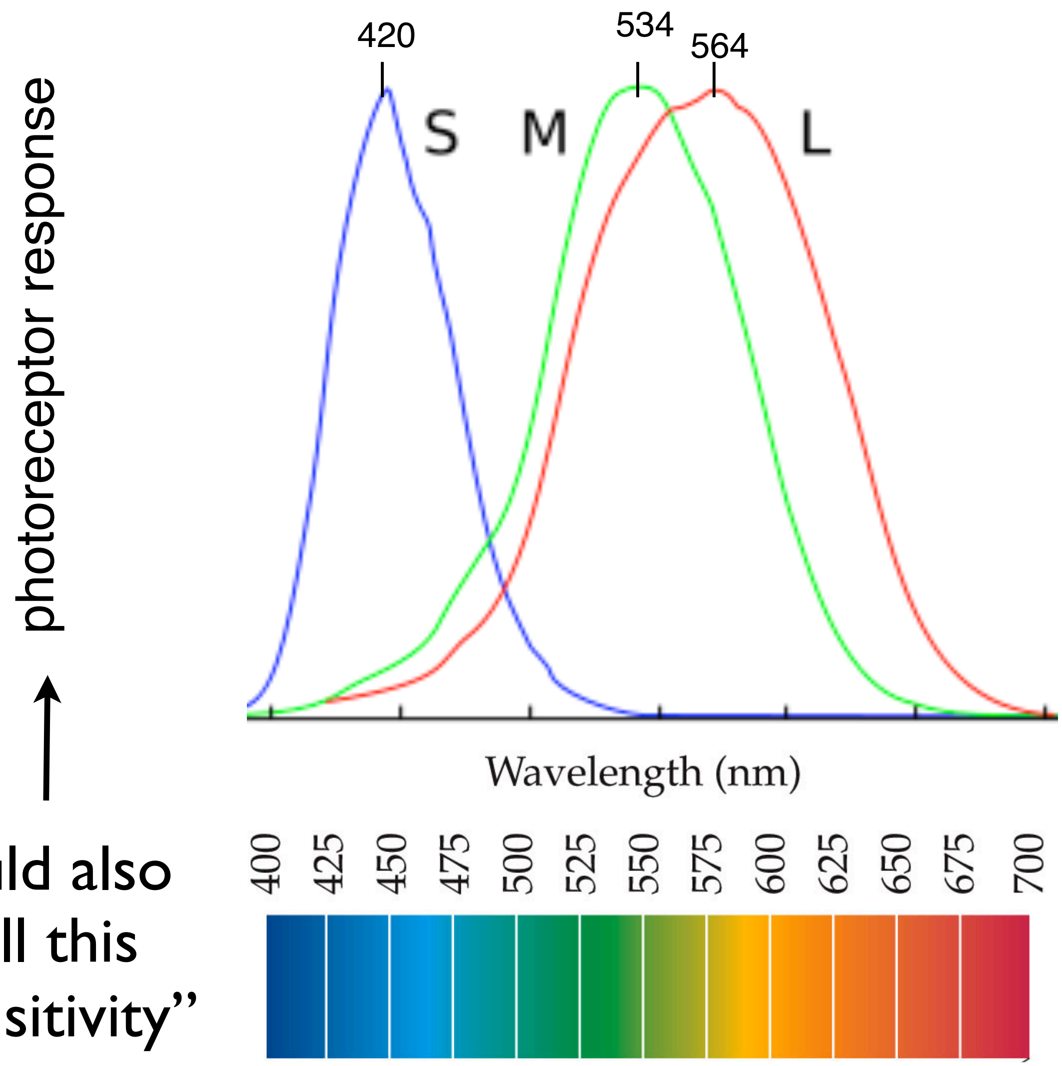
S = short (blue)

M = medium (green)

L = long (red)

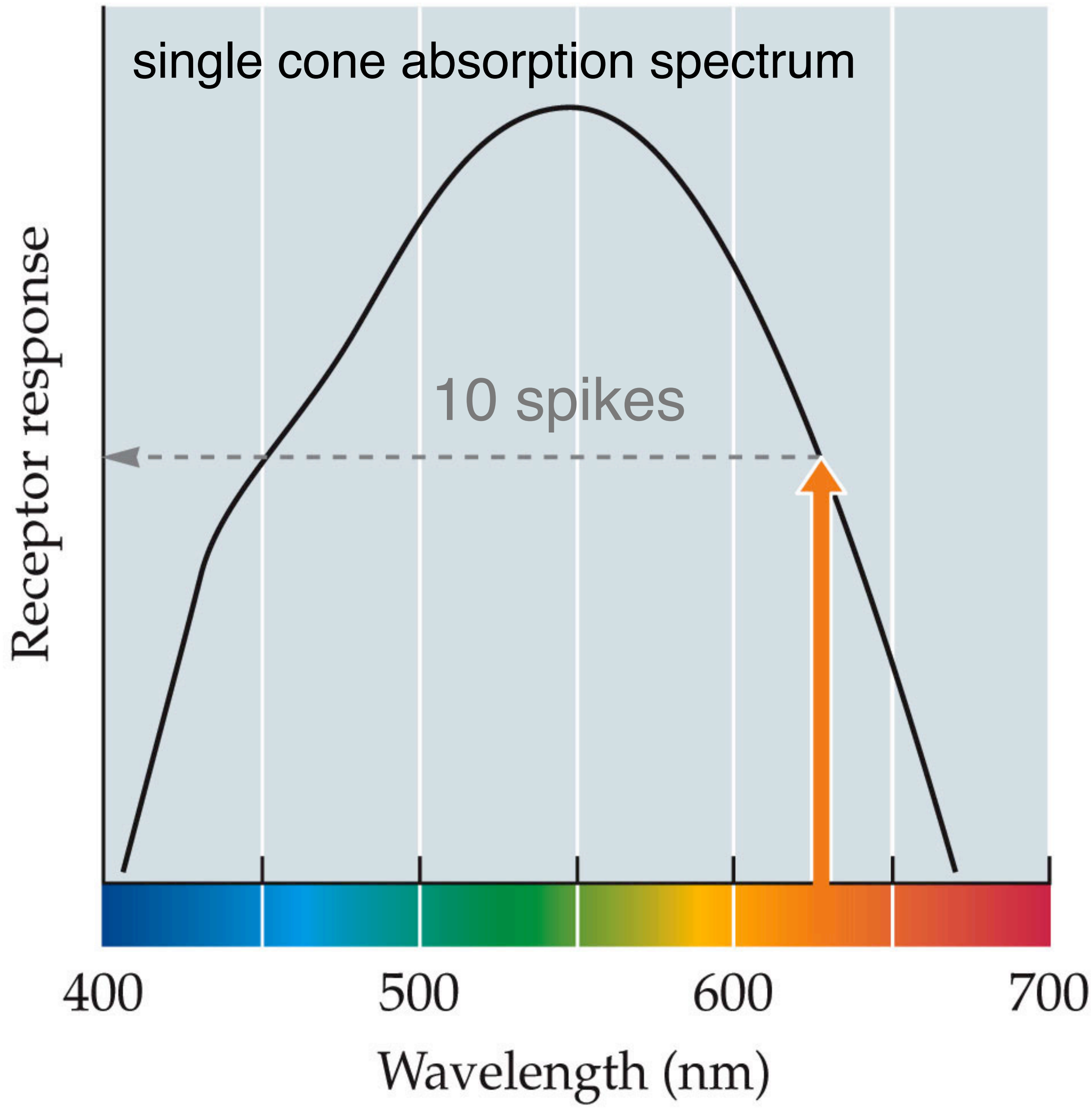
Color vision: Relies entirely on comparison of responses from three cone types!

absorption spectrum - describes response (or “light absorption”) of a photoreceptor as a function of wavelength

