

Color



Fredo's office hours

Fridays 2-3pm in 32-D424

Color



Fredo Durand
MIT EECS 6.8370/6.8371



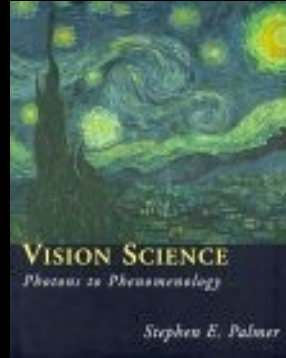
Motivations



Color

- What does RGB really measure?
- Can RGB record all colors?
- Isn't color about wavelength anyway?
- How does this relate to human eyes?
- What are the primary colors? Red Green and Blue? Red Yellow and Blue ? Red, Green Yellow and Blue ?

Selected Bibliography



Vision Science

by Stephen E. Palmer

MIT Press; ISBN: 0262161834

760 pages (May 7, 1999)

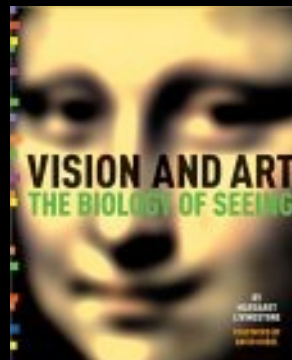


Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition

by Roy S. Berns, Fred W. Billmeyer, Max Saltzman

Wiley-Interscience; ISBN: 047119459X

304 pages 3 edition (March 31, 2000)



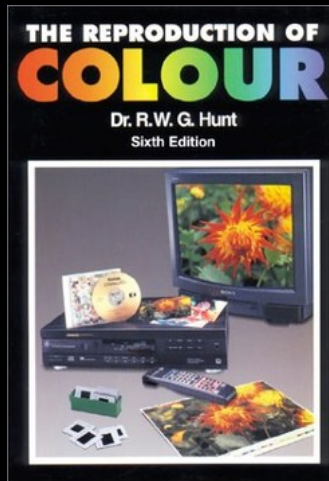
Vision and Art : The Biology of Seeing

by Margaret Livingstone, David H. Hubel

Harry N Abrams; ISBN: 0810904063

208 pages (May 2002)

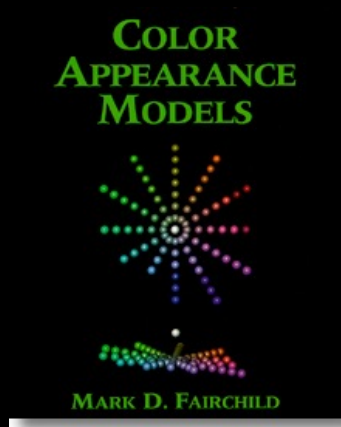
Selected Bibliography



The Reproduction of Color

by R. W. G. Hunt

Fountain Press, 1995

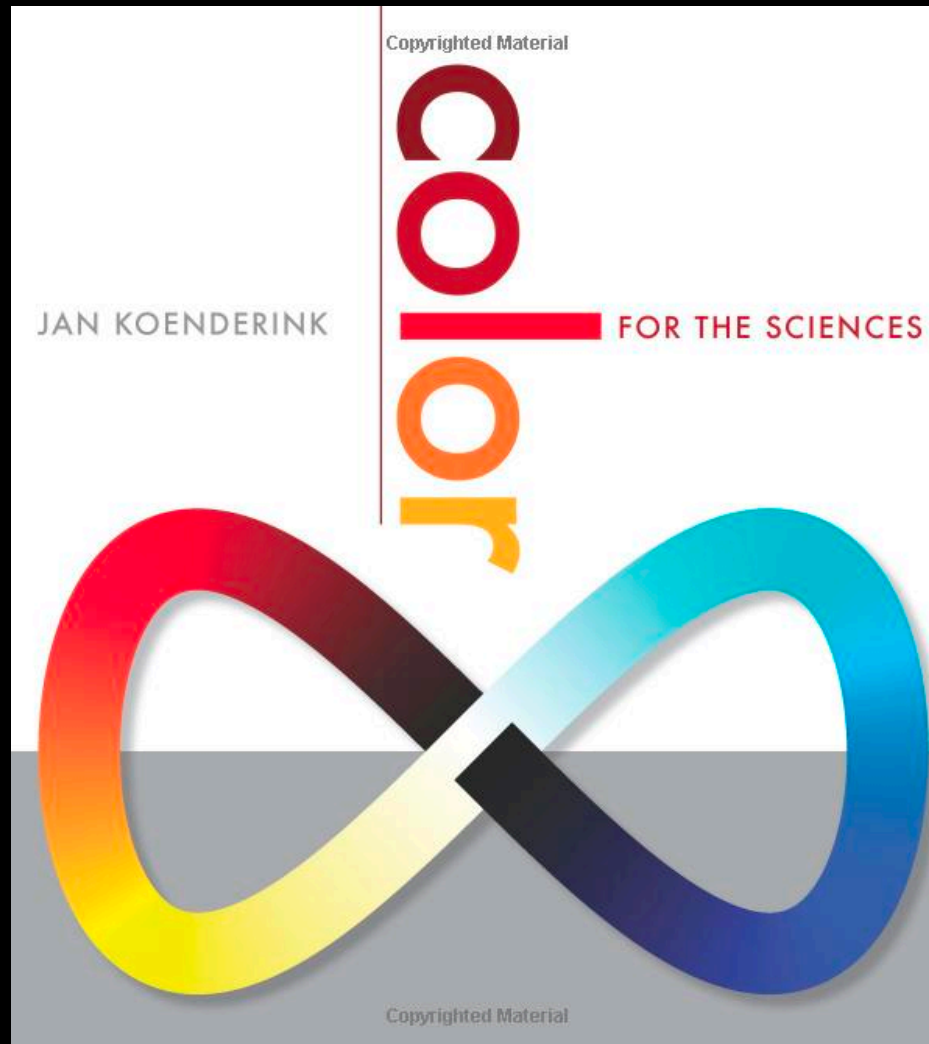


Color Appearance Models

by Mark Fairchild

Addison Wesley, 1998

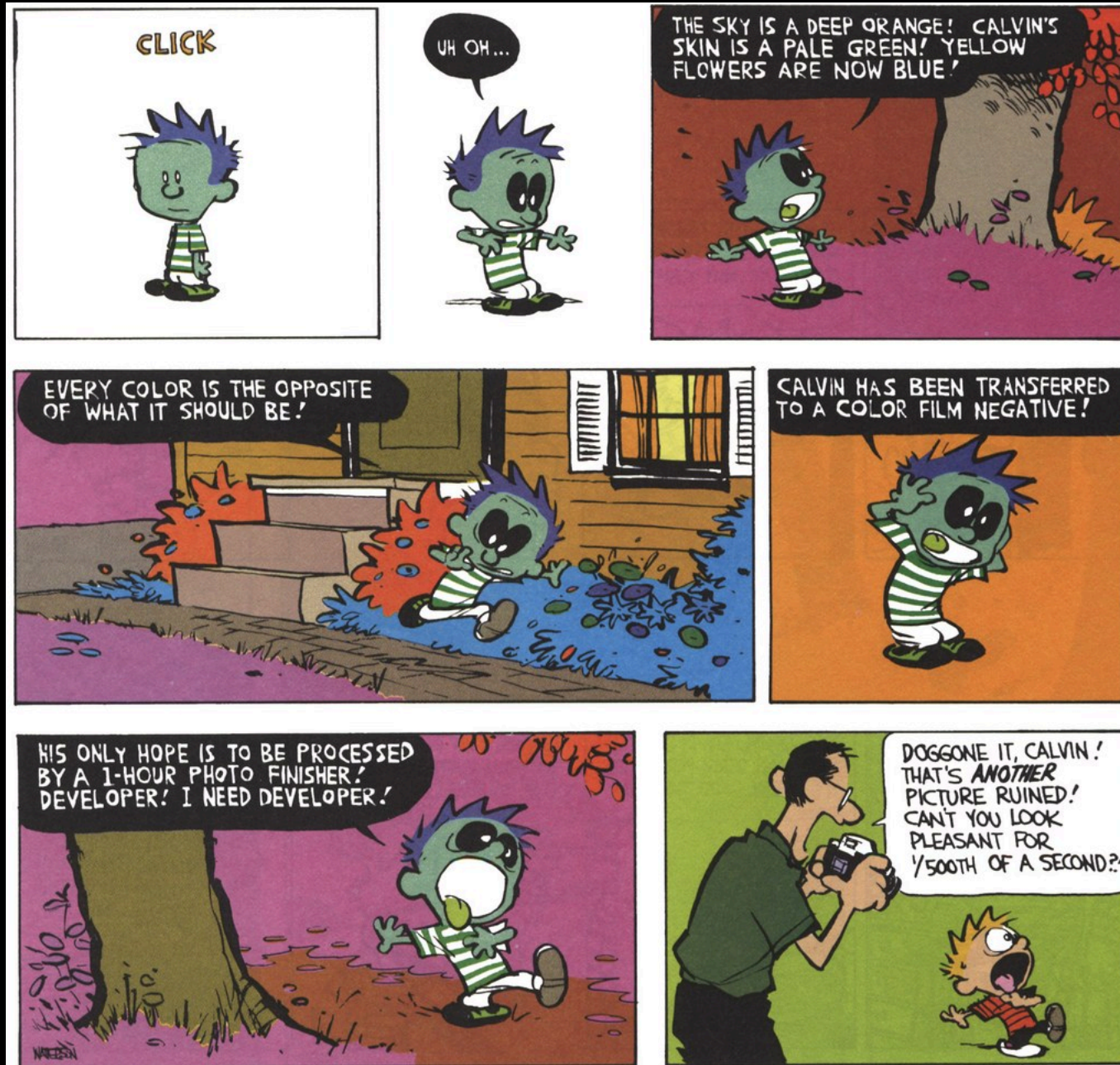
Selected Bibliography



Video: Color Perception in 5 minutes



Questions?

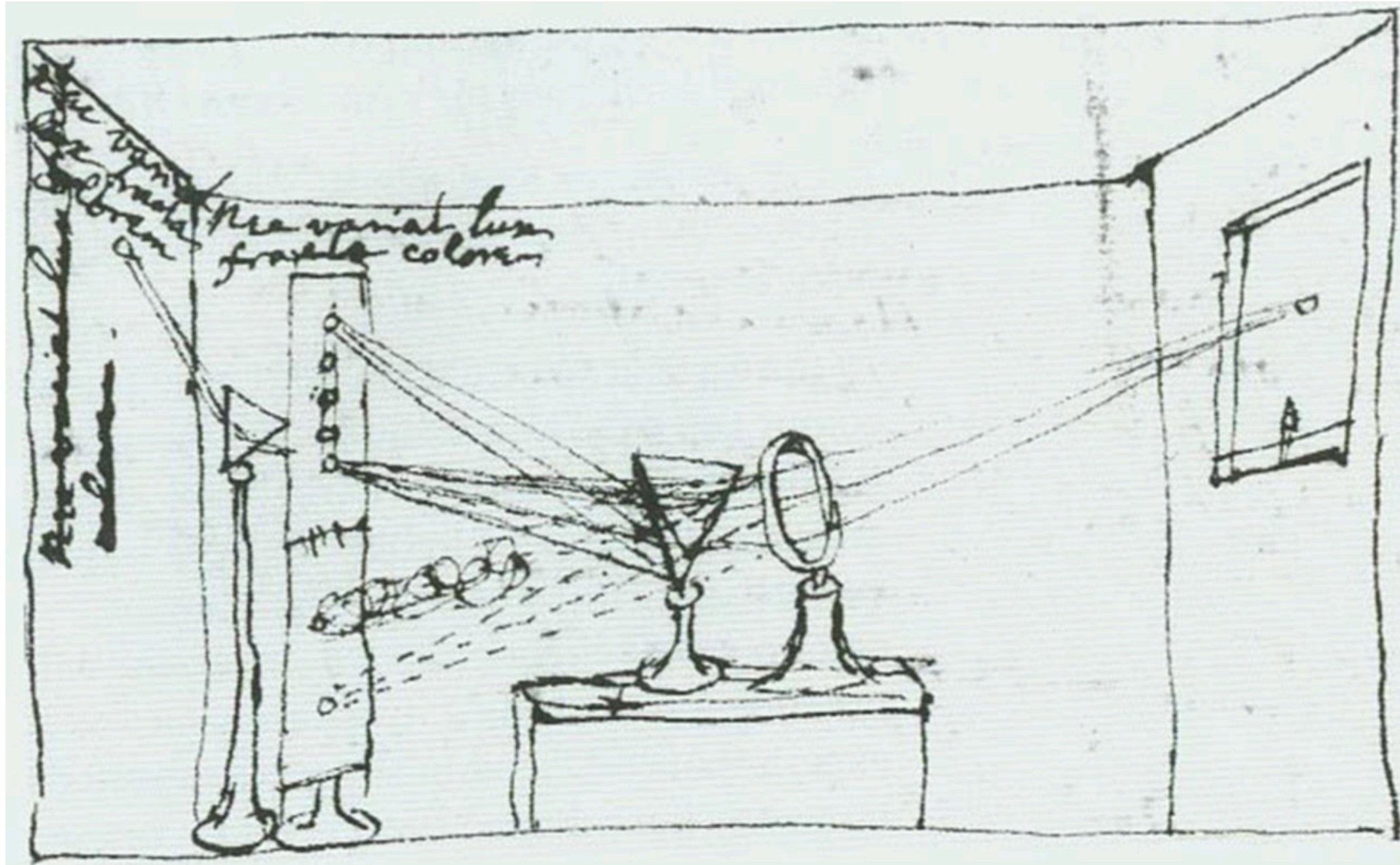




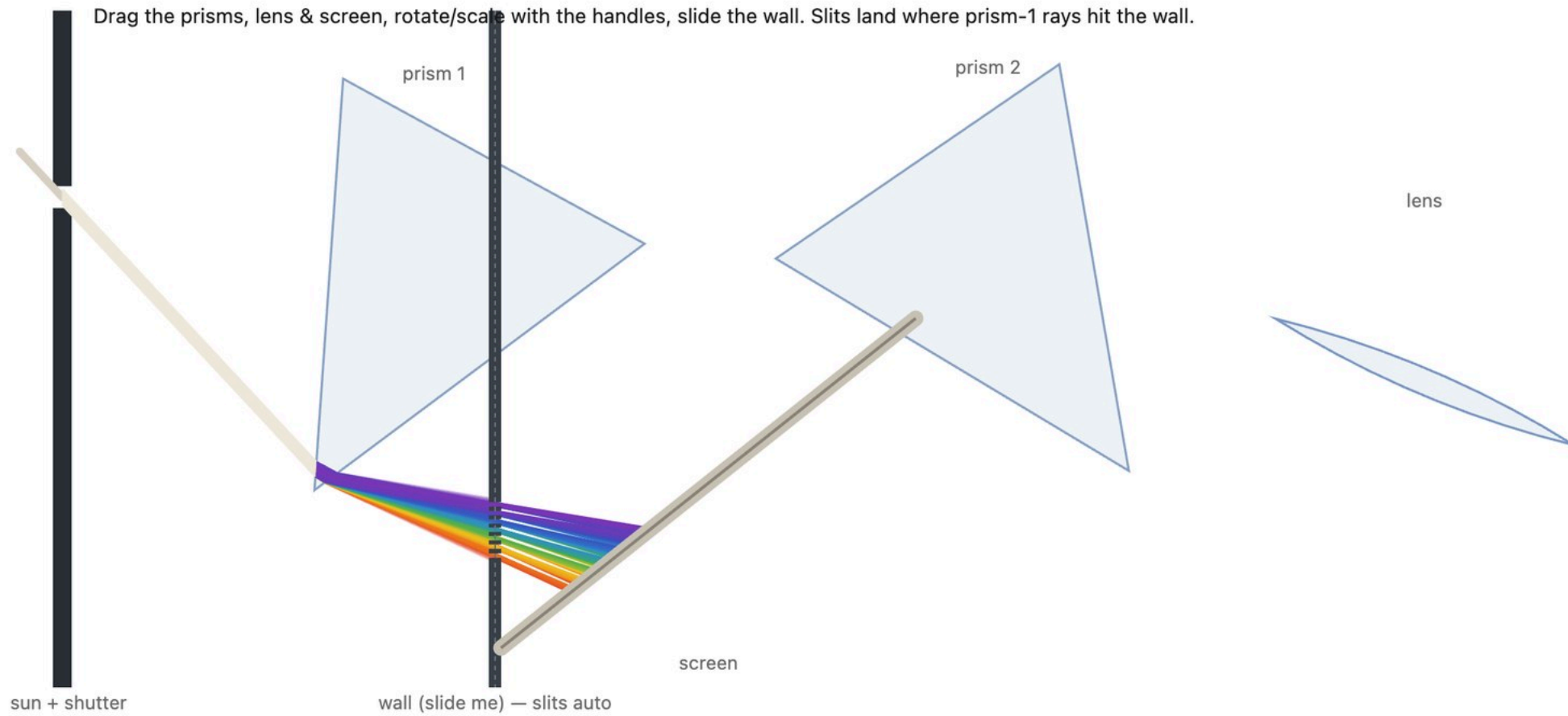
Physical colors: spectra



Newton's experiment

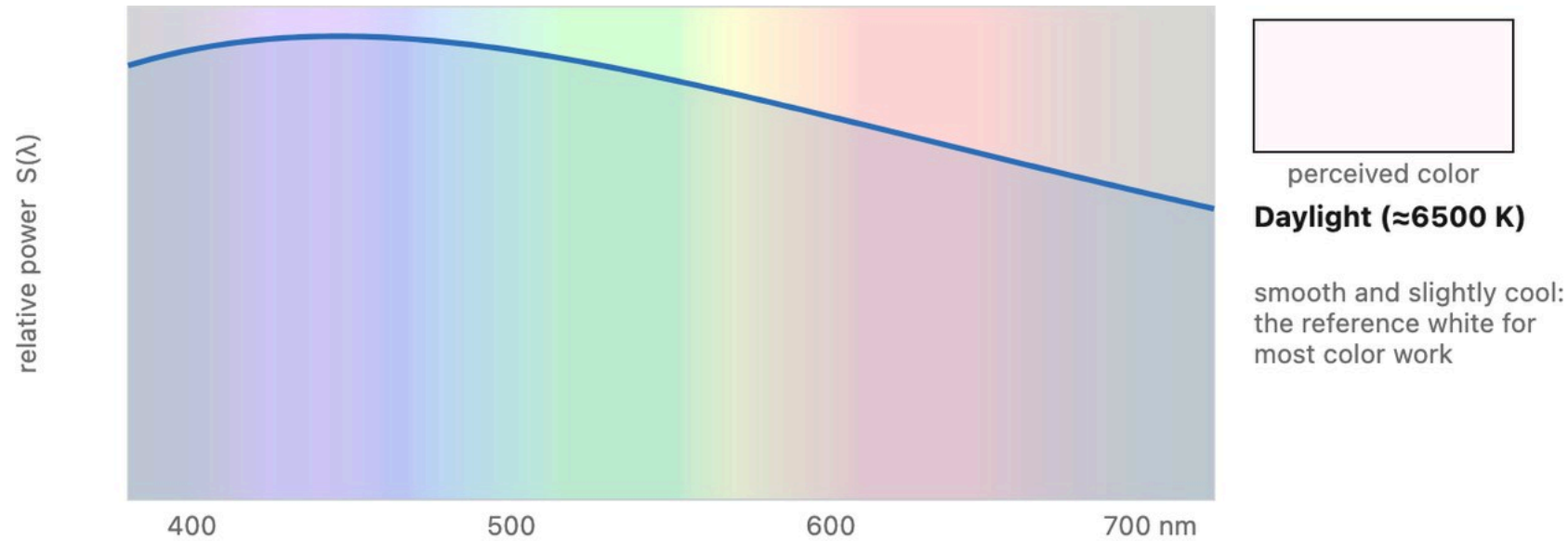


Demo: Newton prism puzzle

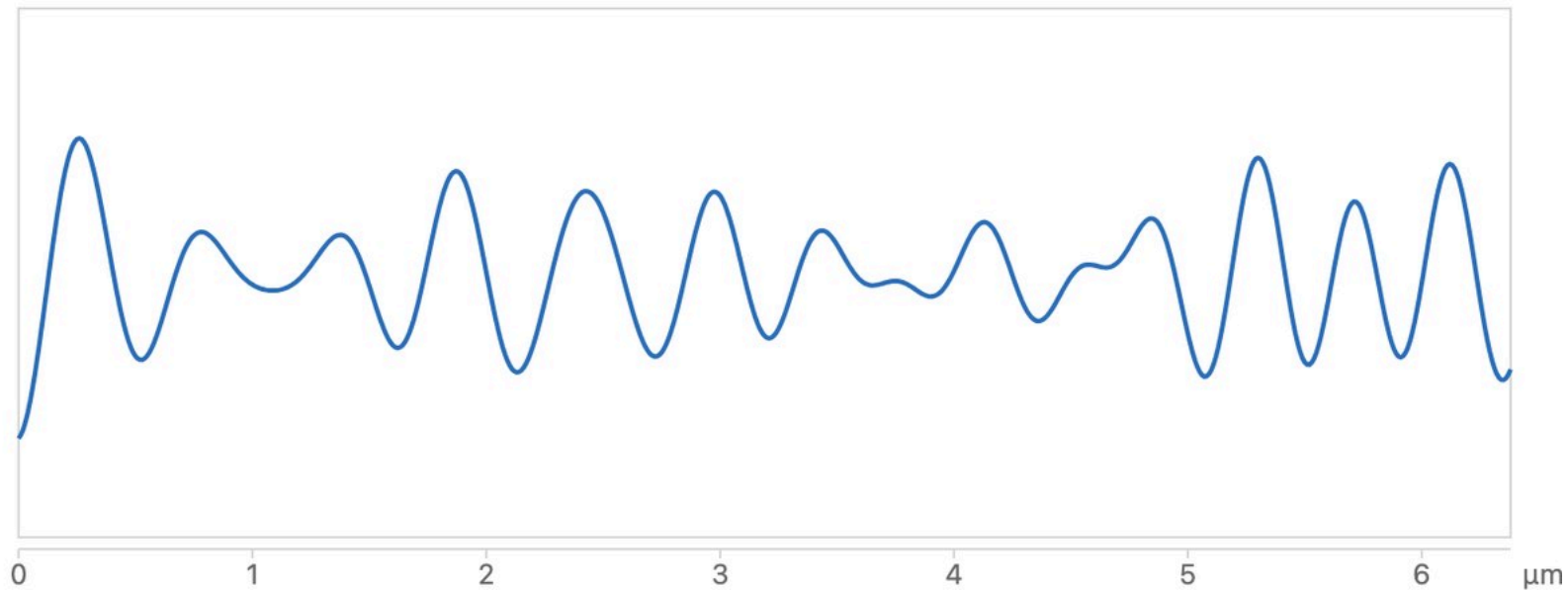


Light is a wave

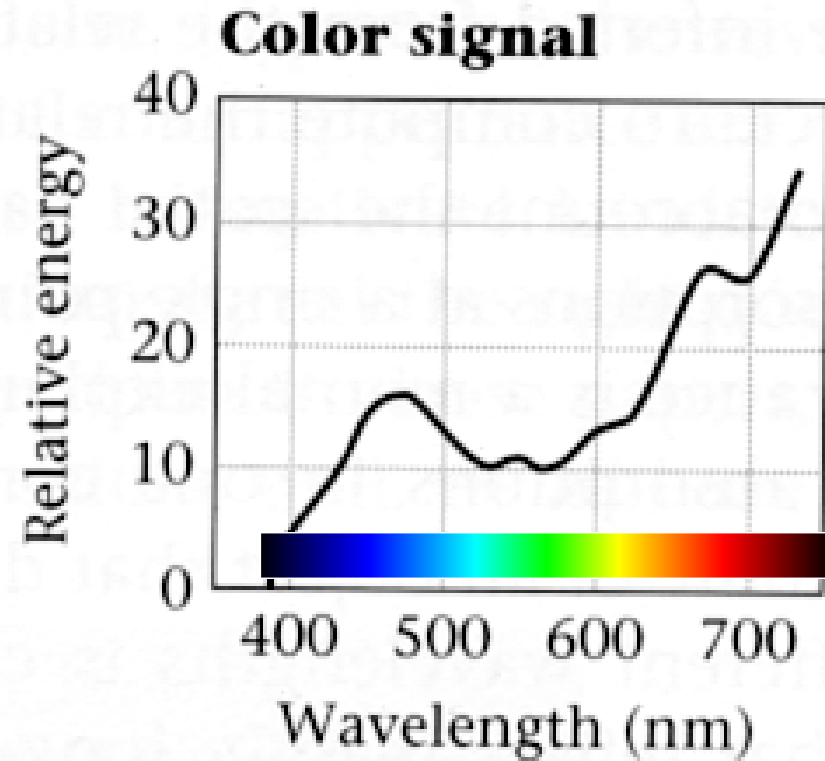
Visible: between 450 and 700nm



the same spectra as 1-D waves (noise-shaped so the power spectrum is $S(\lambda)$; traveling $\rightarrow$)



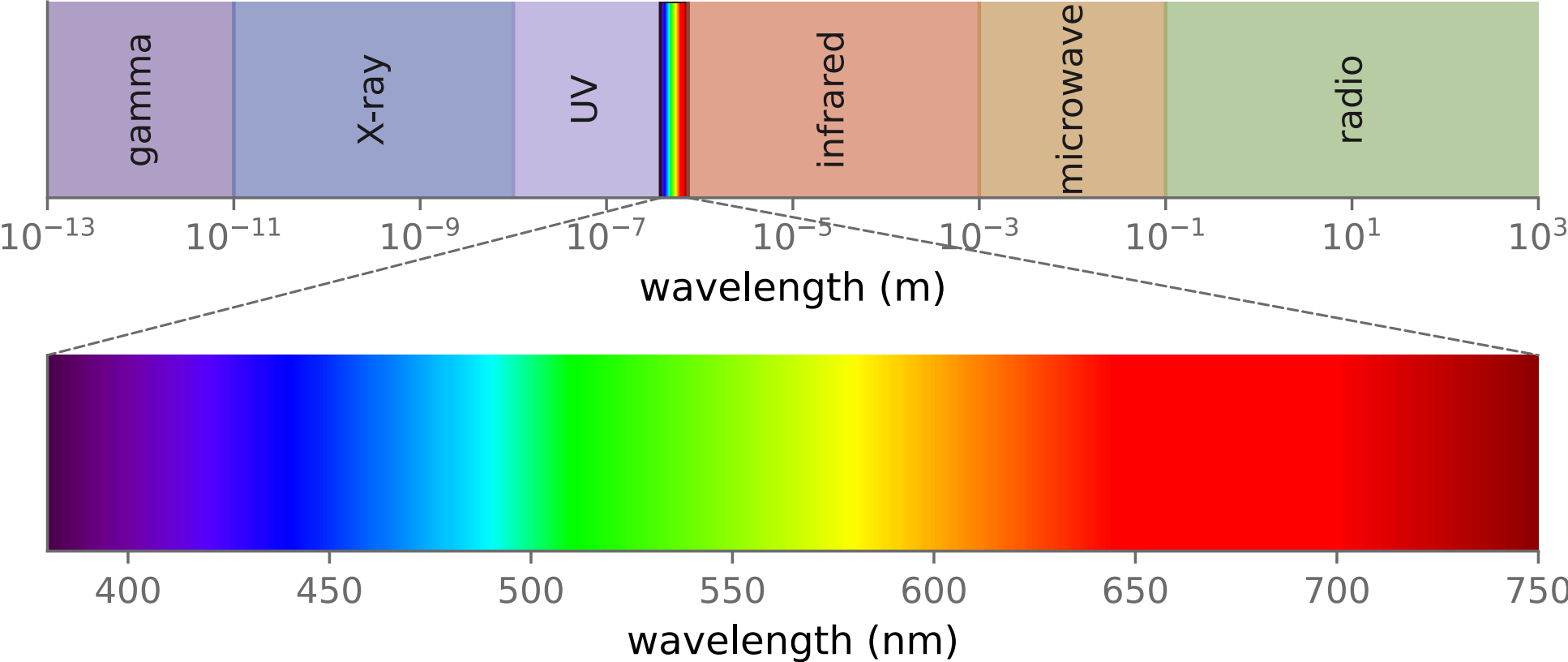
Spectrum

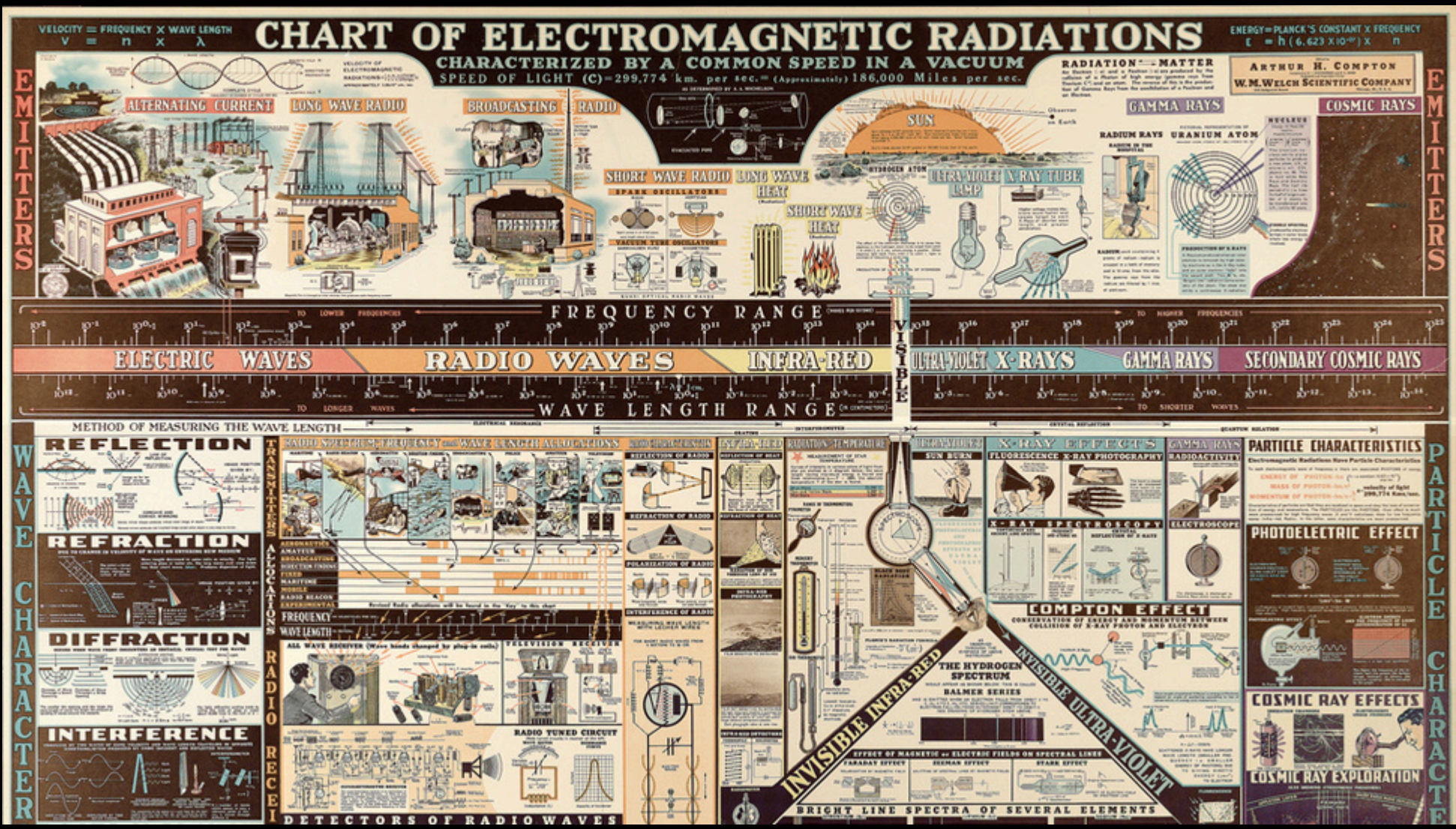


Light is characterized by its spectrum:
amount of energy at each wavelength

This is a full distribution:
one value per wavelength (infinite number of values)

The electromagnetic spectrum (visible light is a thin slice)





Spectrum demo

- Diffraction grating:
 - shifts light as a function of wavelength
 - Allows you to see spectra
 - In particular, using a slit light source, we get a nice band showing the spectrum
- See the effect of filters
- See different light source spectra

Figure-58 Diffraction

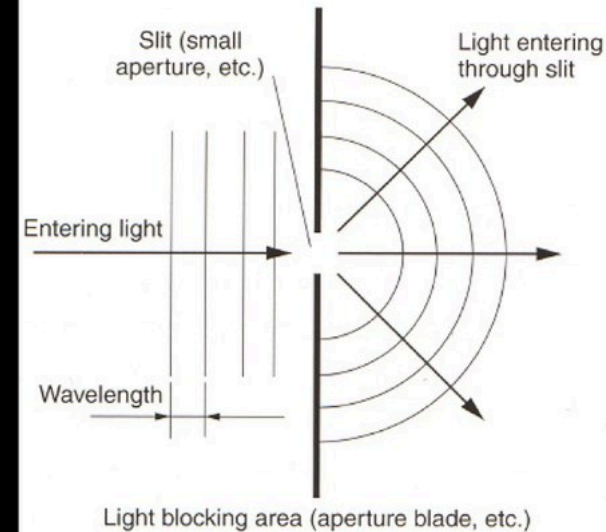
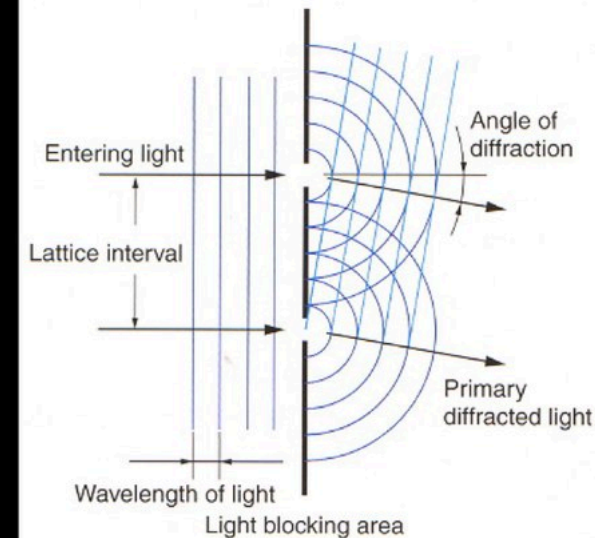
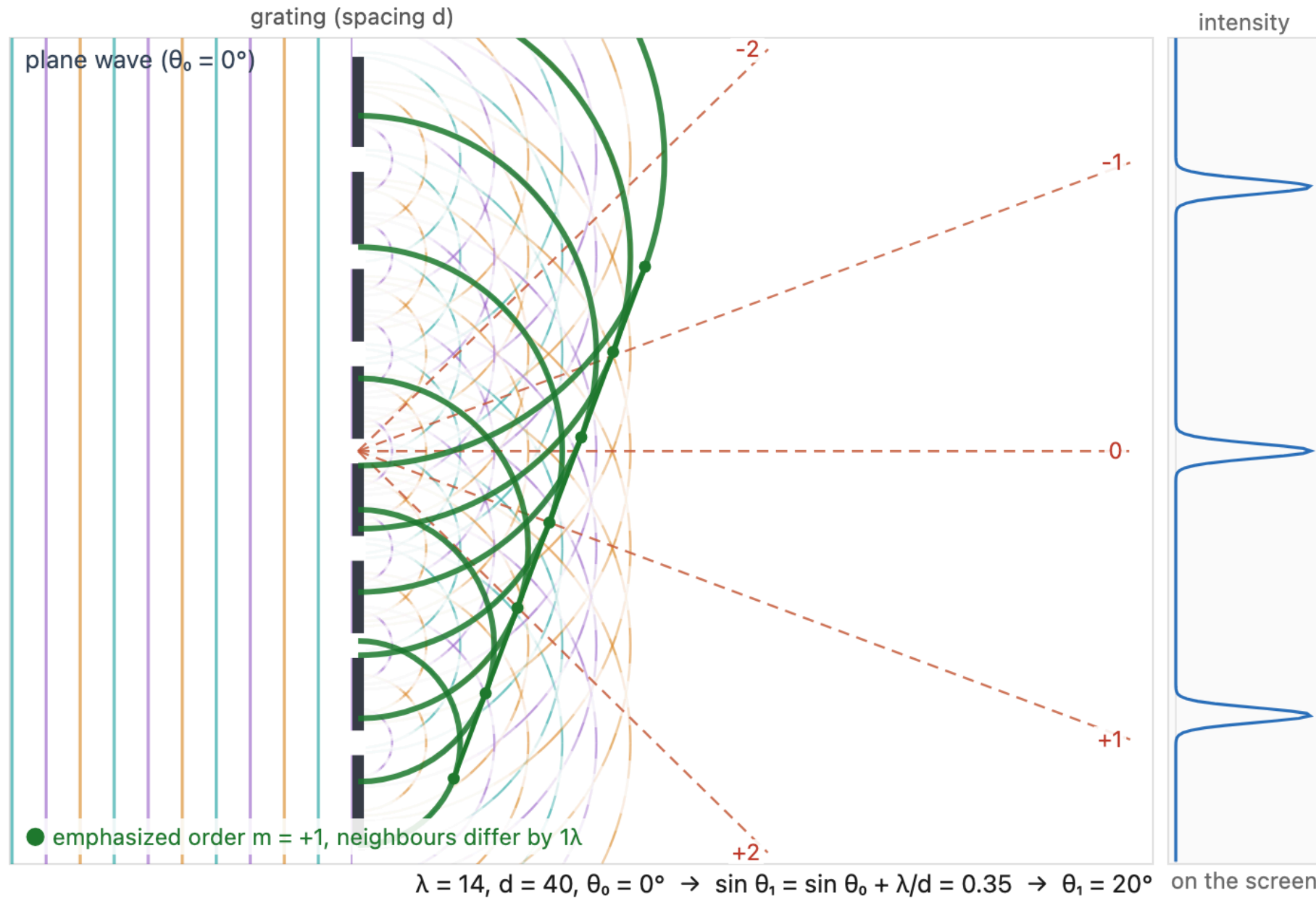


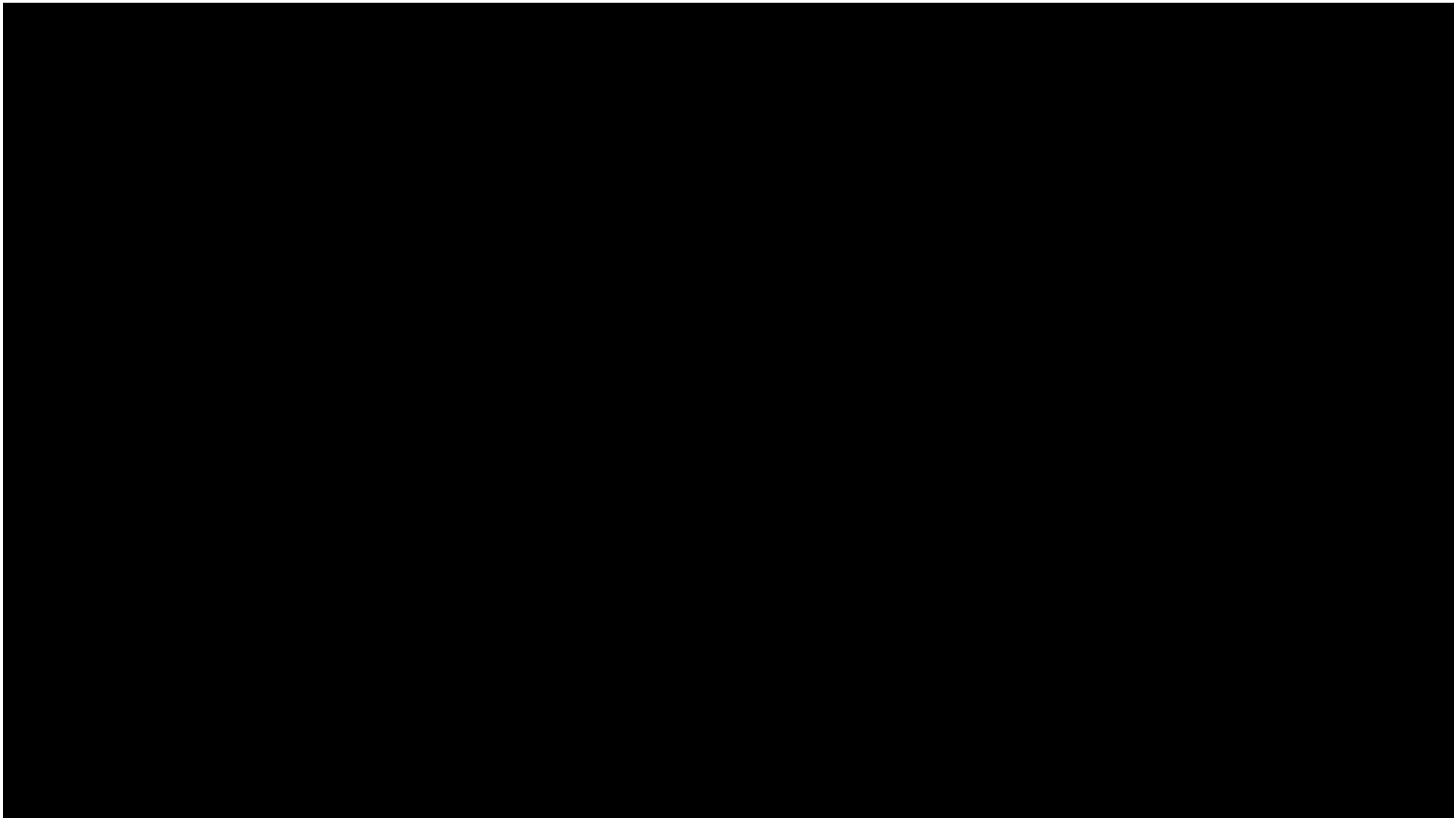
Figure-59 Principle of diffracted light generation



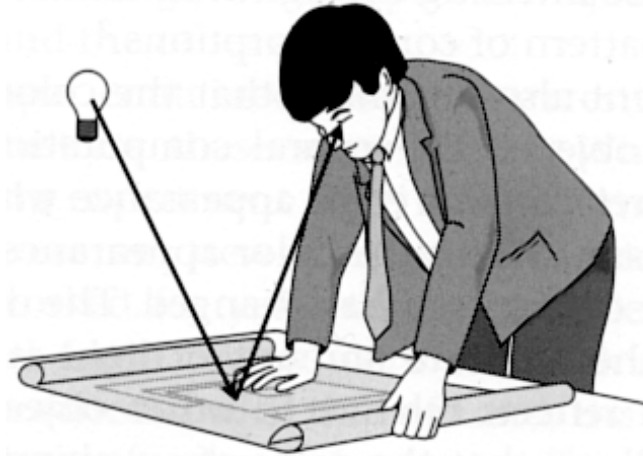
Source: Canon red book

Demo: Diffraction grating





Light-matter interaction

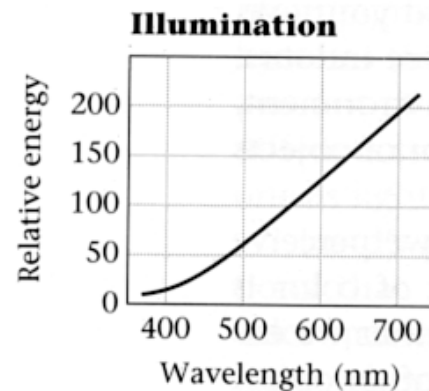


Where spectra come from:

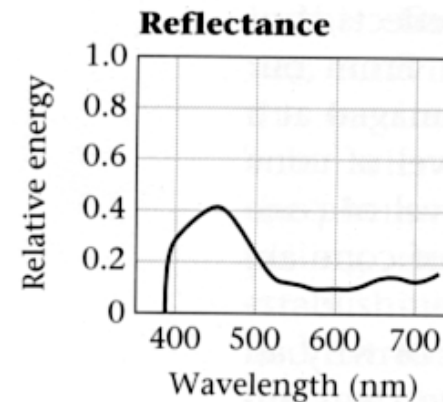
- light source spectrum
- object reflectance (aka spectral albedo)

get multiplied wavelength by wavelength

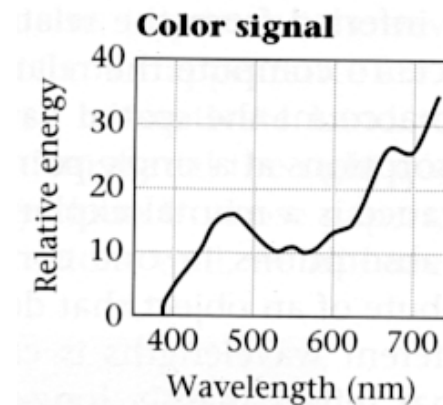
There are different physical processes that explain this multiplication
e.g. absorption, interferences



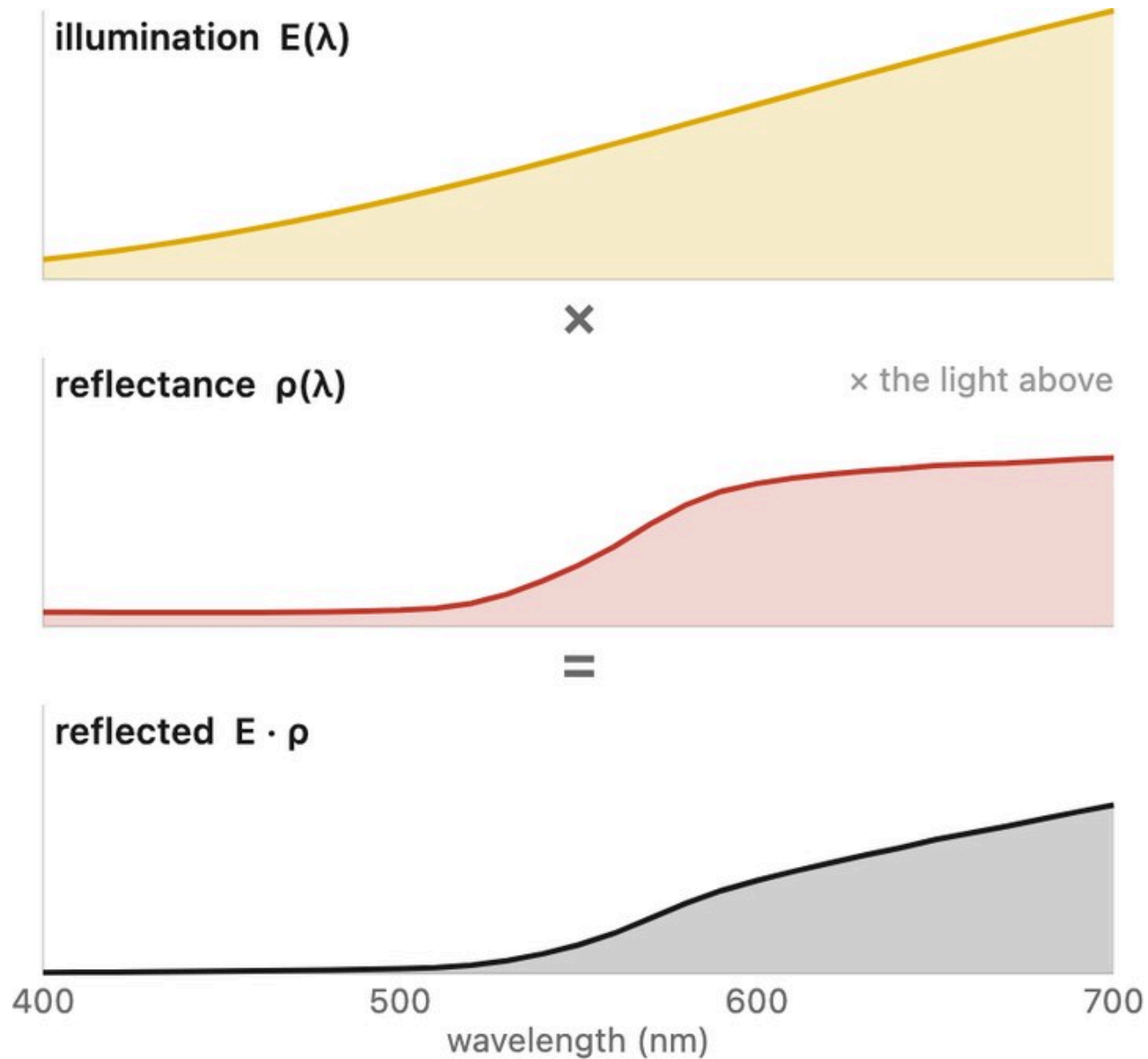
• *



=



Demo: Illumination $\times$ reflectance



colour seen



"orange" under A



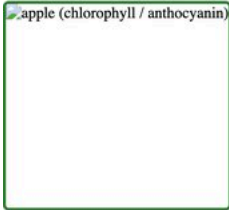
same surface under
D65 daylight (reference)

*the surface is unchanged —
only the light changed the signal,
so white balance must undo it.*

Demo: Pigment against structural color

Where colour comes from. Pigment colour is selective absorption — flat and angle-independent. Structural colour comes from wavelength-scale micro-geometry (interference & diffraction) and is iridescent. Click any photo to enlarge it.

