

# 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

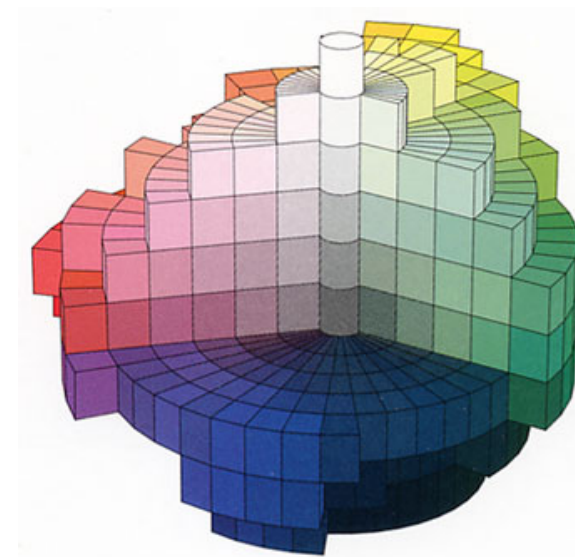
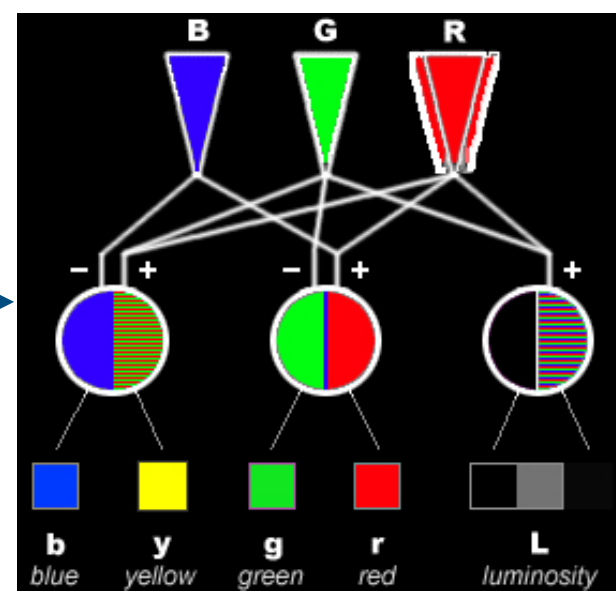
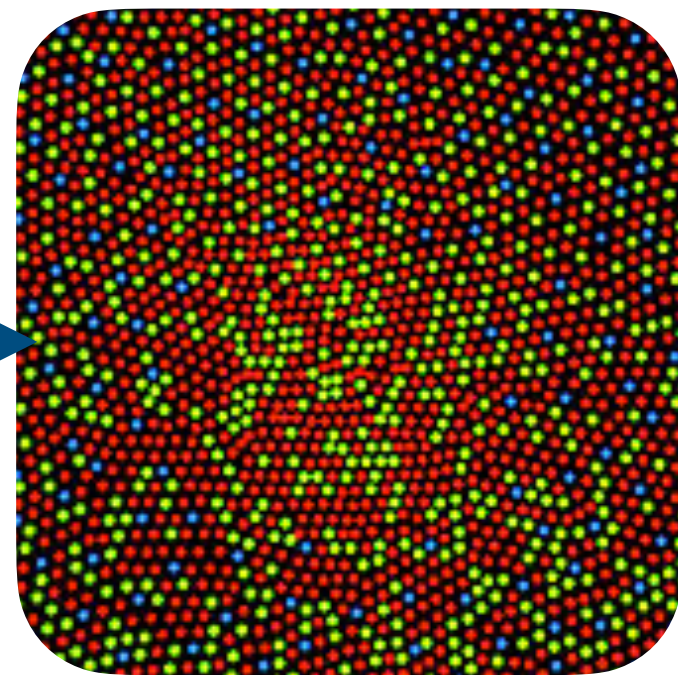
Low-Level

High-Level

Physical World

Visual System

Mental Models



“Teal”

Visible Light

Cone Response

Opponent Encoding

Perceptual Models

Appearance Models

Cognitive Models

# Modeling Color Perception

Low-Level

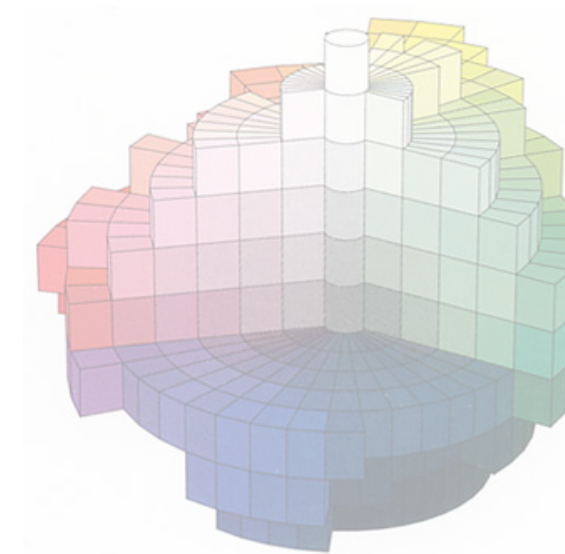
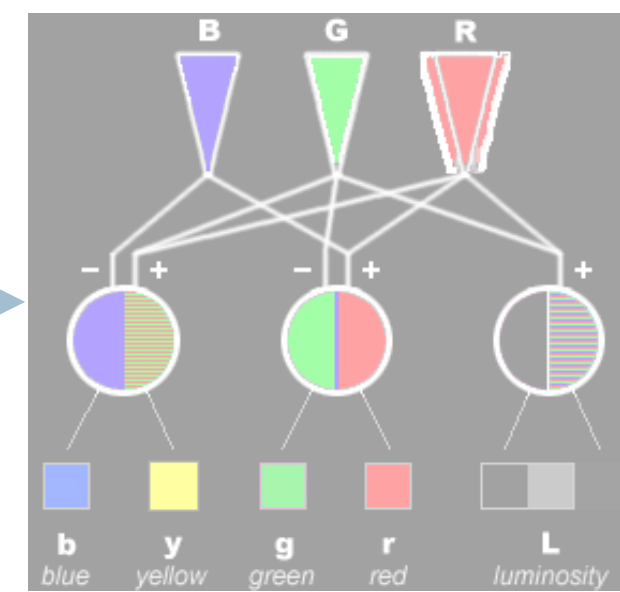
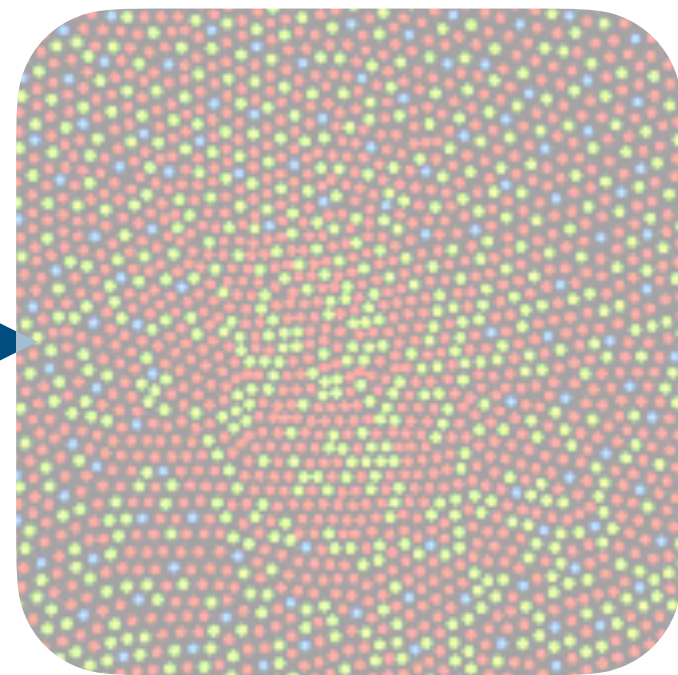
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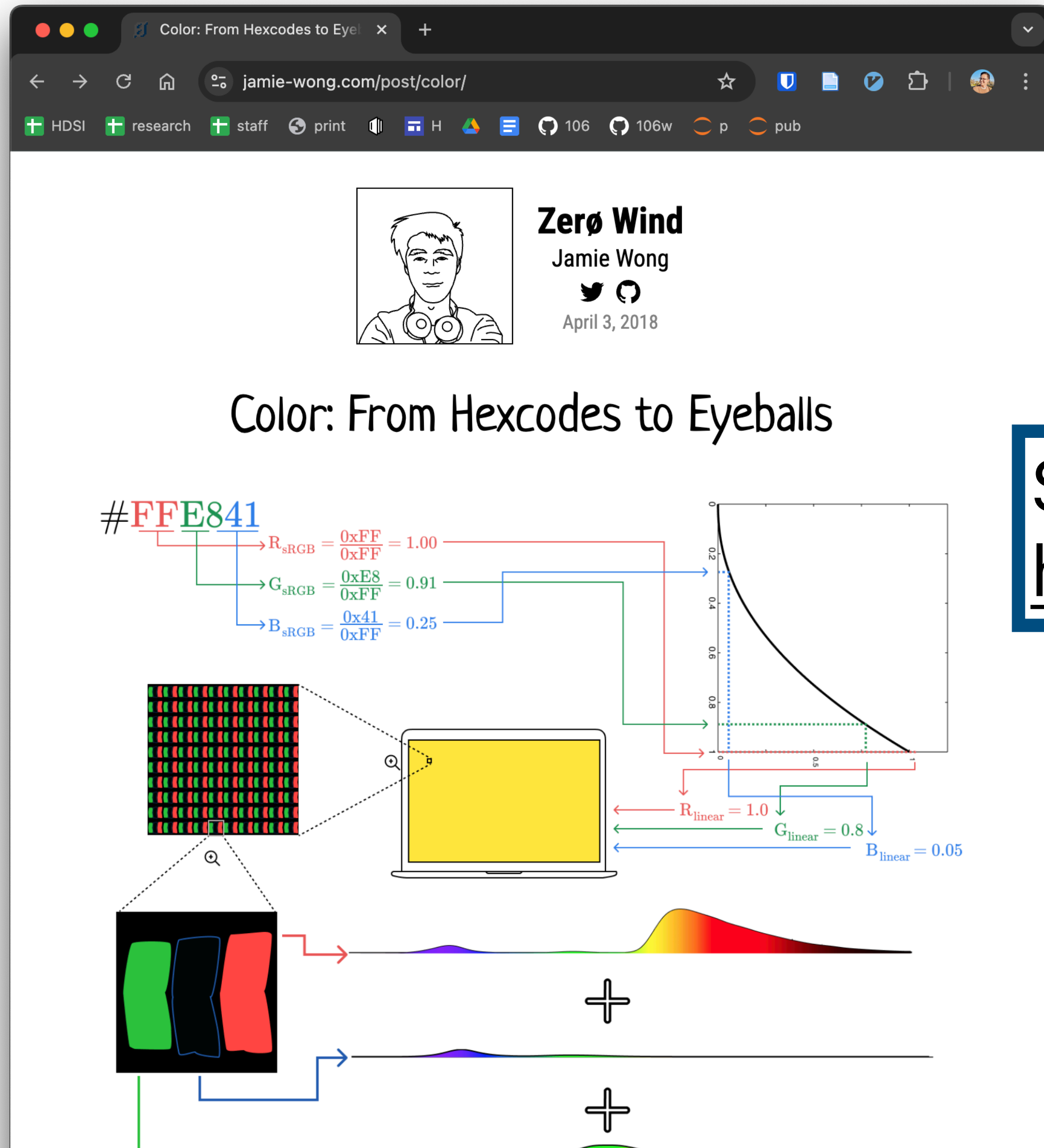
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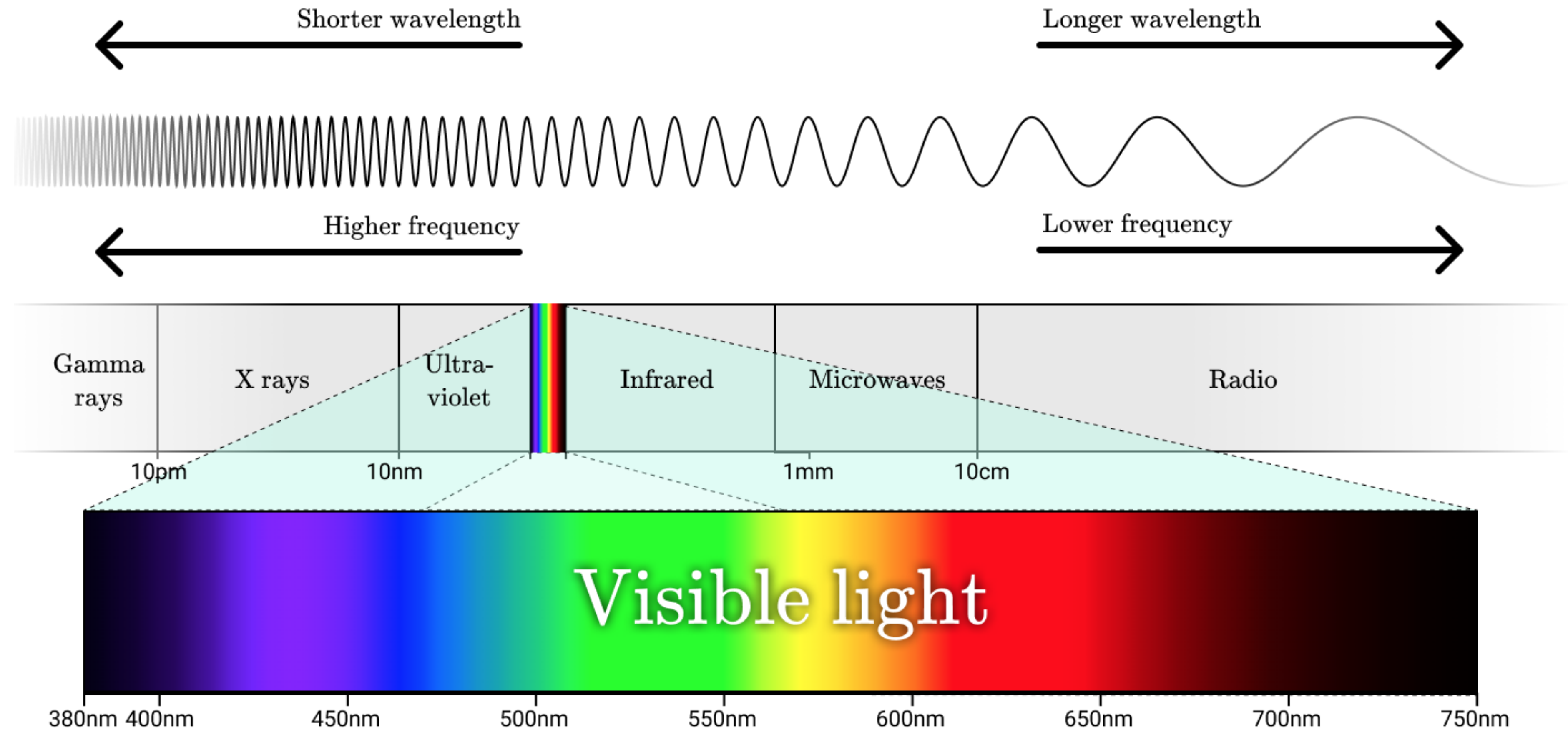
# Credit to Jamie Wong for many of the images



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

# Visible Light

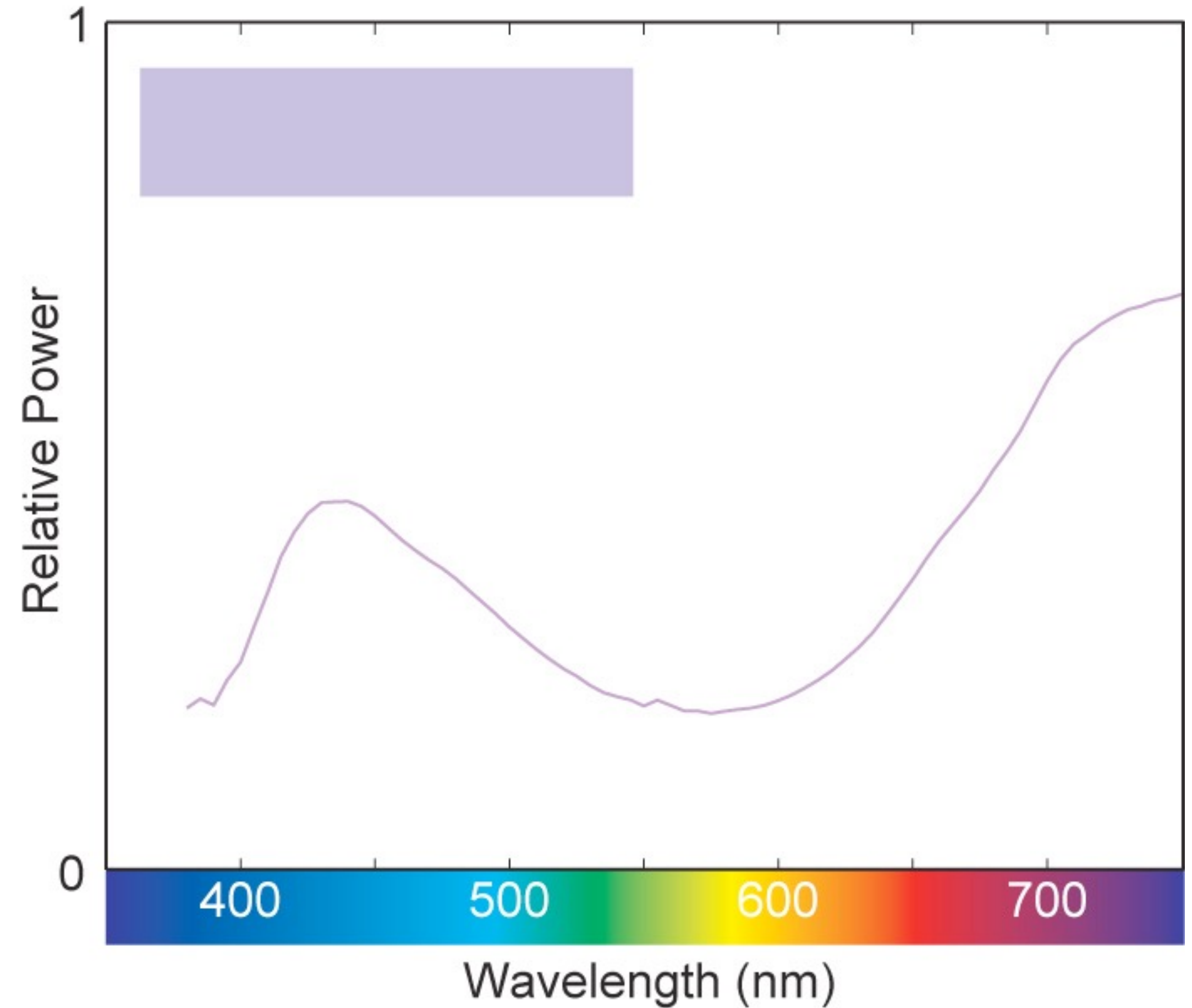
Electromagnetic wave: longer wavelength ( $\lambda$ ) = less energy



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

# Visible Light

Most colors are combinations of spectral (pure) colors



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

# Visible Light



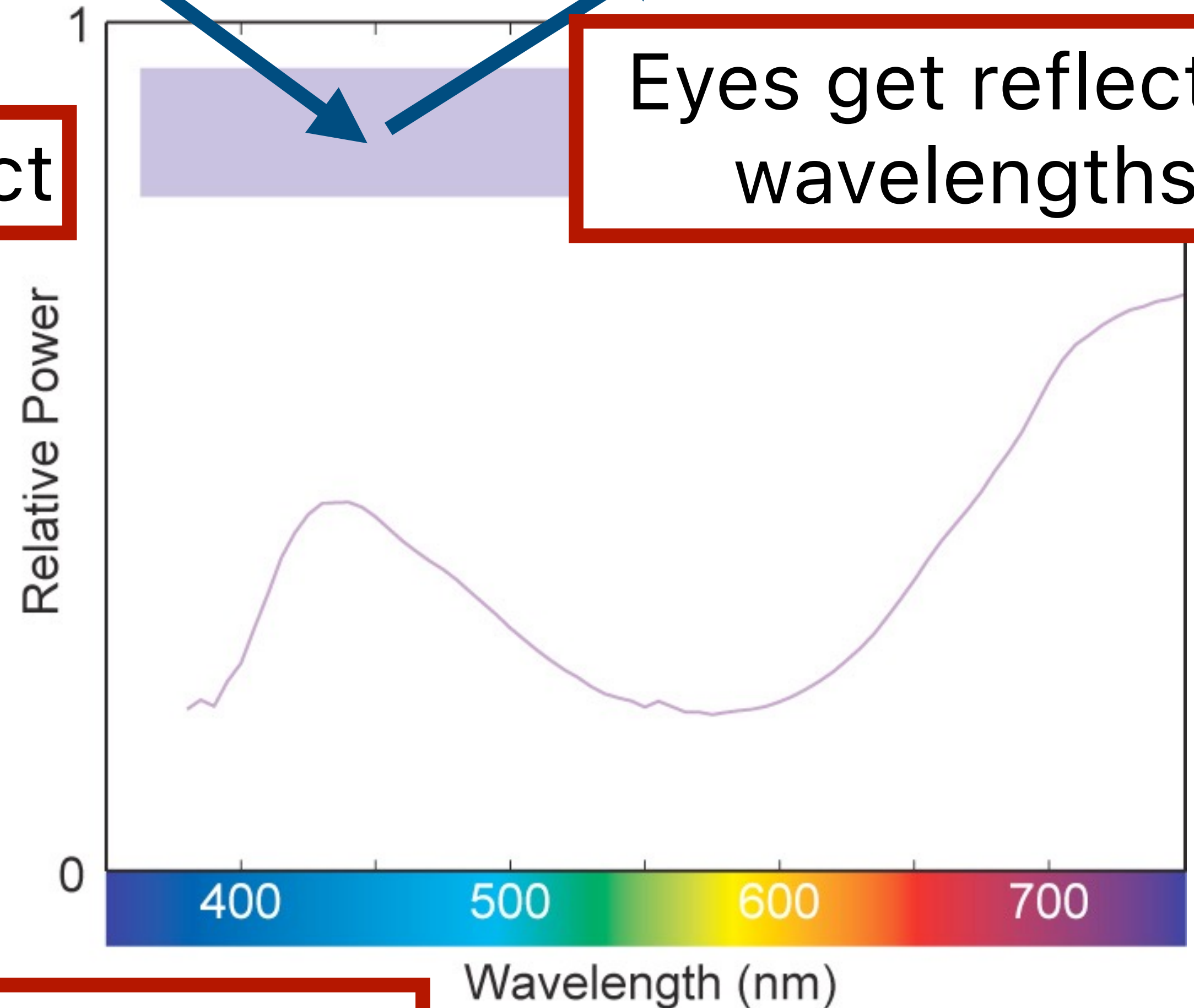
Most colors are combinations of spectral (pure) colors

Light hits object

Eyes get reflected wavelengths

Some wavelengths are reflected, others absorbed

Called a *spectral distribution*

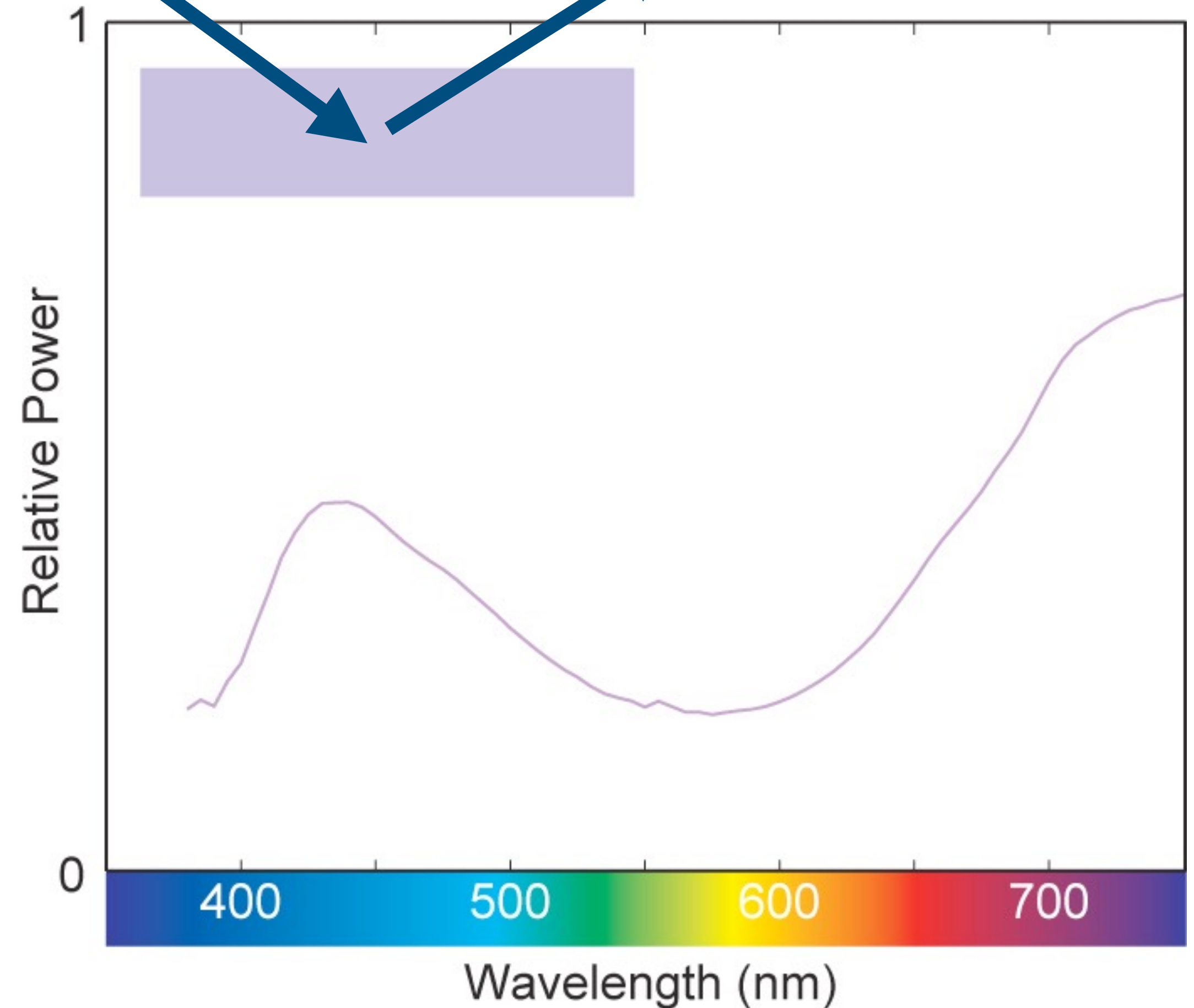


Stone. A Field Guide to Digital Color, 2003]