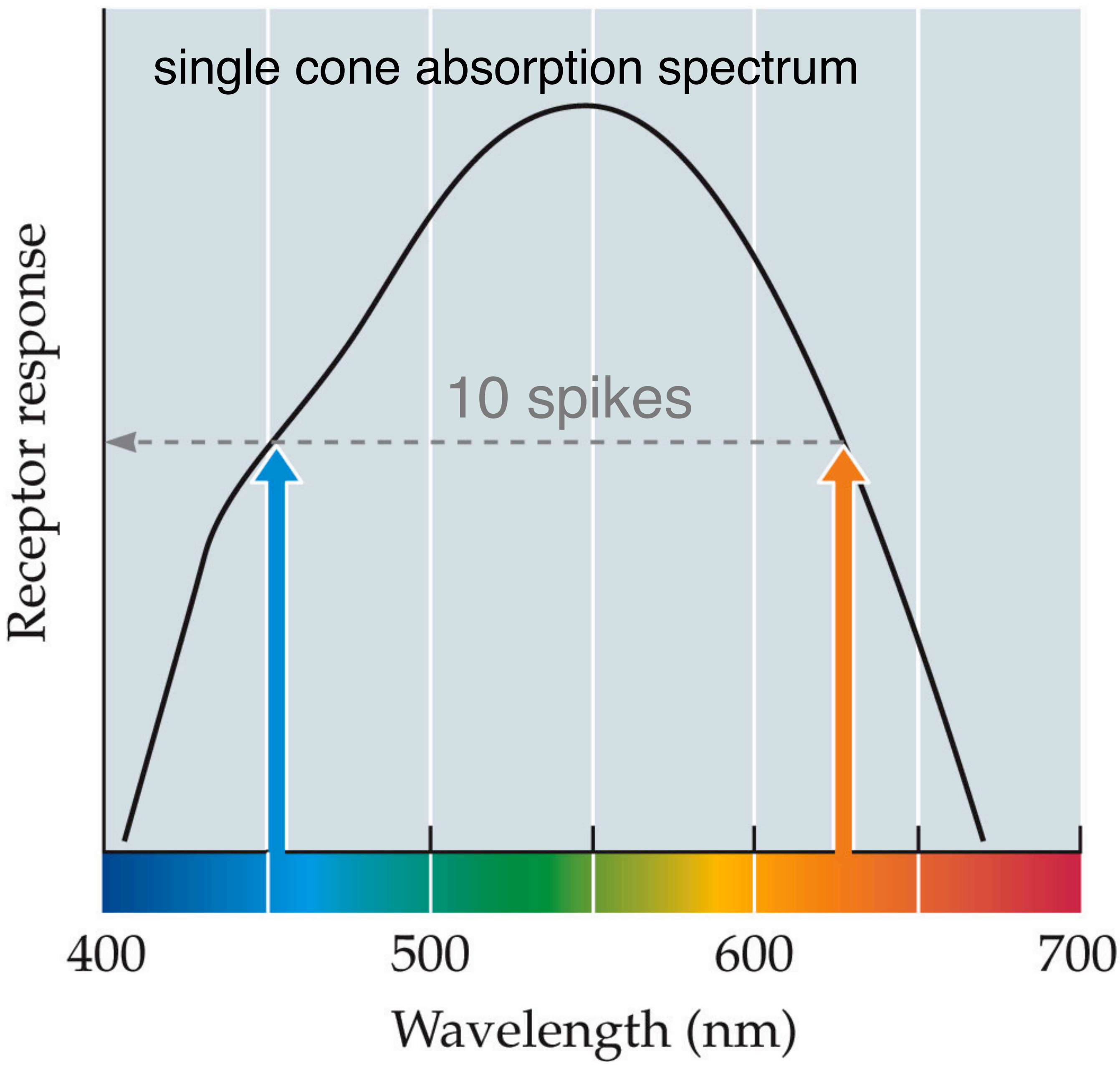


could also call this “sensitivity”

Problem: response from a single cone is ambiguous



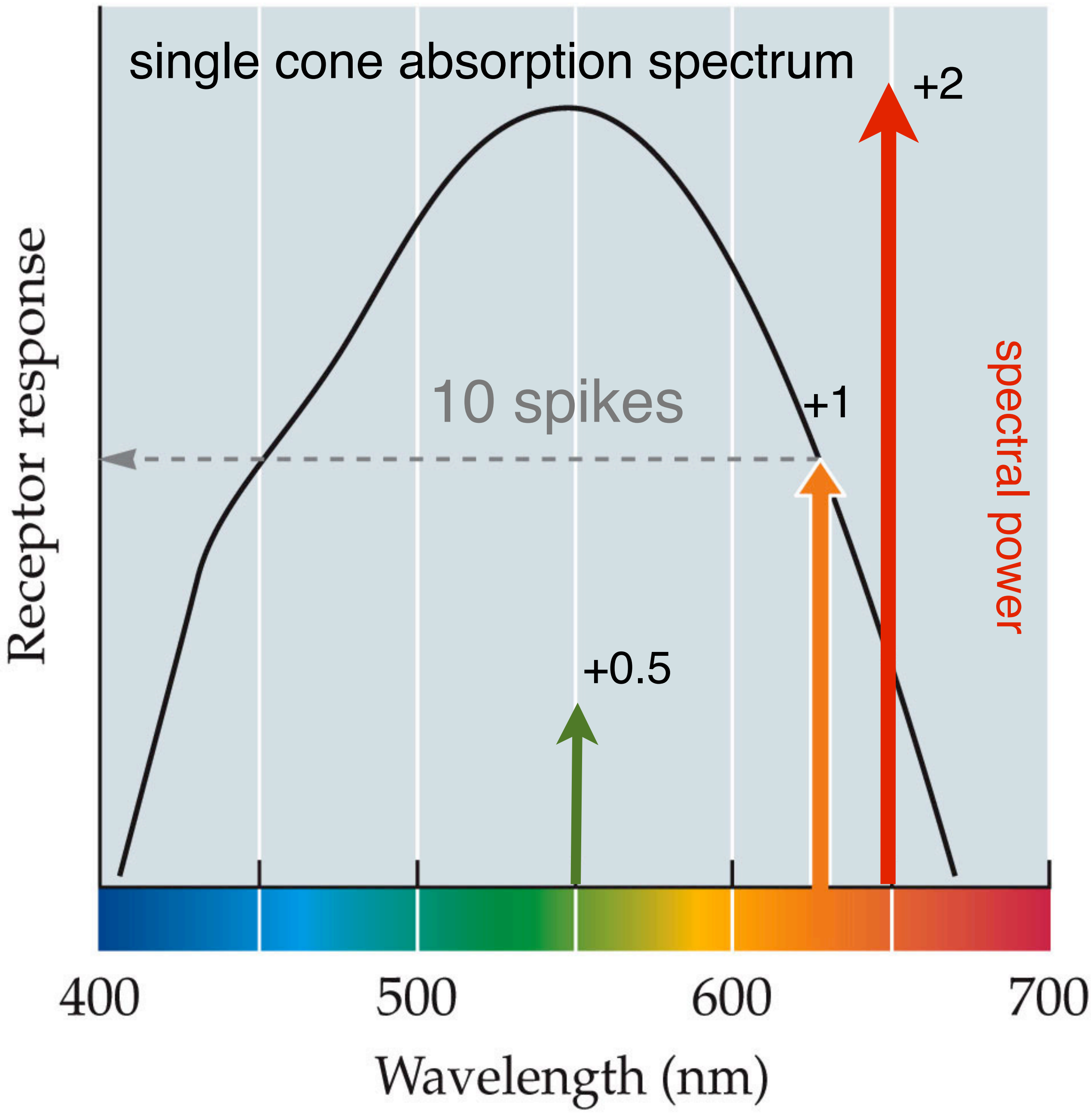
Problem: response from a single cone is ambiguous



- All the photoreceptor gives you is a “response”

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

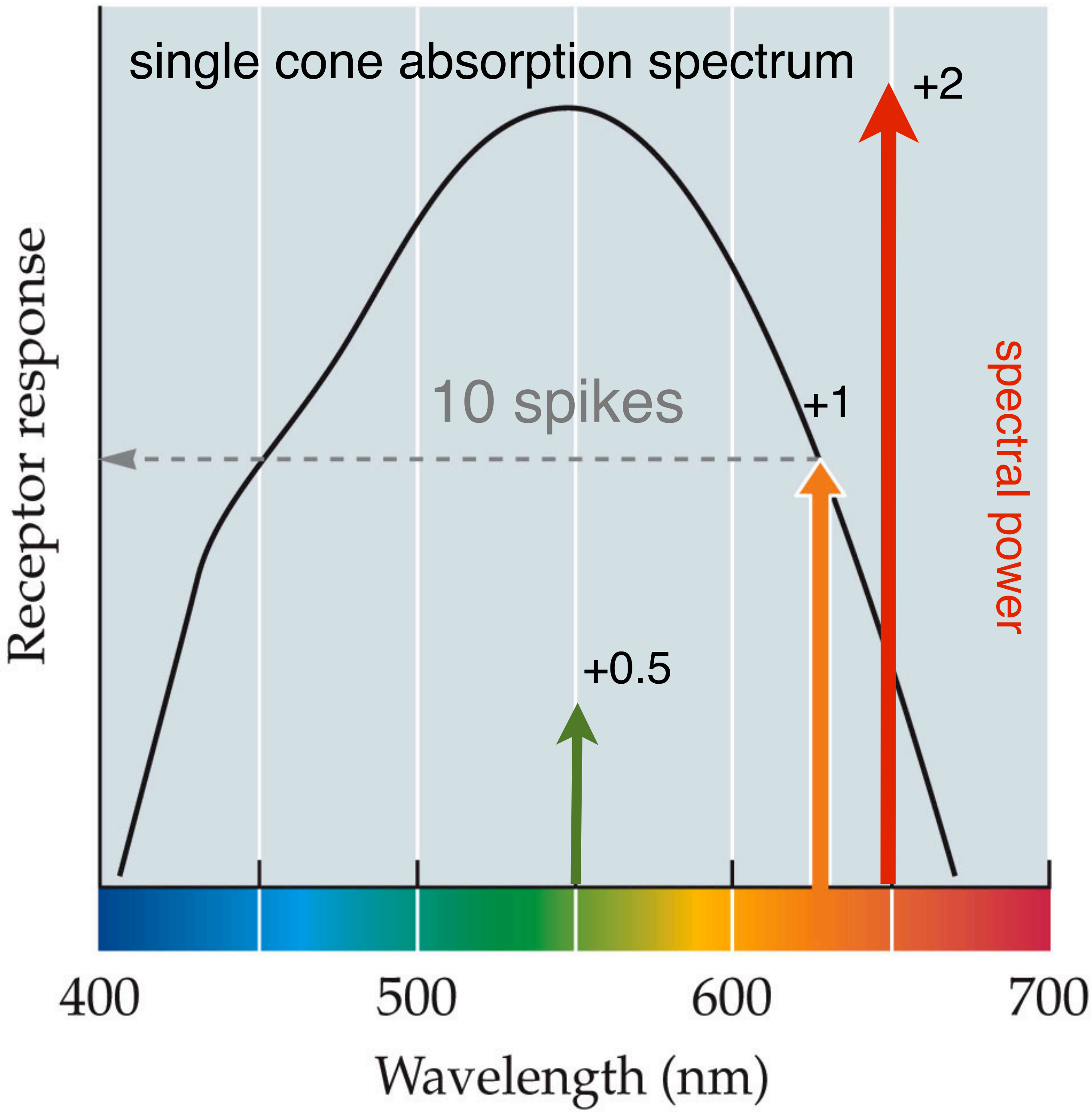
Problem is actually much worse: can't tell a weak signal at the peak sensitivity from a strong signal at an off-peak intensity



