

# Color

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**DSC 106: Data Visualization**

Sam Lau

UC San Diego

# Announcements

Lab 3 due today

Project 2 checkpoint due on Tuesday

## FAQs:

1. When will Project 1 be graded? Aiming for Tuesday!

# Modeling Color Perception

Low-Level

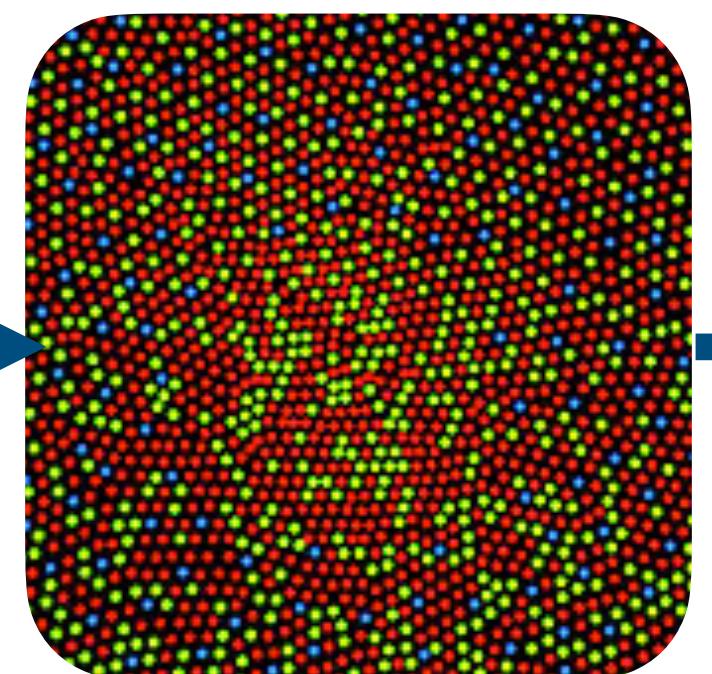
High-Level

Physical World

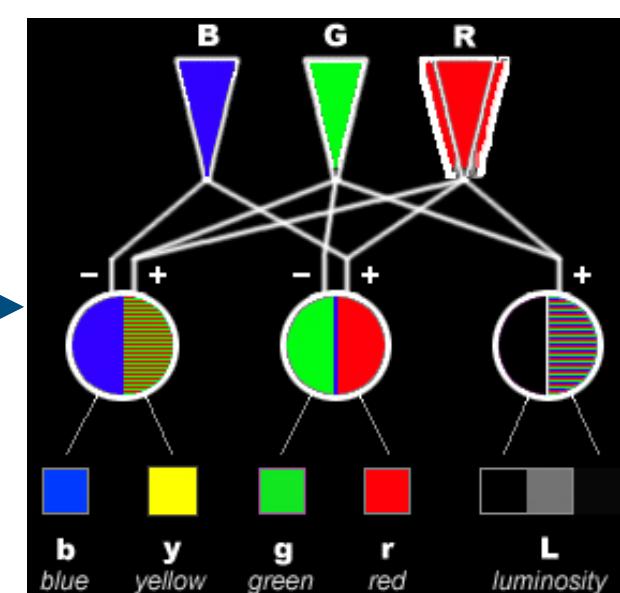


Visible Light

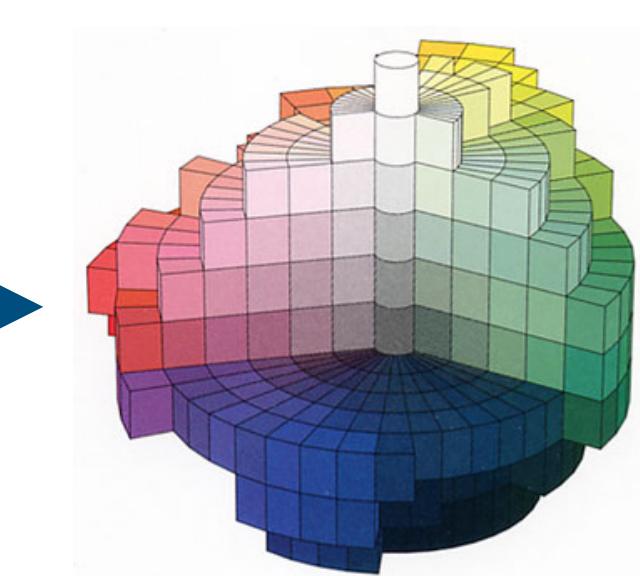
Visual System



Cone Response



Opponent Encoding



Perceptual Models

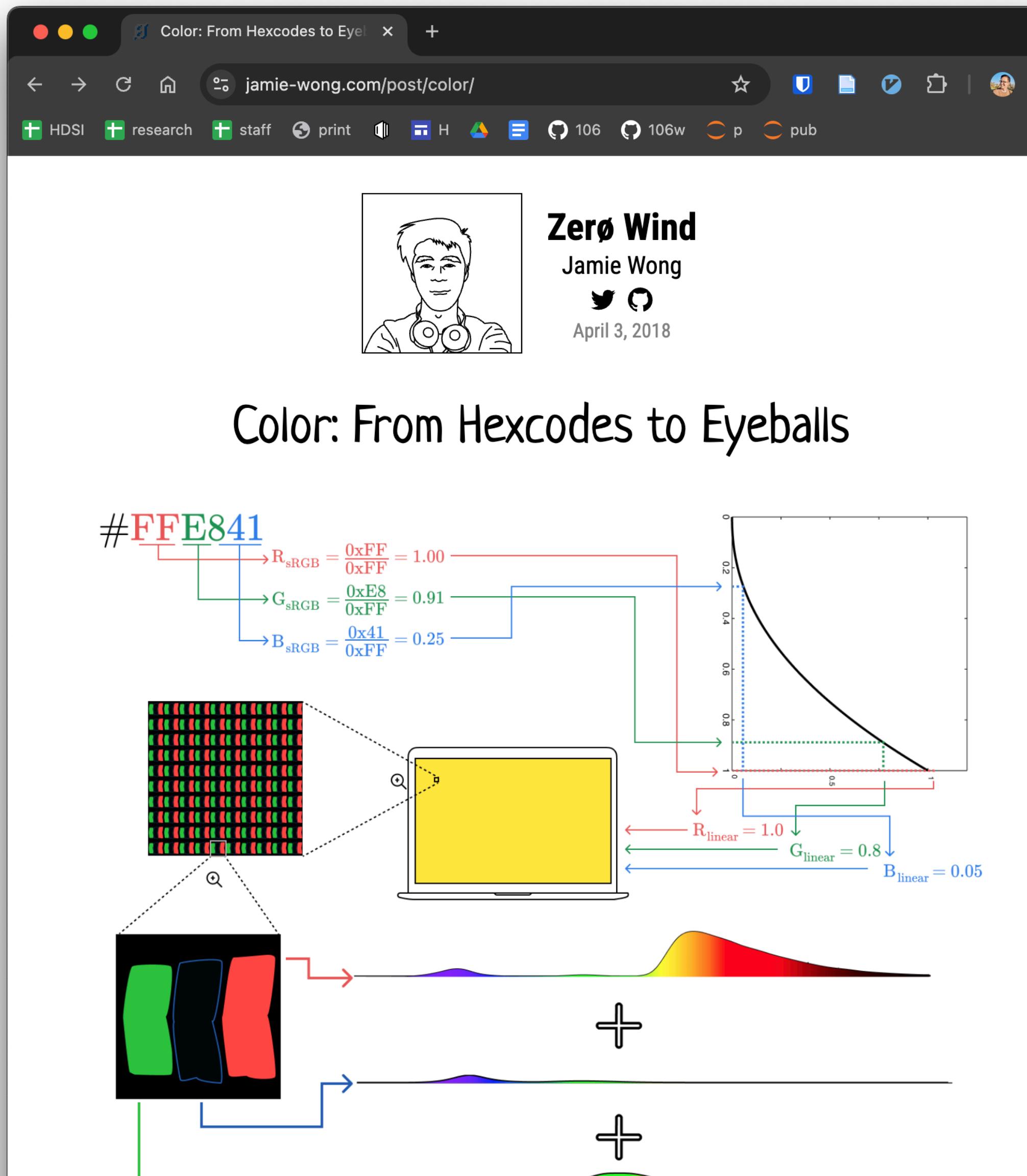


Appearance Models

“Teal”

Cognitive Models

# Credit to Jamie Wong for many the images



See his blog post for more details:  
<https://jamie-wong.com/post/color/>

# Modeling Color Perception

Low-Level

Abstraction

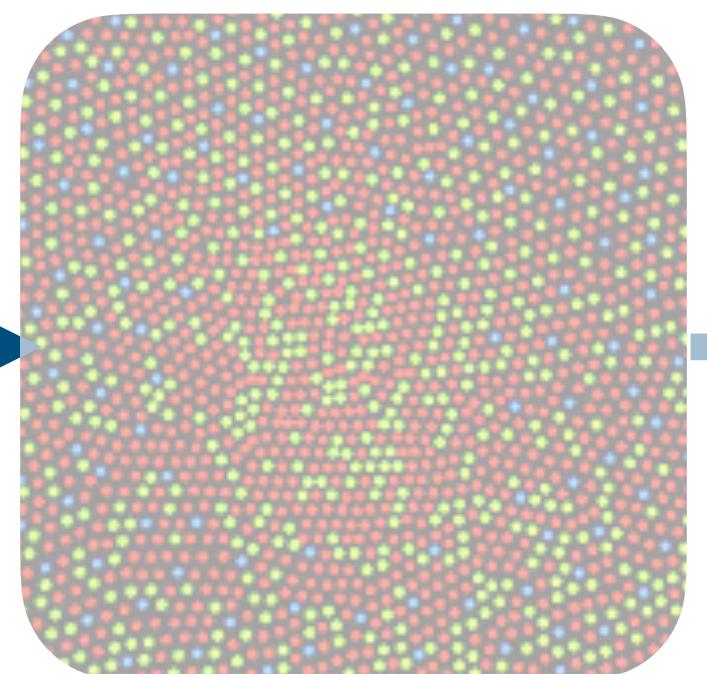
High-Level

Physical World

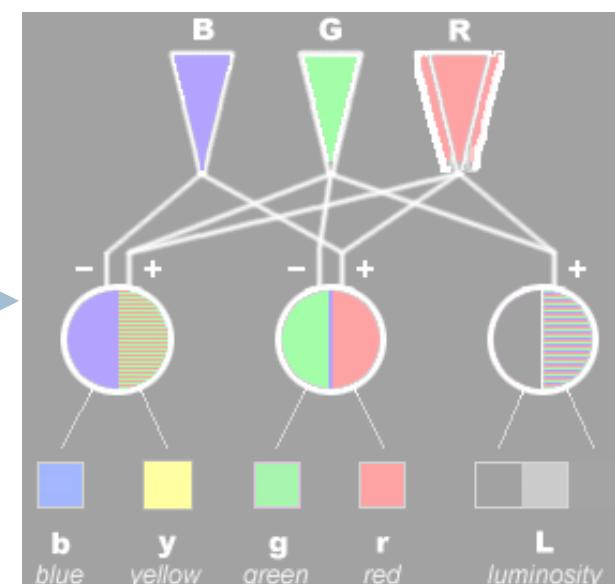


Visible Light

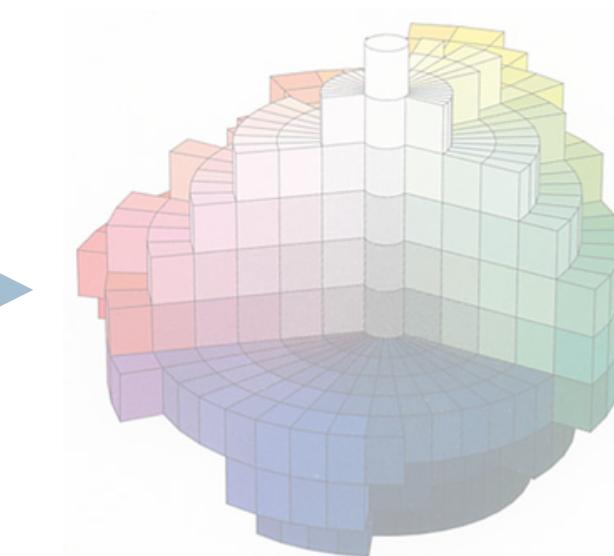
Visual System



Cone Response



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Perceptual Models



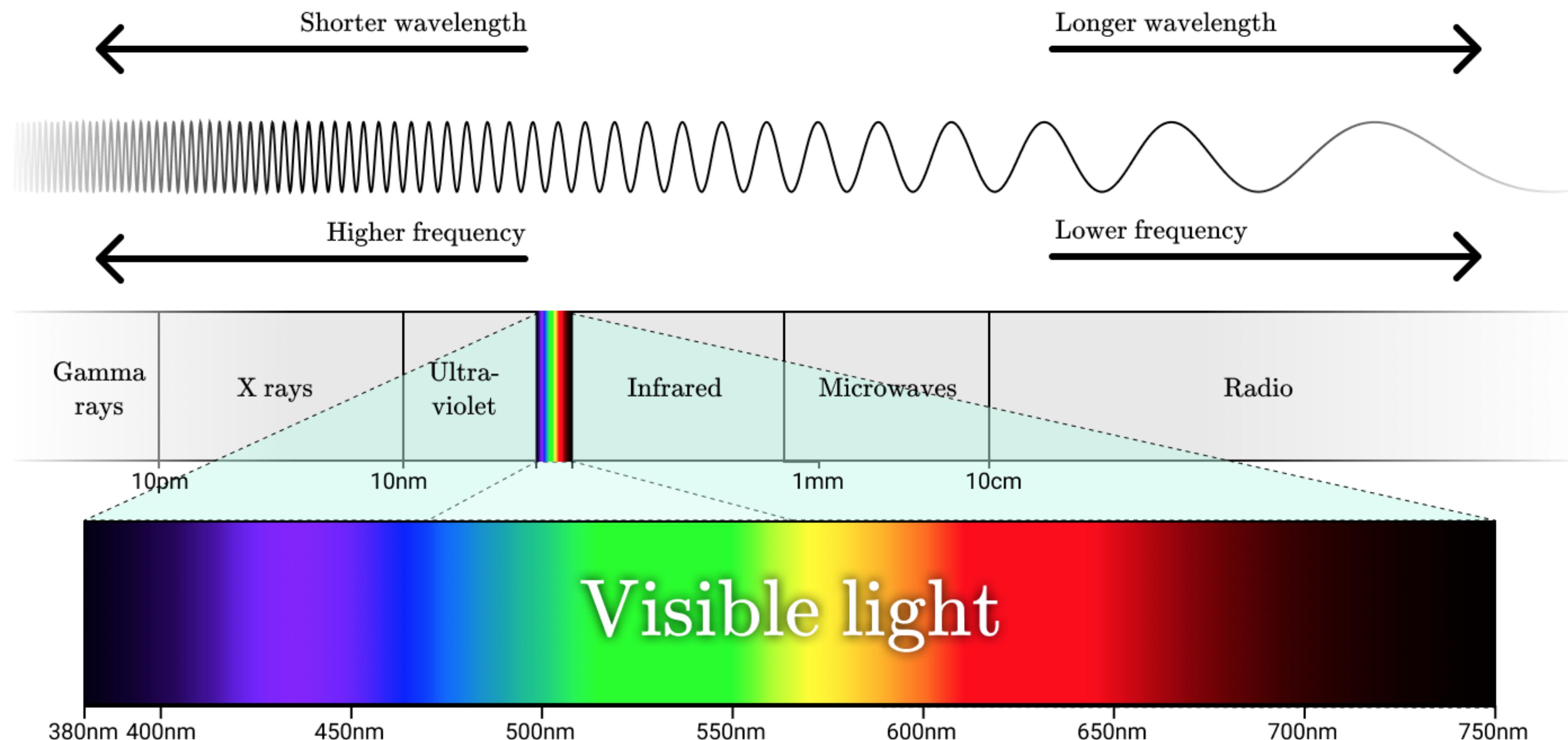
Appearance Models

“Teal”

Cognitive Models

# Visible Light

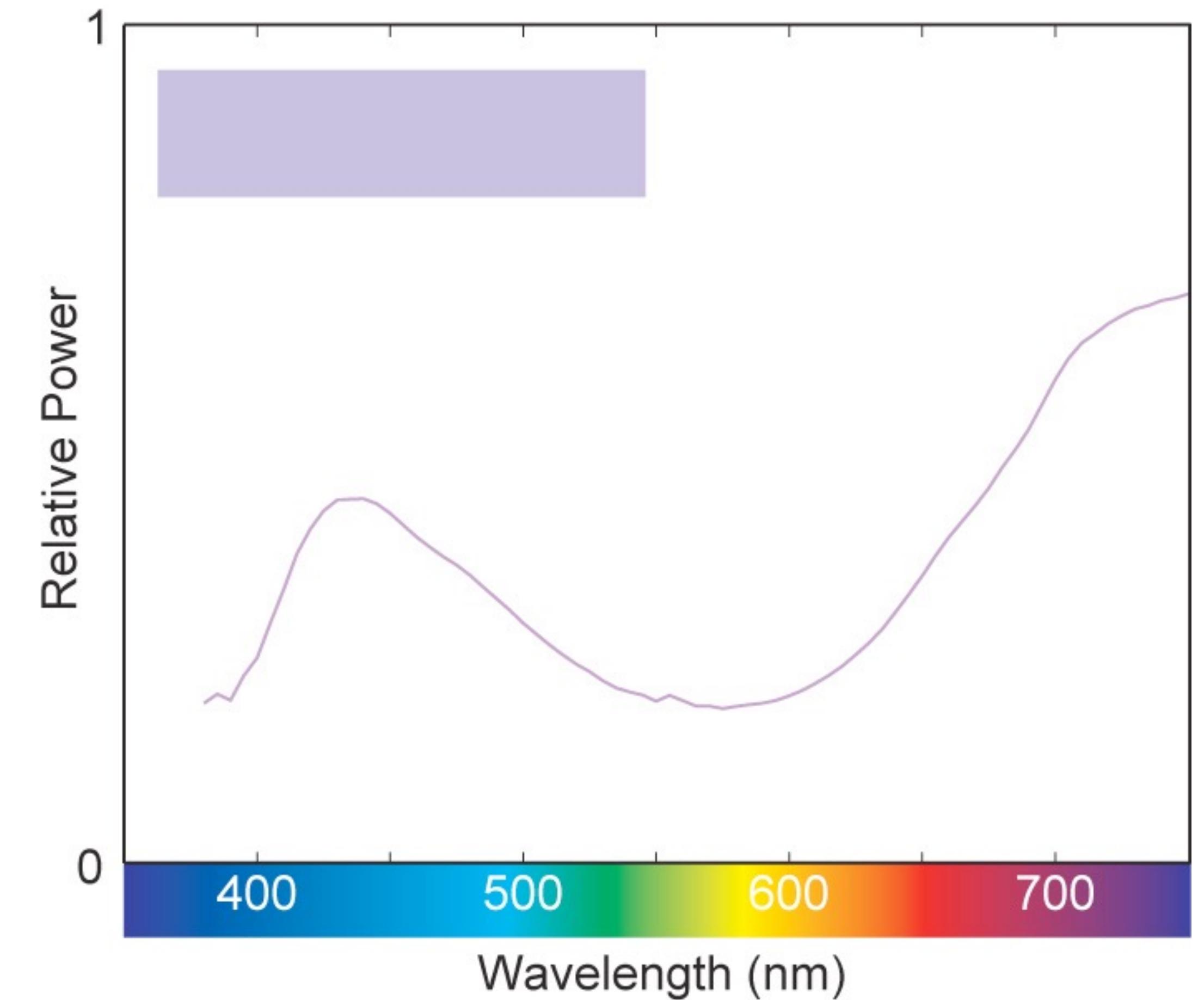
Electromagnetic wave: longer wavelength ( $\lambda$ ) = less energy



Visible light is  $\lambda$  between 370nm – 730nm.

# Visible Light

Most colors are combinations of spectral (pure) colors



# Visible Light

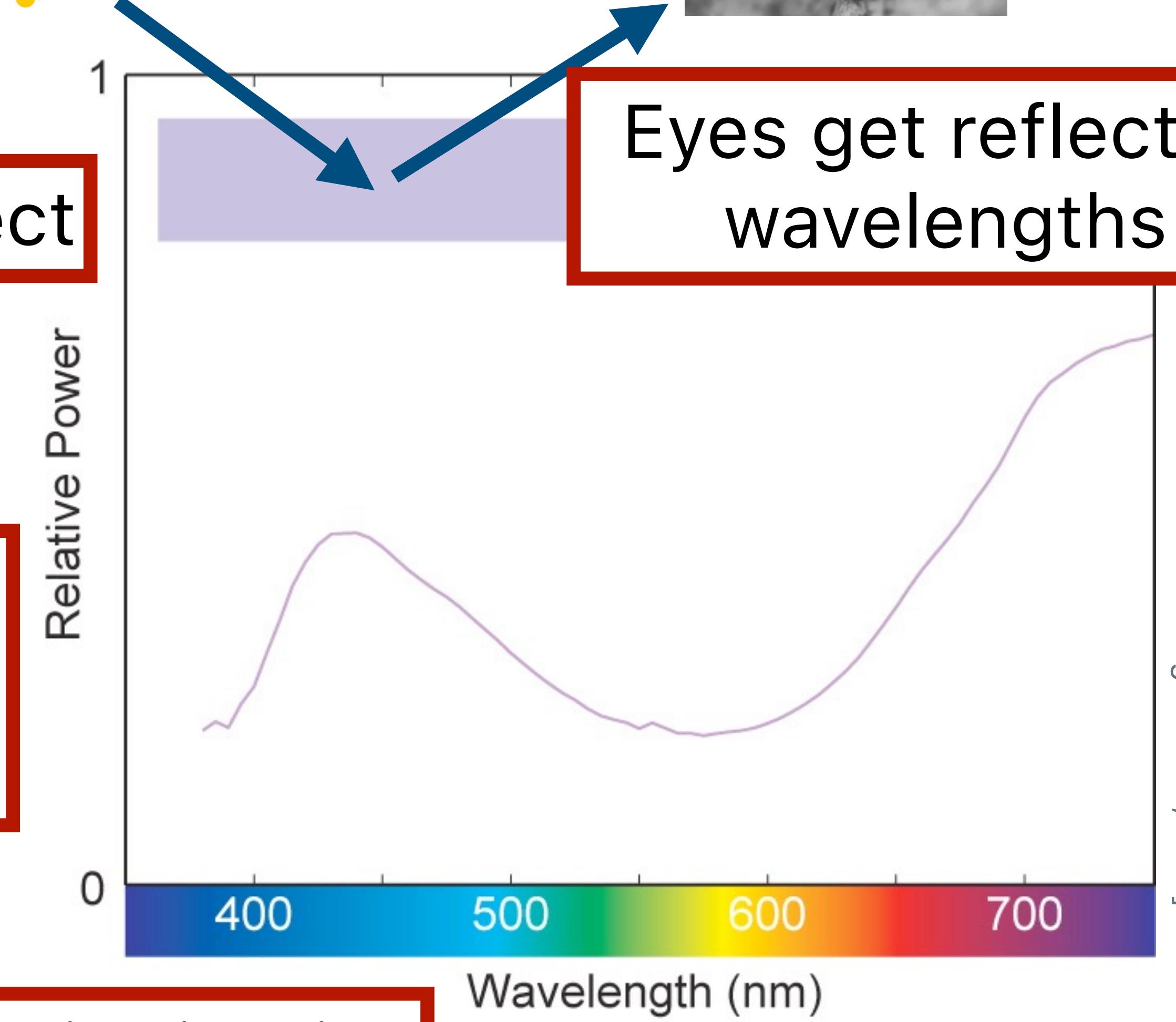
Most colors are combinations of spectral (pure) colors

Light hits object



Some wavelengths are reflected, others absorbed

Called a *spectral distribution*

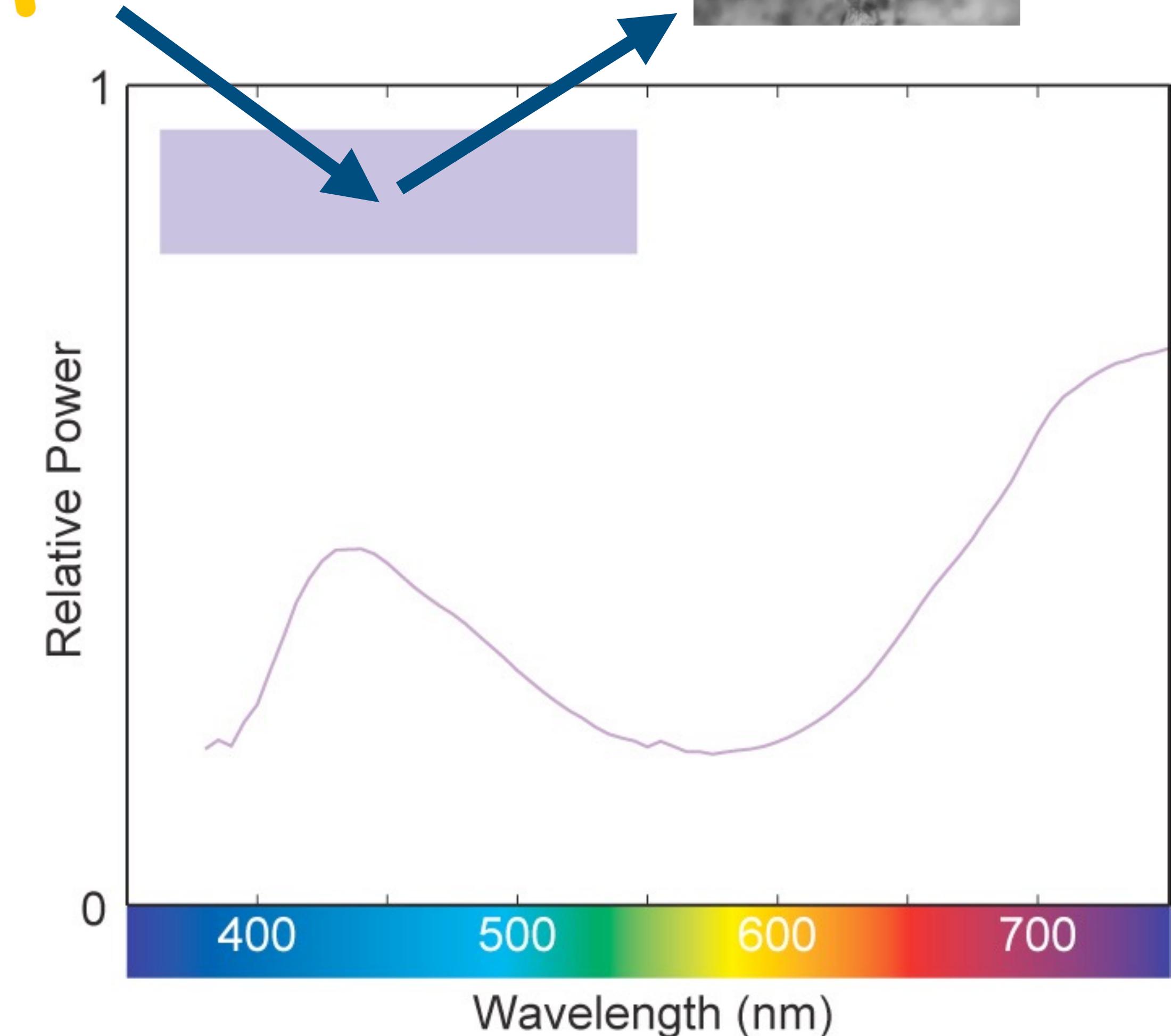


[Stone. A Field Guide to Digital Color, 2003]