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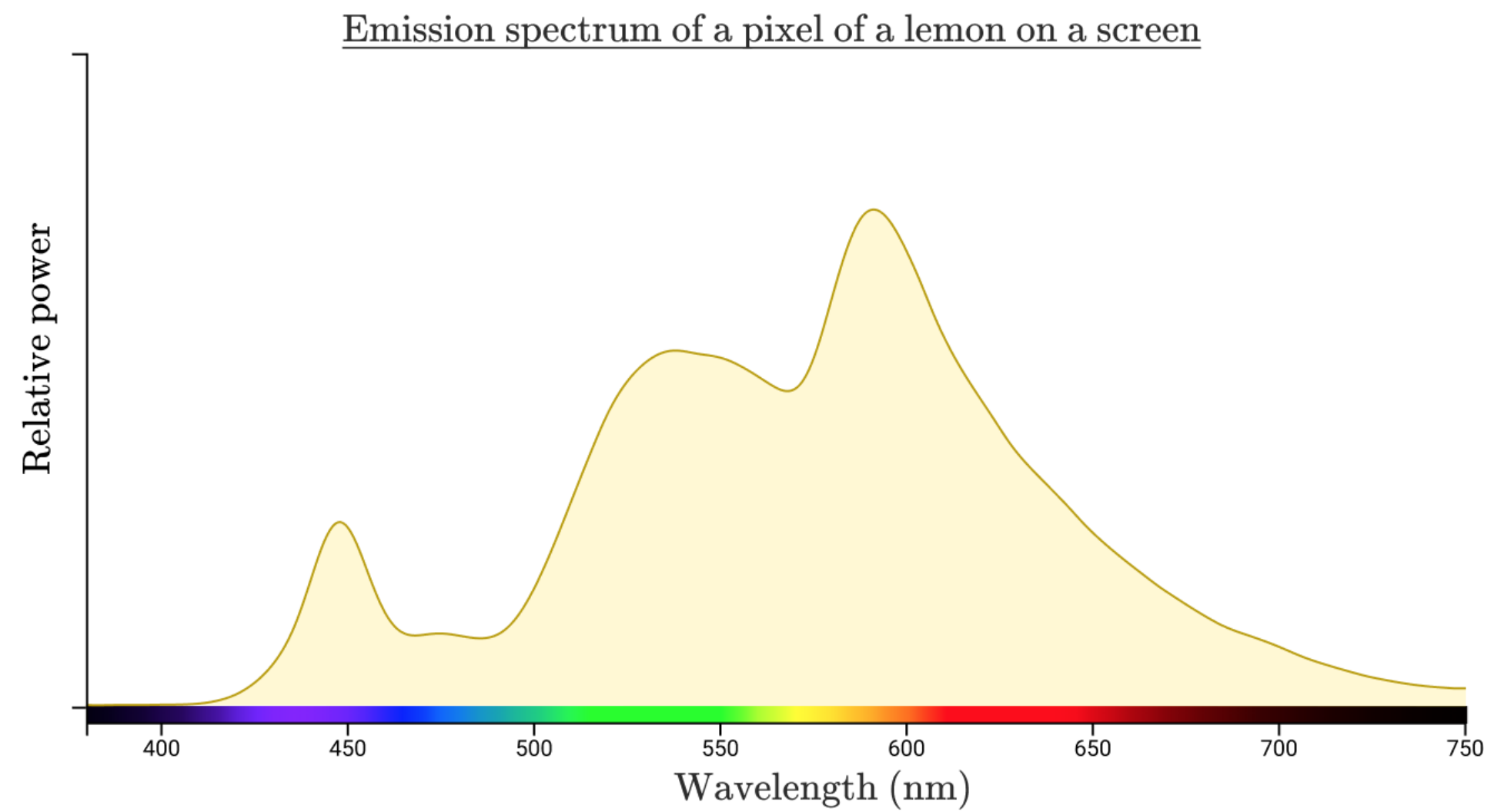
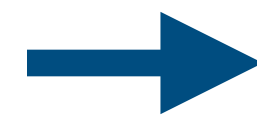
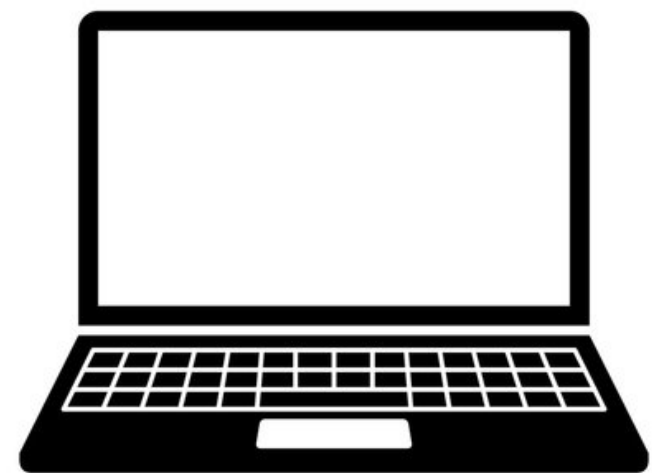
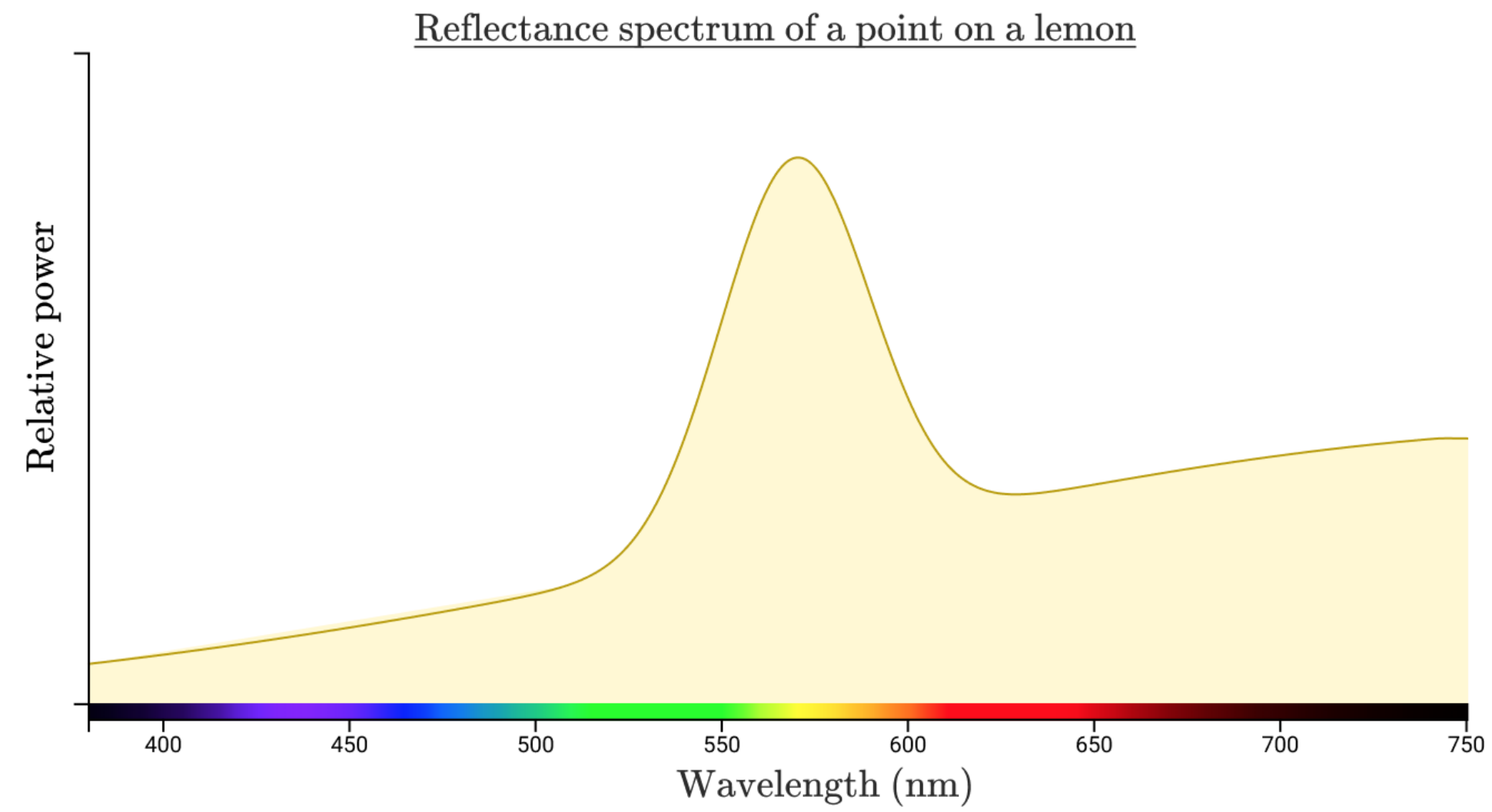
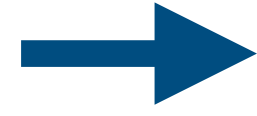
Most colors are combinations of spectral (pure) colors

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

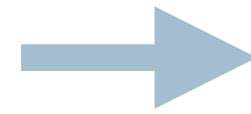
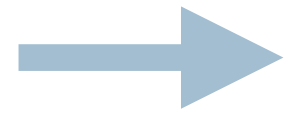


[Maureen Stone. A Field Guide to Digital Color, 2003]

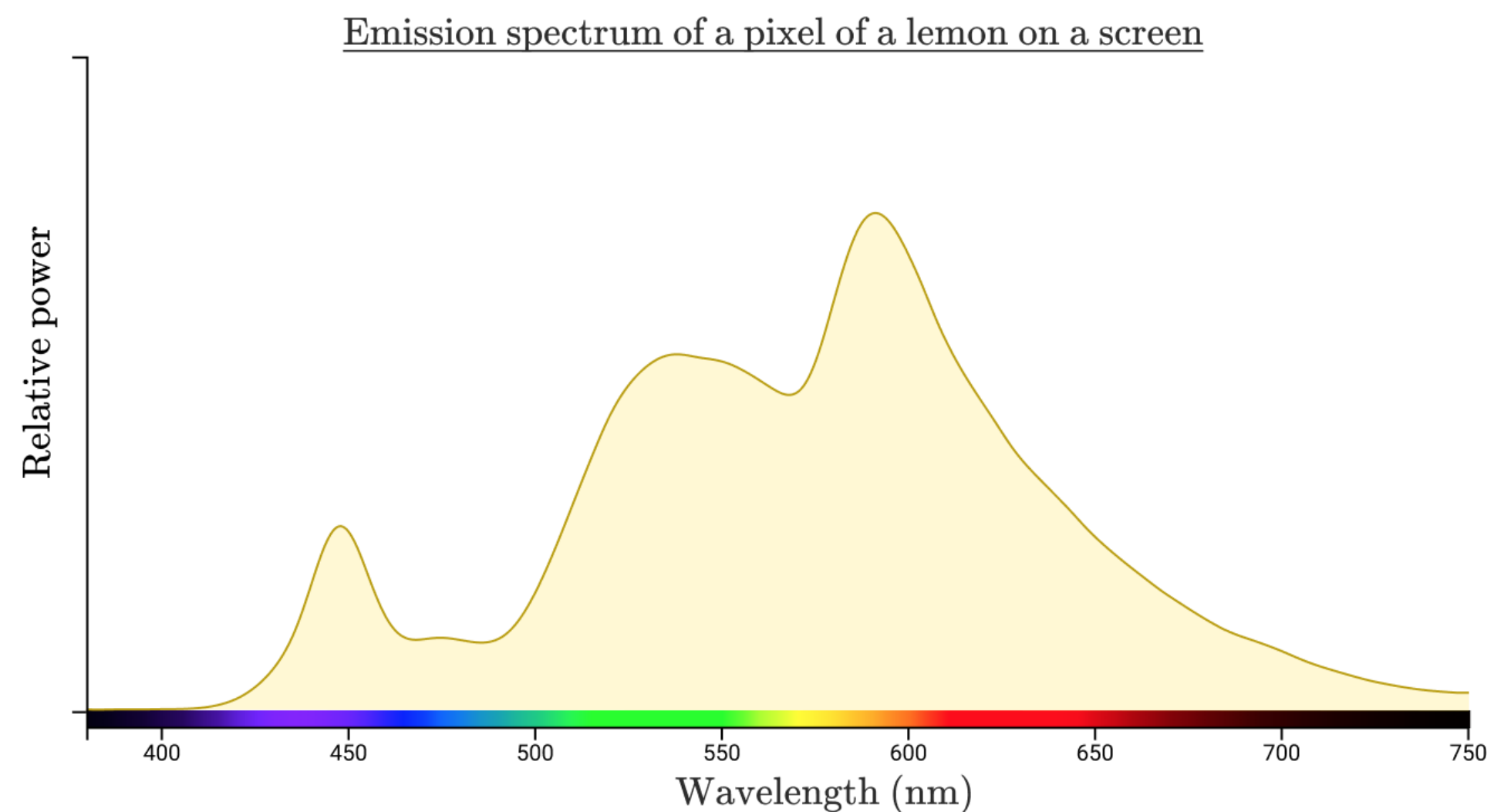
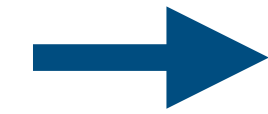
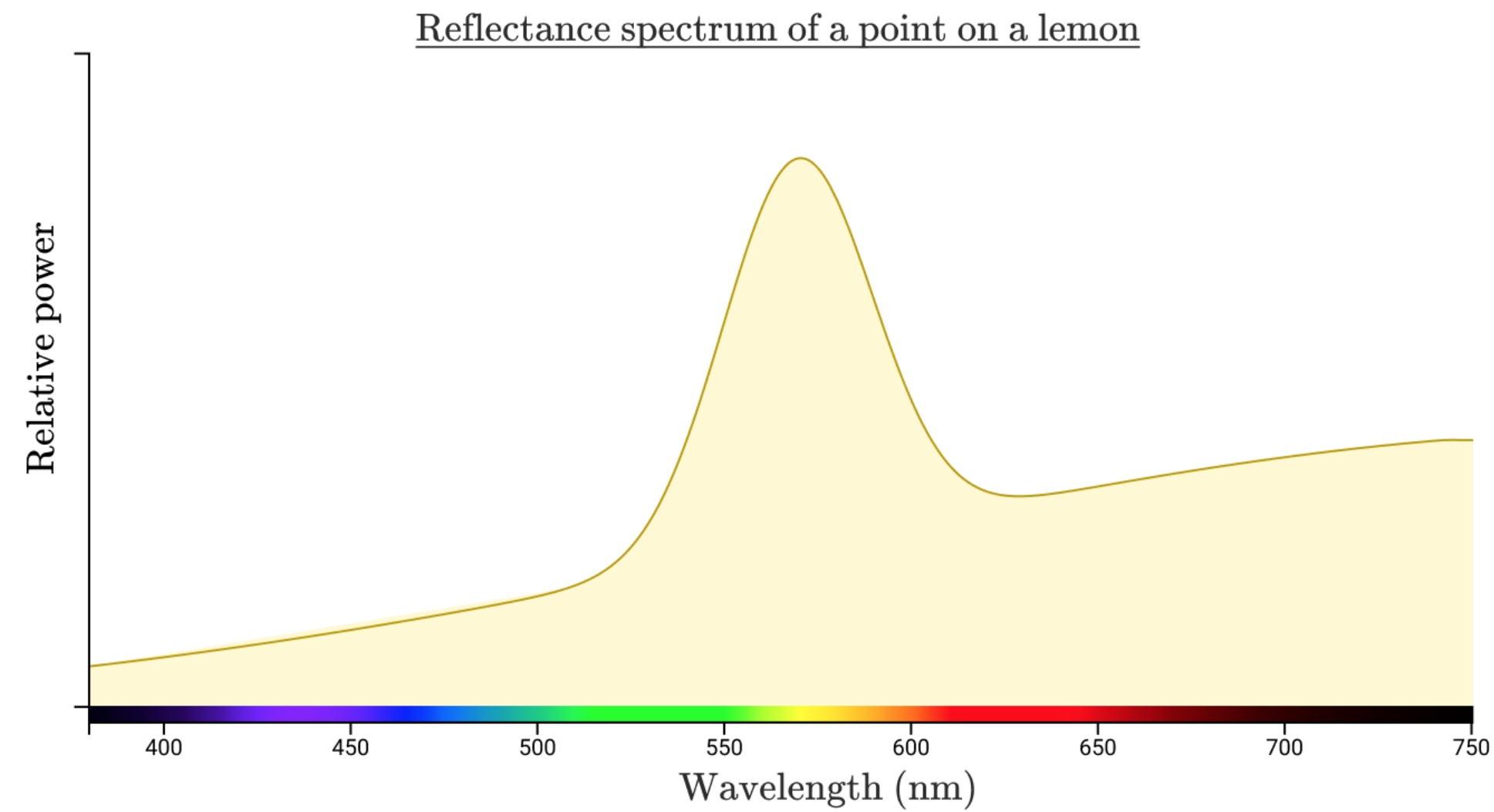
# Metamers



# Metamers



Different spectra,  
but looks the same  
to our eyes!



This is called a  
***metamer***.

Why does this work?

# Modeling Color Perception

Low-Level

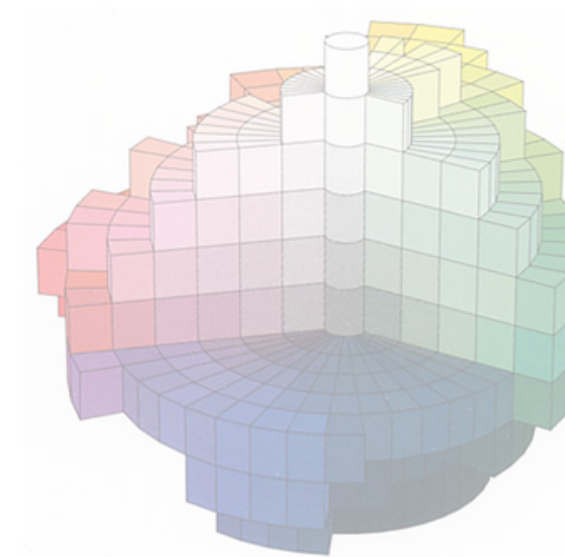
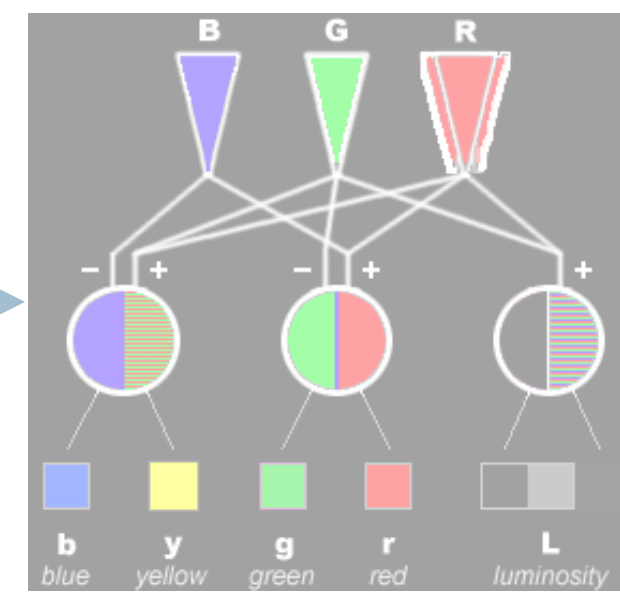
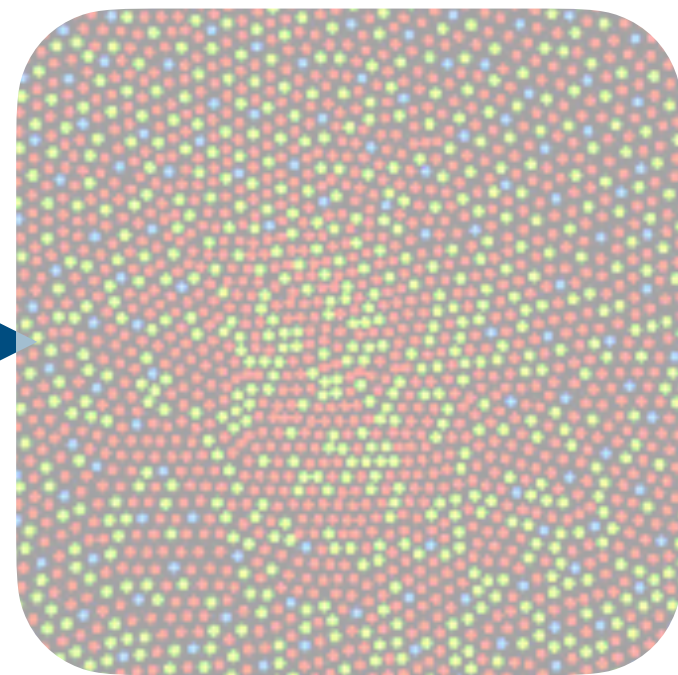
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Mental Models



“Teal”

Visible Light

Cone Response

Opponent Encoding

Perceptual Models

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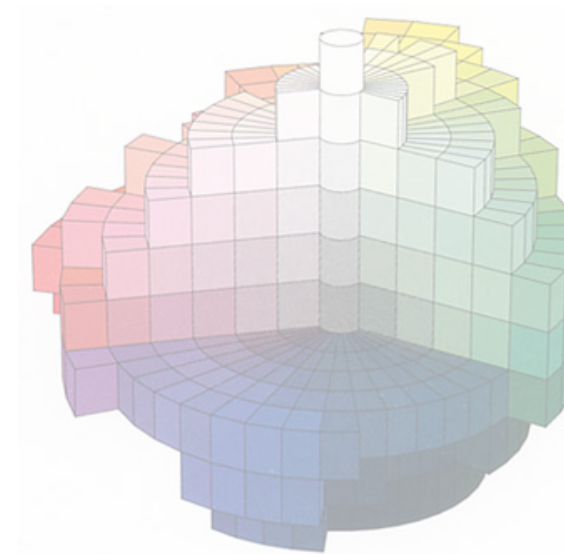
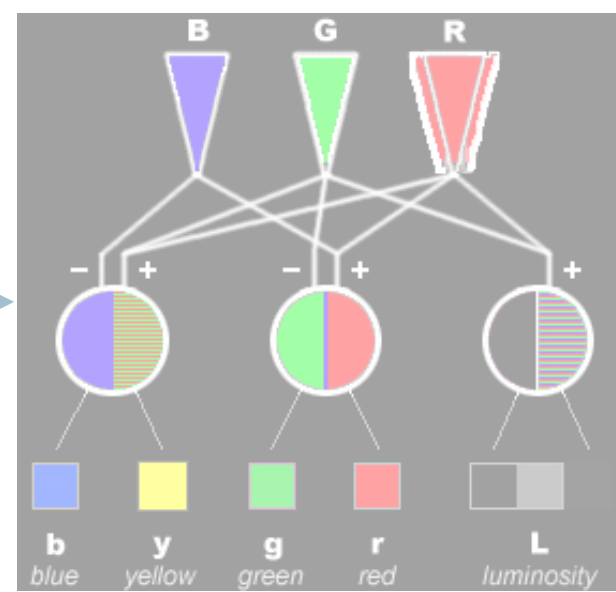
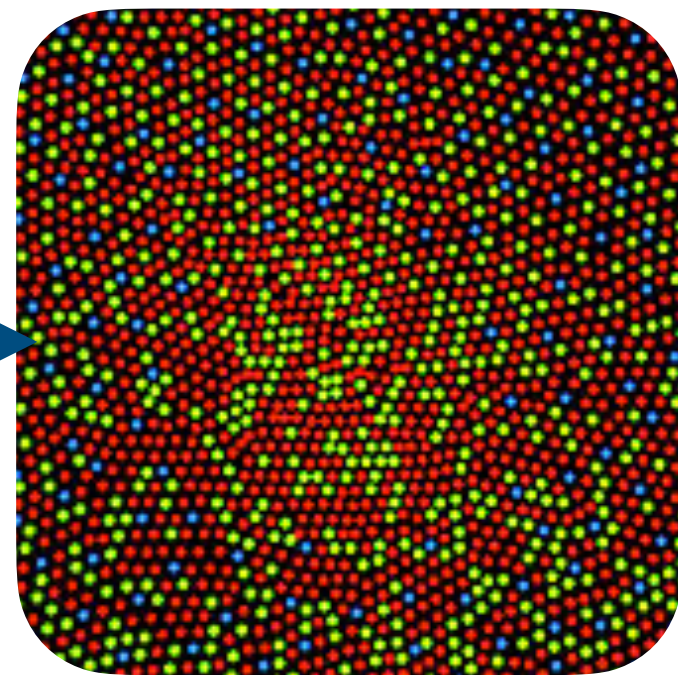
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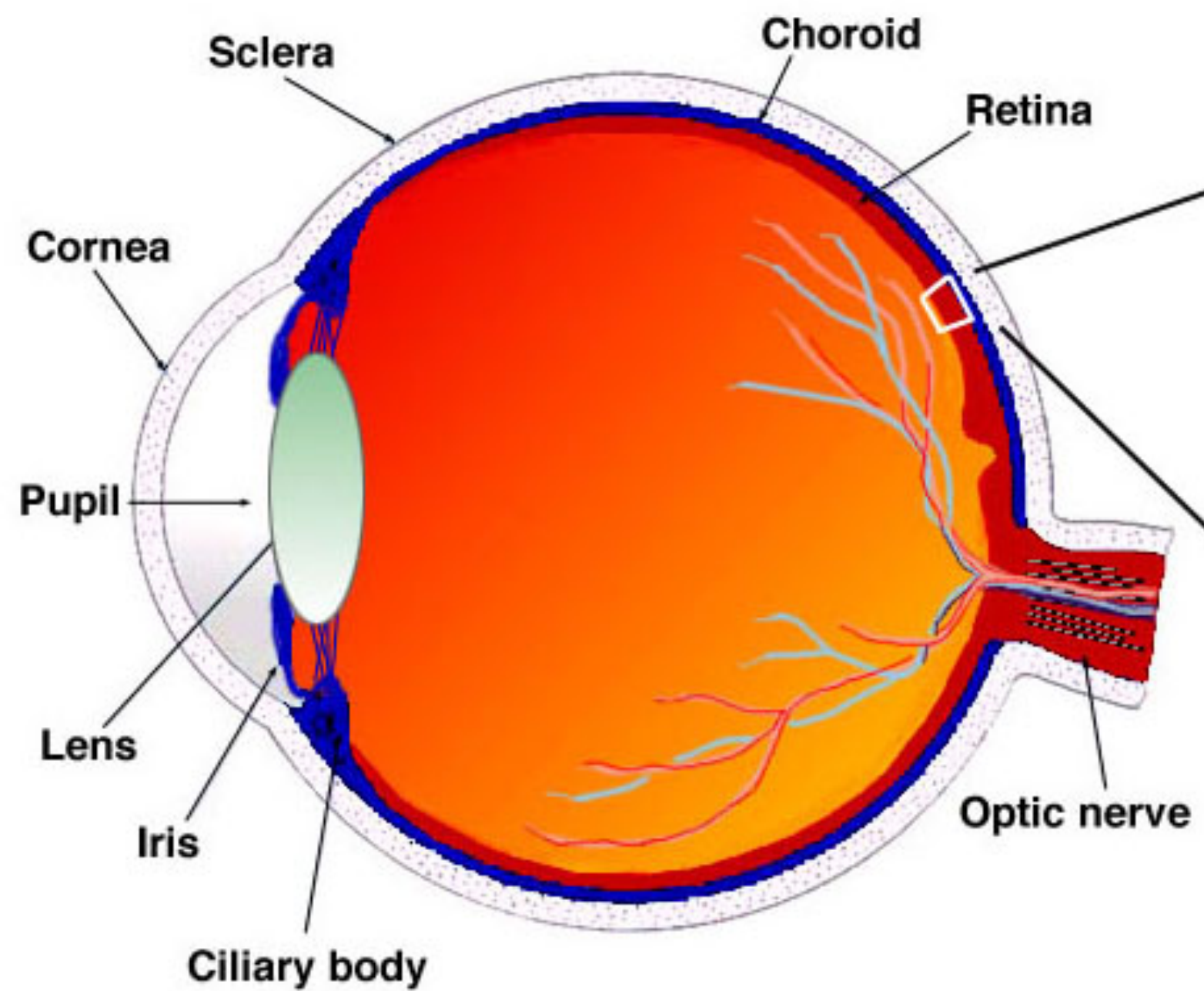
Perceptual Models