- All three of these lights give the same response from this cone

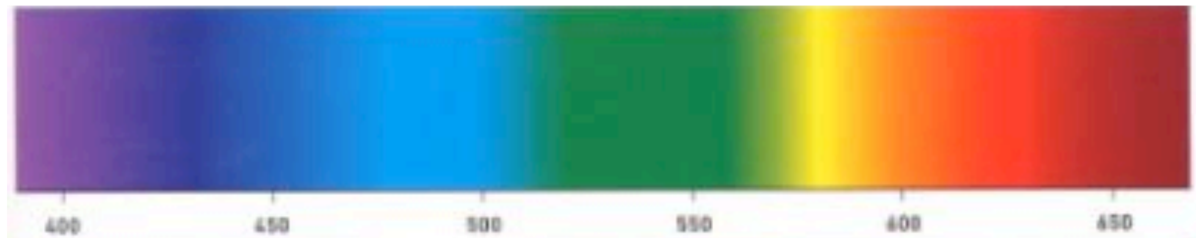
cone respone = *aborption spectrum* x *light intensity*

Problem of **univariance**: infinite set of wavelength+intensity combinations can elicit exactly the same response

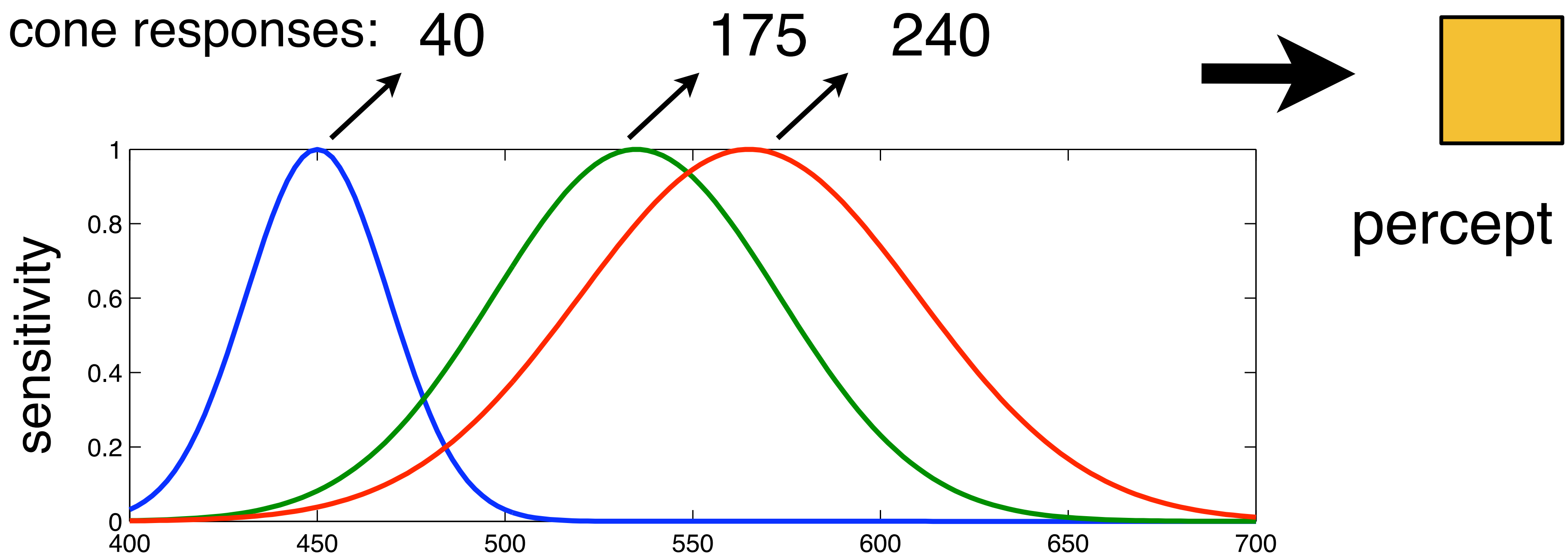


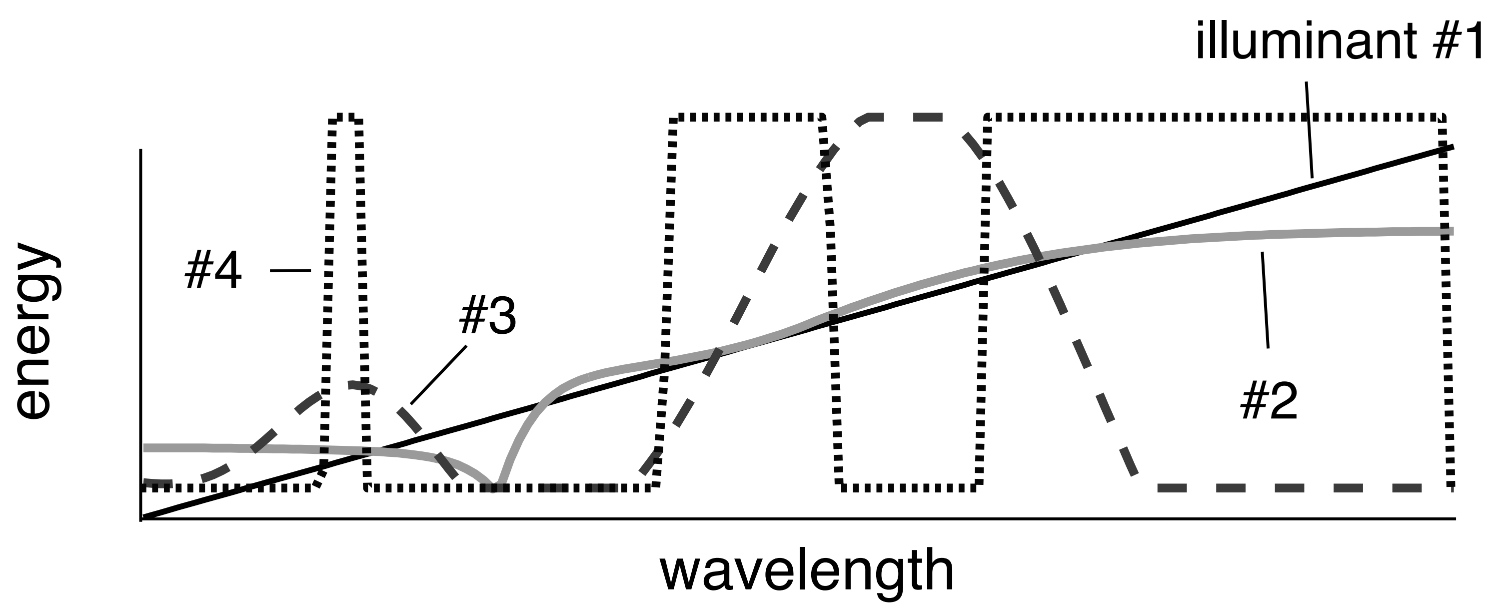
So a single cone can't tell you anything about the color of light!