Pigment — selective absorption, the same colour from every angle



apple (chlorophyll / anthocyanin)

Structural · thin-film interference — one thin layer; a single reflection pair

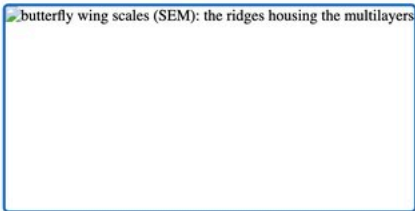


soap bubble

Structural · multilayer interference — a stack of many wavelength-scale layers



Morpho butterfly

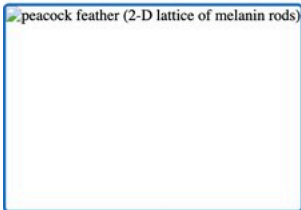


butterfly wing scales (SEM): the ridges housing the multilayers



jewel beetle

Structural · photonic crystal — a 2-D/3-D periodic lattice



peacock feather (2-D lattice of melanin rods)



opal (3-D sphere lattice)

Photos: free-licensed Wikimedia Commons (credited in the book's image credits).

Demo: Color mechanism map



Each dot is one computed spectrum. Examples: a candle flame (~1900 K); a tungsten bulb (~2800 K); the sun (~5800 K).

THE SIX WAYS

- **absorption** pigments, dyes, band gaps
- **structural** thin film, multilayer
- **incandescence** anything hot enough
- **discharge and laser** atomic emission lines
- **scattering** Rayleigh and Mie
- **fluorescence** absorb short, emit long

A single curve, not a region: one number, the temperature, picks the colour. Ideal blackbody colour moves from warm through near-white to blue with temperature; it does not become green or purple.

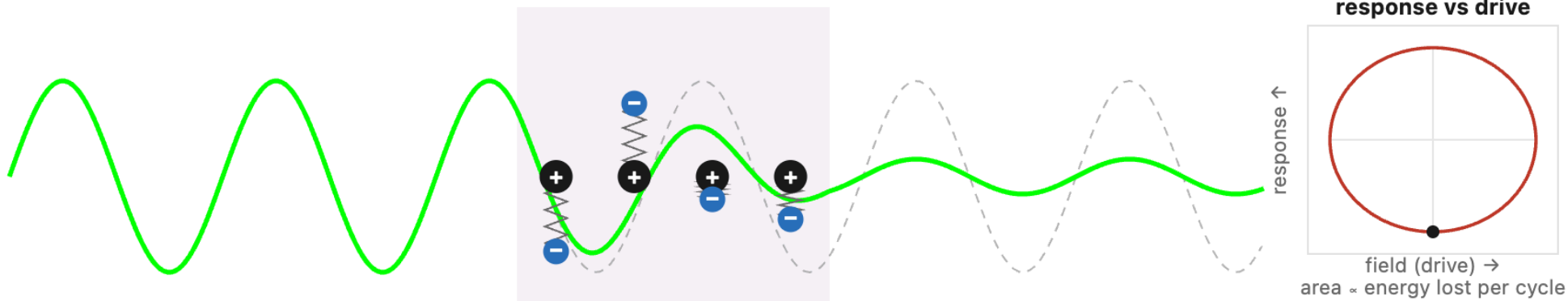
from: Planck's law, 800 K to 20 000 K

Demo: Lorentz resonance

incoming light →

bound-electron response (lags the field)

transmitted →

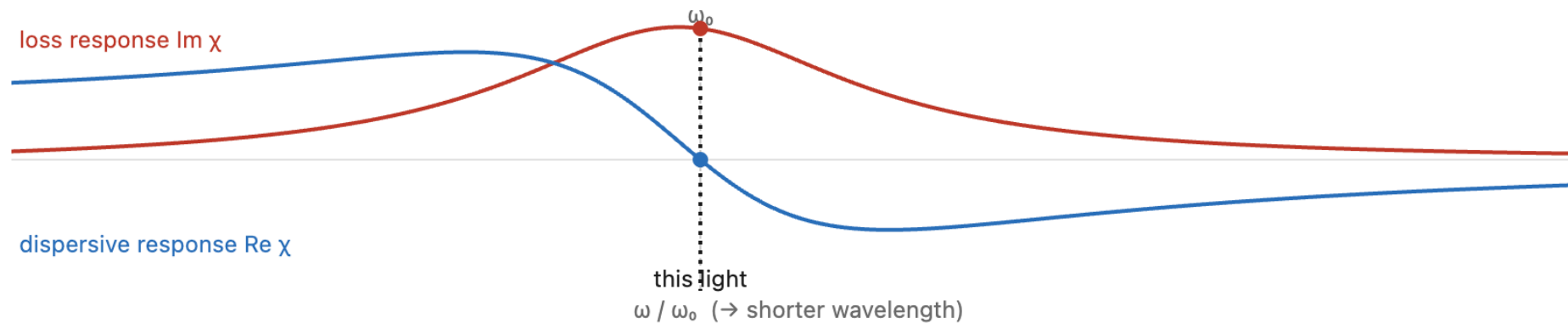


dashed = vacuum reference

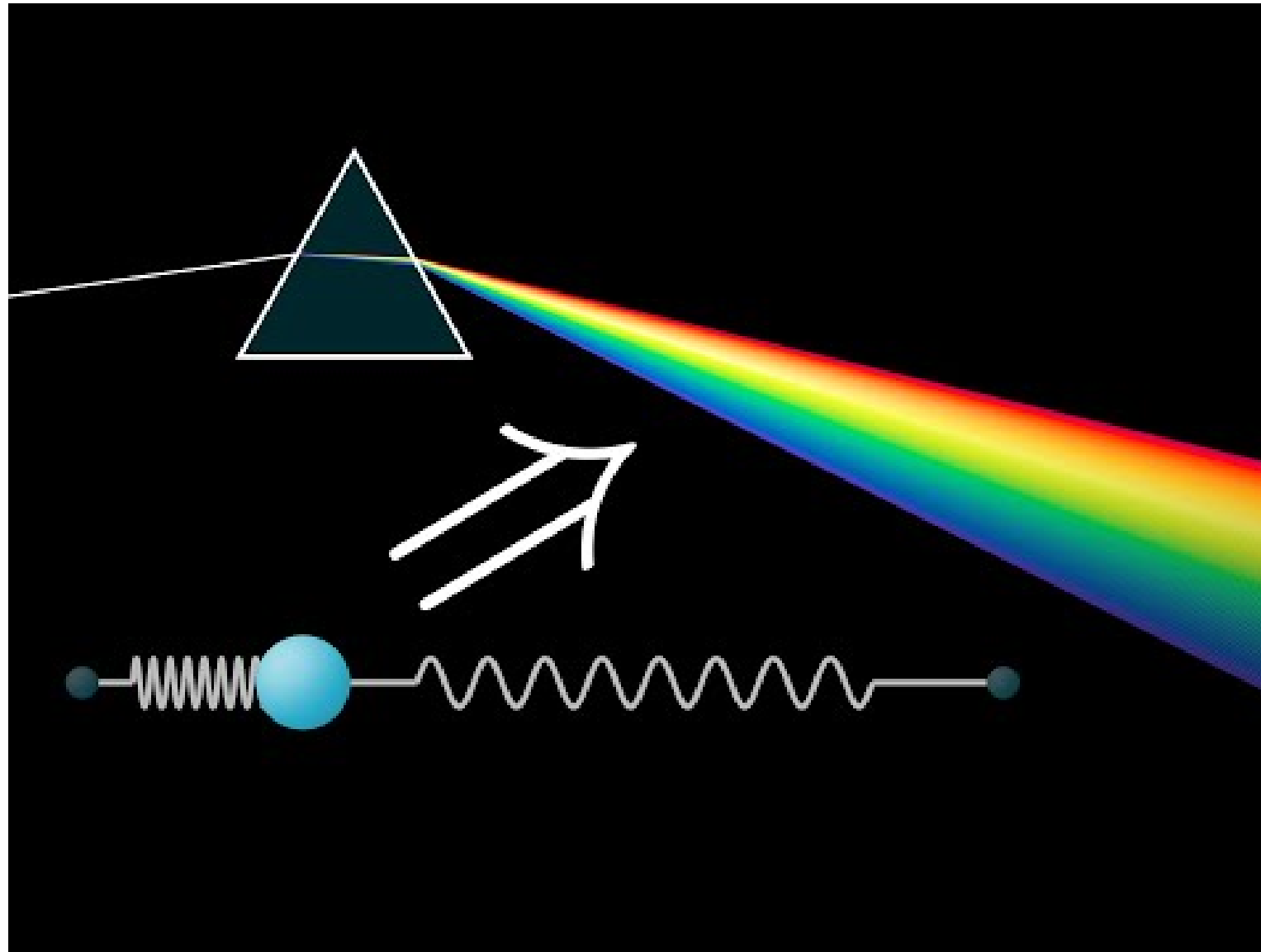
Gold (visible resonance): $\lambda_0 = 520 \text{ nm}$ · $\gamma = 0.42$ | light $\lambda = 520 \text{ nm}$ → $\omega/\omega_0 = 1.00$

≈ resonance → strong absorption (this colour is drained → the material's colour)

schematic phase shift and attenuation



Video: But why would light 'slow down'? (Optics puzzles), by 3Blue1Brown

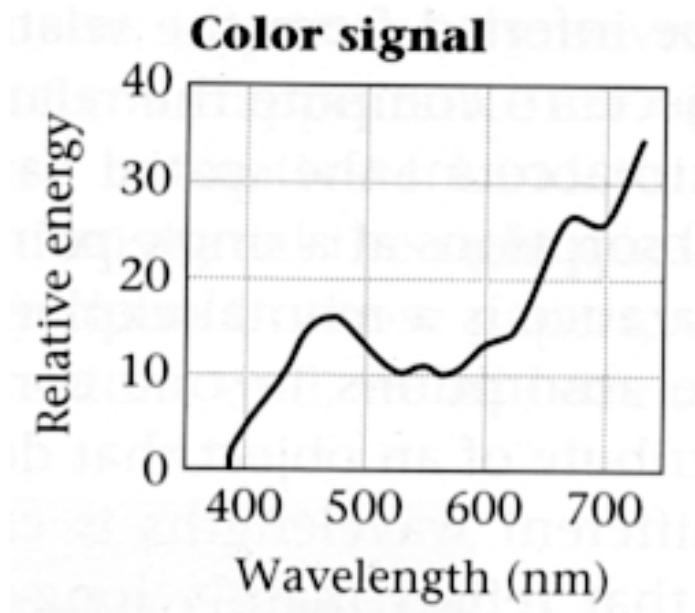


Video: A cephalopod repainting itself, in motion



Questions?

- So far, physical side of colors: **spectra**
 - an infinite number of values
(one per wavelength)
 - depends on light & reflectance

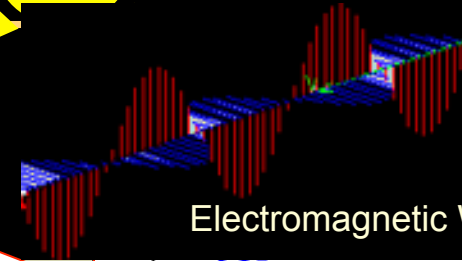
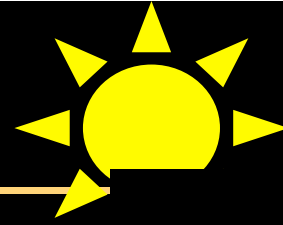




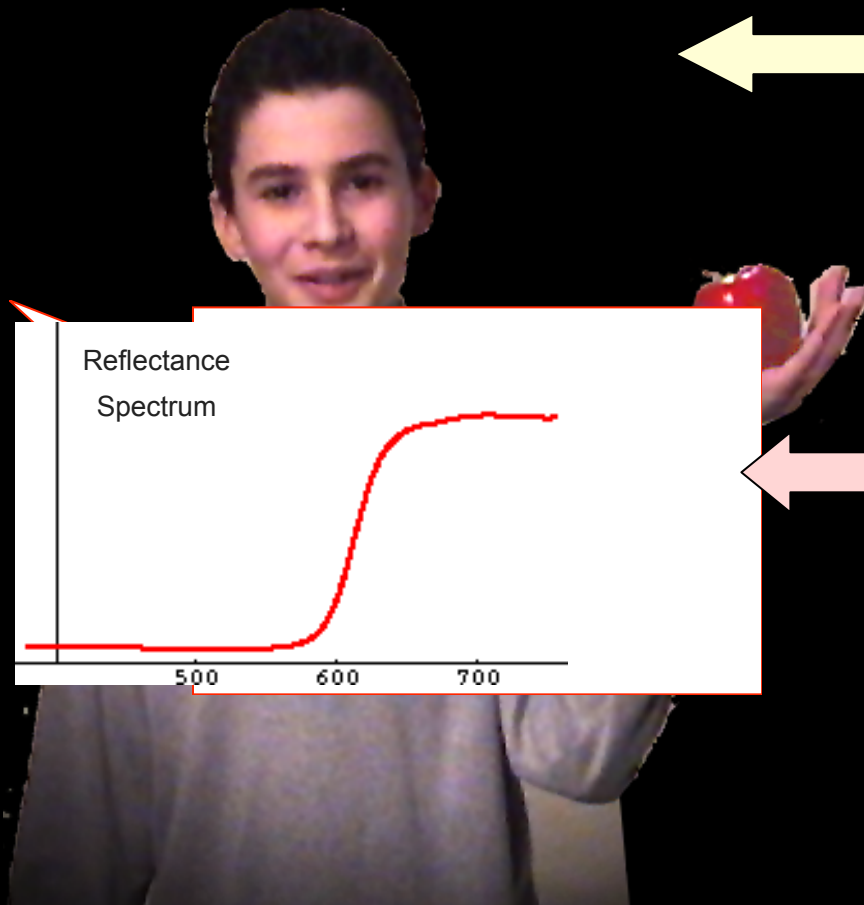
From Physical color to cones



What is Color?

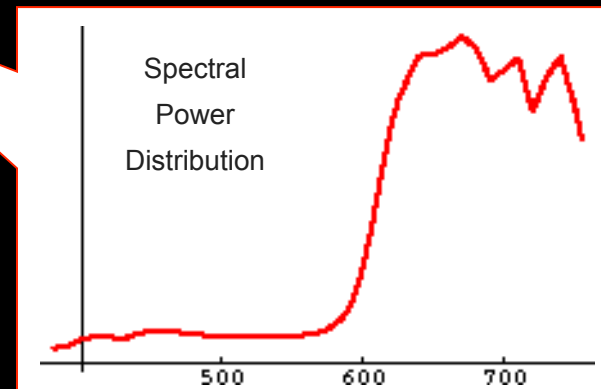
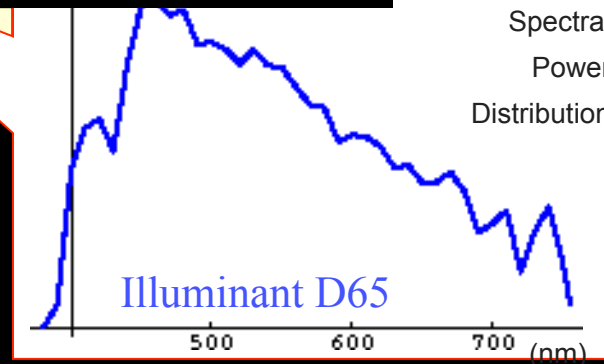


Electromagnetic Wave



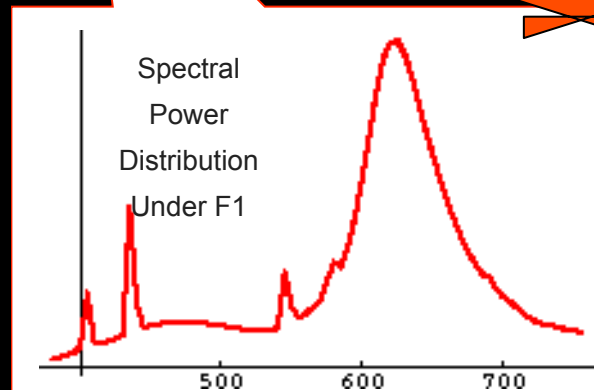
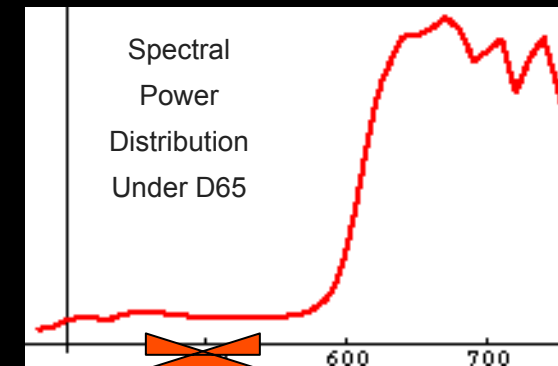
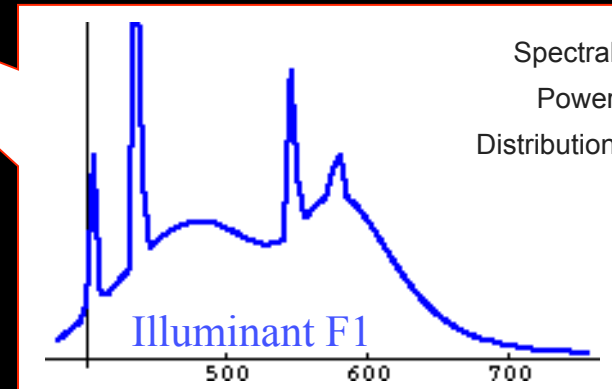
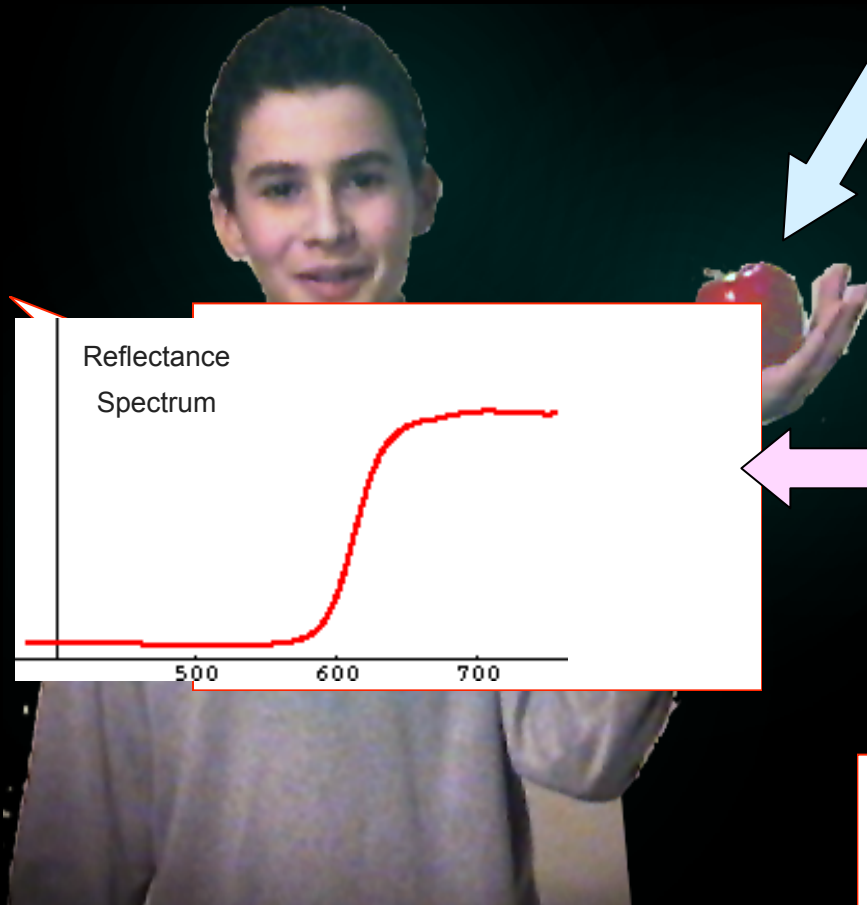
Reflectance Spectrum

500 600 700

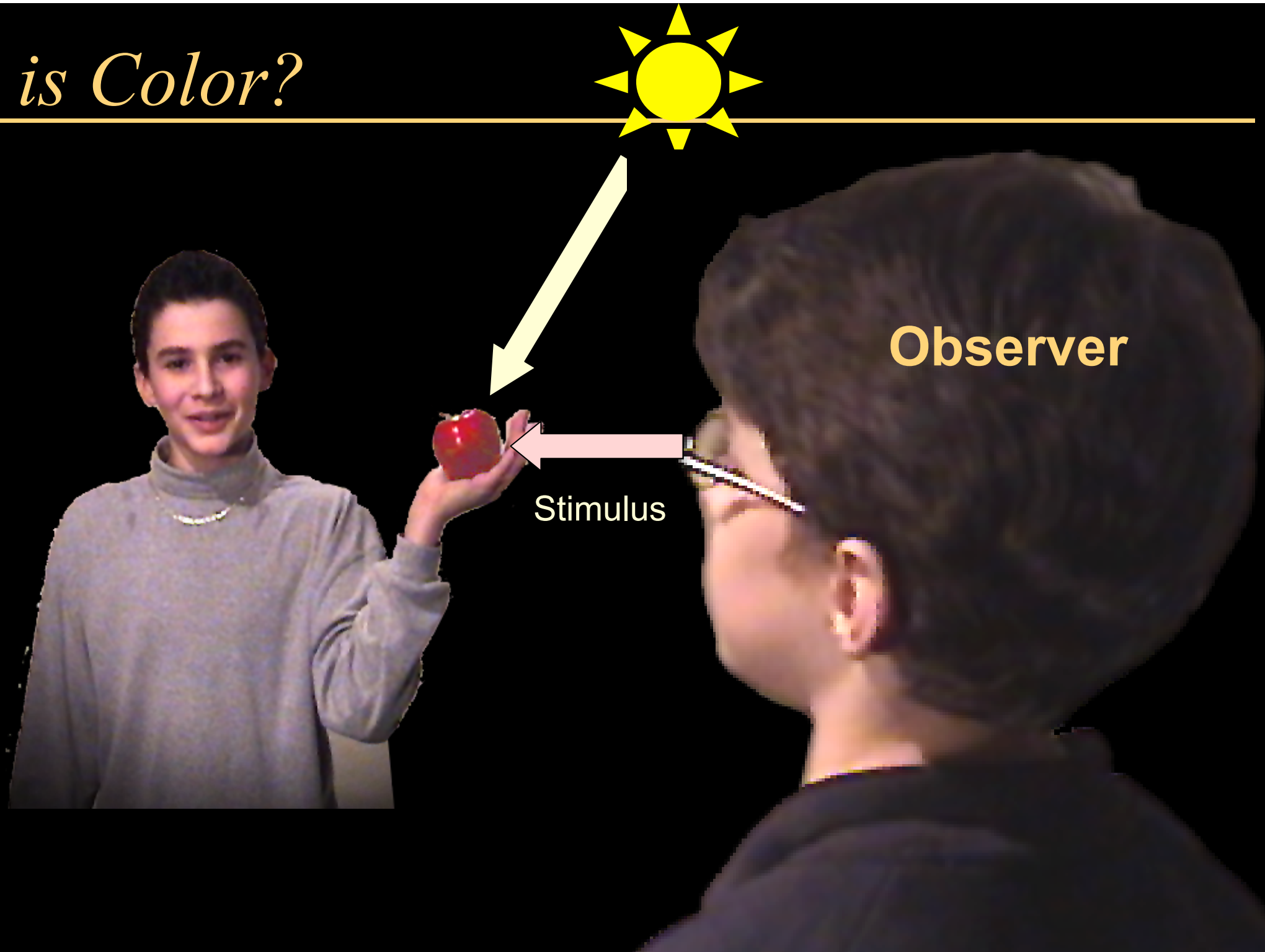


What is Color?

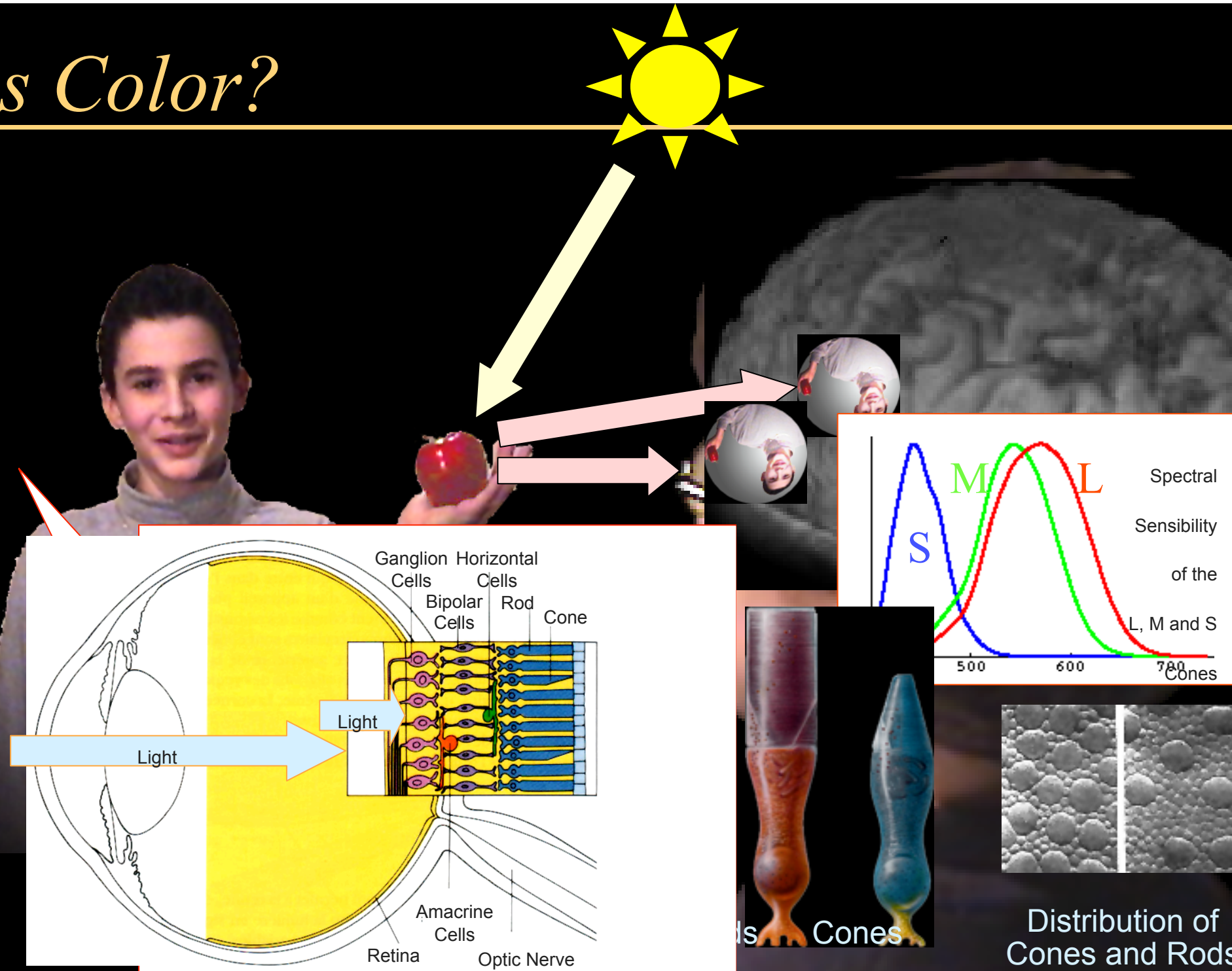
Neon Lamp



What is Color?

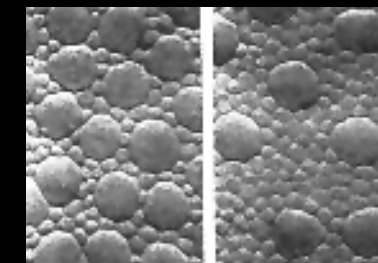
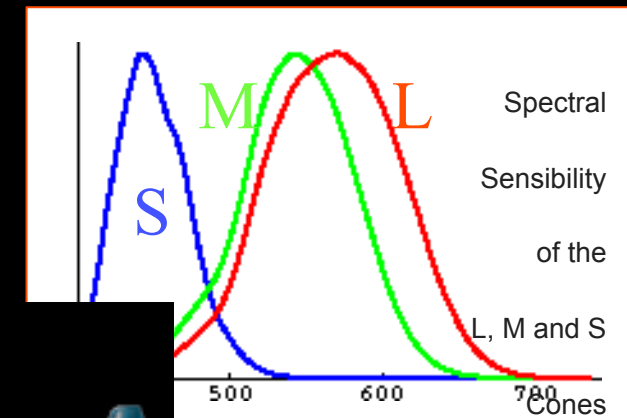
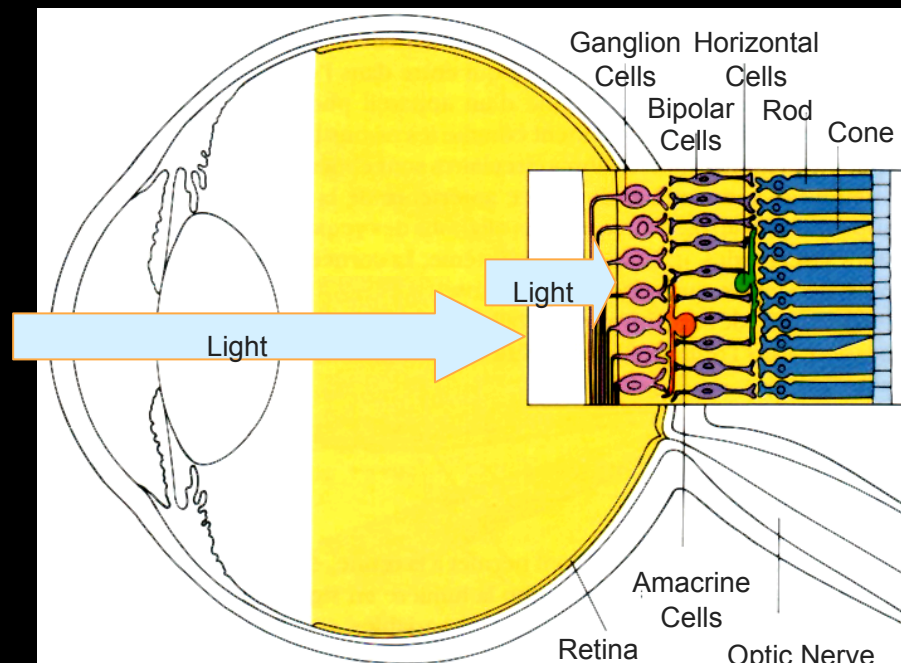


What is Color?



Cones

- We focus on low-level aspects of color
 - Cones and early processing in the retina
- We won't talk about rods (night vision)



Distribution of
Cones and Rods

Summary (and time for questions)

- Spectrum: infinite number of values
 - can be multiplied
 - can be added
- Light spectrum multiplied by reflectance spectrum
 - spectrum depends on illuminant
- Human visual system is complicated

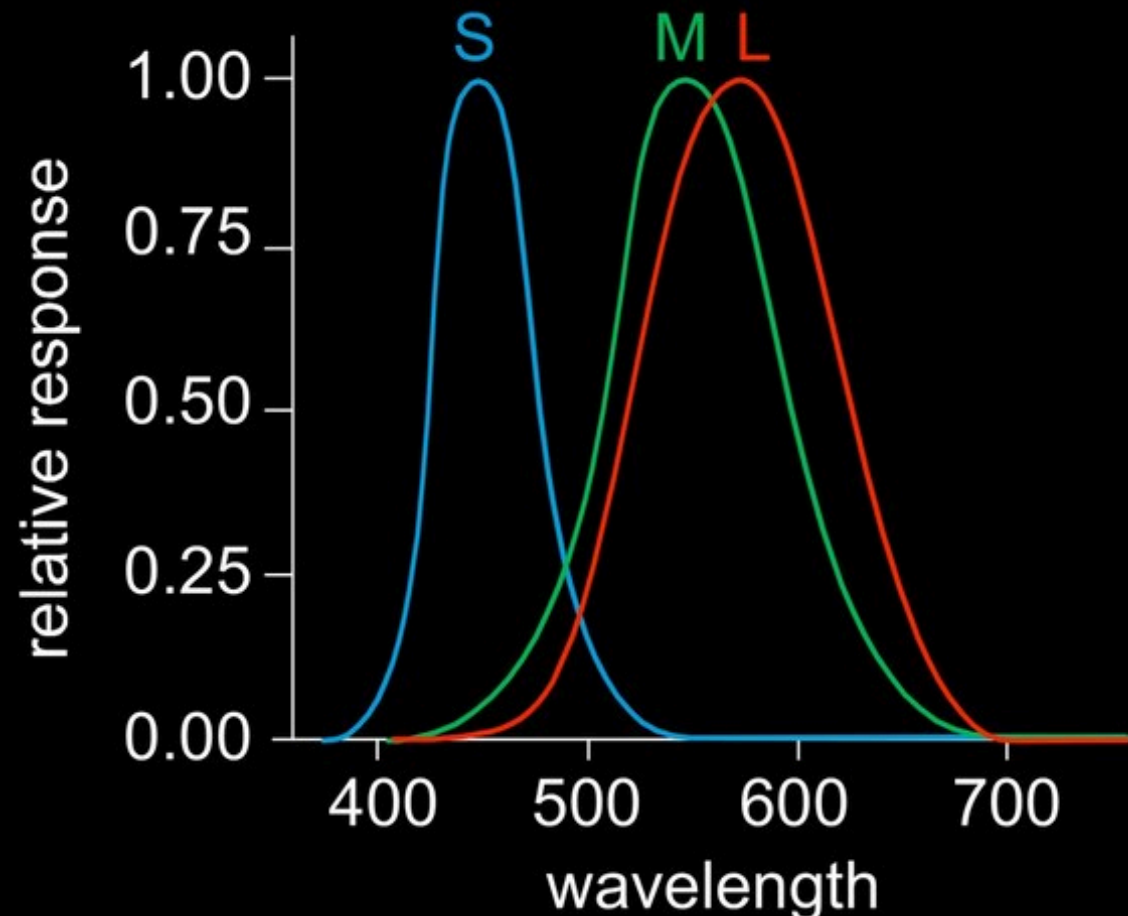


Cone spectral responses



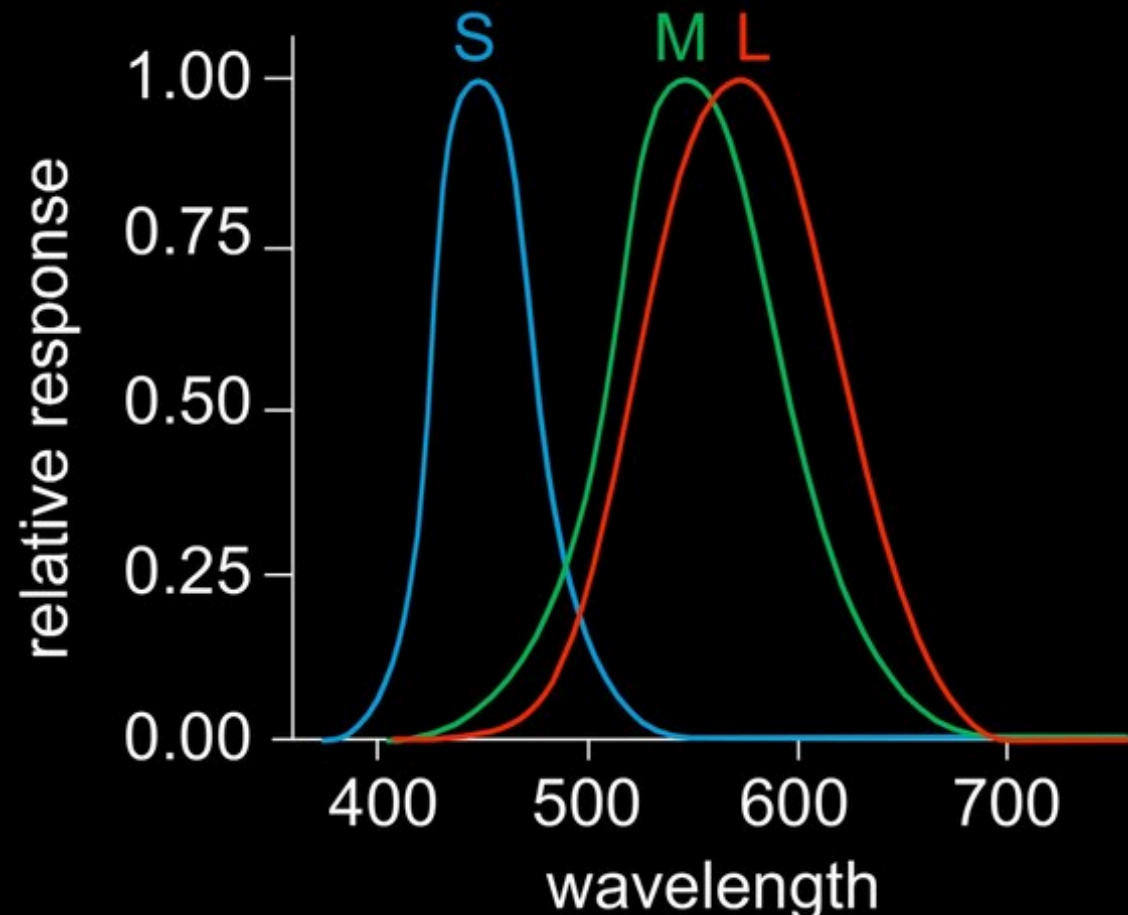
Cone spectral sensitivity

- Short, Medium and Long wavelength
- Response for a cone:

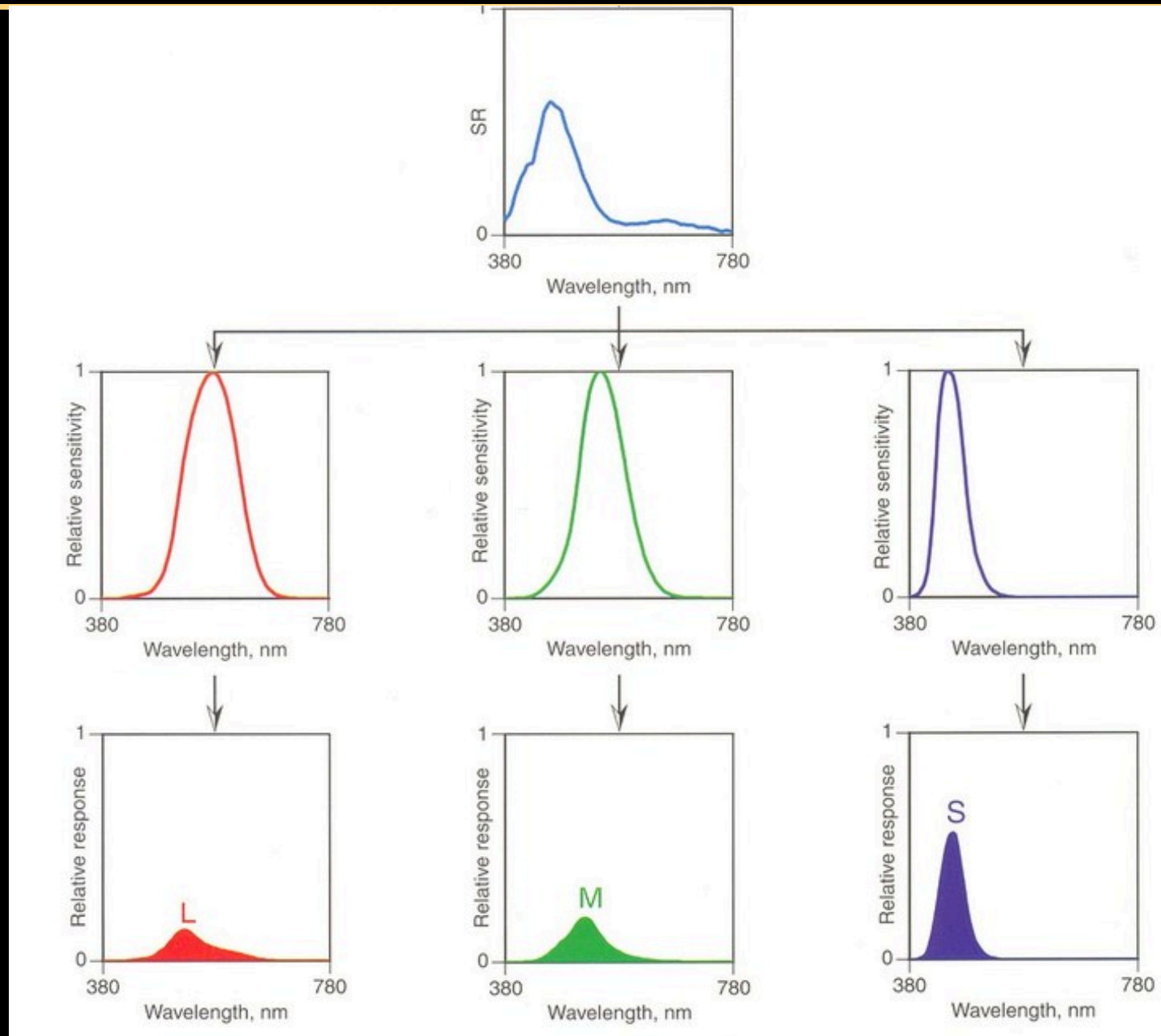


Cone spectral sensitivity

- Short, Medium and Long wavelength
- Response for a cone
$$= \int \lambda \text{ stimulus}(\lambda) * \text{response}(\lambda) d\lambda$$



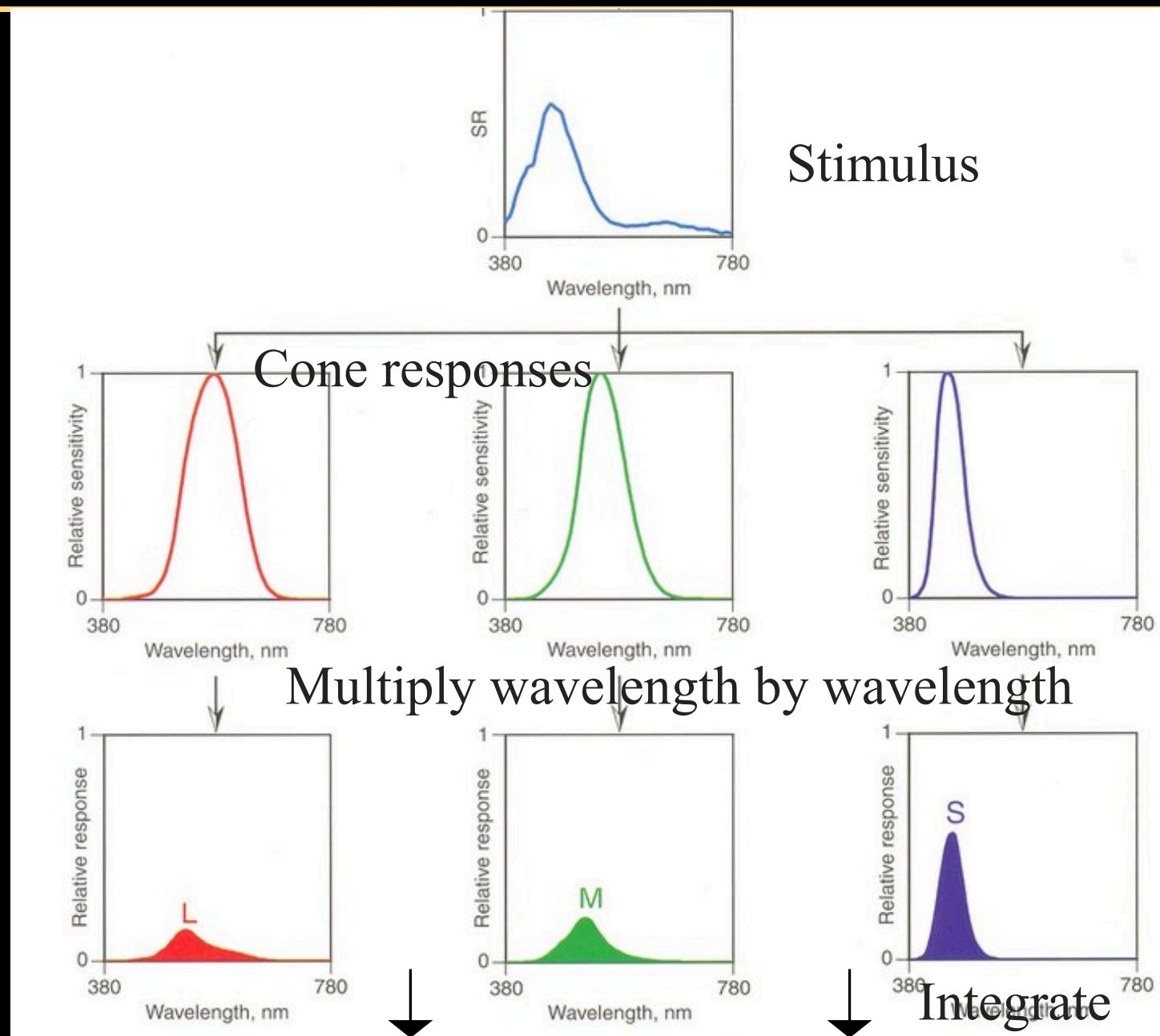
Cone response



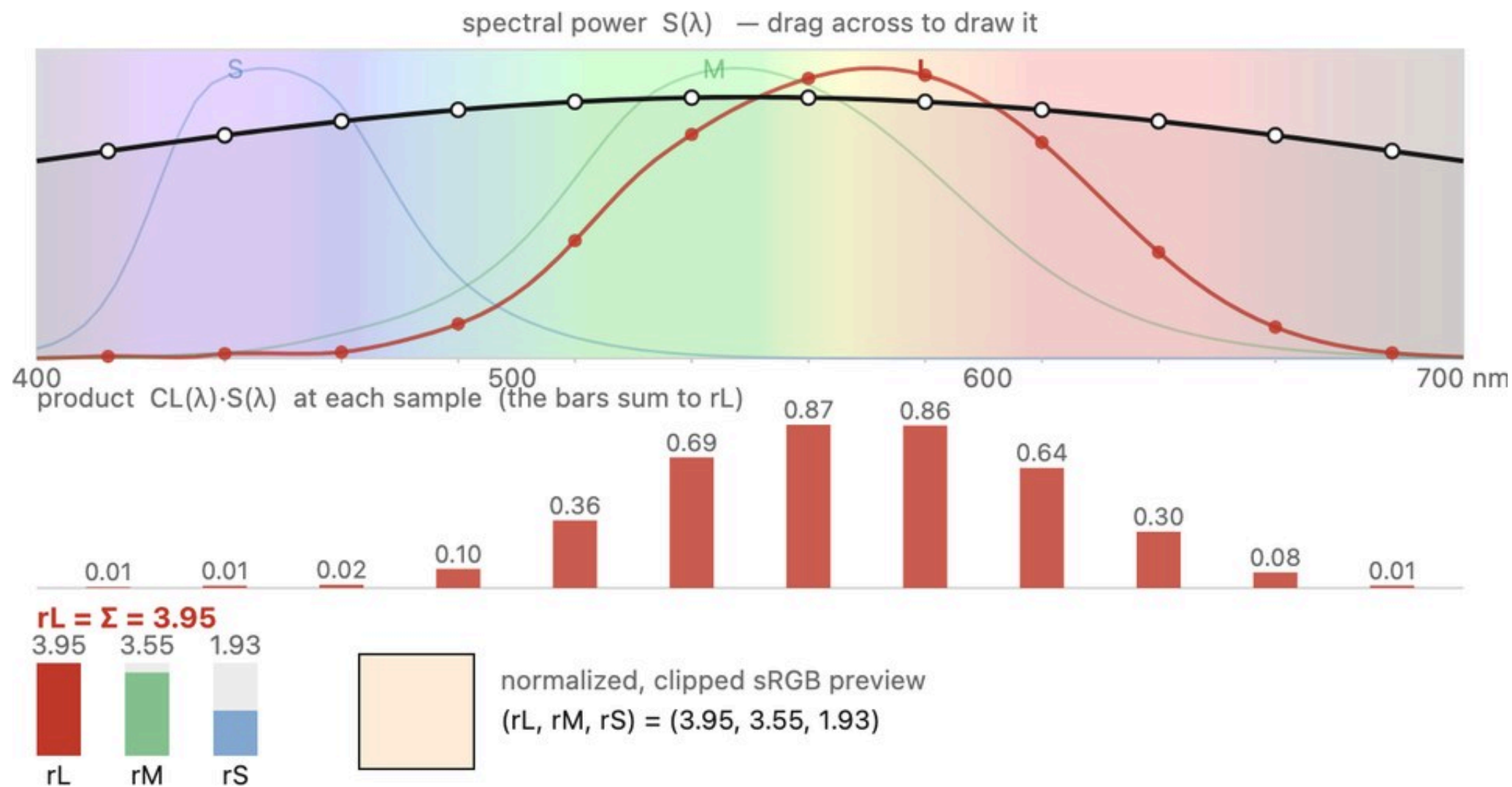
Cone response

Start from infinite number of values (one per wavelength)

End up with 3 values (one per cone type)



Demo: Spectrum → cones

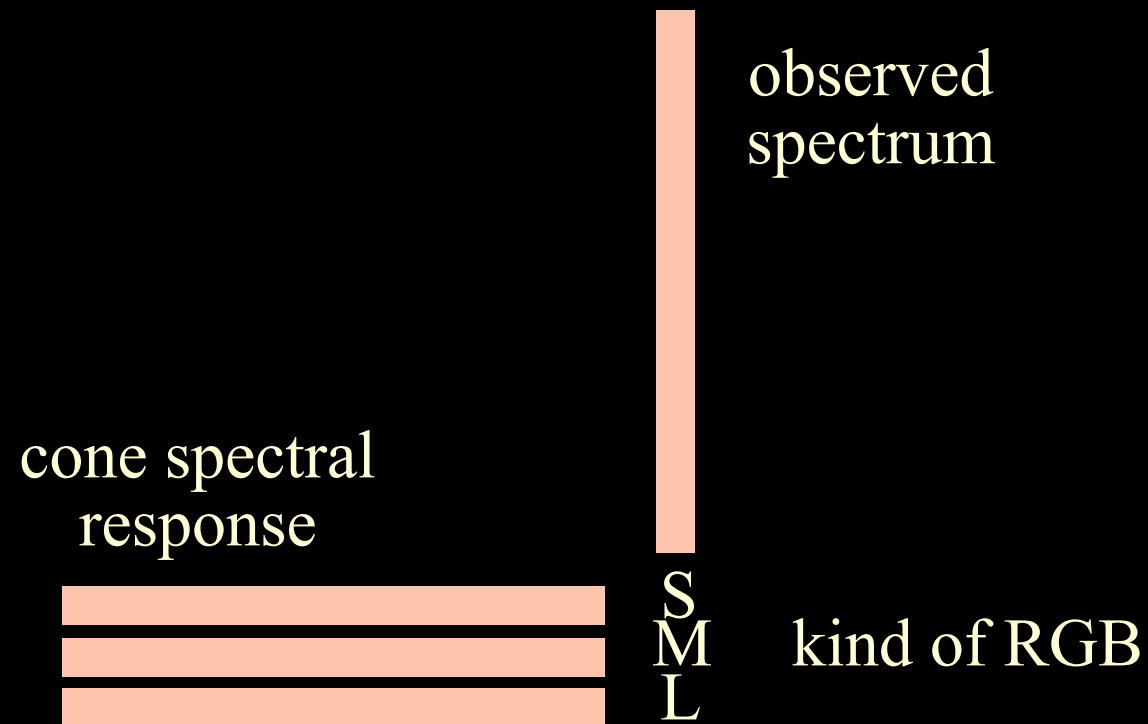


For matrix lovers

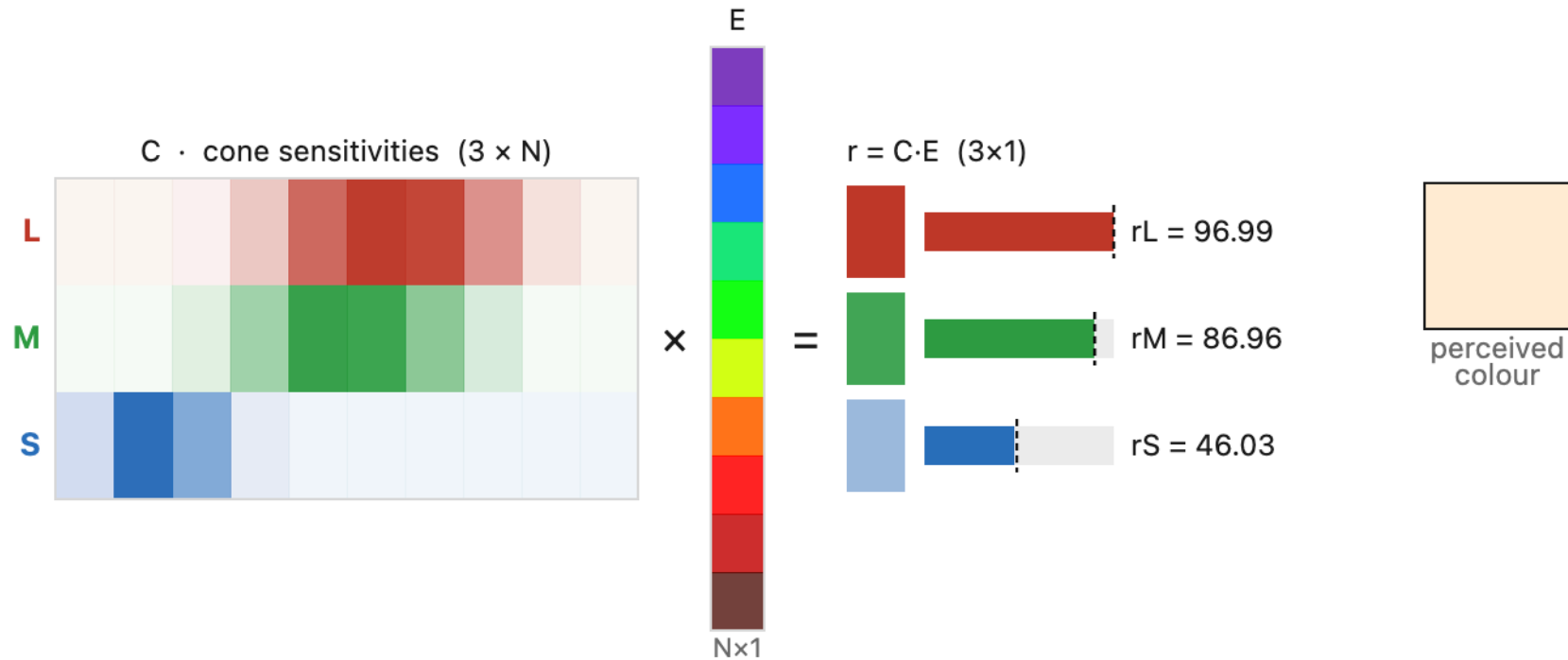
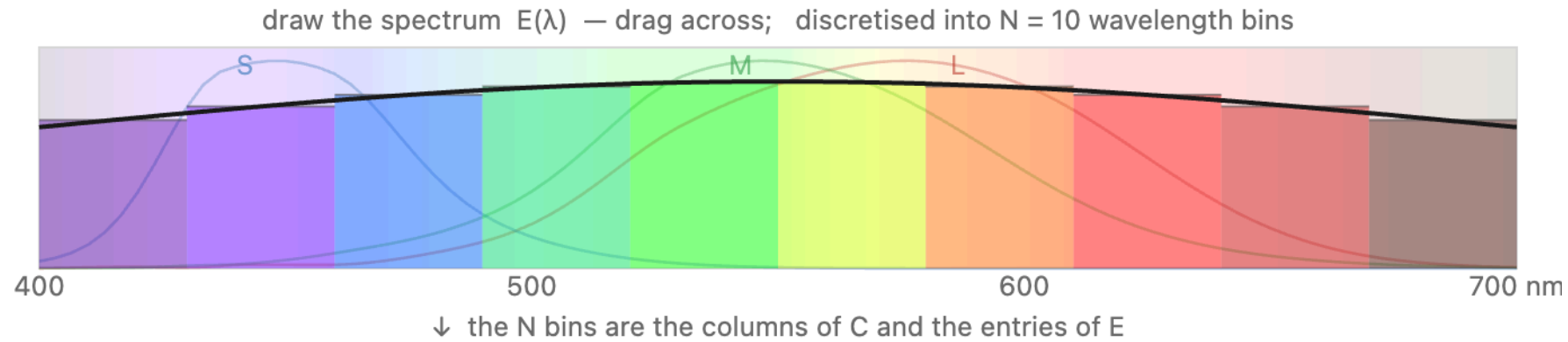
- Spectrum: big long vector size N where $N=\infty$
- Cone response: $3 \times N$ matrix of individual responses

For matrix lovers

- Spectrum: big long vector size N where $N=\infty$
- Cone response: $3 \times N$ matrix of individual responses



Demo: Cone response matrix

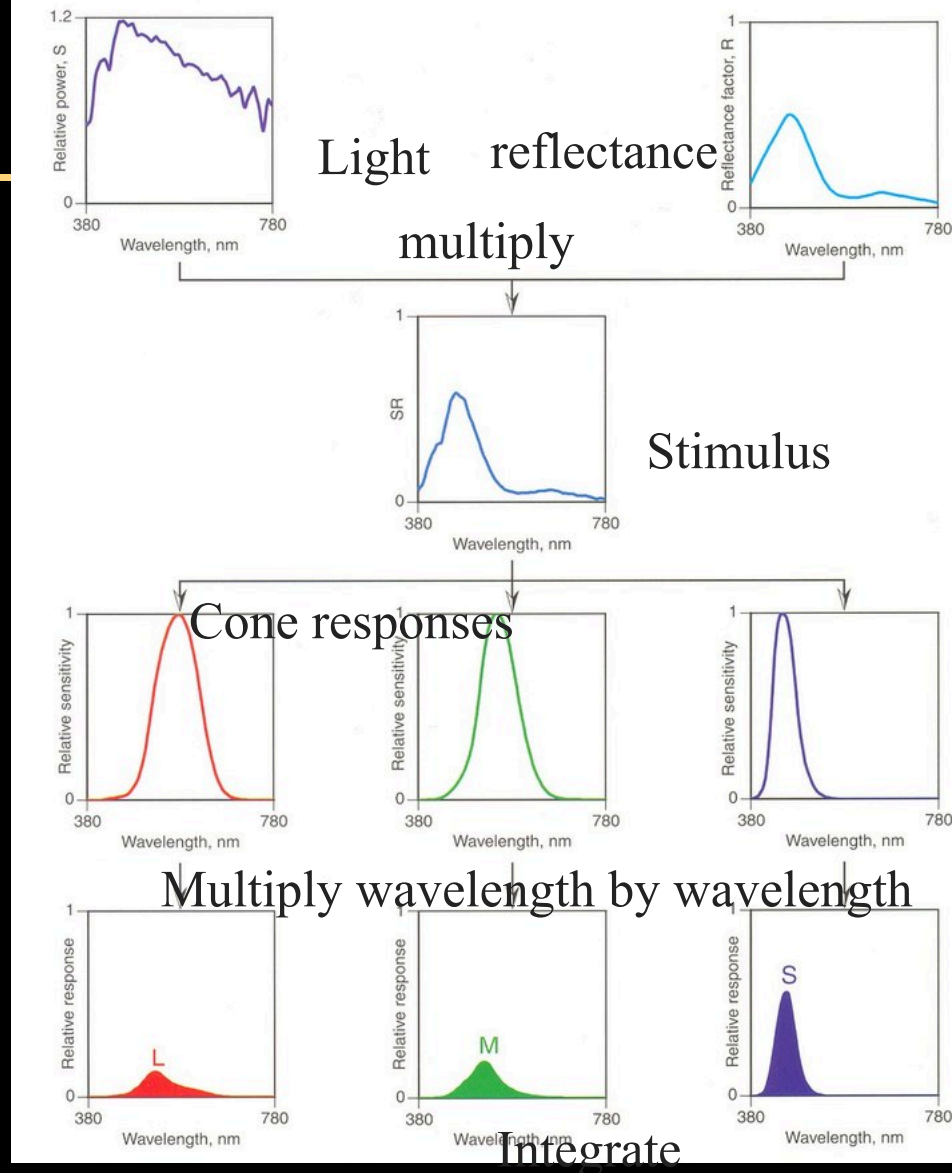


$$r_k = \sum_i c_k(\lambda_i) E(\lambda_i) \Delta\lambda \rightarrow \int c_k(\lambda) E(\lambda) d\lambda \text{ as } N \rightarrow \infty$$

$N = 10$ bins · discrete sum is 0.70% from the exact integral (dashed ticks)

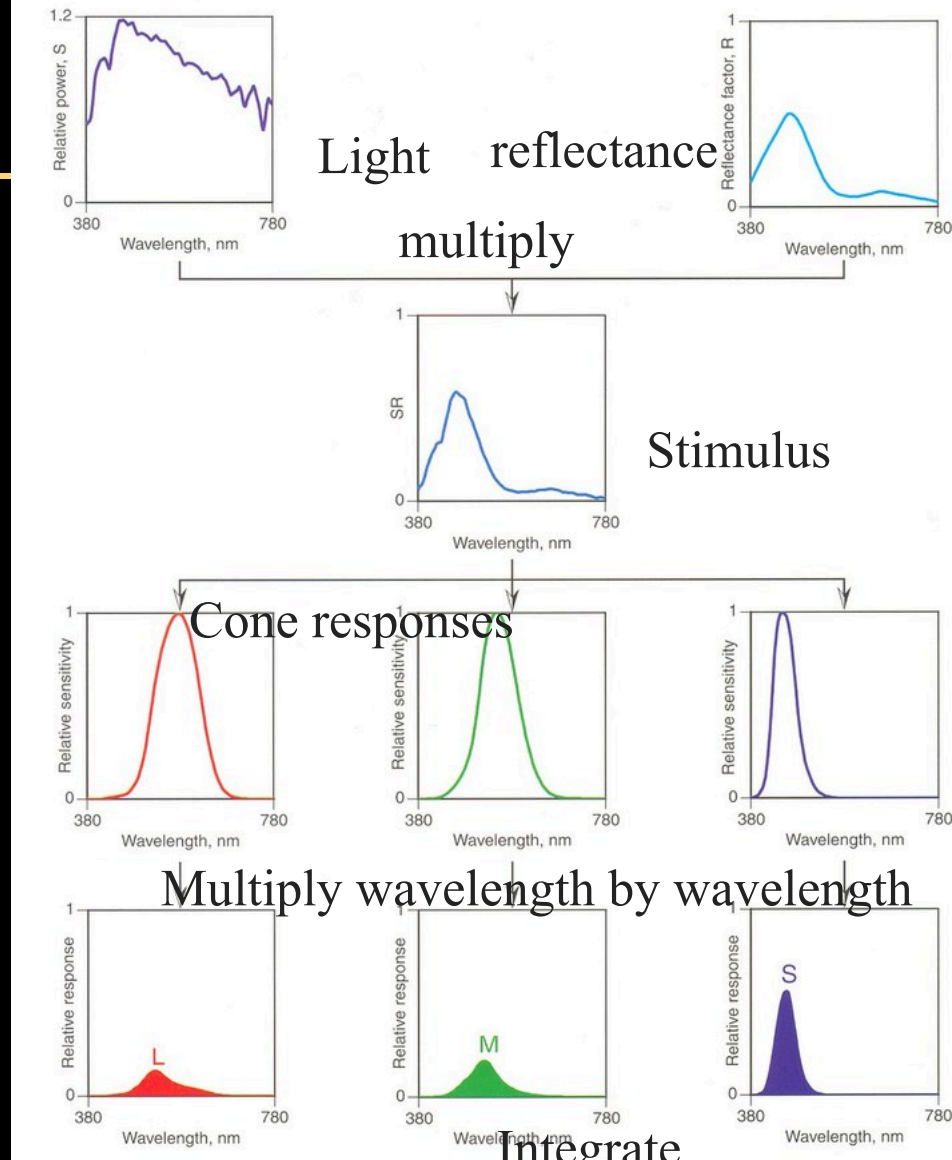
Big picture

- It's all linear!

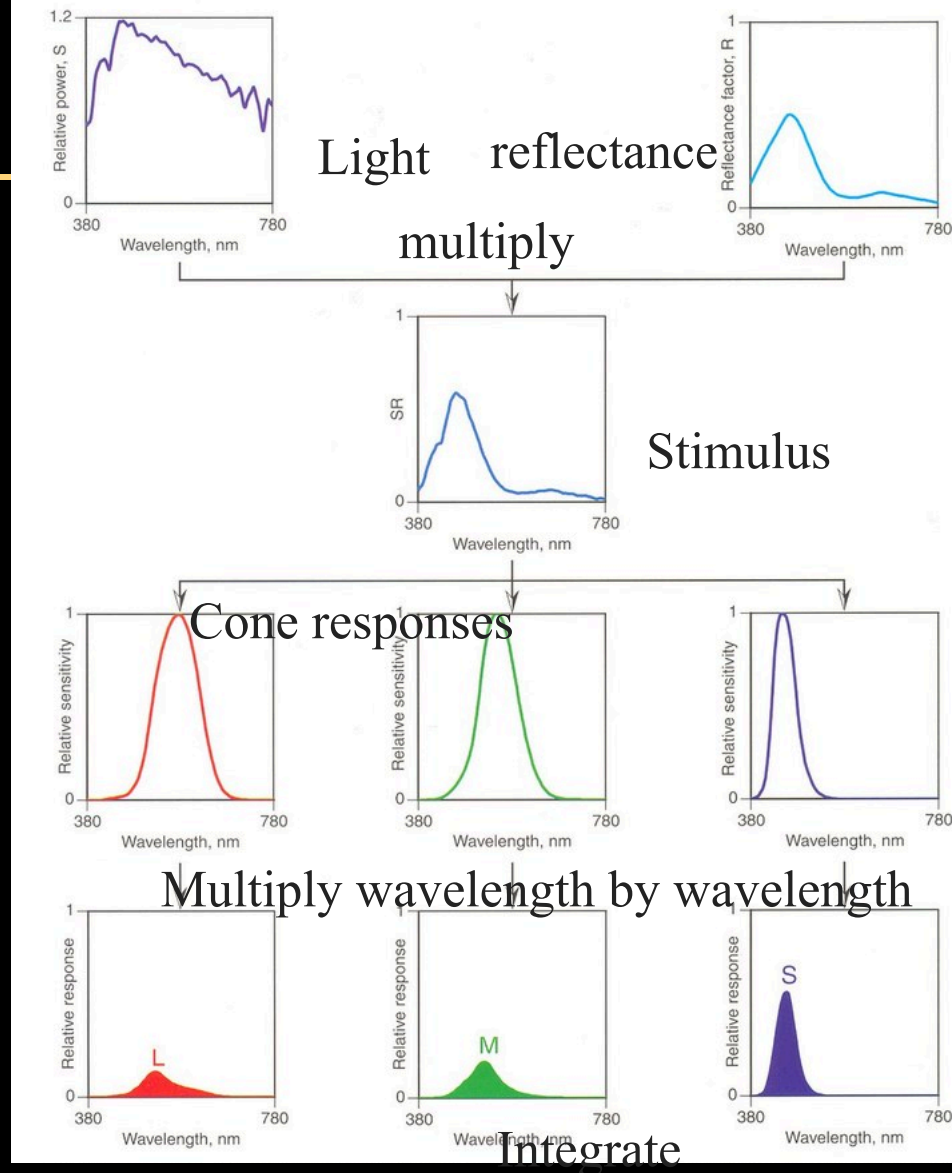


Big picture

- It's all linear!
 - multiply
 - add
- But
 - non-orthogonal basis
 - infinite dimension
 - light must be positive
- Depends on light source

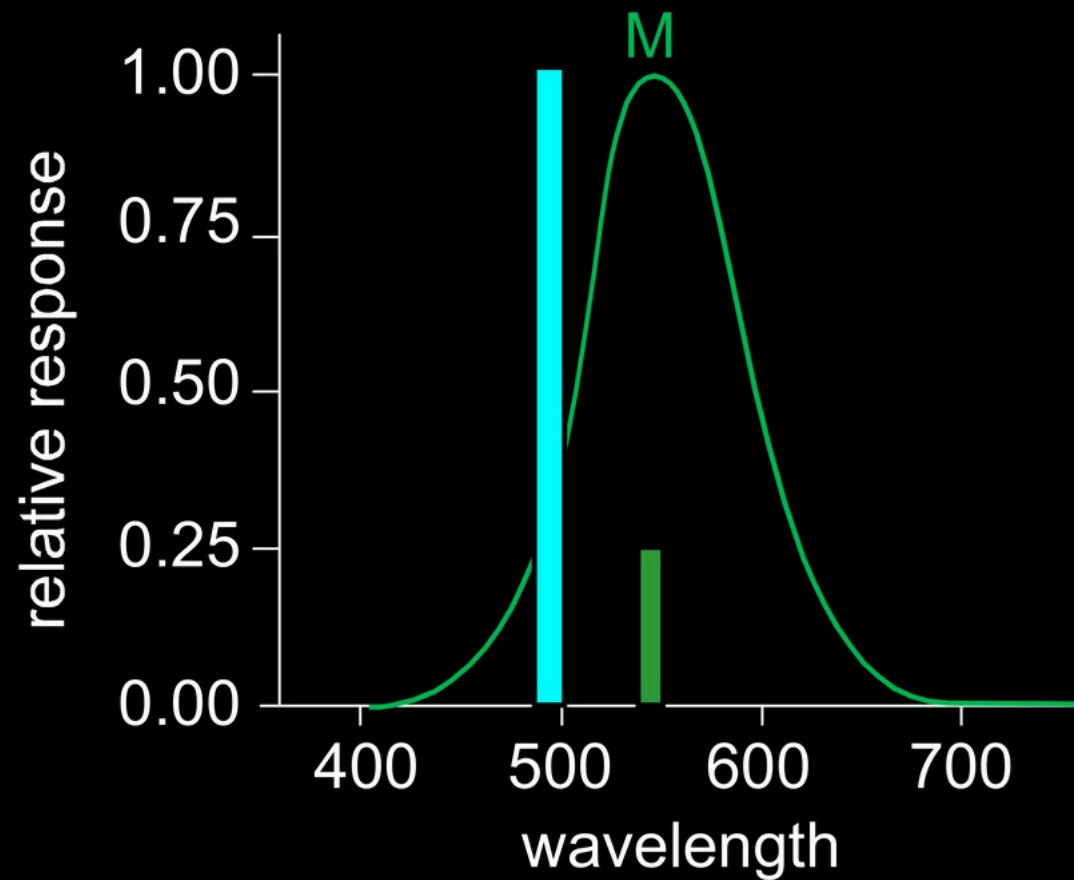


Questions?

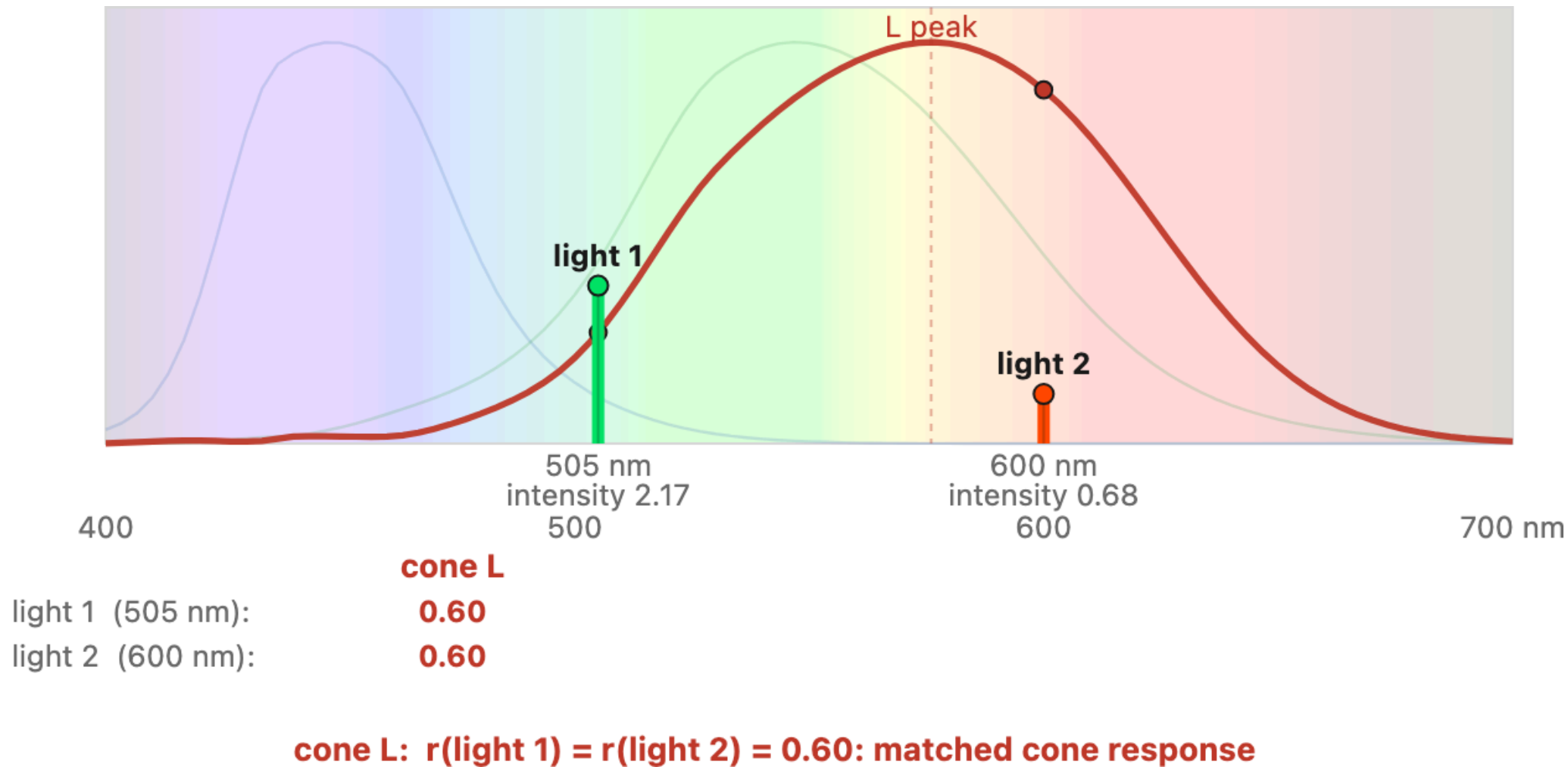


A cone does not “see” colors

- Different wavelength, different intensity
- Same response

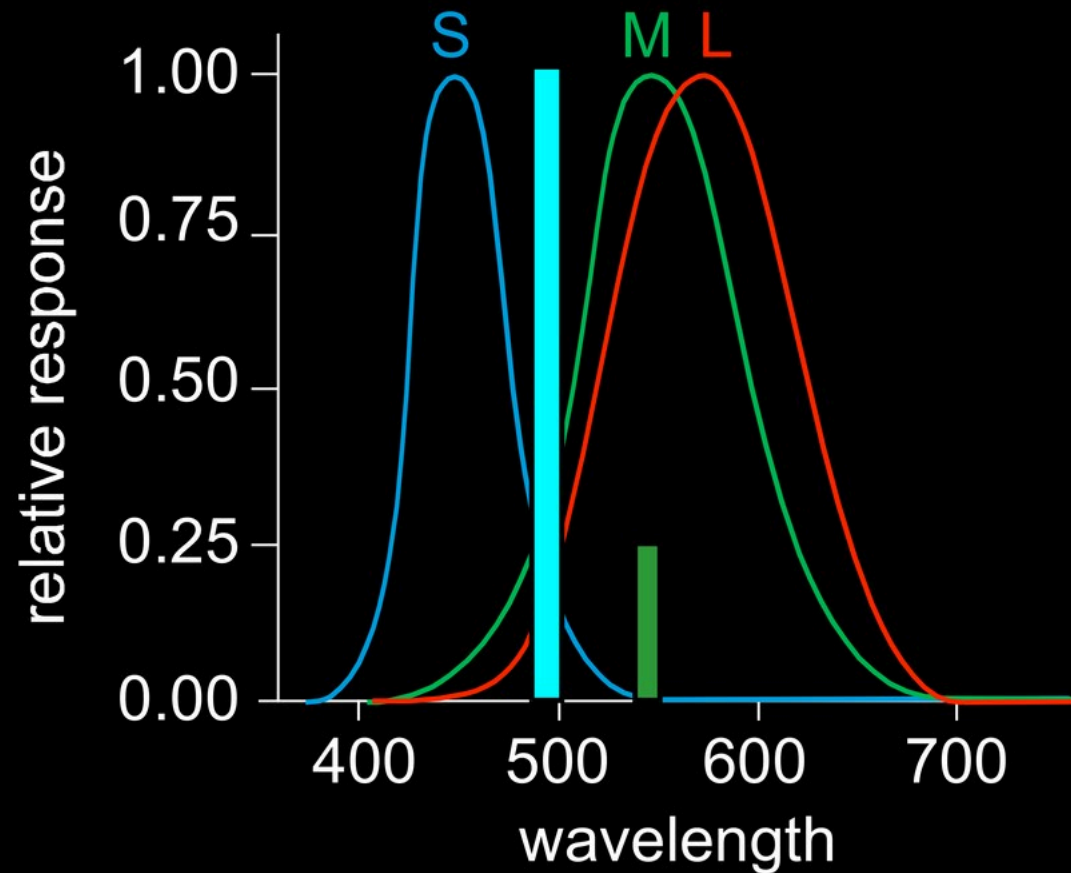


Demo: One cone can't tell colors apart



Response comparison

- Different wavelength, different intensity
- But different response for different cones

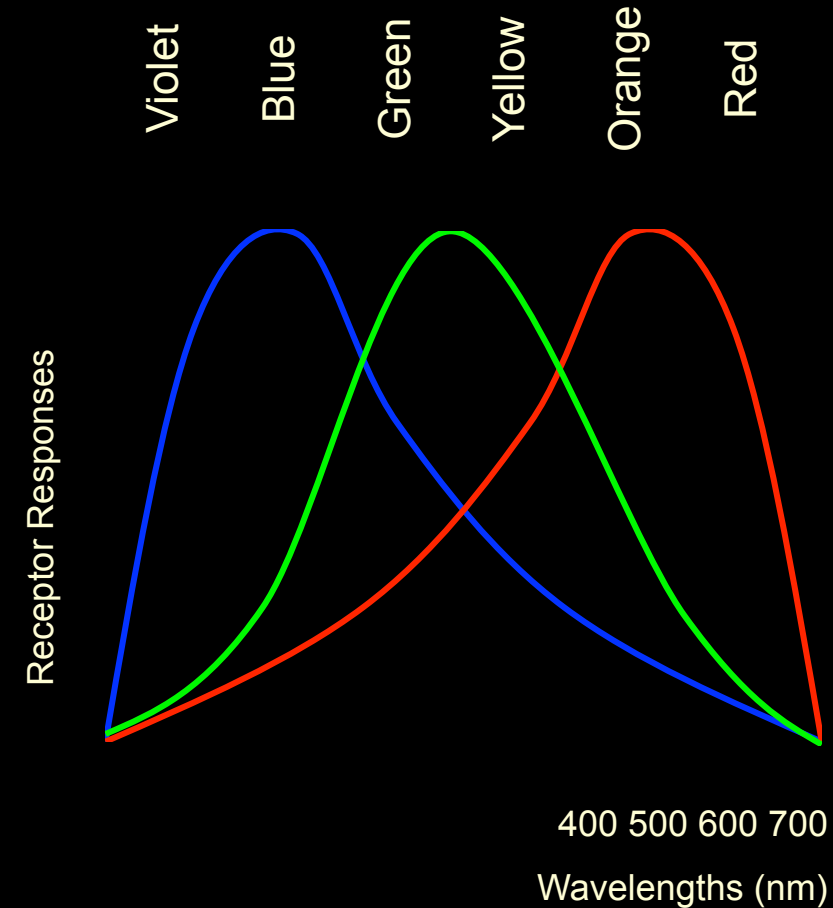


von Helmholtz 1859: Trichromatic theory

- Colors as relative responses (ratios)



Short wavelength receptors
Medium wavelength receptors
Long wavelength receptors



References on different cones

- <http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html>
- <http://www.blueconemonochromacy.org/what-is-bcm/eye-retina-and-cones-2/>
- <http://webvision.med.utah.edu/book/part-iii-retinal-circuits/s-cone-pathways/>
- <http://www.opticsinfobase.org/josa/abstract.cfm?uri=josa-57-11-1289>
- <http://www.cvrl.org/database/text/intros/introdens.htm>
- <http://www.cvrl.org/database/text/density/lmintro.htm>



Color blindness

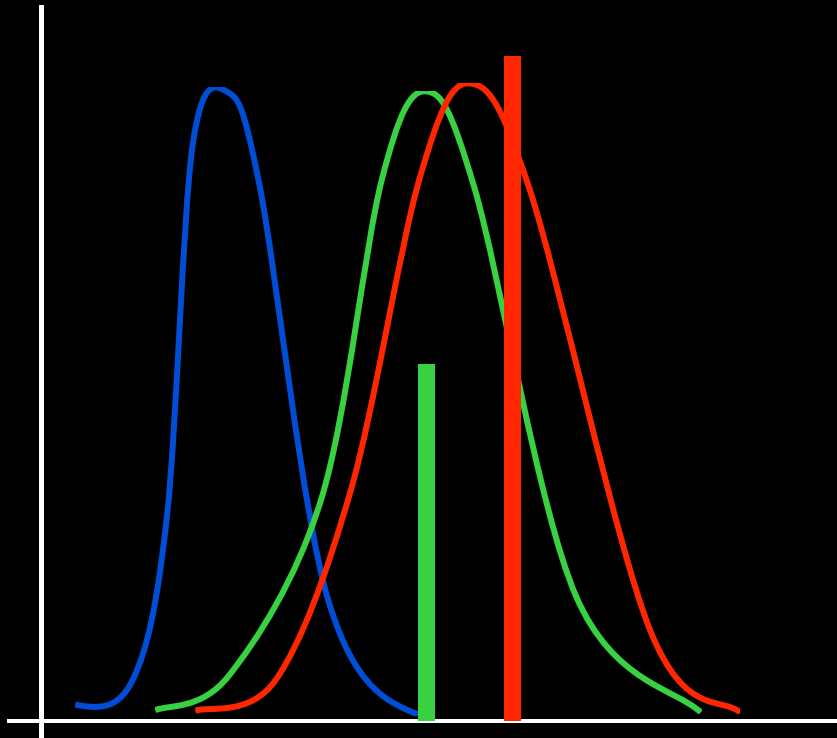


Plan

- Spectra
- Cones and spectral response
- **Color blindness and metamers**
- Color matching
- Color spaces