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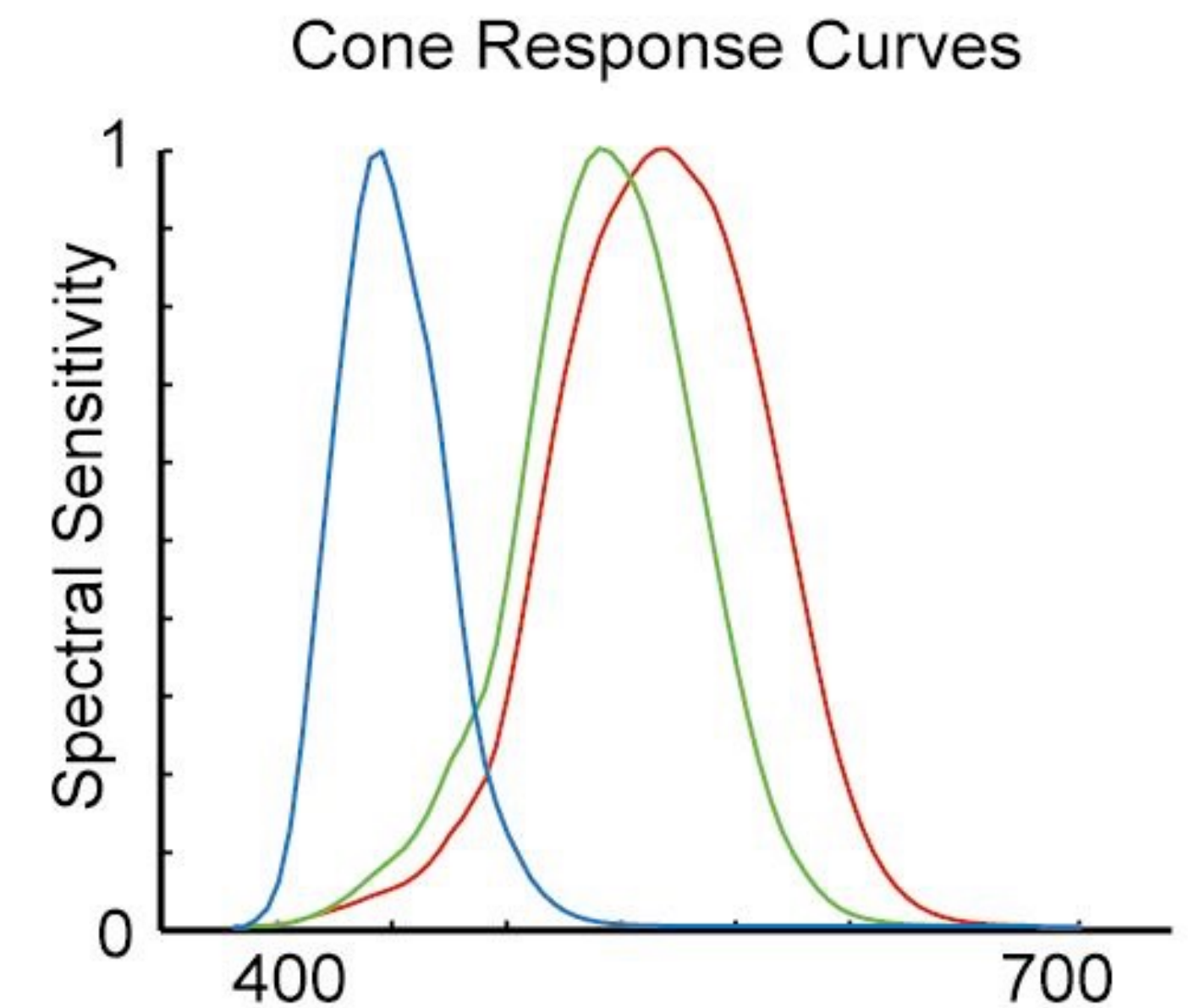
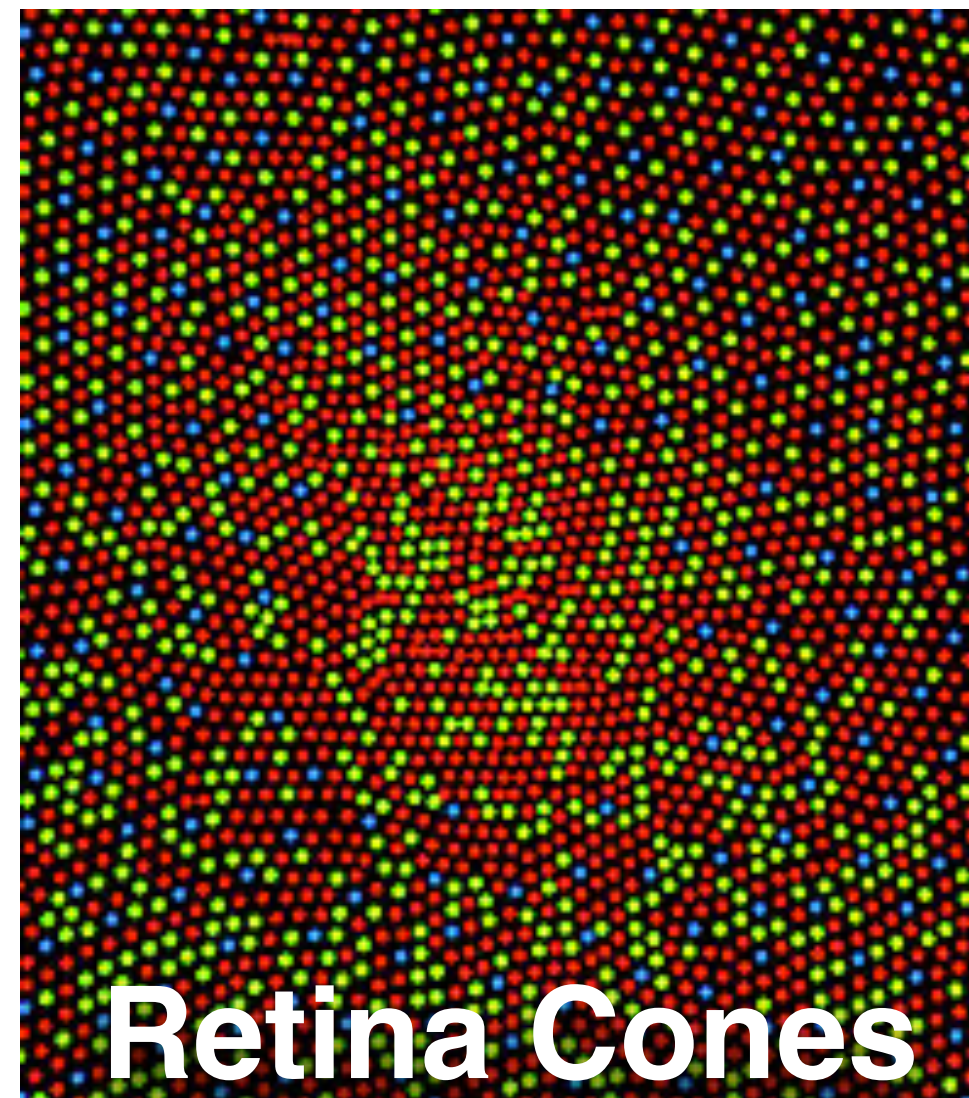
Cognitive Models

# The Retina

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

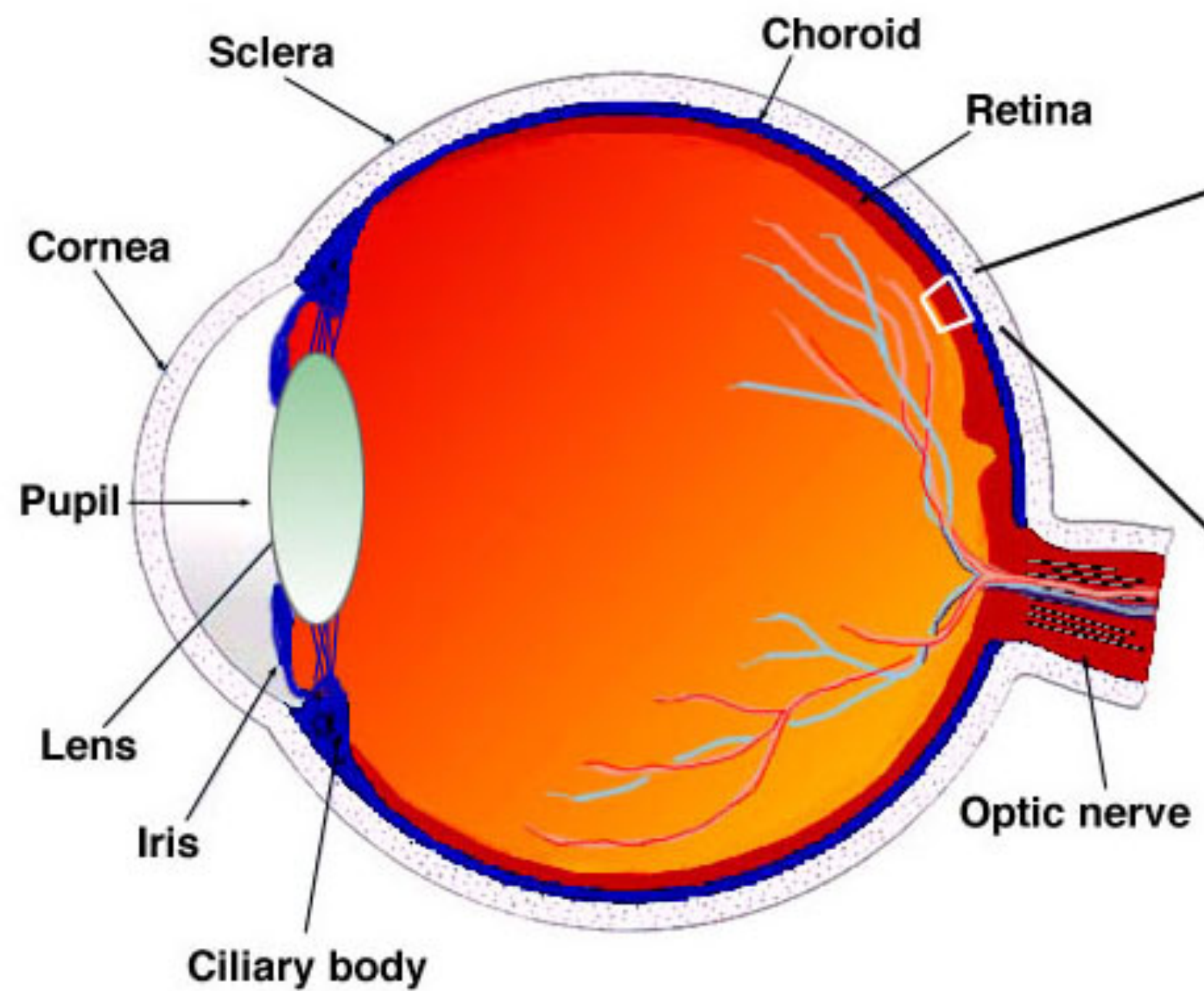


[Helga Kolb Simple Anatomy of the

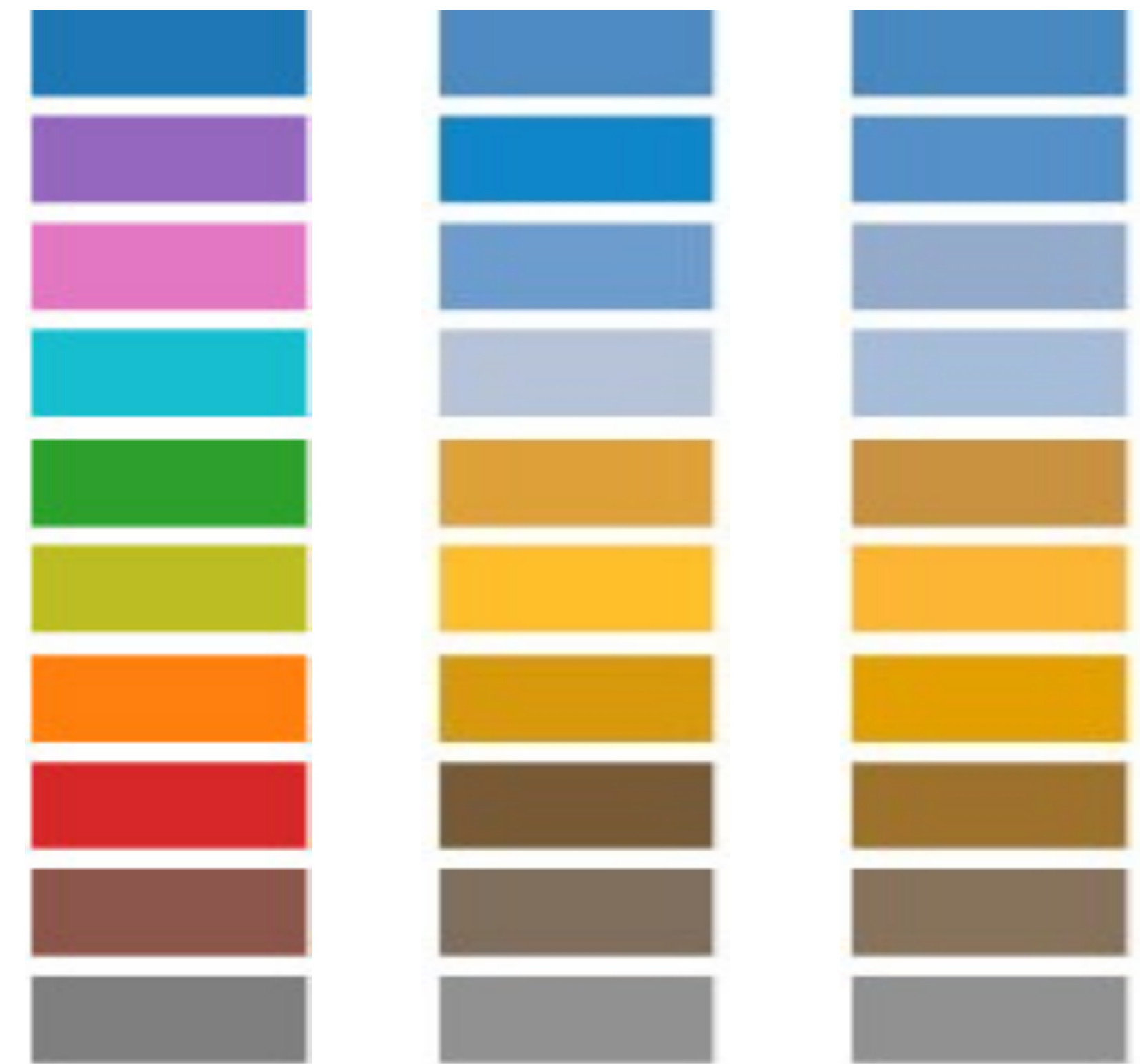
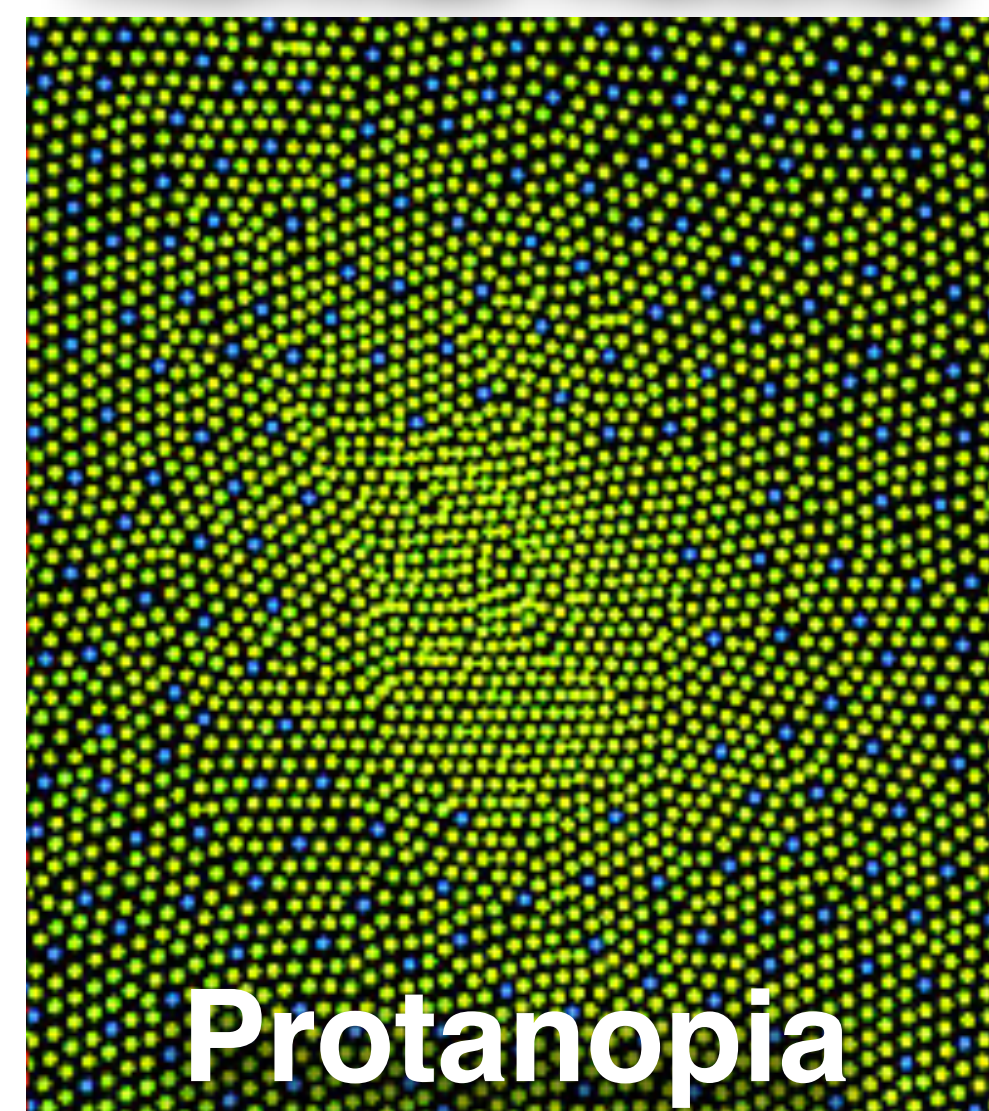
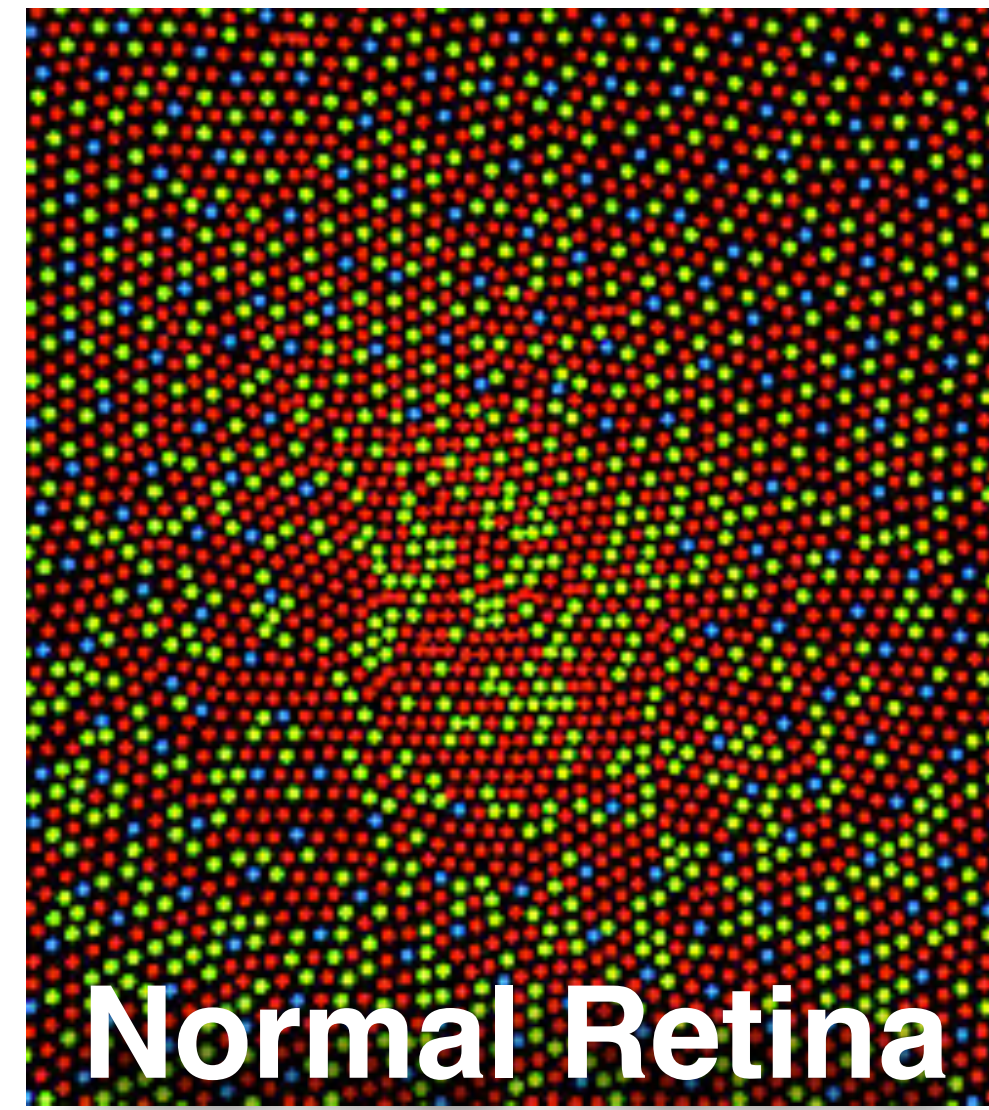


# The Retina

Firefox and Chrome have built in simulators



[Helga Kolb Simple Anatomy of the

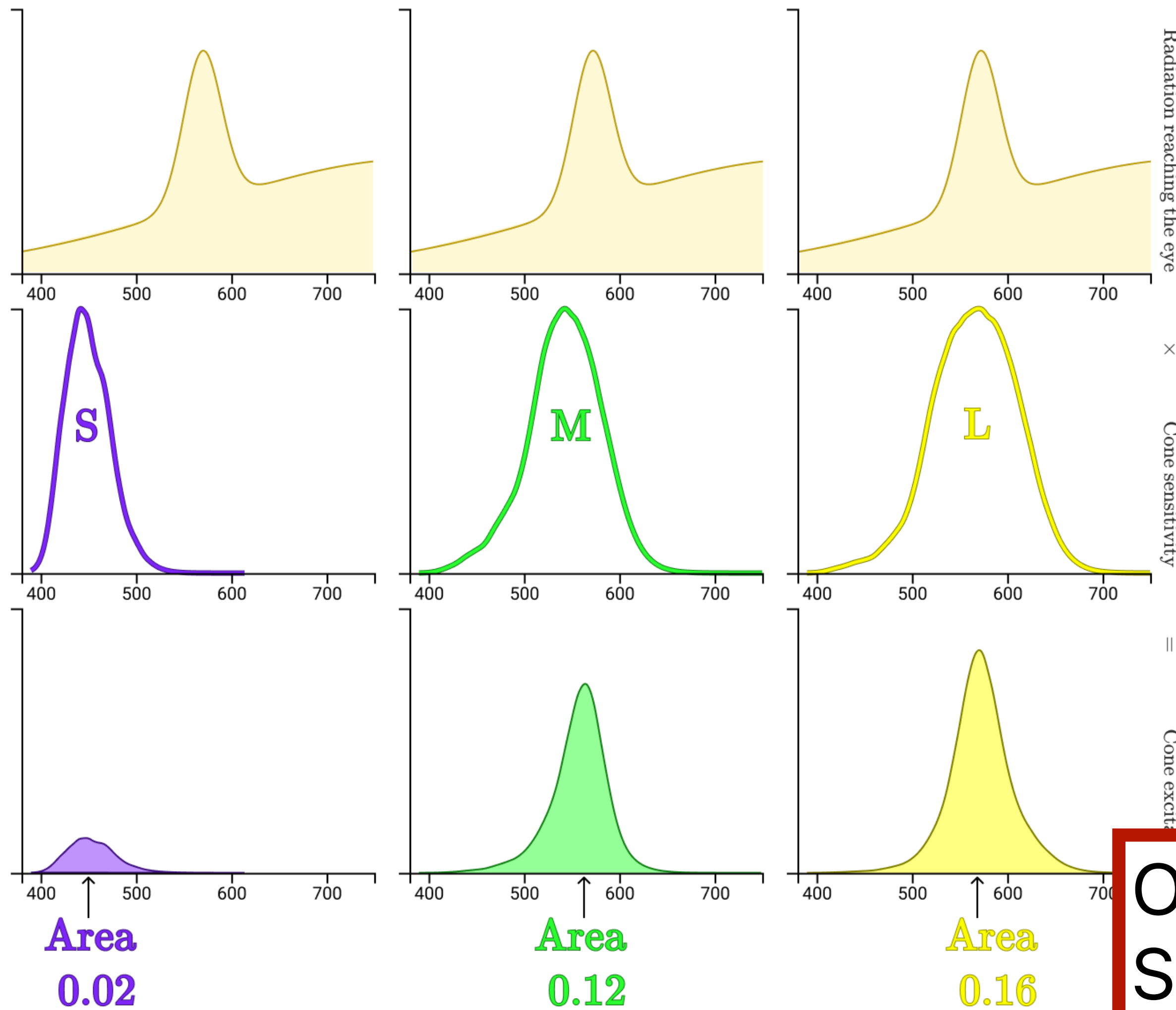


Protanope

Deuteranope

# Tri-Stimulus Response

Sunlight hits lemon



Light spectrum

Cone sensitivity

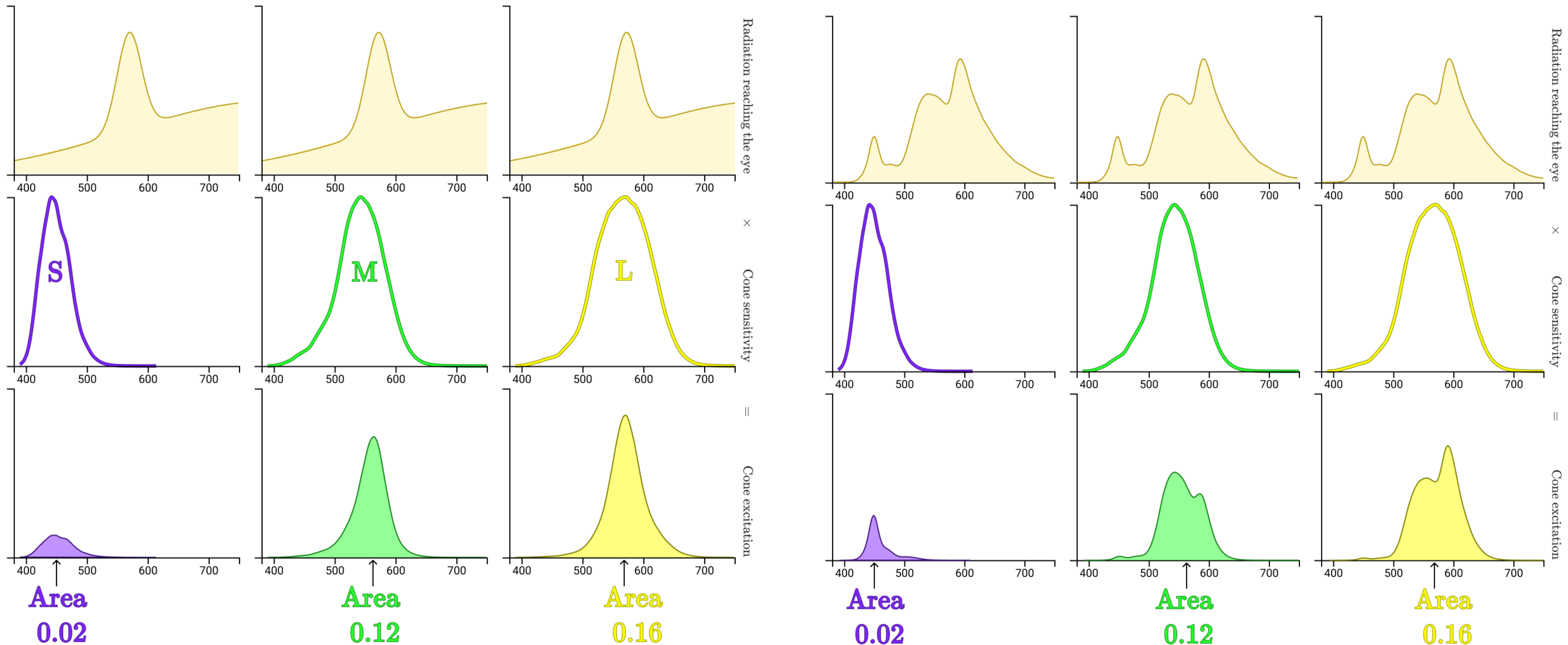
Cone response

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

# Tri-Stimulus Response

Sunlight hits lemon

Image of lemon on screen



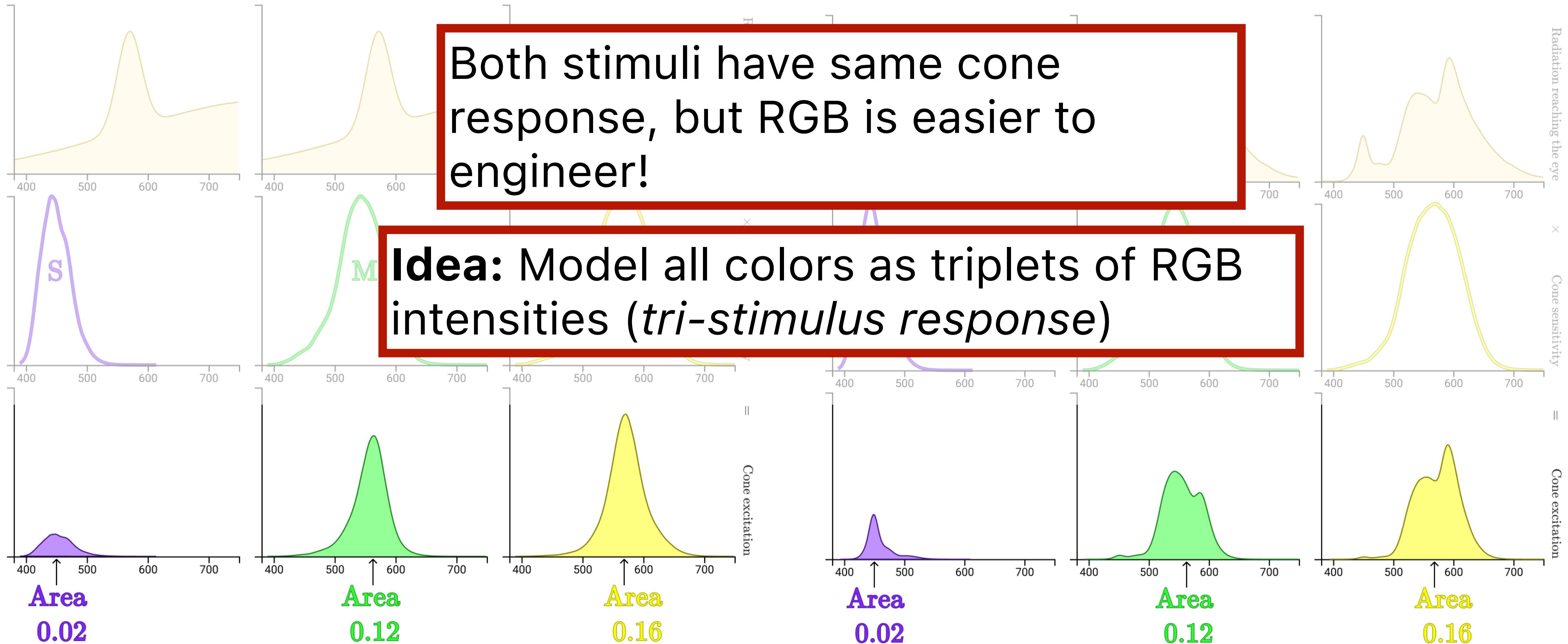
# Tri-Stimulus Response

Sunlight hits lemon

Image of lemon on screen

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

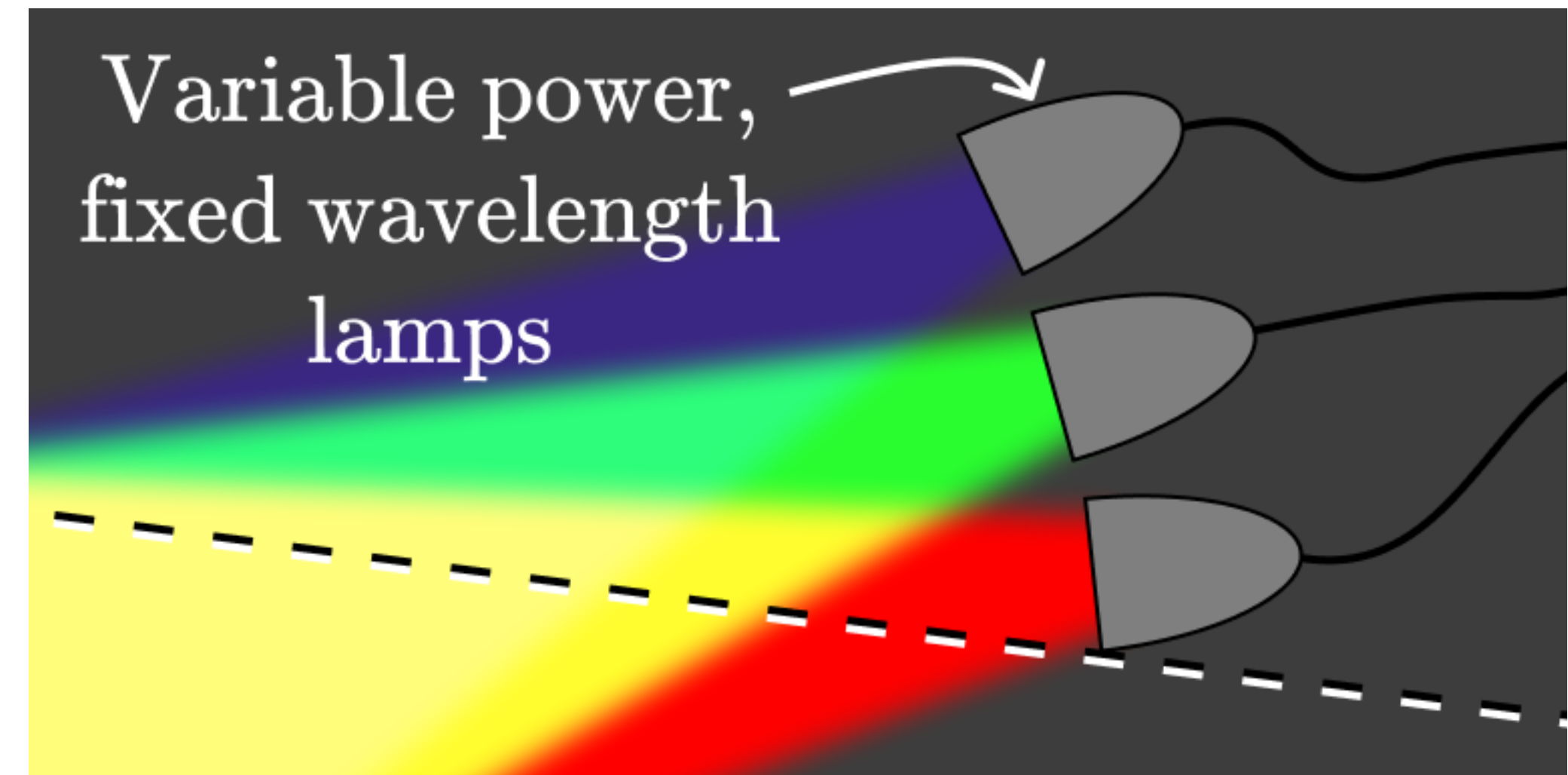
**Idea:** Model all colors as triplets of RGB intensities (*tri-stimulus response*)