Colored stimulus



Response of your
"S" cones





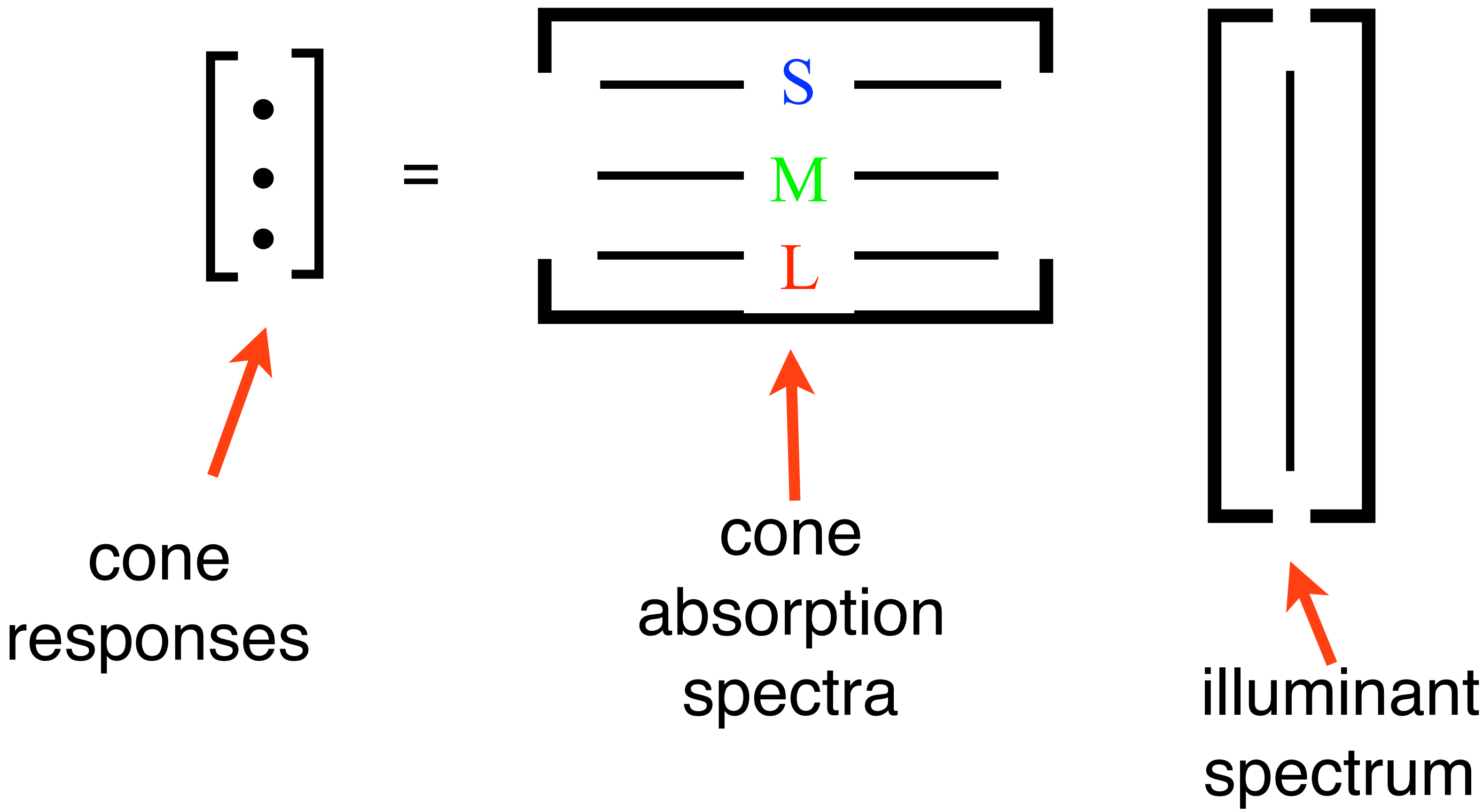
Metamers

- Illuminants that are physically distinct but perceptually indistinguishable

written as a linear matrix equation

(if that's meaningful to you)

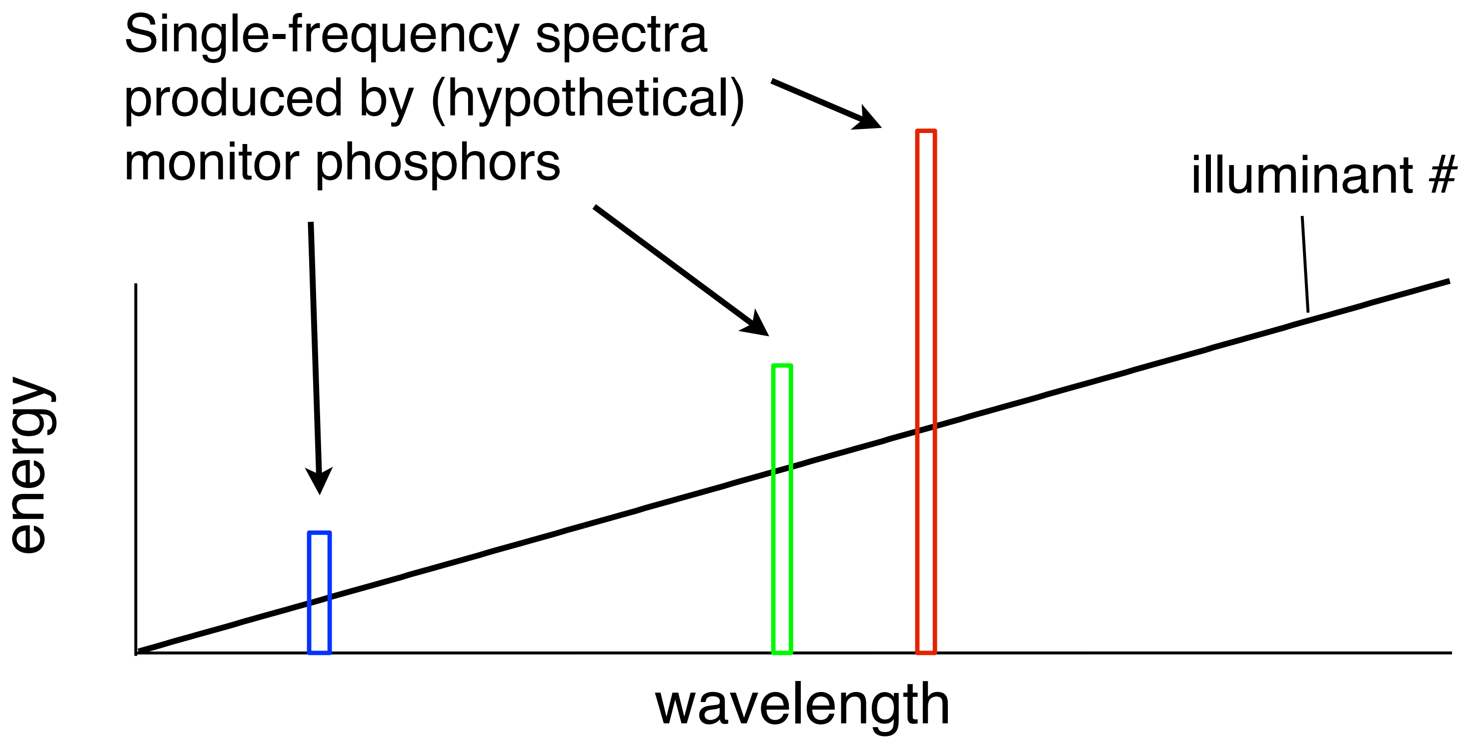
$$\vec{y} = A^T \vec{x}$$



- cone sensitivities define a 3D subspace of color perception
- metamers differ only in the null space!

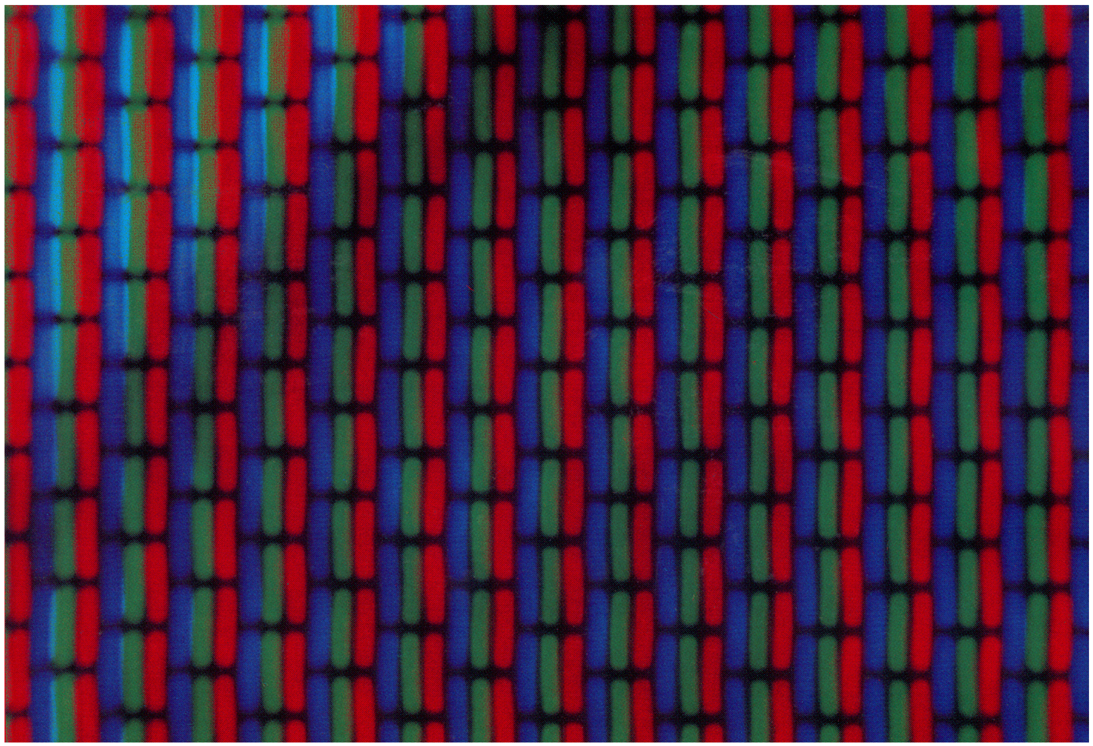
Implication: many things in the natural world have different spectral properties, but look the same to us.