# Visible Light

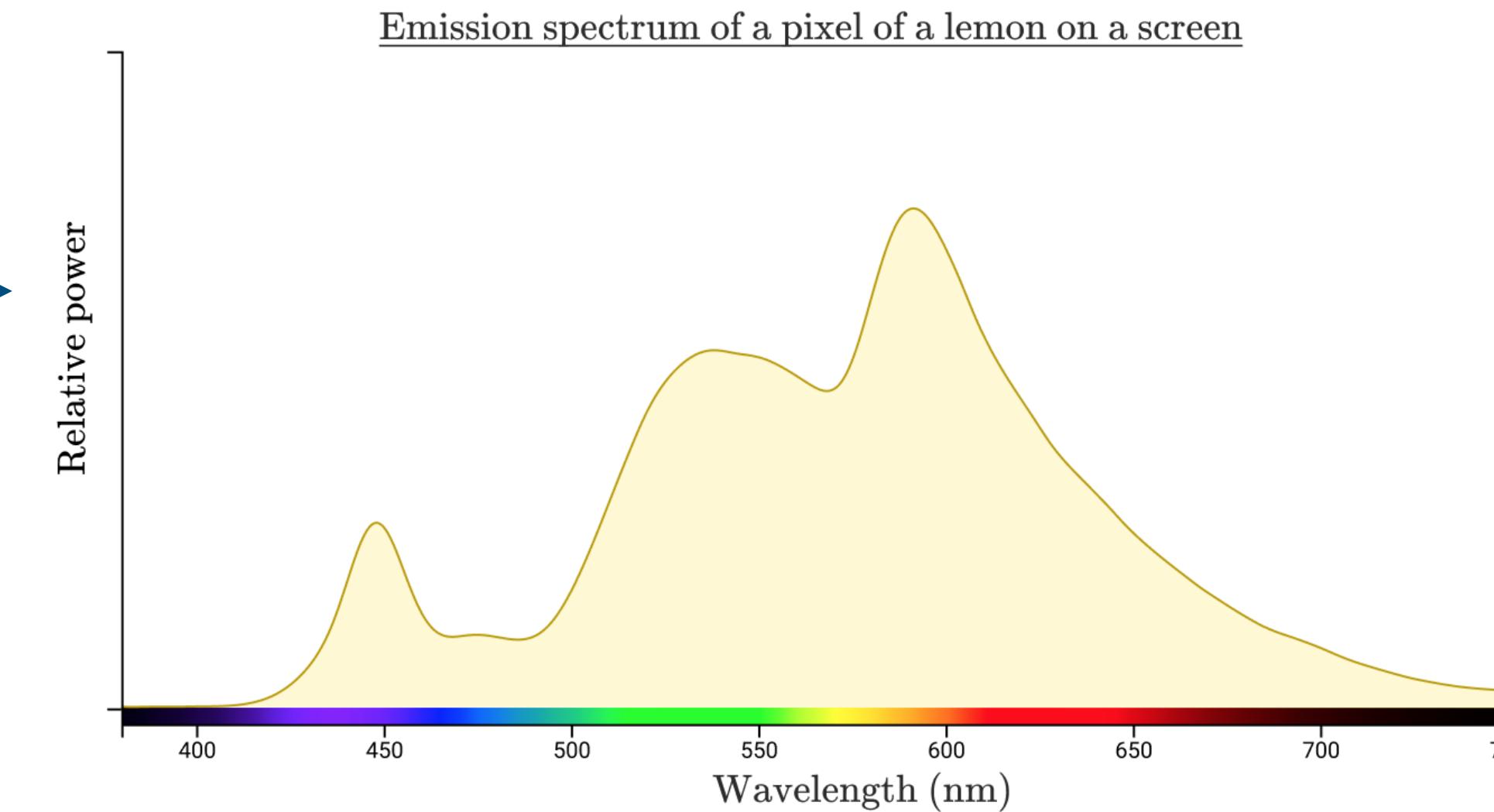
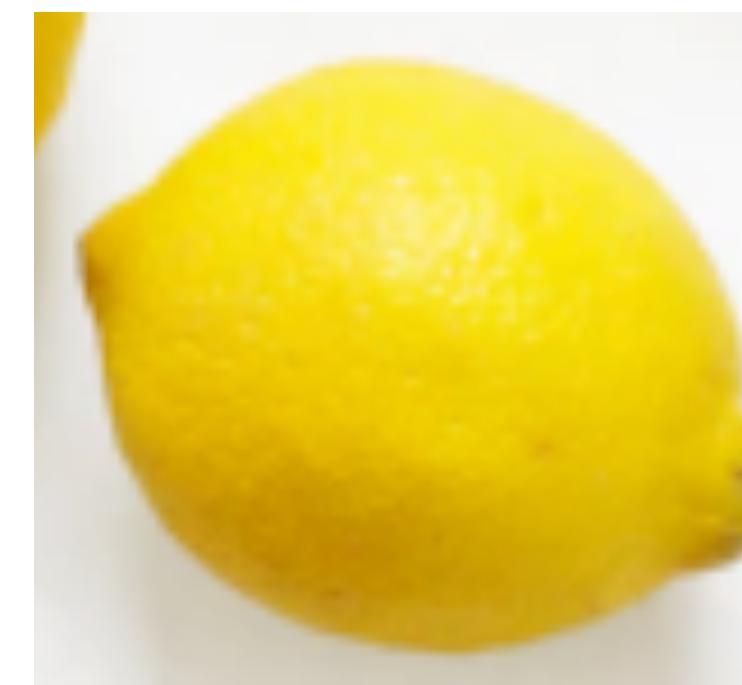
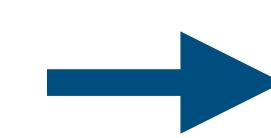
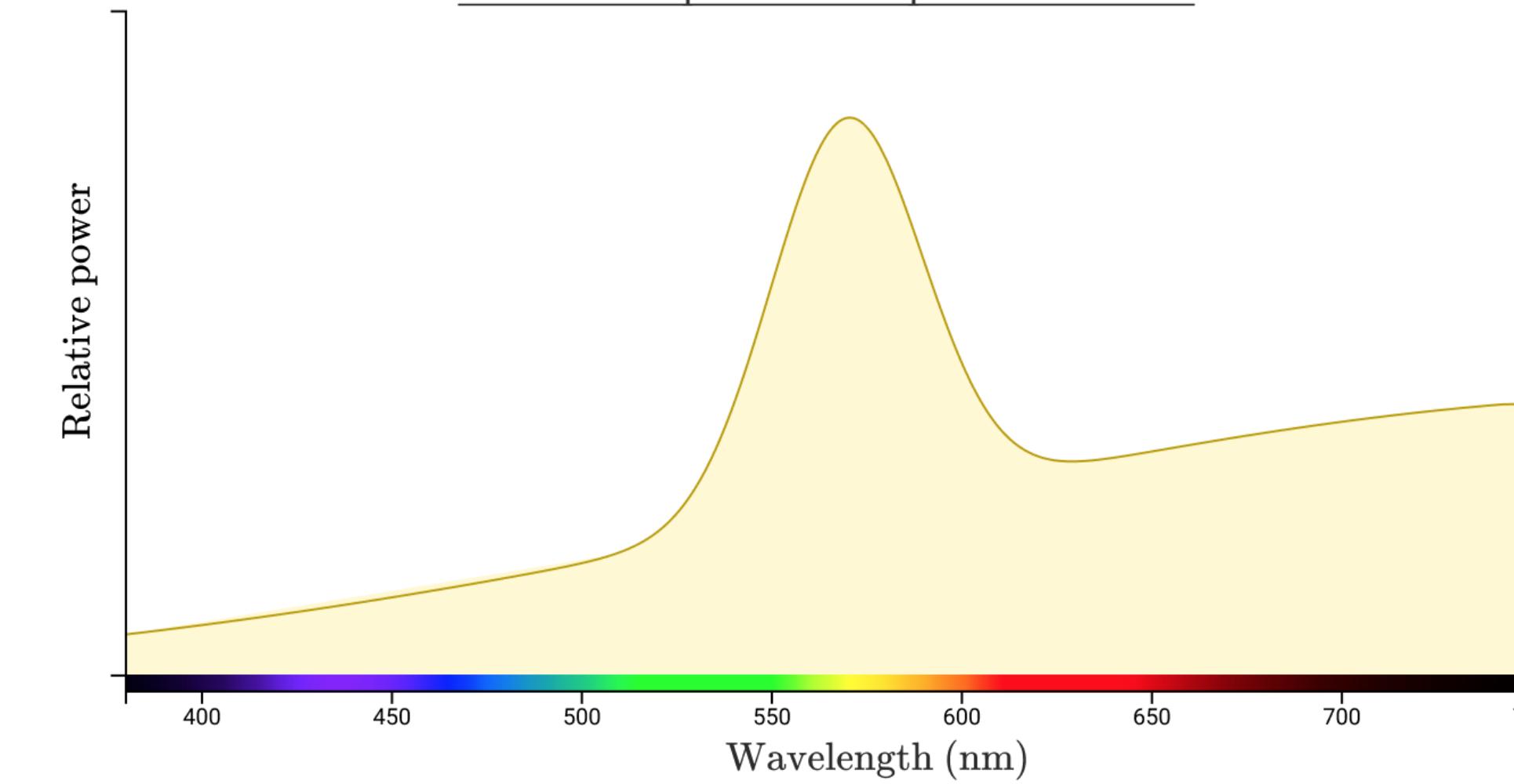
Most colors are combinations of spectral (pure) colors

**Implication:** shine a bunch of lightblubs for each  $\lambda$  = recreate this color

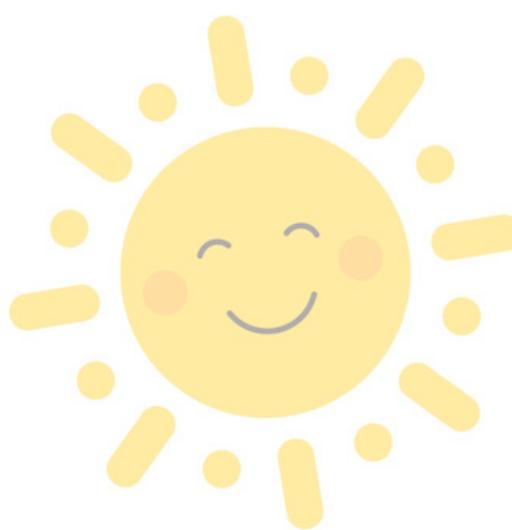


[Maureen Stone. A Field Guide to Digital Color, 2003]

# Metamers



# Metamers



Different spectra,  
but looks the same  
to our eyes!

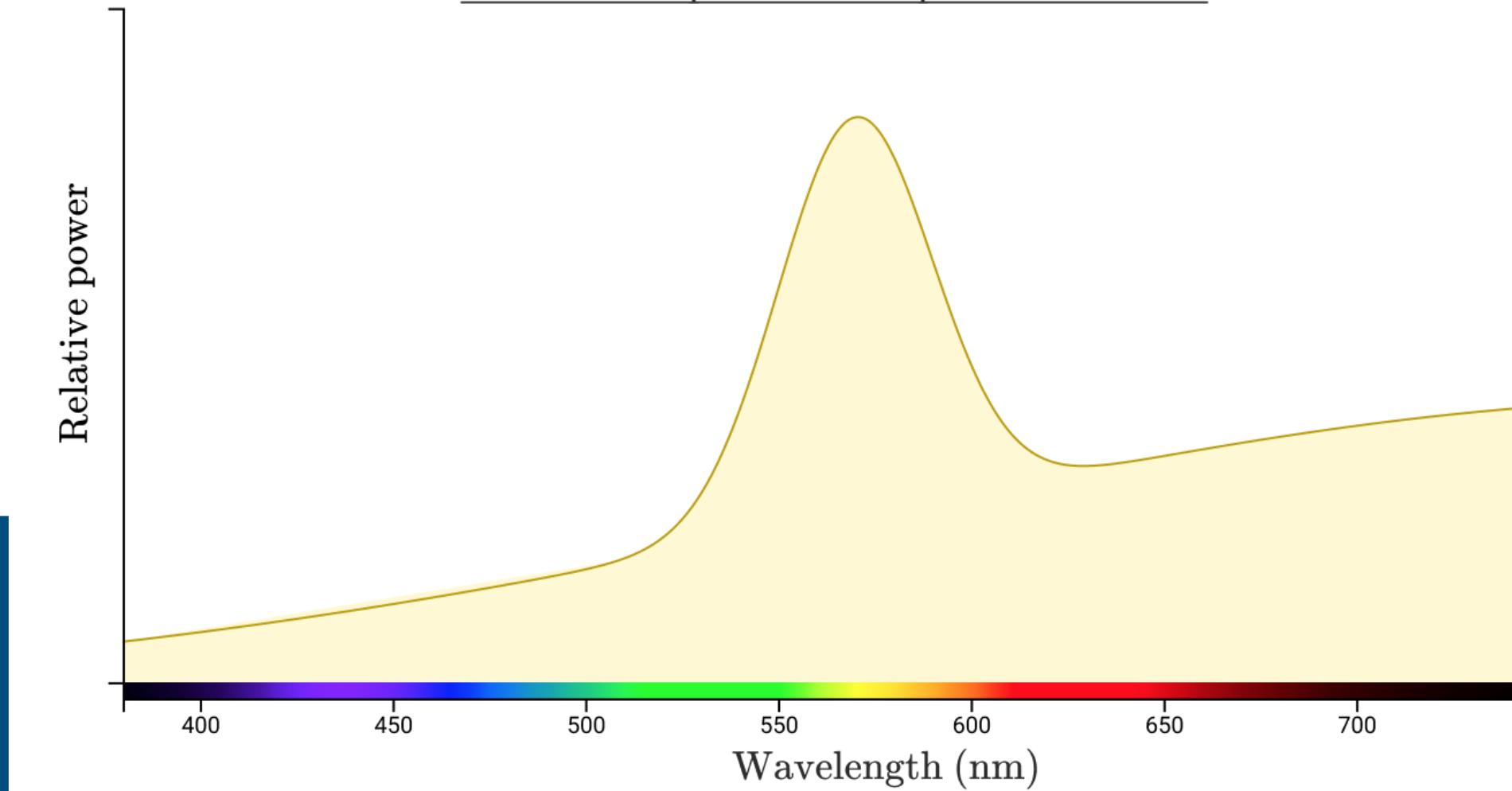


This is called a  
*metamer*.

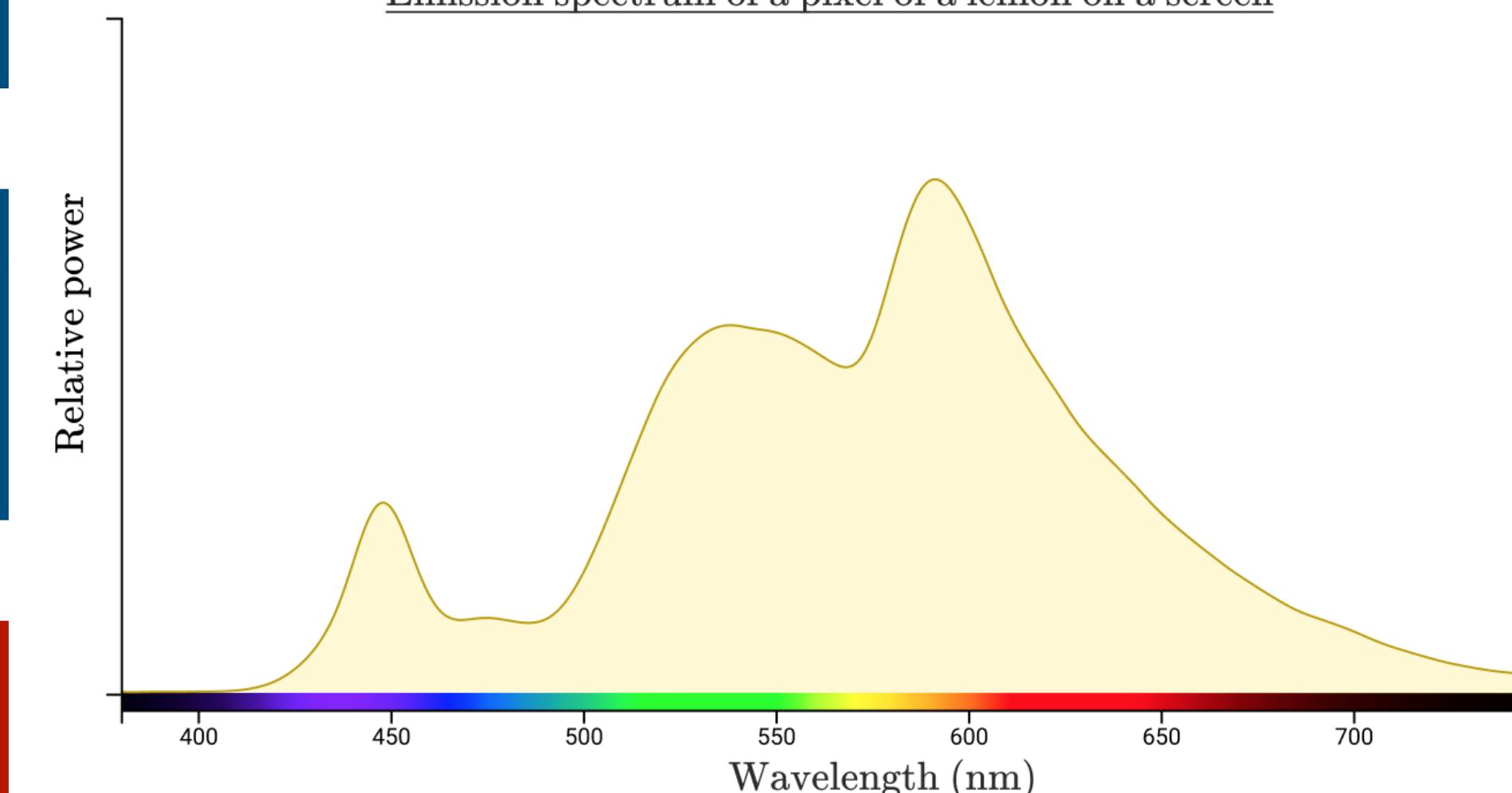
Why does this work?



Reflectance spectrum of a point on a lemon



Emission spectrum of a pixel of a lemon on a screen



# Modeling Color Perception

Low-Level

Abstraction

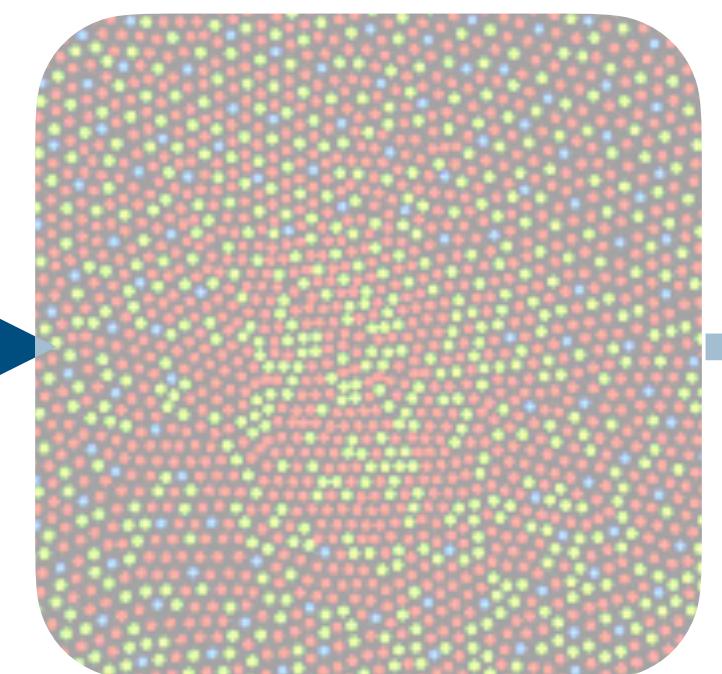
High-Level

Physical World

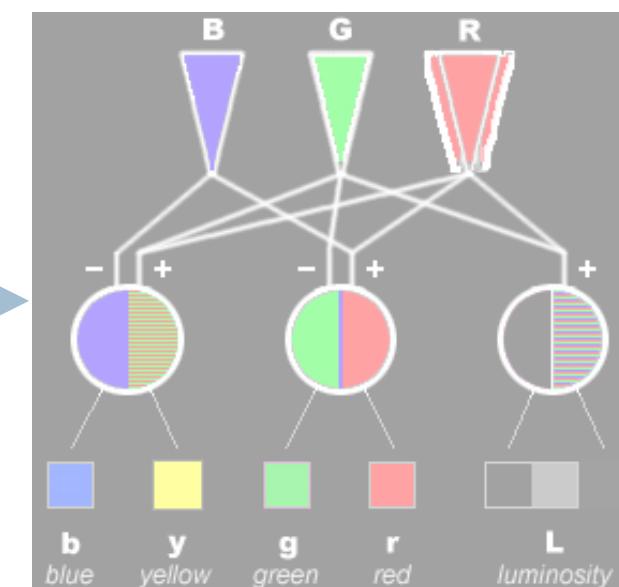


Visible Light

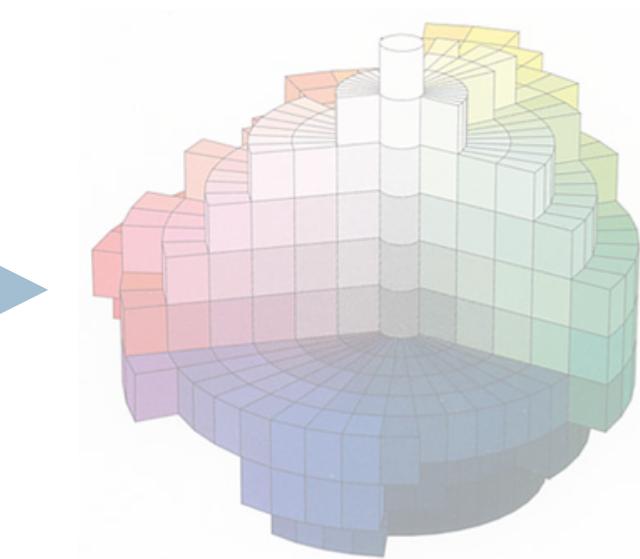
Visual System



Cone Response



Opponent Encoding



Perceptual Models



Appearance Models

“Teal”

Cognitive Models

# Modeling Color Perception

Low-Level

Abstraction

High-Level

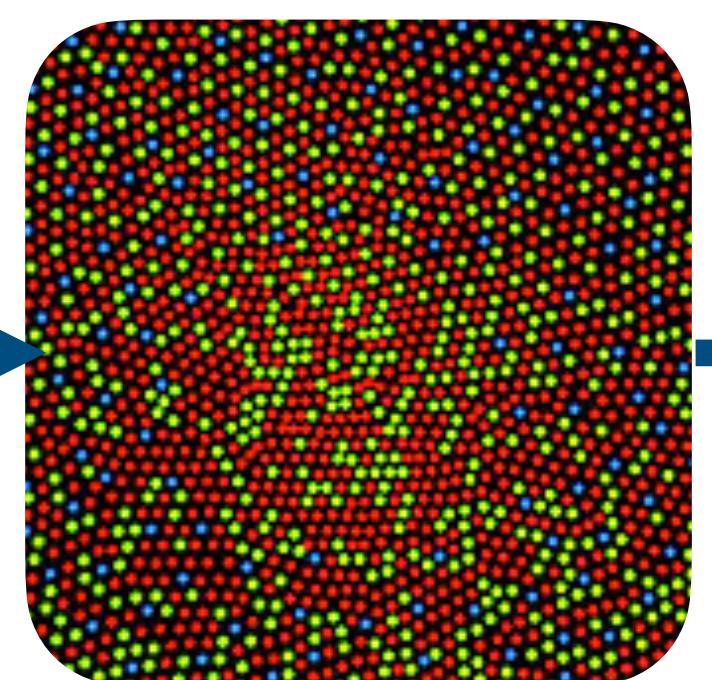
Physical World

Visual System

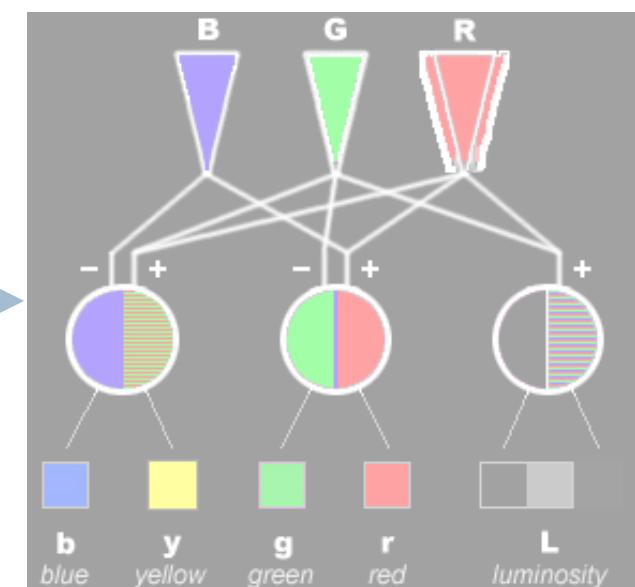
Mental Models



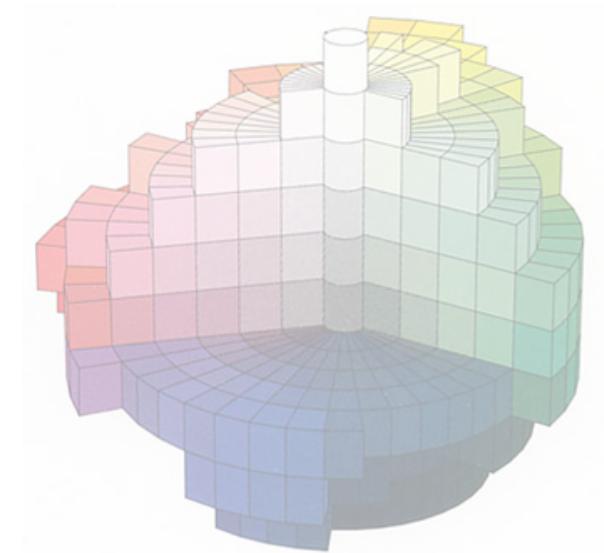
Visible  
Light



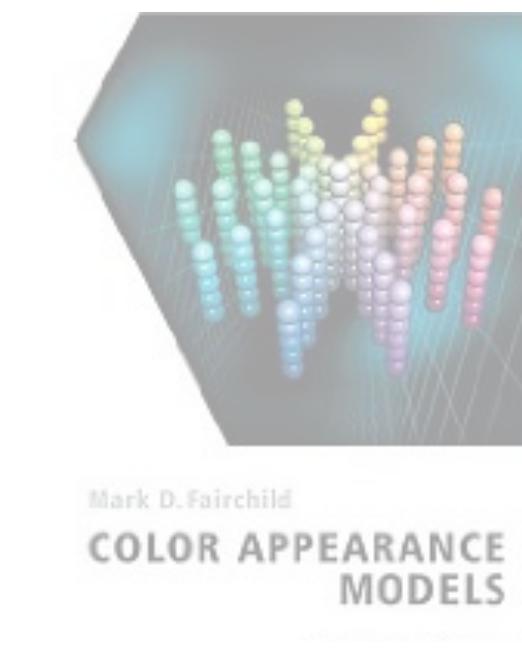
Cone  
Response



Opponent  
Encoding



Perceptual  
Models

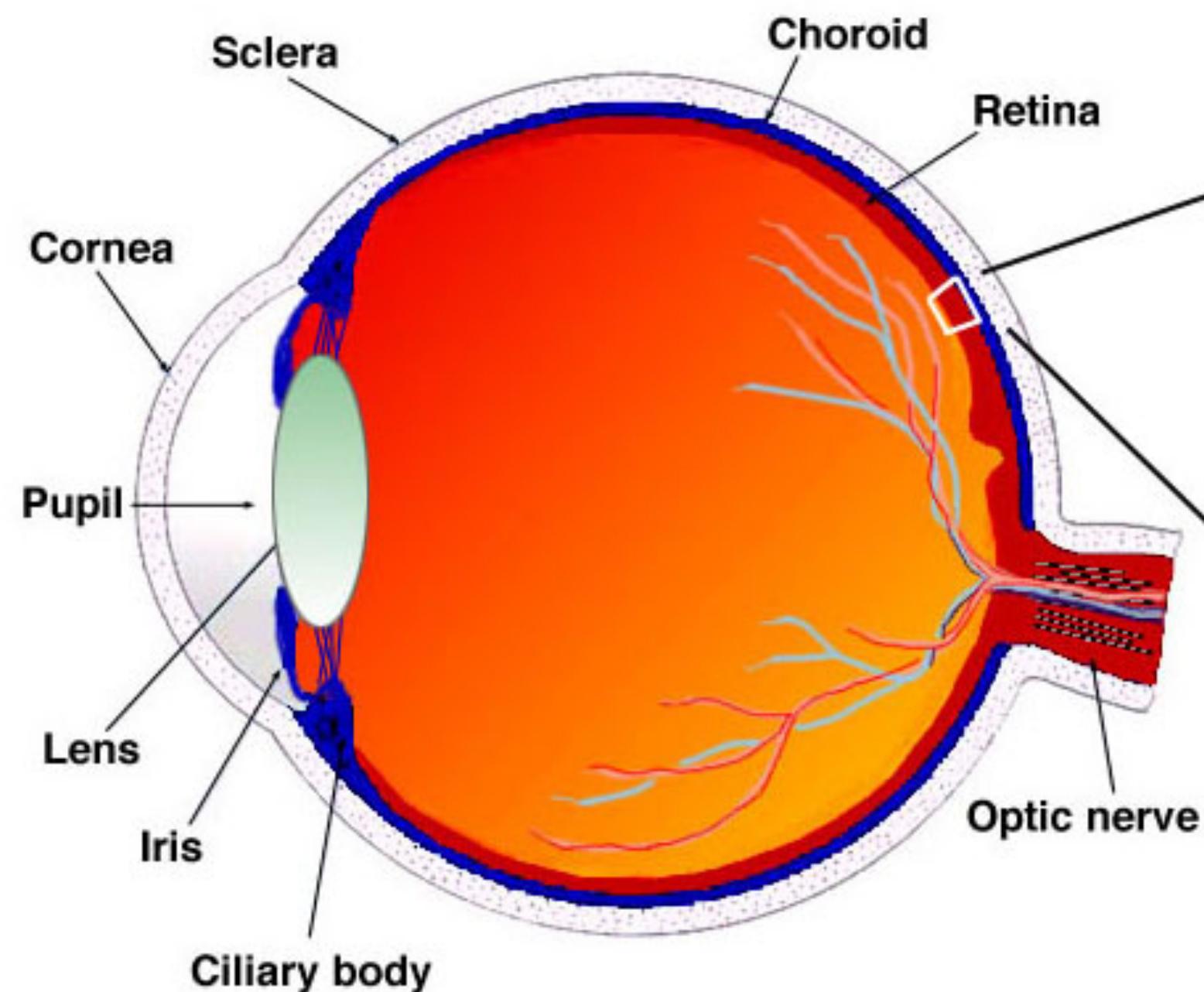


Appearance  
Models

“Teal”