# 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

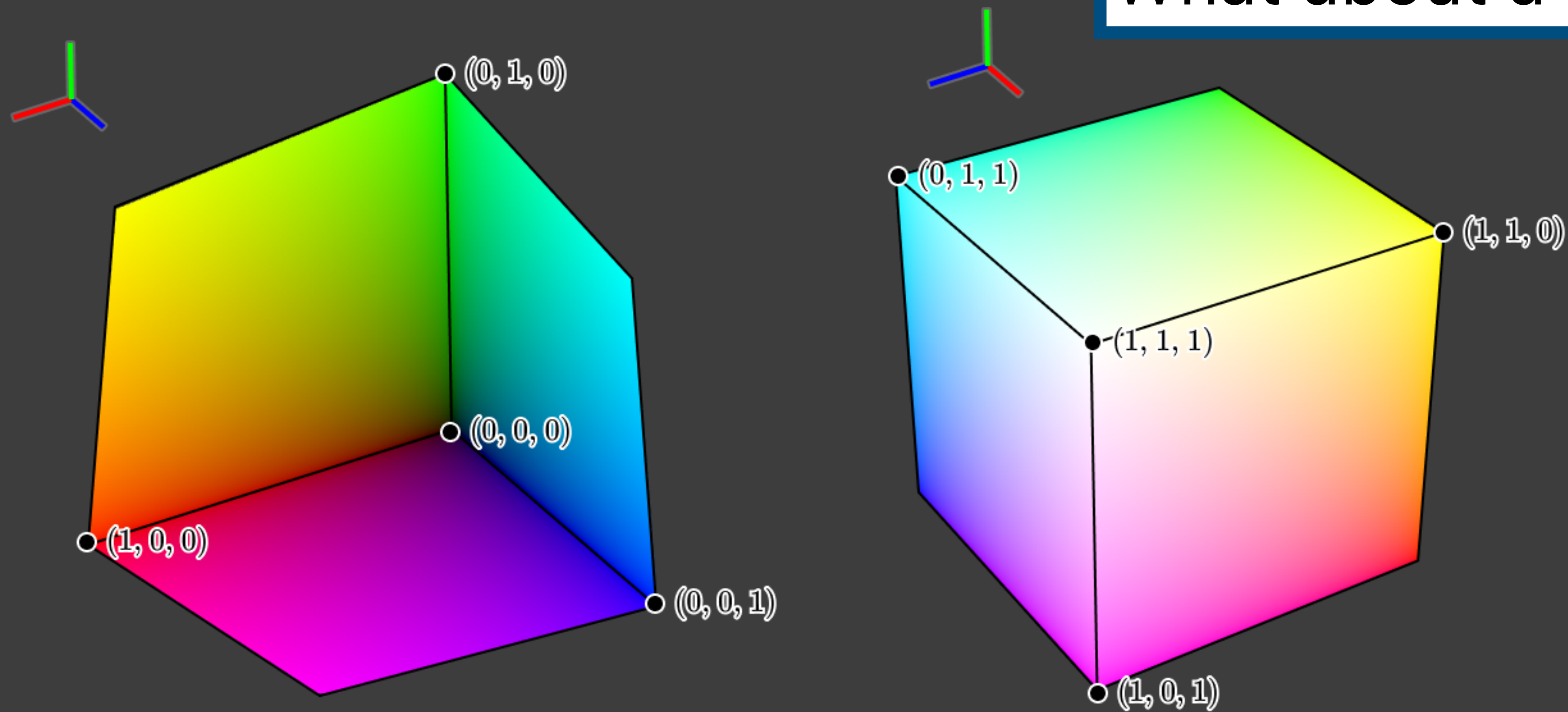
$(1, 0, 0)$  = pure red

...etc.

**How to visualize all colors?**

# CIE XYZ (1931)

What about a 2D visualization?

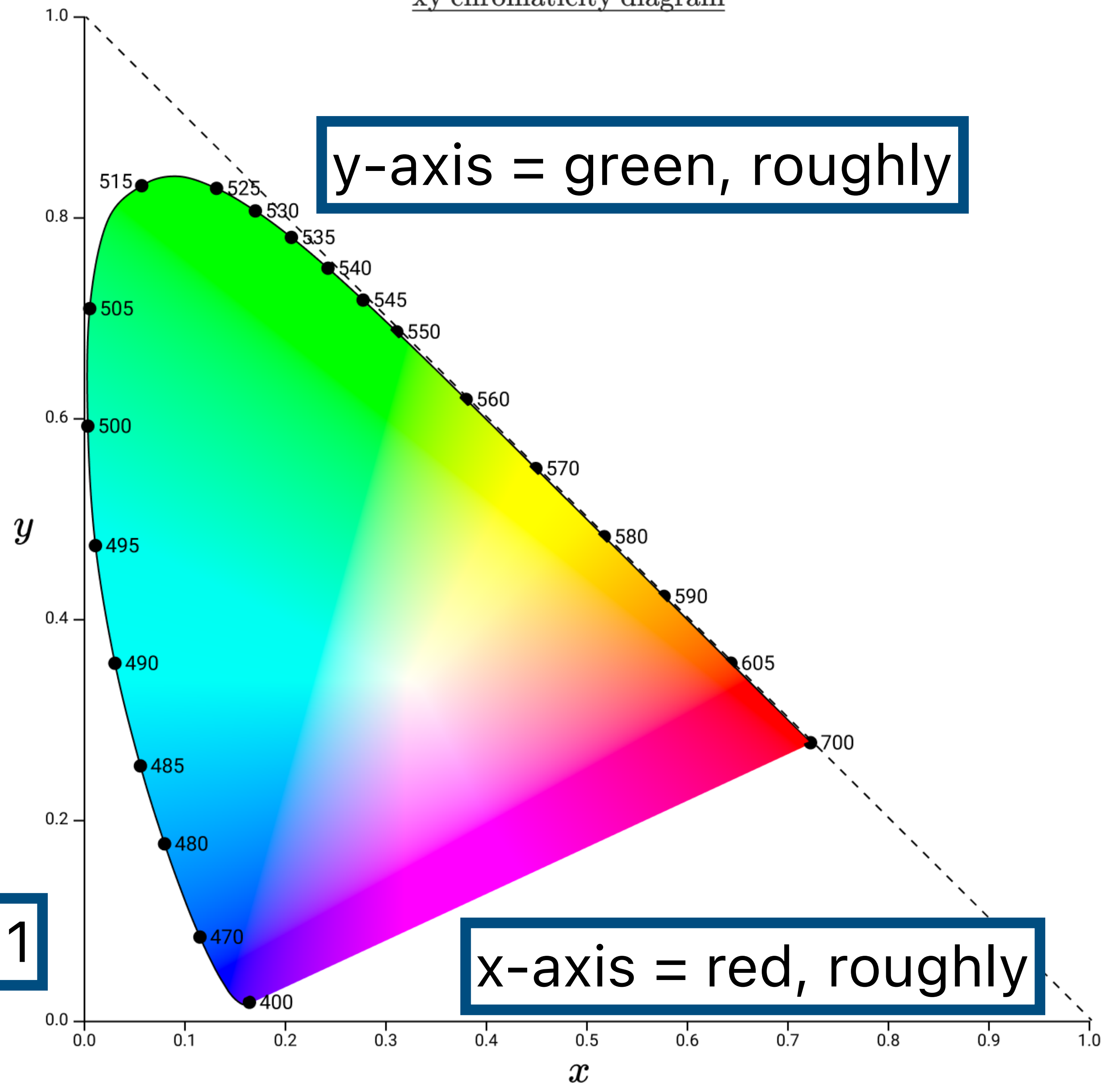


# CIE XYZ (1931)

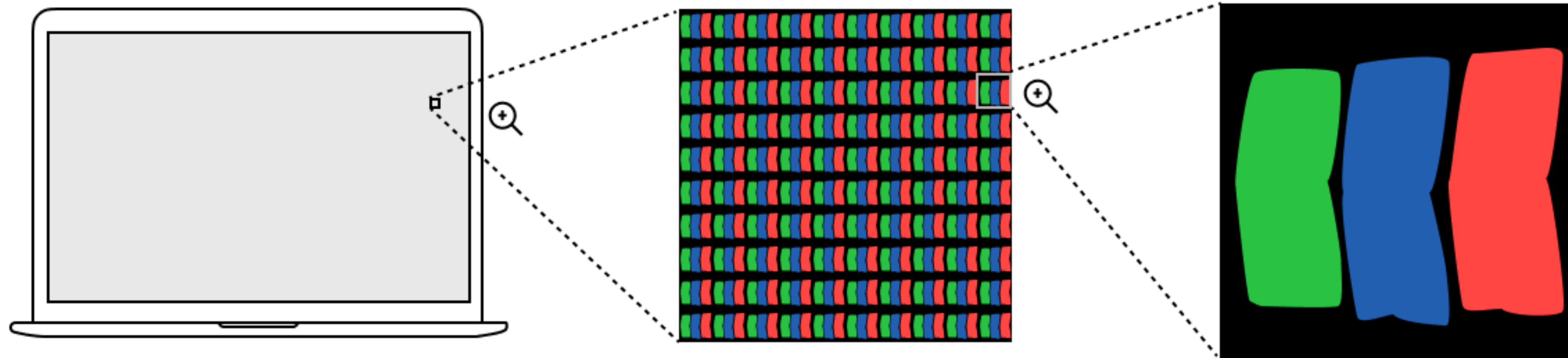
Project into a 2D plane to separate colorfulness from brightness.

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

xy chromaticity diagram



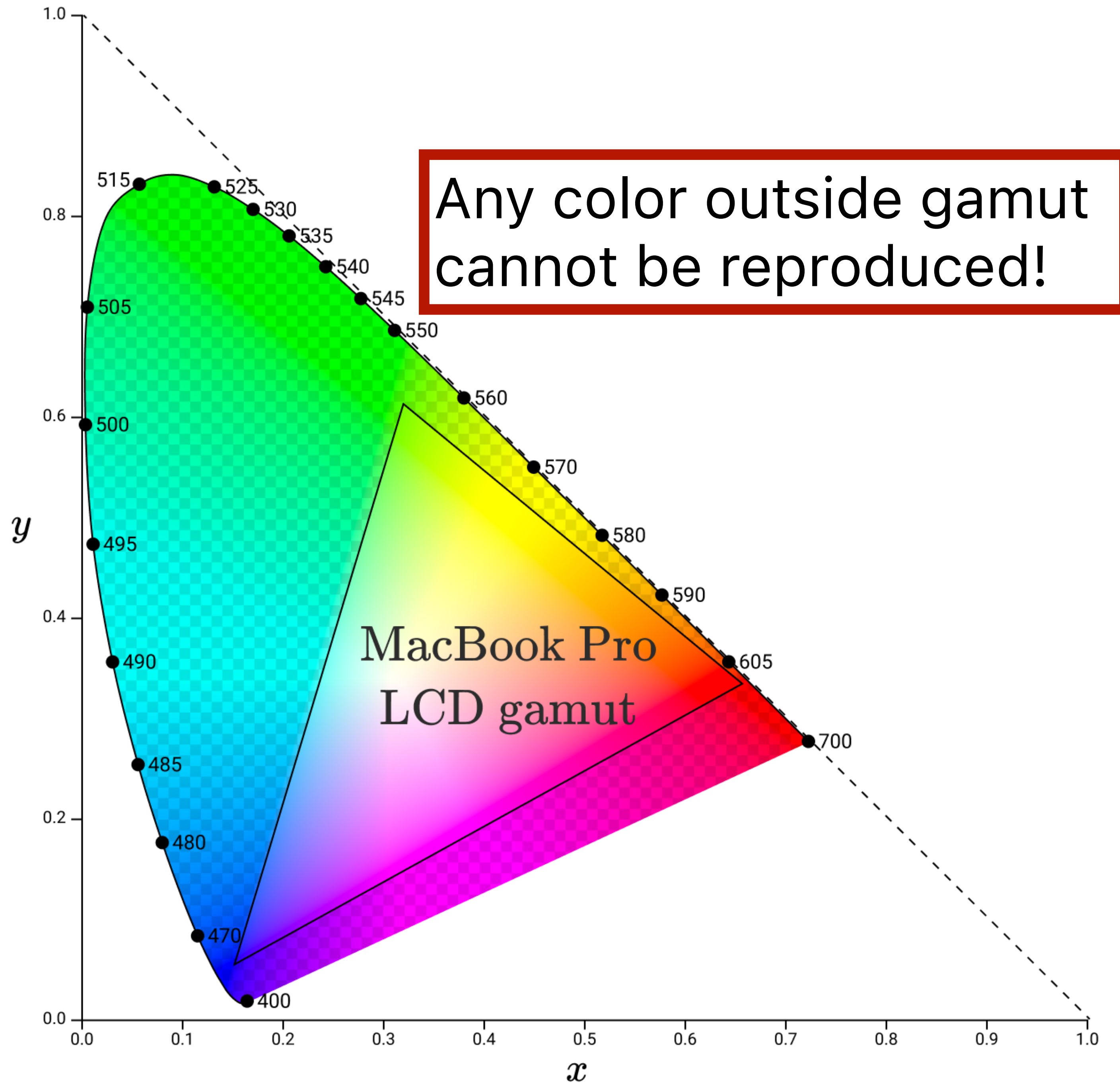
# Our screens



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

# Color Gamuts

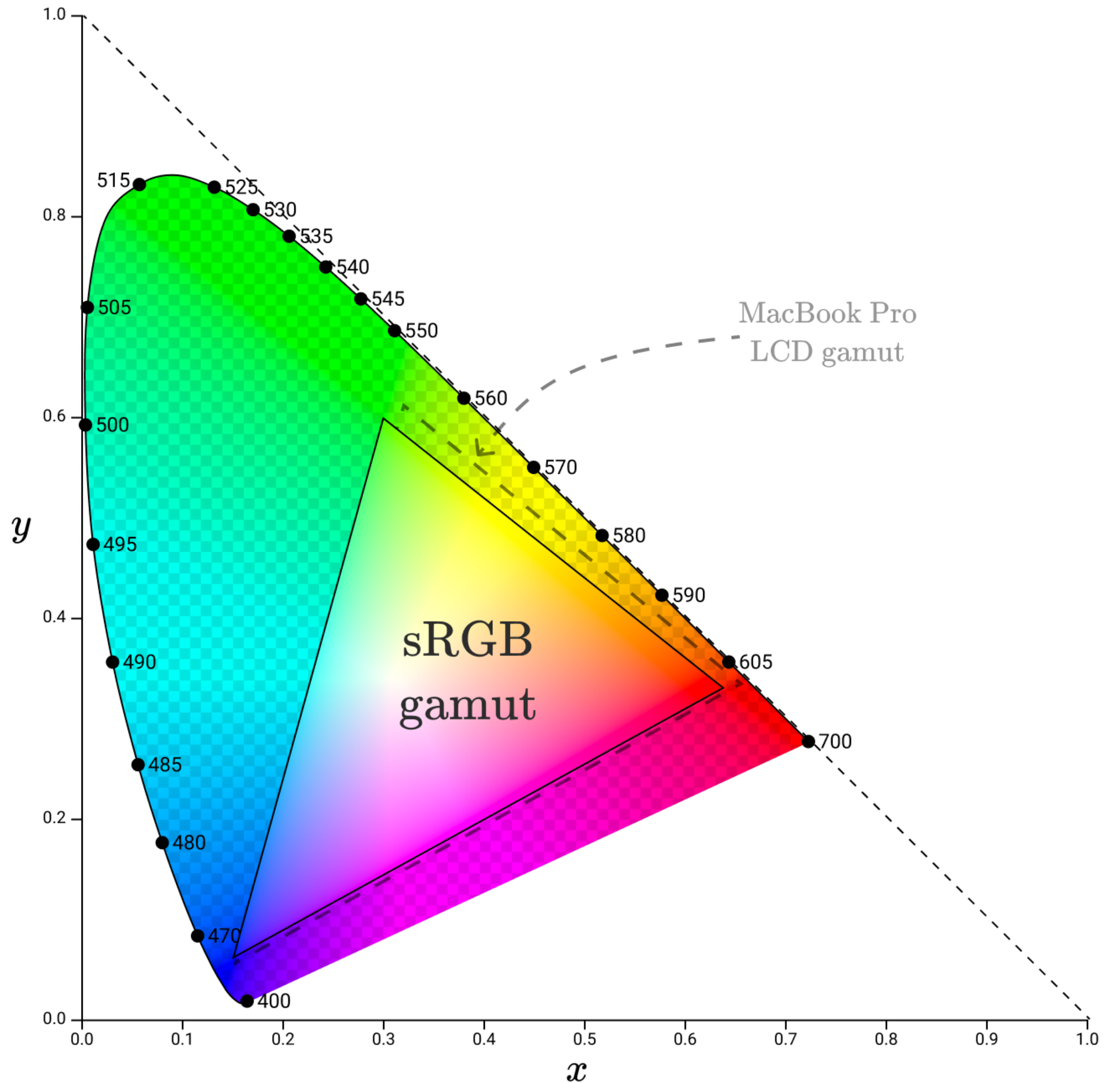
Gamut = portion of color space that can be reproduced by display



# sRGB

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

CSS rgb() uses the sRGB gamut:



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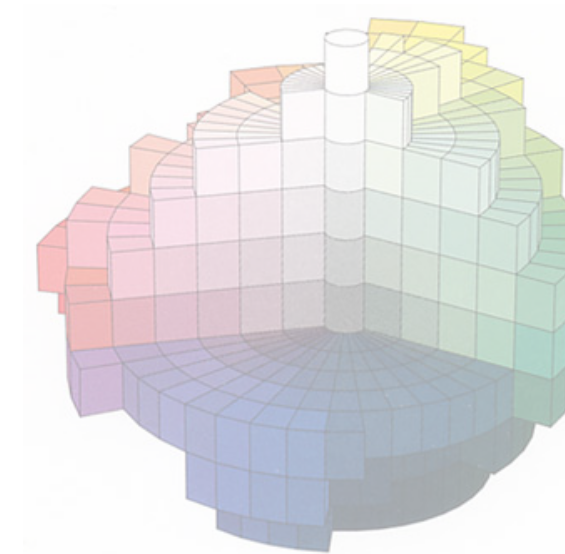
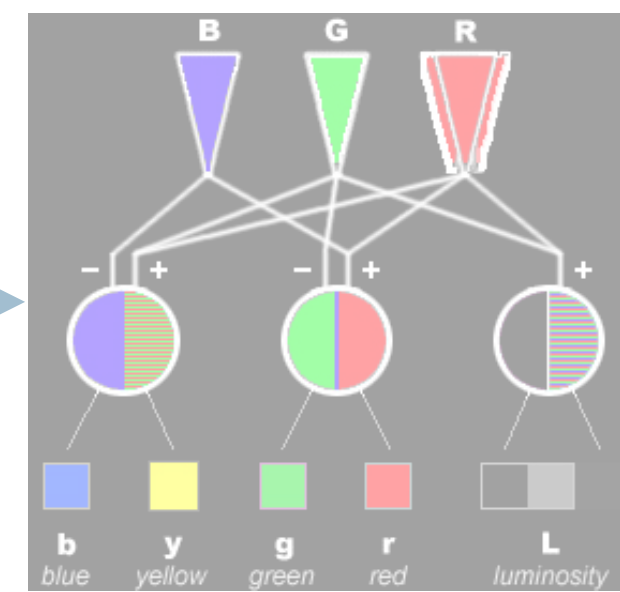
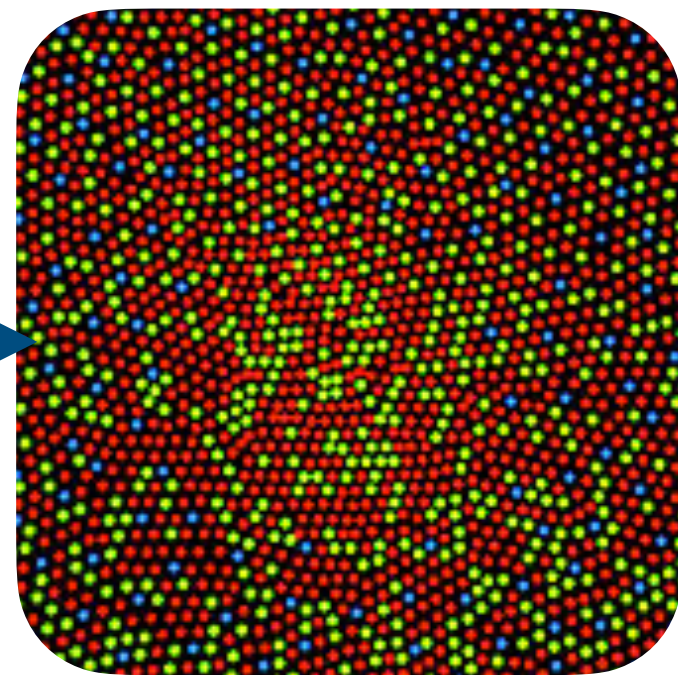
Abstraction

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“Teal”