Response comparison

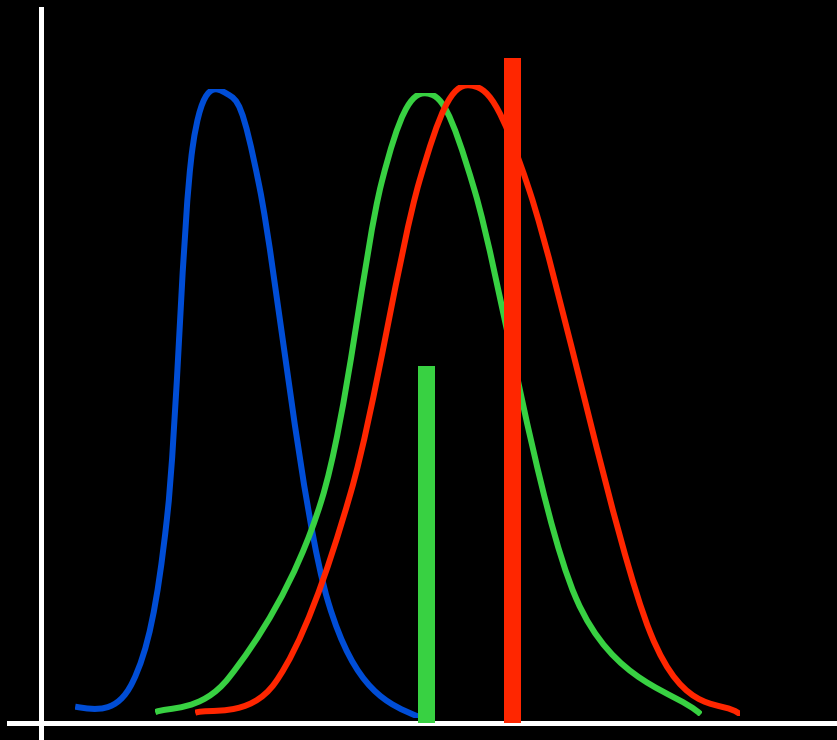
- Different wavelength, different intensity
- But different response for different cones



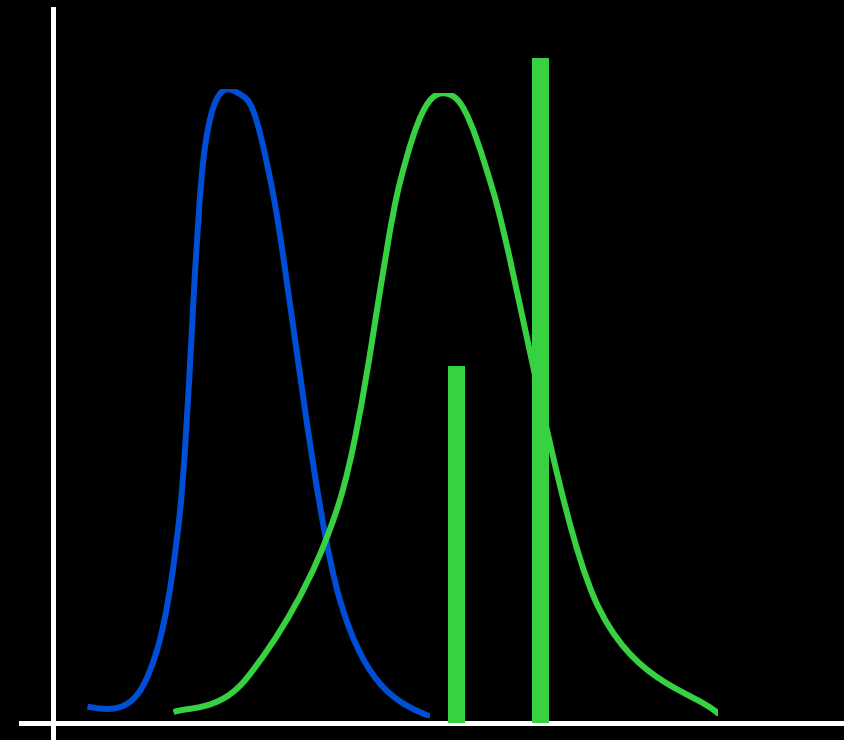
Color blindness

- Classical case: 1 type of cone is missing (e.g. M)
- Makes it impossible to distinguish some spectra

Normal observer



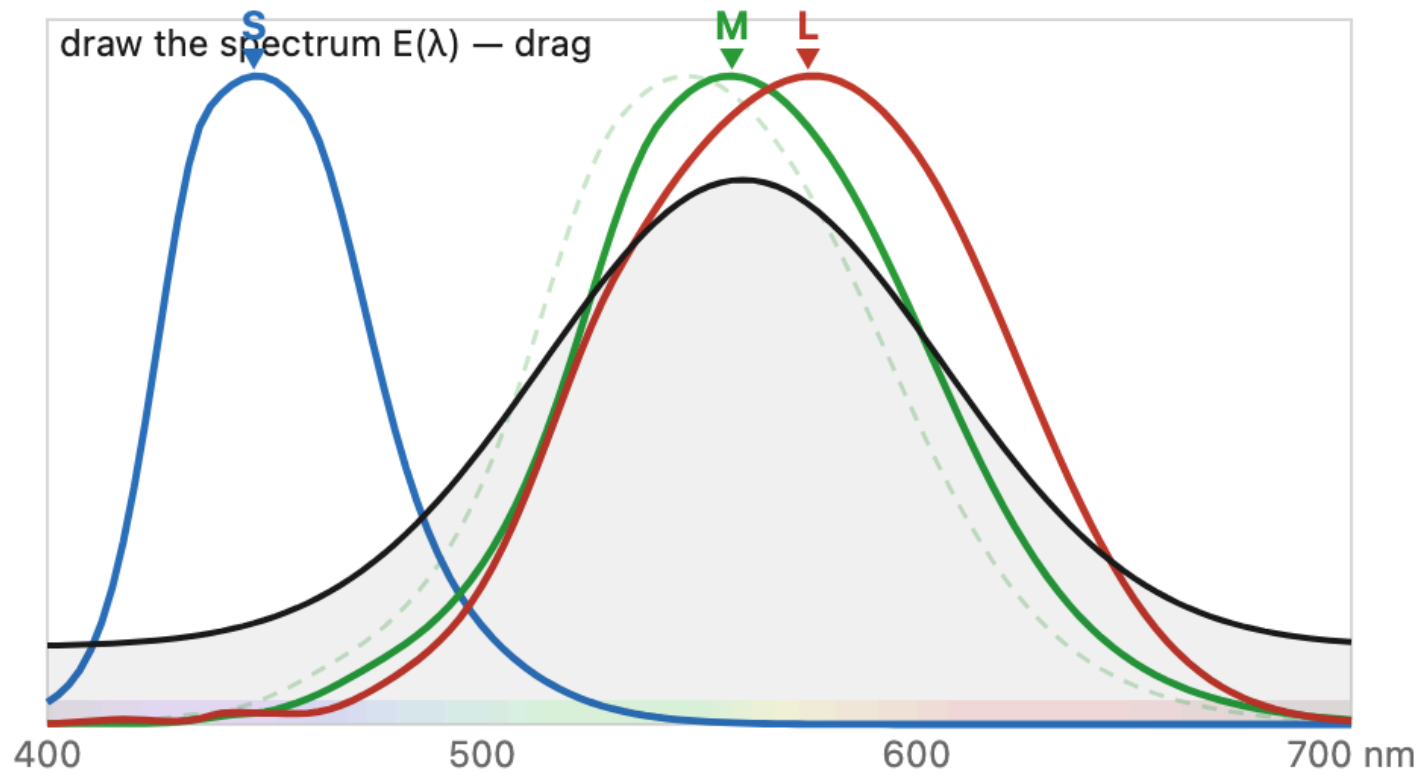
Color blind



Color blindness – more general

- Dalton
- ~14%% male, 2% female
- Genetic
- Dichromate (2% male)
 - One type of cone missing
 - L (protanope), M (deuteranope), S (tritanope)
- Anomalous trichromat
 - Shifted sensitivity
- More at, e.g.

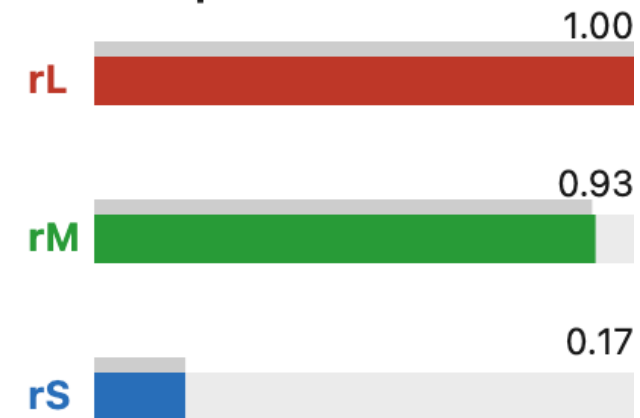
Demo: Abnormal cones



L–M peak separation: 18 nm (normal 28 nm)

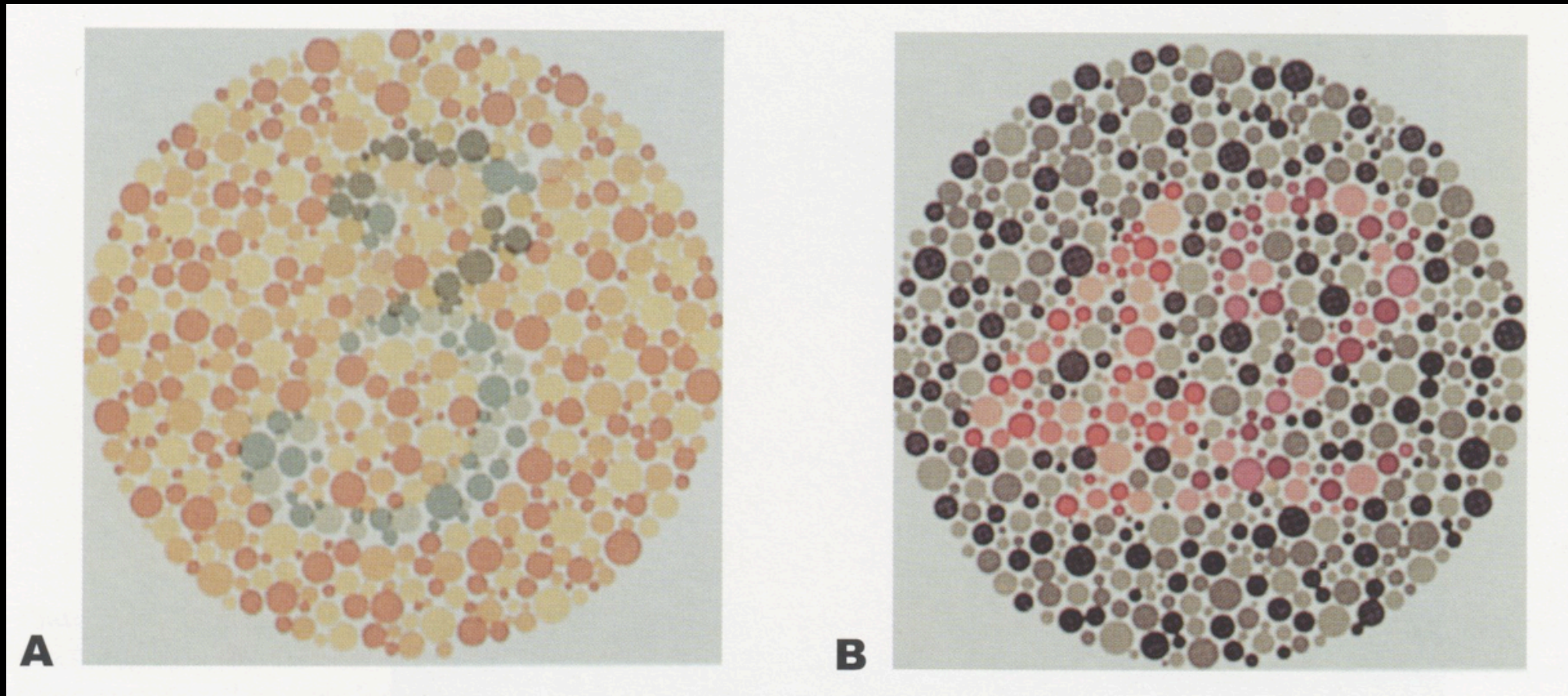
→ r_L and r_M nearly match; red–green discrimination is squeezed

cone responses to E



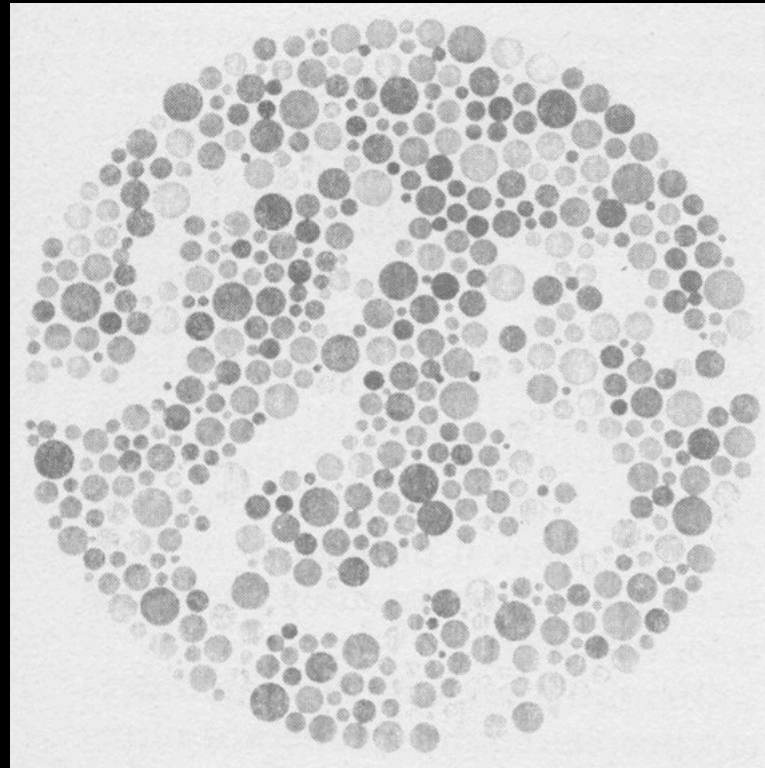
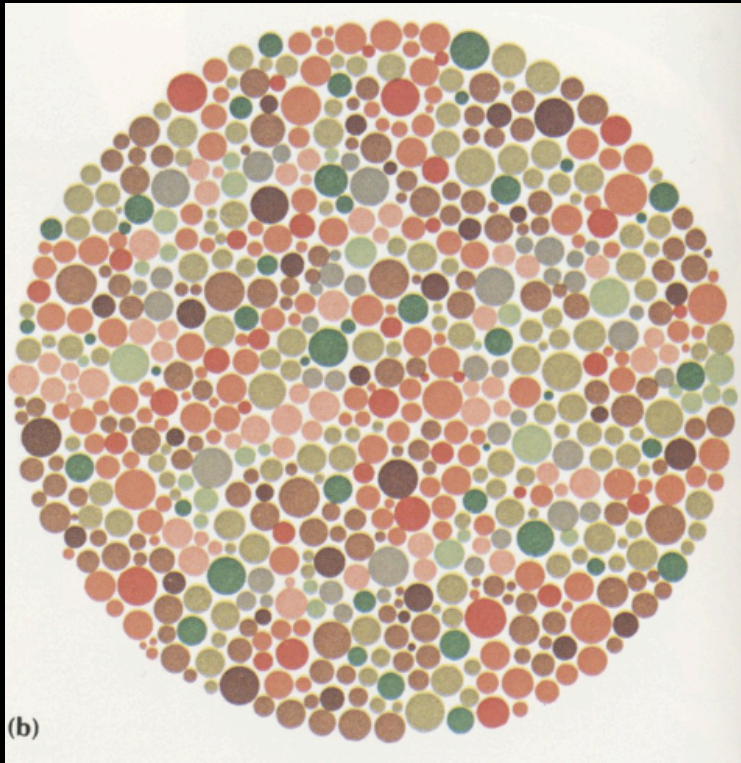
(faint tick = normal response)

Color blindness test



Color blindness test

- Maze in subtle intensity contrast
- Visible only to color blinds
- Color contrast overrides intensity otherwise



Questions?

- Links:
 - Vischeck shows you what an image looks like to someone who is colorblind.
 -
 - Daltonize, changes the red/green variation to brightness and blue/yellow variations.
 -
 -

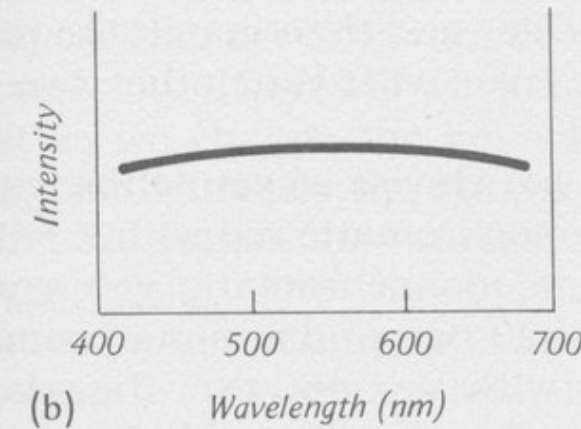
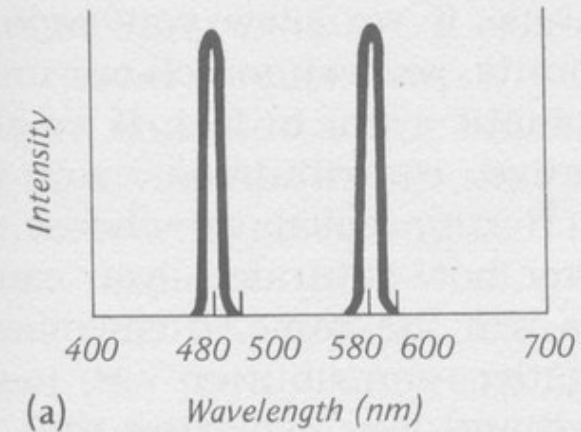


Metamers



Metamers

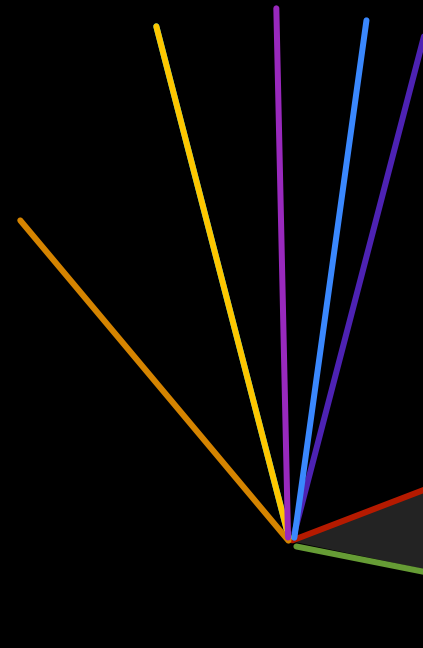
- We are all color blind!
- These two different spectra elicit the same cone responses
- Called metamers



Metamers

- Essentially, we have projected from an infinite-dimensional spectrum to a 3D space:
we lose information

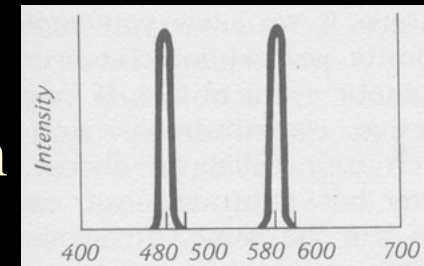
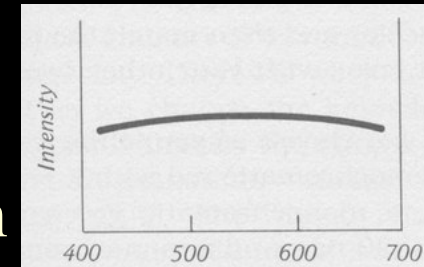
infinite set of bases



spectrum

spectrum

cone subspace (3D)



Demo: Metamer explorer

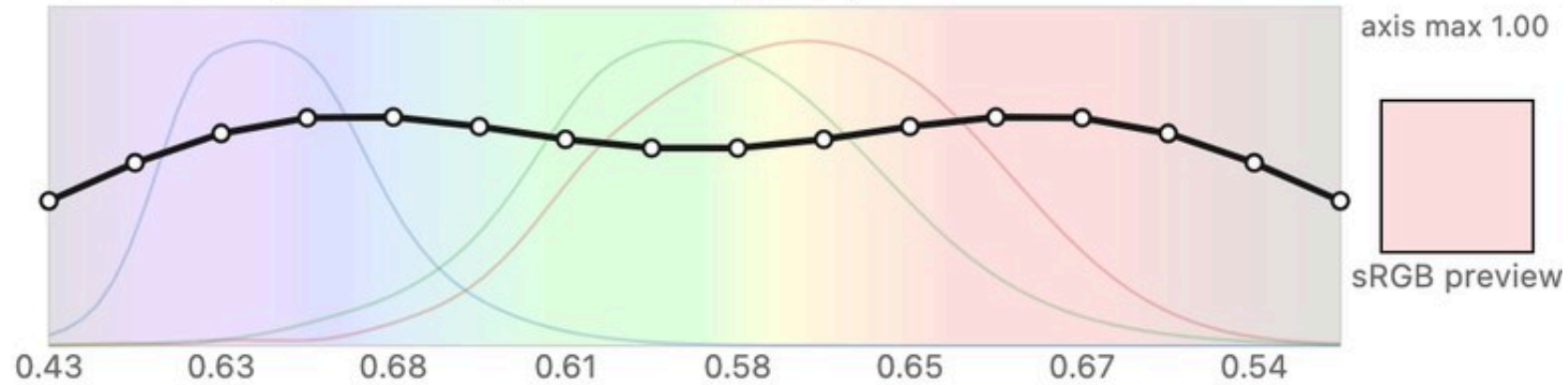
cone responses

$rL = 3.44$ 

$rM = 3.03$ 

$rS = 1.89$ 

spectrum 1 (draw it: drag across the panel)



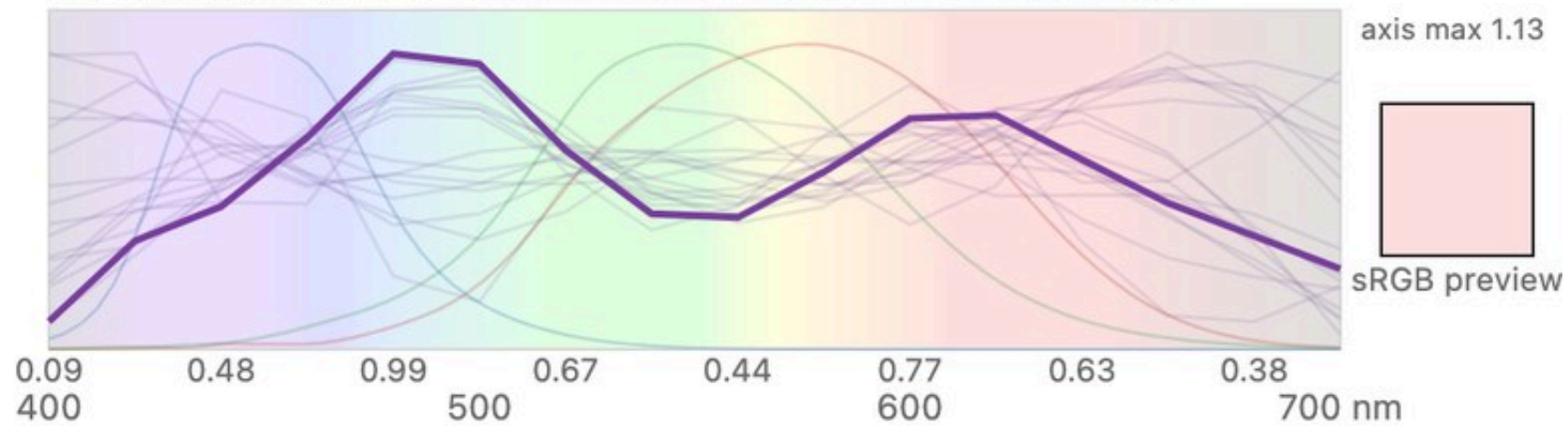
cone responses

$rL = 3.44$ 

$rM = 3.03$ 

$rS = 1.89$ 

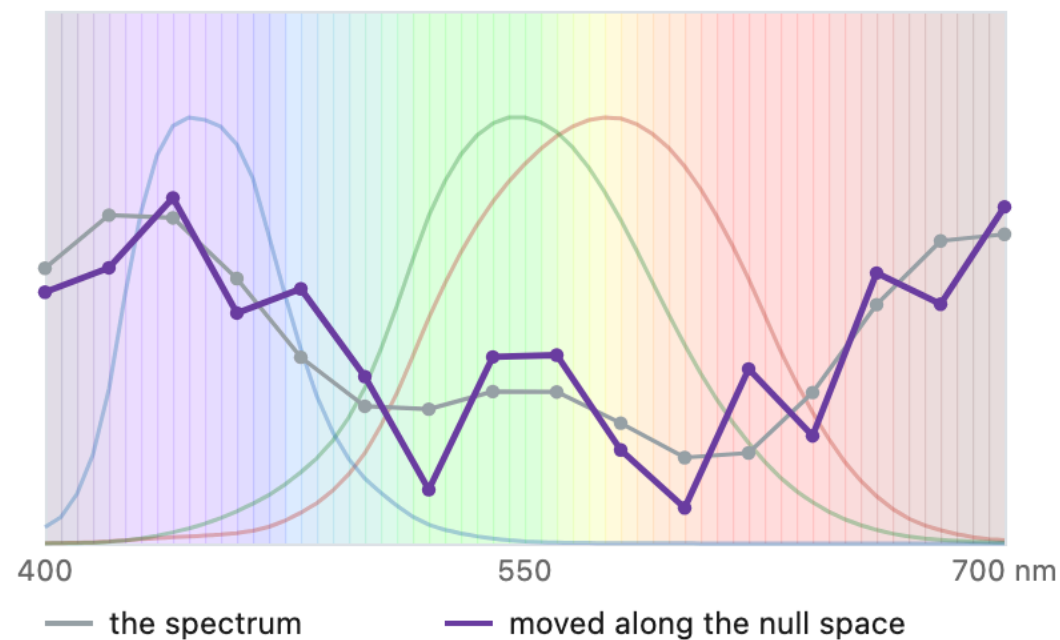
spectrum 2 (metamer: different spectrum, same responses)



same three sampled cone responses → a model metamer

Demo: Spectra projected onto the cone subspace

the spectrum, at N = 16 samples

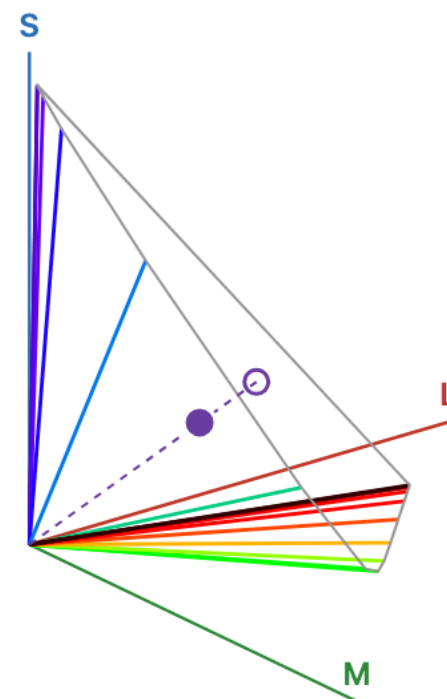


cone responses

L		0.107	unchanged	 both look like this
M		0.101	unchanged	
S		0.119	unchanged	

null space: 13 dimensions of 16

response space (L, M, S): drag to orbit

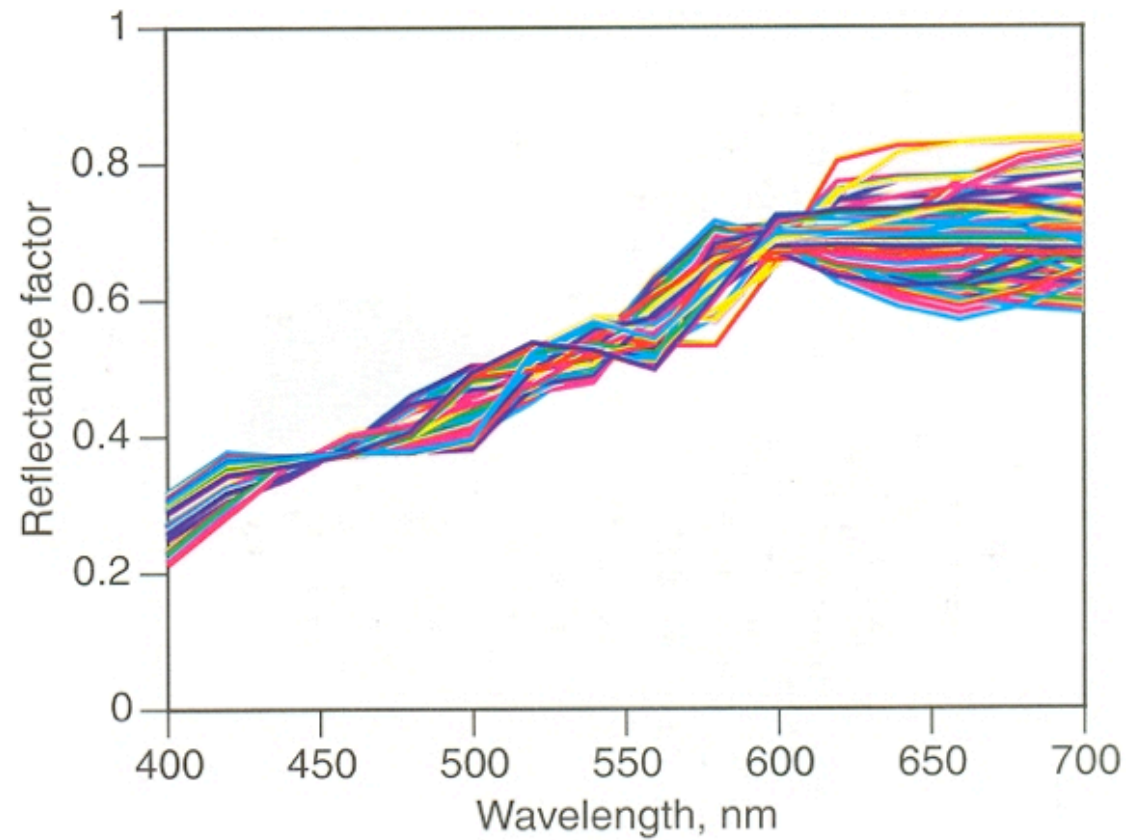


● the spectrum's response, shared by every metamer

○ where its ray crosses $L + M + S = 1$, inside the locus

one ray per sampled wavelength, drawn to $L + M + S = 1$

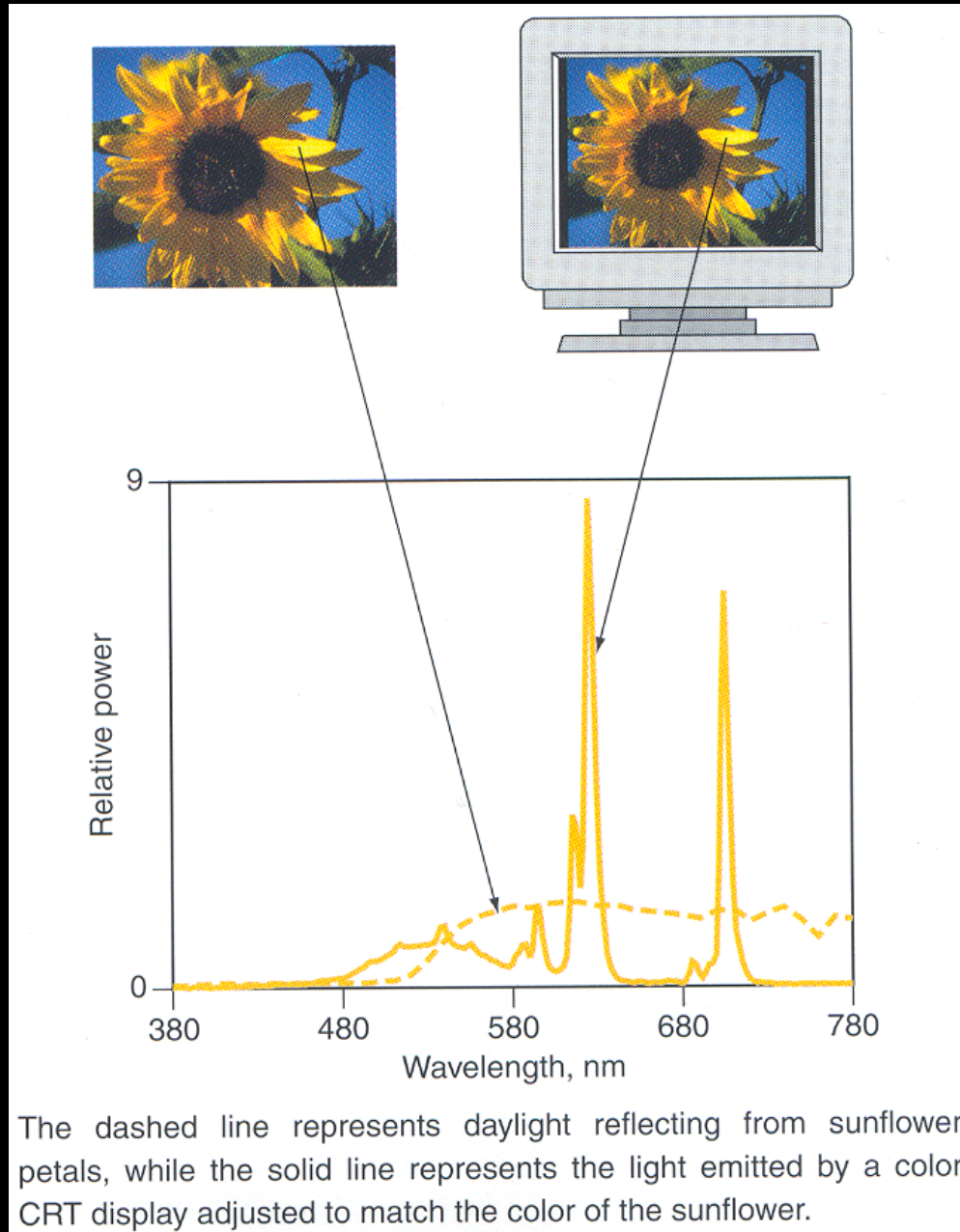
There is an infinity of metamers



Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]

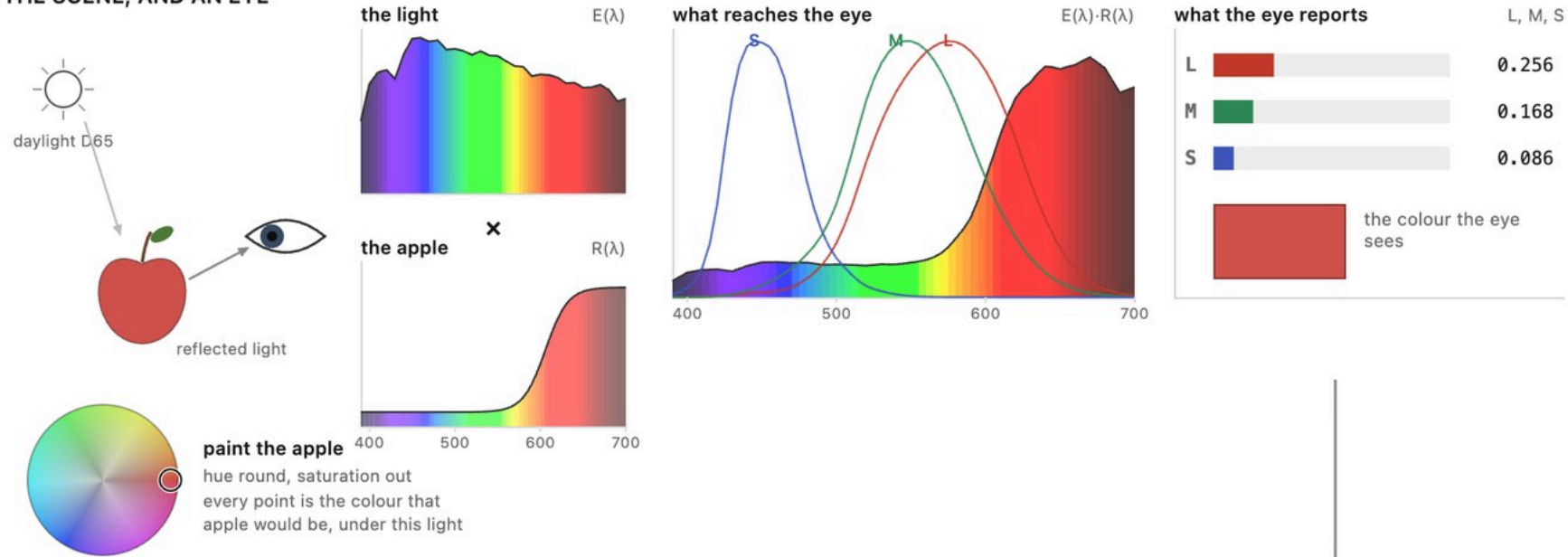
Good news: color reproduction

- 3 primaries are (to a first order) enough to reproduce all colors

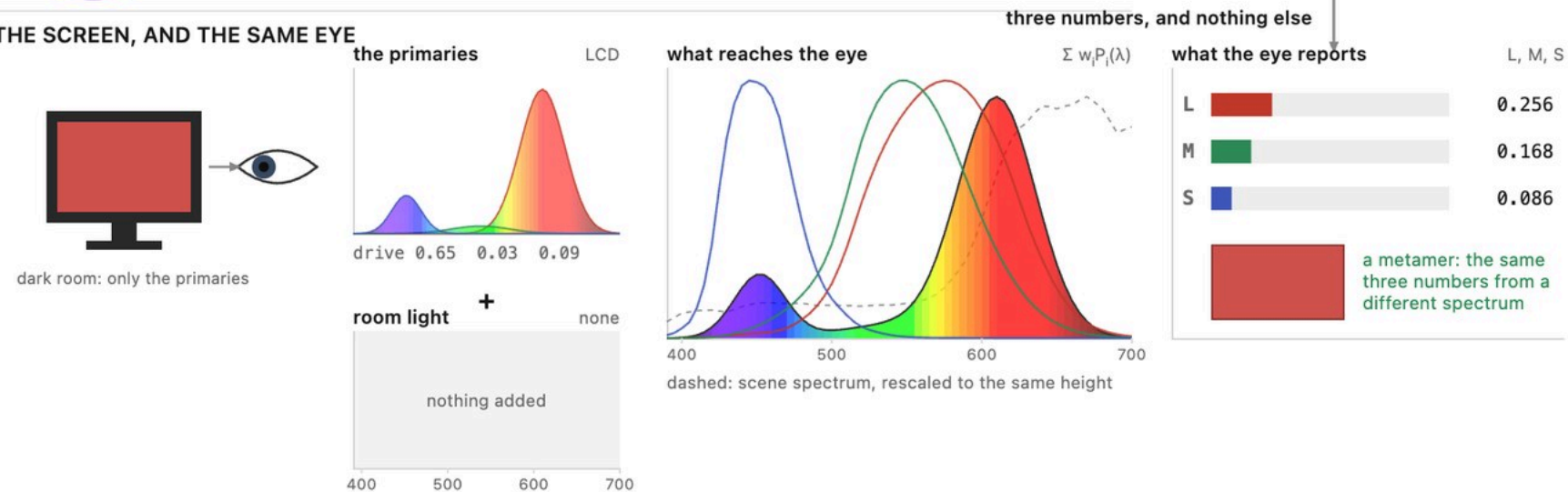


Demo: Color reproduction end to end

THE SCENE, AND AN EYE



THE SCREEN, AND THE SAME EYE



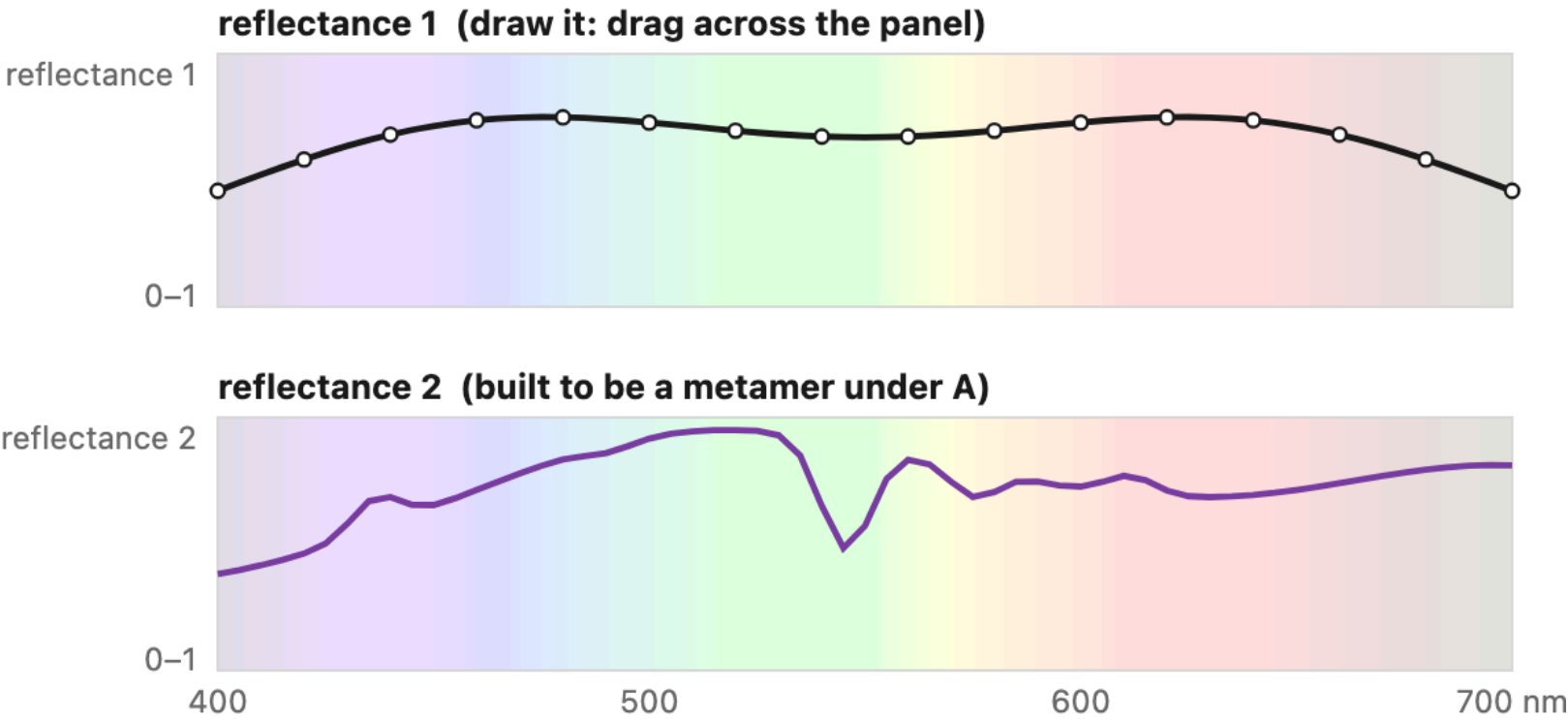
Recap

- Spectrum: infinite number of values
- projected according to cone spectral response
=> 3 values
- metamers: spectra that induce the same response
(physically different but look the same)
- Questions?