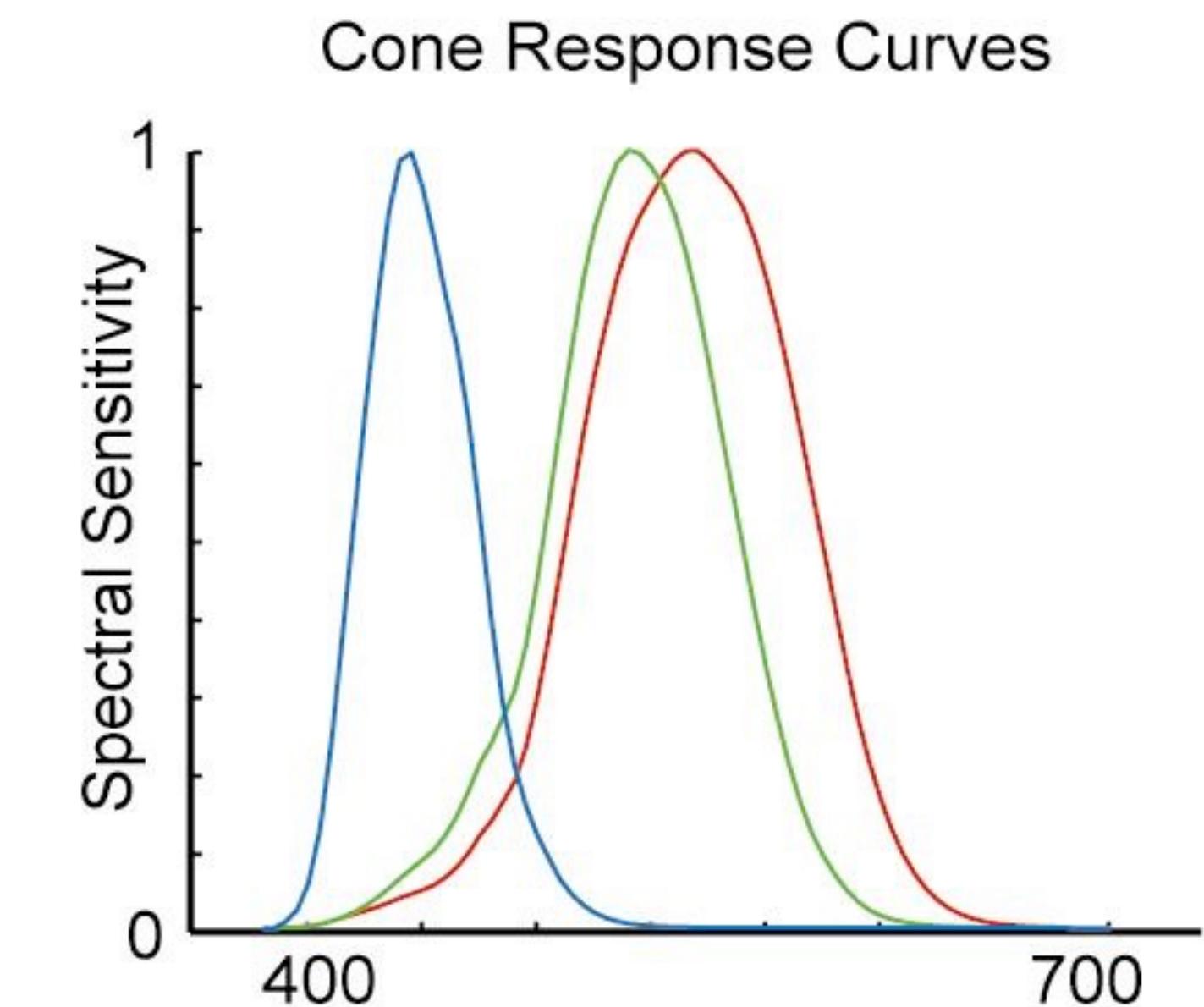
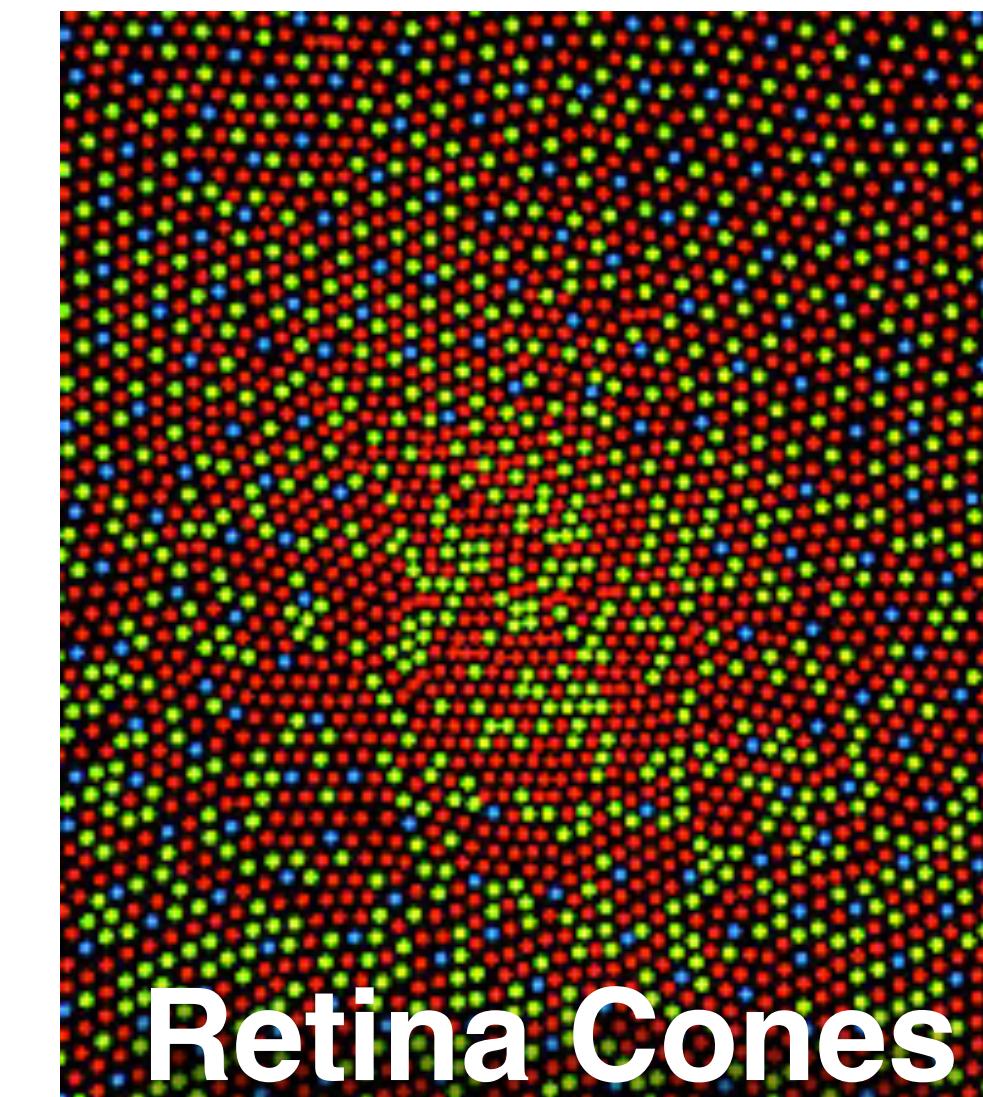
Cognitive  
Models

# The Retina

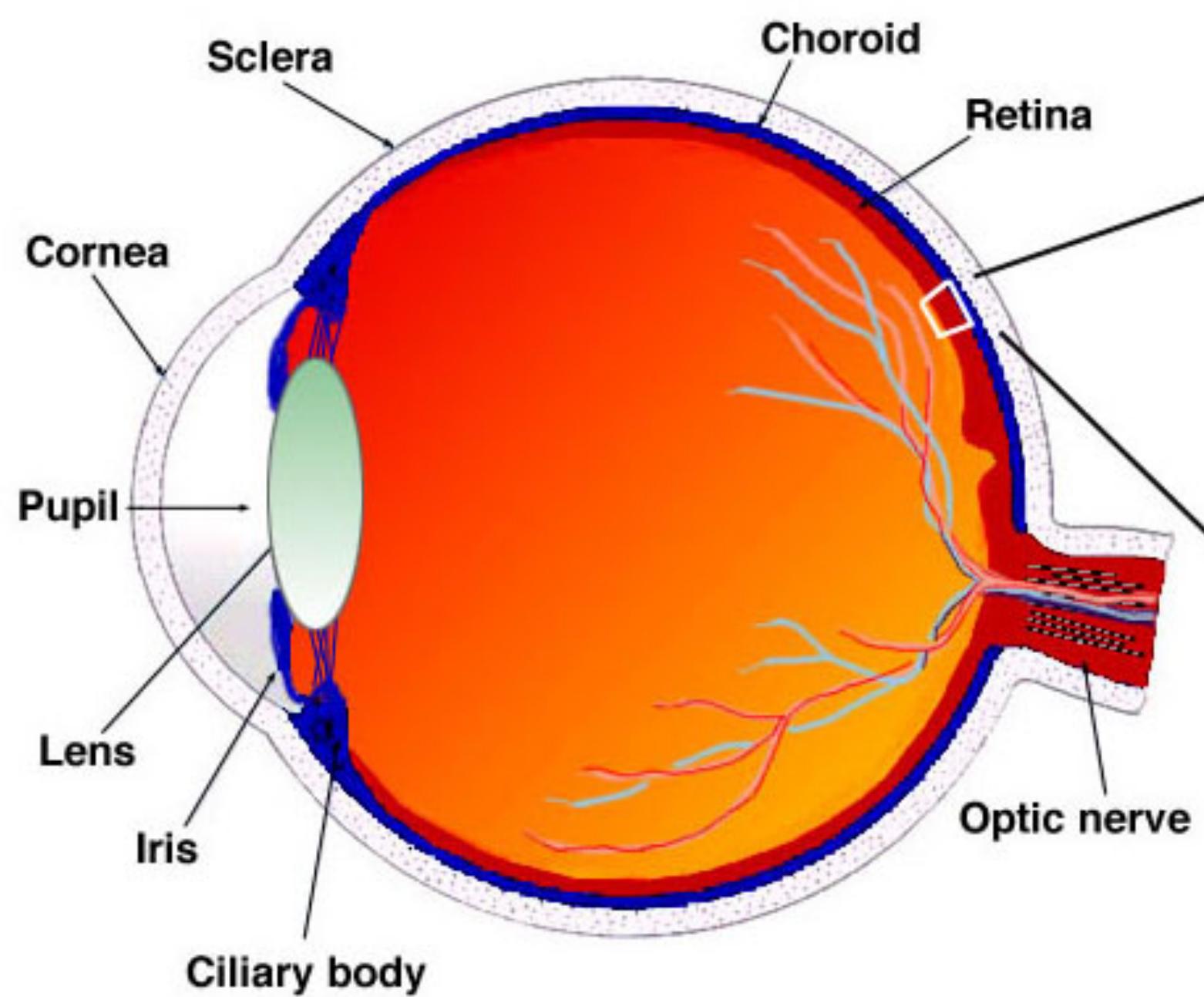


[Heldia Kolb Simple Anatomy of the

Photoreceptors on retina:  
**rods** – low-light levels, little color vision  
**cones** – color vision!  
short, middle, long ~ blue, green, red

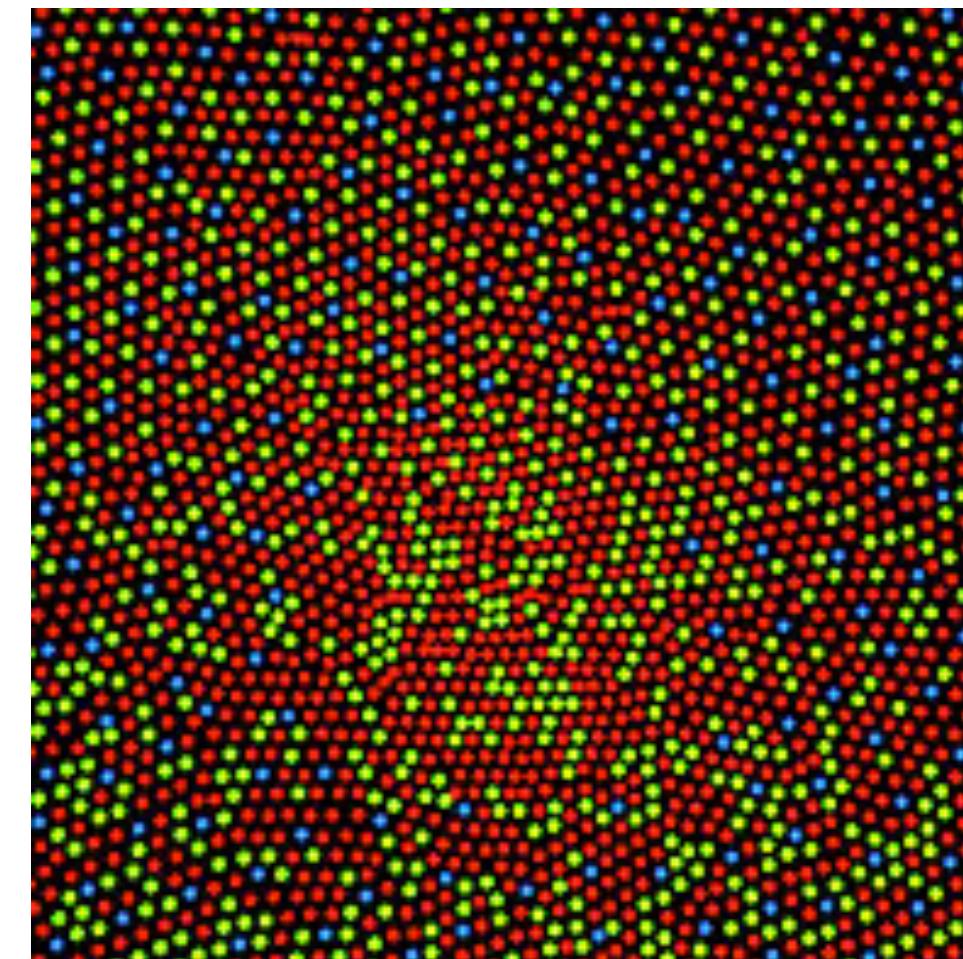


# The Retina

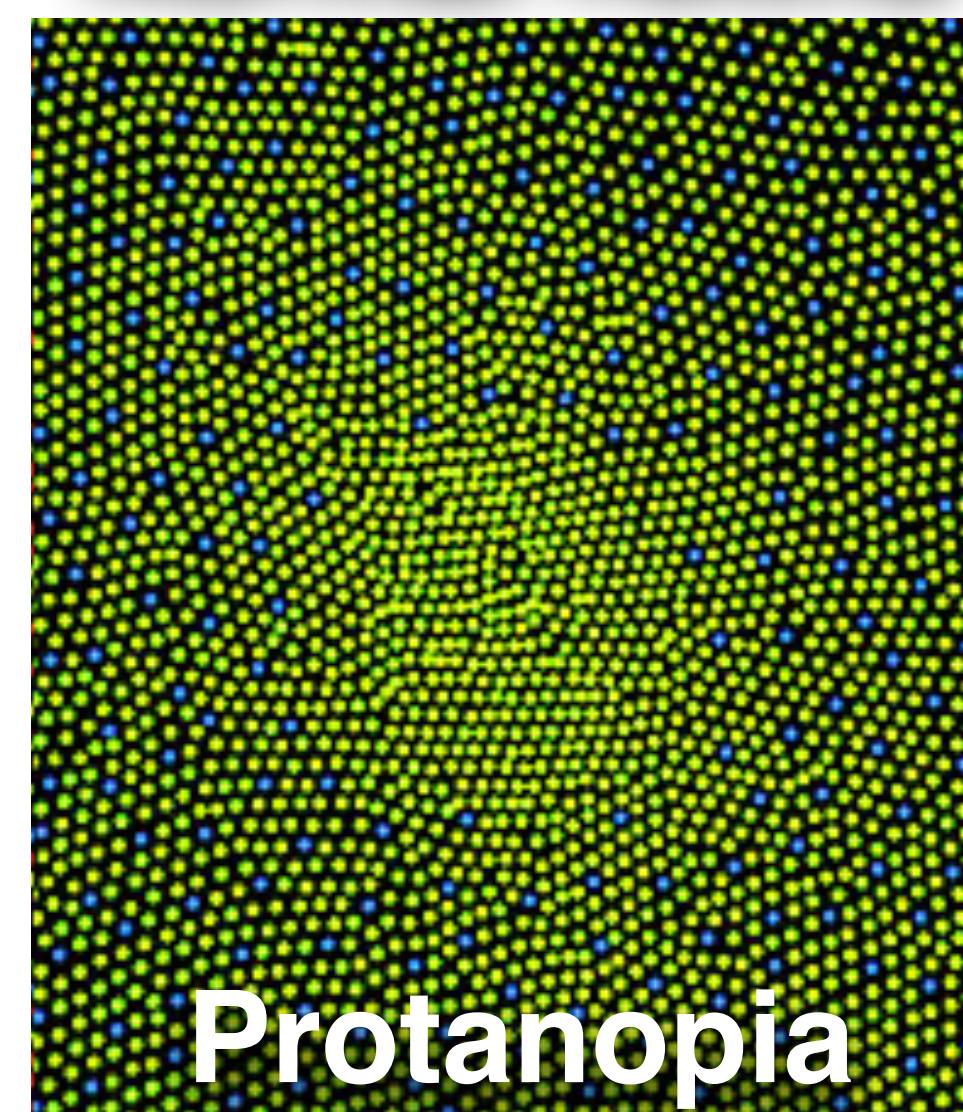


[Hilda Kolb Simple Anatomy of the

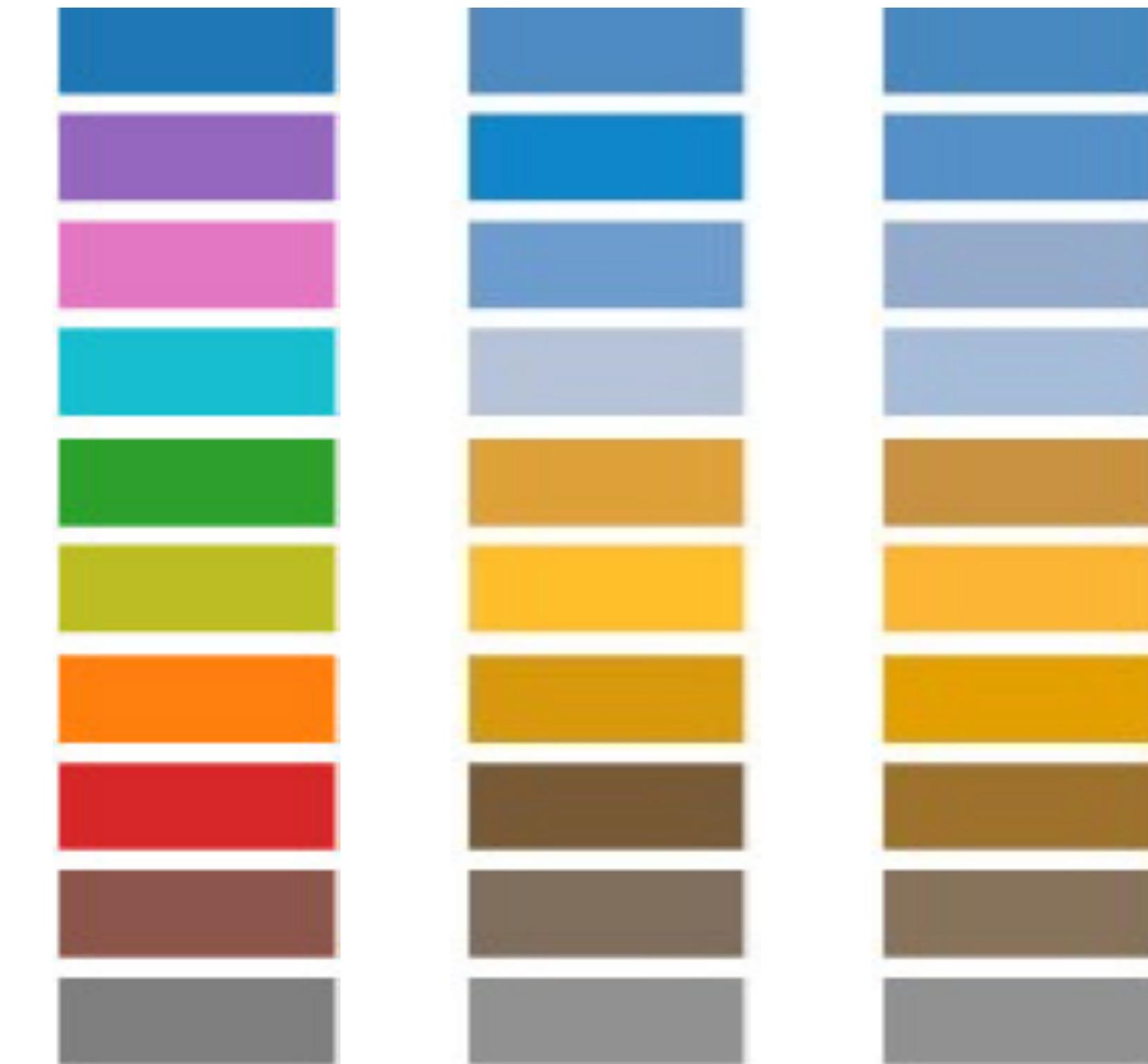
Firefox and Chrome have built in simulators



Normal Retina



Protanopia

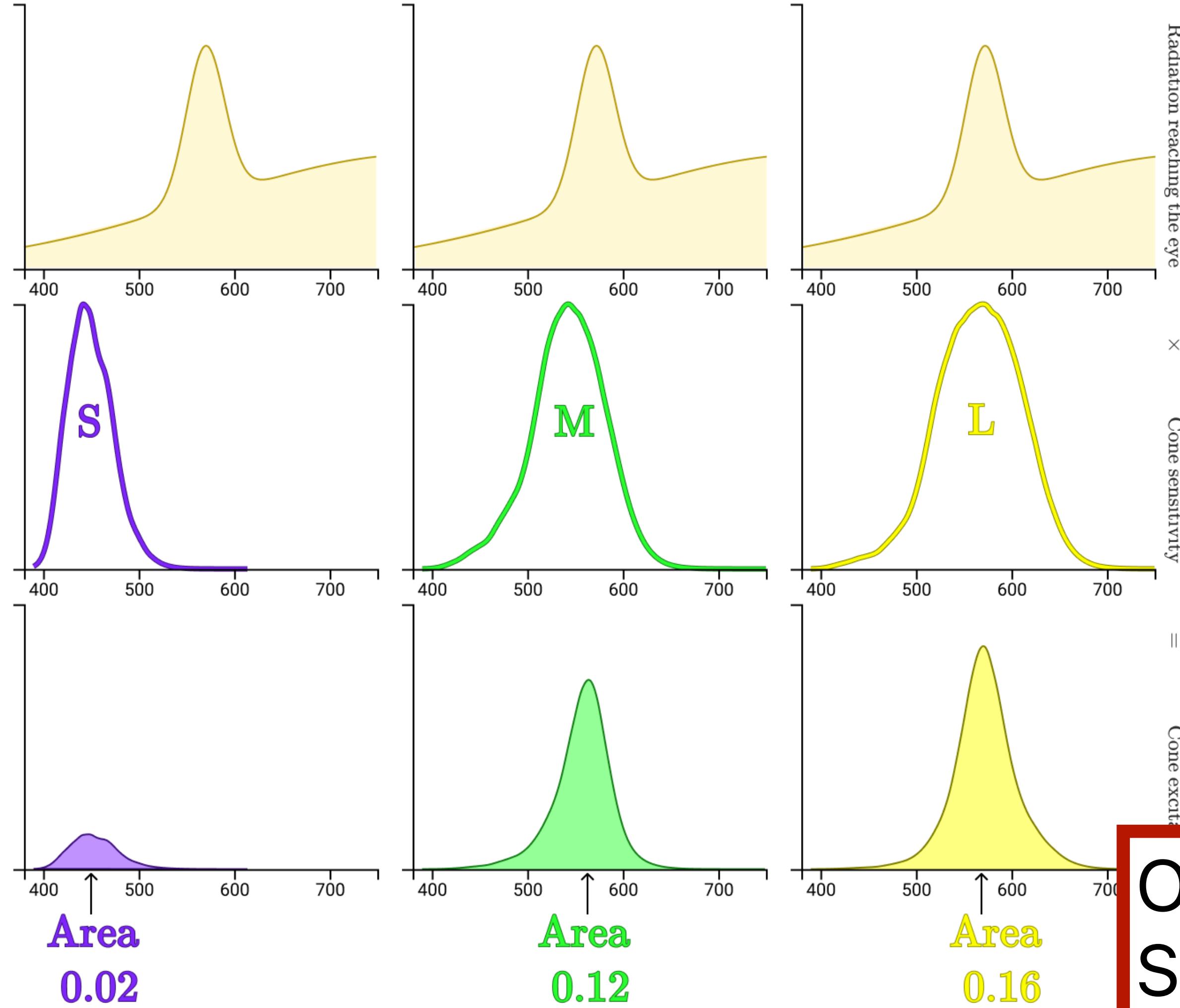


Protanope

Deutanope

# Tri-Stimulus Response

Sunlight hits lemon



Light spectrum

Cone sensitivity

Cone response

Output = 0.16 red, 0.12 green, 0.02 blue  
Seem familiar?