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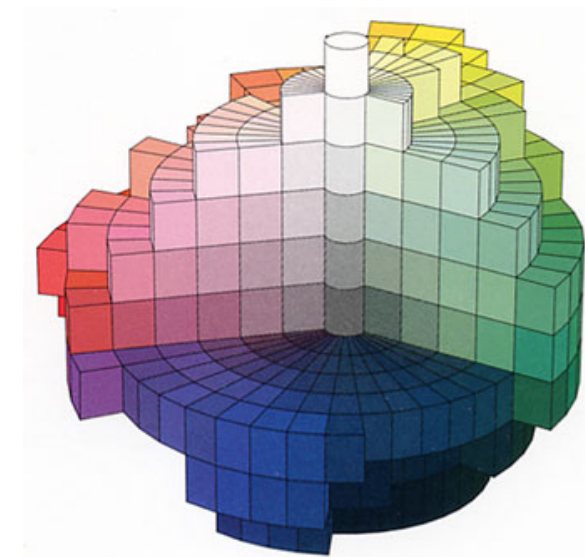
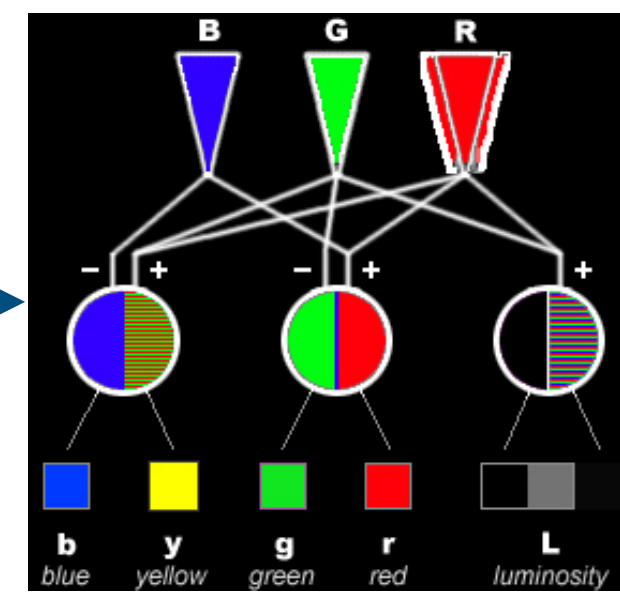
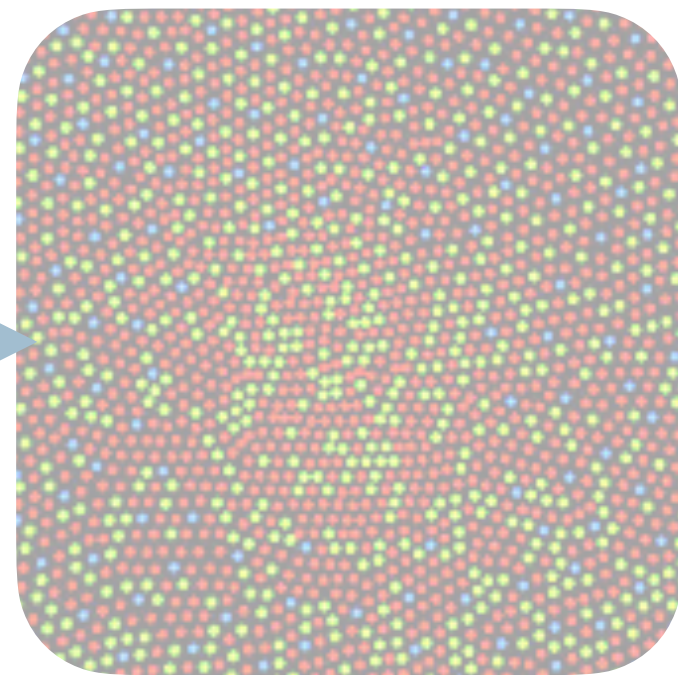
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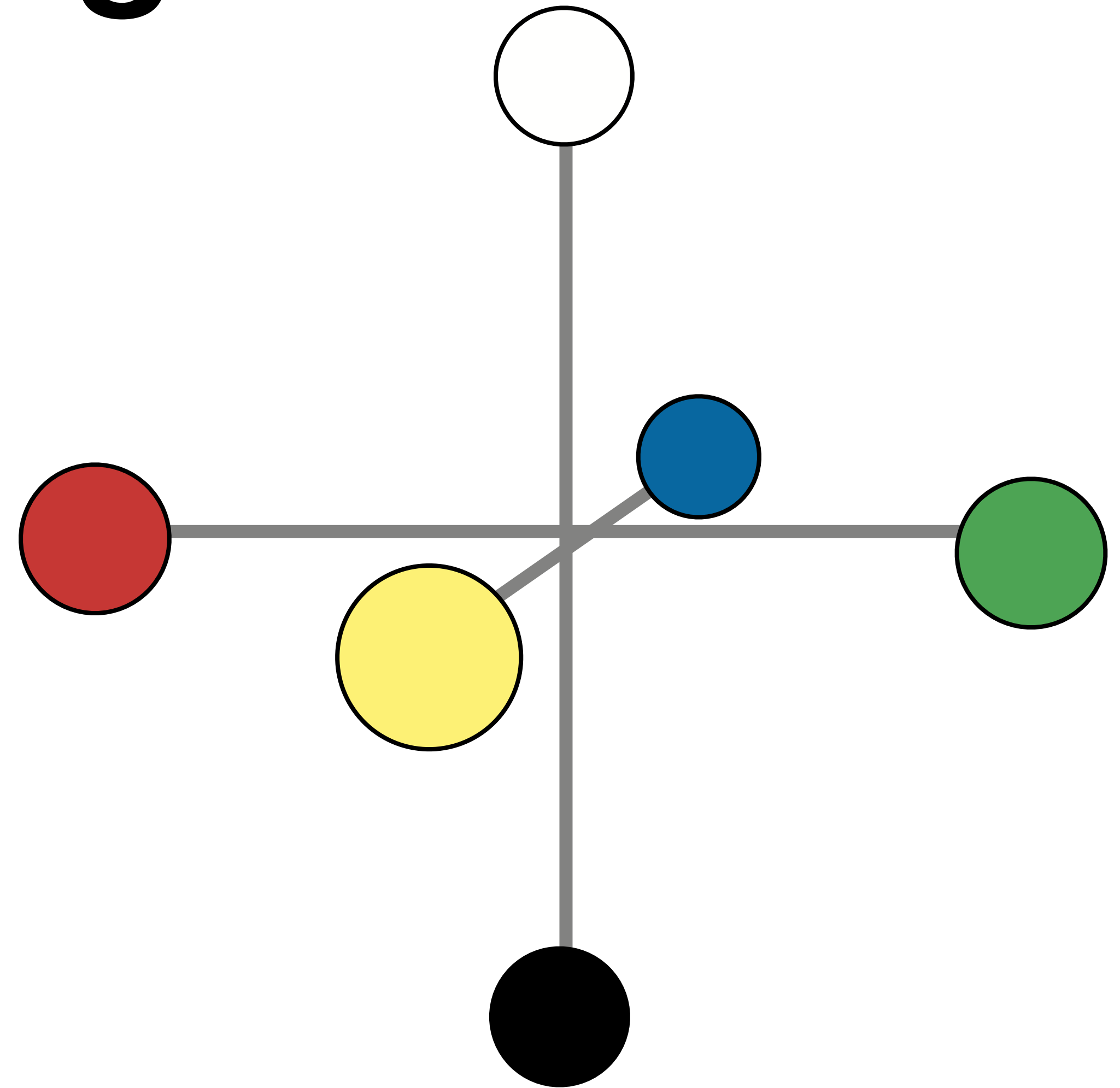
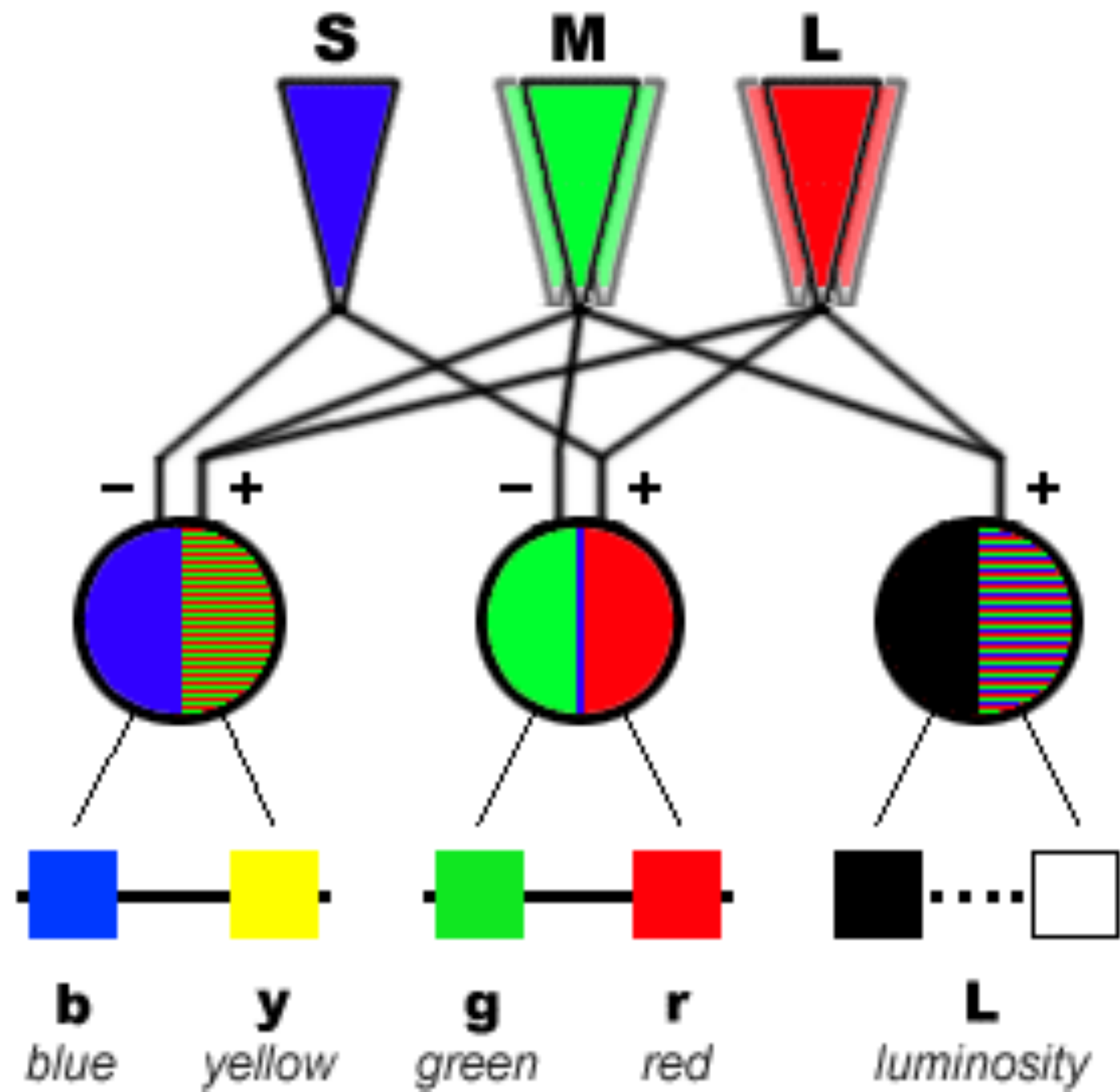
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# Opponent Encoding



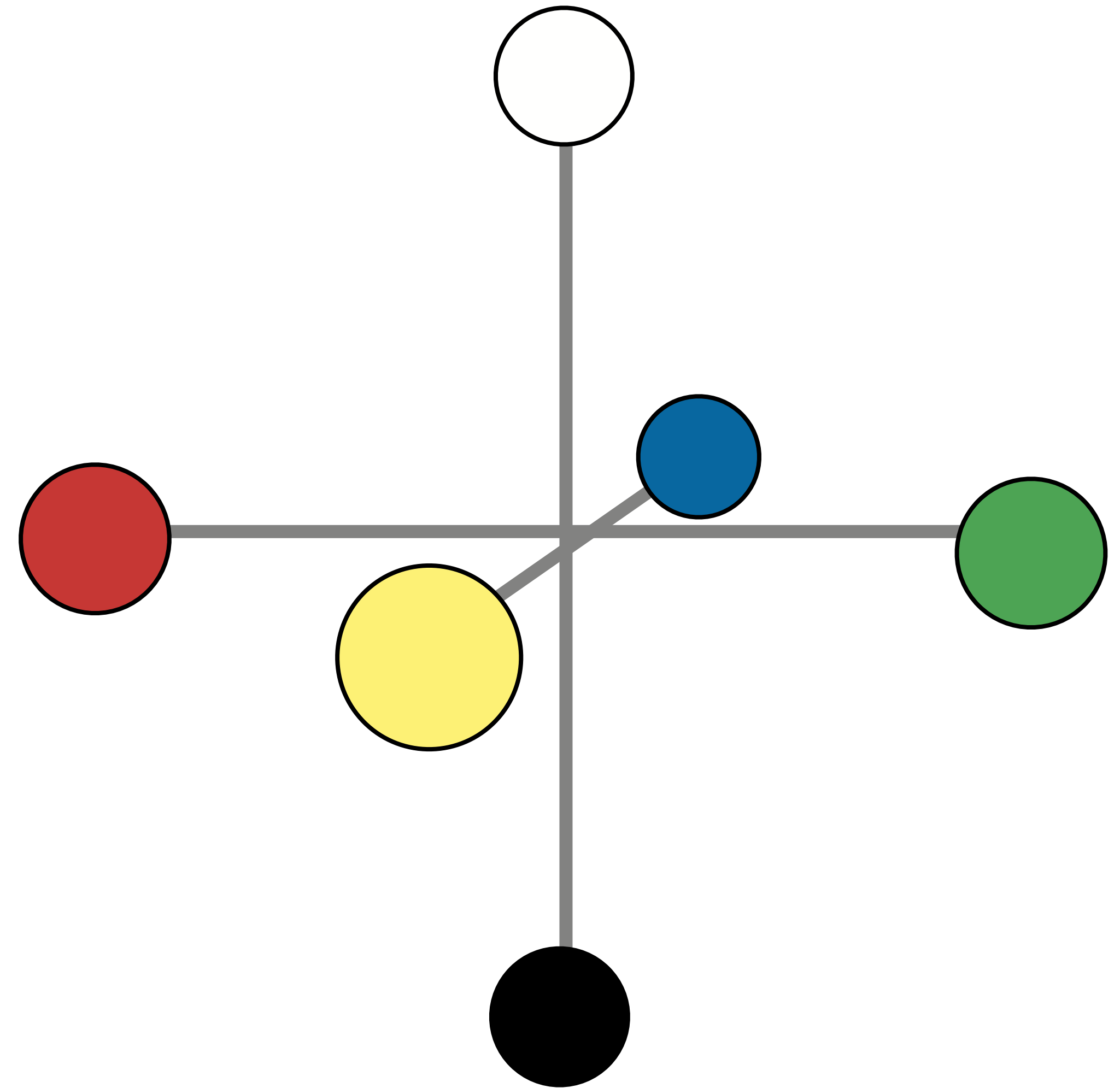
# CIE LAB Color Space

Axes correspond to opponent signals:

$L^*$  = luminance

$a^*$  = red-green contrast

$b^*$  = yellow-blue contrast

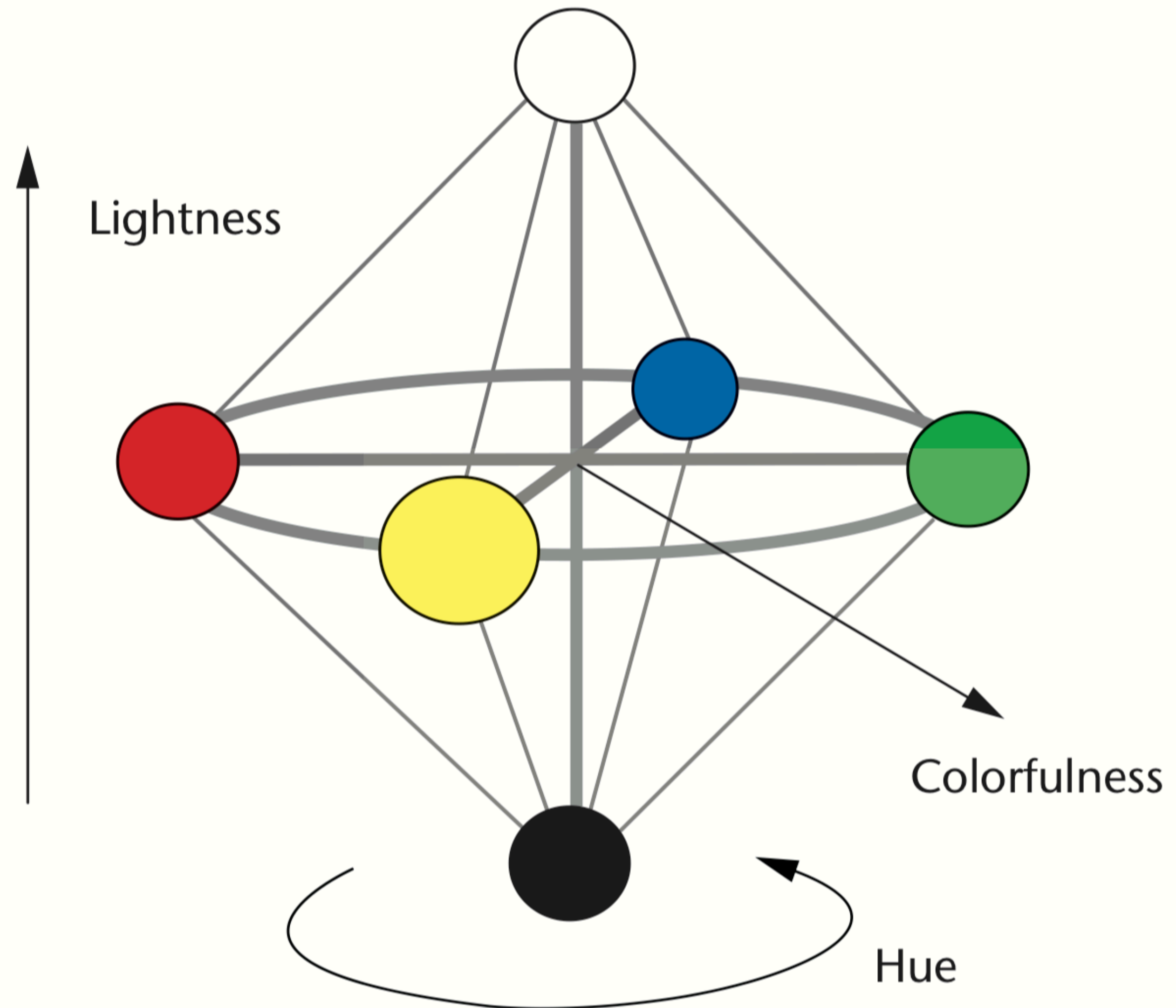


# OKLAB Color Space

Oklab is modern version of CIELAB that we recommend

In CSS:

```
oklch(65% 50% 0)
```



# OKLAB Color Space



Rainbow in Oklab

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

**But still be wary!**

JND issues  
Colorblind issues



"Angry rainbow" in sRGB

# Modeling Color Perception

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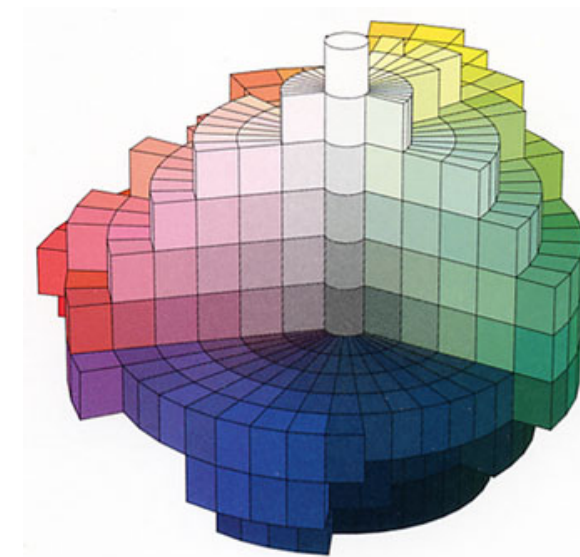
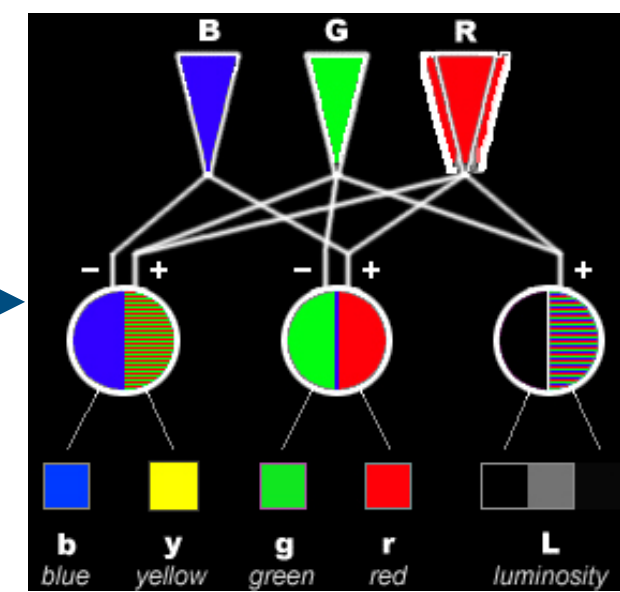
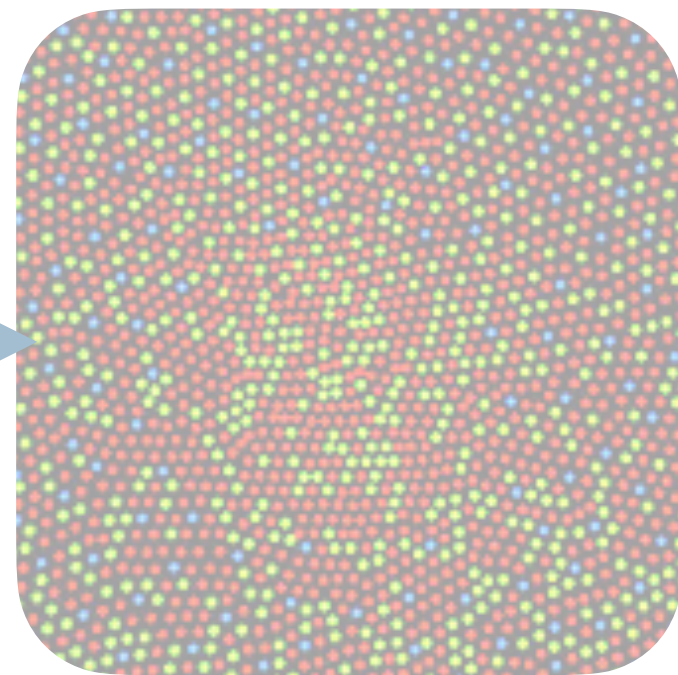
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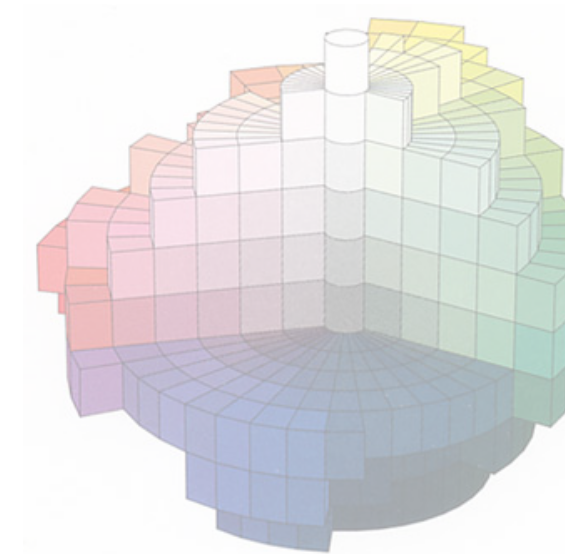
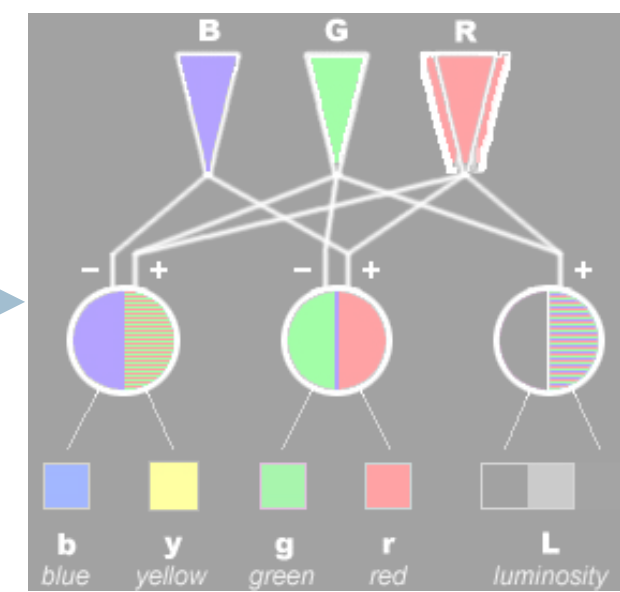
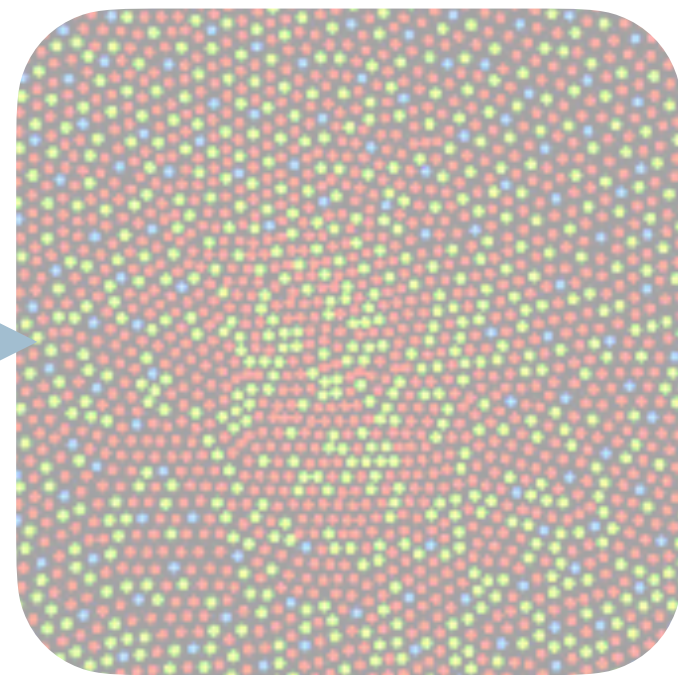
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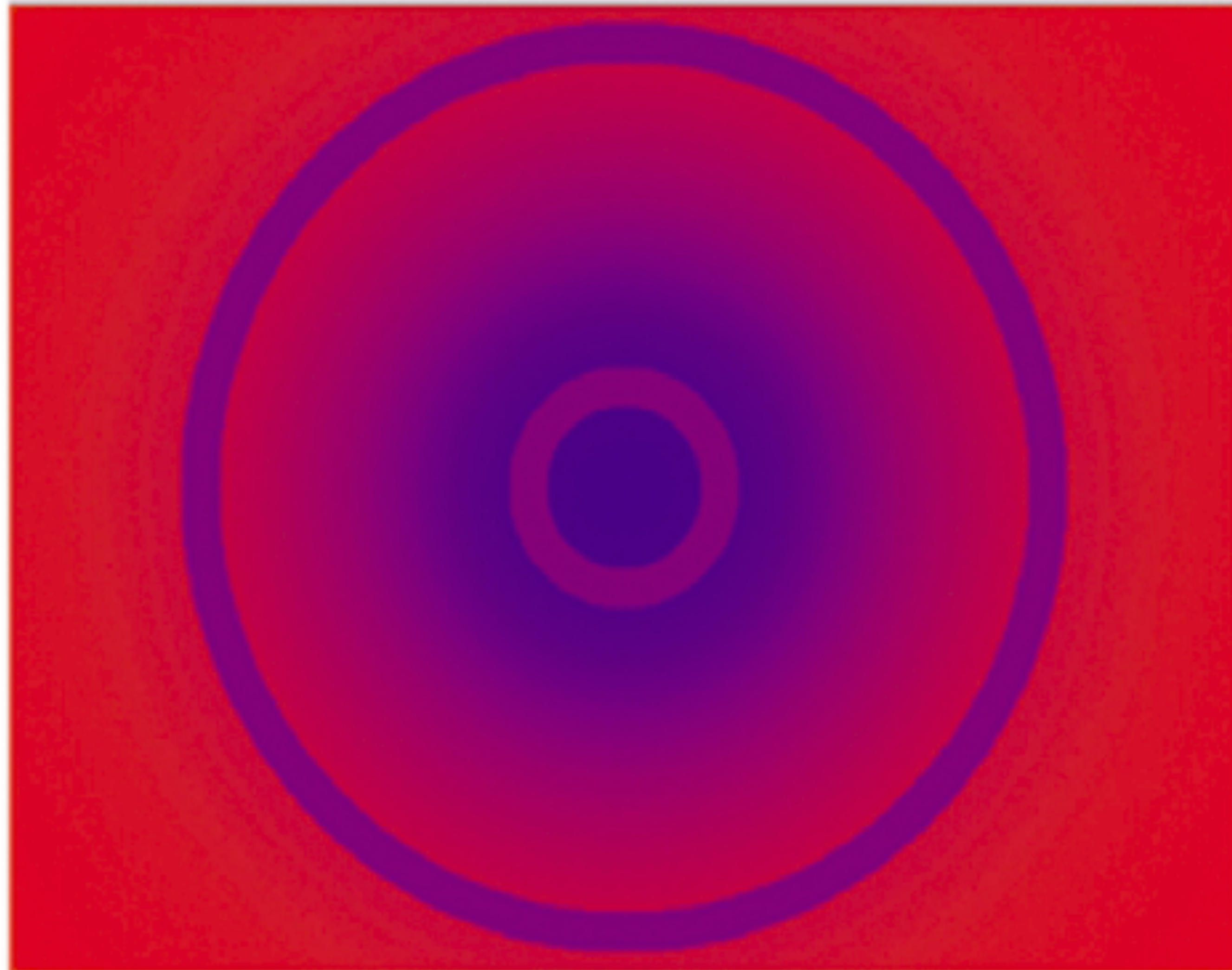
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# Simultaneous Contrast

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



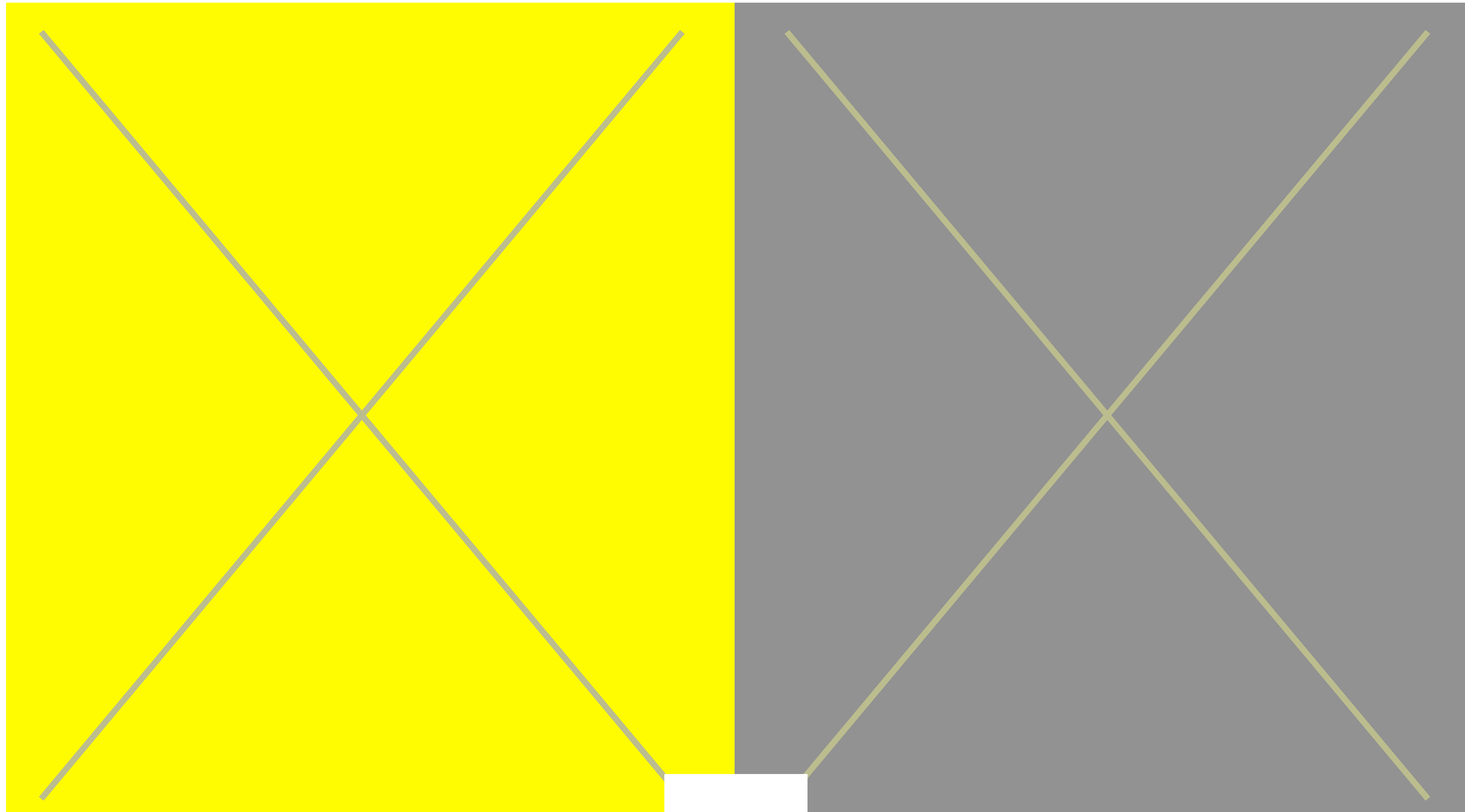
The inner and outer thin rings are, in fact, the same physical purple!