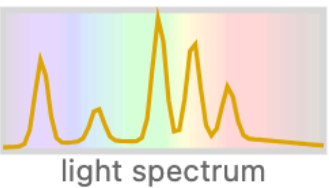
Metamerism & light source

- Metamers under a given light source
- May not be metamers under a different lamp

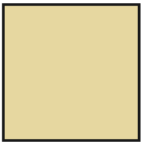
Demo: Metamerism illumination



A: fluorescent-like



light spectrum



refl 1



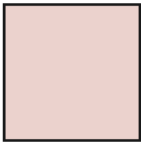
refl 2

same color ✓ (metamer)

B: blackbody (6500 K)



light spectrum



refl 1



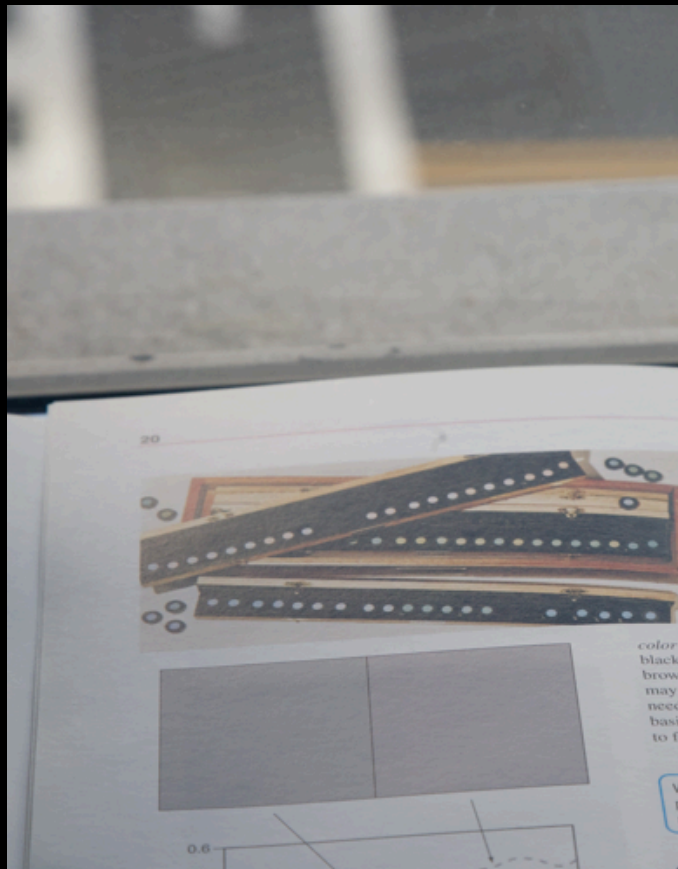
refl 2

colors differ ✗

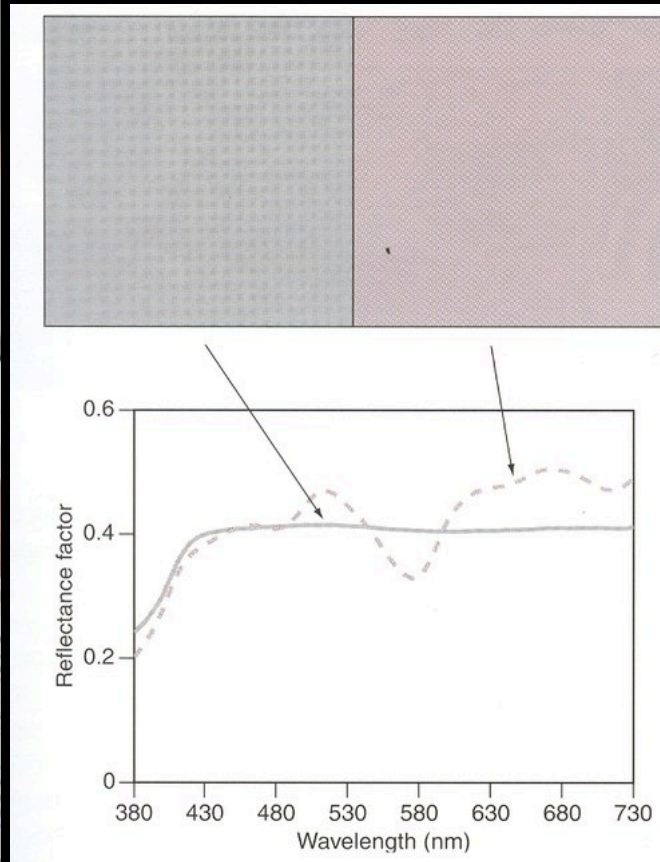
matches under A, but the match breaks under B

Illuminant metamerism example

- Two grey patches in Billmeyer & Saltzman's book look the same under daylight but different under neon or halogen (& my camera agrees ;-)



Daylight



Scan (neon)

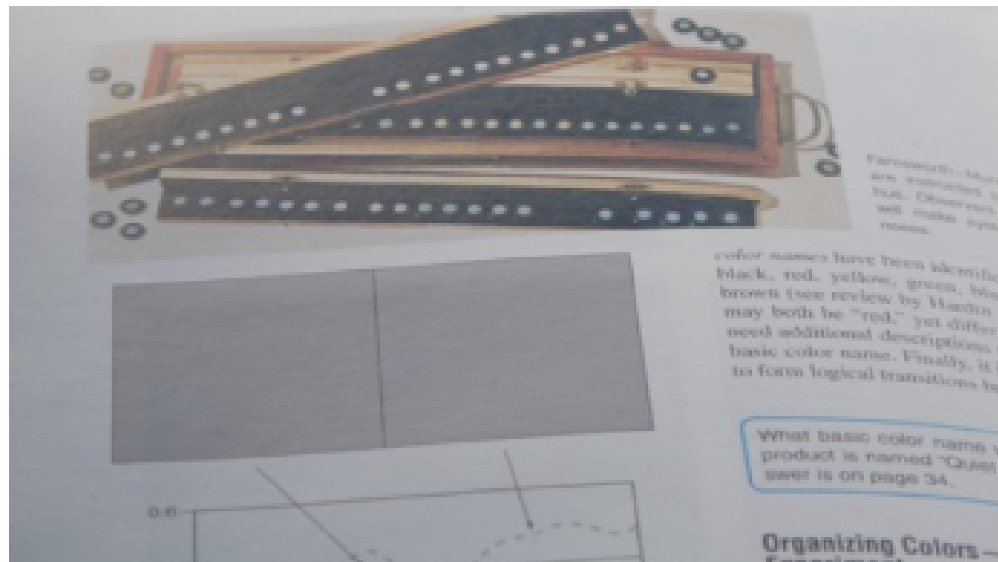


Hallogen

Demo: Illuminant metamerism, photographed

Illuminant metamerism, photographed: same patches, two lights

Under daylight
the two gray patches match



Under a halogen lamp
the match breaks (right patch goes pink)



Bad consequence: cloth matching

- Clothes appear to match in store (e.g. under neon)
- Don't match outdoor

Recap

- Spectrum is an infinity of numbers
- Projected to 3D cone-response space
 - for each cone, multiply per wavelength and integrate
 - a.k.a. dot product
- Metamerism: infinite-D points projected to the same 3D point (different spectrum, same perceived color)
 - affected by illuminant
 - enables color reproduction with only 3 primaries

Questions?



Meryon (a colorblind painter), *Le Vaisseau Fantôme*



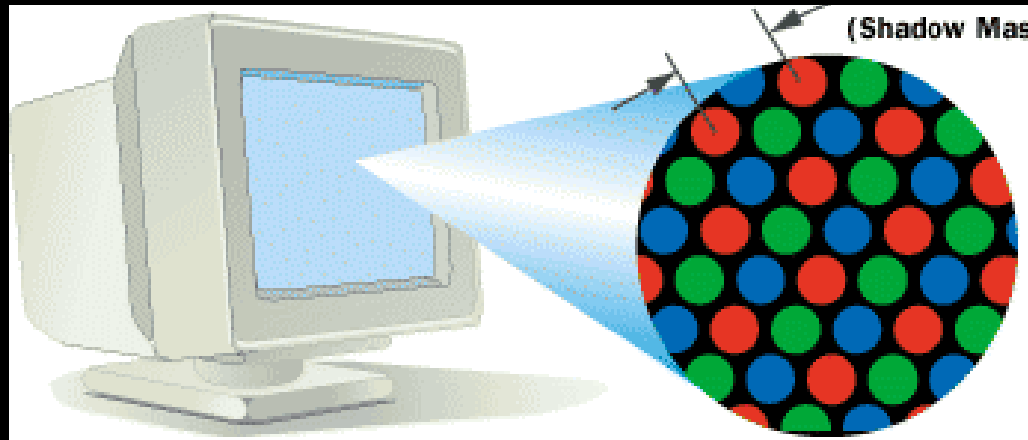
Analysis & Synthesis



Analysis & Synthesis

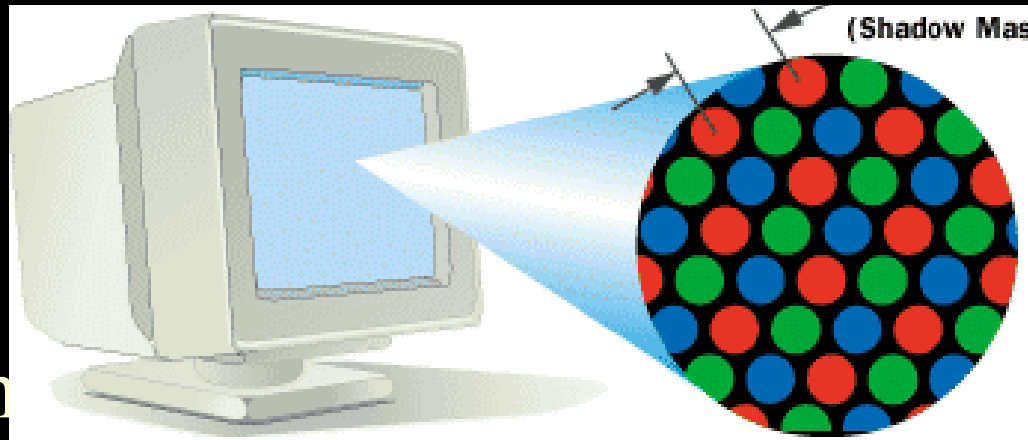
- Now let's talk about technology
- We want to measure & reproduce color as seen by humans
- No need for full spectrum
- Only need to match up to metamerism

Analysis & Synthesis



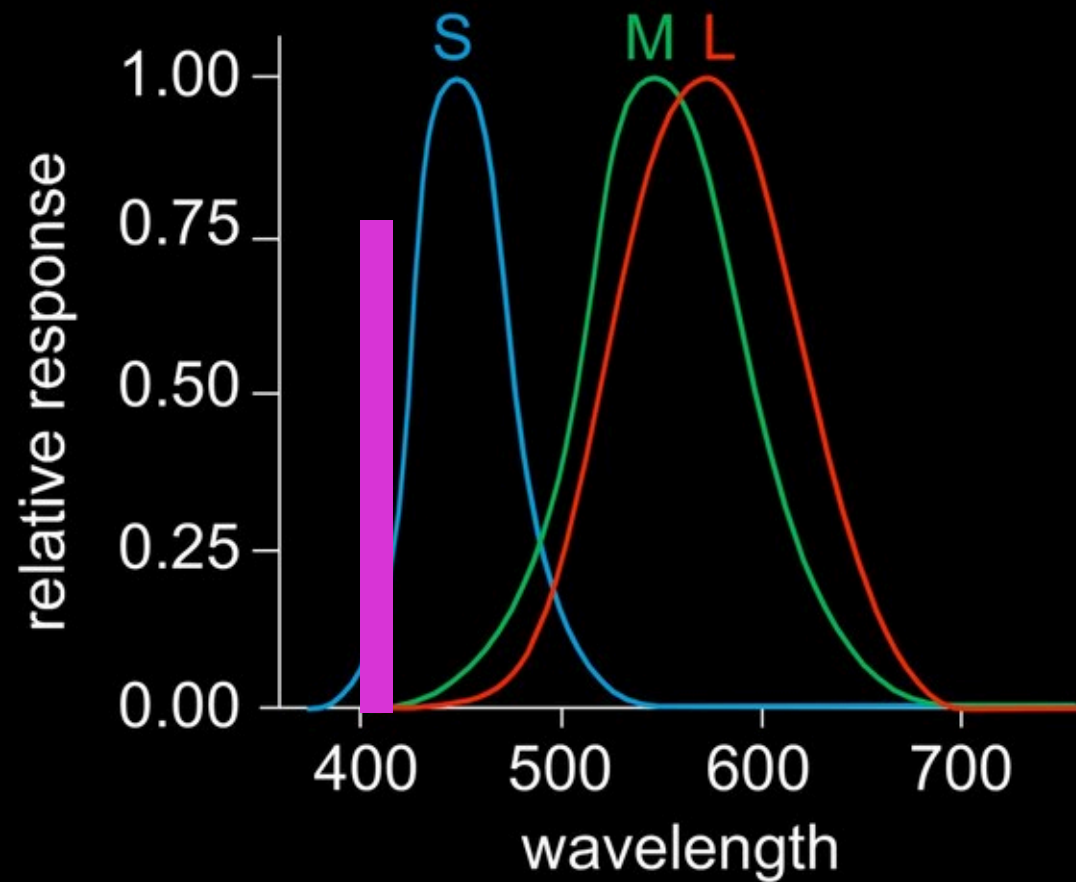
Analysis & Synthesis

- Focus on additive color synthesis
- We'll use 3 primaries (e.g. red green and blue) to match all colors



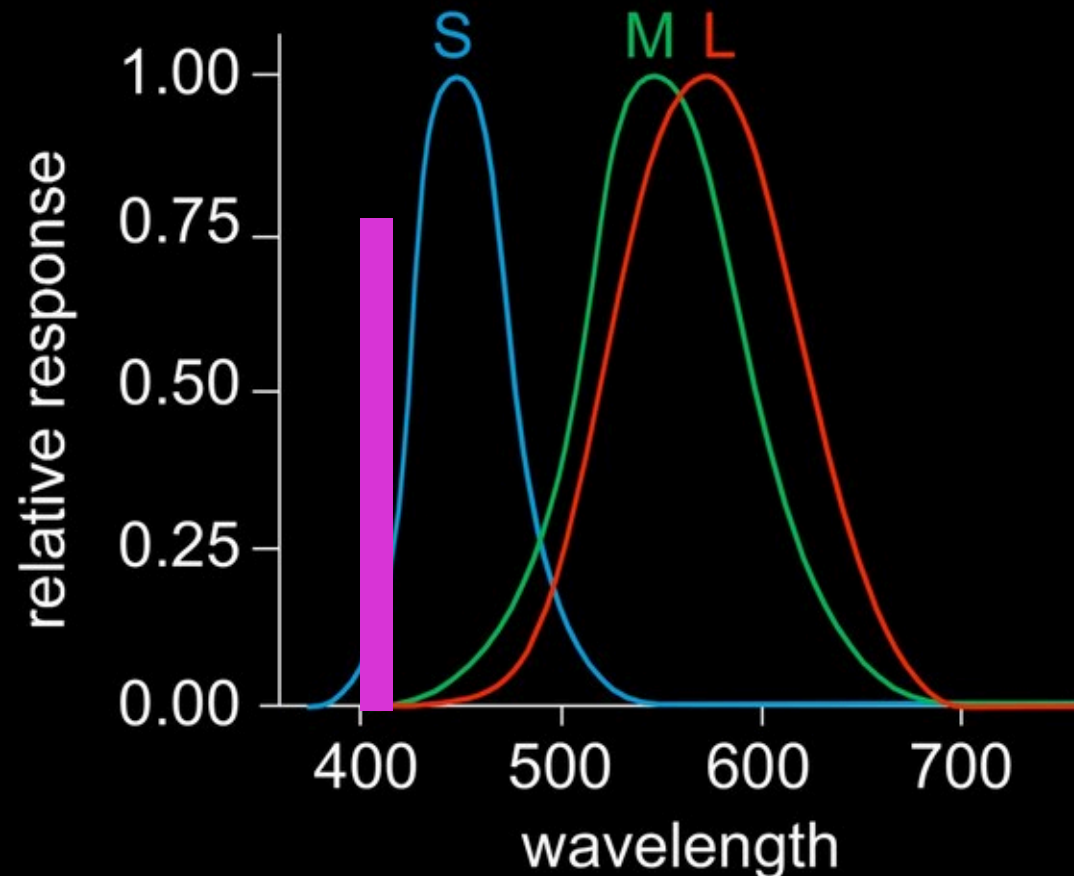
- When
- How do we tell the amount of each primary needed to reproduce a given target color?

Additive Synthesis - wrong way

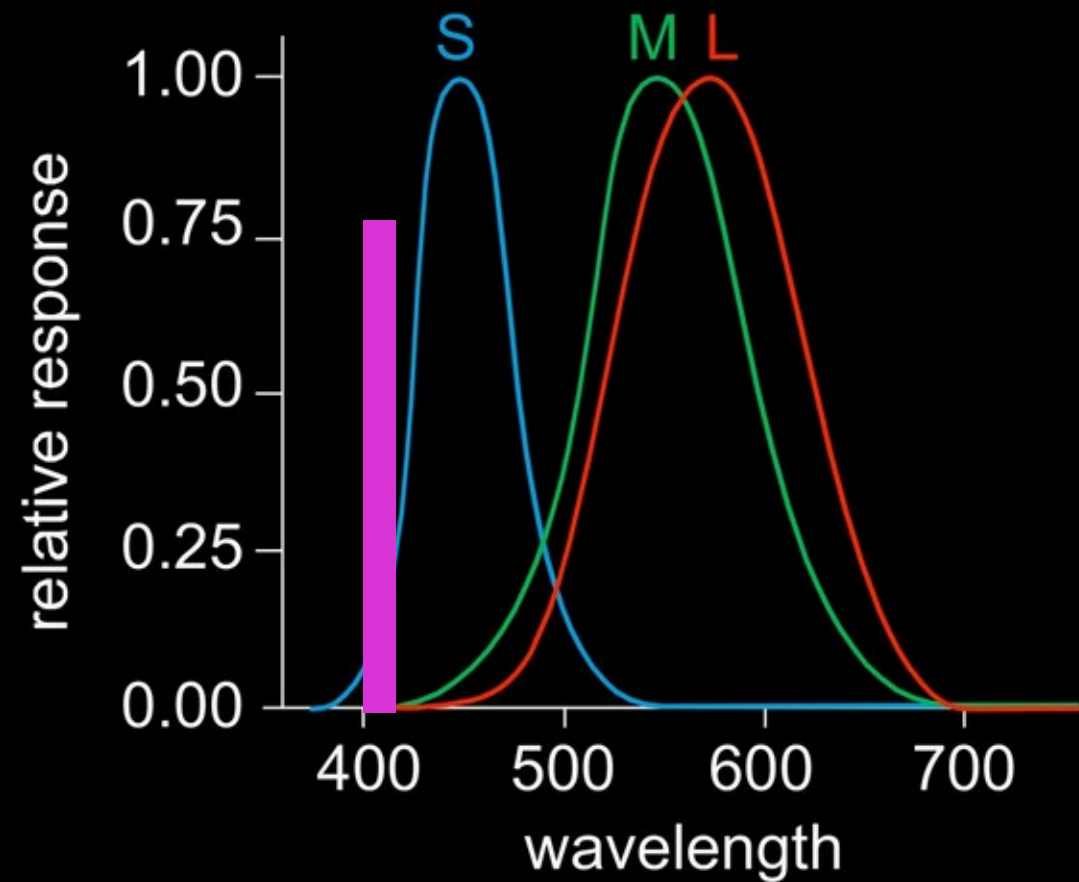


Additive Synthesis - wrong way

- Take a given stimulus and the corresponding responses s , m , l (here 0.5, 0, 0)

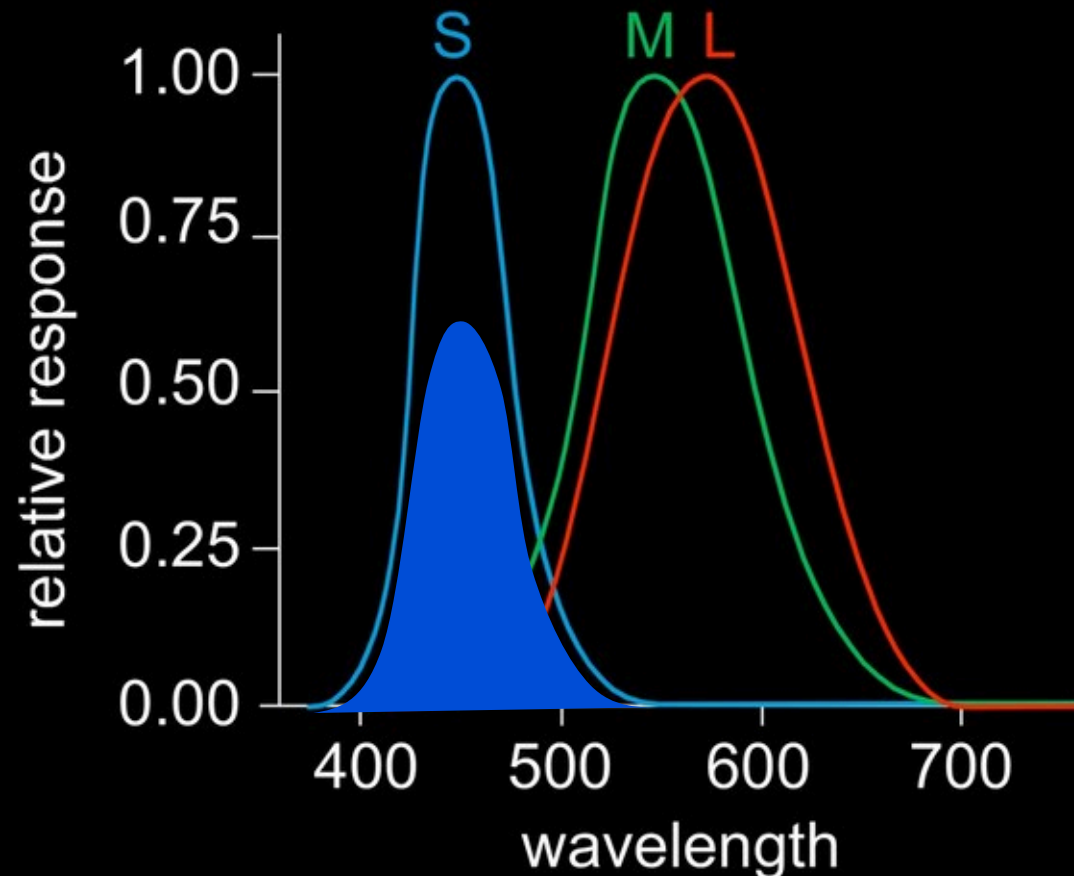


Additive Synthesis - wrong way



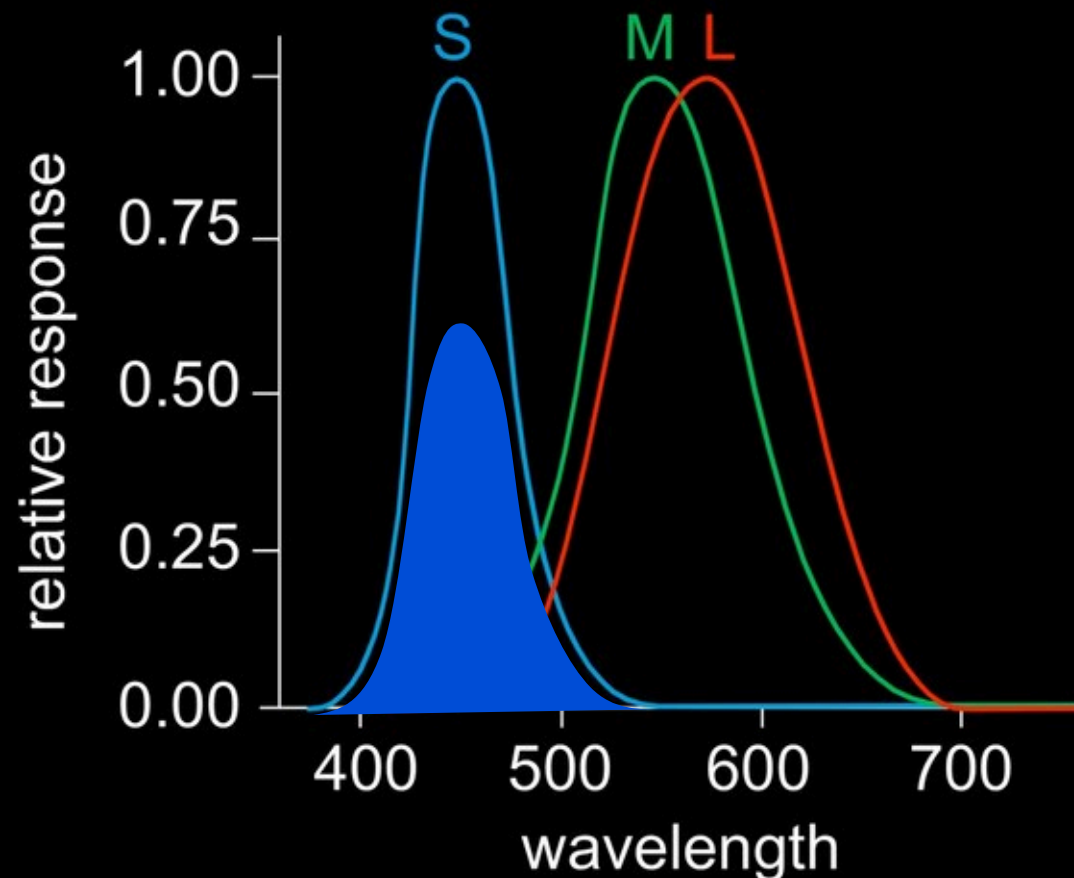
Additive Synthesis - wrong way

- Use it to scale the cone spectra (here $0.5 * S$)
- You don't get the same cone response!
(here 0.5, 0.1, 0.1)



What's going on?

- The three cone responses are not orthogonal
- i.e. they overlap and “pollute” each other



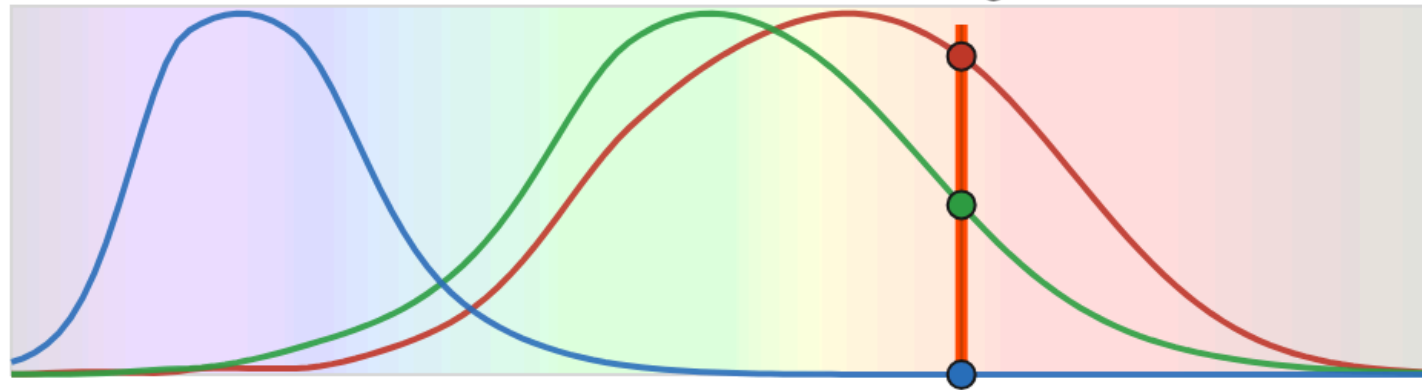
Demo: Incorrect synthesis

$r_L = 0.88$

$r_M = 0.47$

$r_S = 0.00$

Analysis: three cone responses to the test light



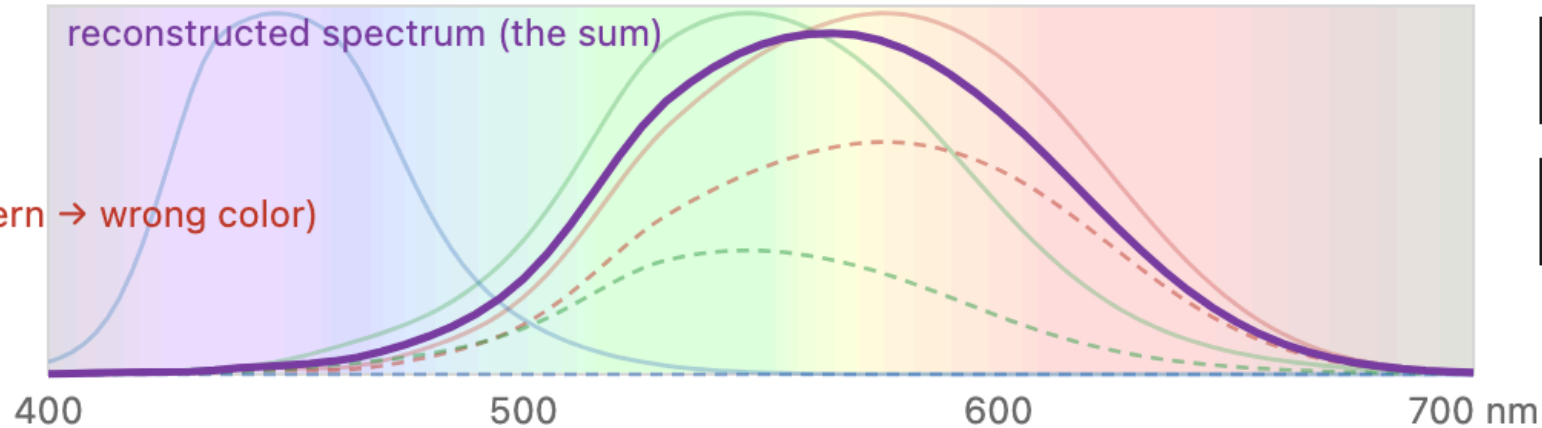
Incorrect synthesis: sum of cone spectra scaled by those responses

$r'_L = 21.21$

$r'_M = 19.08$

$r'_S = 0.99$

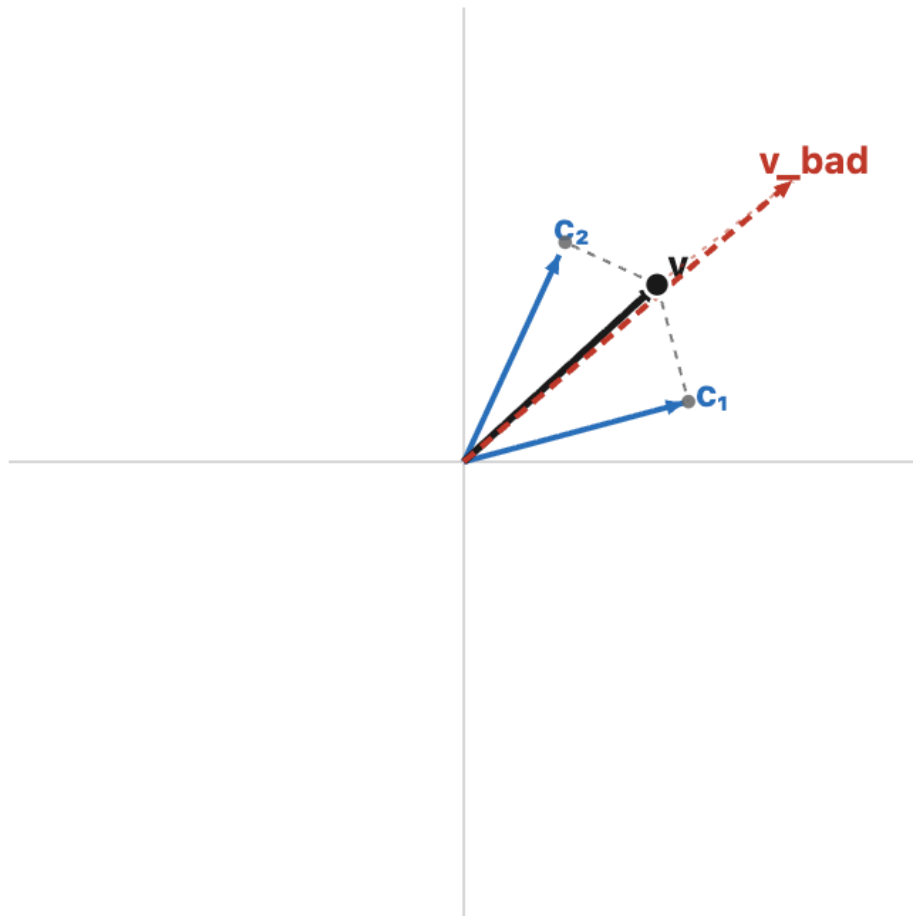
$r' \neq r$ (different pattern $\rightarrow$ wrong color)



Geometry

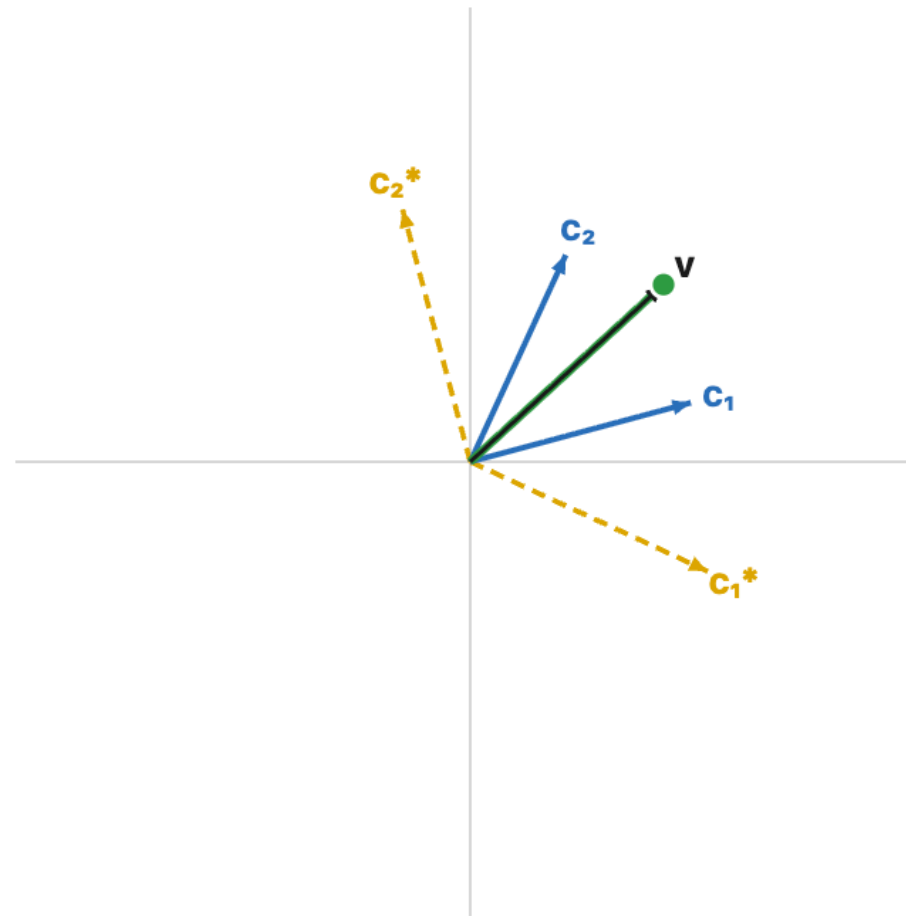
Demo: Dual basis reconstruction

Naive: coefficients = responses $v \cdot c_i$



$$v_bad = (v \cdot c_1)c_1 + (v \cdot c_2)c_2 \rightarrow \text{error } 0.75$$

Correct: coefficients = $v \cdot c_i^*$ (dual basis)



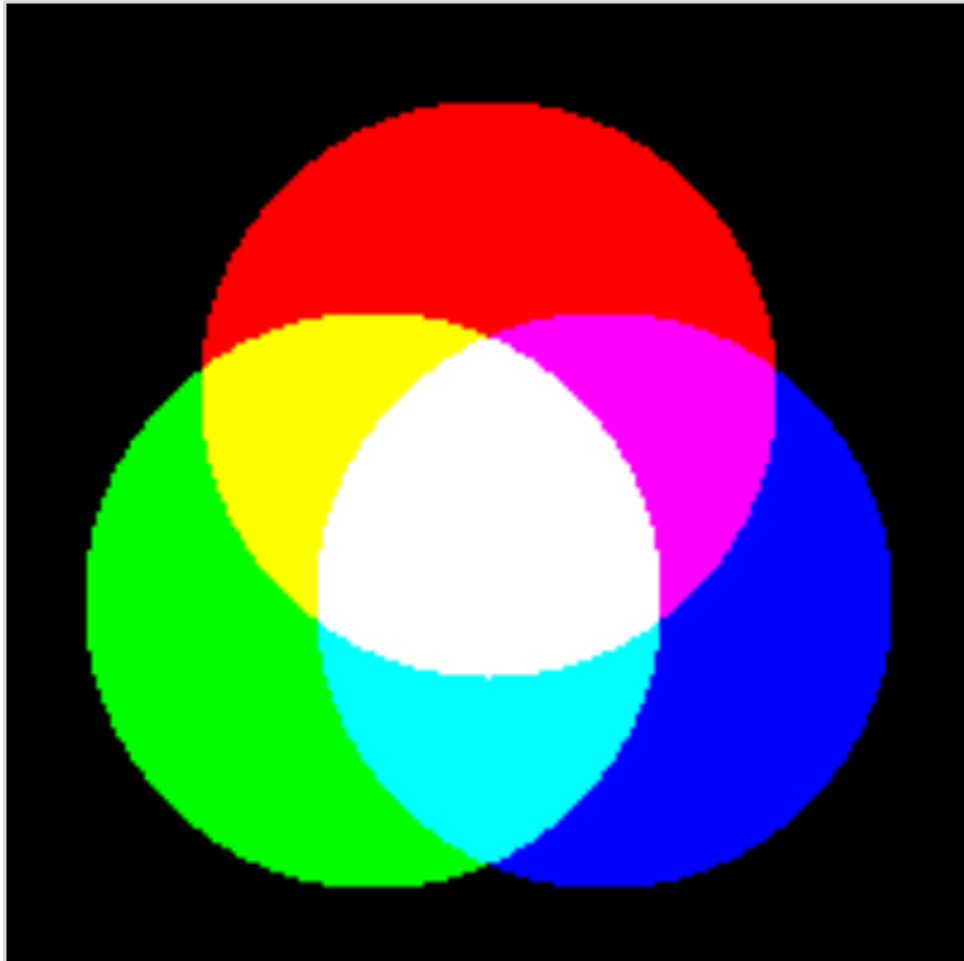
$$v = a_1 c_1 + a_2 c_2 \text{ exactly } (a_i = v \cdot c_i^*)$$

dashed arrows show dual directions, not lengths

Demo: Additive subtractive

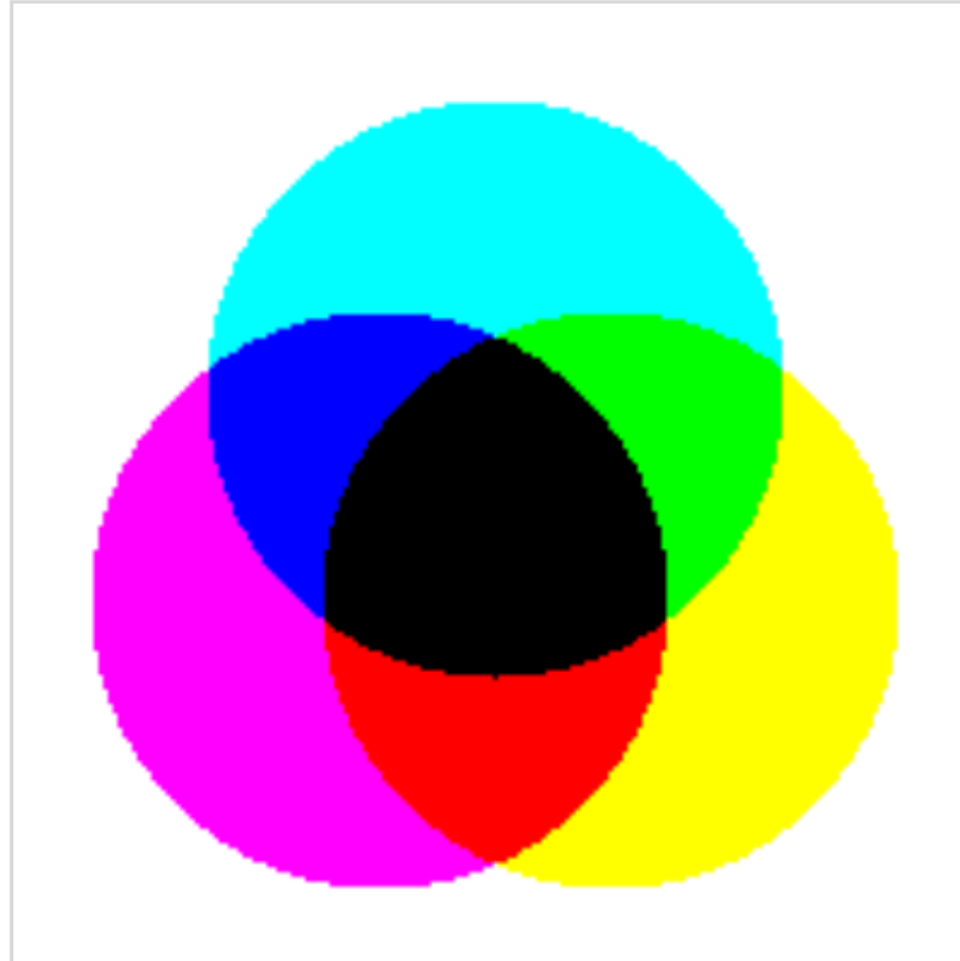
Additive (lights): overlaps ADD

R+G+B → white

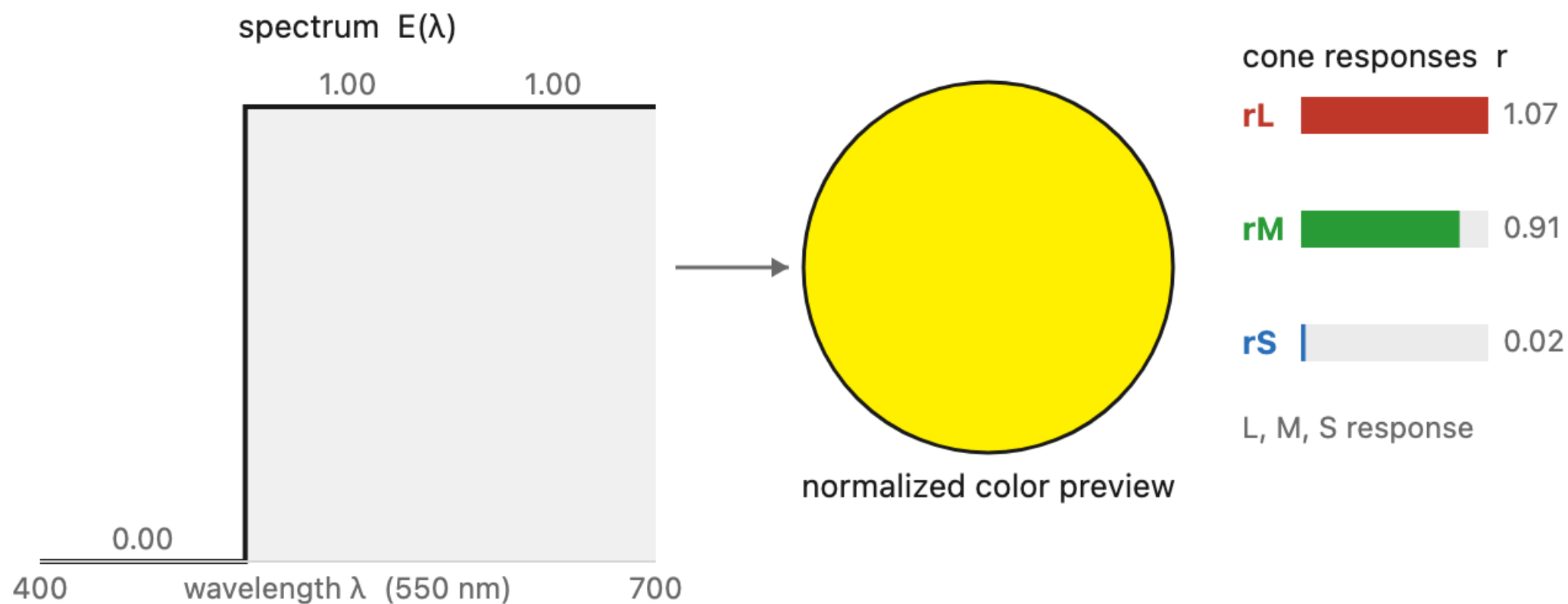


Subtractive (filters): overlaps MULTIPLY

C+M+Y → black



Demo: Trichromatic mixer





CIE color matching



Standard color spaces

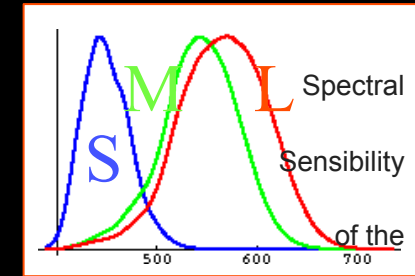
- We need a well-agreed color space
- Many possible definition
 - Including cone response (LMS)
 - Unfortunately not really used,
(because not known when colorimetry was invented)
- The good news is that color vision is linear and 3-dimensional, so any new color space based on color matching can be obtained using 3x3 matrix
 - But there are also non-linear color spaces
(e.g. Hue Saturation Value, Lab)

Overview

- Most standard color space: CIE XYZ
- LMS and the various flavors of RGB are just linear transformations of the XYZ basis
 - 3x3 matrices

Why not measure cone sensitivity?