# Tri-Stimulus Response

Sunlight hits lemon

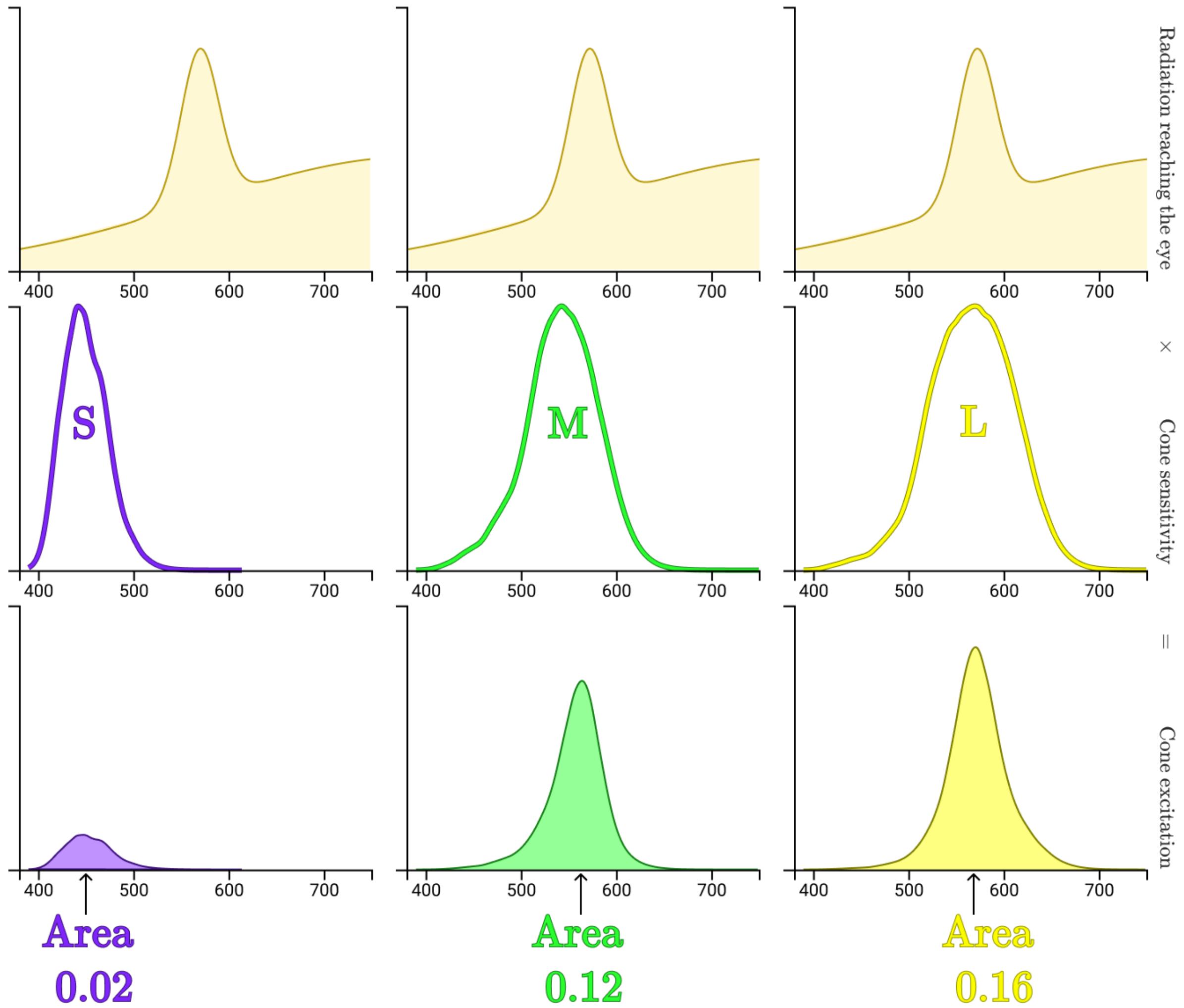
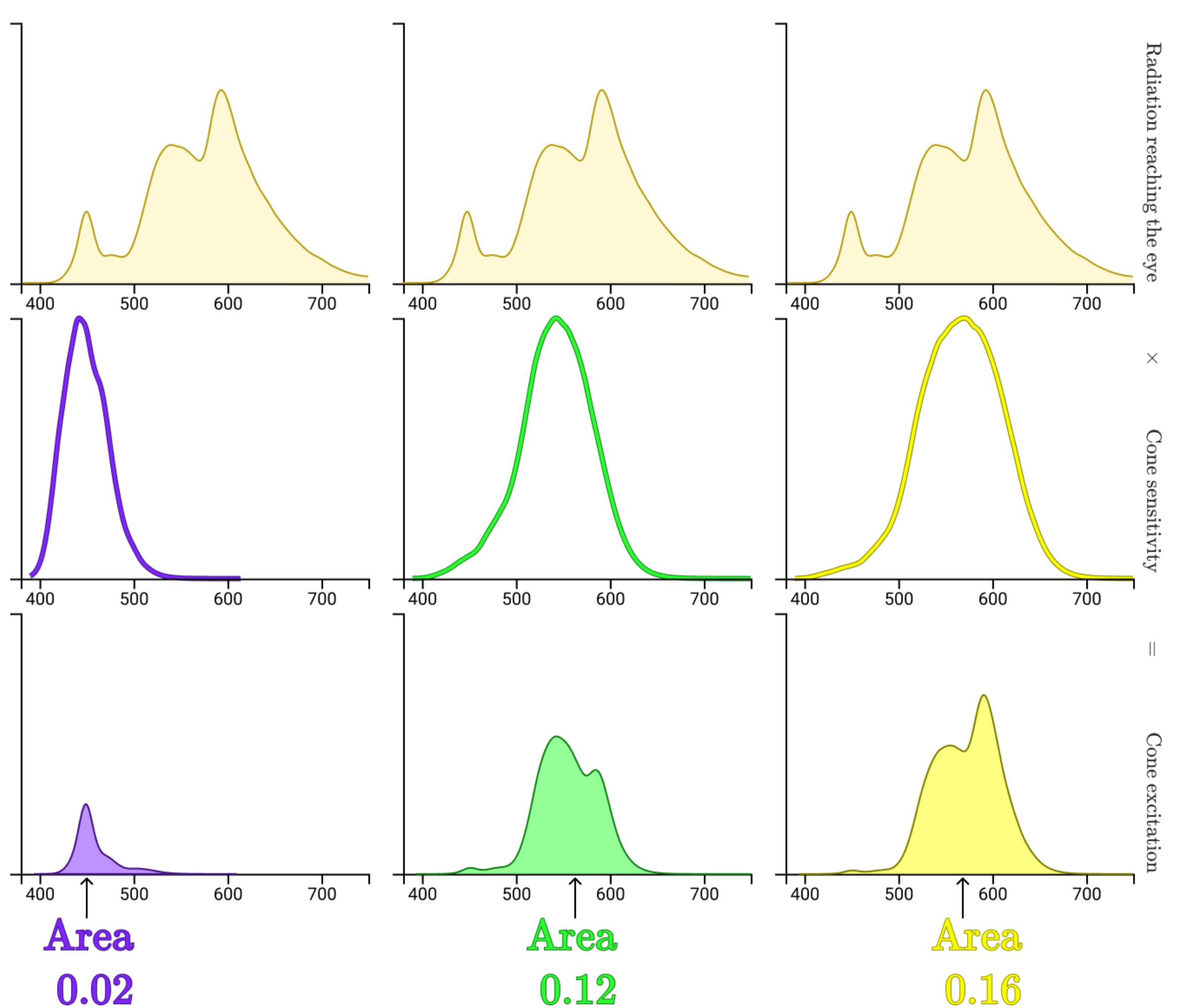
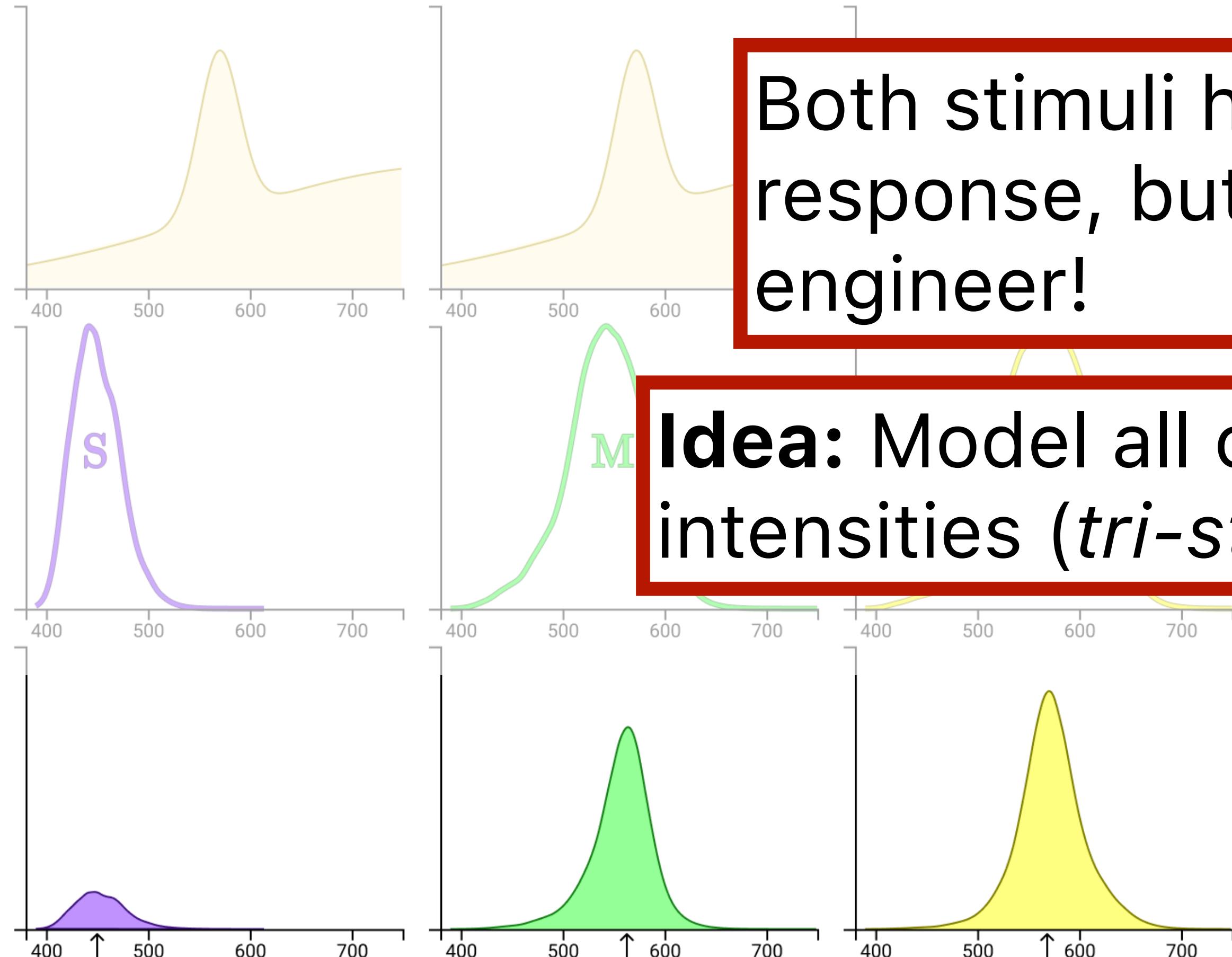


Image of lemon on screen



# Tri-Stimulus Response

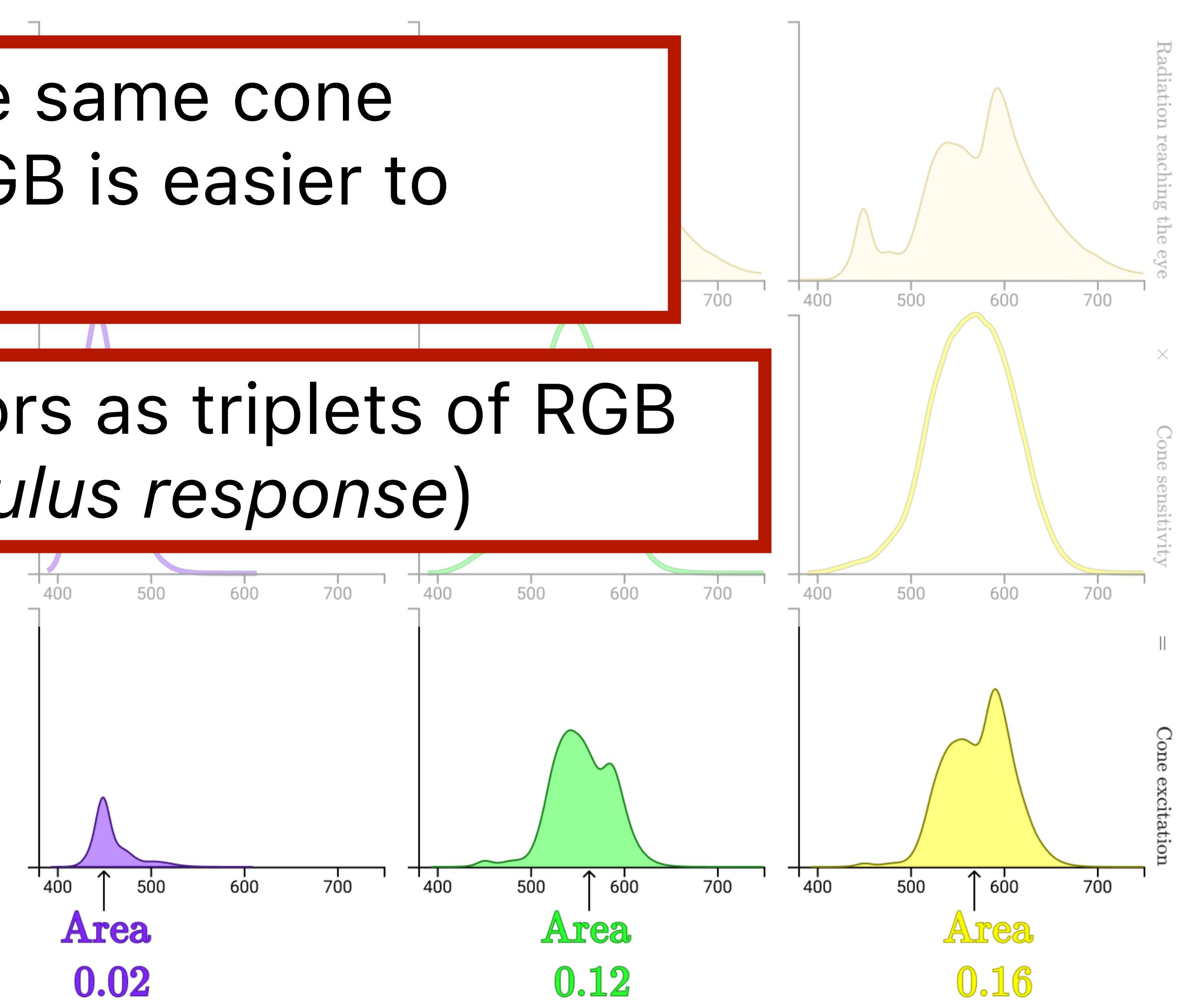
Sunlight hits lemon



Both stimuli have same cone response, but RGB is easier to engineer!

Idea: Model all colors as triplets of RGB intensities (*tri-stimulus response*)

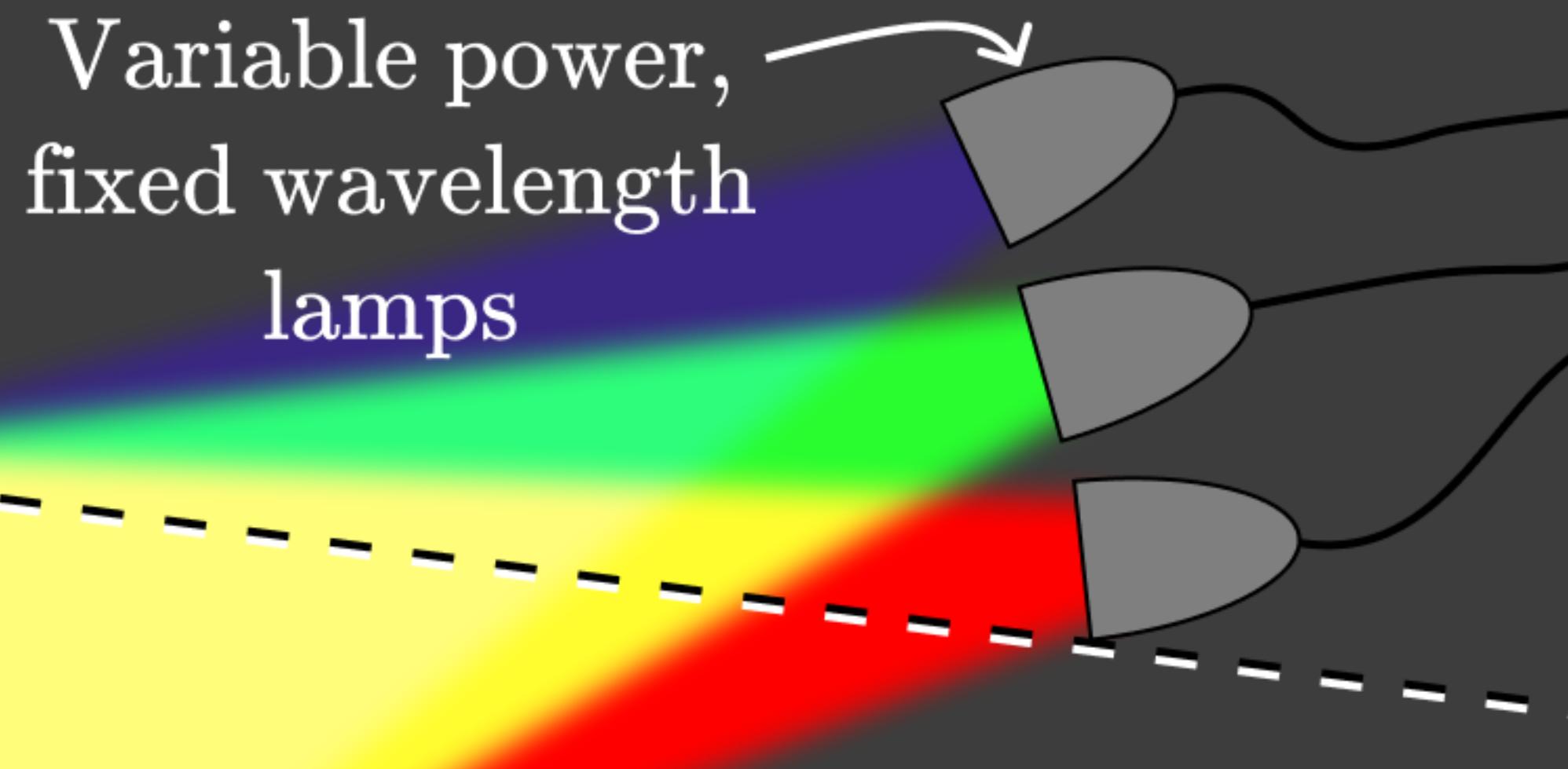
Image of lemon on screen



# CIE XYZ (1931)

Take red, green, blue lamp,  
record RGB tuples ( $r$ ,  $g$ ,  $b$ ).

Normalize values to be  
between 0 and 1.



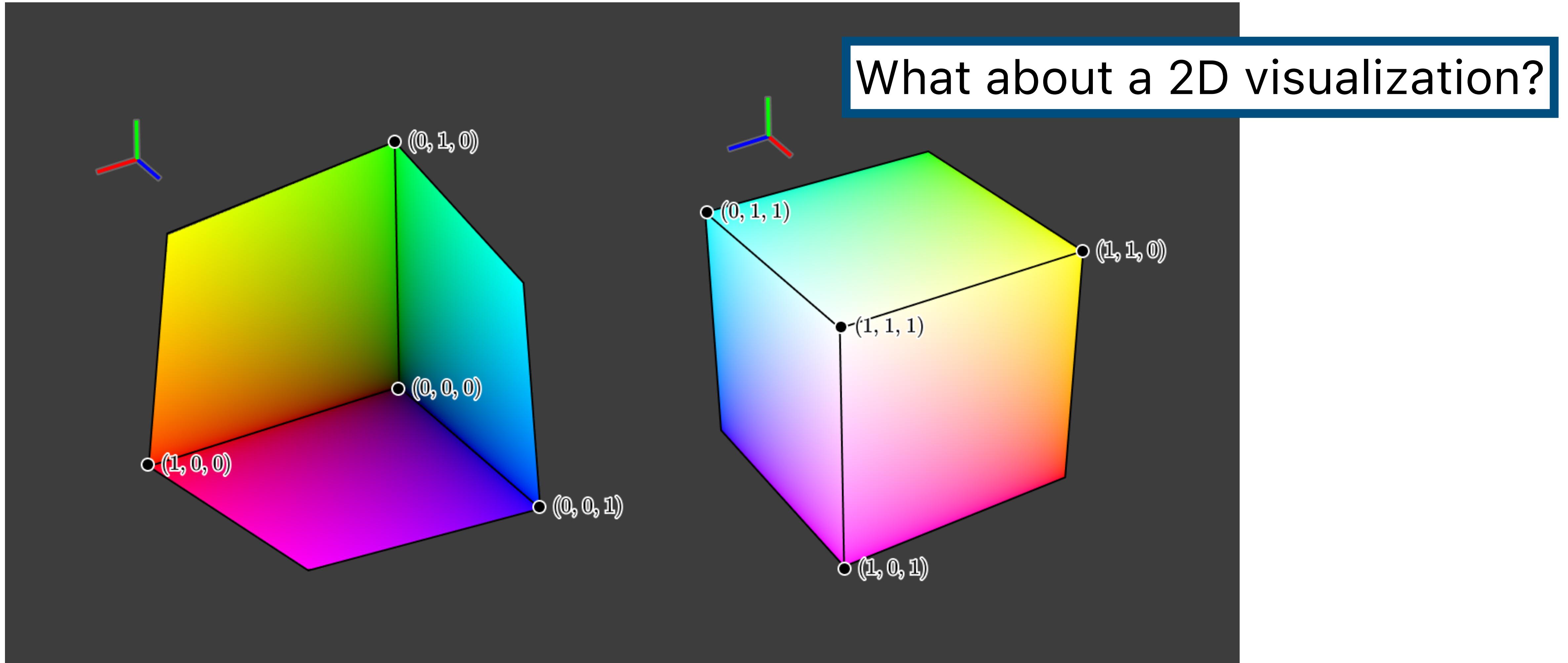
$(1, 1, 1)$  = white light

$(1, 0, 0)$  = pure red

...etc.