[Donald Macleod]

# Simultaneous Contrast

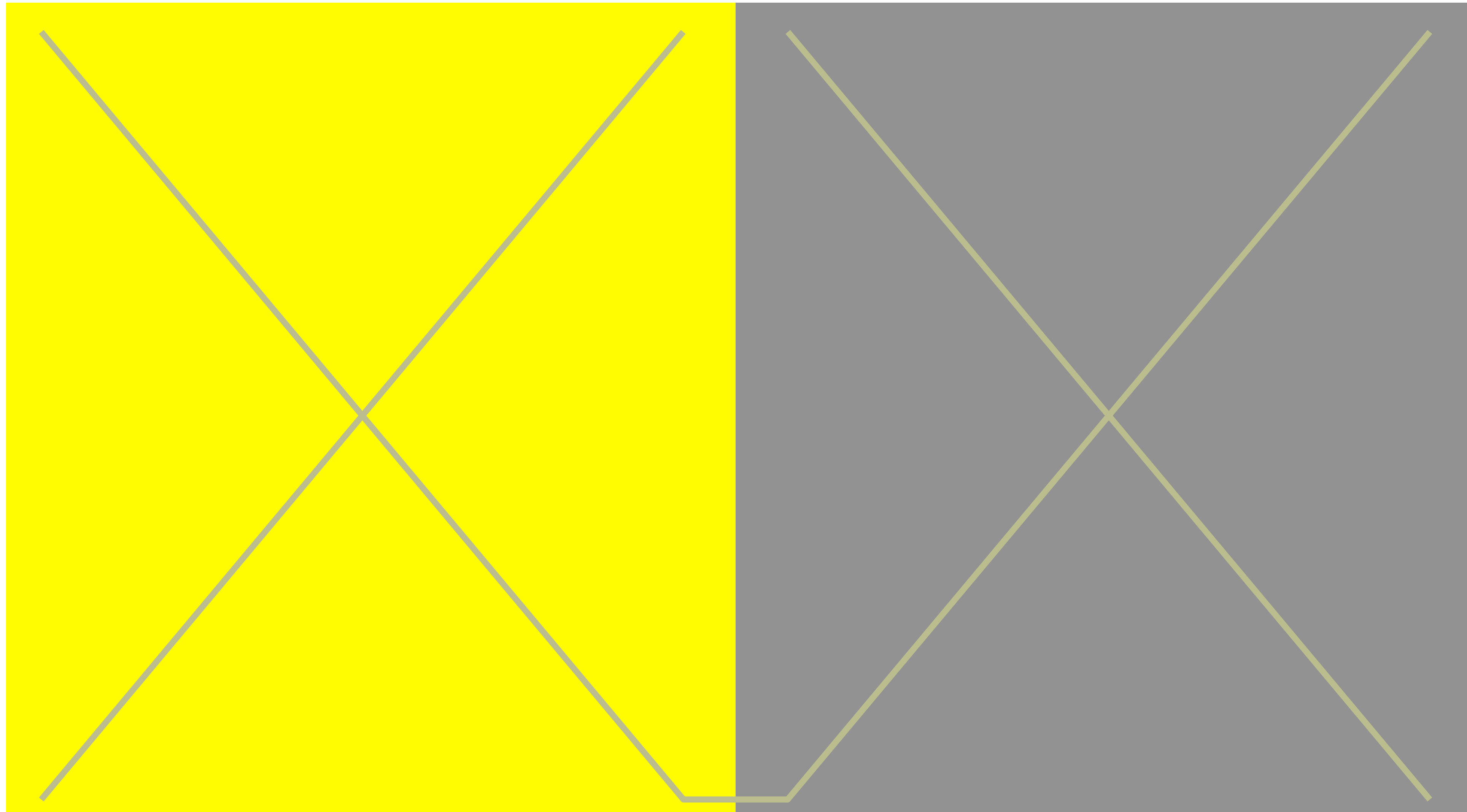
Two colors side-by-side interact and affect our perception

Josef Albers



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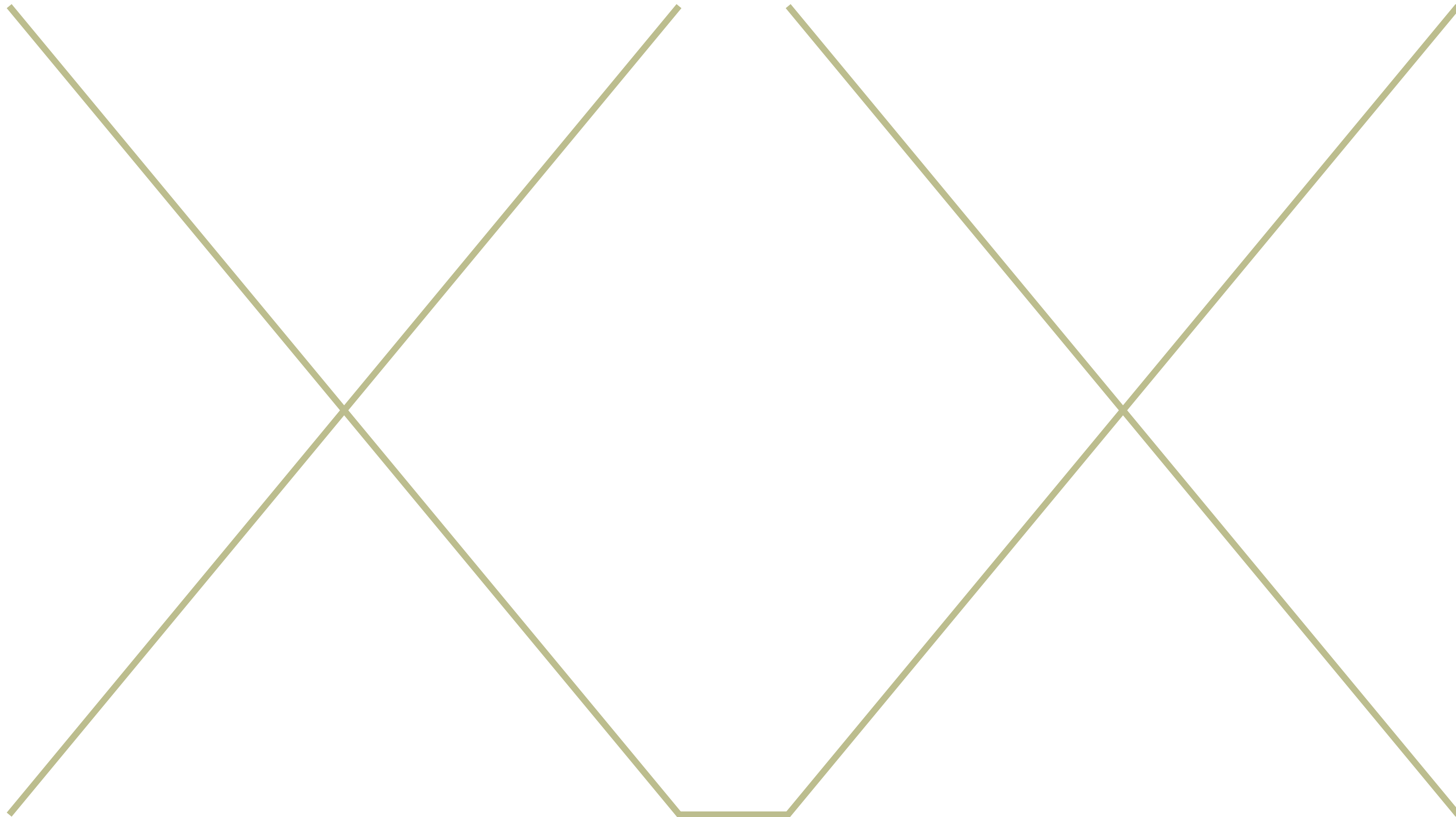


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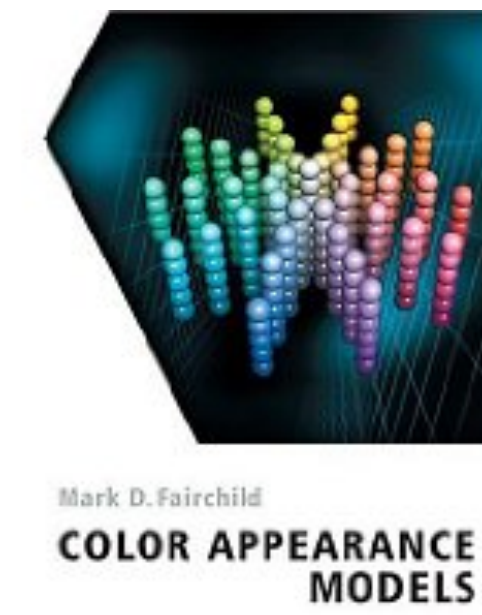
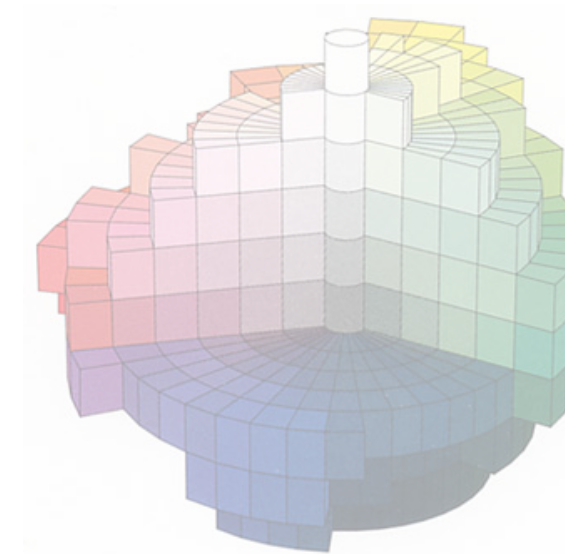
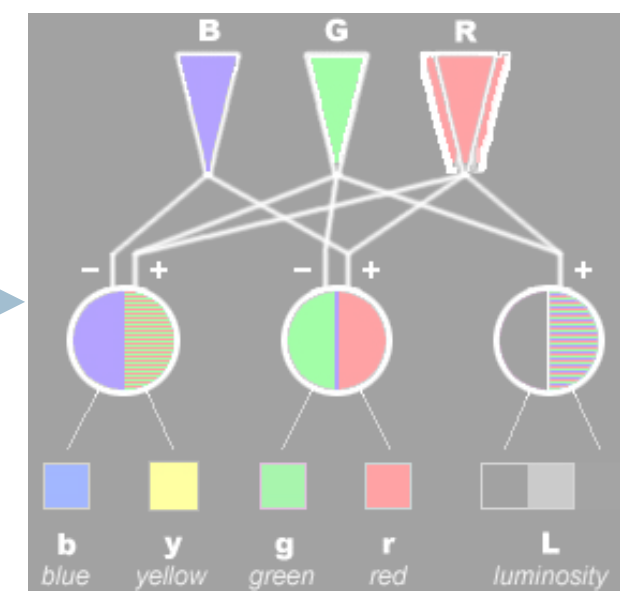
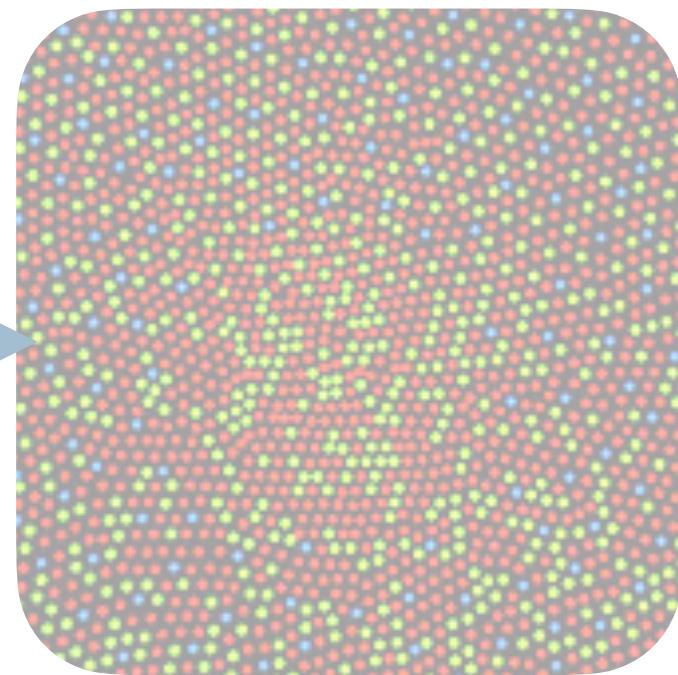
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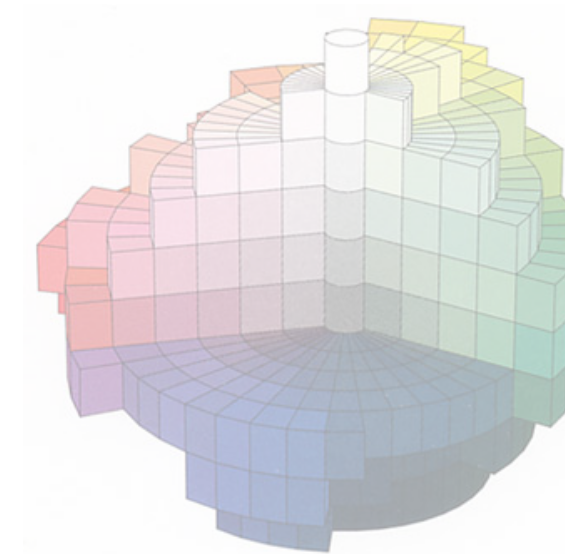
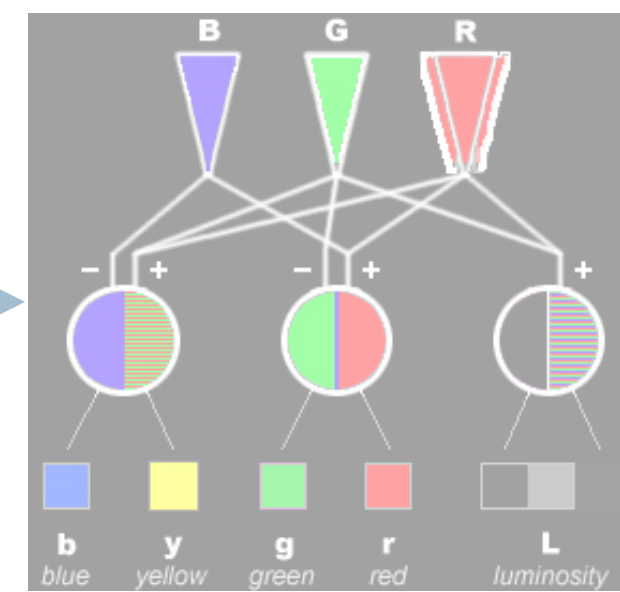
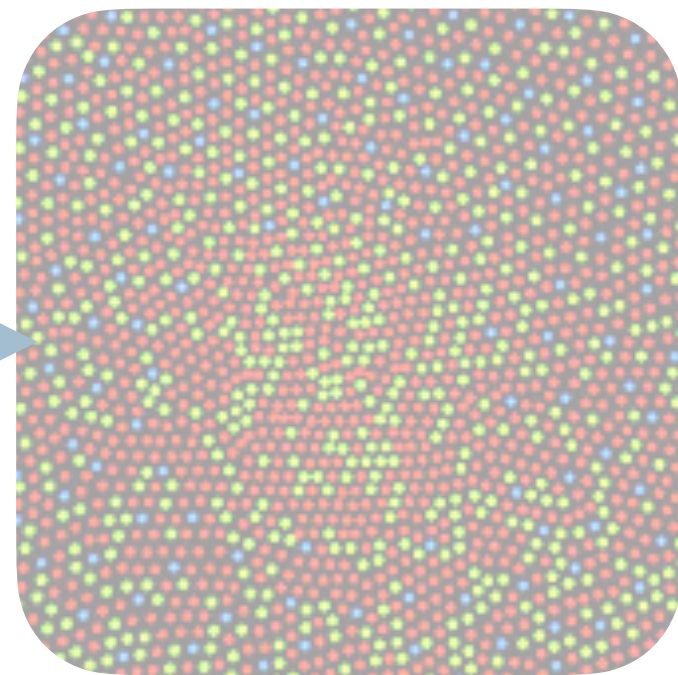
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**“Teal”**

Visible  
Light

Cone  
Response

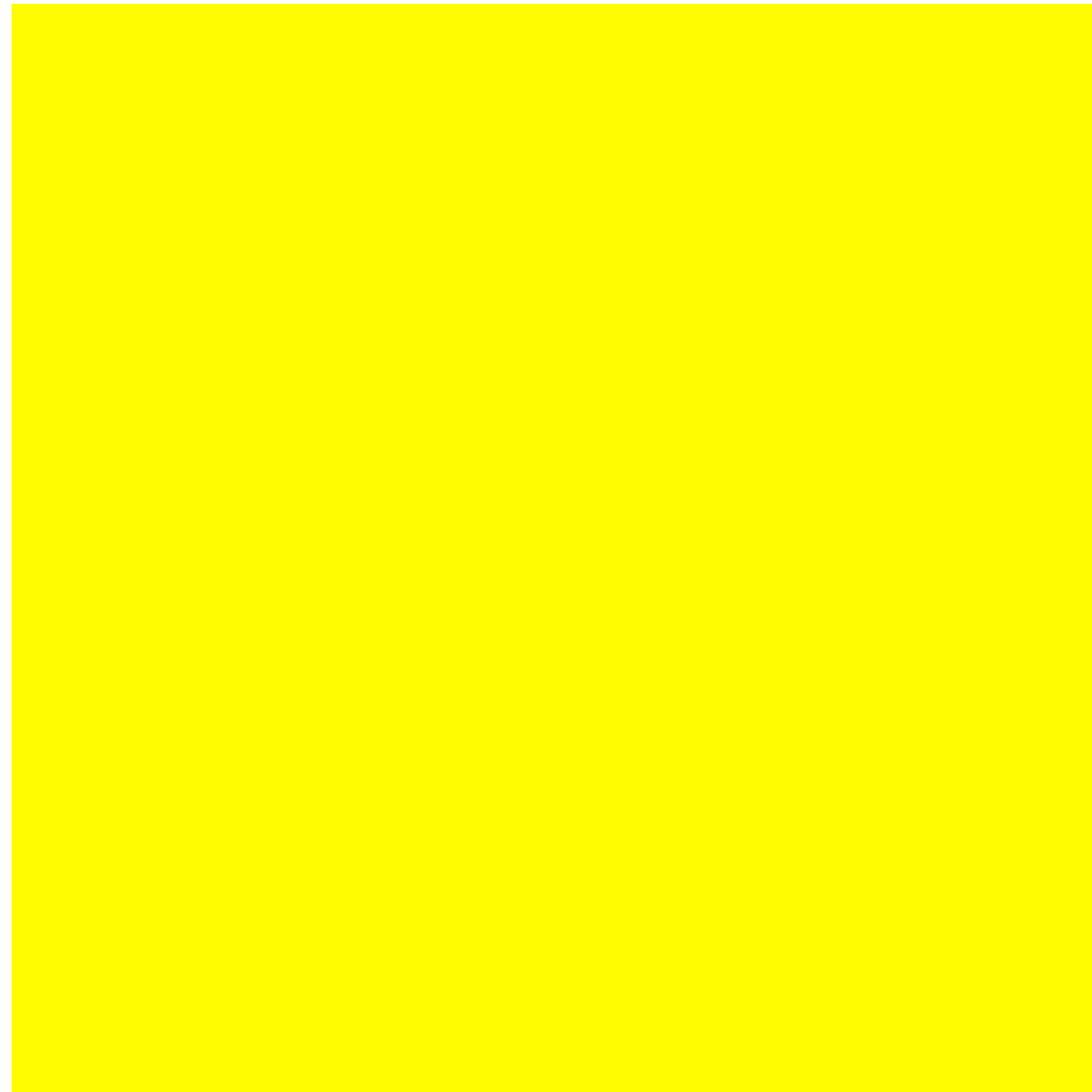
Opponent  
Encoding

Perceptual  
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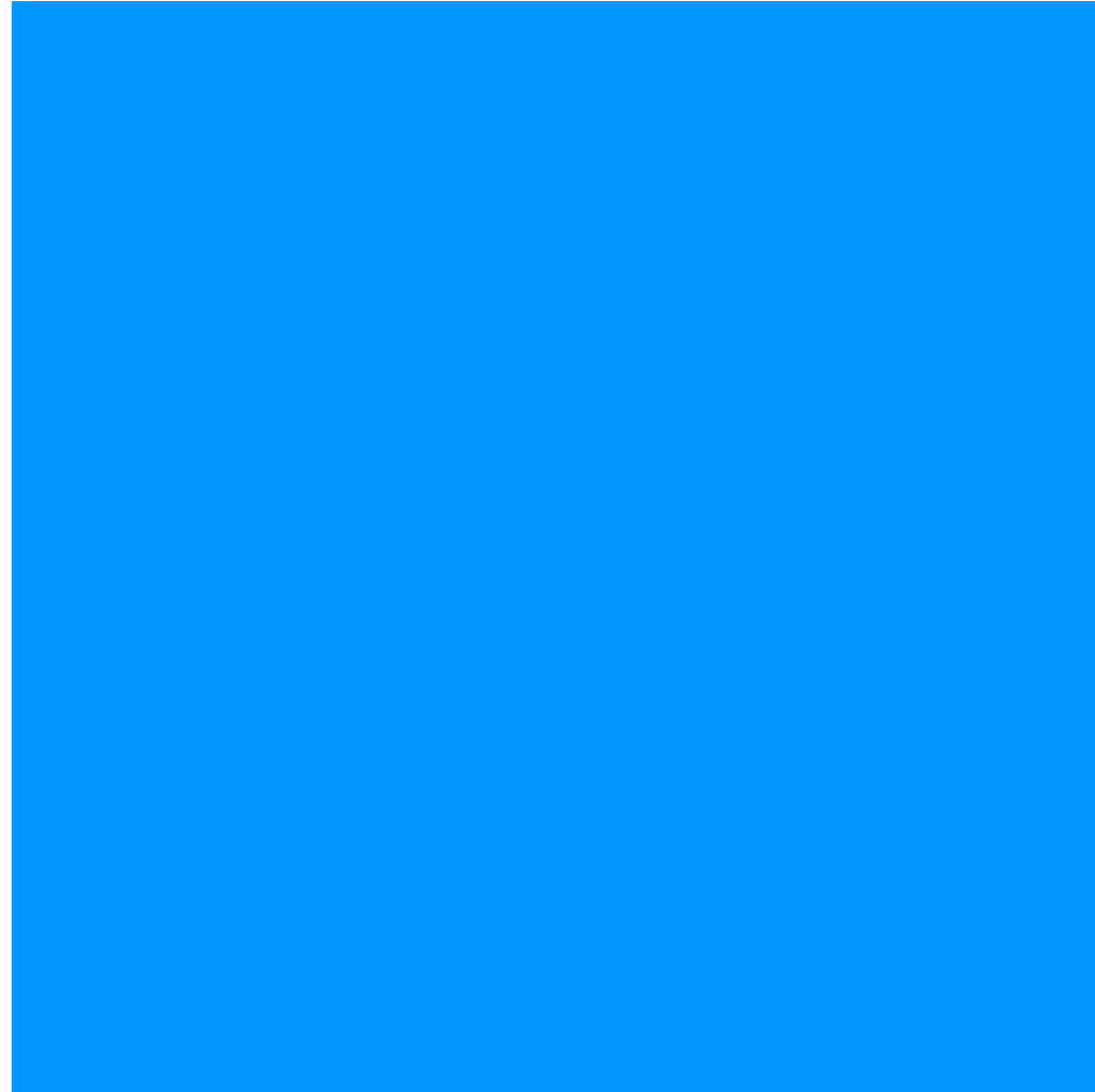
Appearance  
Models

Cognitive  
Models

# What color is this?



# What color is this?



# What color is this?



tryclassbuzz.com:  
**color**

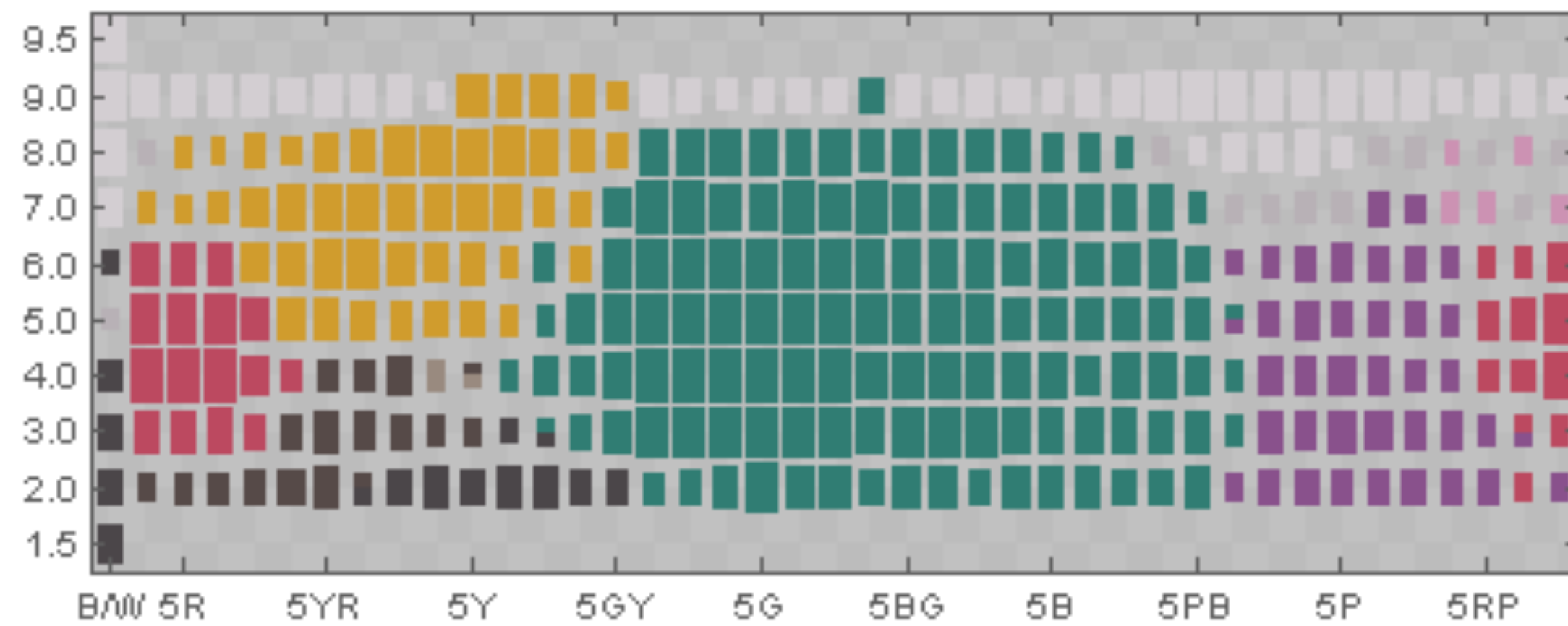
# Color Naming



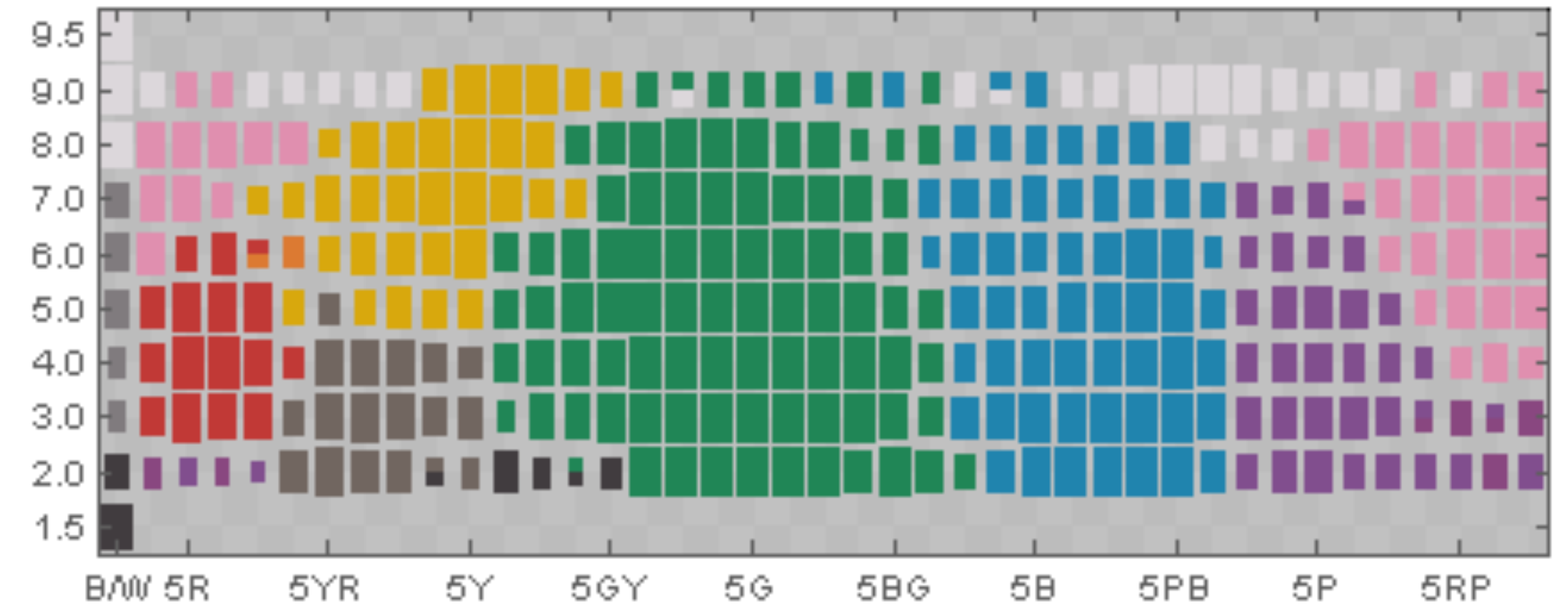
Task: Mark all the chips you would label as "red", "green", etc.