- Less directly measurable
 - electrode in photoreceptor?
 - not available when color spaces were defined
- Most directly available measurement:
 - notion of metamers & color matching
 - directly in terms of color reproduction:
**given an input color,
how to reproduce it with 3 primary colors?**
 - Commission Internationale de l'Eclairage

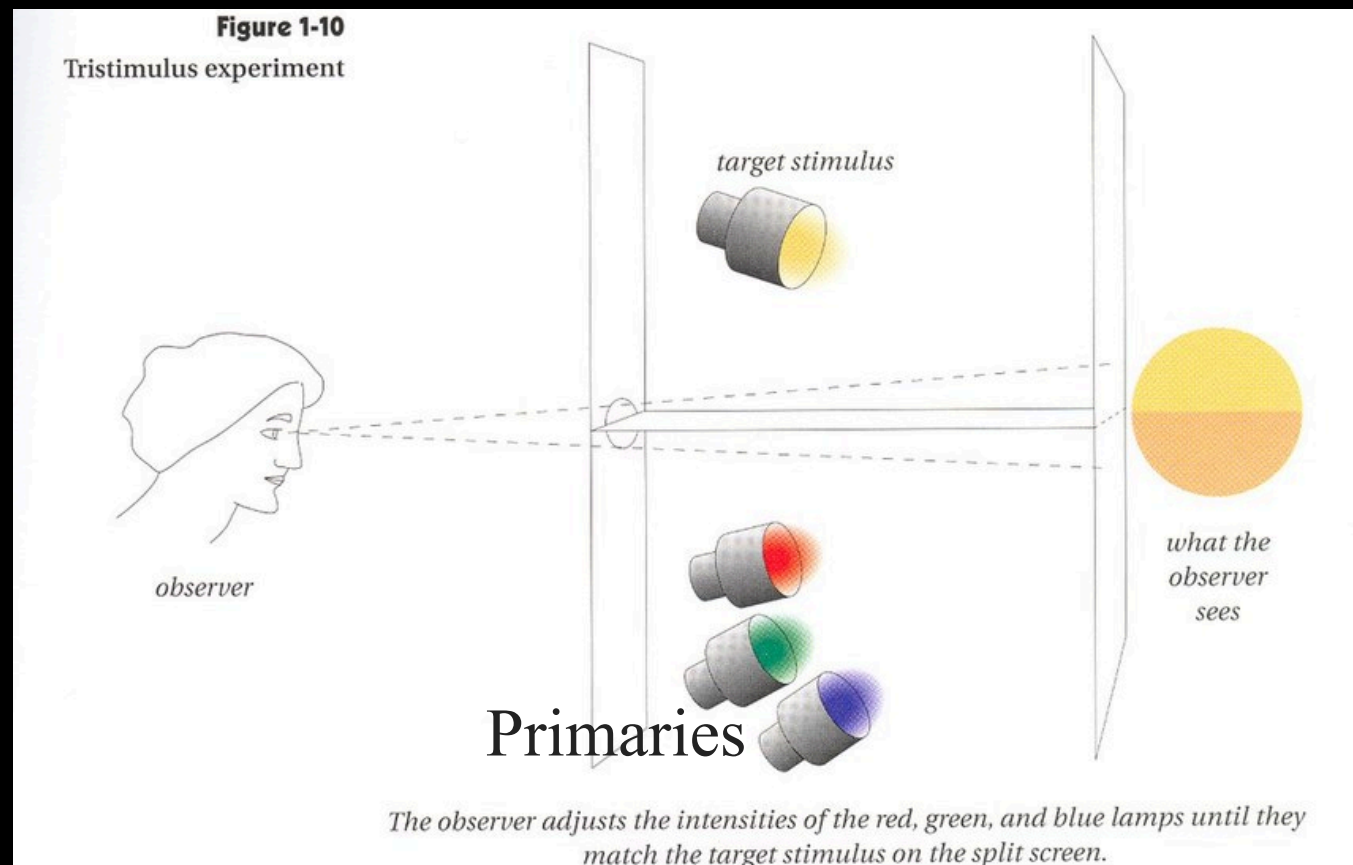


L, M and S

Cones

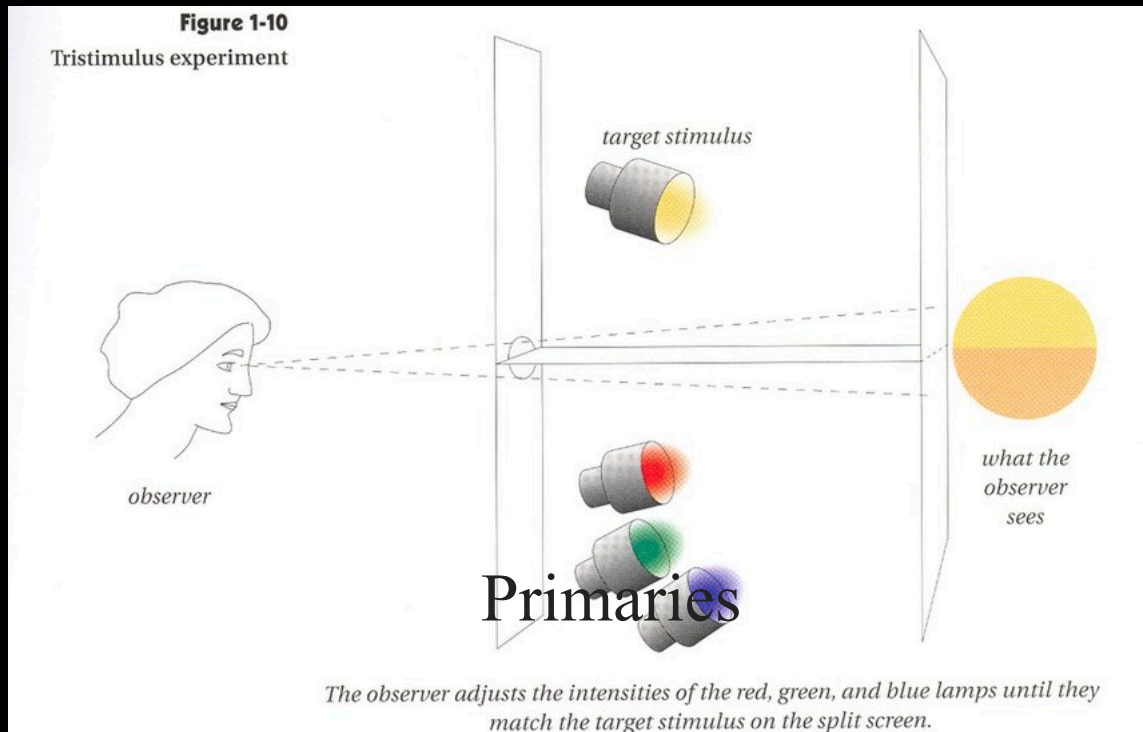
CIE color matching

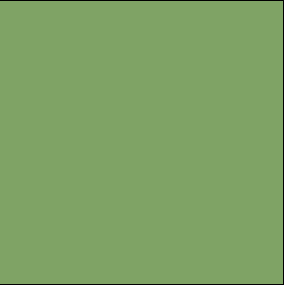
- **Given an input color, how to reproduce it with 3 primary colors?**
 - (Idea by Maxwell)



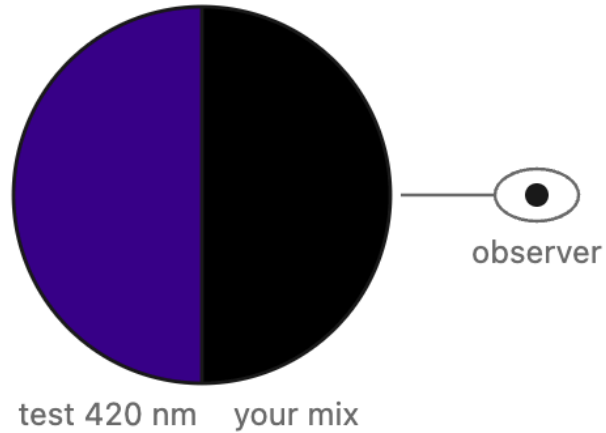
CIE color matching

- Primaries (synthesis) at 435.8, 546.1 and 700nm
 - Chosen for robust reproduction, good separation in red-green
 - Don't worry, we'll be able to convert it to any other set of primaries (Linear algebra to the rescue!)
- Resulting 3 numbers for each input wavelength are called tristimulus values





Demo: Color-matching experiment



match error 0.33

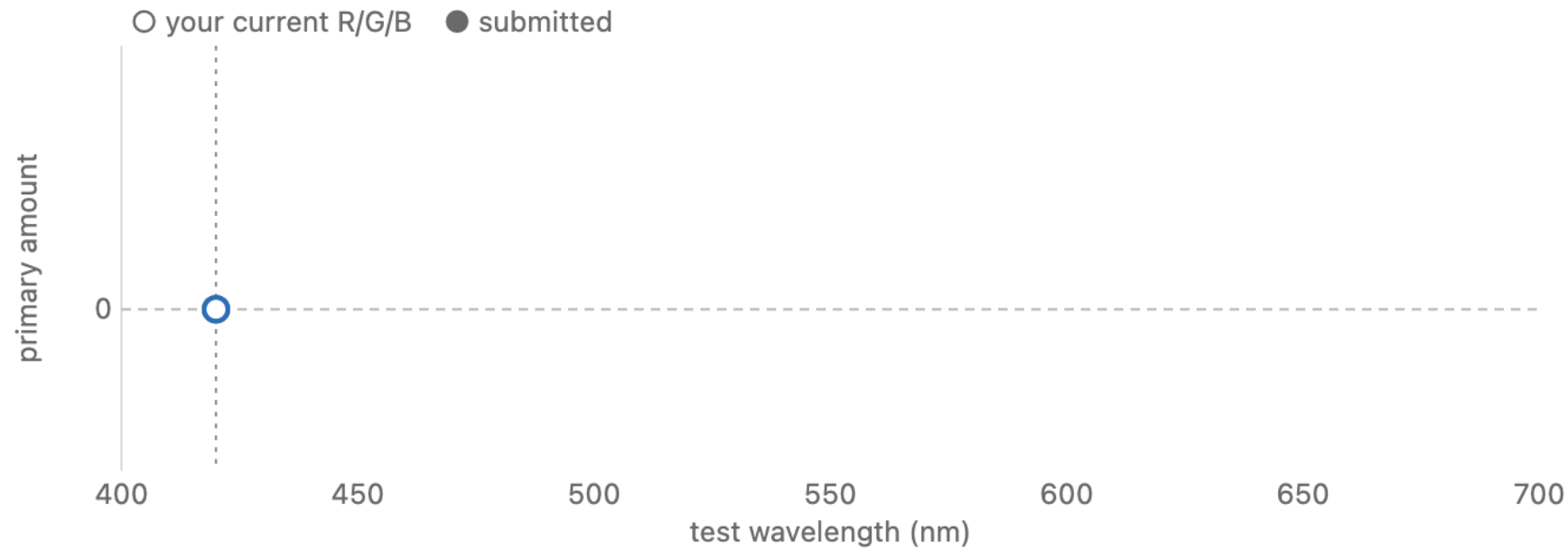
needed for a perfect match:

$R = 0.04$

$G = -0.04$ (negative $\rightarrow$ add to test)

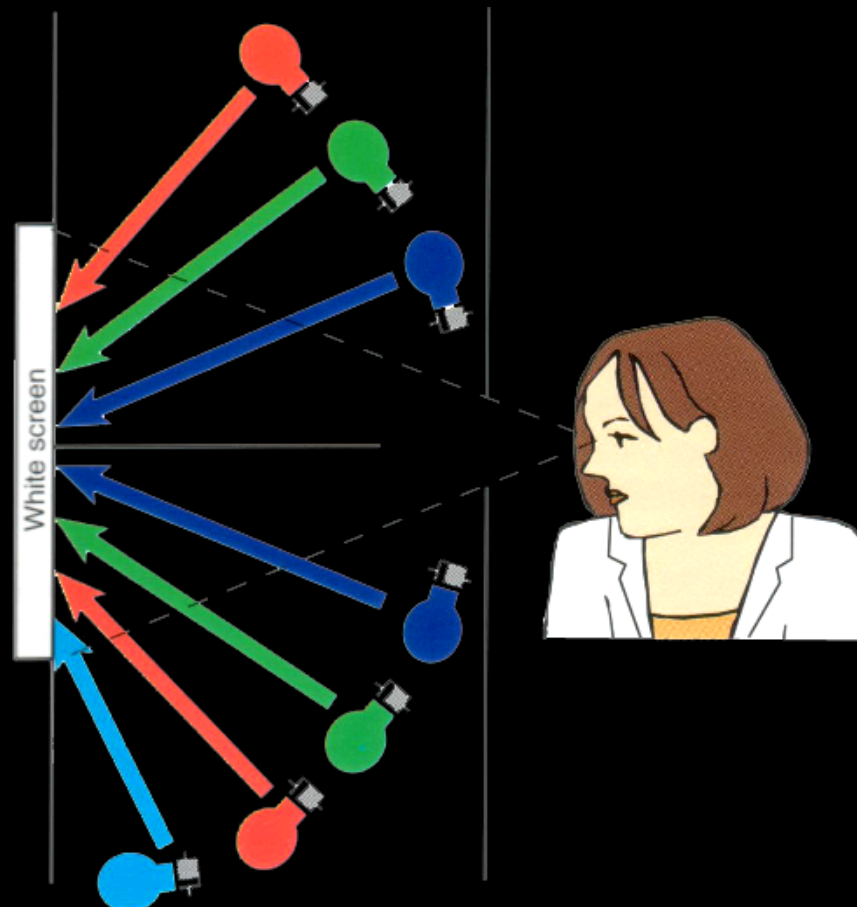
$B = 0.25$

submitted points so far: 0



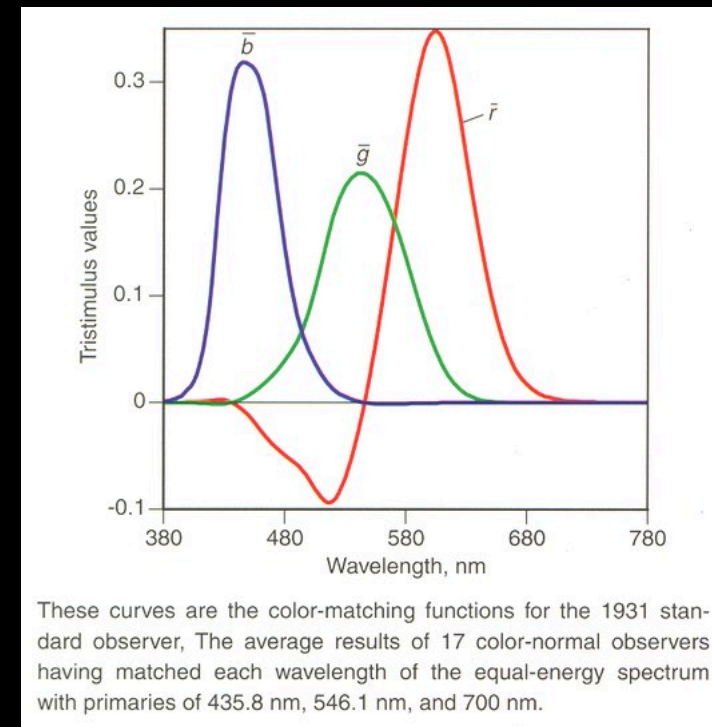
Color Matching Problem

- Some colors cannot be produced using only positively weighted primaries
- Solution: add light on the other side!

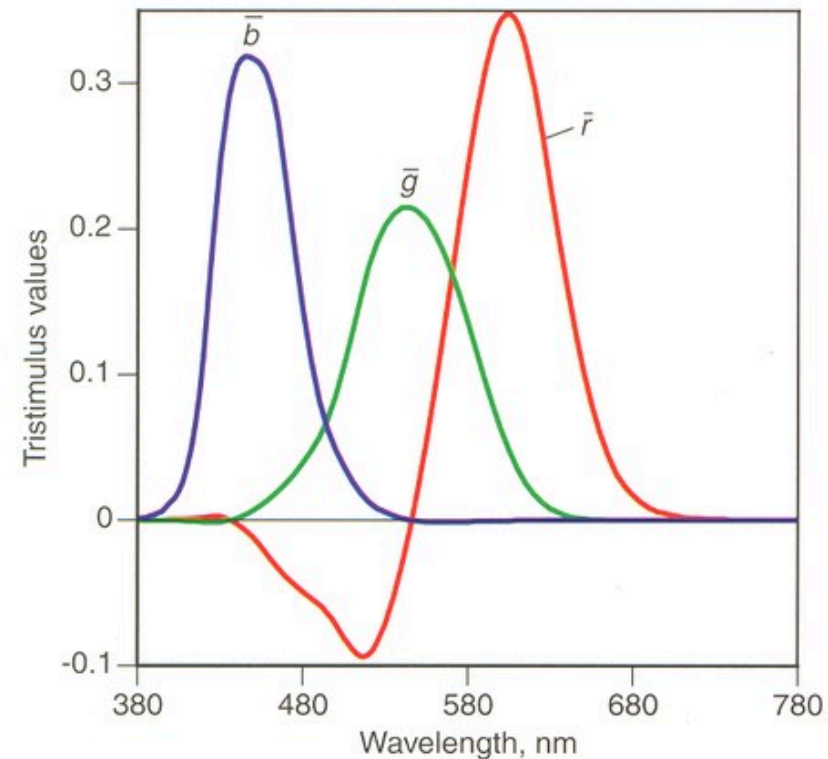


CIE color matching

- Meaning of these curves: a monochromatic wavelength λ can be reproduced with $b(\lambda)$ amount of the 435.8nm primary, $+g(\lambda)$ amount of the 546.1 primary, $+r(\lambda)$ amount of the 700 nm primary
- This fully specifies the color perceived by a human
- Careful: this is not your usual rgb



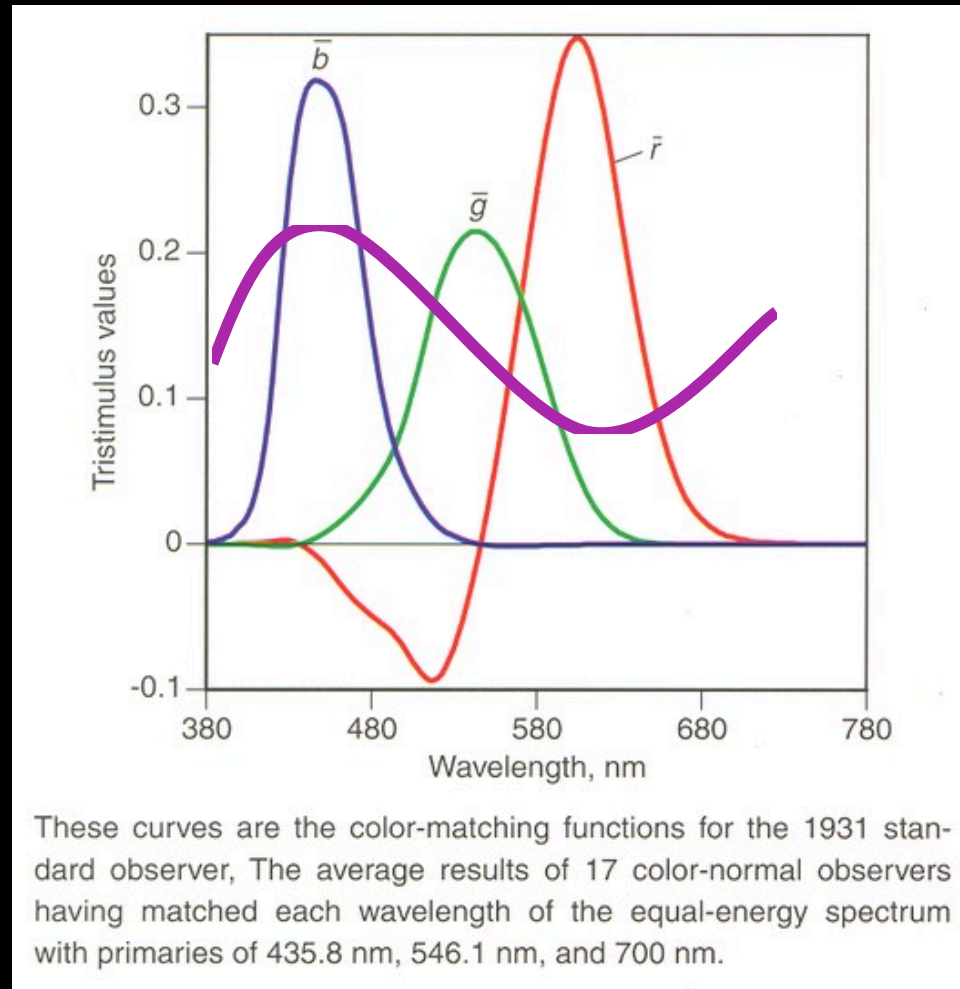
CIE color matching: what does it mean?



These curves are the color-matching functions for the 1931 standard observer, The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

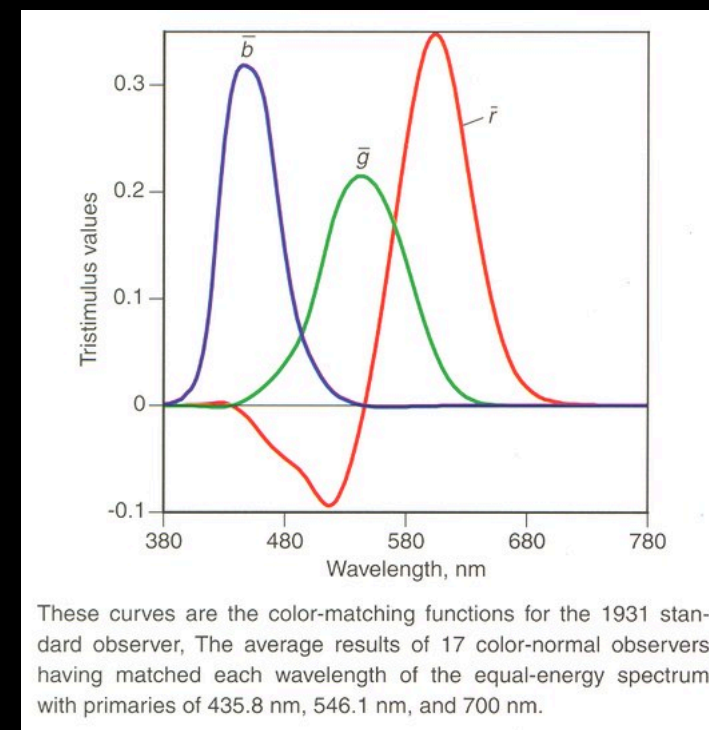
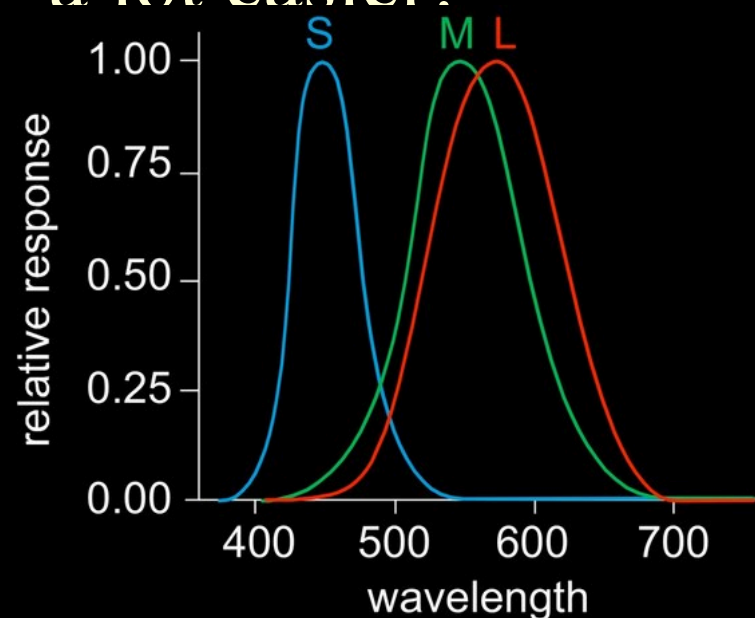
CIE color matching: what does it mean?

- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)



Relation to cone curves

- Project to the same subspace
 - b, g, and r are linear combinations of S, M and L
- Related by 3x3 matrix.
- Unfortunately unknown at that time. This would have made life a lot easier!

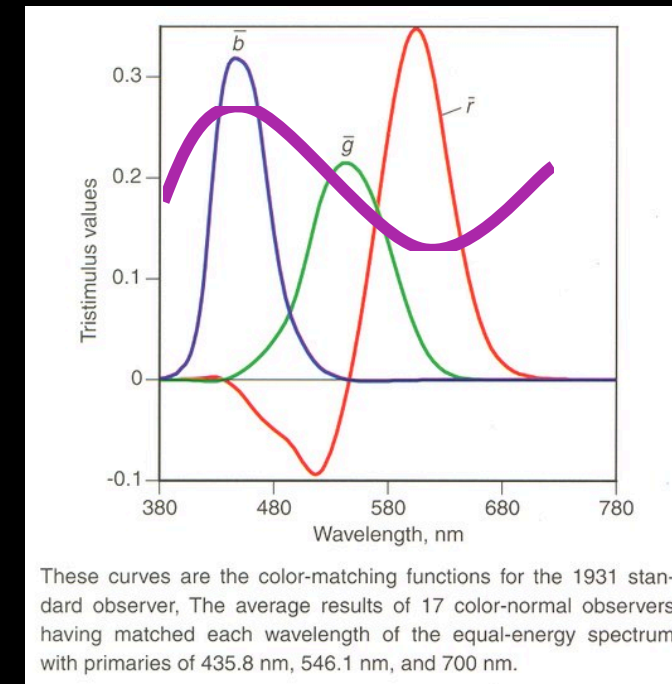


Recap

- Spectra : infinite dimensional
- Cones: 3 spectral responses
- Metamers: spectra that look the same (same projection onto cone responses)
- CIE measured color response:
 - chose 3 primaries
 - tristimulus curves to reproduce any wavelength
- Questions?

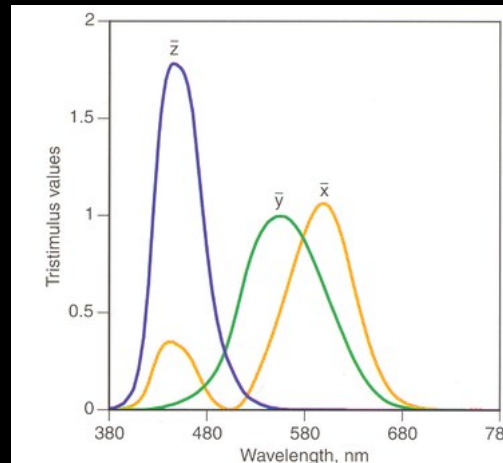
How to build a measurement device?

- Idea:
 - Start with light sensor sensitive to all wavelength
 - Use three filters with spectra b , r , g
 - measure 3 numbers
- This is pretty much what the eyes do!

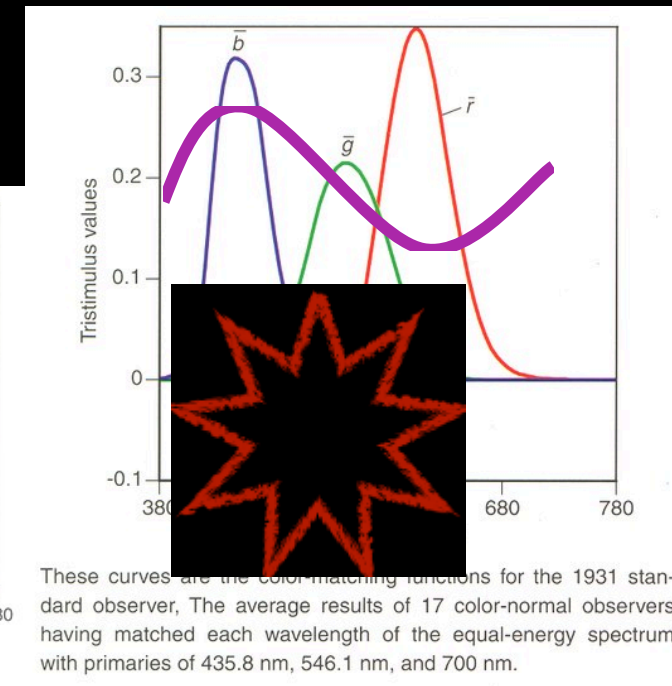


CIE's problem

- Obvious solution:
use cone response!
 - but unknown at the time
- => new set of tristimulus curves
 - linear combinations of b, g, r
 - pretty much add enough b and g until r is positive



The 1931 standard observer, as it is usually shown.



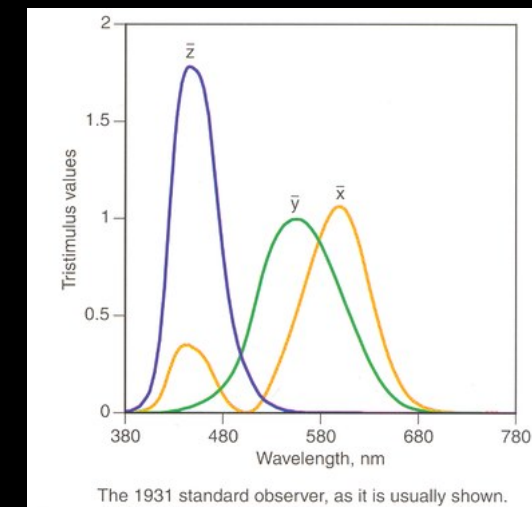
These curves are the color matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

CIE XYZ space

- The most standard color space
- Based on tristimulus curves
- Y corresponds to luminance/brightness
- Linear transform compared to RGB or LMS



$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



XYZ to RGB & back

- e.g.

- sRGB to XYZ

0.412424	0.212656	0.0193324
0.357579	0.715158	0.119193
0.180464	0.0721856	0.950444

- Adobe RGB to XYZ

0.576700	0.297361	0.0270328
0.185556	0.627355	0.0706879
0.182135	0.0153847	0.991248

- NTSC RGB to XYZ

0.606734	0.298839	0.000000
0.173564	0.586811	0.0661196
0.200112	0.114350	1.11491

- XYZ to sRGB

3.24071	-0.969258	0.0556352
-1.53726	1.87599	-0.203996
-0.498571	0.0415557	1.05707

- XYZ to Adobe RGB

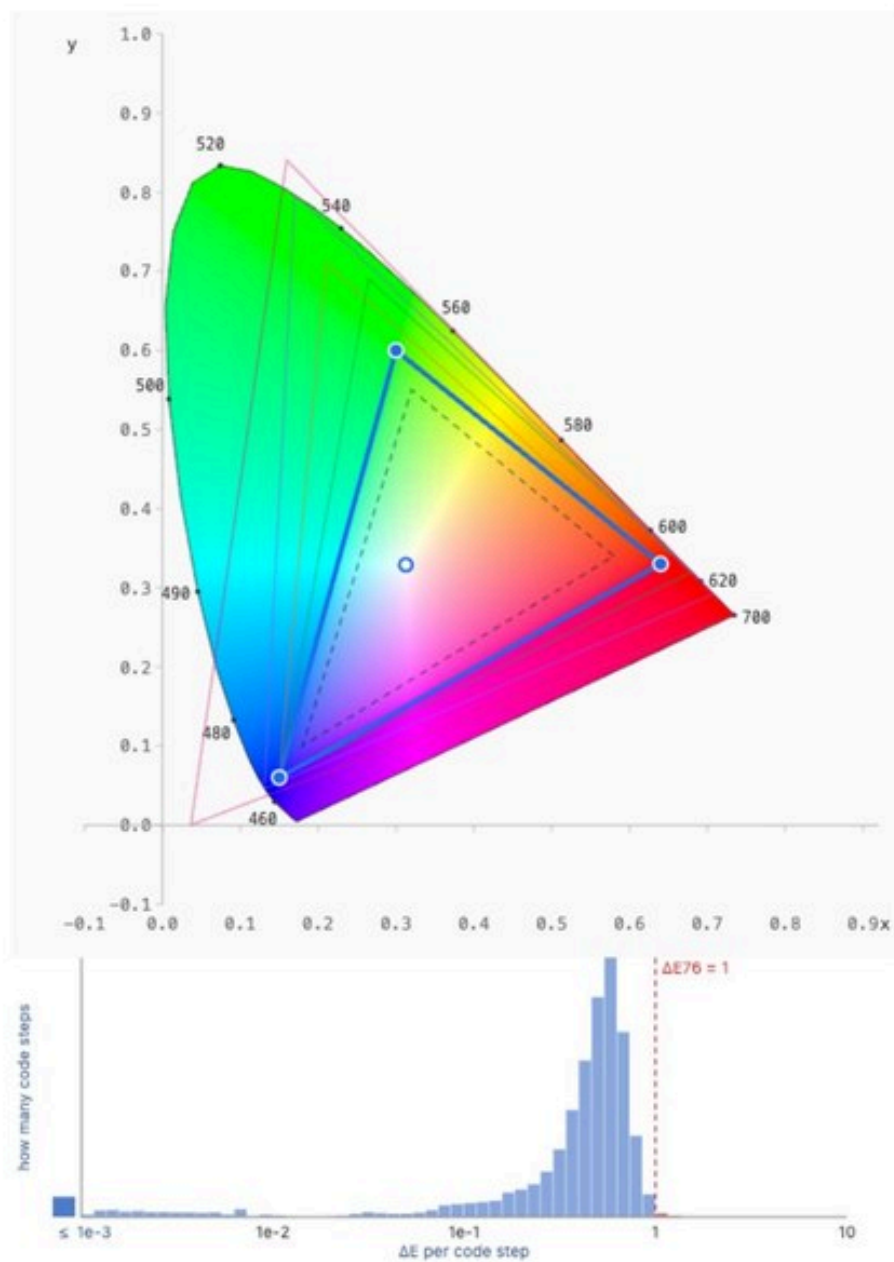
2.04148	-0.969258	0.0134455
-0.564977	1.87599	-0.118373
0.344713	0.0415557	1.01527

- XYZ to NTSC RGB

1.91049	-0.984310	0.0583744
-0.532592	1.99845	-0.118518
-0.288284	-0.0282980	0.898611

Demo: C

Color spaces: sRGB primaries, 8 bits, pure power 2.2



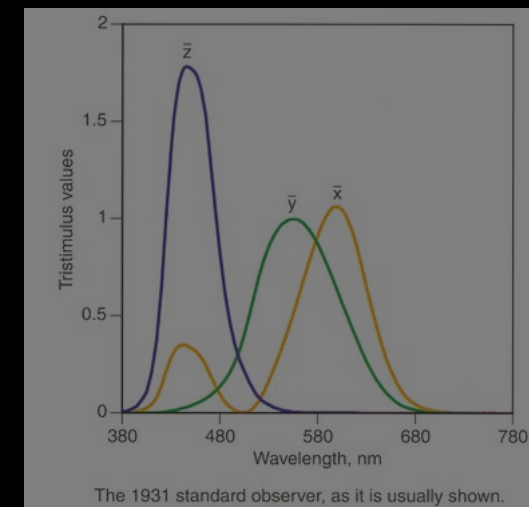
Quantization uses a pure-power model, not the specified sRGB transfer function. The plotted threshold is $\Delta E_{76} = 1$, a rough visibility proxy. Actual 8-bit sRGB code 1 to white spans about 11.7 stops.

CIE XYZ space: QUESTIONS?