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

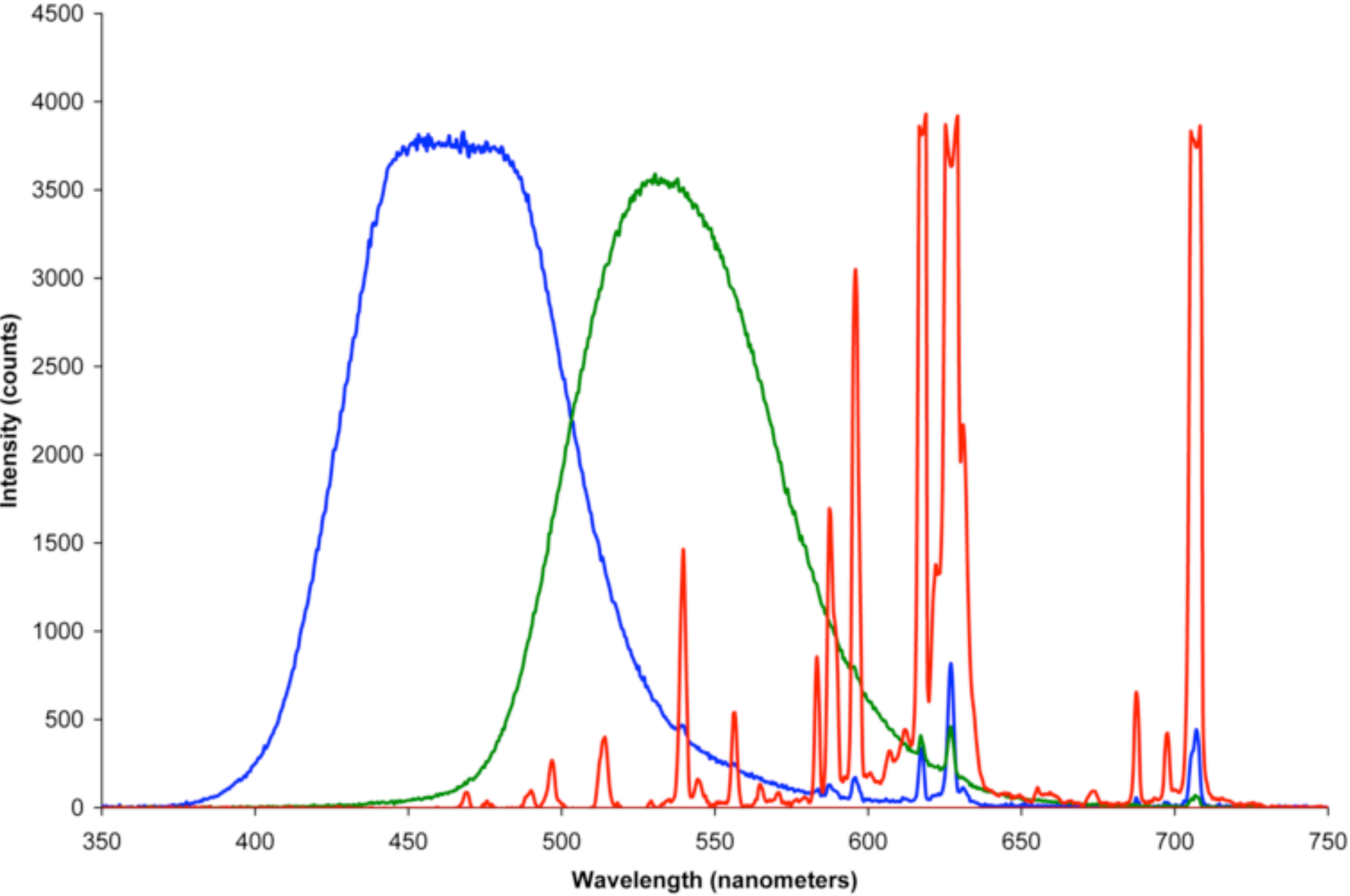


Monitor phosphors produce “metameric match” to illuminant #1 (or any other possible illuminant).

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.

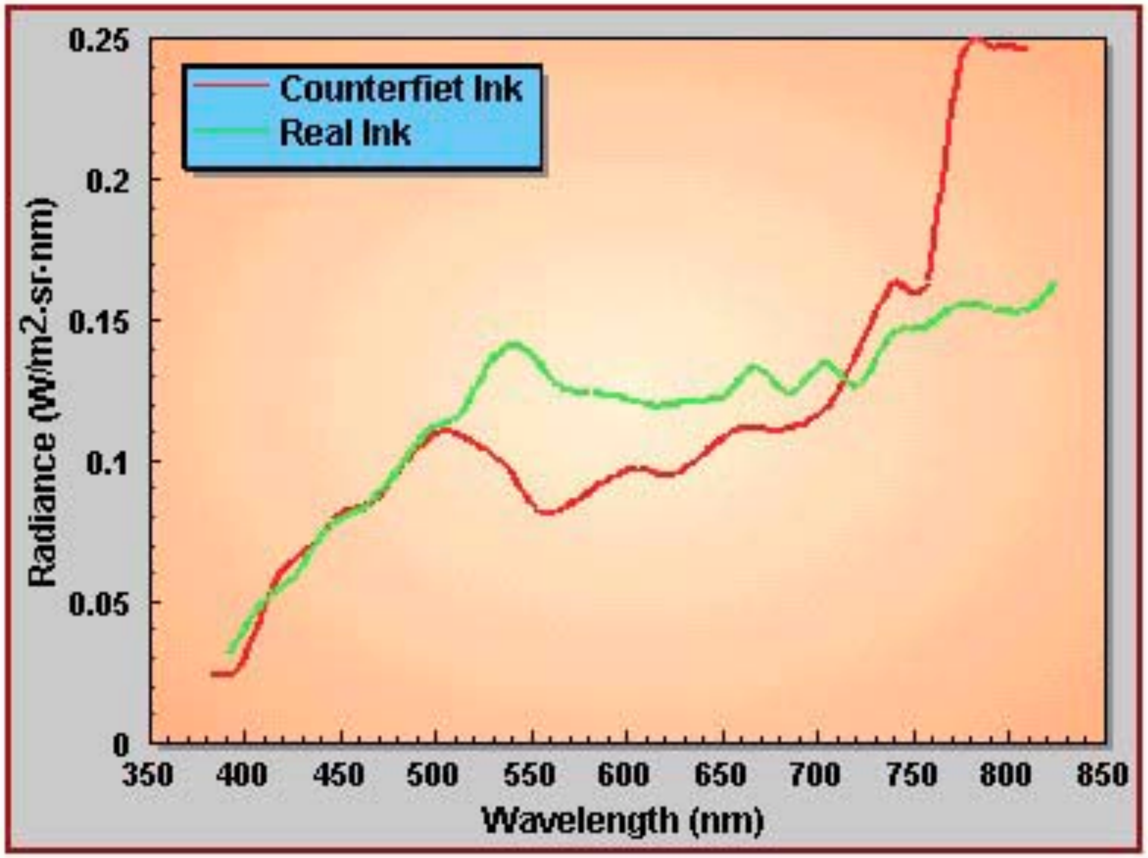
hyperspectral marvel:
mantis shrimp (stomatopod)

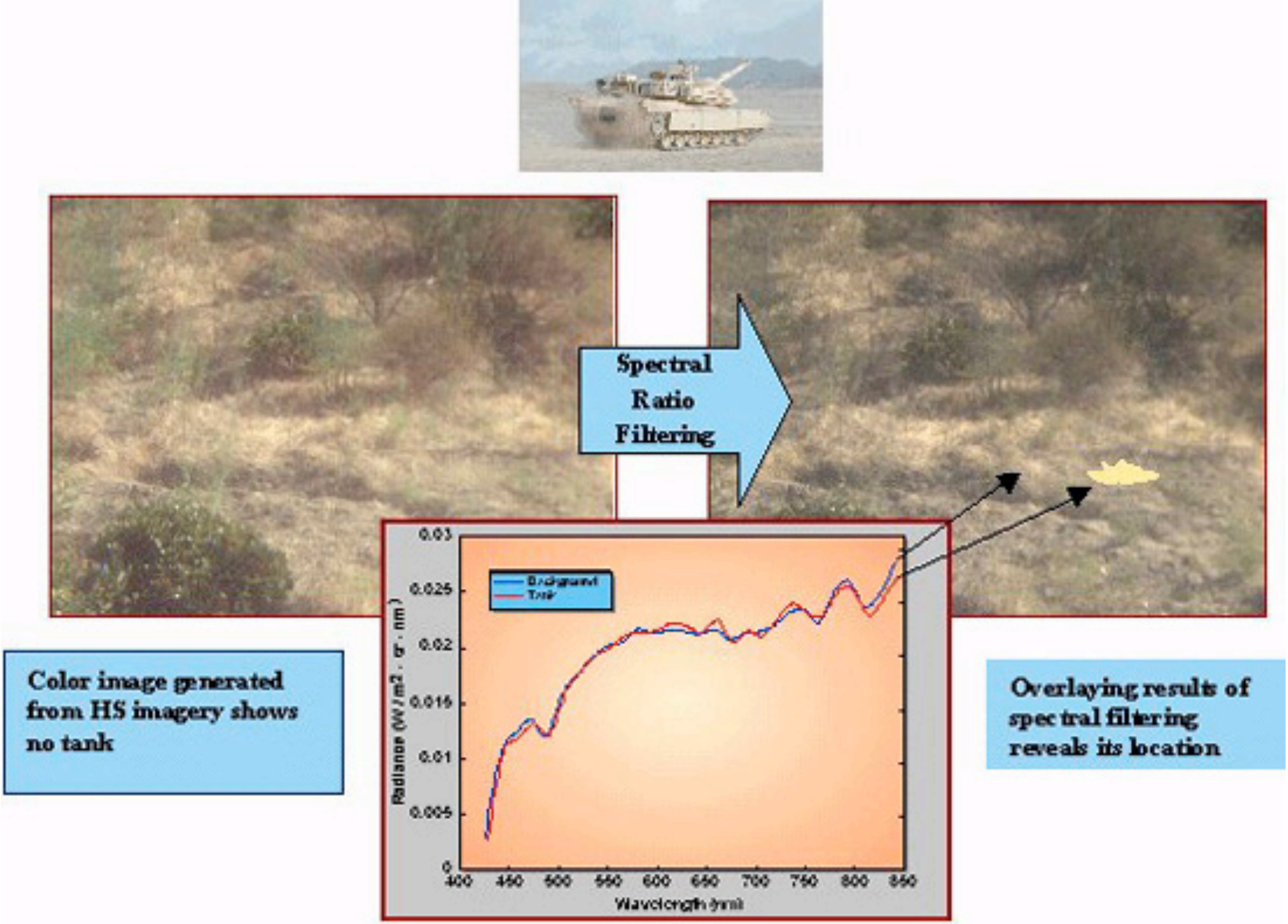
- 12 different cone classes
- sensitivity extending into UV range