**How to visualize all colors?**

# CIE XYZ (1931)

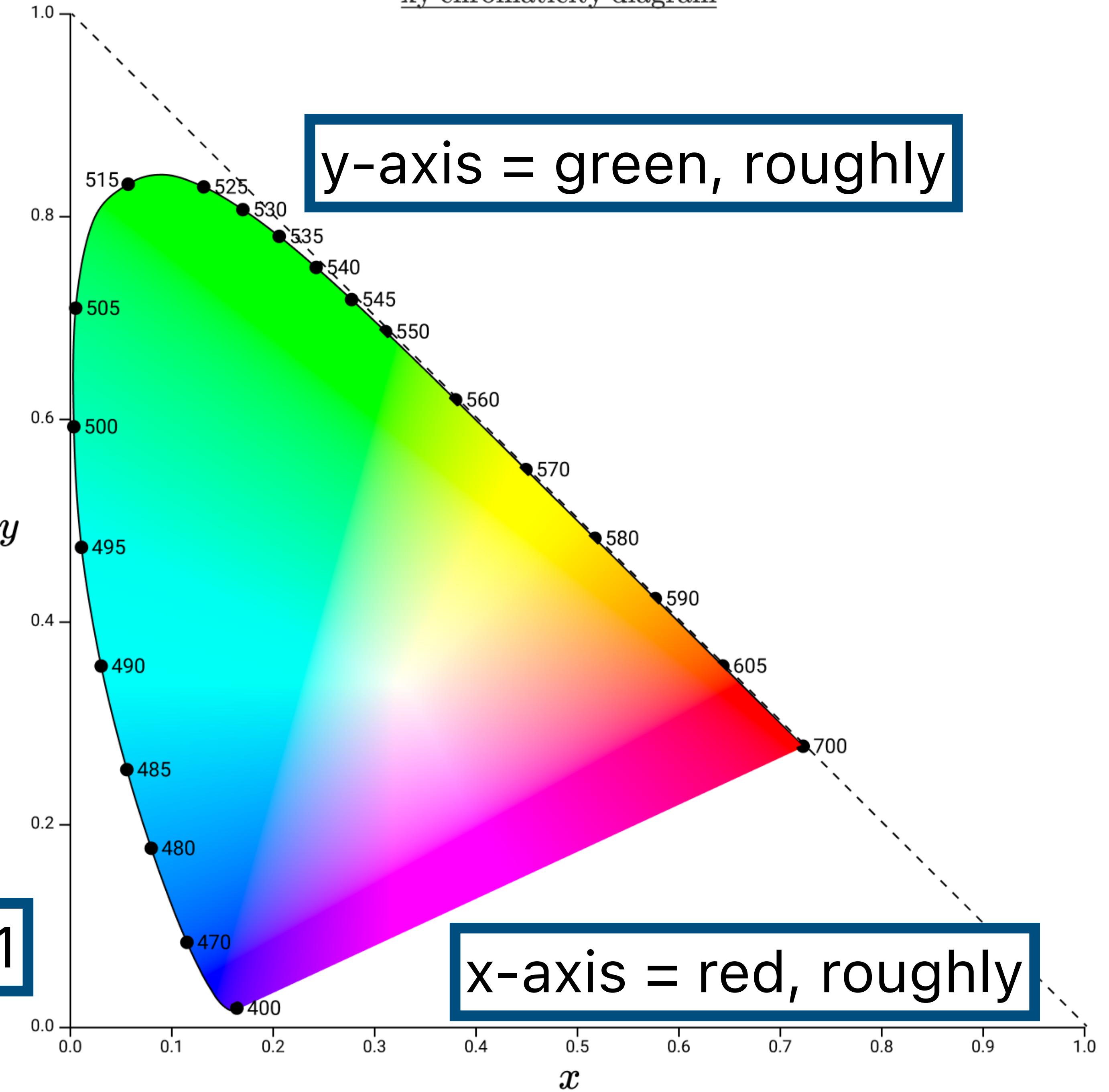


# CIE XYZ (1931)

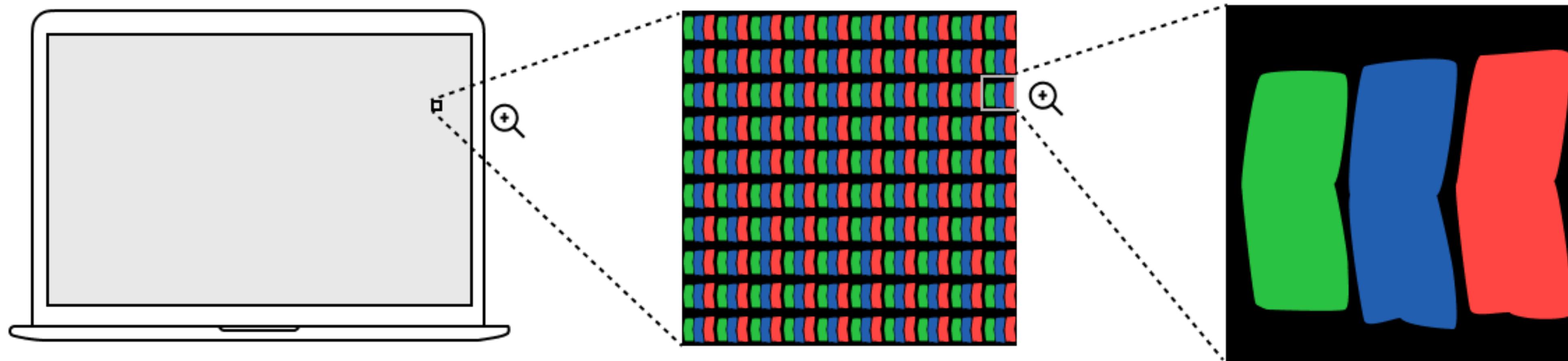
Project into a 2D plane to separate colorfulness from brightness.

$$x + y + z \text{ (blue)} = 1$$

xy chromaticity diagram



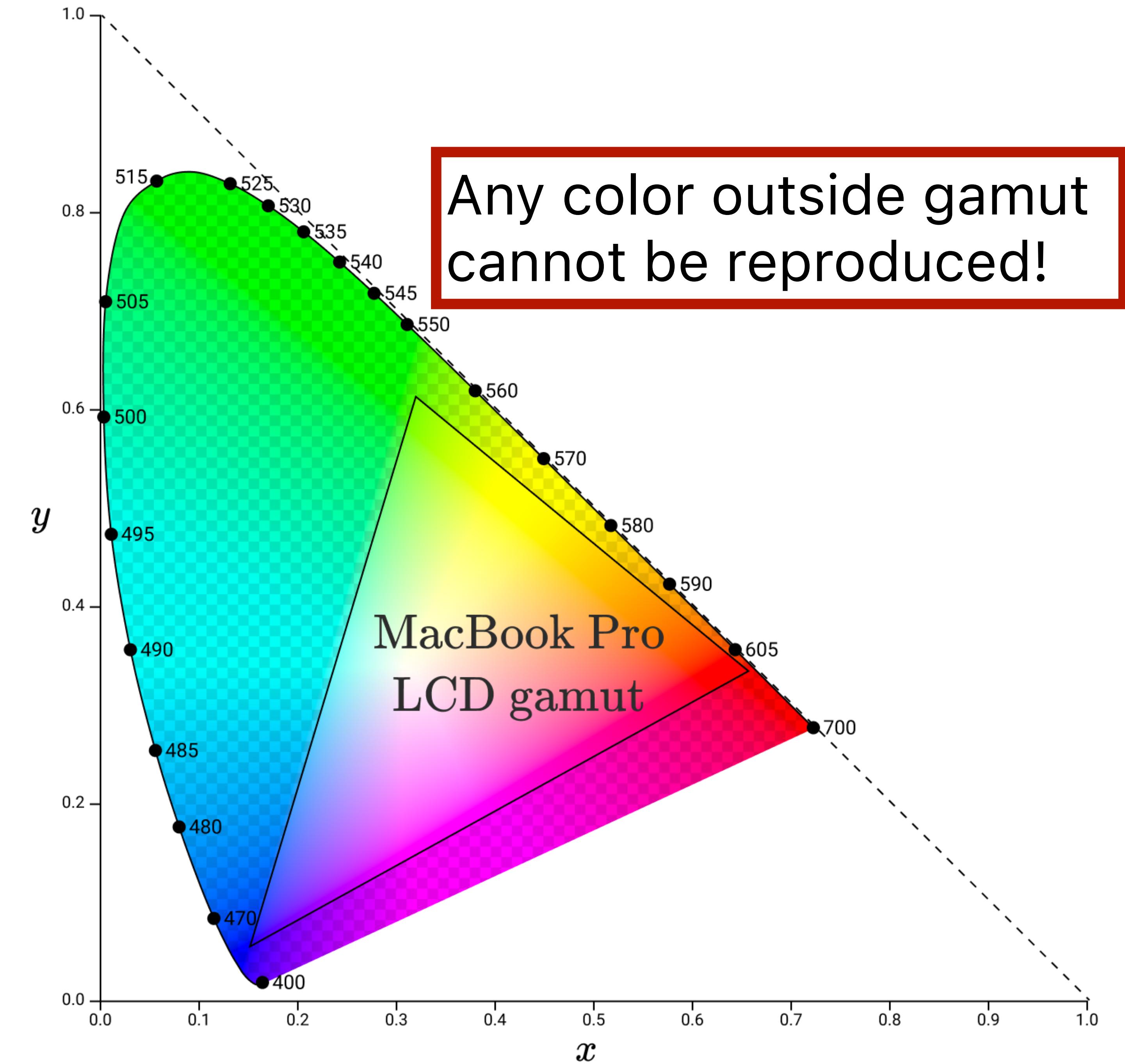
# Our screens



**Not the same as the 1931 CIE light bulbs!**

# Color Gamuts

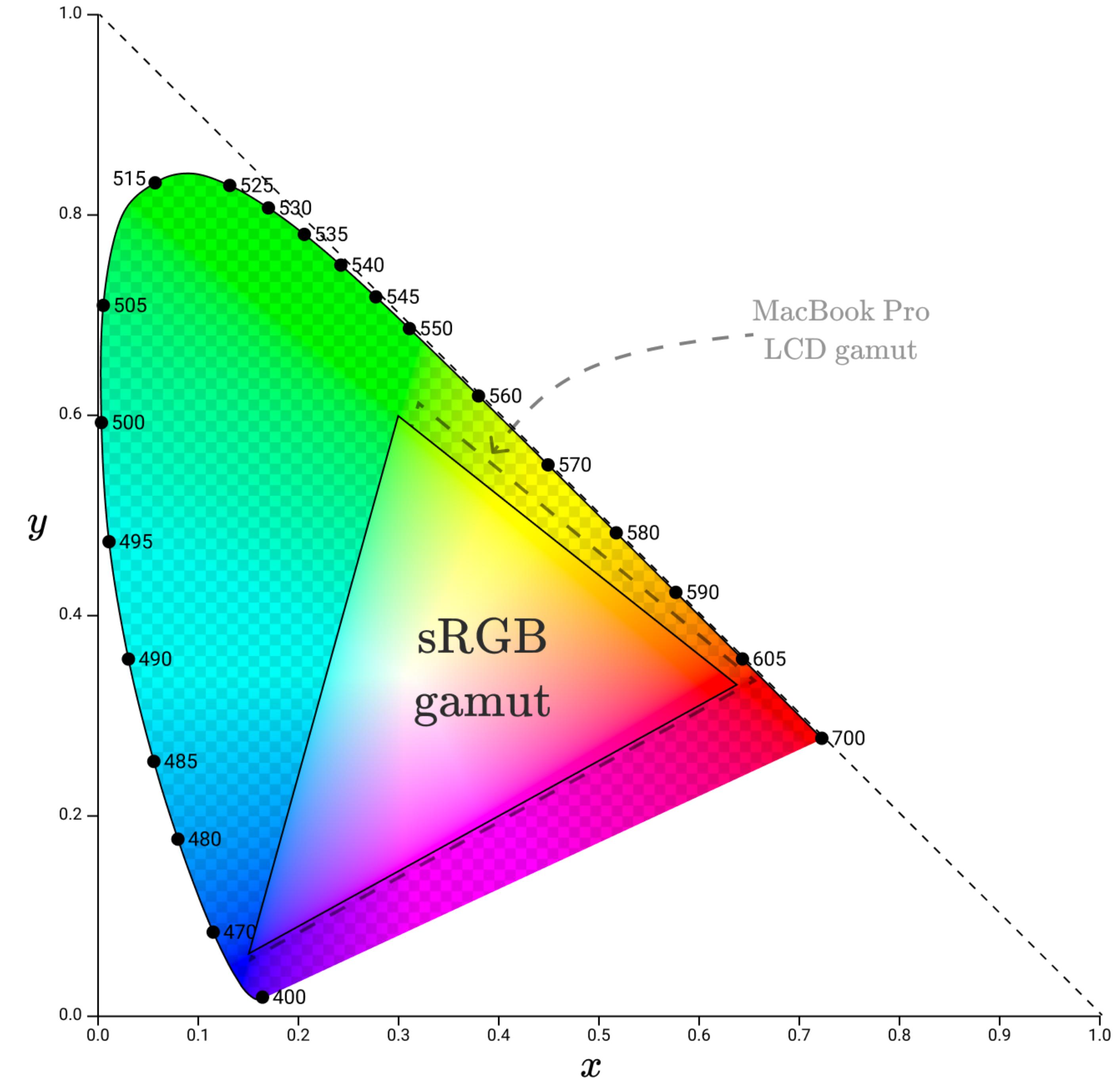
Gamut = portion of color space that can be reproduced by display



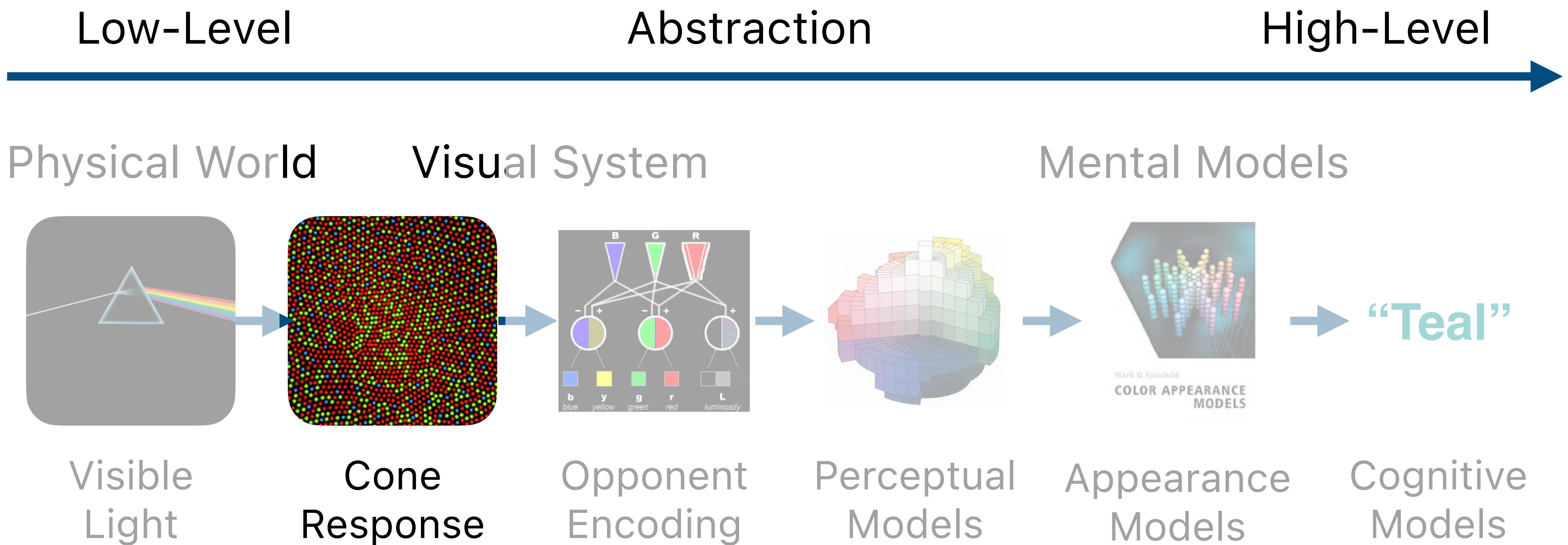
# sRGB

Gamut = portion of color space that can be reproduced by display

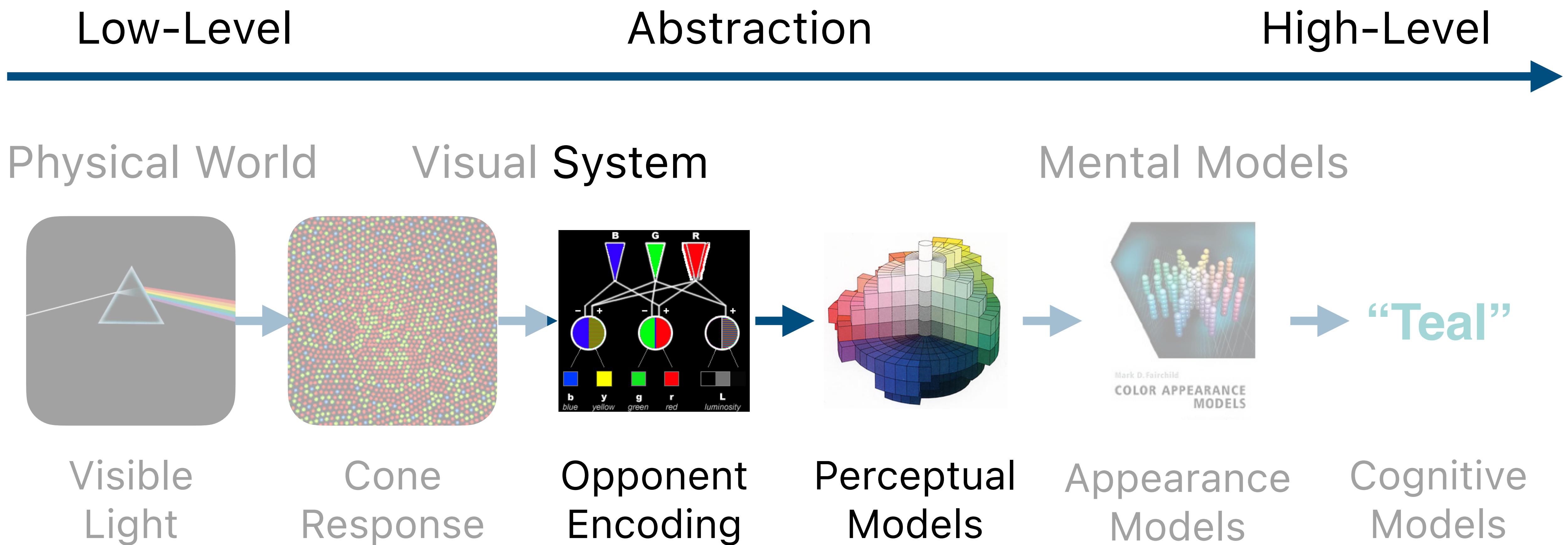
CSS `rgb()` uses the sRGB gamut:



# Modeling Color Perception



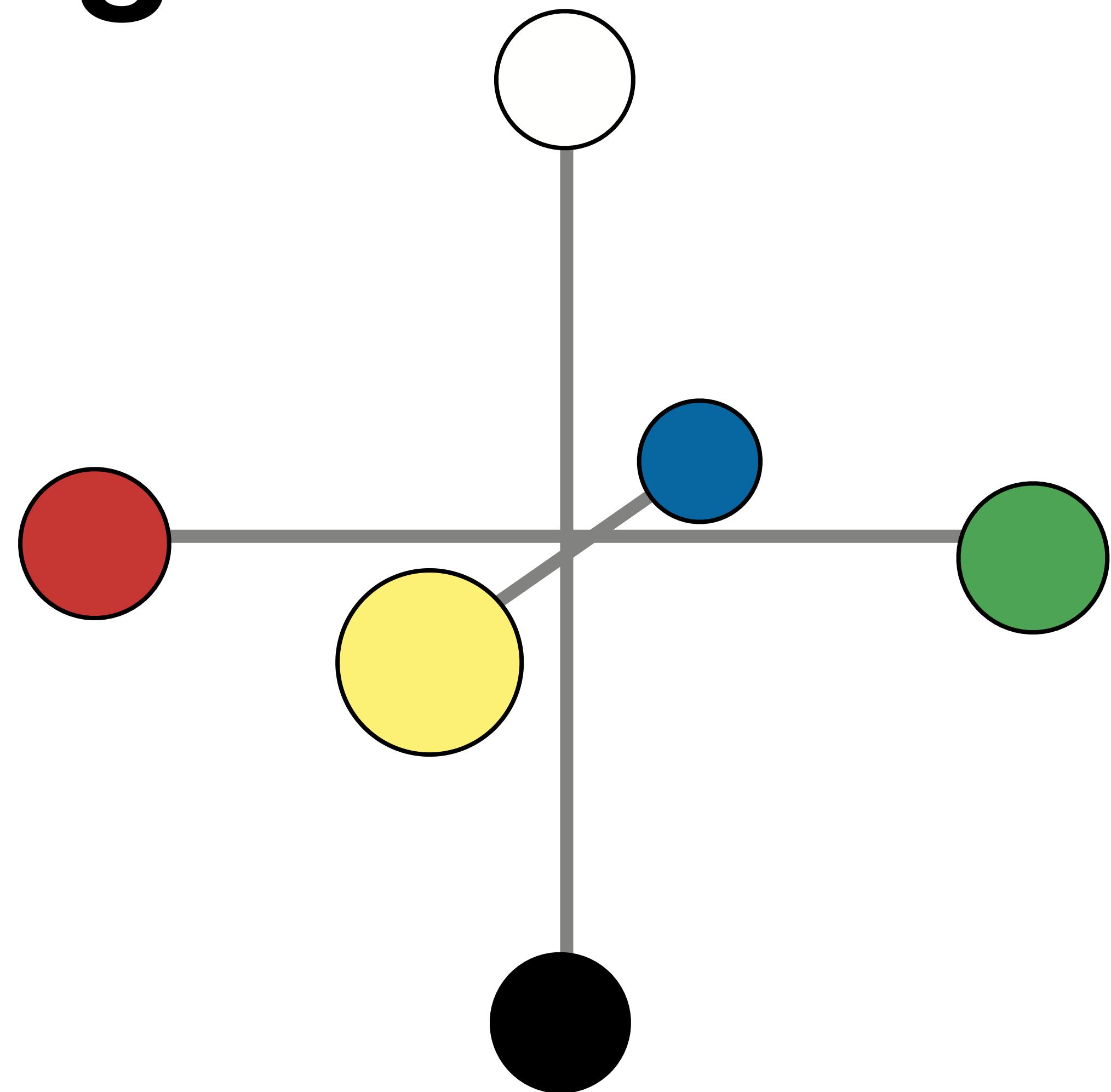
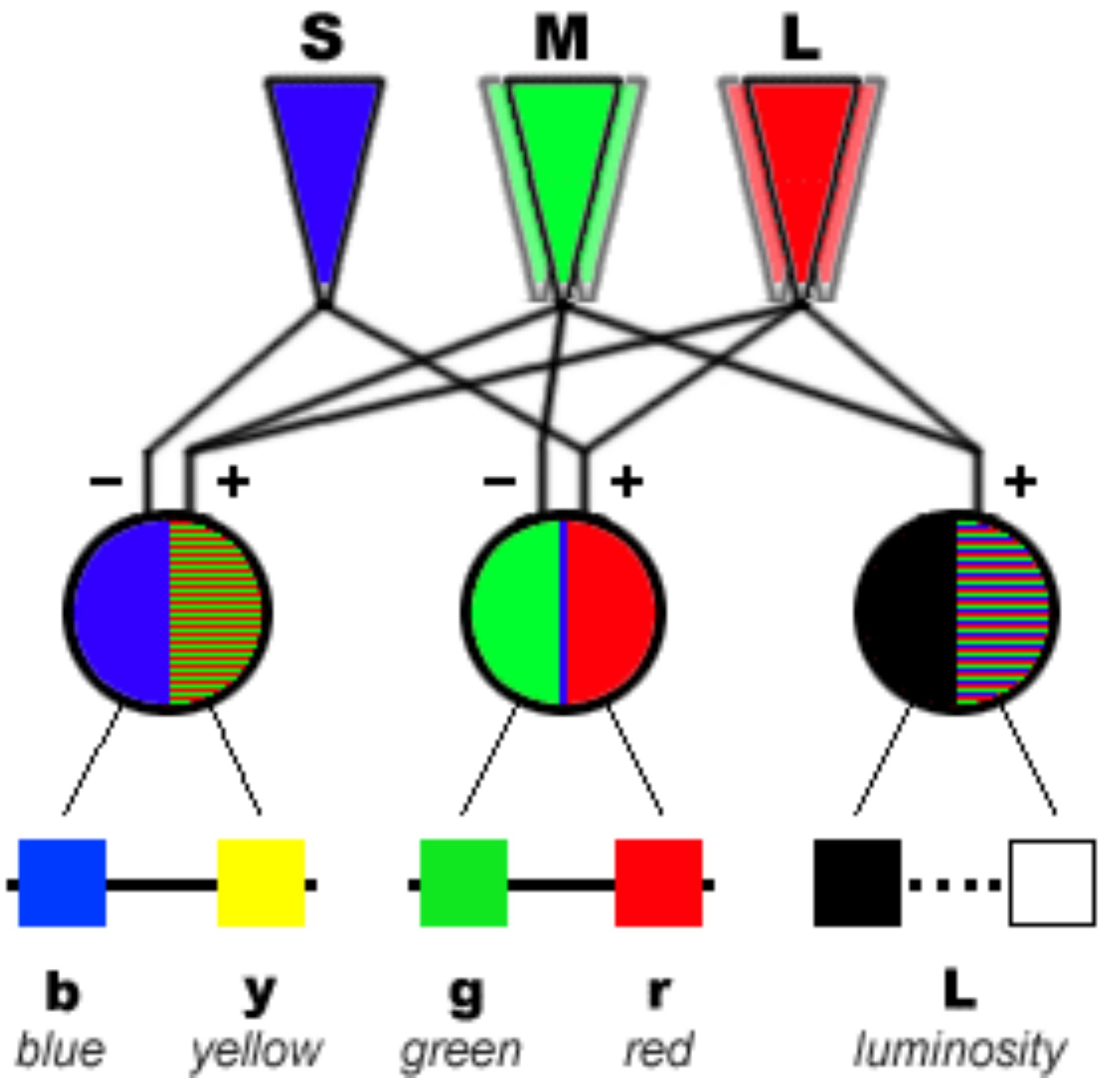
# Modeling Color Perception







# Opponent Encoding



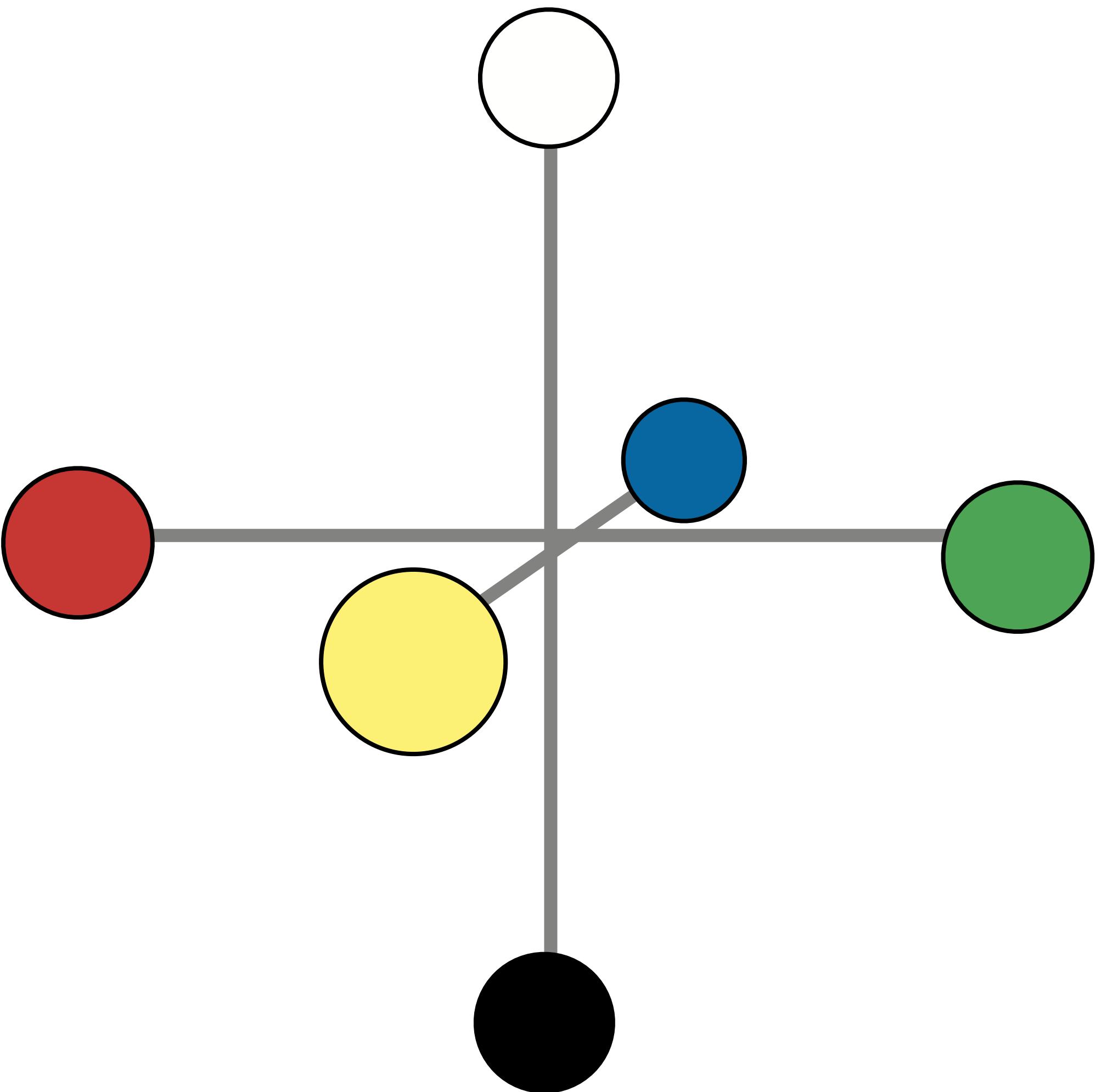
# CIE LAB Color Space

Axes correspond to opponent signals:

$L^*$  = luminance

$a^*$  = red-green contrast

$b^*$  = yellow-blue contrast

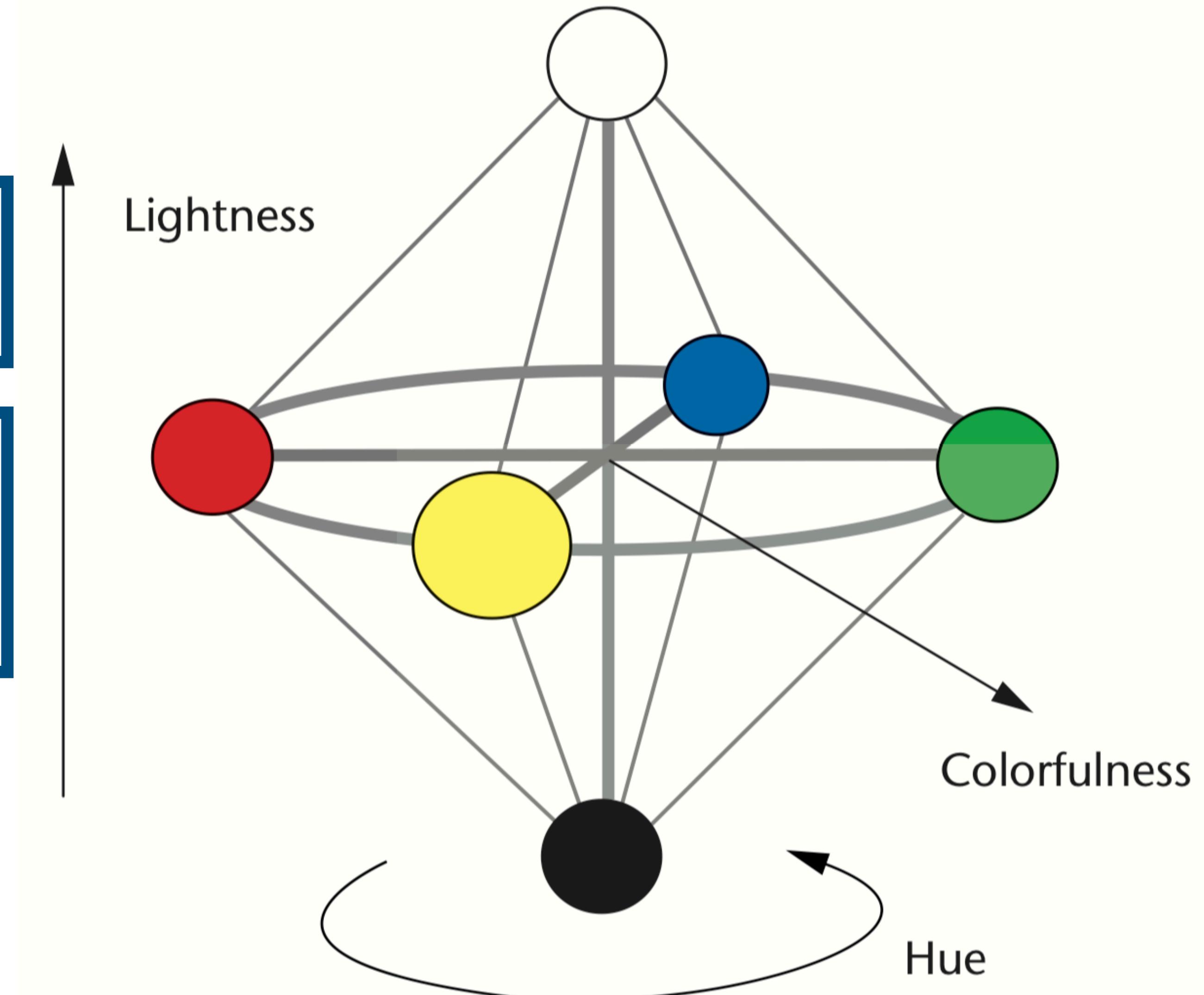


# OKLAB Color Space

Oklab is modern version of CIELAB that we recommend

In CSS:

`oklch(65% 50% 0)`



# OKLAB Color Space



Rainbow in Oklab



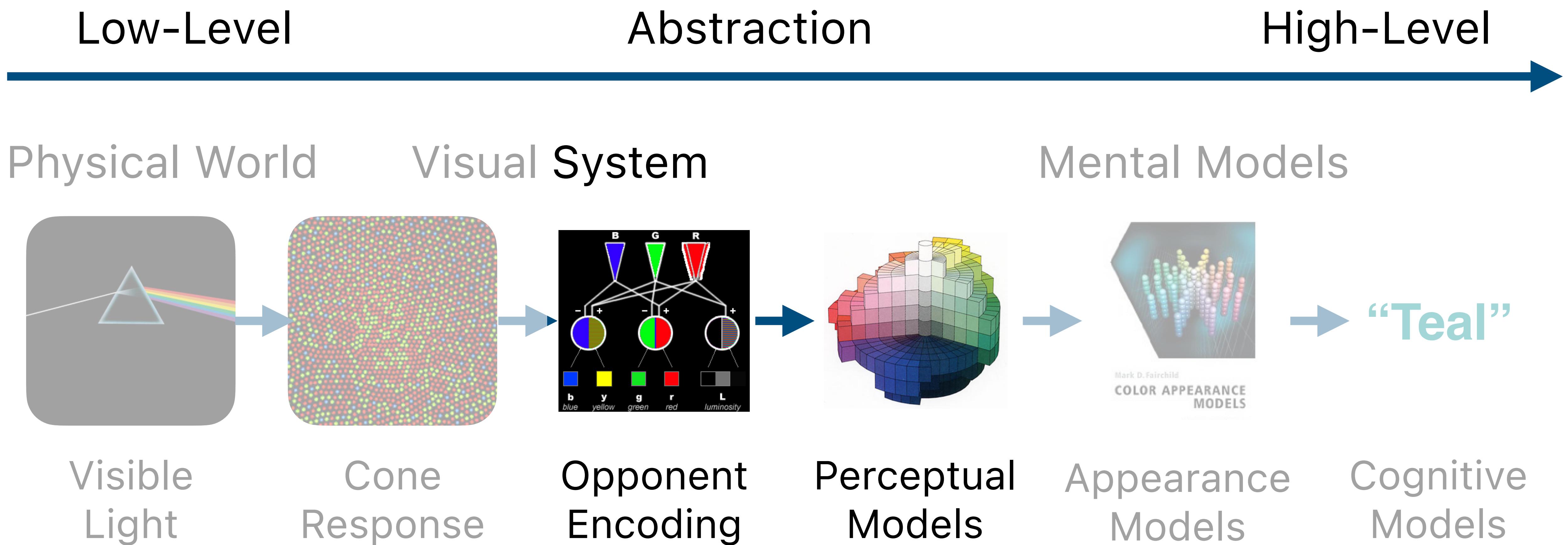
“Angry rainbow” in sRGB

Notice that there  
aren't bright “bands”:  
**perceptually uniform**

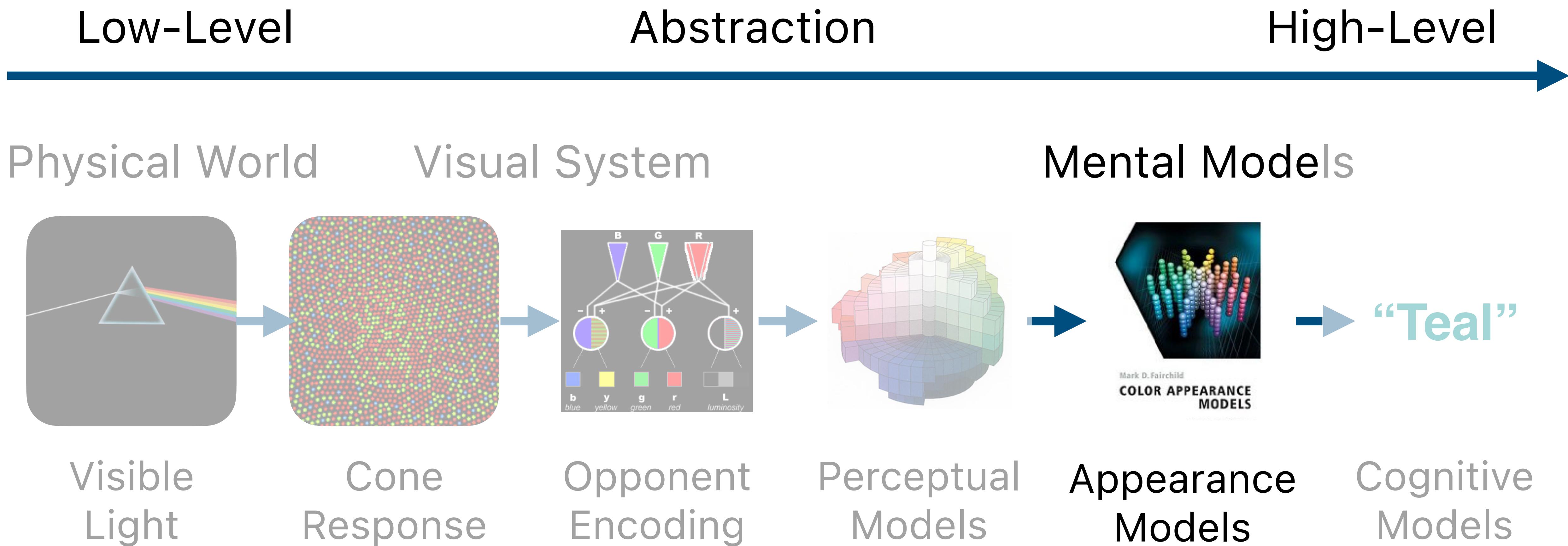
**But still be wary!**

JND issues  
Colorblind issues

# Modeling Color Perception

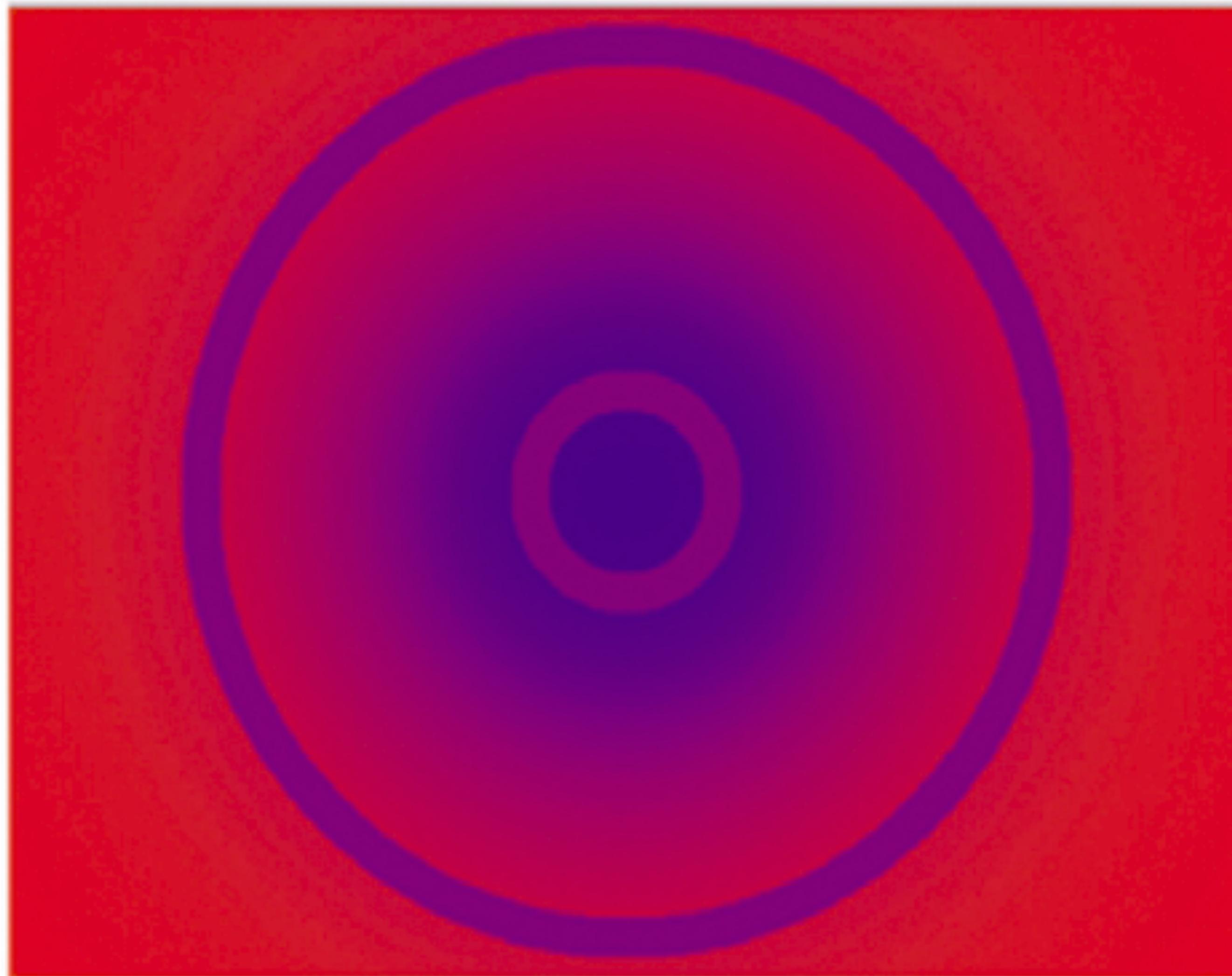


# Modeling Color Perception



# Simultaneous Contrast

Two colors side-by-side interact and affect our perception

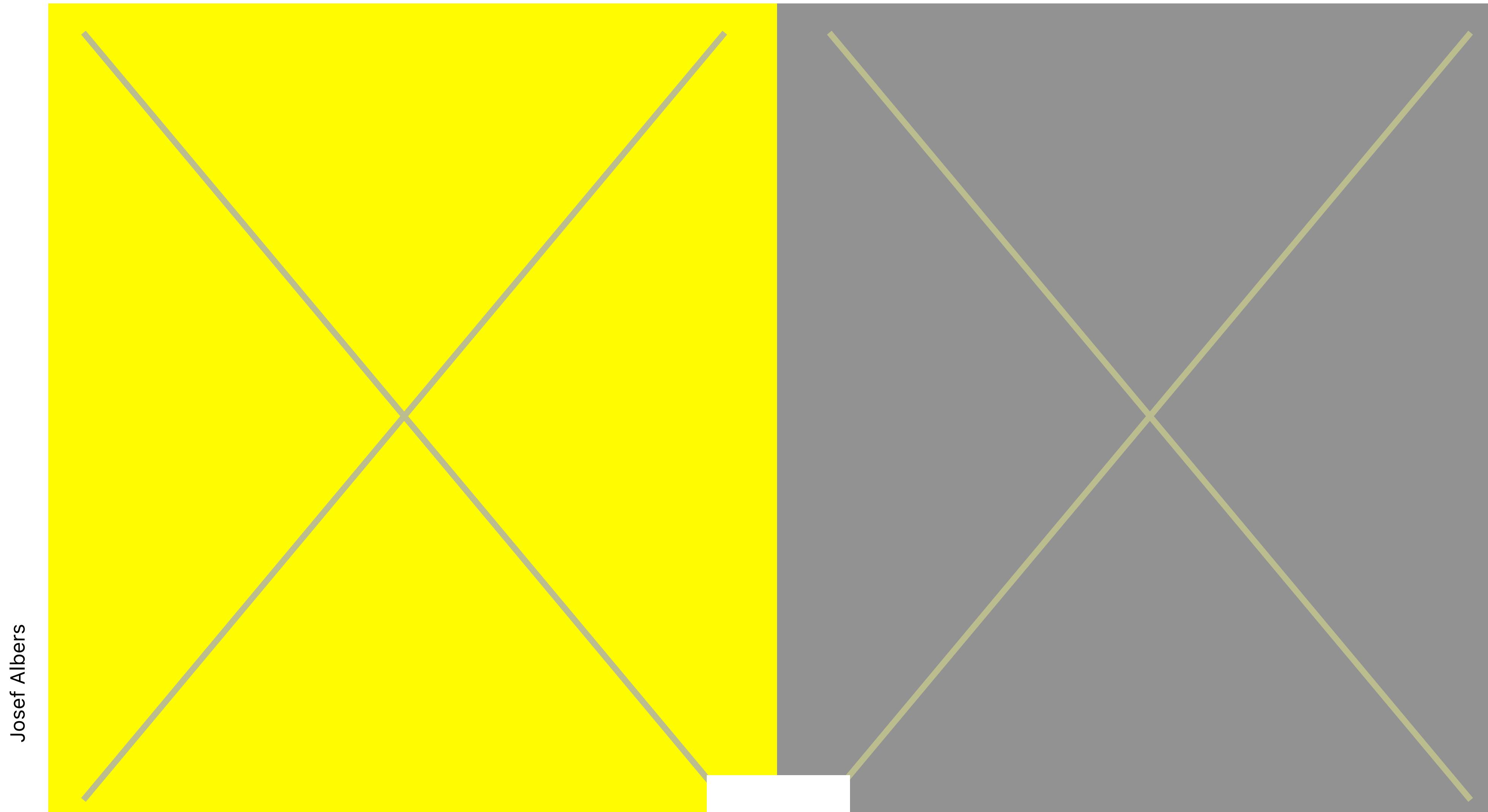


[Donald Macleod]

The inner and outer thin rings are, in fact, the same physical purple!

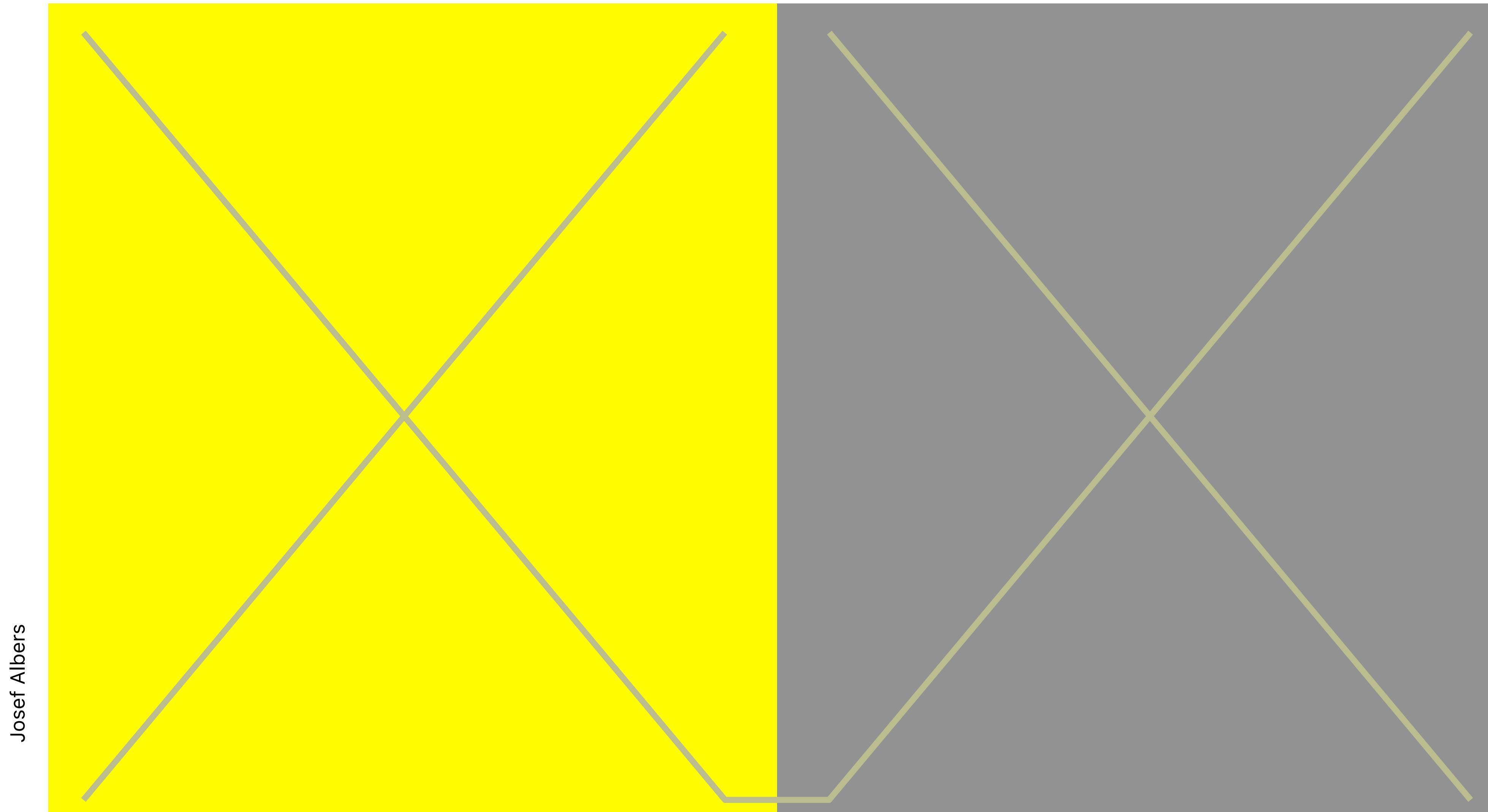
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Two colors side-by-side interact and affect our perception



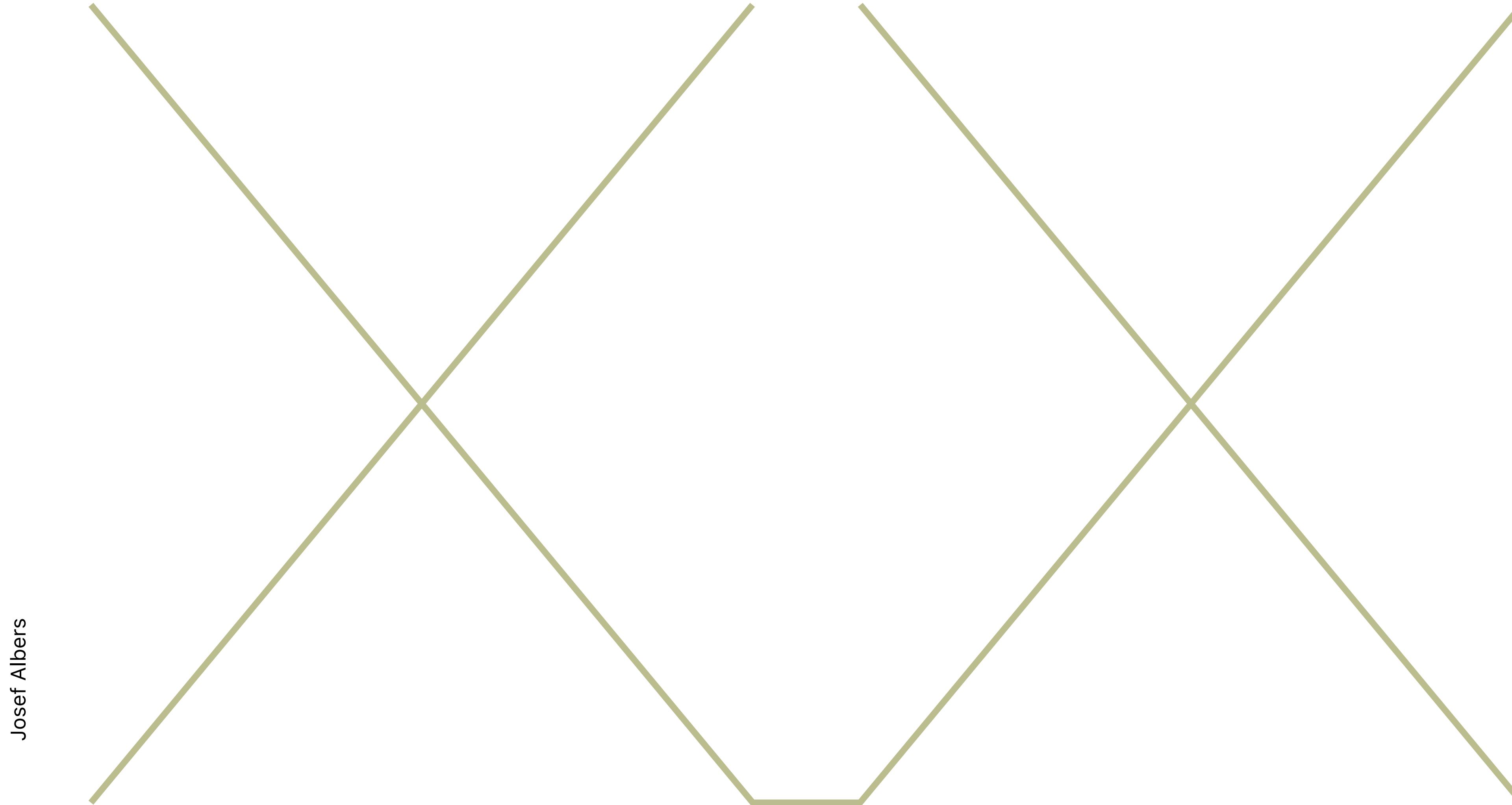
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Two colors side-by-side interact and affect our perception

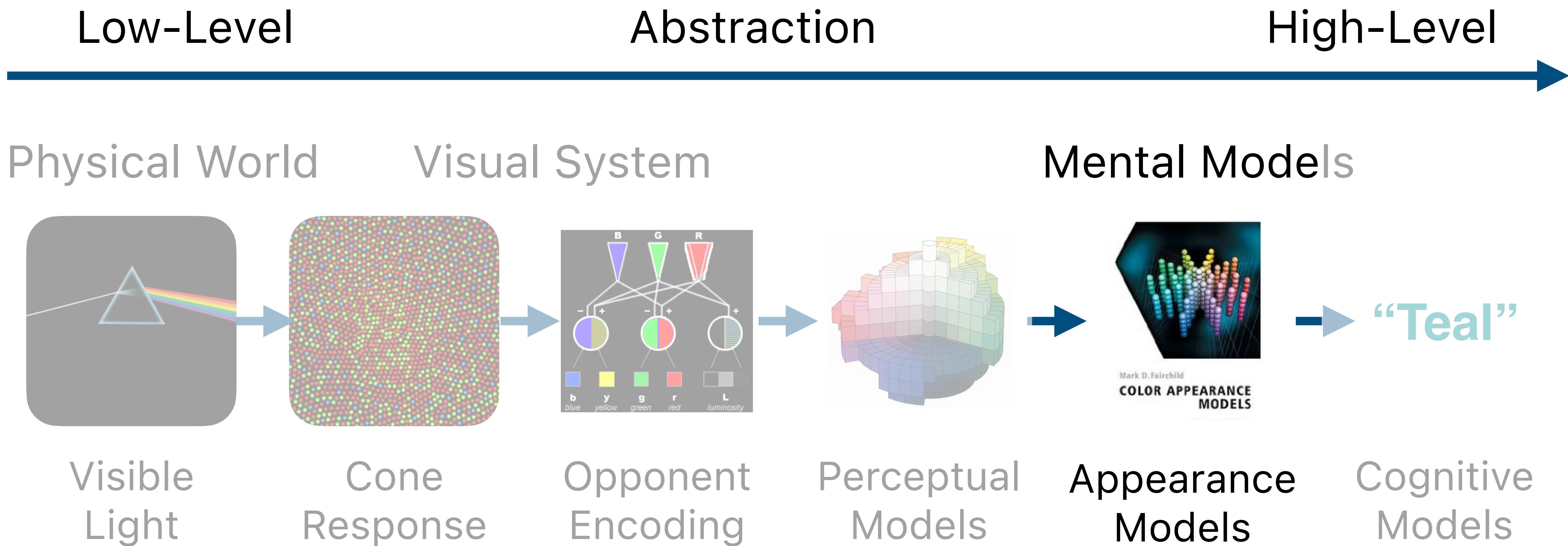


# Simultaneous Contrast

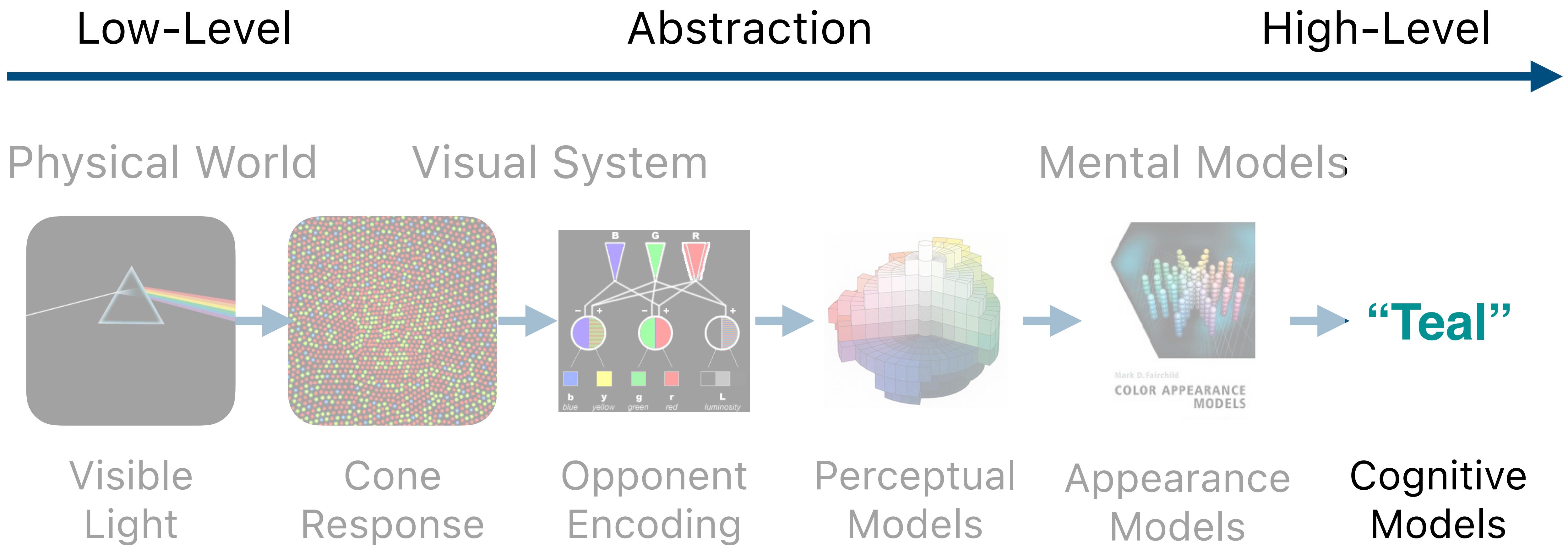
Two colors side-by-side interact and affect our perception