# Color Naming

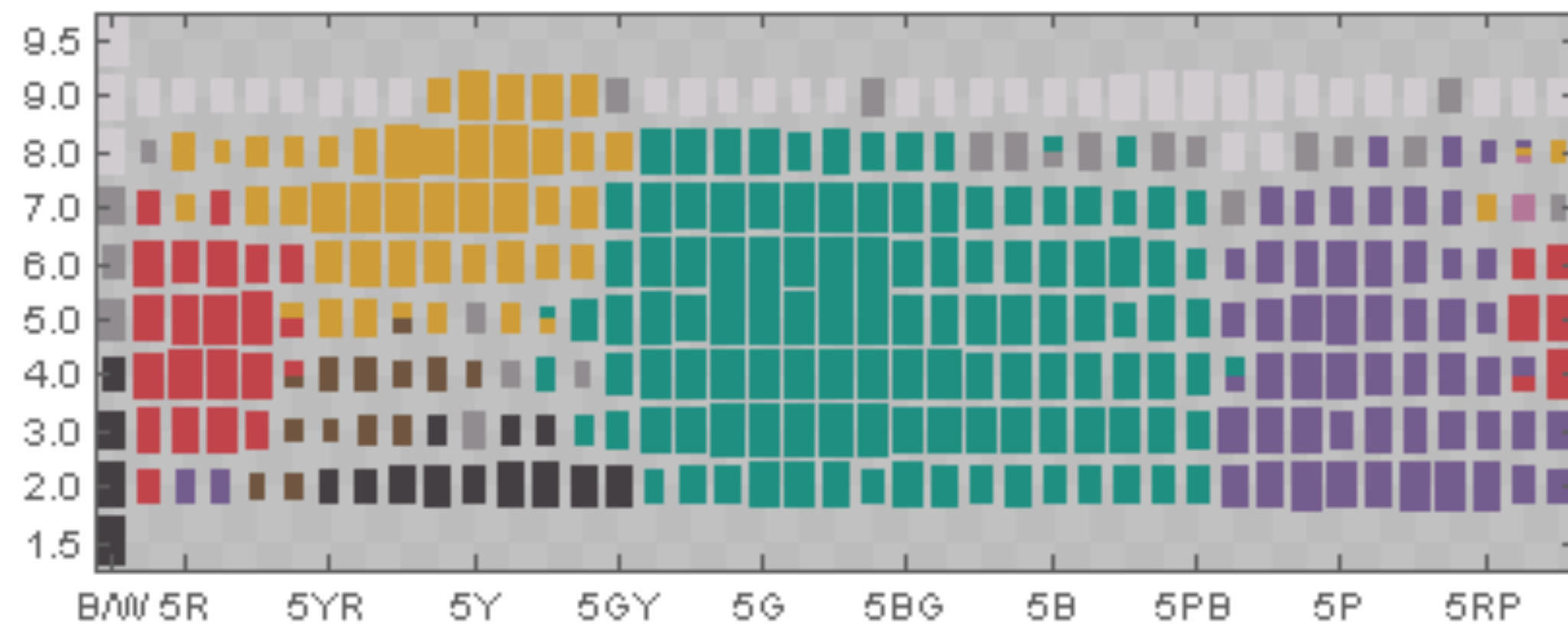
Language #72 (Mixteco)  
Mutual info = 0.942 / Contribution = 0.476



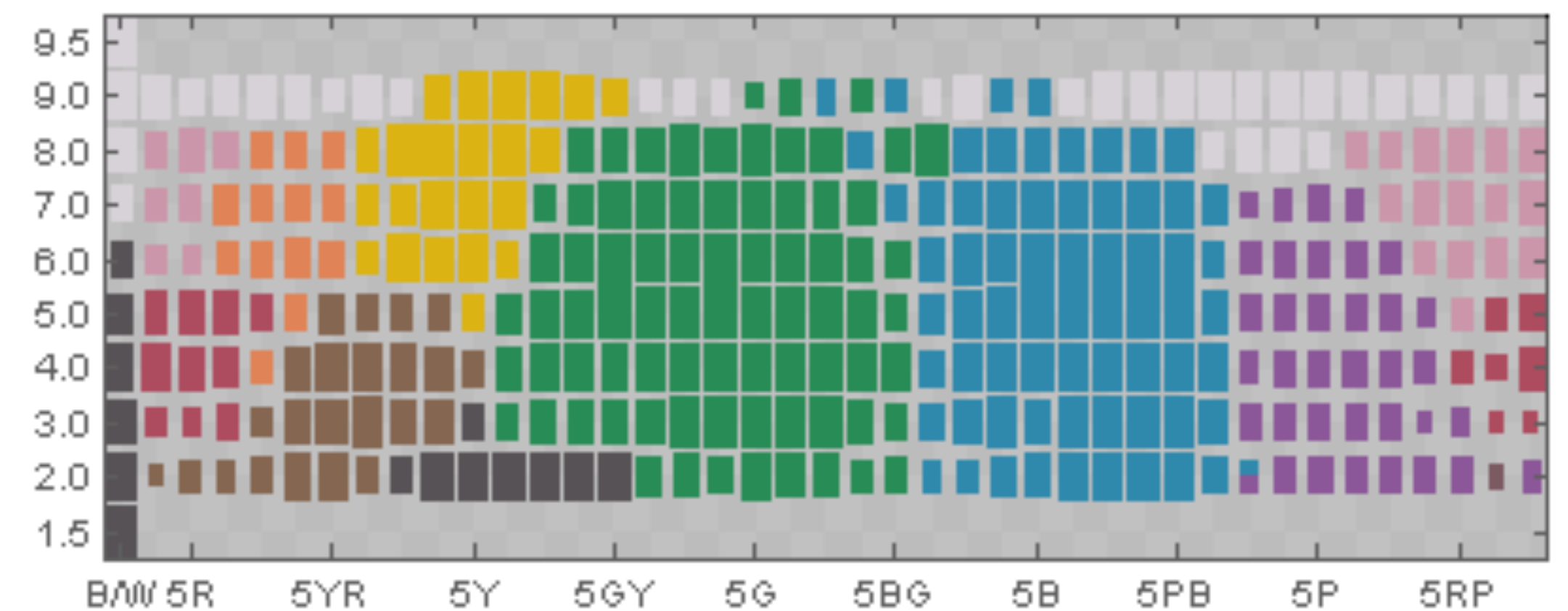
Language #19 (Camsa)  
Mutual info = 0.939 / Contribution = 0.487

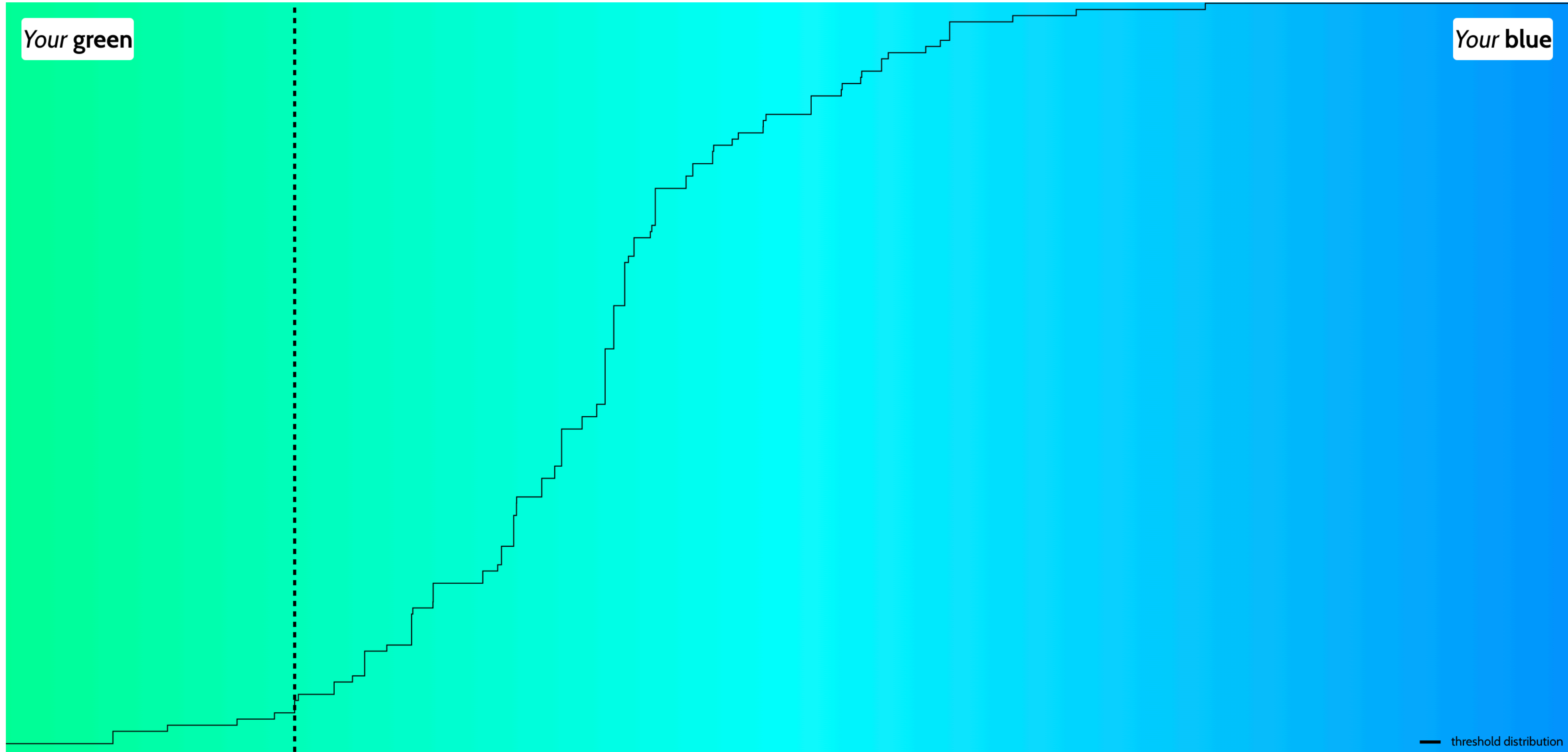


Language #98 (Tiapaneco)  
Mutual info = 0.942 / Contribution = 0.524



Language #24 (Chavacano)  
Mutual info = 0.939 / Contribution = 0.513

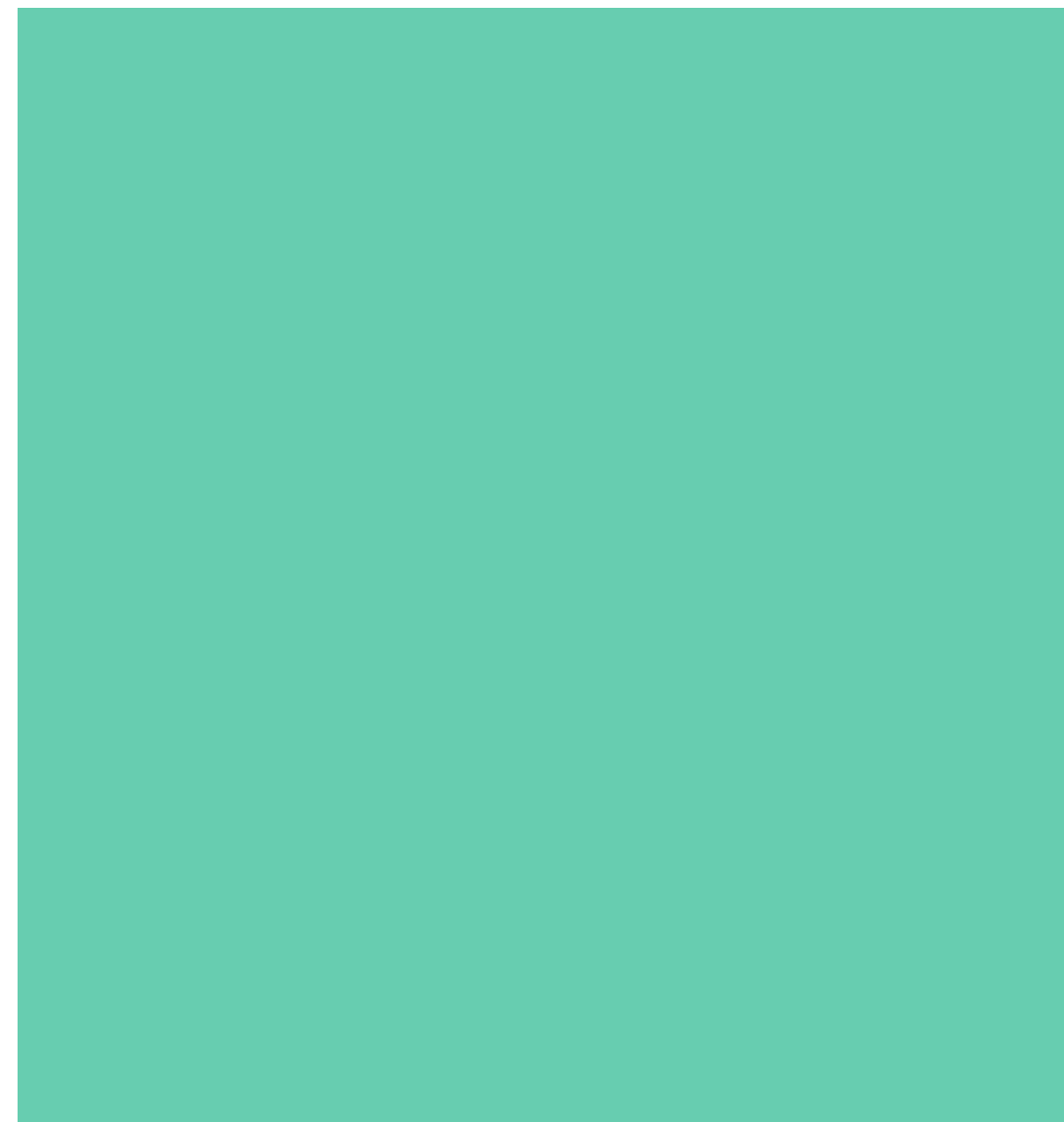
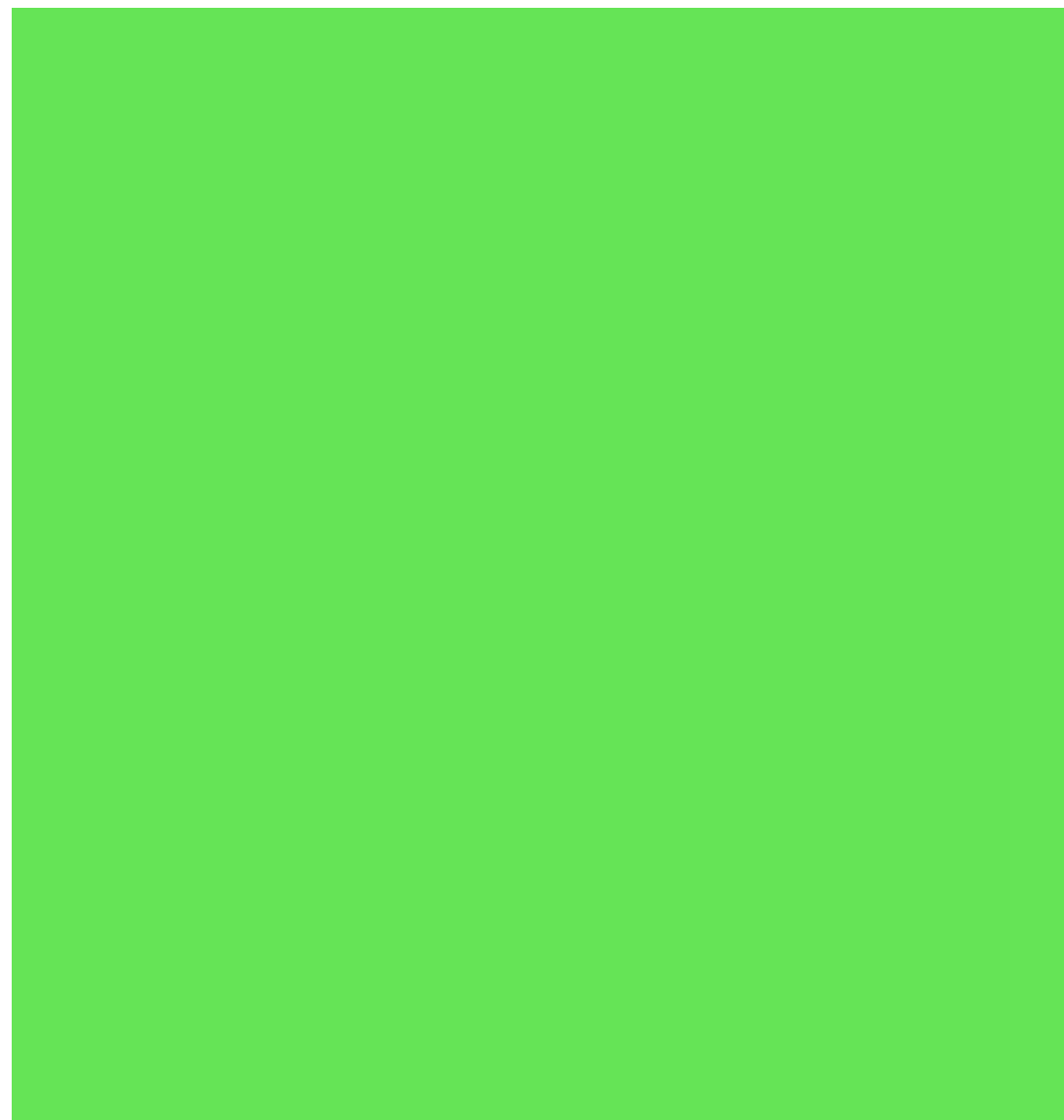




<https://ismy.blue/>

# Color Naming Affects Perception

Green



Blue



# Color Naming Affects Perception

Minimize overlap and ambiguity of colors

Color Name Distance										Saliency	Name	
0.00	1.00	1.00	0.89	0.08	1.00	0.19	1.00	1.00	0.88		.44	<b>blue</b> 61.5%
1.00	0.00	0.99	1.00	1.00	0.81	1.00	0.78	1.00	0.99		.21	<b>red</b> 21.1%
1.00	0.99	0.00	1.00	0.98	0.99	1.00	1.00	0.10	1.00		.39	<b>green</b> 42.8%
0.89	1.00	1.00	0.00	0.92	1.00	0.80	0.84	1.00	0.31		.42	<b>purple</b> 57.8%
0.08	1.00	0.98	0.92	0.00	1.00	0.21	1.00	0.97	0.88		.24	<b>blue</b> 40.4%
1.00	0.81	0.99	1.00	1.00	0.00	1.00	0.92	1.00	1.00		.28	<b>orange</b> 36.3%
0.19	1.00	1.00	0.80	0.21	1.00	0.00	0.94	0.97	0.58		.16	<b>blue</b> 25.6%
1.00	0.78	1.00	0.84	1.00	0.92	0.94	0.00	0.99	0.76		.10	<b>pink</b> 21.8%
1.00	1.00	0.10	1.00	0.97	1.00	0.97	0.99	0.00	0.96		.21	<b>green</b> 30.8%
0.88	0.99	1.00	0.31	0.88	1.00	0.58	0.76	0.96	0.00		.25	<b>purple</b> 22.7%
<b>Excel-10</b>										<i>Average</i> 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										Saliency	Name
<b>0.00</b>	1.00	1.00	1.00	0.96	1.00	1.00	0.99	1.00	<b>0.19</b>	.47	<b>blue</b> 65.3%
1.00	<b>0.00</b>	1.00	0.98	1.00	1.00	1.00	1.00	0.97	1.00	.87	<b>orange</b> 92.2%
1.00	1.00	<b>0.00</b>	1.00	1.00	1.00	1.00	1.00	<b>0.70</b>	0.99	.70	<b>green</b> 81.3%
1.00	0.98	1.00	<b>0.00</b>	1.00	0.96	0.99	1.00	1.00	1.00	.64	<b>red</b> 79.3%
0.96	1.00	1.00	1.00	<b>0.00</b>	0.95	0.83	0.98	1.00	0.97	.43	<b>purple</b> 52.5%
1.00	1.00	1.00	0.96	0.95	<b>0.00</b>	0.99	0.96	0.96	1.00	.47	<b>brown</b> 60.5%
1.00	1.00	1.00	0.99	0.83	0.99	<b>0.00</b>	1.00	1.00	1.00	.47	<b>pink</b> 60.3%
0.99	1.00	1.00	1.00	0.98	0.96	1.00	<b>0.00</b>	1.00	0.99	.74	<b>grey</b> 83.7%
1.00	0.97	<b>0.70</b>	1.00	1.00	0.96	1.00	1.00	<b>0.00</b>	1.00	.11	<b>yellow</b> 20.1%
<b>0.19</b>	1.00	0.99	1.00	0.97	1.00	1.00	0.99	1.00	<b>0.00</b>	.25	<b>blue</b> 27.2%
<i>Average</i> 0.96										.52	

[Heer and Stone, CHI 2012]

Tableau-10

Default color palette for Tableau: better!

# **Putting it together: Designing colormaps**

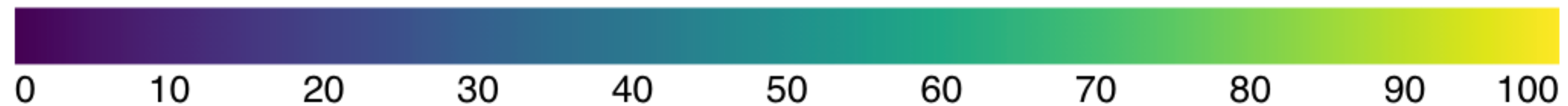
# Discrete (binary, categorical)

## Symbol Legend



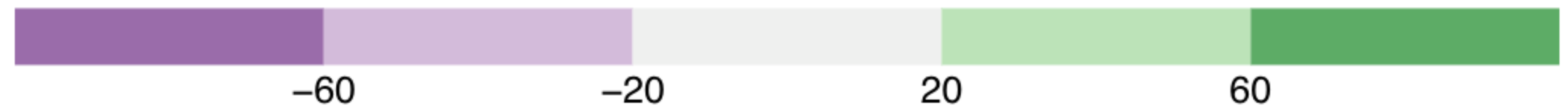
# Continuous (sequential, diverging, cyclic)

## Gradient Legend



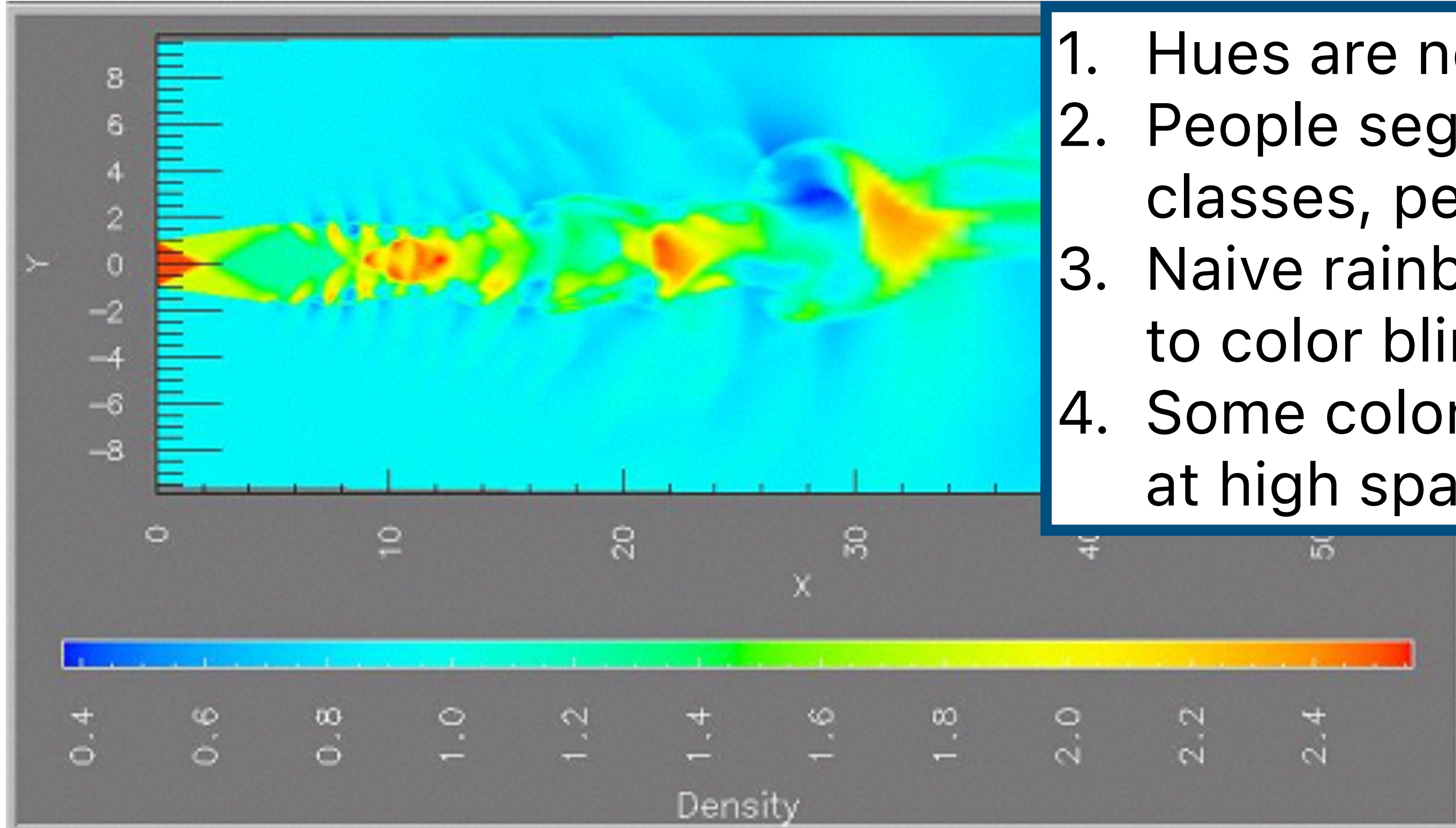
# Discretized Continuous

## Discrete Gradient



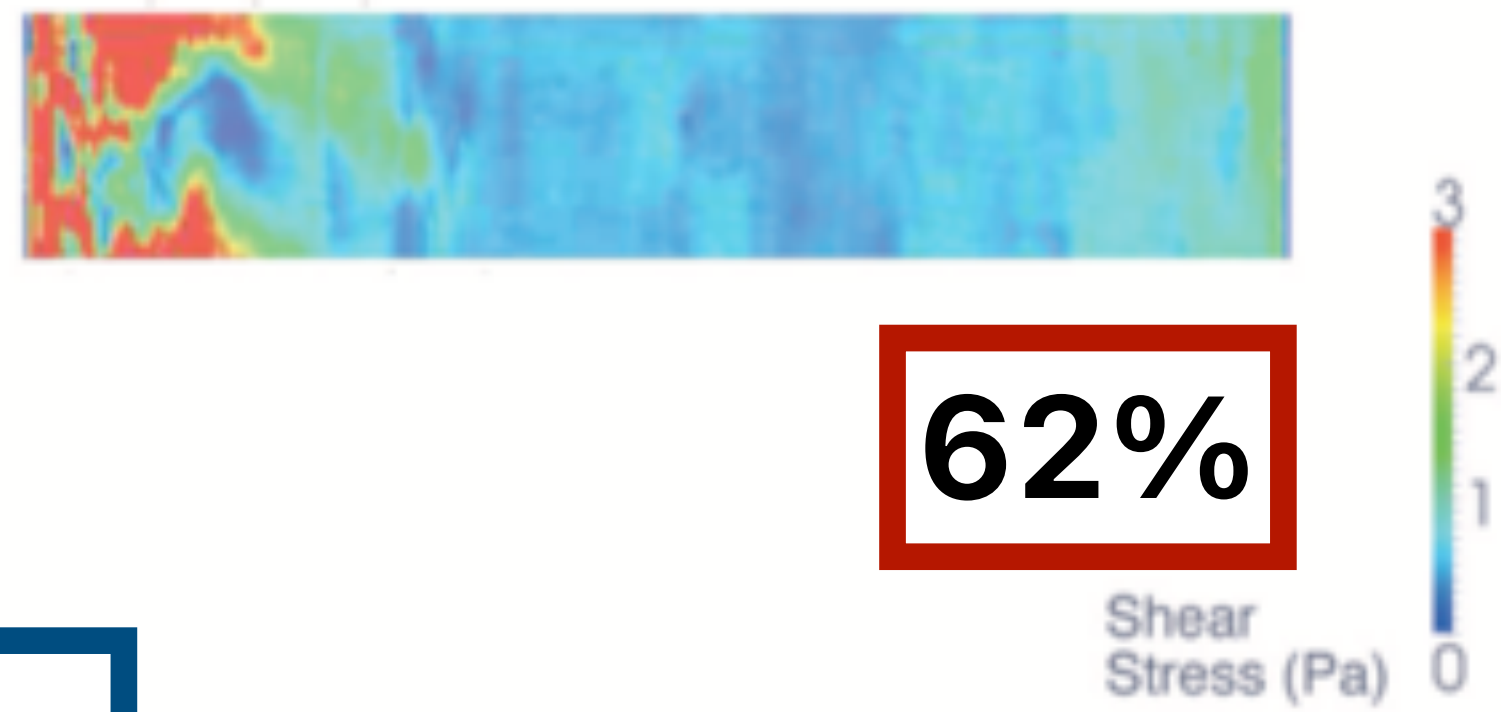
In general, prefer this over continuous!