- No surprise that they never invented color TV!

Real vs. Conterfeit $$

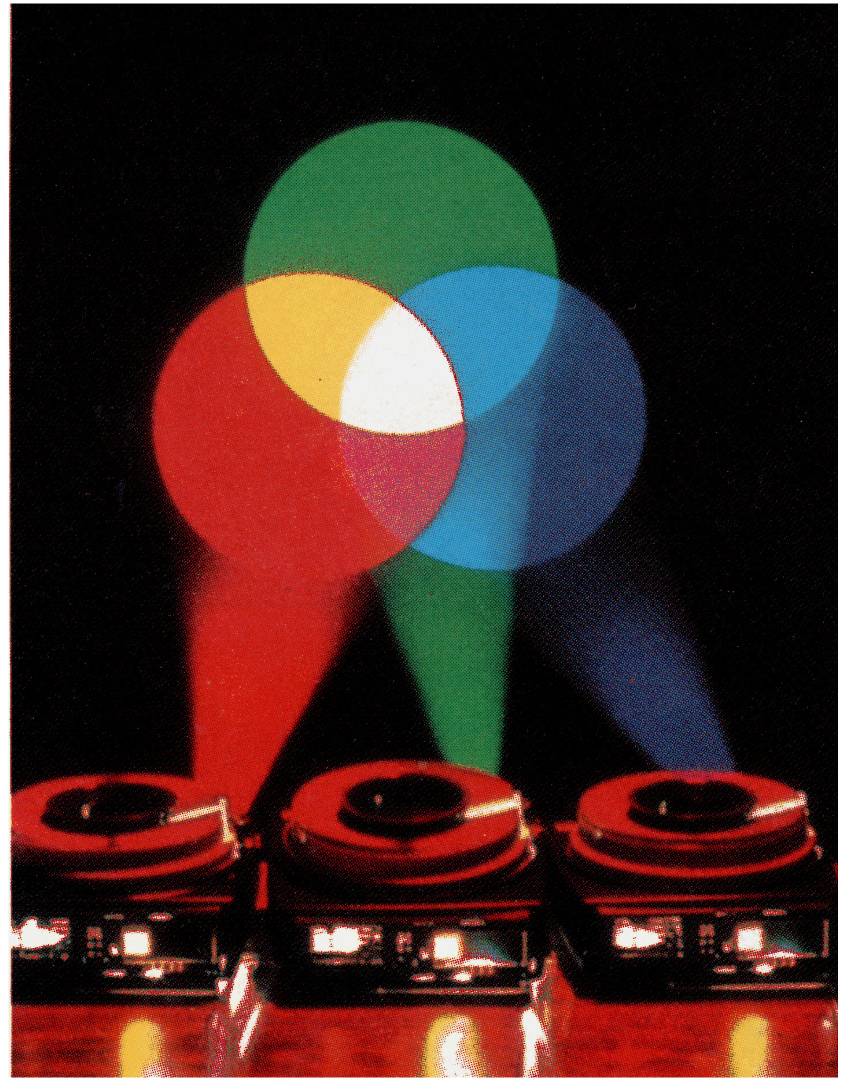
Output of hyper-spectral camera
(colorized artificially)




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

3 “primary” lights

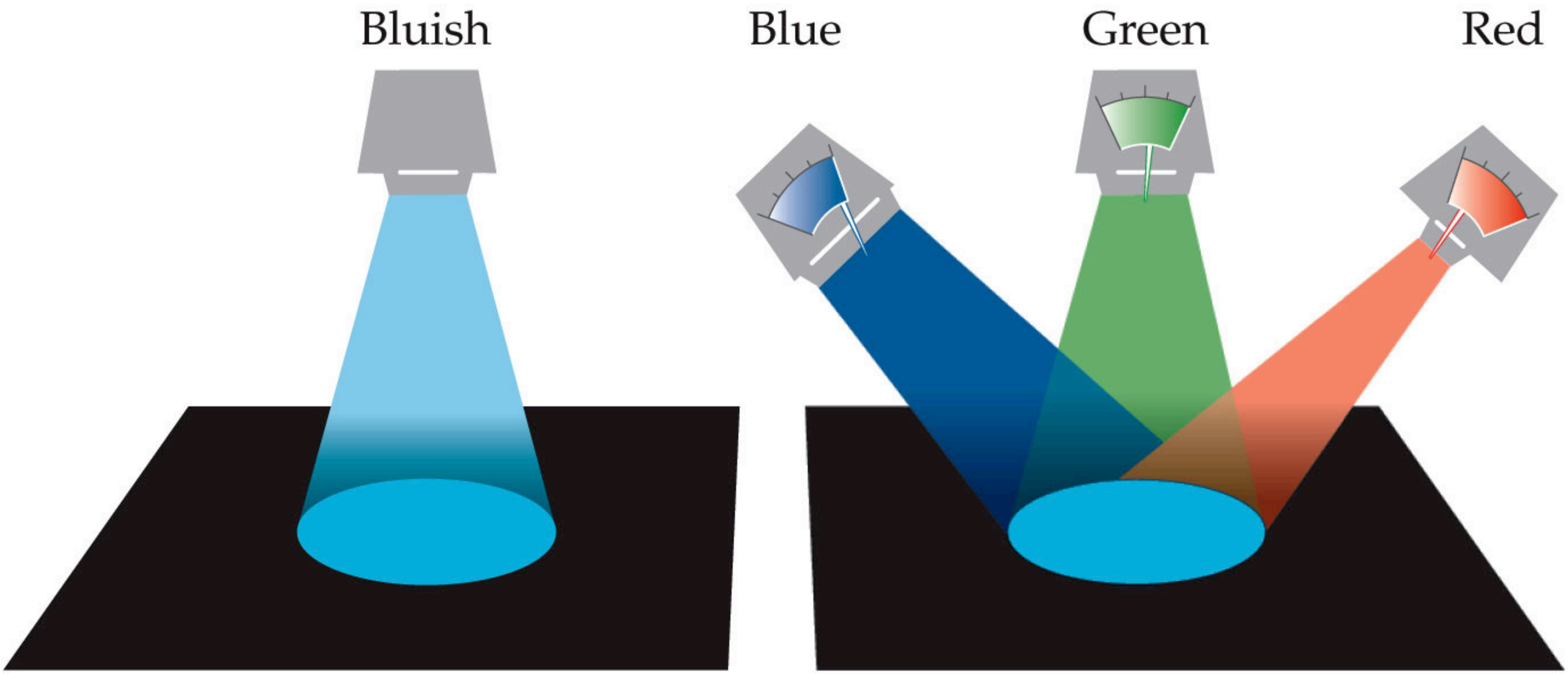
<u>any</u> color can be made by combining three suitable lights...



R G B

How did they figure this out?