# Modeling Color Perception



# Modeling Color Perception



# What color is this?



# What color is this?

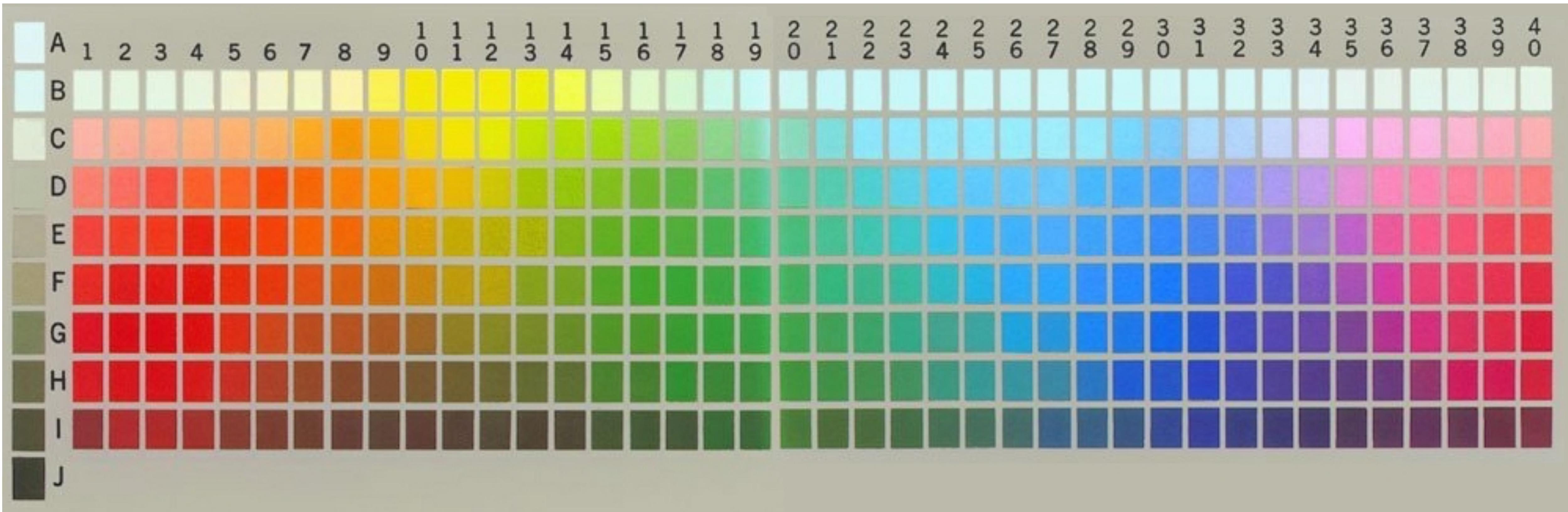


# What color is this?



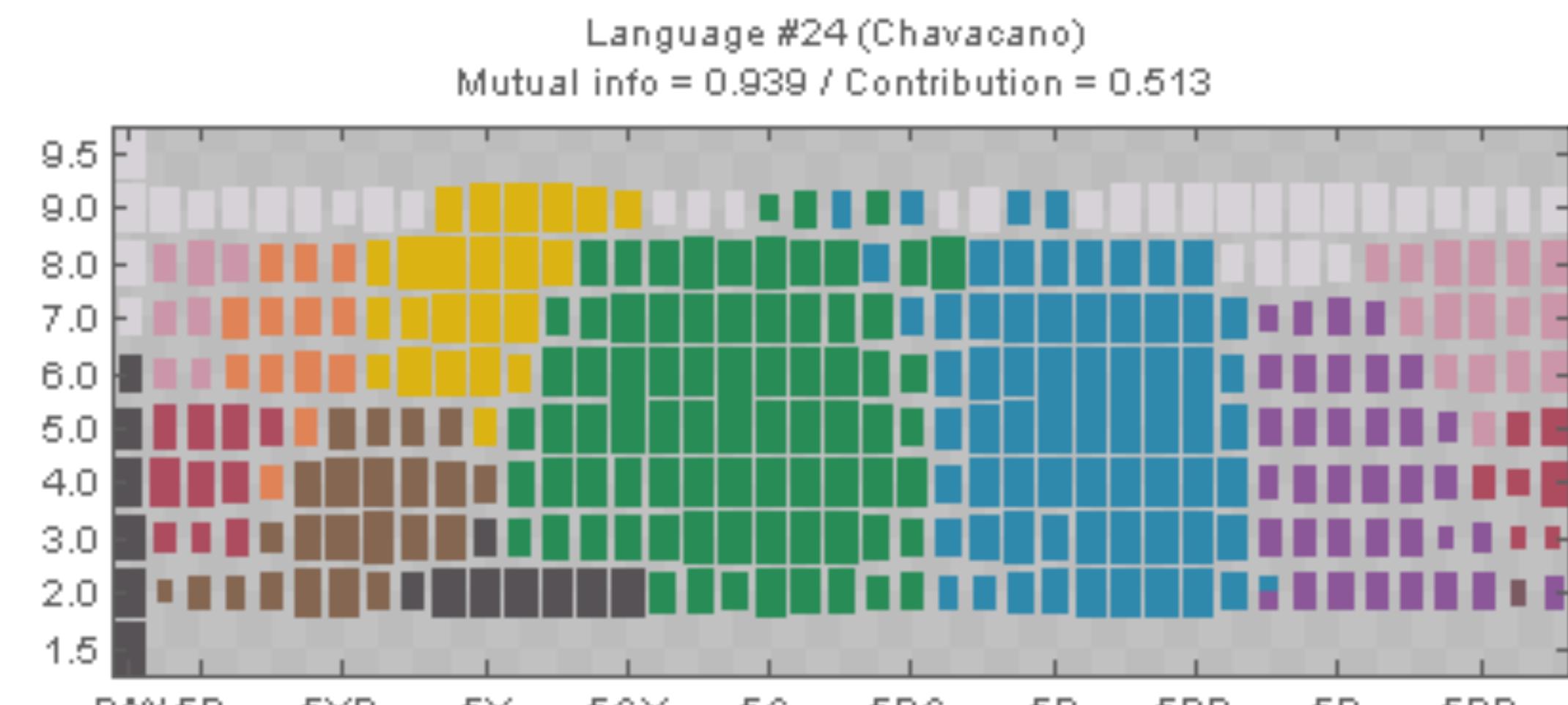
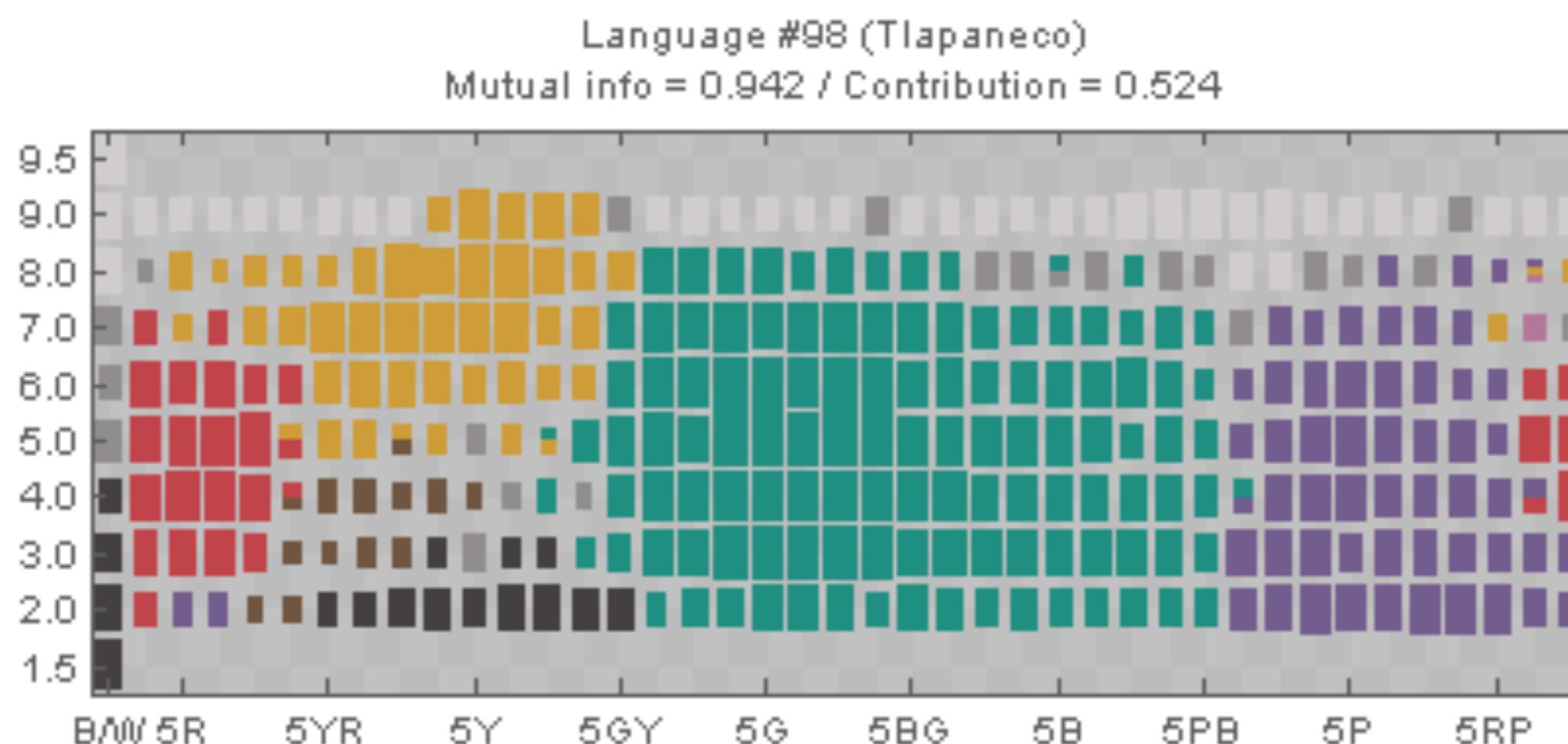
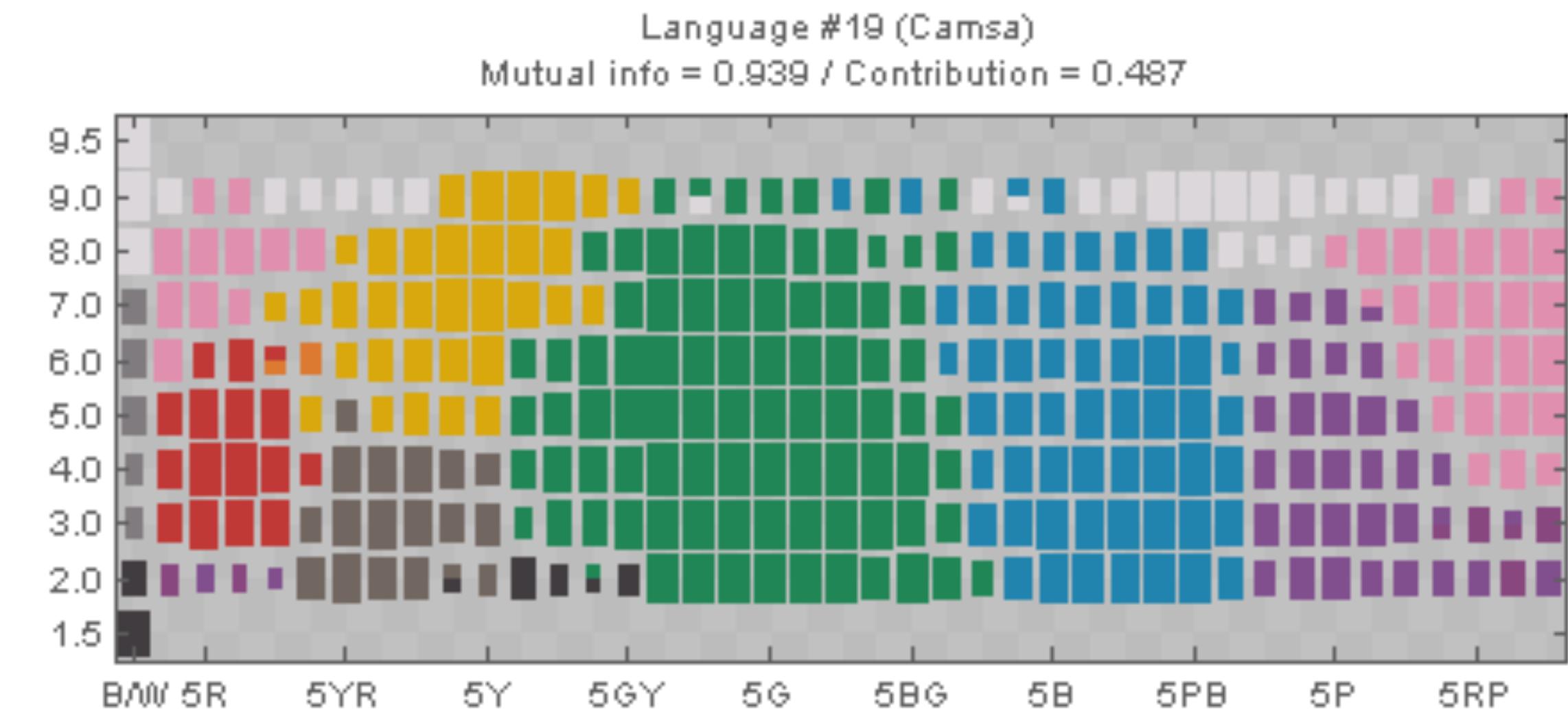
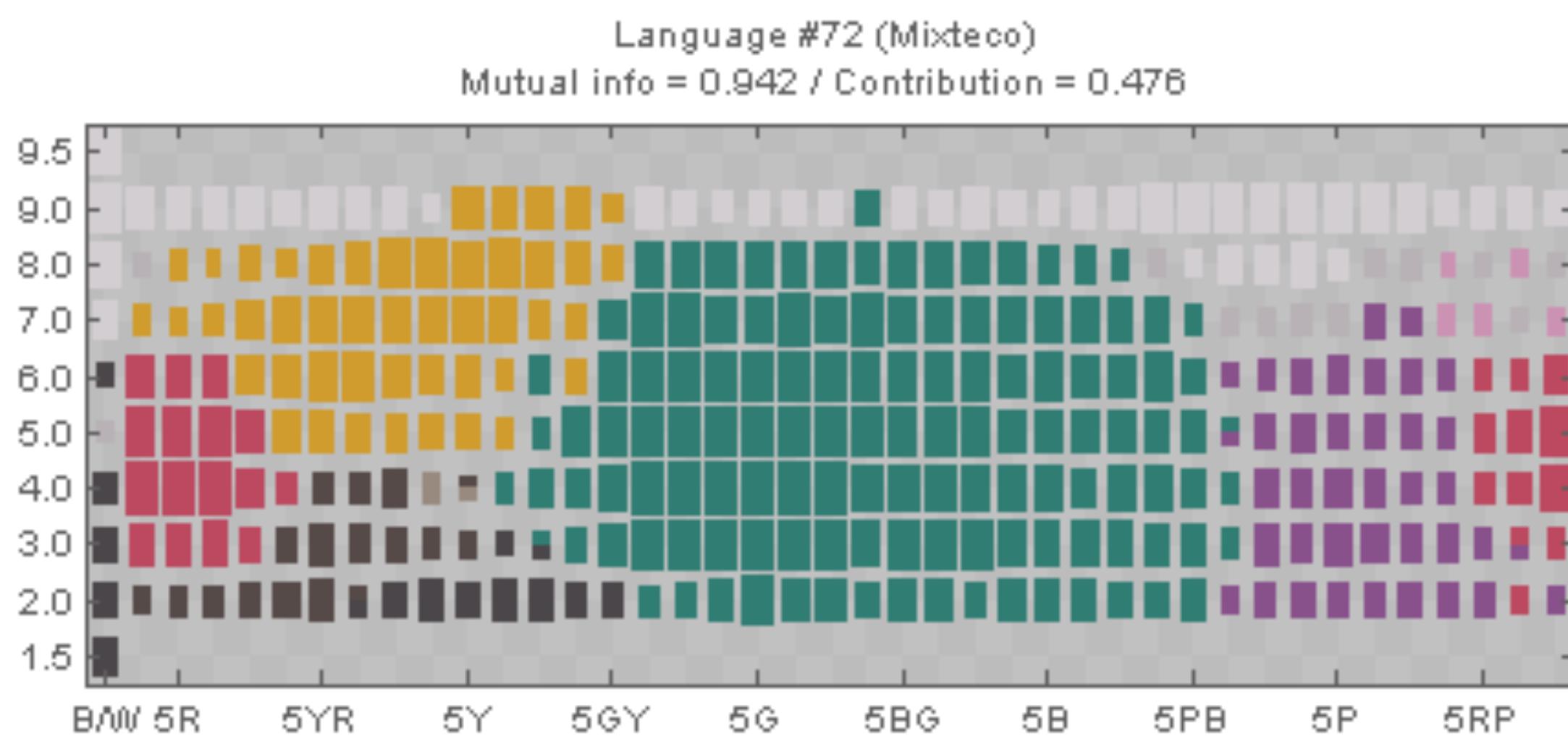
tryclassbuzz.com:  
color

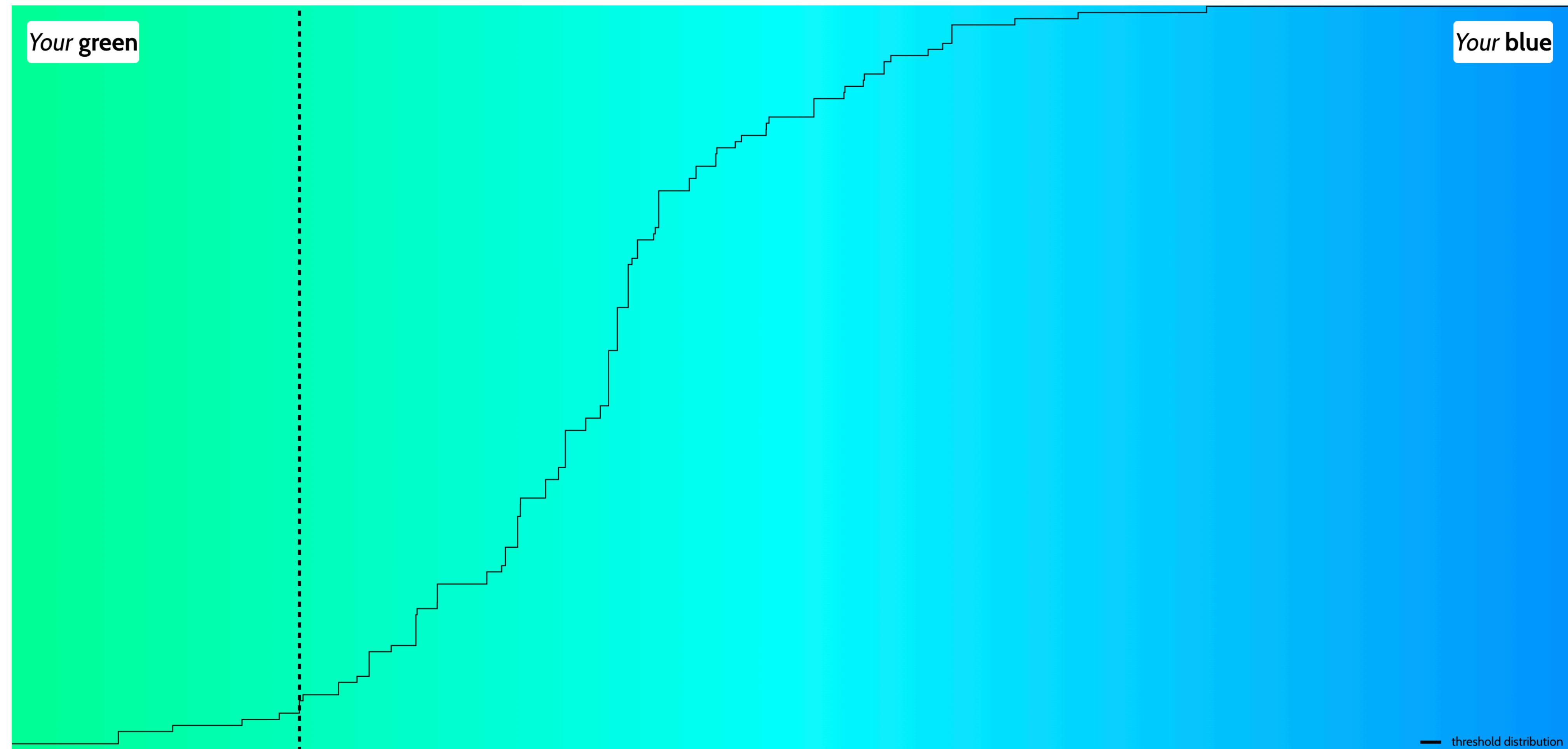
# Color Naming



Task: Mark all the chips you would label as "red", "green", etc.

# Color Naming





<https://ismy.blue/>

# Color Naming Affects Perception

Green



Blue



# Color Naming Affects Perception

Minimize overlap and ambiguity of colors

Color Name Distance												Salience	Name
0.00	1.00	1.00	0.89	0.08	1.00	0.19	1.00	1.00	0.88		.44	blue	61.5%
1.00	0.00	0.99	1.00	1.00	0.81	1.00	0.78	1.00	0.99		.21	red	21.1%
1.00	0.99	0.00	1.00	0.98	0.99	1.00	1.00	0.10	1.00		.39	green	42.8%
0.89	1.00	1.00	0.00	0.92	1.00	0.80	0.84	1.00	0.31		.42	purple	57.8%
0.08	1.00	0.98	0.92	0.00	1.00	0.21	1.00	0.97	0.88		.24	blue	40.4%
1.00	0.81	0.99	1.00	1.00	0.00	1.00	0.92	1.00	1.00		.28	orange	36.3%
0.19	1.00	1.00	0.80	0.21	1.00	0.00	0.94	0.97	0.58		.16	blue	25.6%
1.00	0.78	1.00	0.84	1.00	0.92	0.94	0.00	0.99	0.76		.10	pink	21.8%
1.00	1.00	0.10	1.00	0.97	1.00	0.97	0.99	0.00	0.96		.21	green	30.8%
0.88	0.99	1.00	0.31	0.88	1.00	0.58	0.76	0.96	0.00		.25	purple	22.7%
Excel-10												Average	0.86
													.27

[Heer and Stone, CHI 2012]

Default color palette for Excel: confusion!

# Color Naming Affects Perception

Minimize overlap and ambiguity of colors

Color Name Distance											Salience	Name
0.00	1.00	1.00	1.00	0.96	1.00	1.00	0.99	1.00	0.19	.47	blue	65.3%
1.00	0.00	1.00	0.98	1.00	1.00	1.00	1.00	0.97	1.00	.87	orange	92.2%
1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.70	0.99	.70	green	81.3%
1.00	0.98	1.00	0.00	1.00	0.96	0.99	1.00	1.00	1.00	.64	red	79.3%
0.96	1.00	1.00	1.00	0.00	0.95	0.83	0.98	1.00	0.97	.43	purple	52.5%
1.00	1.00	1.00	0.96	0.95	0.00	0.99	0.96	0.96	1.00	.47	brown	60.5%
1.00	1.00	1.00	0.99	0.83	0.99	0.00	1.00	1.00	1.00	.47	pink	60.3%
0.99	1.00	1.00	1.00	0.98	0.96	1.00	0.00	1.00	0.99	.74	grey	83.7%
1.00	0.97	0.70	1.00	1.00	0.96	1.00	1.00	0.00	1.00	.11	yellow	20.1%
0.19	1.00	0.99	1.00	0.97	1.00	1.00	0.99	1.00	0.00	.25	blue	27.2%

Tableau-10      Average 0.96      .52

[Heer and Stone, CHI 2012]

Default color palette for Tableau: better!