- The most standard color space
- Based on tristimulus curves
- Y corresponds to luminance/brightness
- Linear transform compared to RGB or LMS



$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$





Chromaticity diagram



Chromaticity diagrams: motivation

- 3D space are tough to visualize
- Chrominance is our notion of color, as opposed to brightness/luminance
- Recall that our eyes correct for multiplicative scale factors
 - discount light intensity

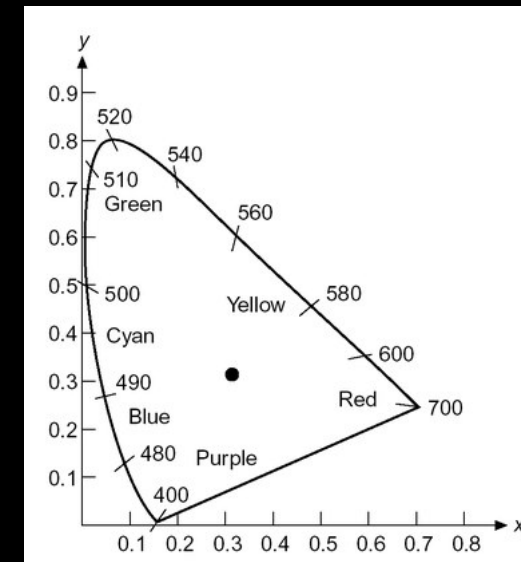


Chromaticity diagrams

- Project XYZ to 2D
- normalize against by $X + Y + Z$:

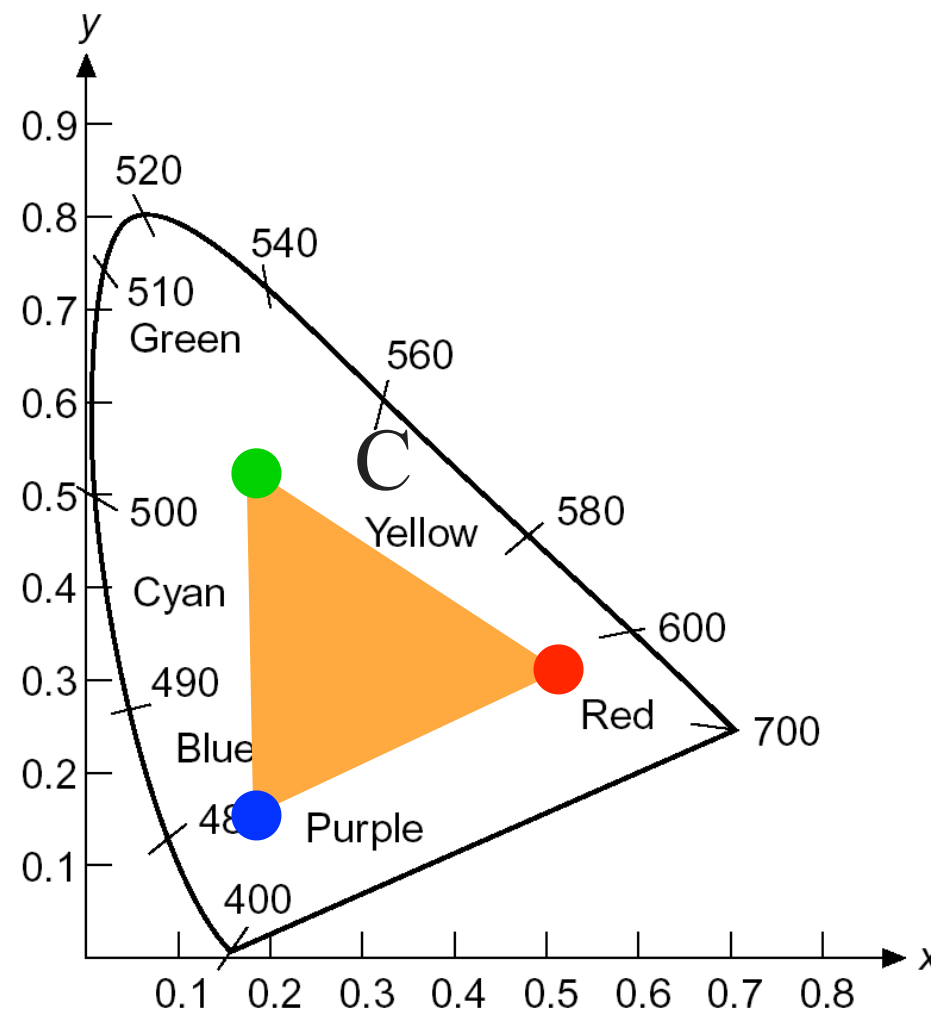
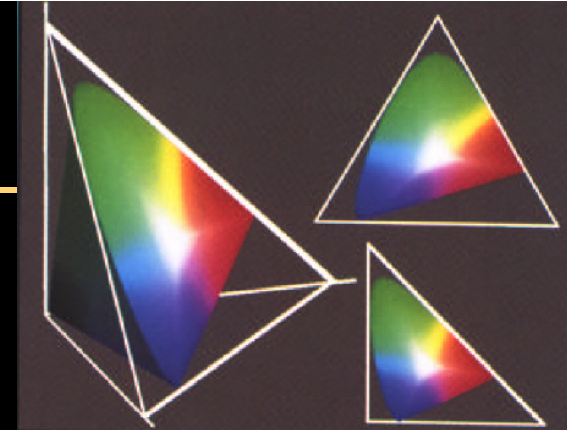
$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z};$$

— equivalent to perspective projection to plane $X+Y+Z=1$

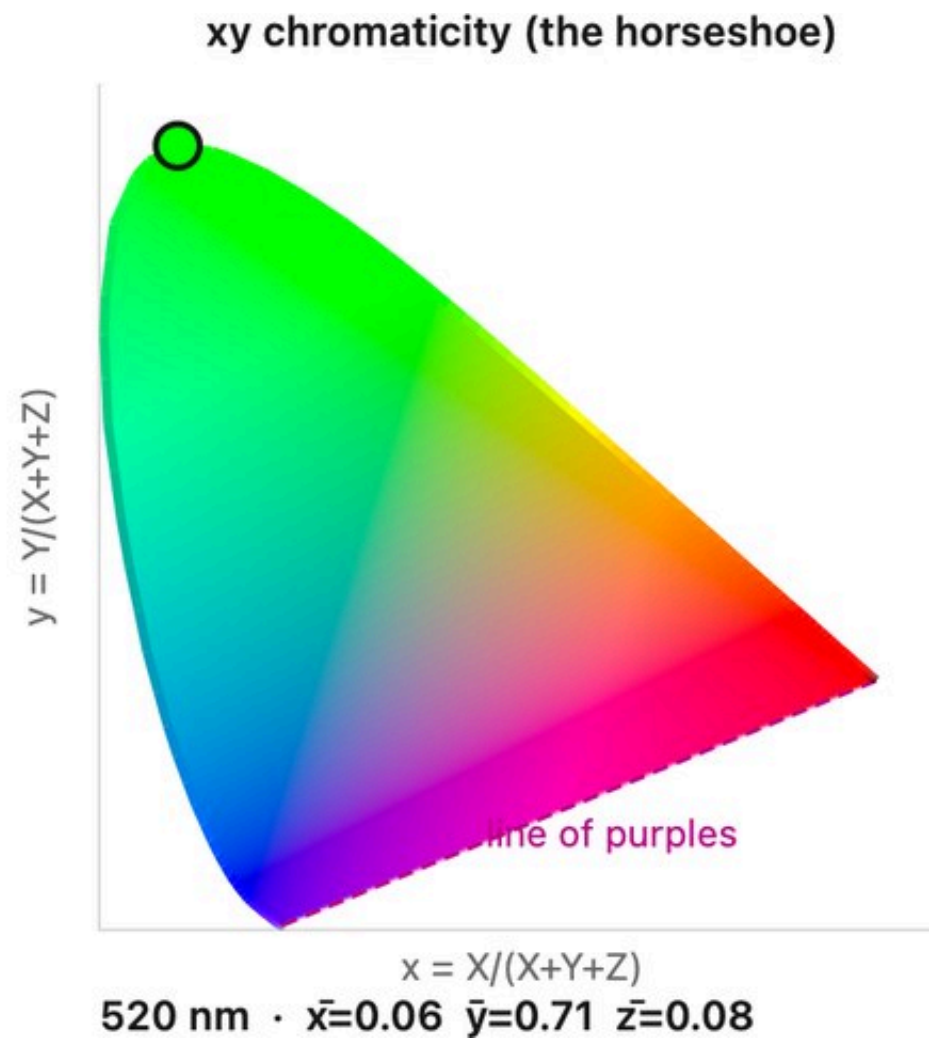
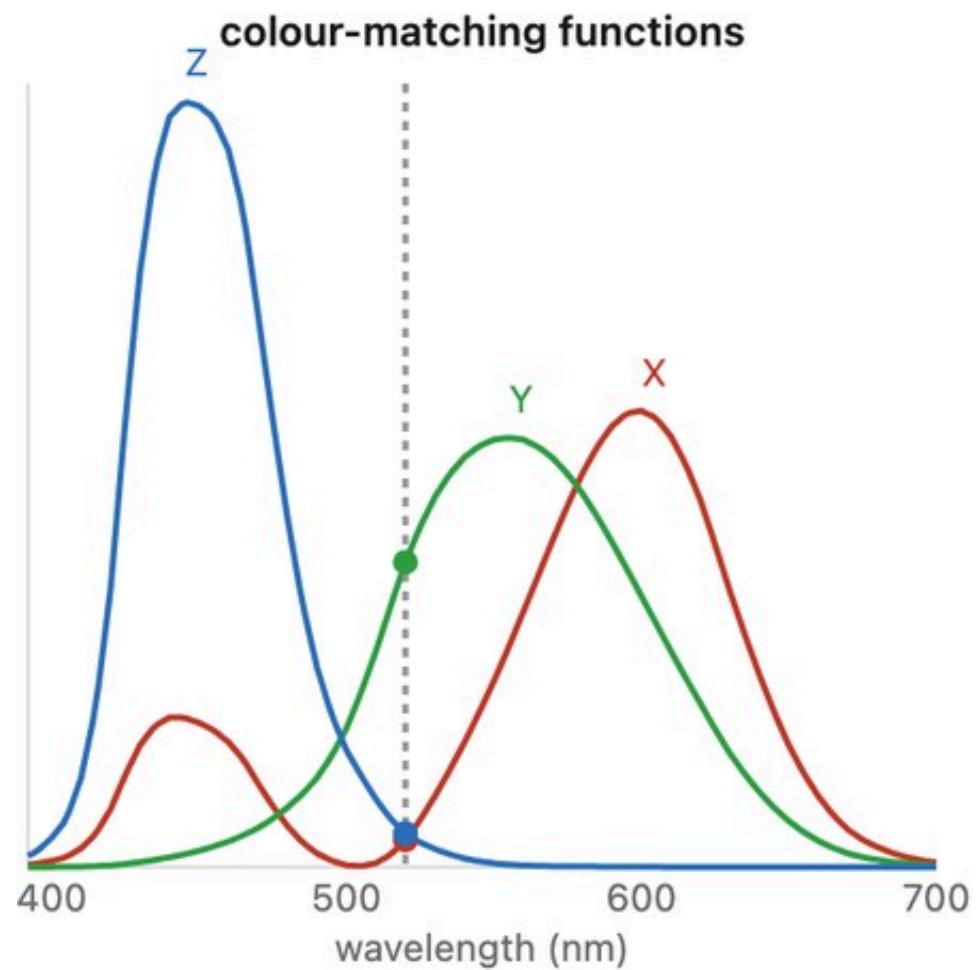


Color gamut

- Given 3 primaries
- The realisable chromaticities lay in the triangle in xy chromaticity diagram
- Because we can only add light, no negative light

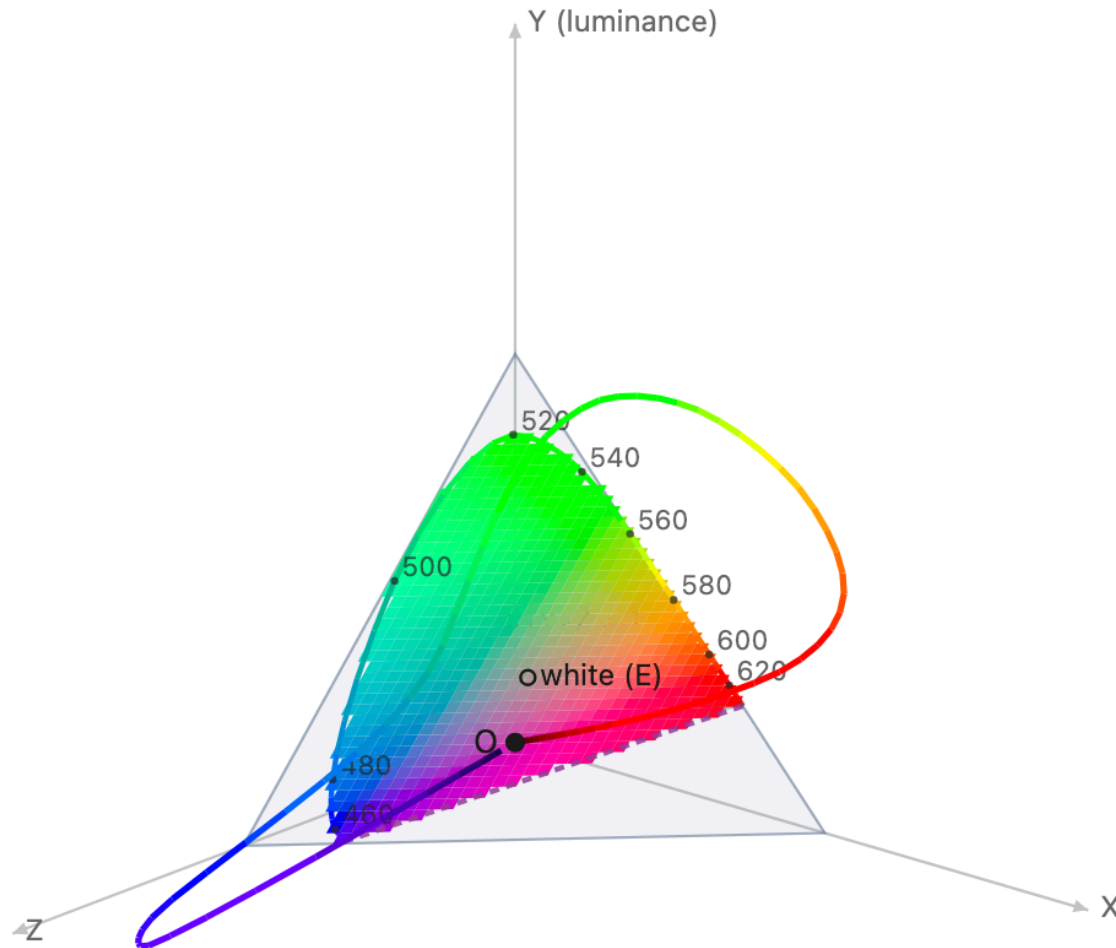


Demo: LMS horseshoe



Demo: Chromaticity (3-D)

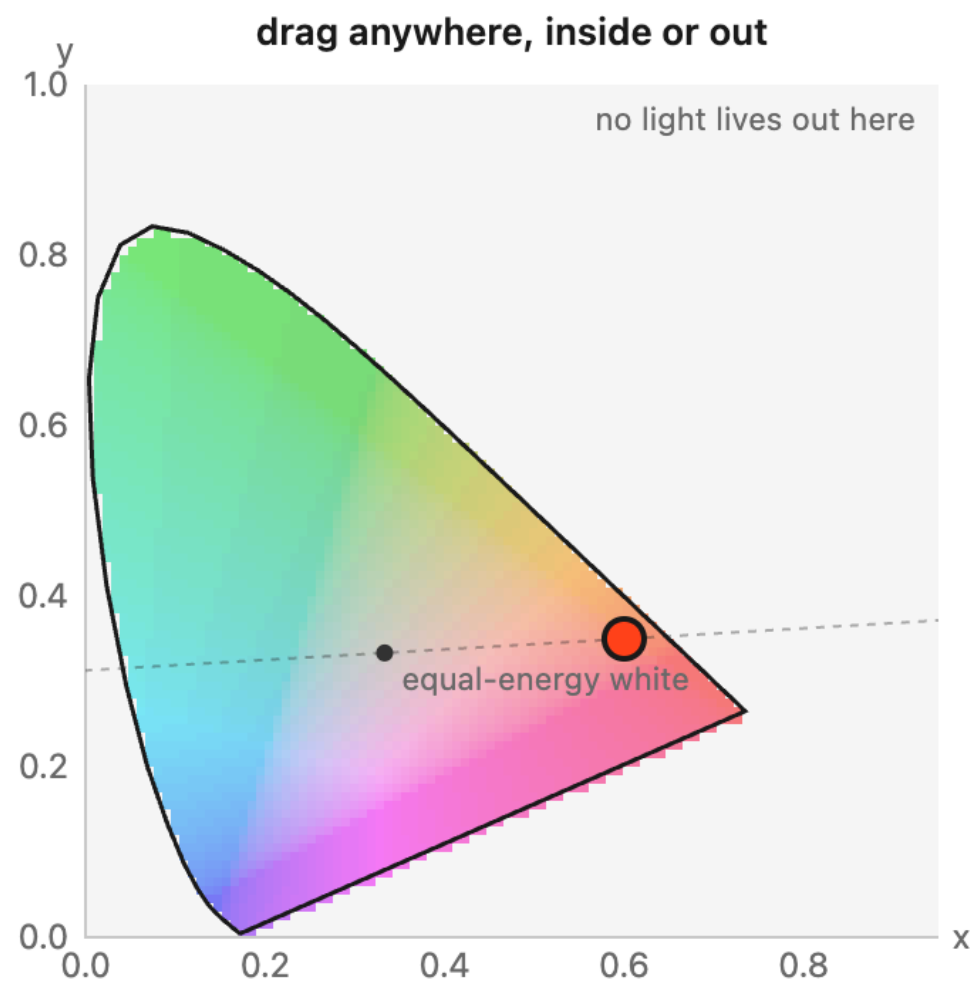
normalize by $X+Y+Z$: (x, y) — bounded horseshoe



— spectral locus $(\bar{X}, \bar{Y}, \bar{Z})$ — the 3-D curve

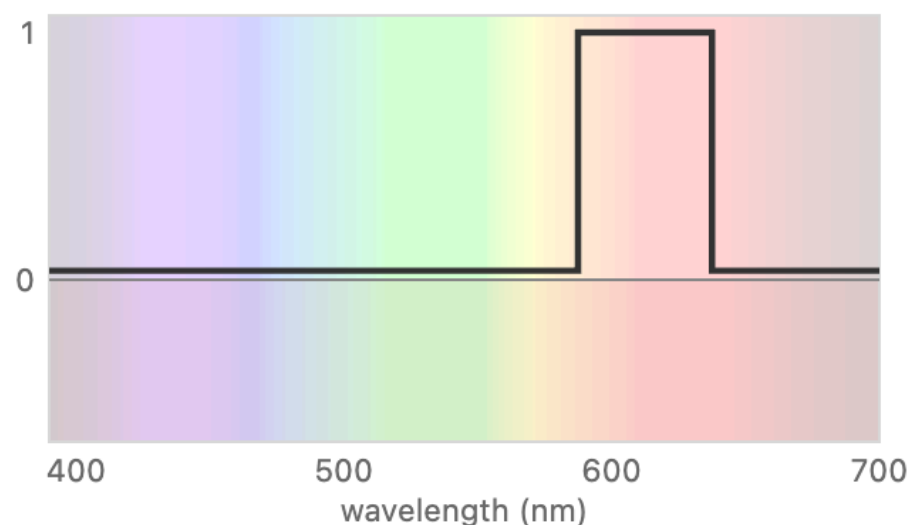
drag to orbit

Demo: What spectrum makes this color



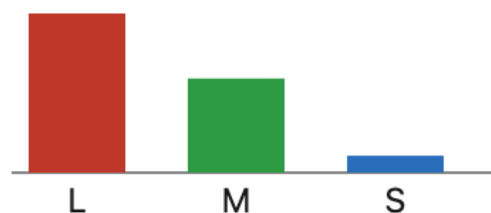
two-level spectral approximation

both levels nonnegative (equal-energy illumination)



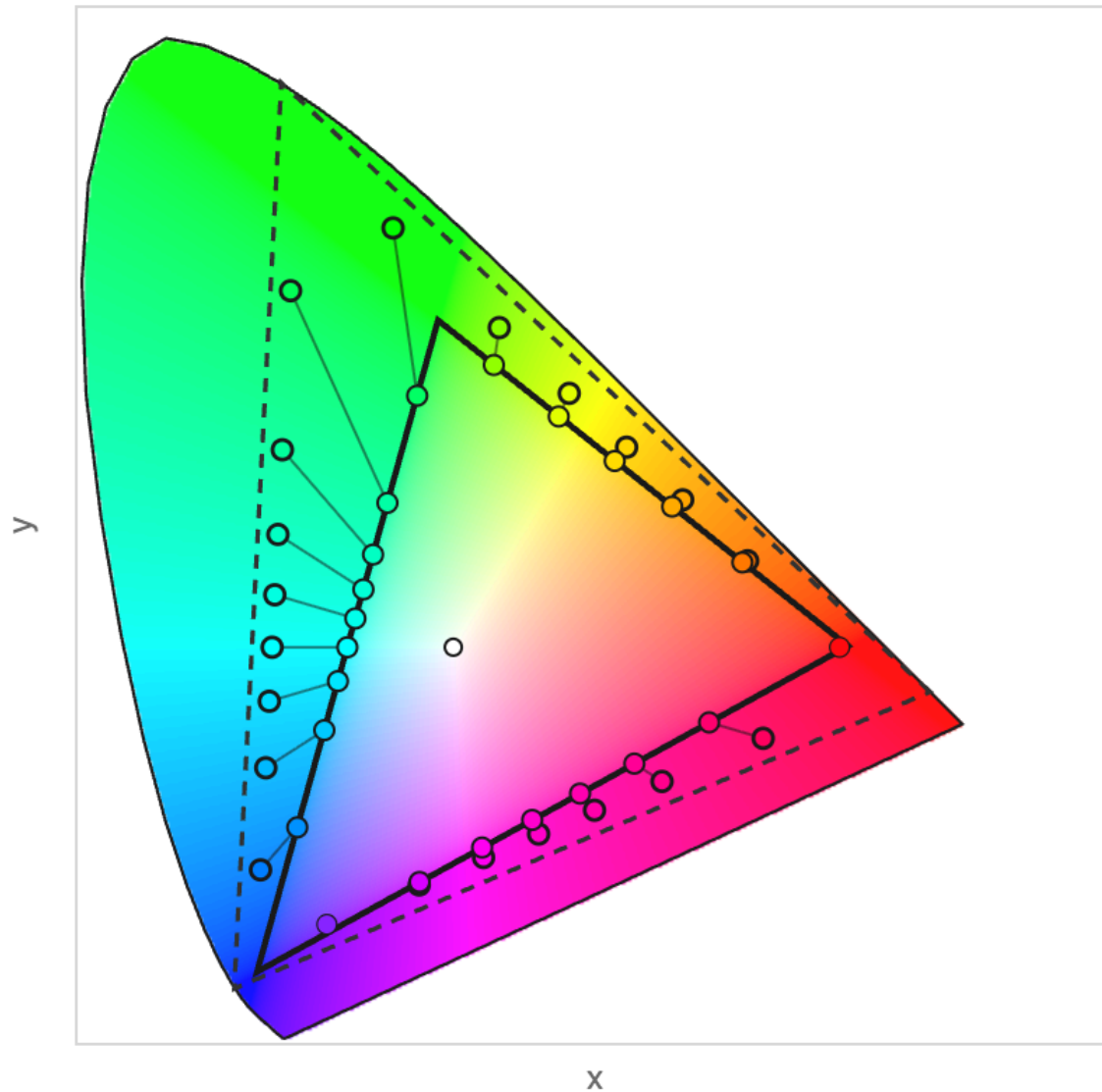
band 587.5–635 nm levels 1.00 / 0.04

cone response



nonnegative LMS alone does not prove physicality

Demo: Gamut mapping



--- source: Rec.2020

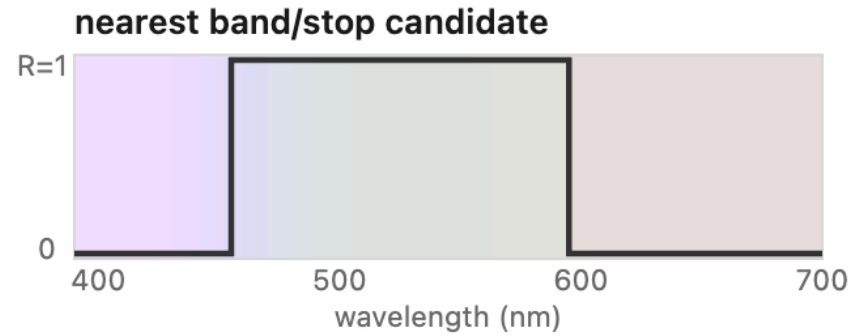
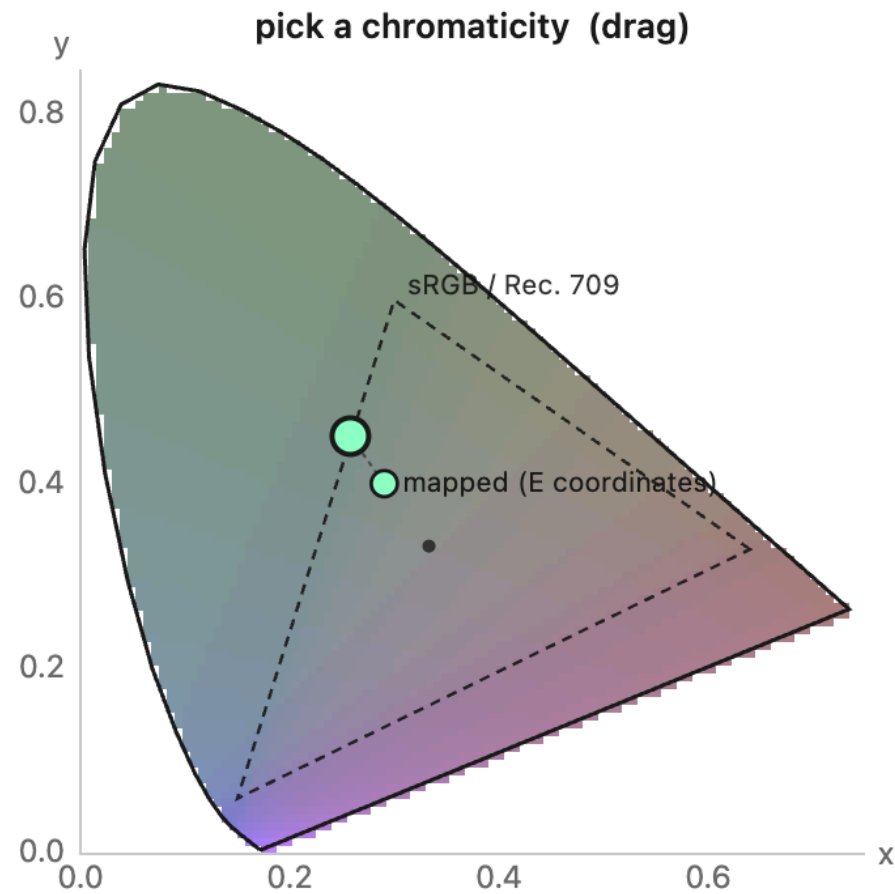
— dest: sRGB

○ out-of-gamut color

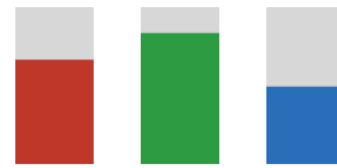
→ where it is mapped

Clip toward white: pull
straight in to white,
keeping xy direction;
hue may shift.

Demo: Optimal reflectance



cone response

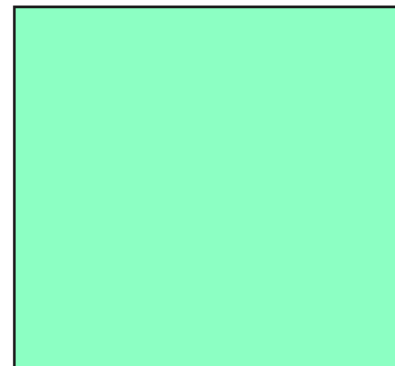


average albedo

44%

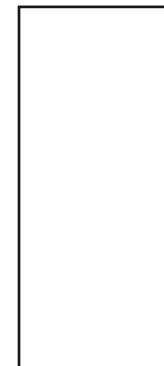
mean reflectance

outside sRGB - mapped, 35% toward neutral
RGB rendition (equal-energy light)



this color

band 455–590 nm



white

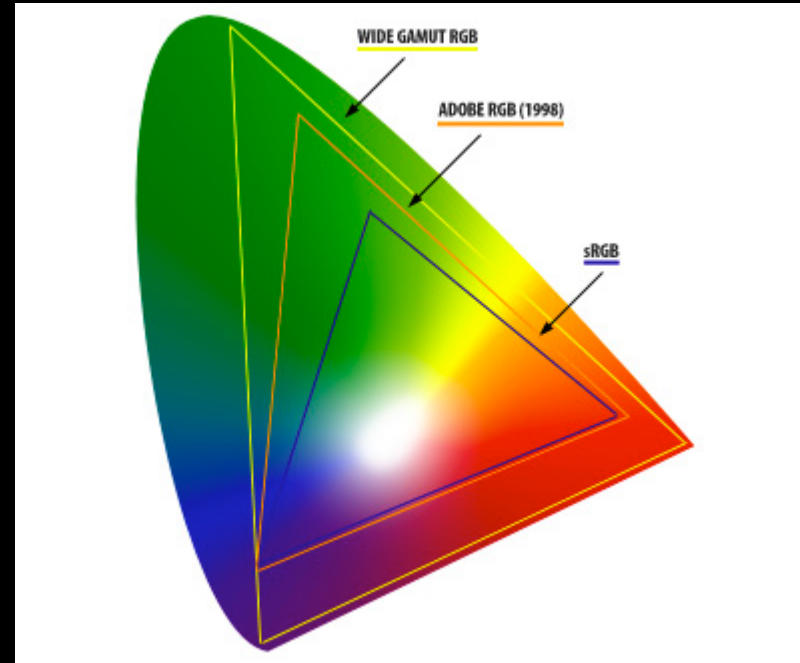
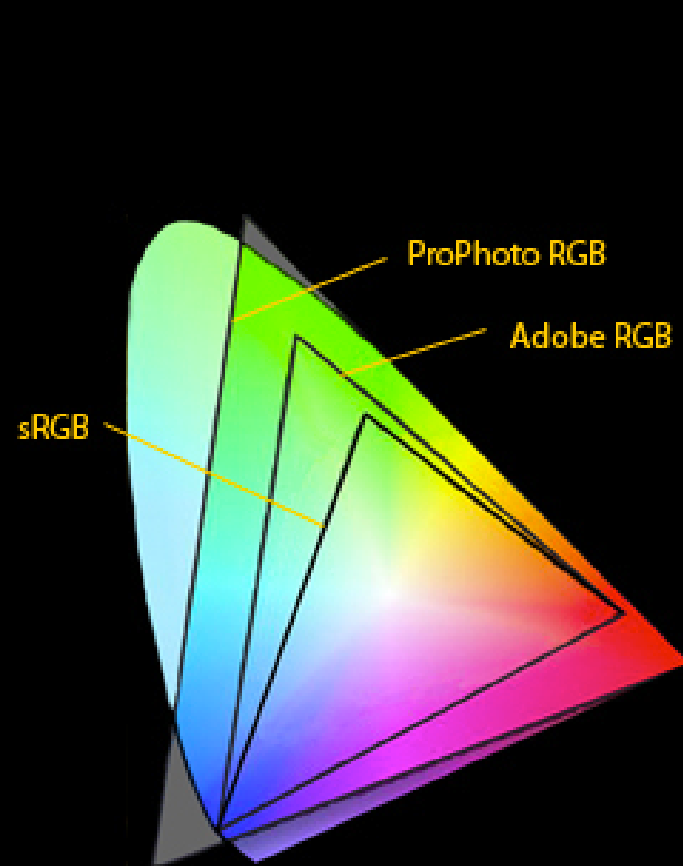
RGB limitations

- [Color Gamut](#) is the range of colors that can be displayed or reproduced by a particular device, such as a monitor or printer.

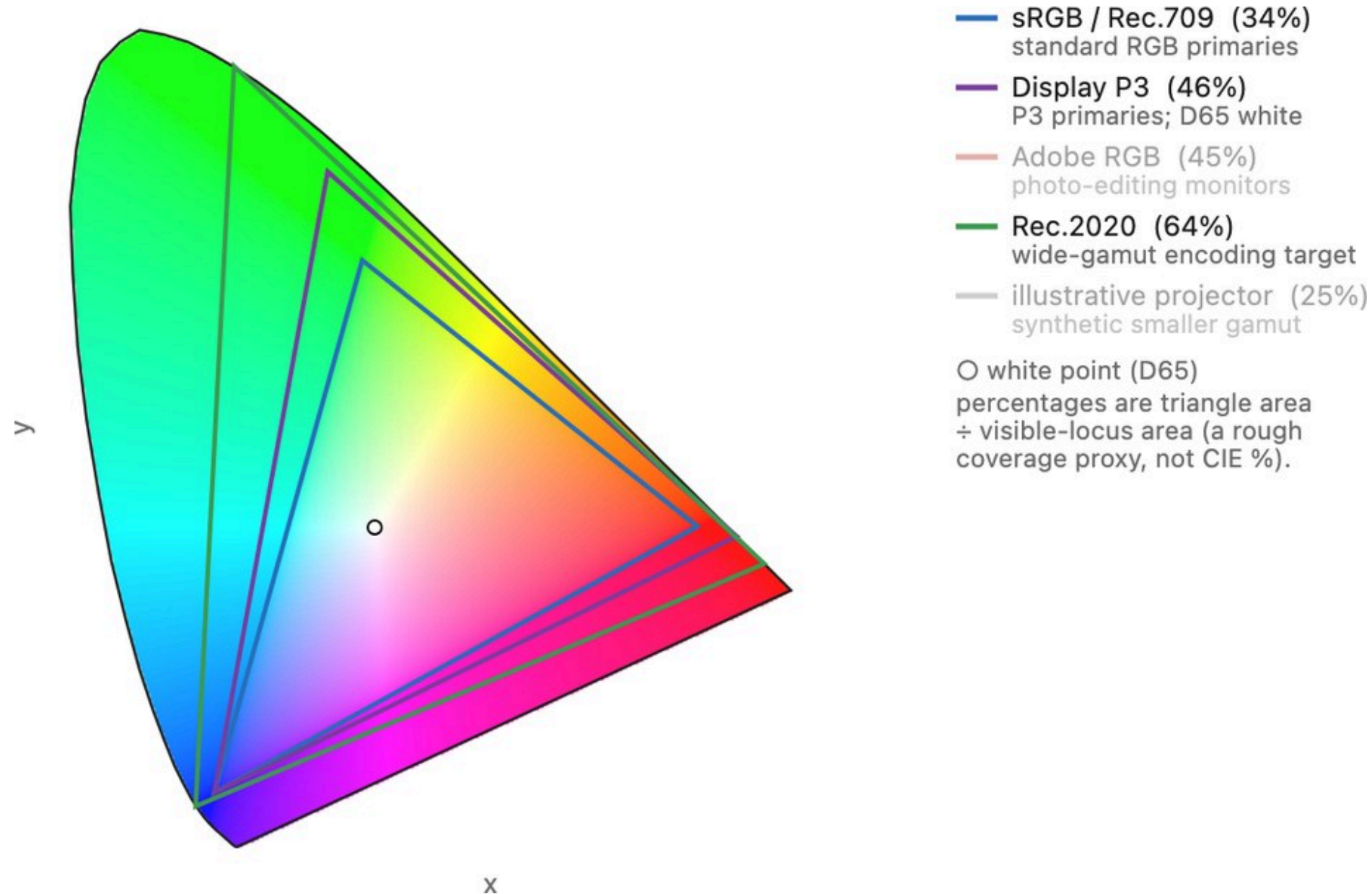
Color Gamut is measured in two ways:

- [Color Volume](#) is the range of colors that can be displayed or reproduced by a particular device, such as a monitor or printer.

Color



Demo: Display gamuts, toggled



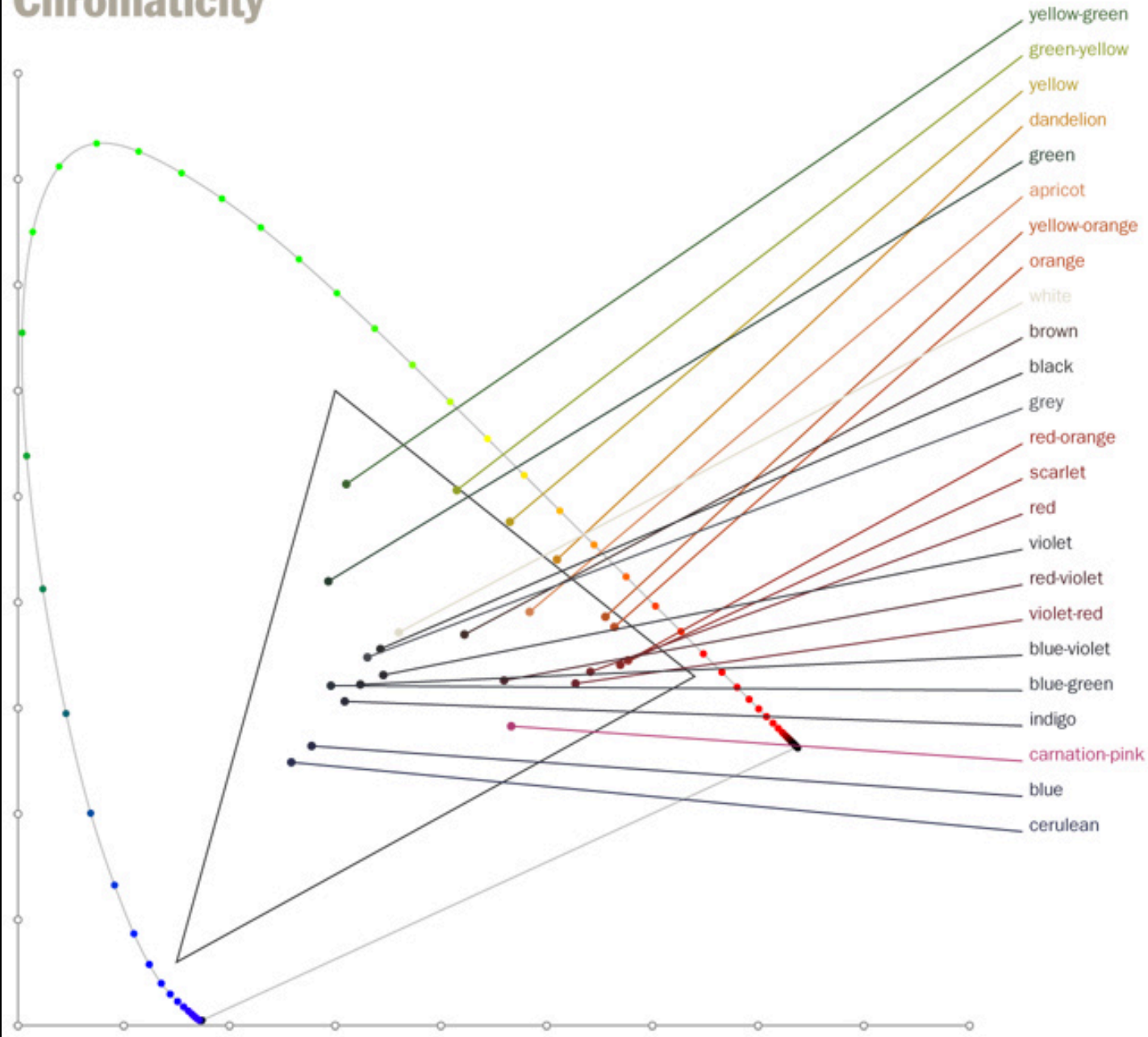
Recap

- Metamers enable color reproduction
- CIE defined XYZ using color matching experiments
- Linear transform to/from RGB or LMS
- Chromaticity diagram: 2D version, remove luminance
- Lack of negative numbers makes life hard

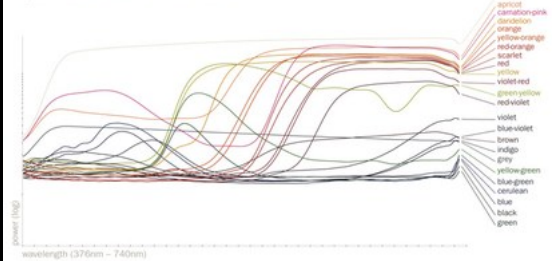
Questions?

- Chromaticity of crayons

Chromaticity

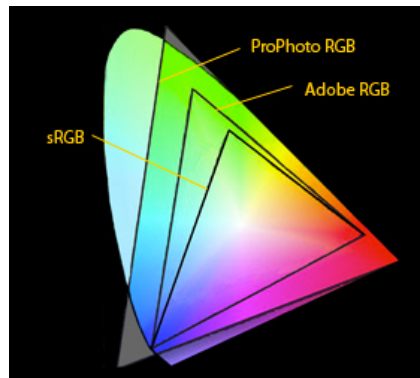


Spectral Power Distribution



Take home message

- Cone spectra are non-orthogonal
- Analysis spectrum (camera, eyes) cannot be the same as synthesis one (display)
- Impossible to encode all possible colors without something negative
 - CIE XYZ only needs positive coordinates, but would need primaries with negative light
 - RGB can use physical (non-negative) primaries, but needs negative coordinates for some colors



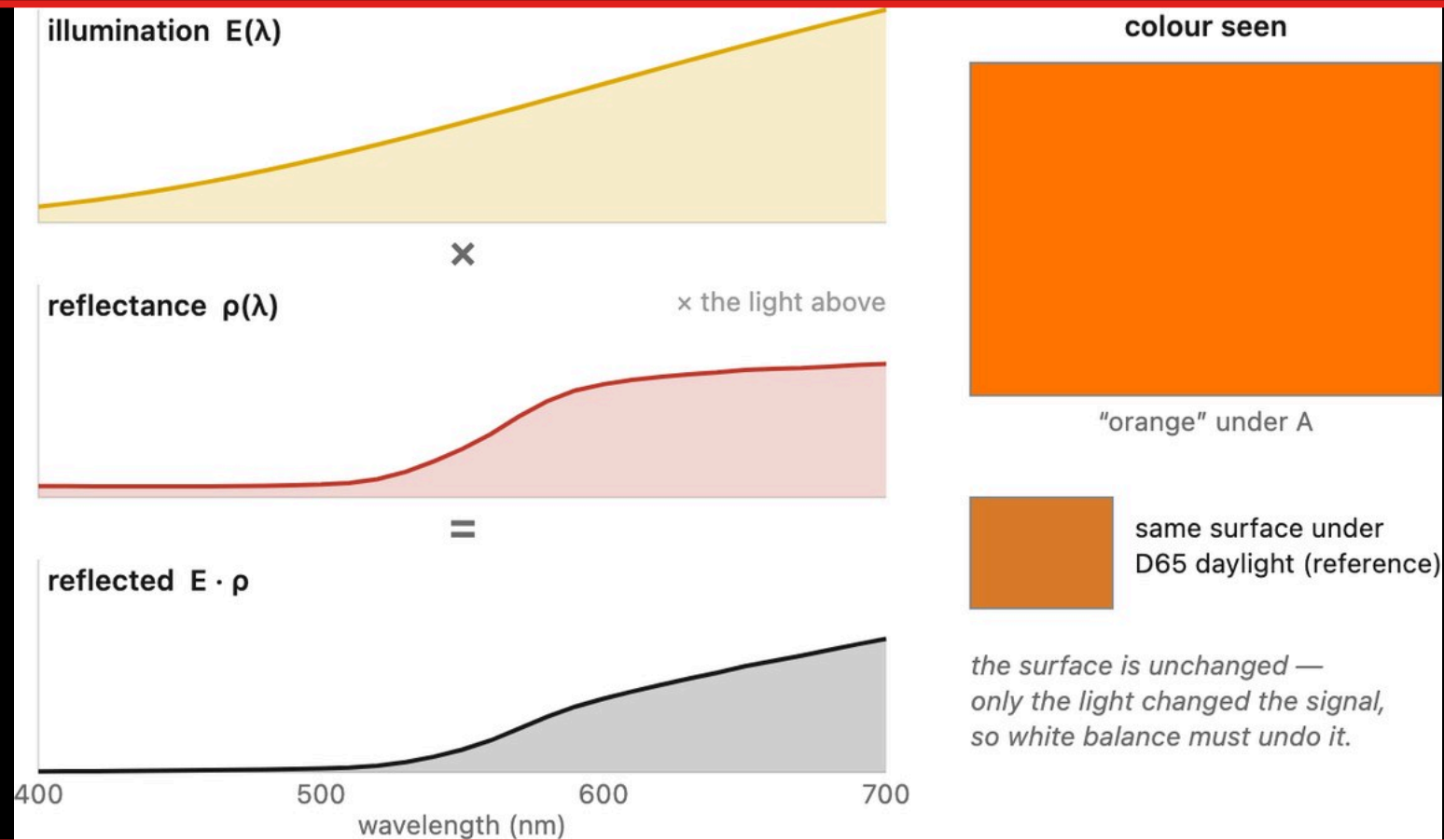


Color TLDR



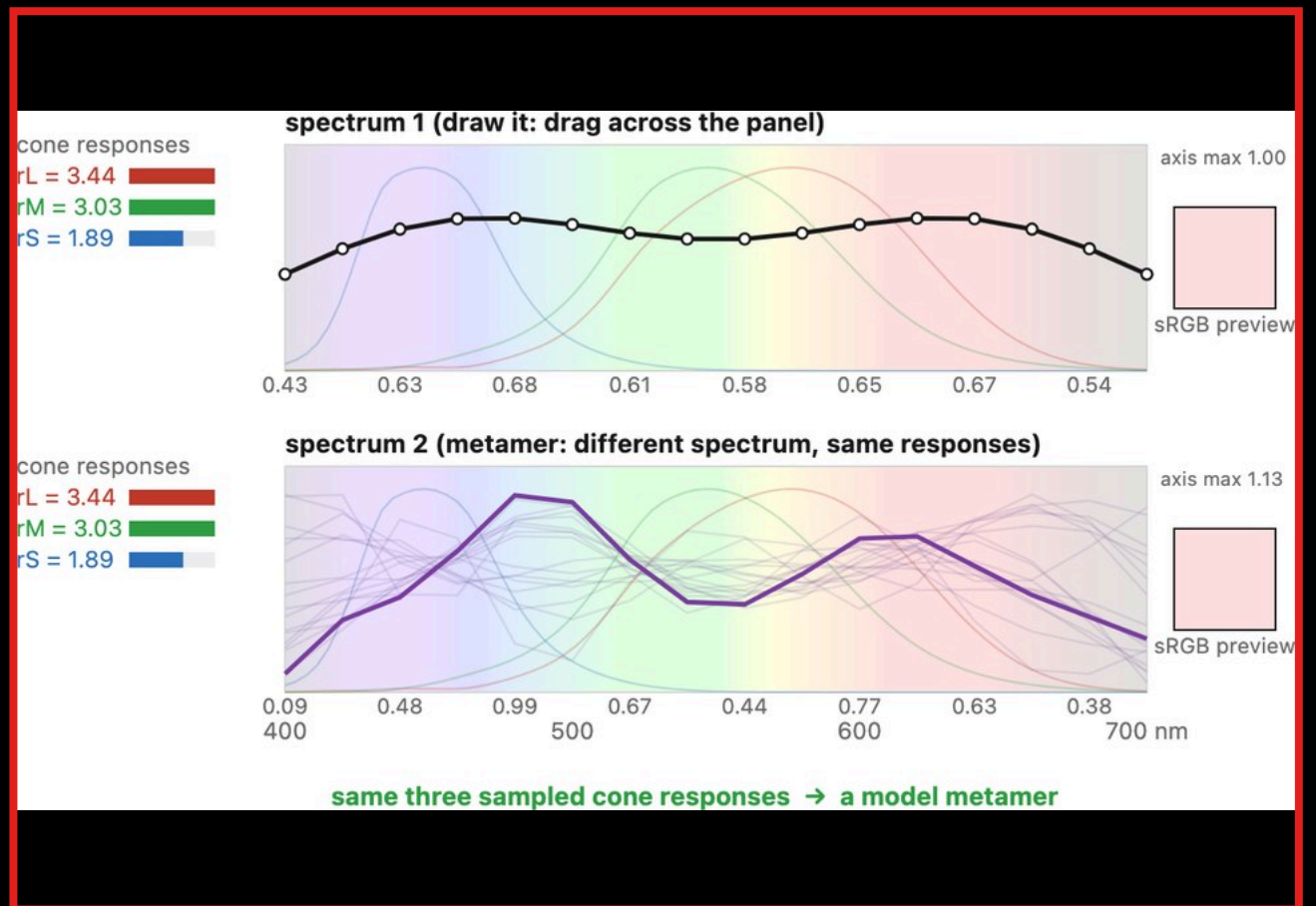
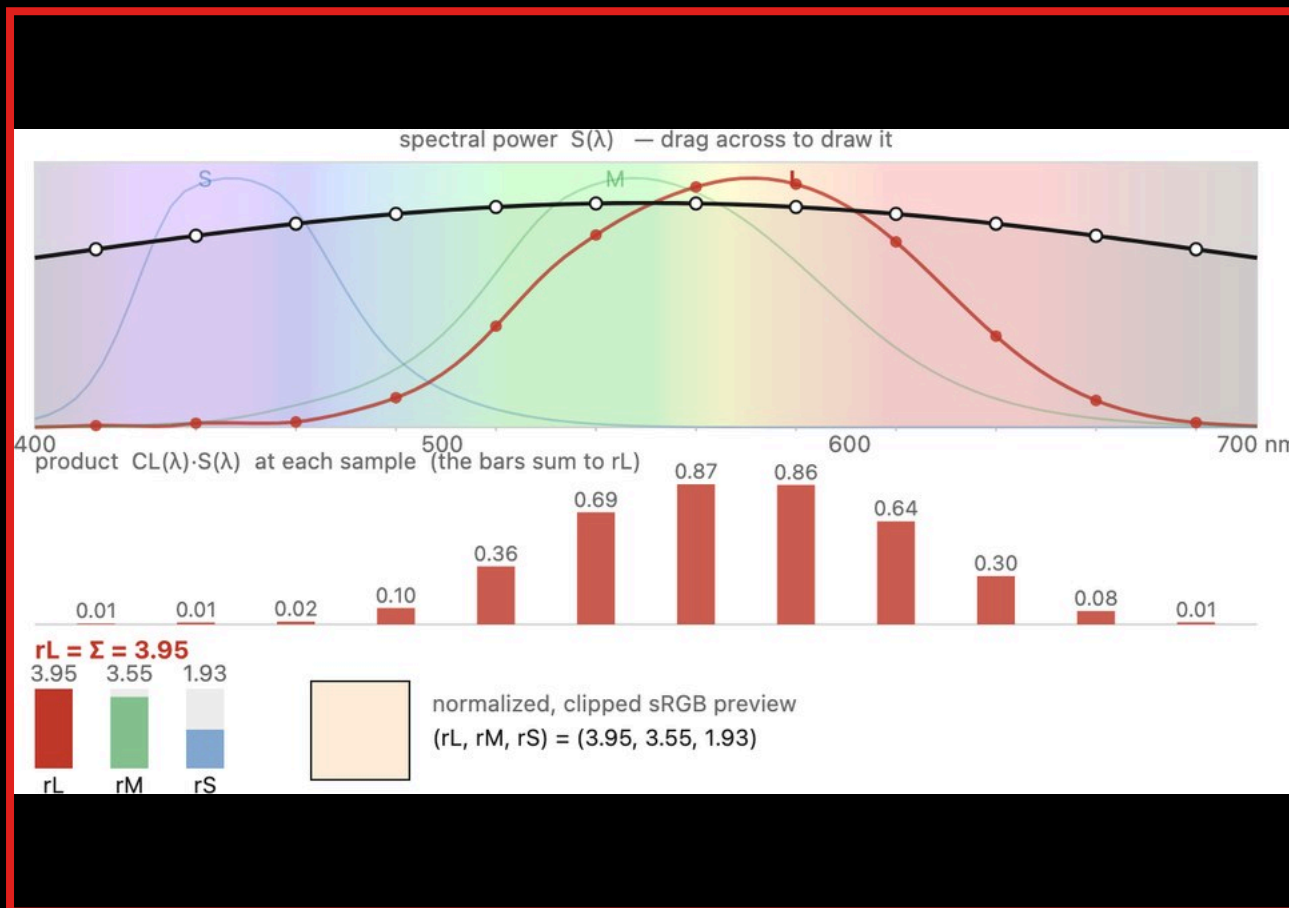
Physical color

- A light is a spectrum: its power at each wavelength.
- A surface returns the illuminant times its reflectance, $C(\lambda) = S(\lambda) \cdot \rho(\lambda)$.
- Change the light and the stimulus changes, though the surface has not.