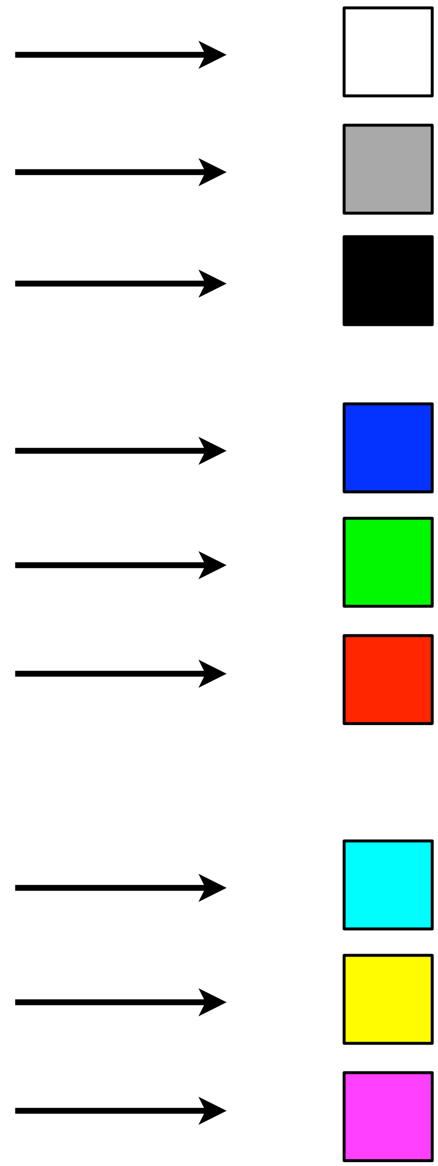
James Maxwell: color-matching experiment



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)

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

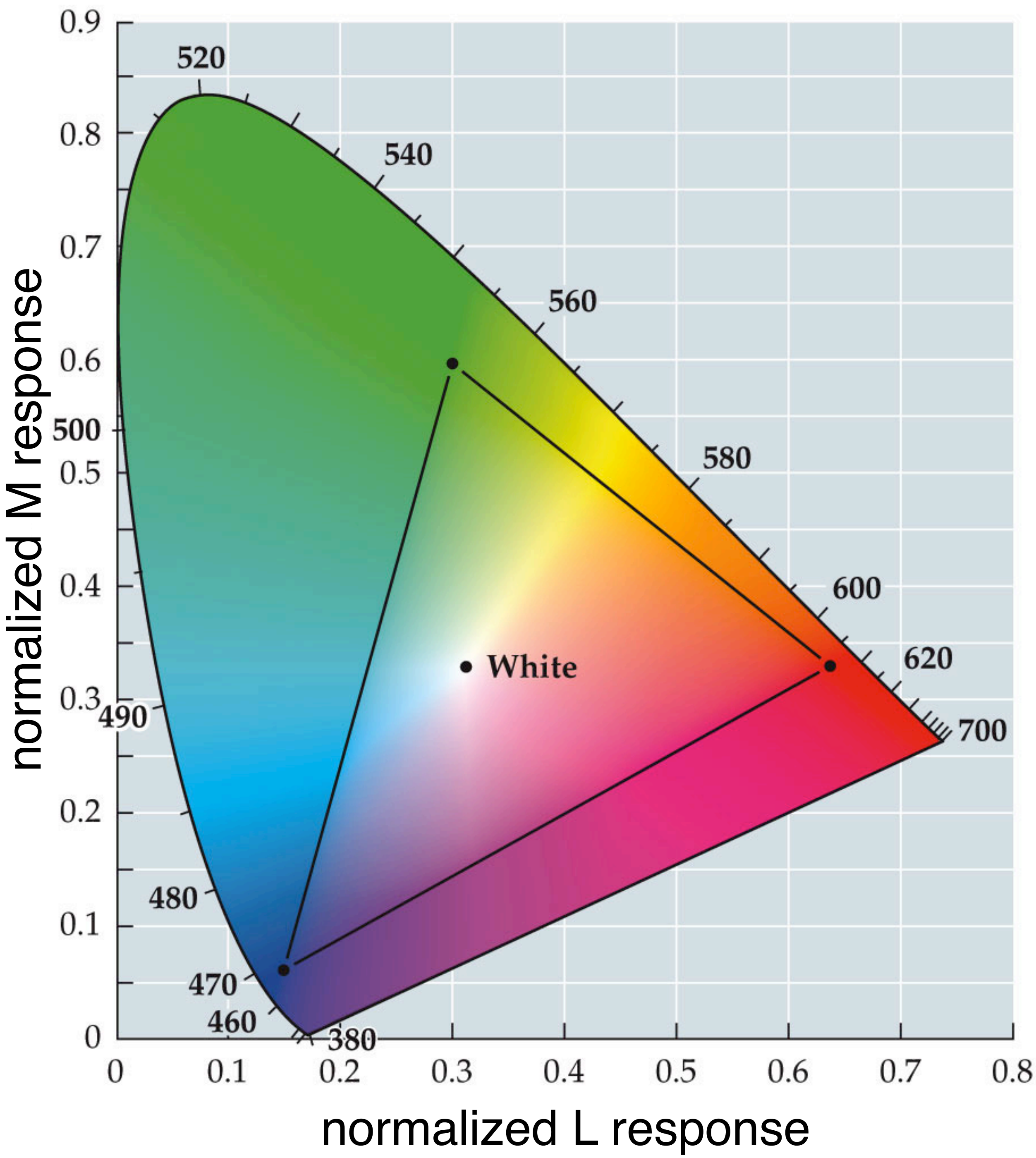
Color space: A three-dimensional space that describes all possible color percepts.

Several ways to describe this space:

- **RGB color space**: Defined by the outputs of Long, Medium, Short wavelength (or R, G, B) lights.

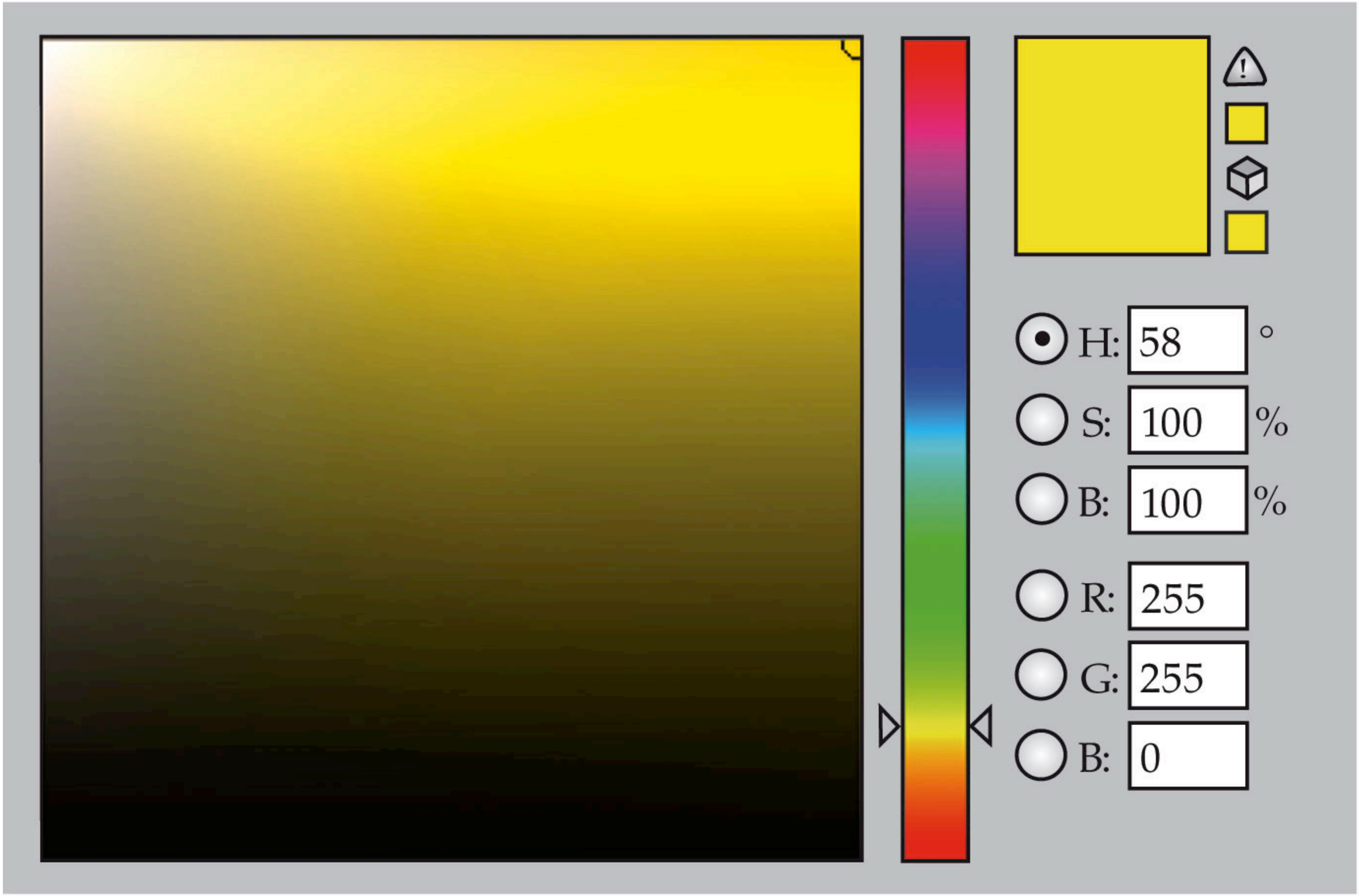
- **HSB color space**: Defined by hue, saturation, and brightness
  - **Hue**: The chromatic (color) aspect of light
  - **Saturation**: The chromatic strength of a hue
  - **Brightness**: The distance from black in color space

2D slice of color space



- hue around the edge
- saturation increasing from center to edge
- brightness not shown