# **Putting it together: Designing colormaps**

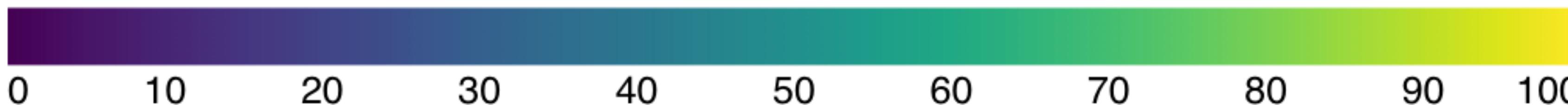
## Discrete (binary, categorical)

### Symbol Legend



## Continuous (sequential, diverging, cyclic)

### Gradient Legend



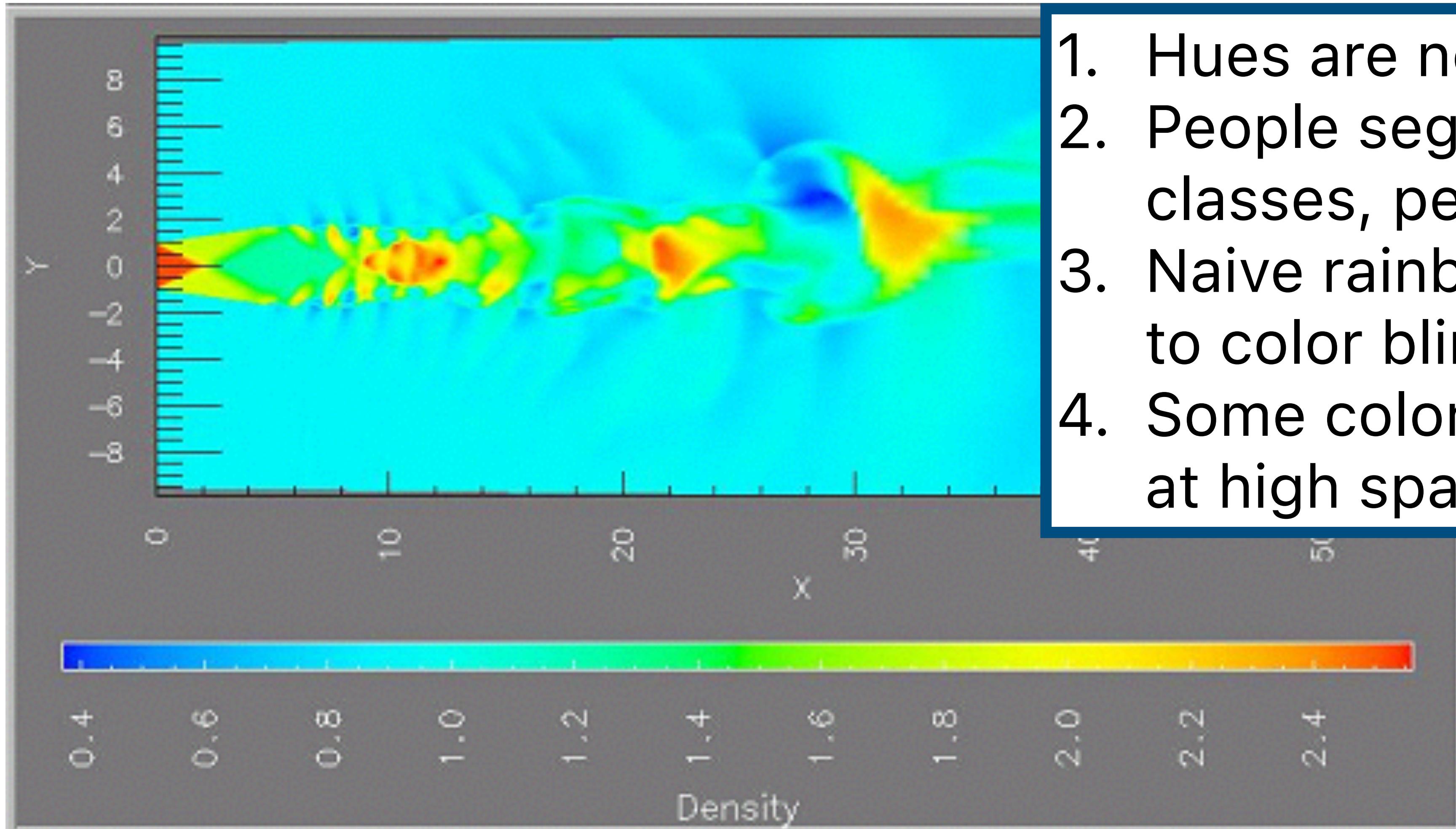
## Discretized Continuous

In general, prefer this over continuous!

### Discrete Gradient



# Beware of naive rainbows!

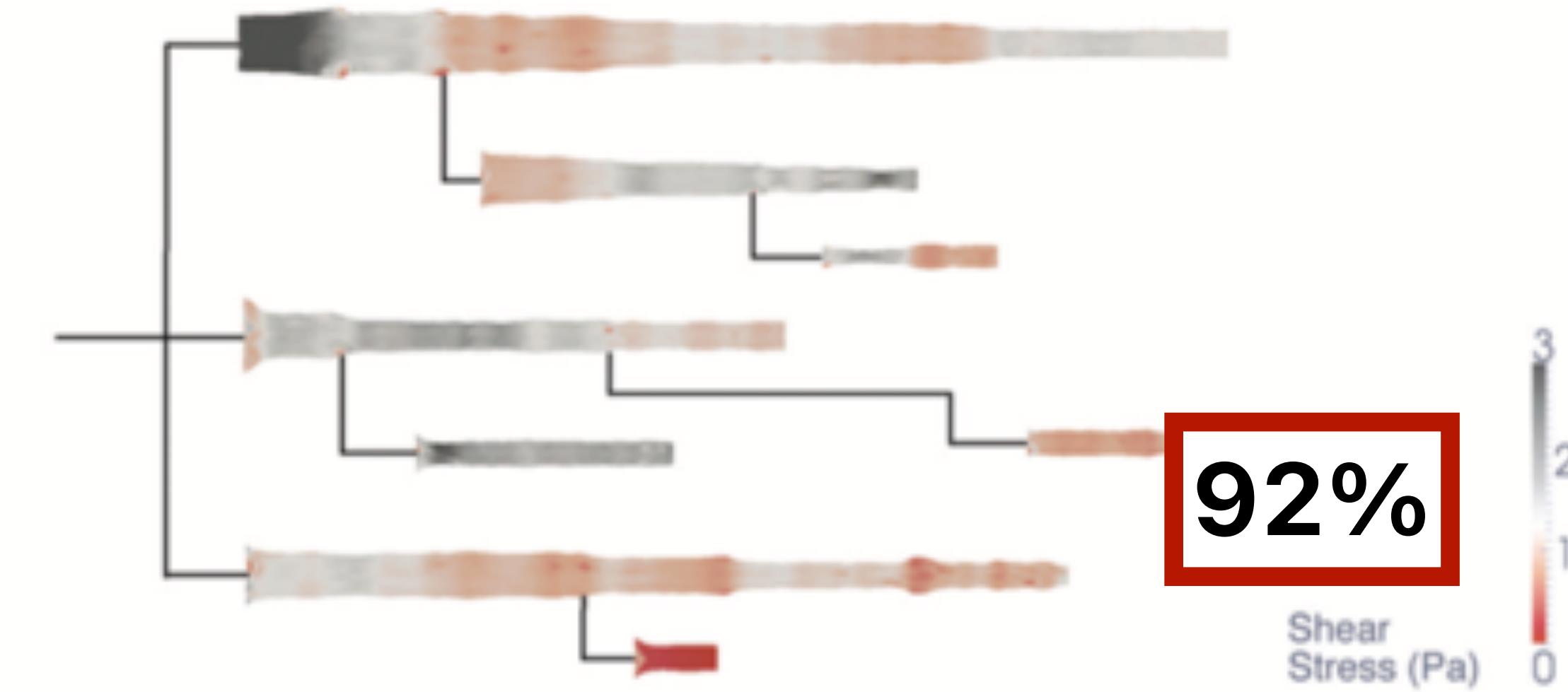


1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naive rainbows are unfriendly to color blind viewers
4. Some colors are less effective at high spatial frequencies

# Beware of naive rainbows!



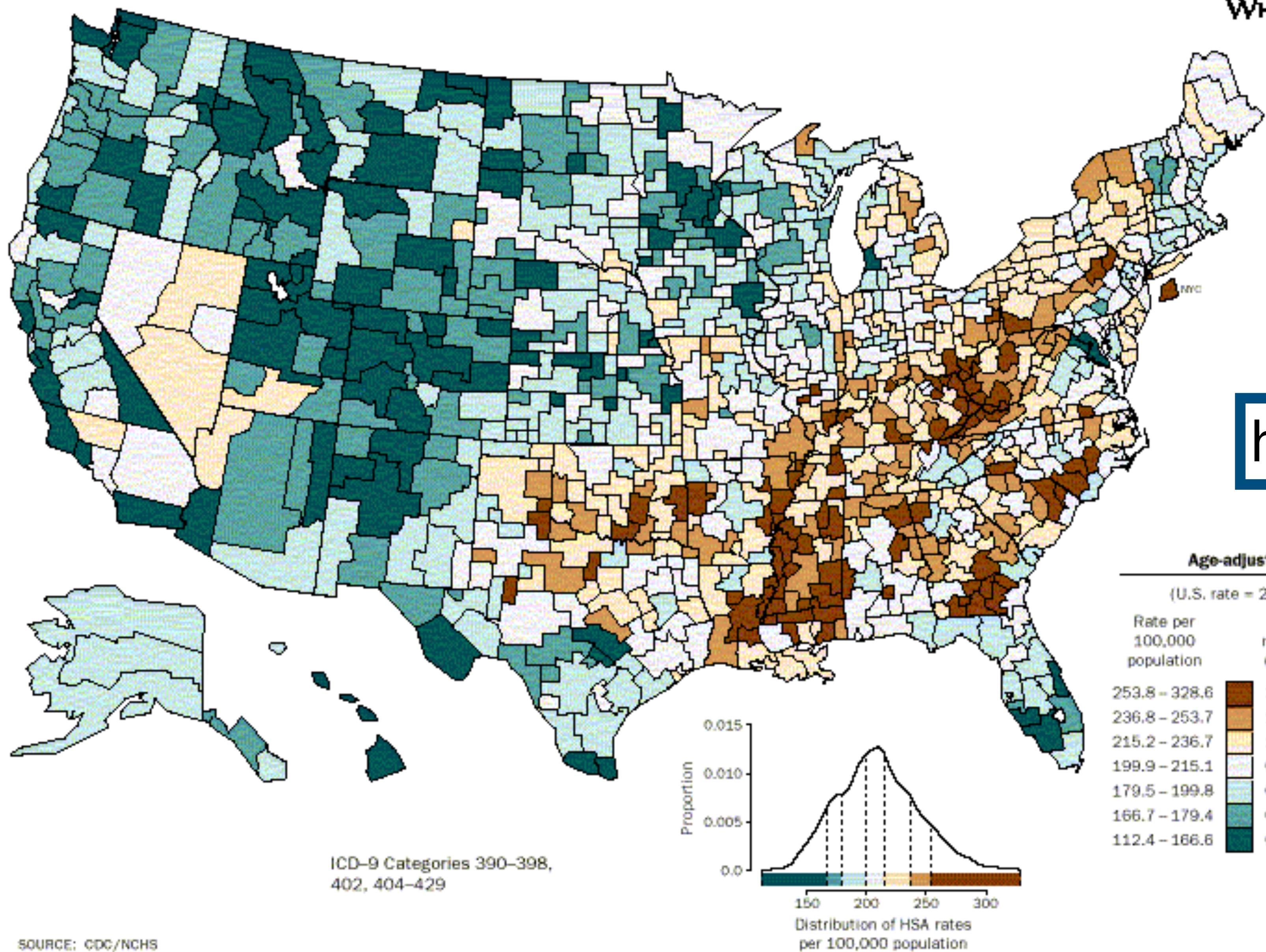
Rainbow Palette



Diverging Palette



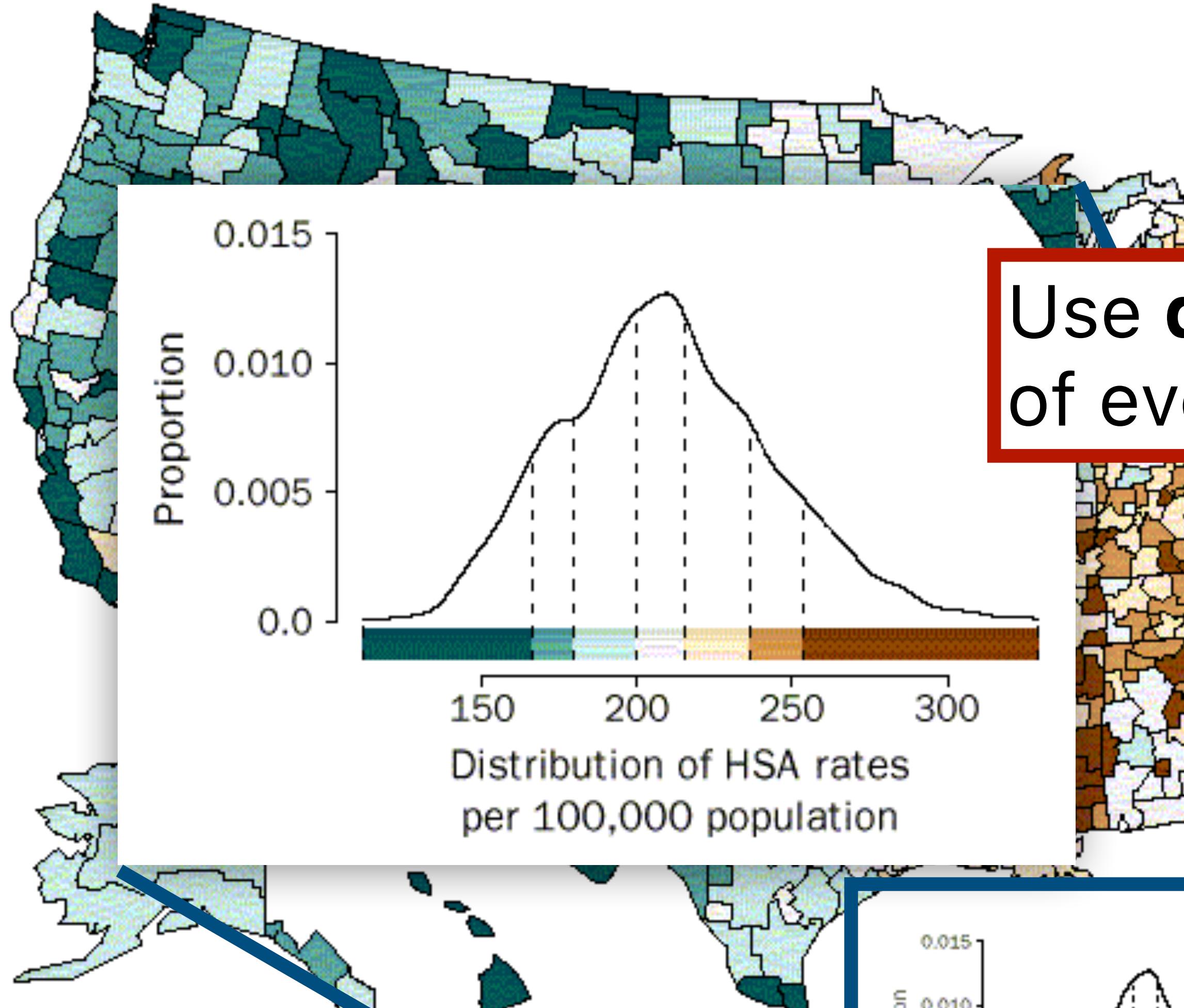
32 AGE-ADJUSTED DEATH RATES BY HSA, 1988-92



Cynthia Brewer  
<https://colorbrewer2.org/>



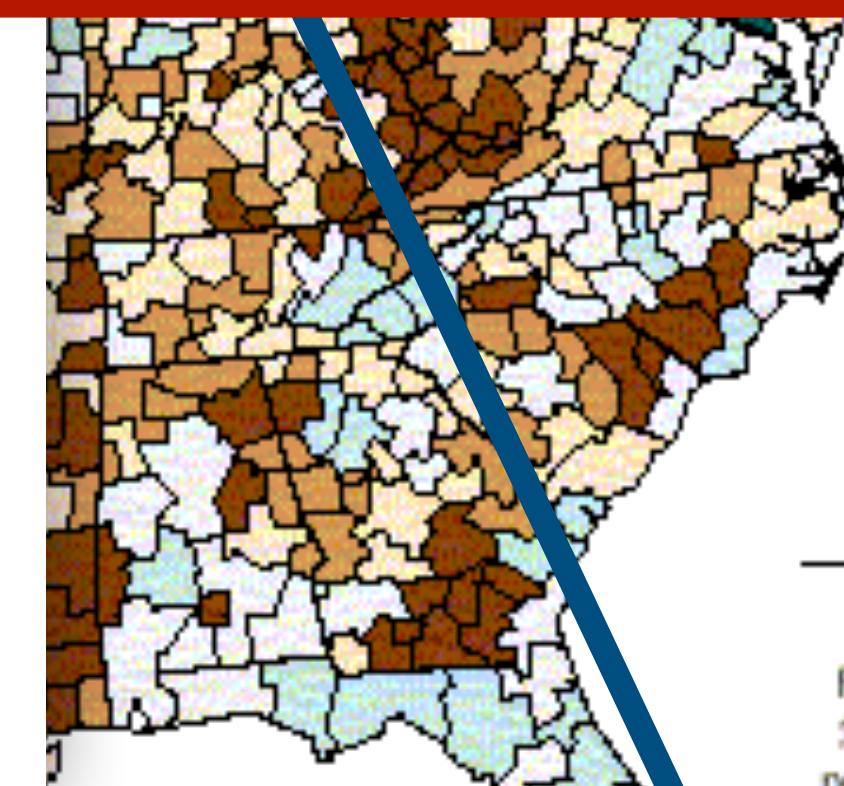
## AGE-ADJUSTED DEATH RATES BY HSA, 1988-92



SOURCE: CDC/NCHS

HEART DISEASE  
WHITE MALE

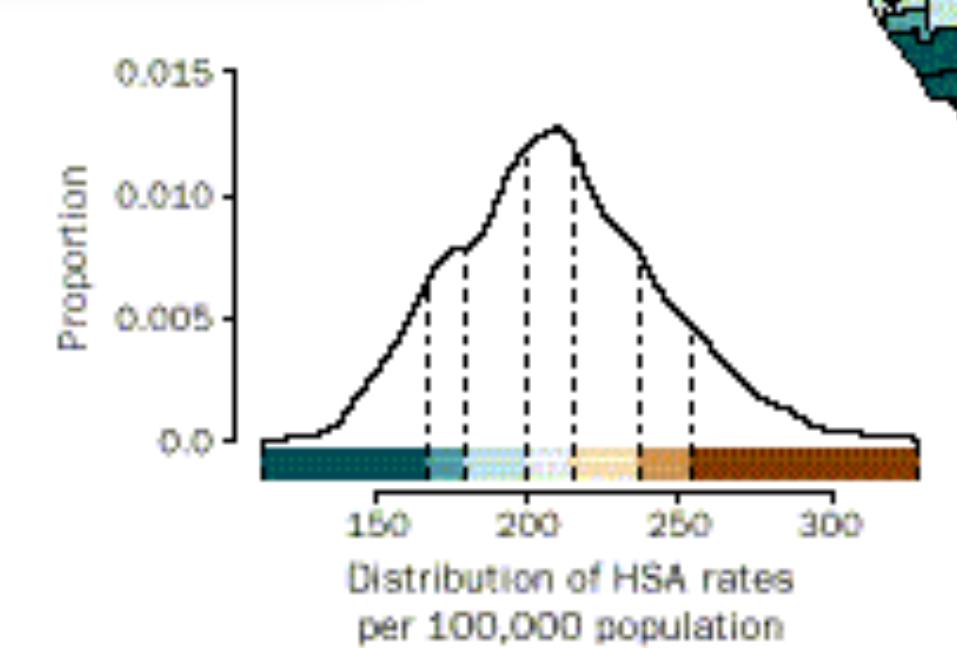
Use quantiles instead  
of evenly-spaced bins



## Age-adjusted

(U.S. rate = 205.0)

Rate per 100,000 population	Comparative mortality ratio (HSA to U.S.)
253.8 - 328.6	1.24 - 1.60
236.8 - 253.7	1.16 - 1.24
215.2 - 236.7	1.05 - 1.16
199.9 - 215.1	0.98 - 1.05
179.5 - 199.8	0.88 - 0.98
166.7 - 179.4	0.81 - 0.88
112.4 - 166.6	0.55 - 0.81



<https://colorbrewer2.org/>



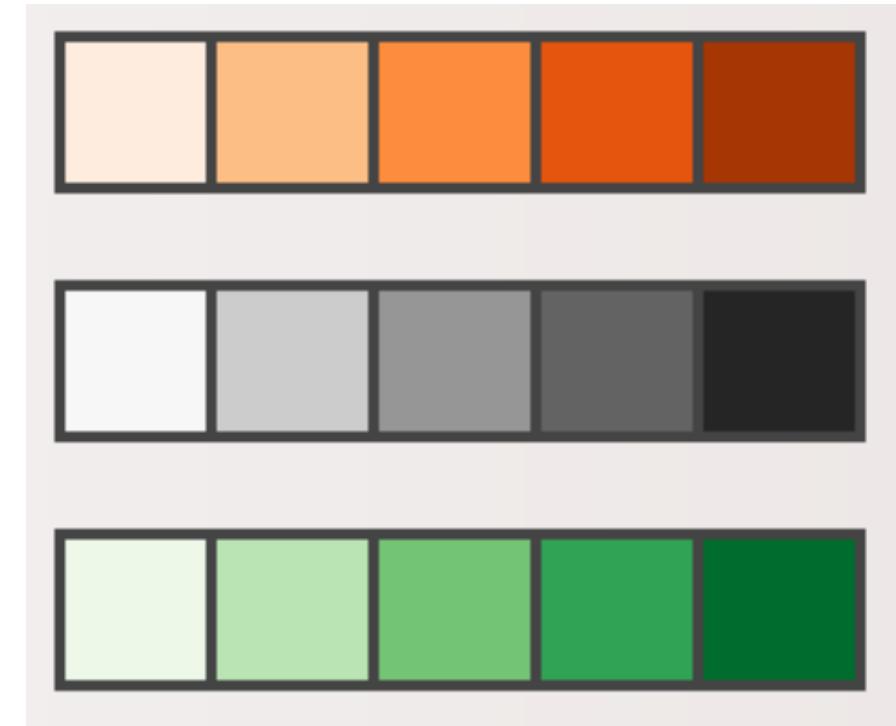
Cynthia Brewer

# Quantitative Color Encoding

## Sequential Color Scale

Ramp in luminance, possibly also hue.

Typically higher values map to darker colors.

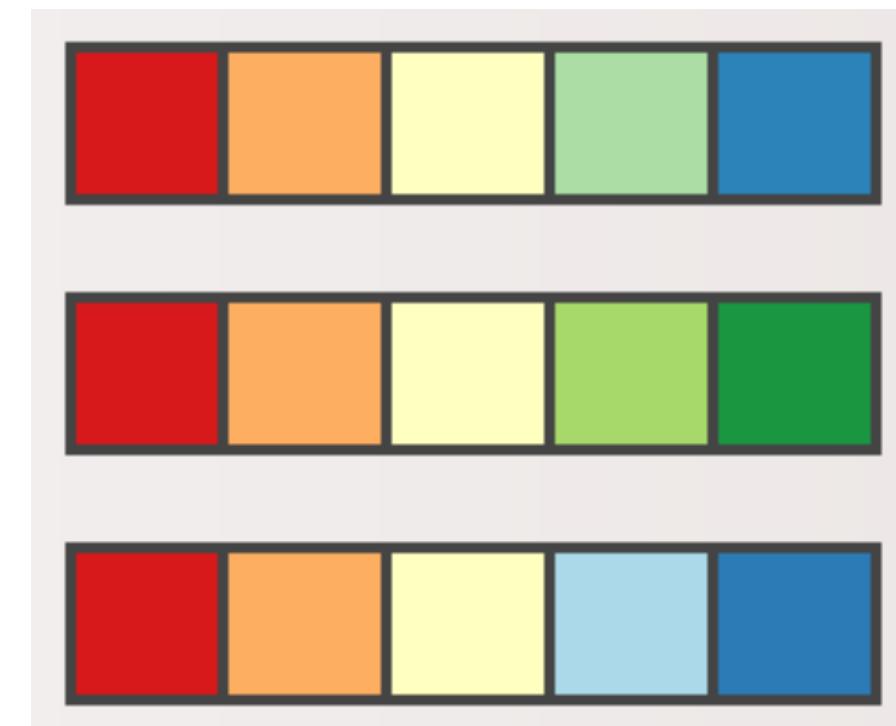


## Diverging Color Scale

Useful when data has a meaningful “midpoint.”

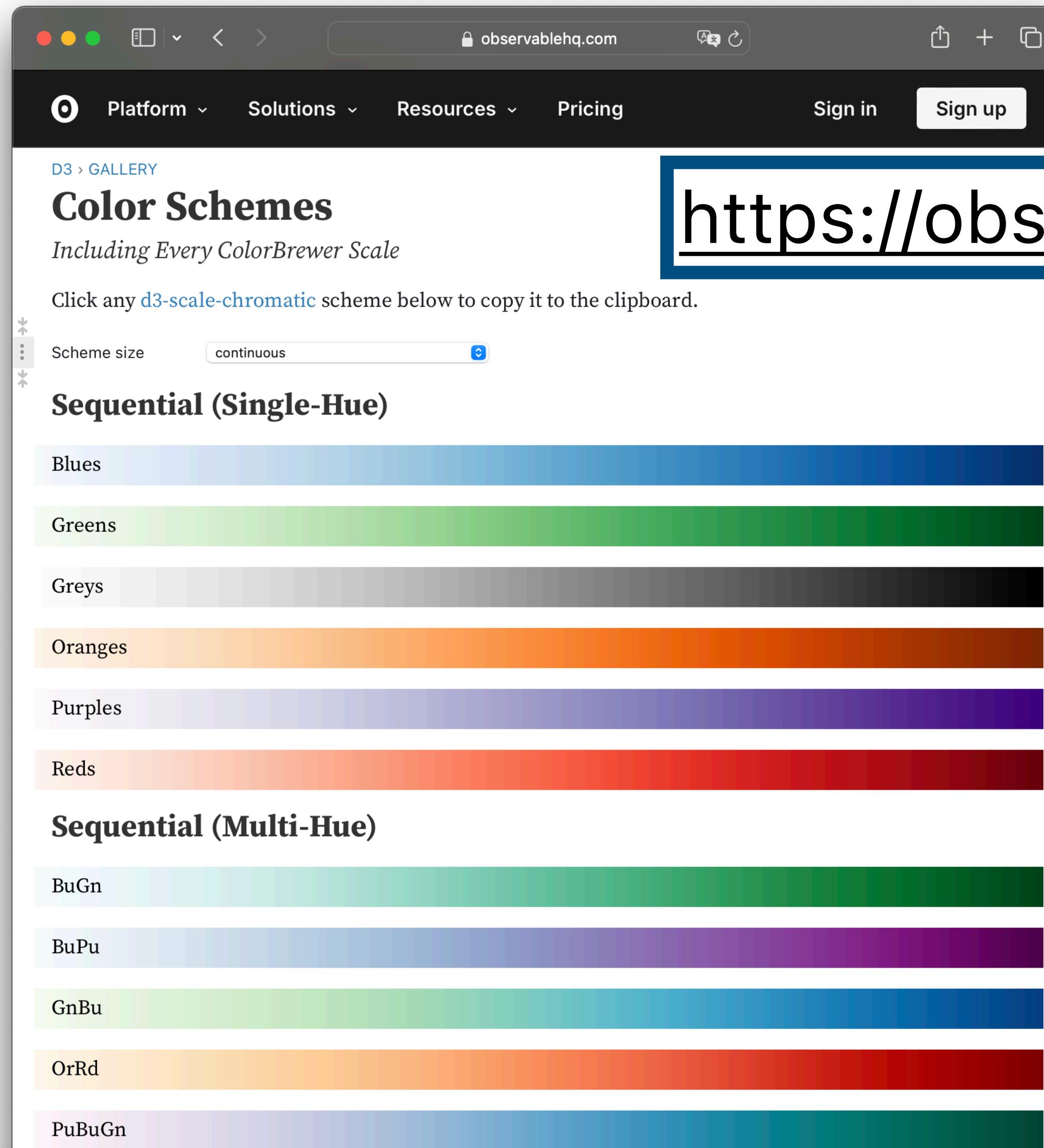
Use neutral color (e.g., gray) for midpoint.

Use saturated colors for endpoints.



**Limit number of steps in color to 3–7!**

# Use Perceptually Uniform Color Schemes!



The screenshot shows a web browser window for observablehq.com. The URL https://observablehq.com/@d3/color-schemes is displayed in a dark blue header bar. The main content area is titled "Color Schemes" and "Including Every ColorBrewer Scale". It features a list of color schemes under two categories: "Sequential (Single-Hue)" and "Sequential (Multi-Hue)".

**Sequential (Single-Hue)**

- Blues
- Greens
- Greys
- Oranges
- Purples
- Reds

**Sequential (Multi-Hue)**

- BuGn
- BuPu
- GnBu
- OrRd
- PuBuGn

Click any `d3-scale-chromatic` scheme below to copy it to the clipboard.

Scheme size: continuous

Sign in | Sign up

D3 > GALLERY

<https://observablehq.com/@d3/color-schemes>

# Takeaways

Use only a few colors (~5 ideally)

Colors should be distinctive and named.

Use/respect cultural conventions; appreciate symbolism.

Get it right in black and white.

Respect the color blind.

Take advantage of perceptual color spaces.