Cones, LMS, and metamerism

- Each cone integrates the spectrum against its sensitivity: three numbers, L, M, S.
- The curves overlap, so the axes are not orthogonal, and light cannot be negative.
- Different spectra with the same L, M, S are metamers. That is what lets three primaries reproduce color.



Light and chromatic adaptation

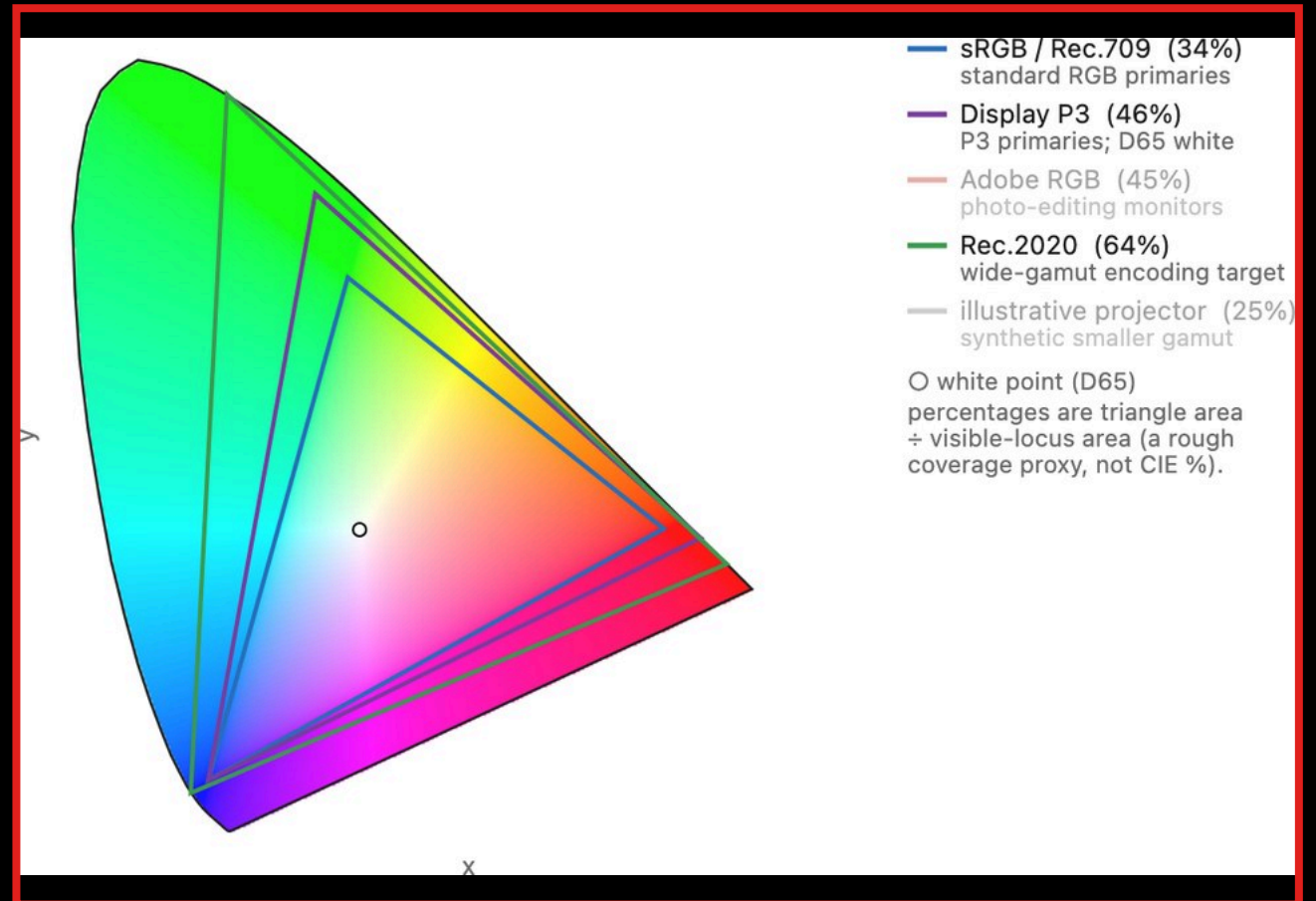
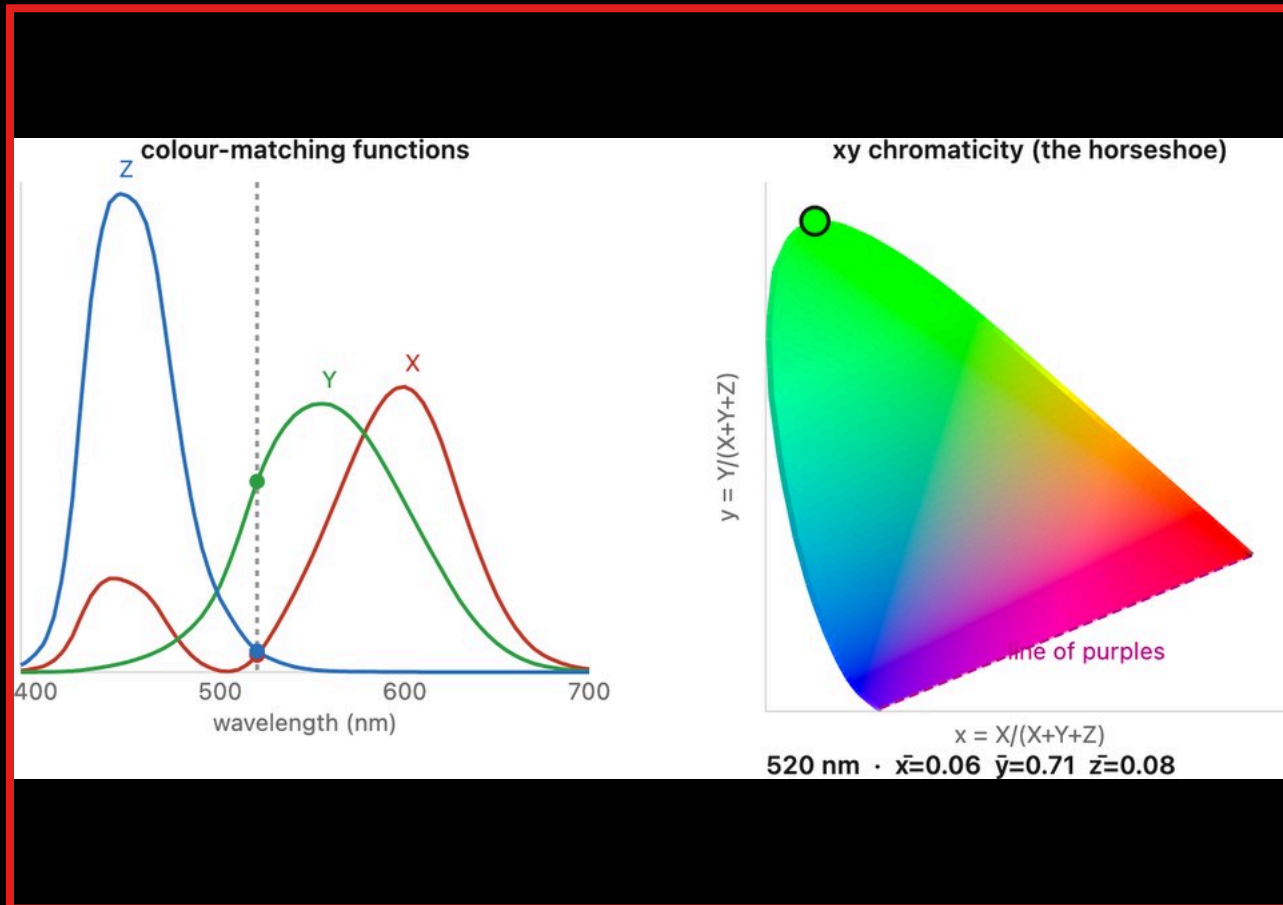
- Vision is after the surface, not the light, so it divides the illuminant out.
- Light adaptation rescales to the overall level of the scene.
- Chromatic adaptation scales each cone's gain toward the color of the light (von Kries).
- Both are multiplicative, which is why vision is largely invariant to multiplication.

XYZ

- The standard coordinates everyone converts through, one 3×3 matrix away from LMS.
- Built from color-matching experiments, before cone responses could be measured.
- Y is luminance. X and Z are otherwise arbitrary.

Chromaticity and gamut

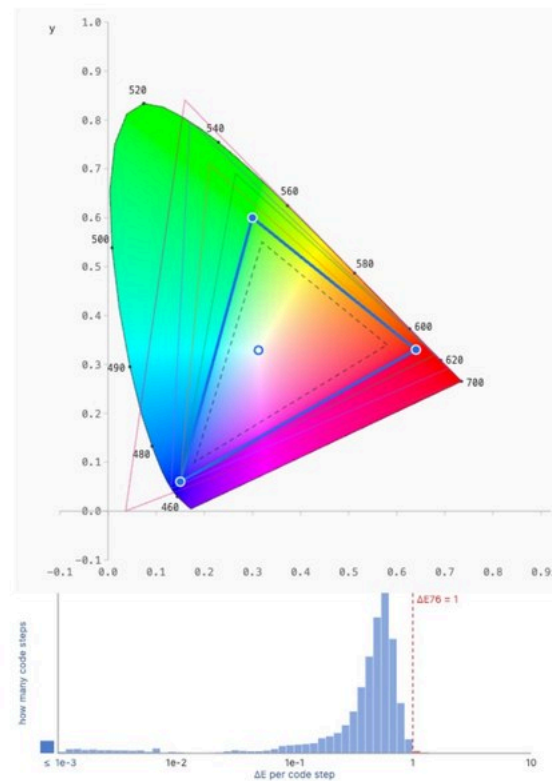
- Divide XYZ by $X + Y + Z$ to drop brightness: the 2-D chromaticity diagram.
- Real colors fill a horseshoe, with single wavelengths on its edge.
- A device's primaries span a triangle inside it, its gamut. Colors outside must be mapped in.



Linear RGB, and why there are many

- sRGB, Adobe RGB, Display P3, Rec.2020, ProPhoto: each is one 3×3 matrix from XYZ.
- They differ in their primaries, so in gamut, and in how thinly they spread a bit budget.

Color spaces: sRGB primaries, 8 bits, pure power 2.2

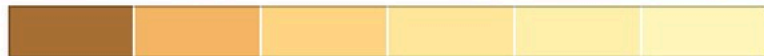


Quantization uses a pure-power model, not the specified sRGB transfer function. The plotted threshold is $\Delta E_{76} = 1$, a rough visibility proxy. Actual 8-bit sRGB code 1 to white spans about 11.7 stops.

White balance and white point

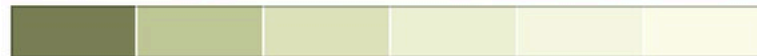
- White balance corrects the data for the color of the scene's light: one gain per channel.
- The white point is the neutral a color space is defined against (D65, D50).
- Two different whites.

as shot, under tungsten (CIE A, 2856 K)



a neutral wedge, as shot

with your gains



the same wedge, corrected: gray means you are there

off by 0.68 stops on the worst cone

your gains L 0.89 M 1.06 S 1.90 the answer L 0.89 M 1.06 S 3.04

a camera would call this 3050 K, tint -34

click either picture on something that ought to be gray, and it will be

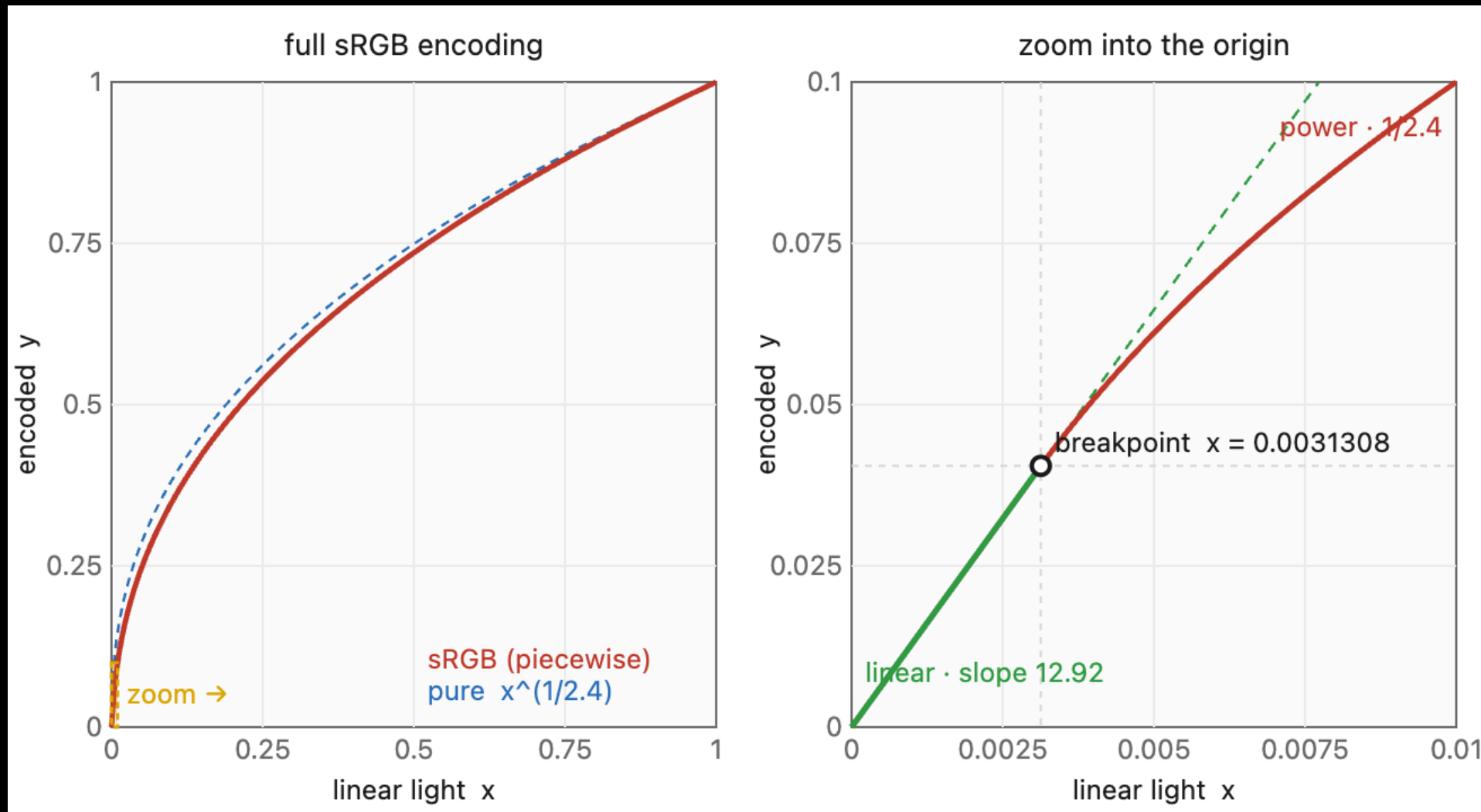
Gamma is for encoding (and doesn't hurt processing much)

- A power curve puts code values where the eye can use them, so 8 bits look smooth.
- Its job is storage. Steps come out roughly perceptual, which rarely hurts processing.
- Gamma is not log, and "gamma correction" is a misnomer.



sRGB

- The default for JPEG, PNG and the web, and what to assume for a file with no profile.
- Rec. 709 primaries, a D65 white, stored through a piecewise curve near 2.2.
- Its numbers are code, not light: decode before any light math.



RAW files

- Scene-linear sensor readings before any tone curve: the place for physical work such as HDR, denoising and white balance.
- Camera filters only approximate the cones, so no 3×3 matrix maps camera RGB exactly to XYZ.
- Each camera model gets a fitted color-correction matrix, which is why two cameras render a scene a little differently.

Log is for high dynamic range, video, and some processing

- Equal steps are equal ratios, stops, so a change of light becomes a shift.
- The working space for HDR tone mapping, and what video cameras record (S-Log, Log-C, V-Log).
- Guard against zero: $\log 0$ is minus infinity.

Opponent (luma-chroma) spaces

- The eye recodes the cones into one luminance and two opponent color channels, a linear map.
- YCbCr applies its matrix after gamma, so it gives luma, not luminance.
- Fine for storage and compression, which is why JPEG uses it. Be careful with it for serious processing.

Demo: Blur the chroma, not the luma

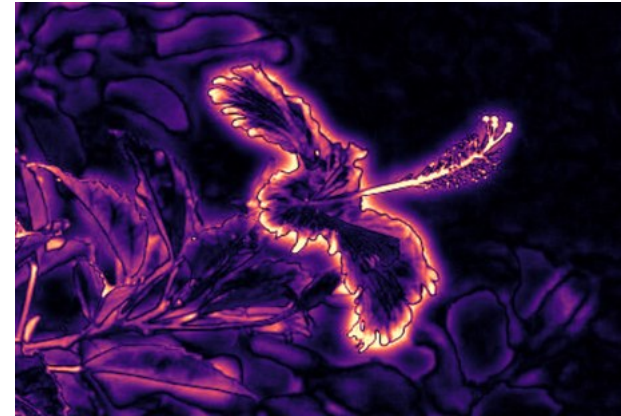
original



chroma blurred ($\sigma=7$), luma untouched



|difference| $\times 6$



luma Y' (kept sharp)



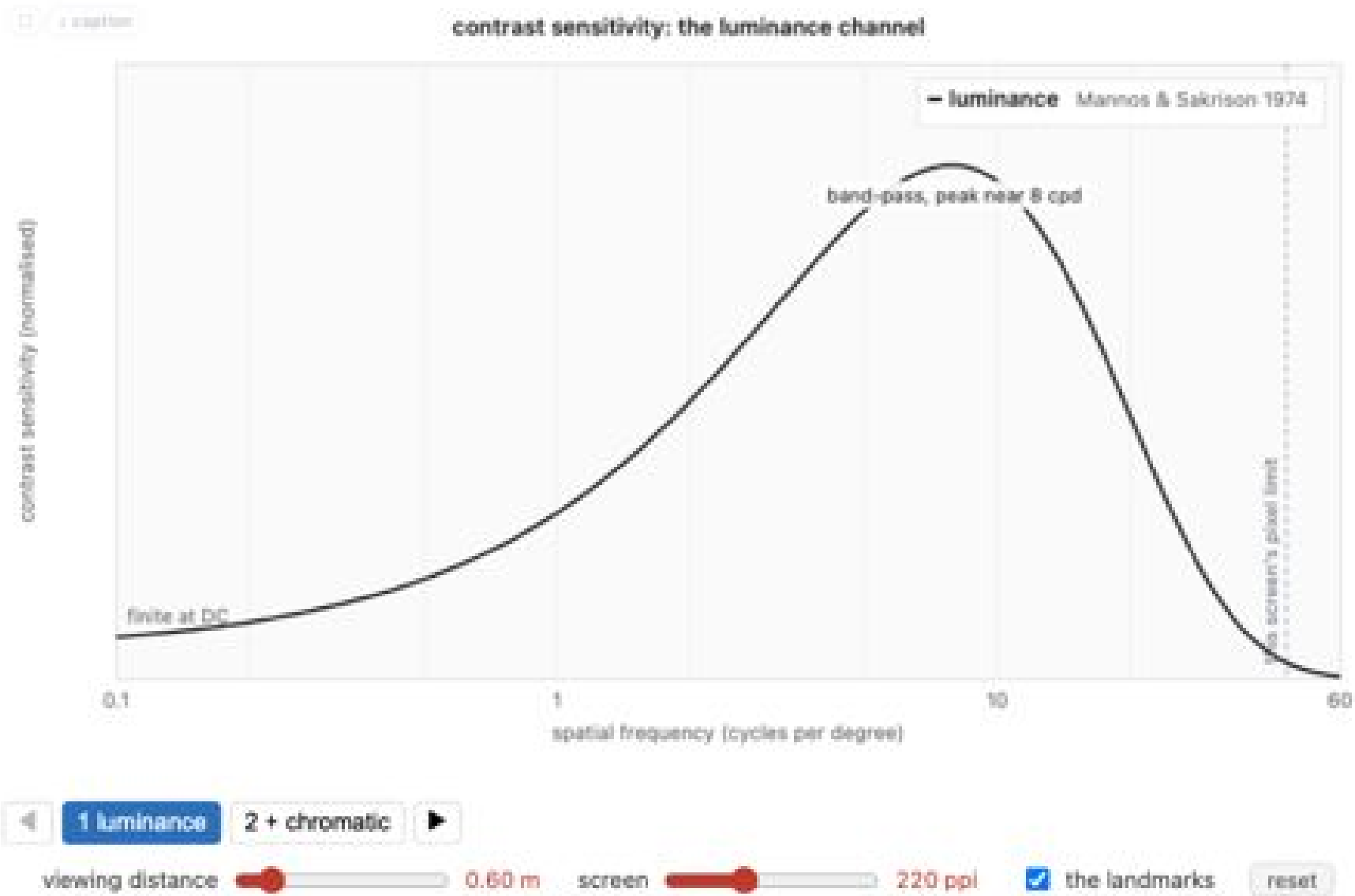
chroma (original)



chroma (blurred $\sigma=7$)

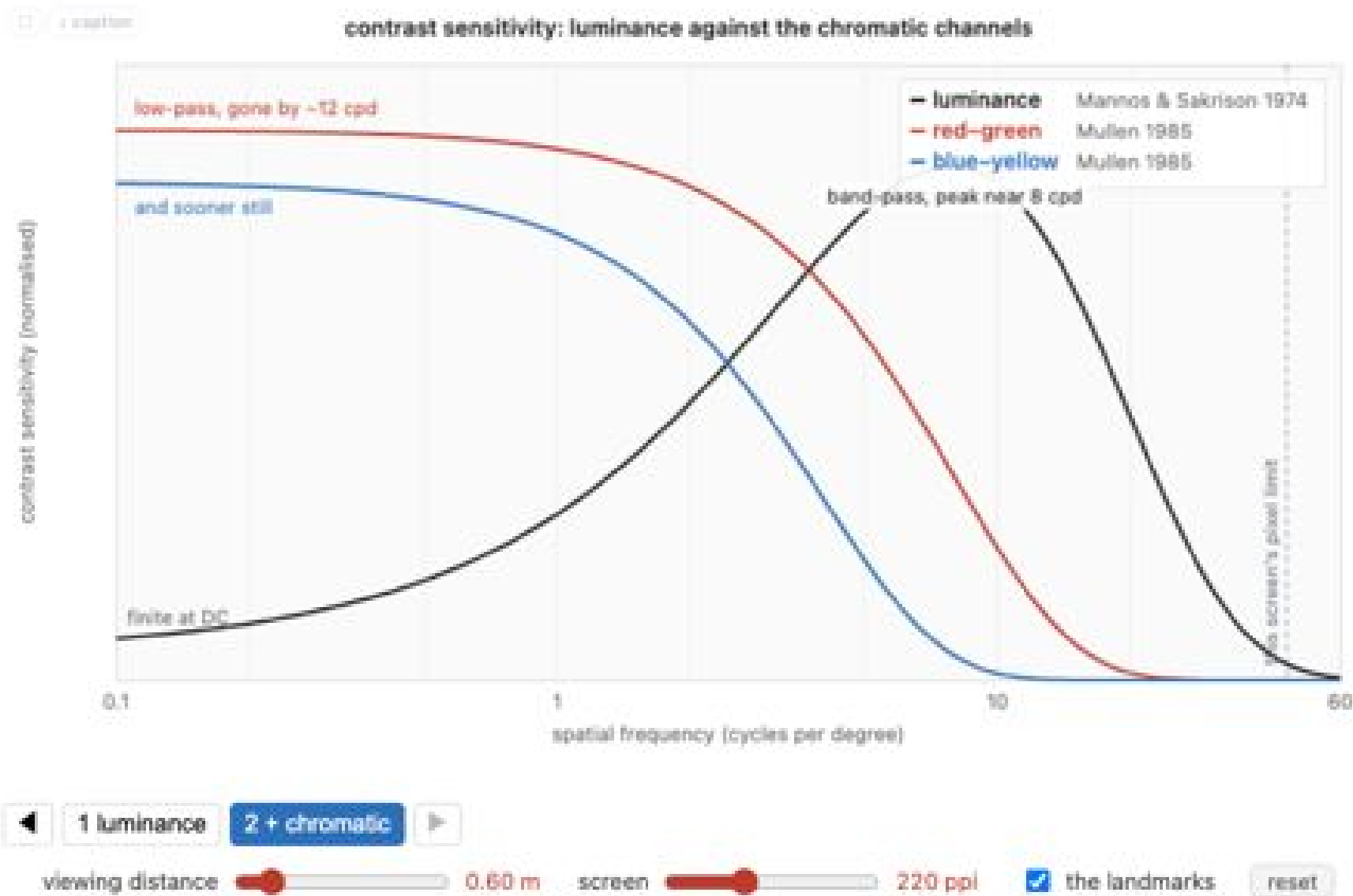


Demo: Contrast sensitivity, luminance and colour: luminance



Demo courtesy of Frédo Durand, MIT.

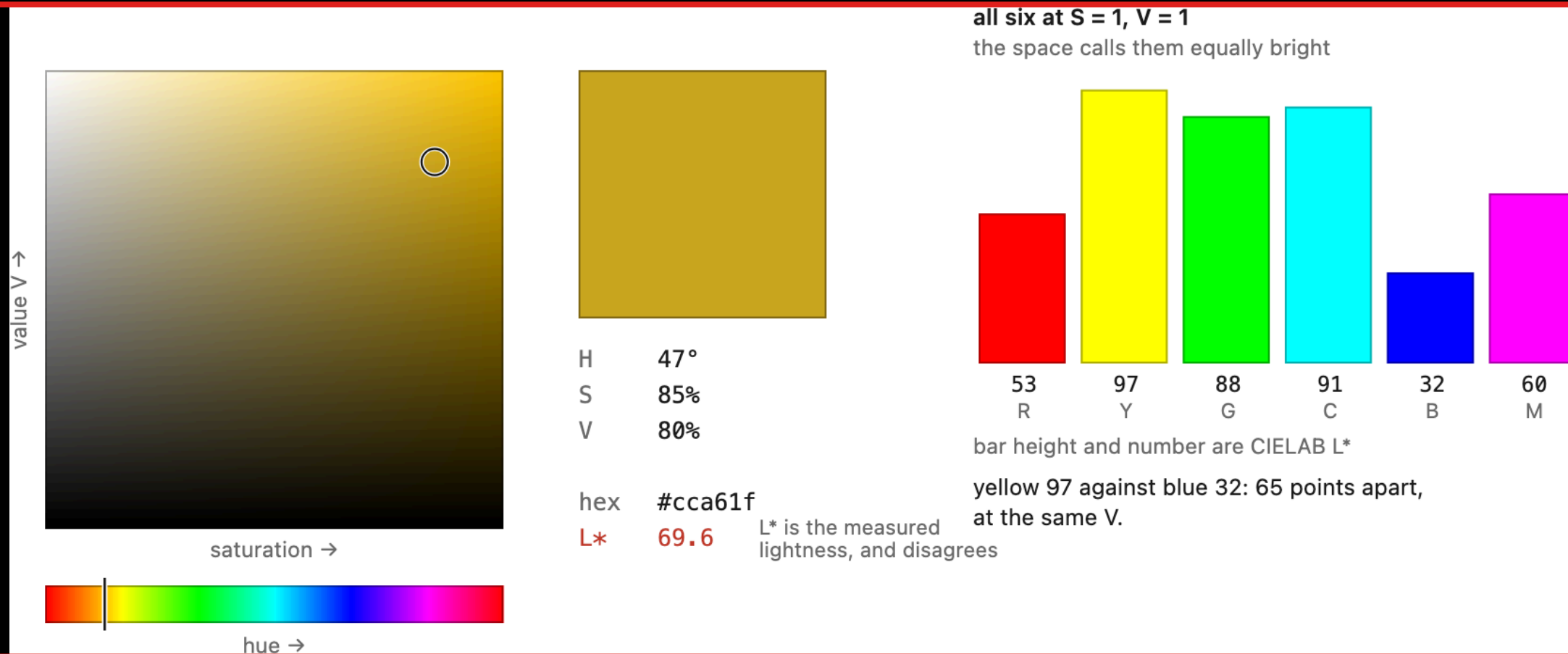
Demo: Contrast sensitivity, luminance and colour: + chromatic



Demo courtesy of Frédo Durand, MIT.

HSV is for UI

- Hue, saturation and value by simple arithmetic on encoded RGB.
- Good for picking colors, misleading for anything quantitative.
- For controls that behave perceptually, use OKLCH (or CIELCh, HSLuv).

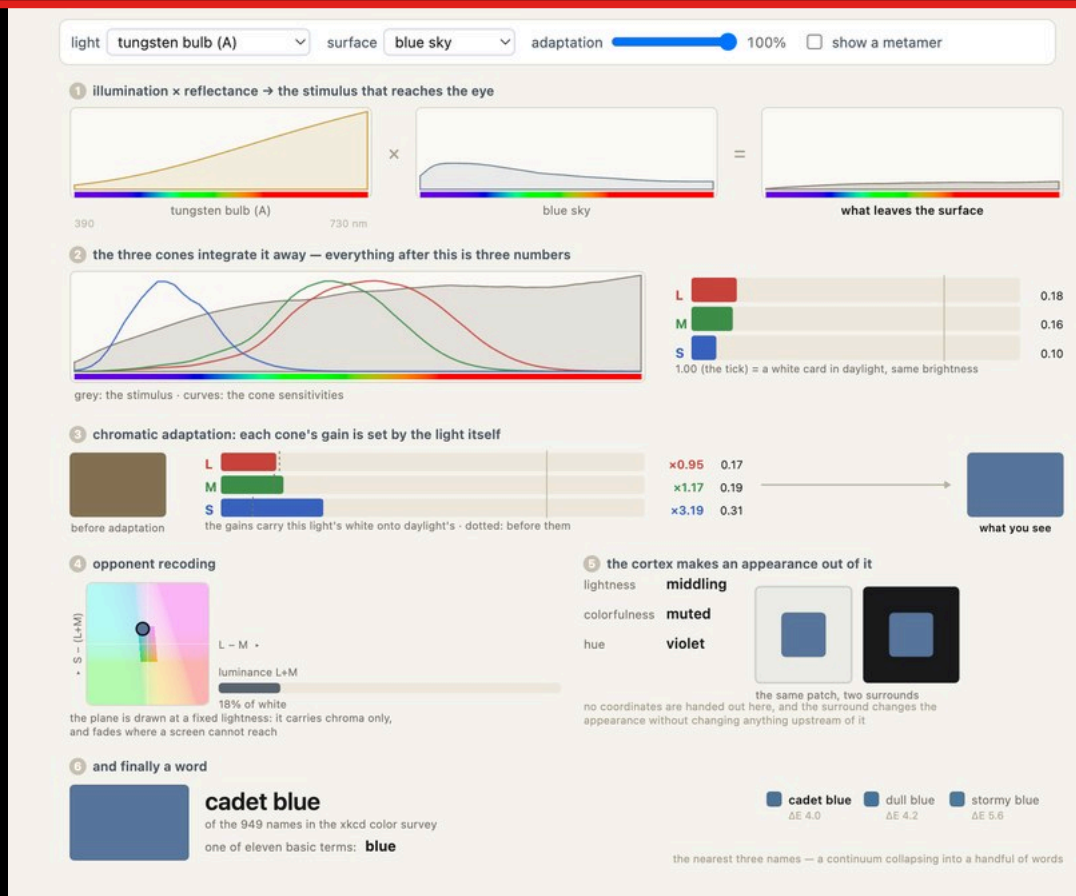


Perceptually uniform spaces are for differences

- CIELAB and Oklab warp color so that equal distances look equally different.
- Use them to measure a difference, set a tolerance, draw an even gradient or map a gamut.
- Chong's log space is close to uniform and also invariant to the illuminant.

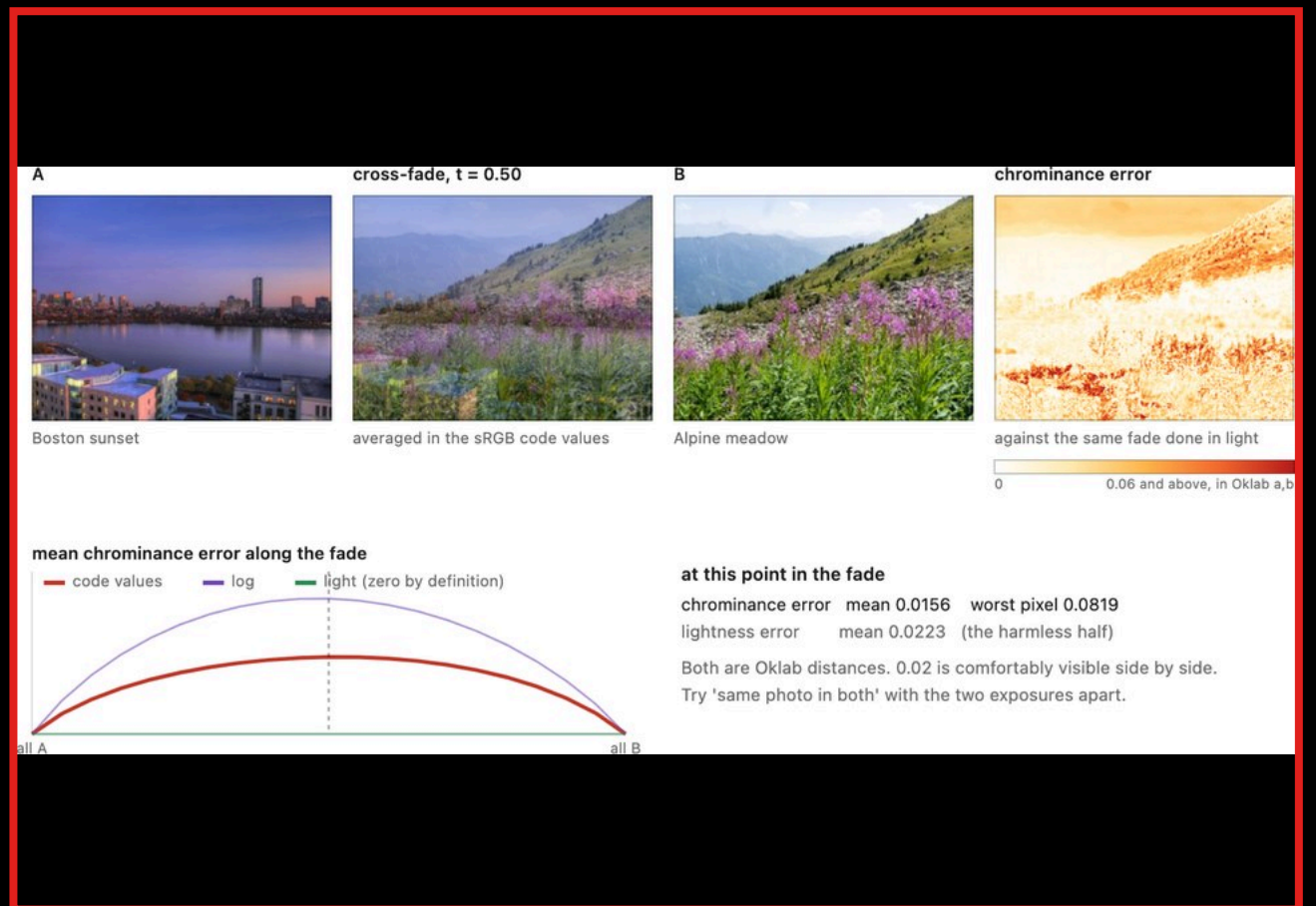
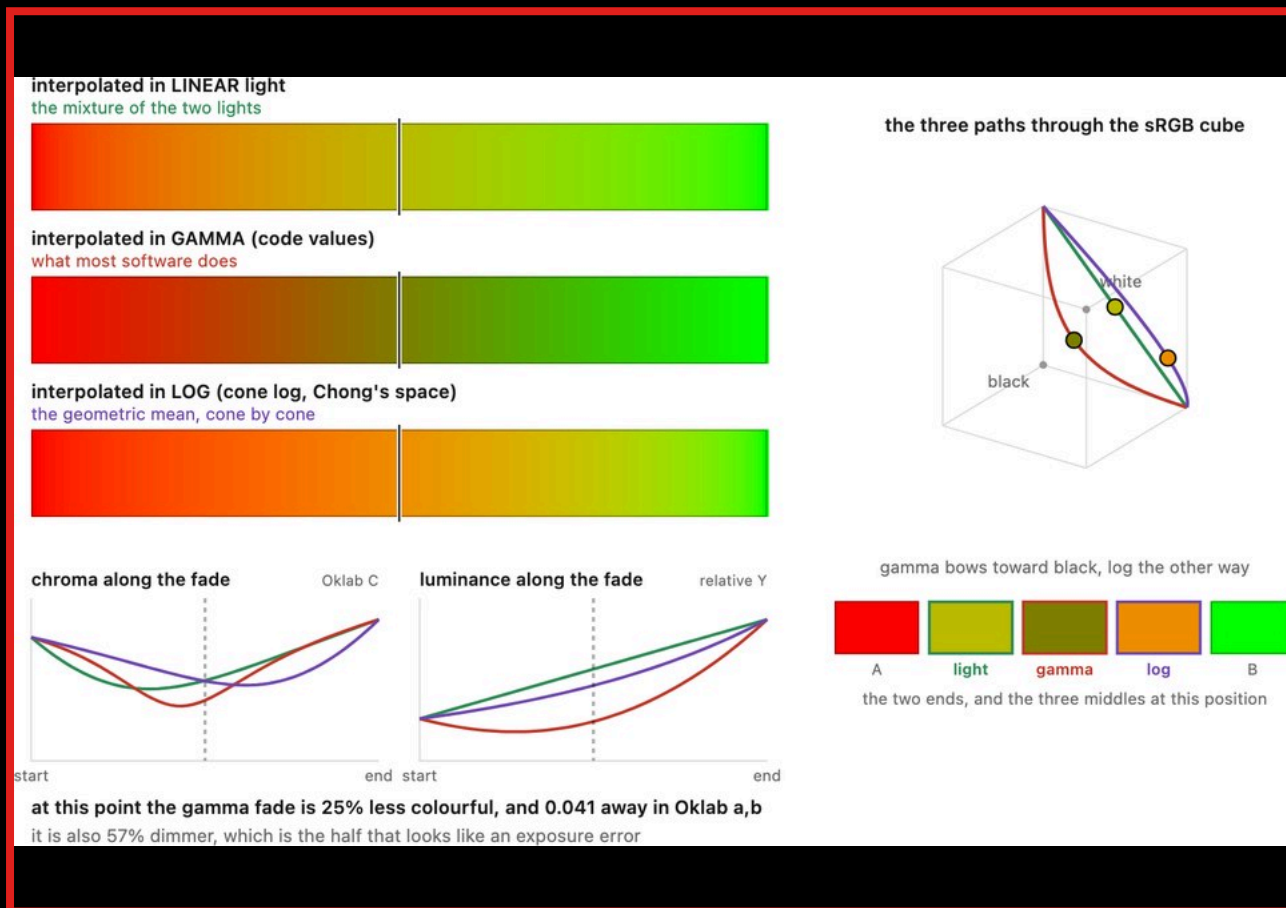
The full chain: from physical color to perceptual color to color names and memory

- Illumination times reflectance, then three cone numbers, then von Kries gains.
- Opponent recoding in the retina, then appearance and constancy in the cortex.
- Finally names and memory: about eleven basic color terms, and remembered colors more saturated than real ones.



Color and encoding in the real world

- Camera ISPs, HDR and deblurring code, and renderers work in linear light because their math demands it.
- PyTorch and OpenCV leave the encoding to the caller.
- Averaging gamma-coded colors makes colors that are in neither end.



What color space and encoding to do what?

- Physical light, blur, resize, compositing: linear.
- Raw processing (demosaic, white balance, color correction, denoising): camera-linear.
- Compression and video: YCbCr or ICtCp.
- High range (HDR, tone mapping, grading): scene-linear or log.
- Perceptual work (differences, gradients, gamut mapping, hue edits): Oklab or CIELAB.
- Display and delivery: sRGB, Display P3, PQ or HLG, tagged.
- When in doubt: sRGB.

Demo: One light to one word

Speaker notes