Color picker

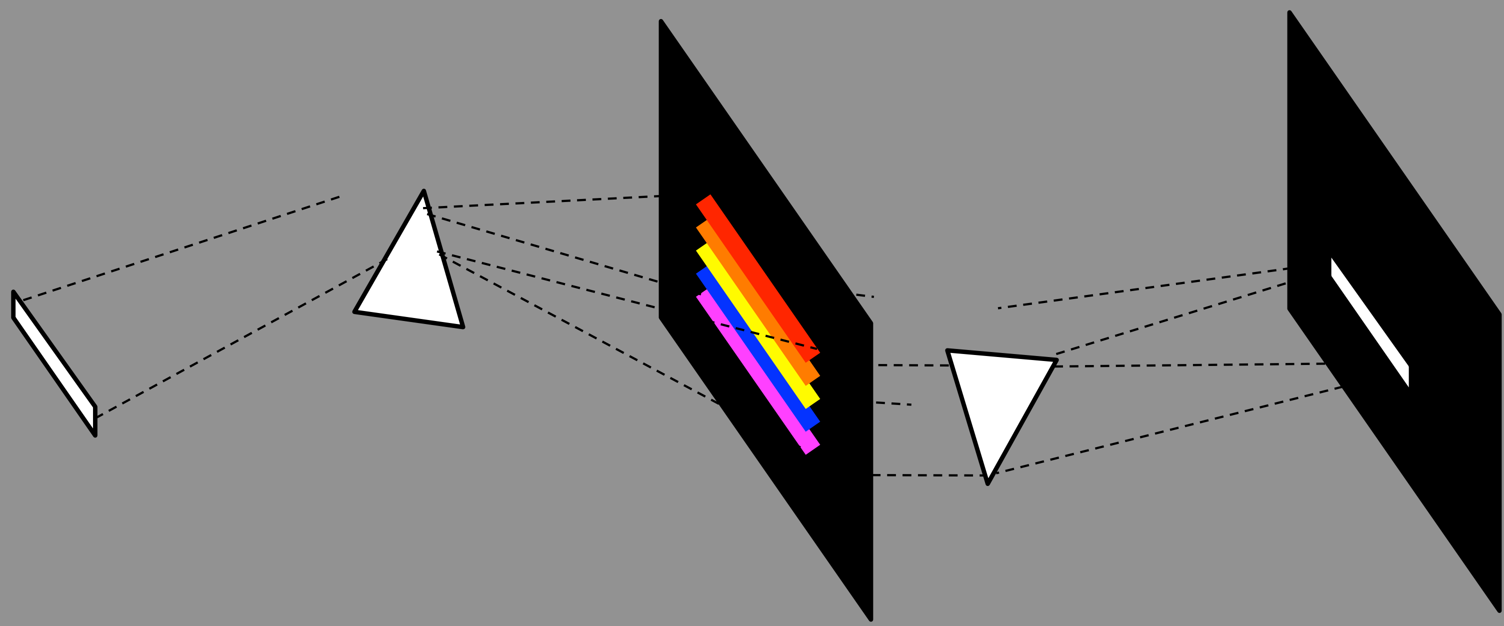


Trichromatic color vision:

(Young & Helmholtz theory)

- three lights needed to make a specific color percept, due to use of 3 distinct cones with different sensitivities

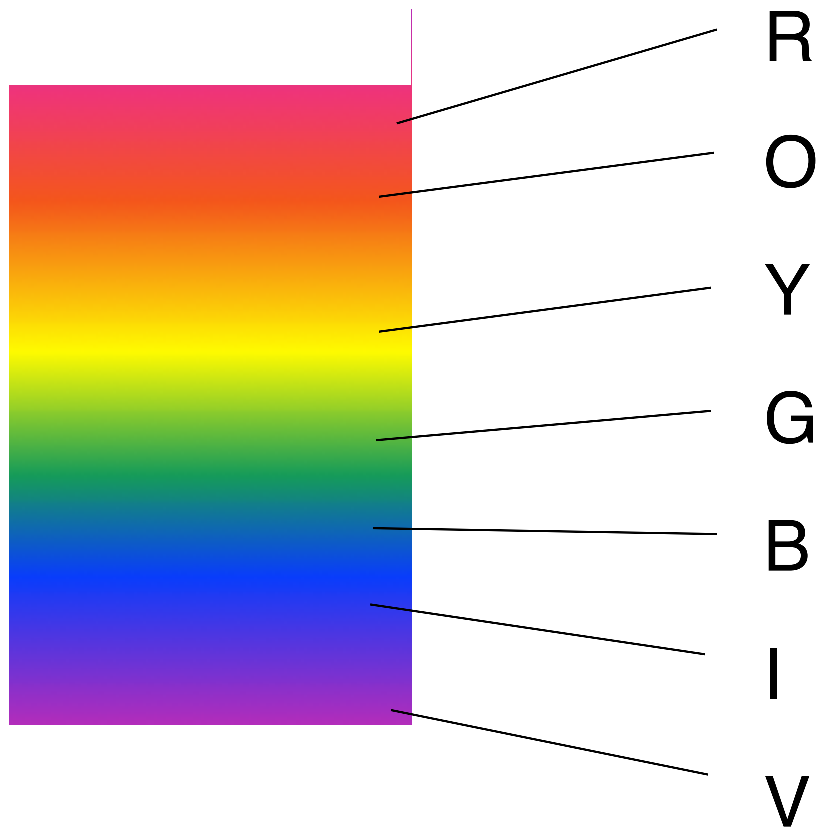
- colors uniquely defined by combinations of cone activations



Late 17th Century: Isaac Newton

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

Newton's Spectrum:

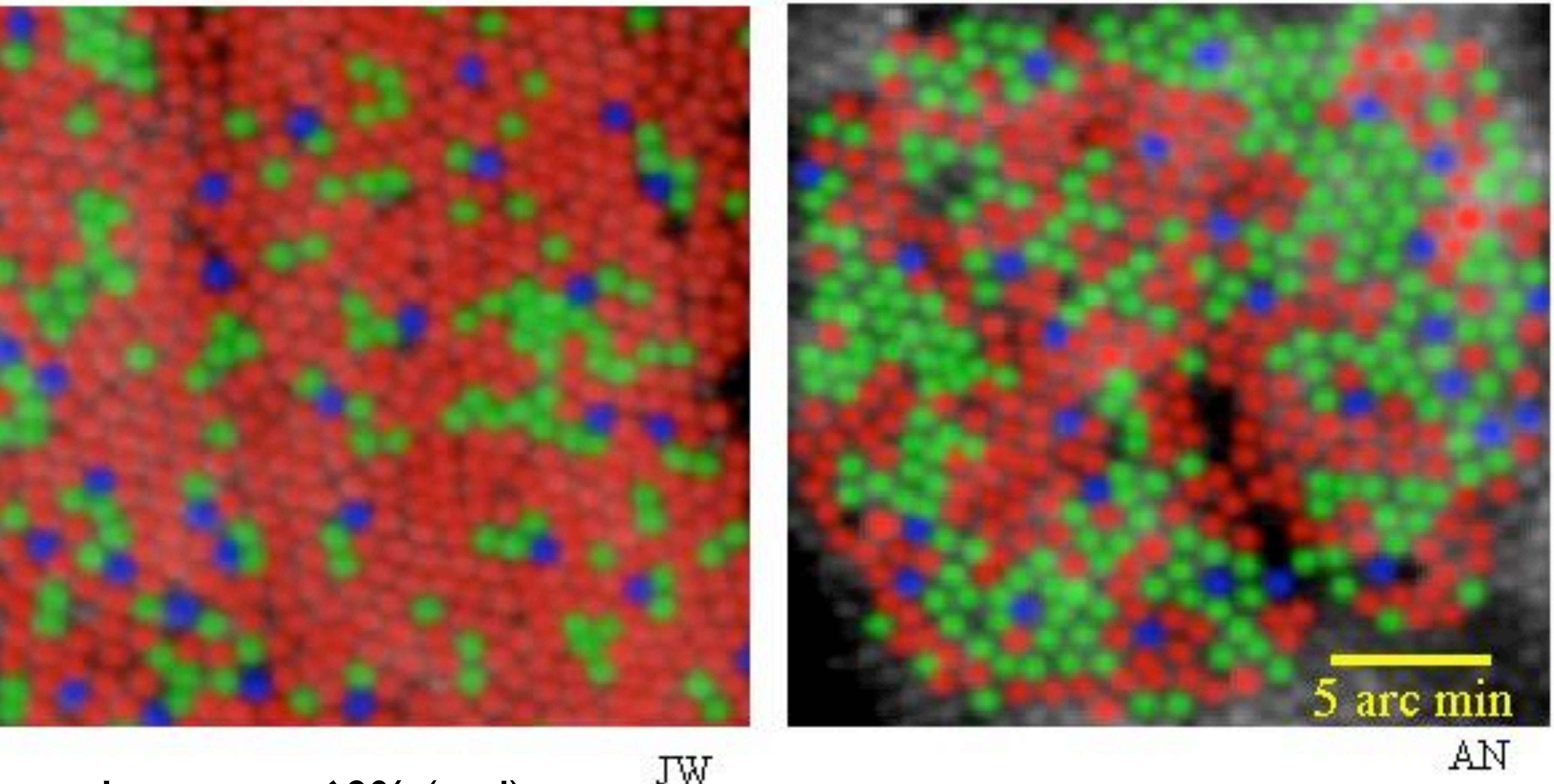


Newton's Theory:

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