# Beware of naive rainbows!

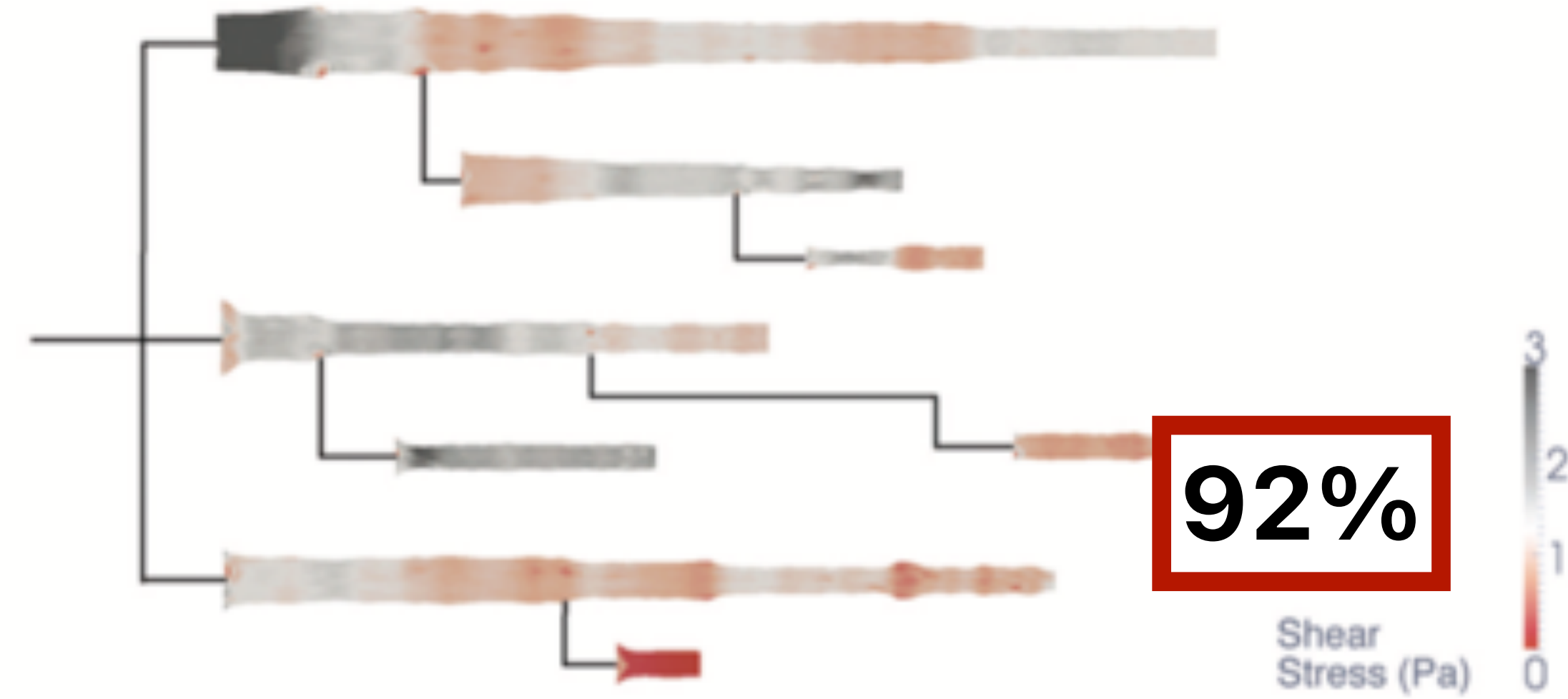
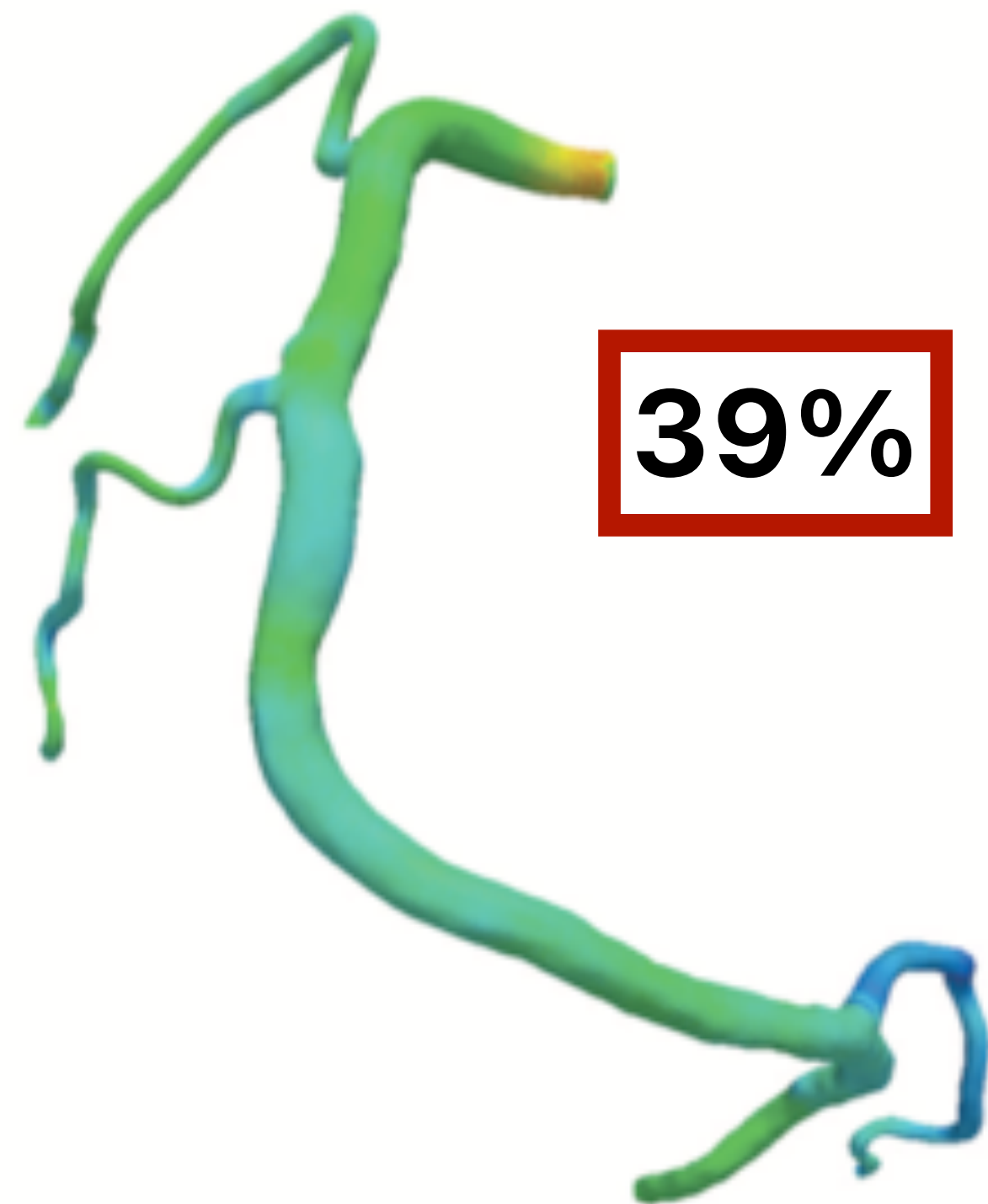


1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naive rainbows are unfriendly to color blind viewers
4. Some colors are less effective at high spatial frequencies

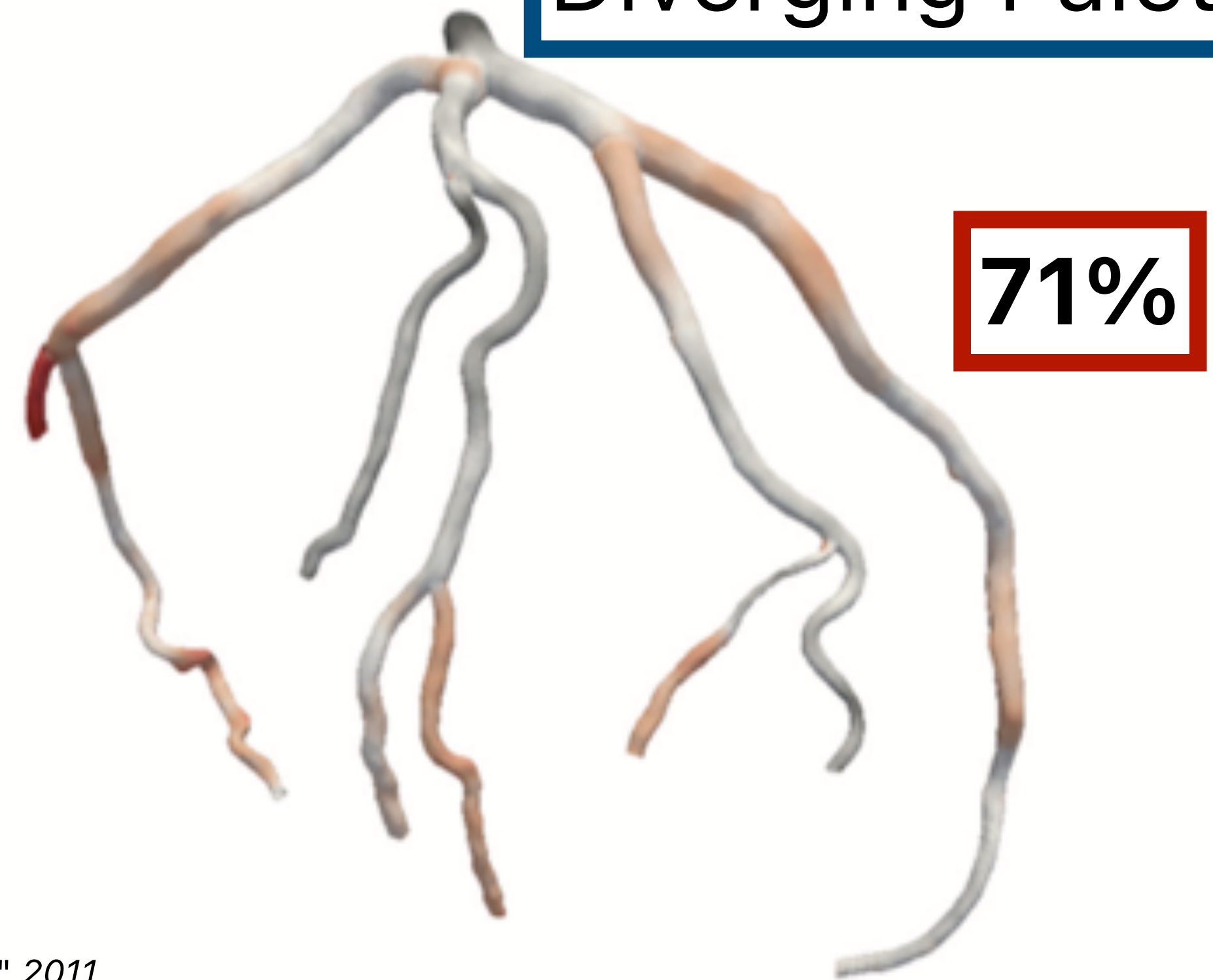
# Beware of naive rainbows!



Rainbow Palette

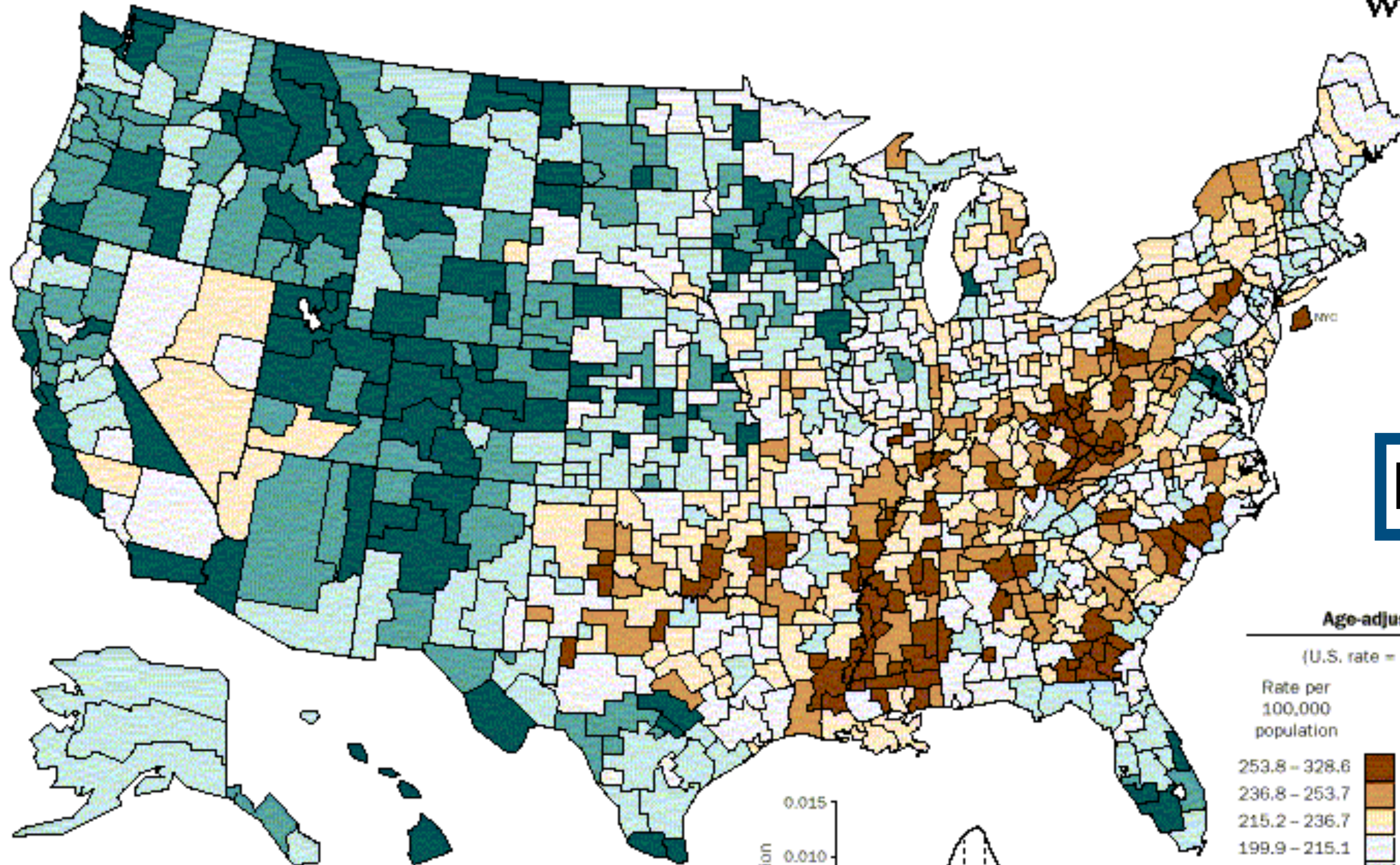


Diverging Palette



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

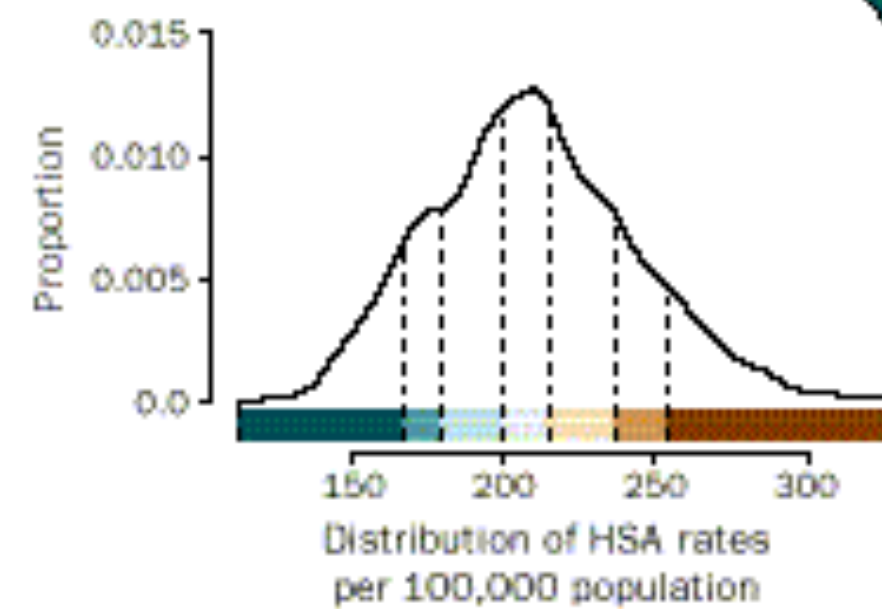
## HEART DISEASE WHITE MALE



Cynthia Brewer

<https://colorbrewer2.org/>

ICD-9 Categories 390-398,  
402, 404-429



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

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

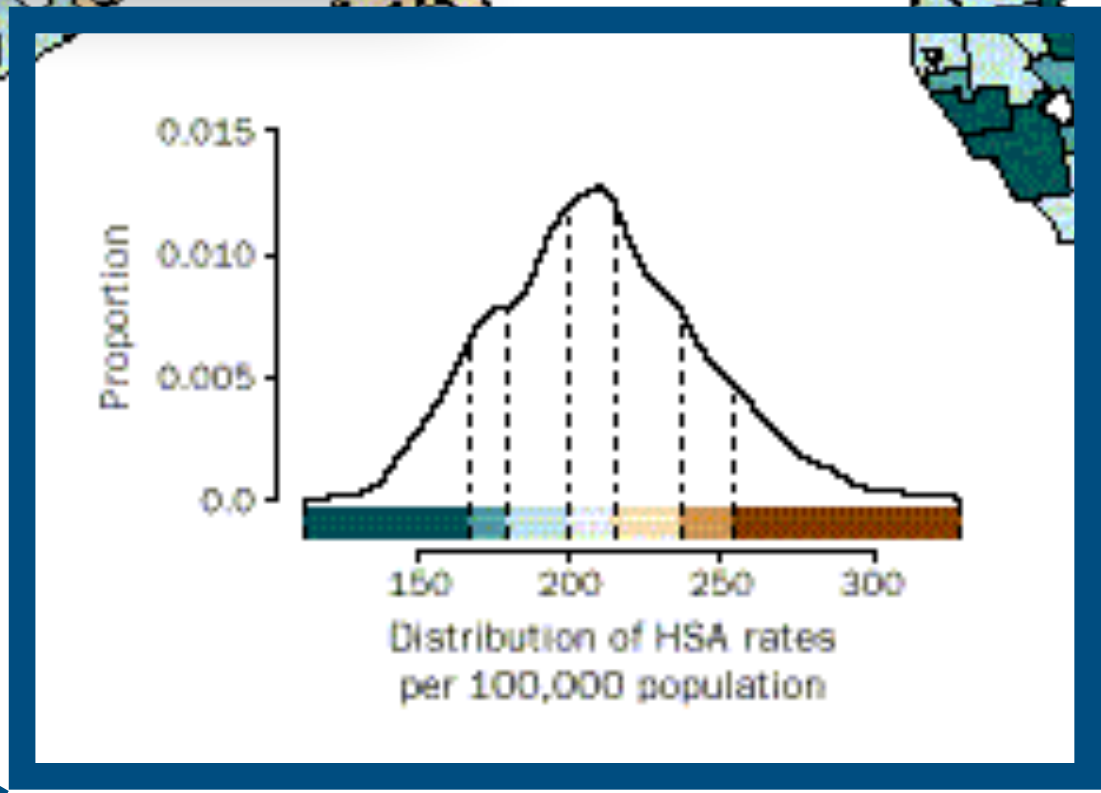
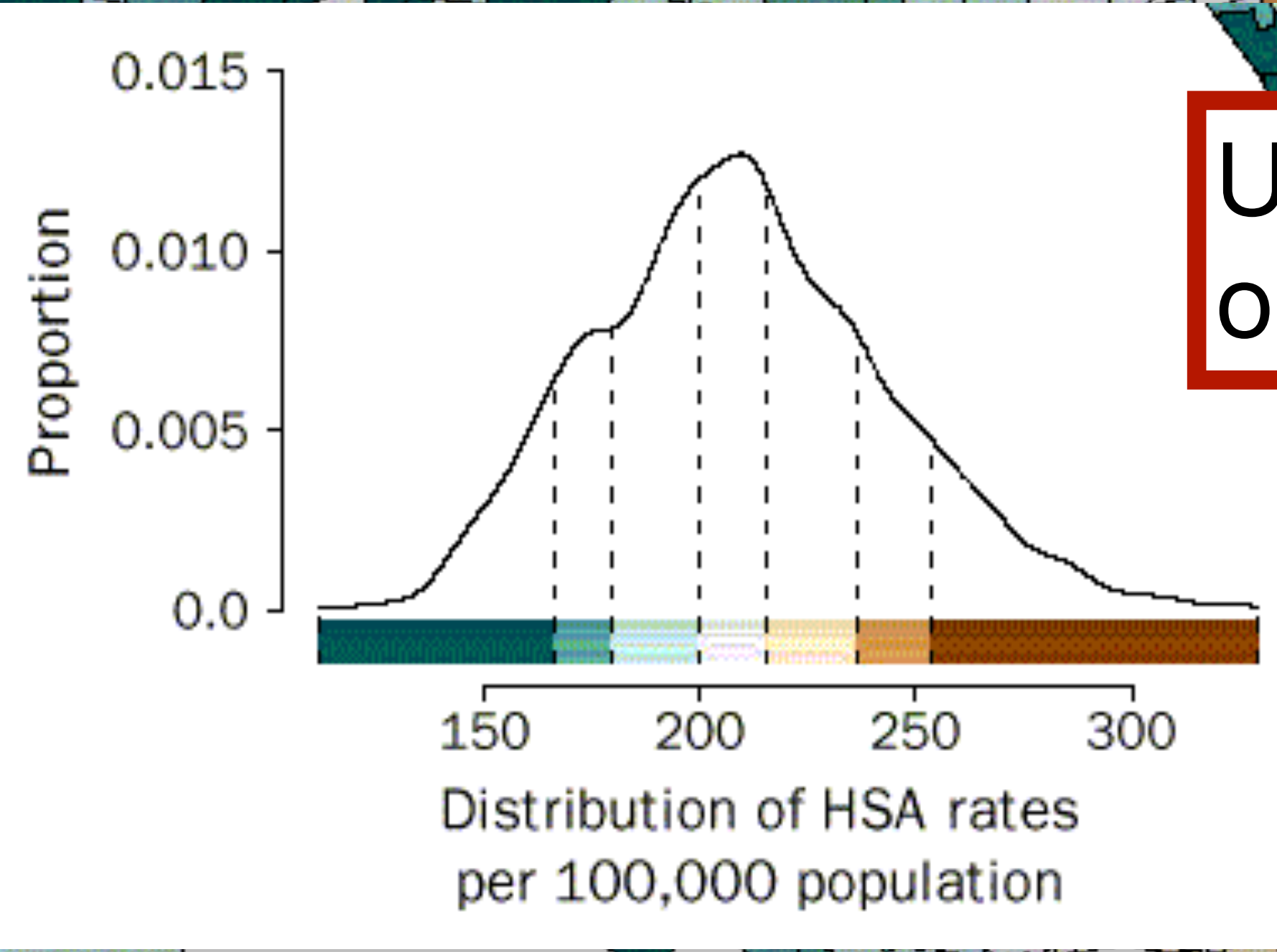
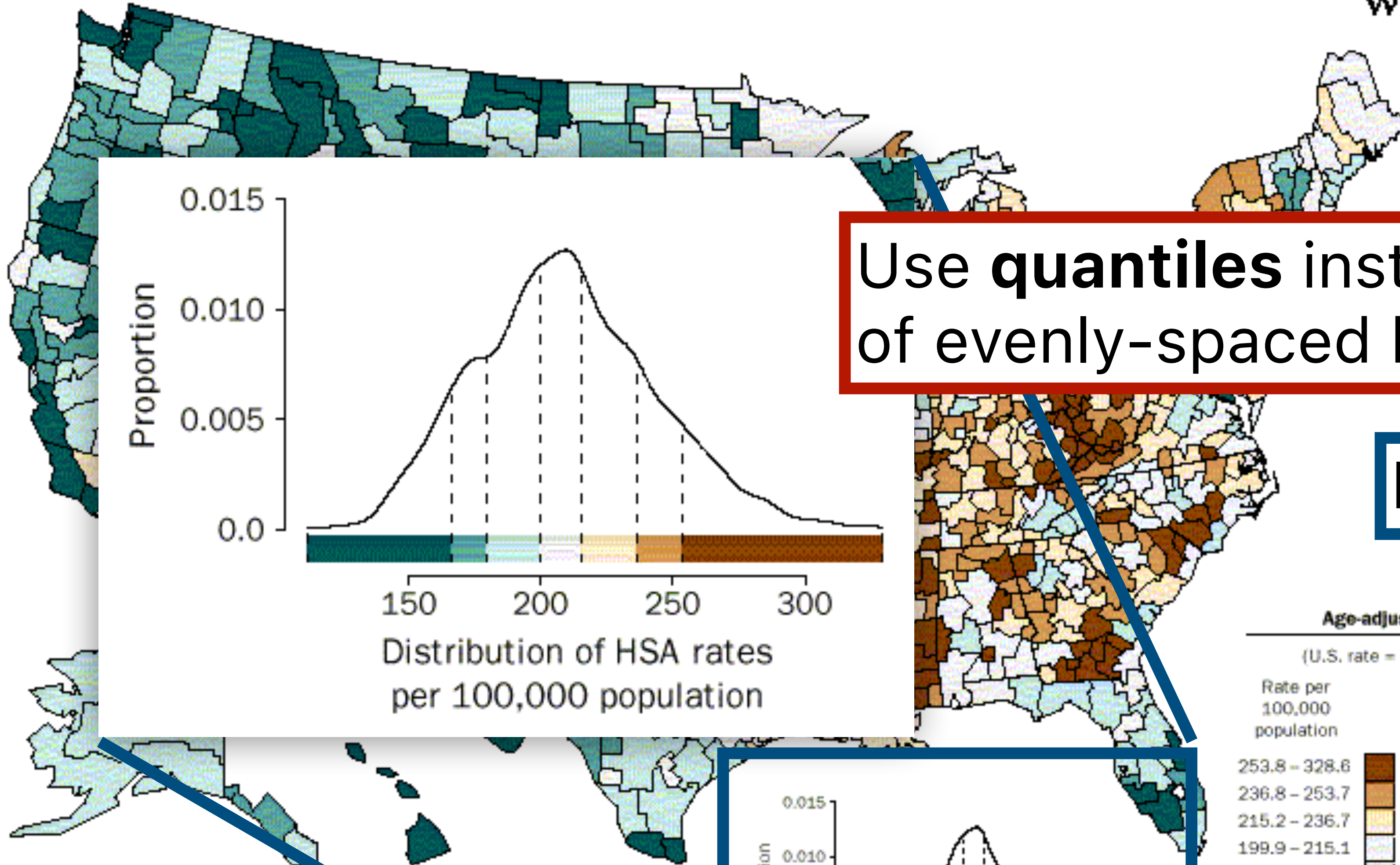
HEART DISEASE  
WHITE MALE



Cynthia Brewer

<https://colorbrewer2.org/>

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

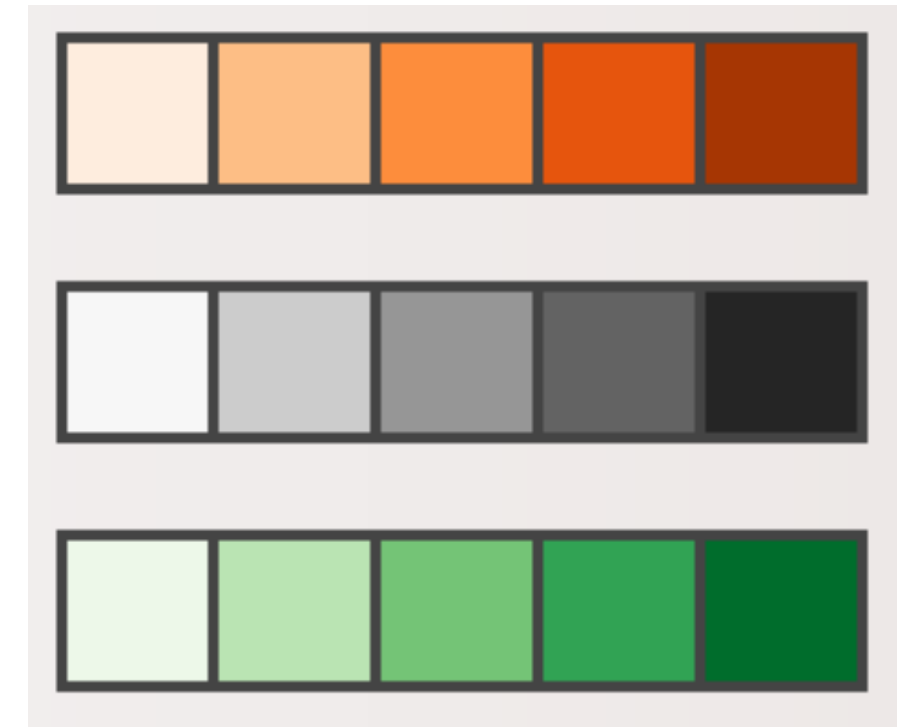
ICD-9 Categories 390-398, 402, 404-429

SOURCE: CDC/NCHS

# Quantitative Color Encoding

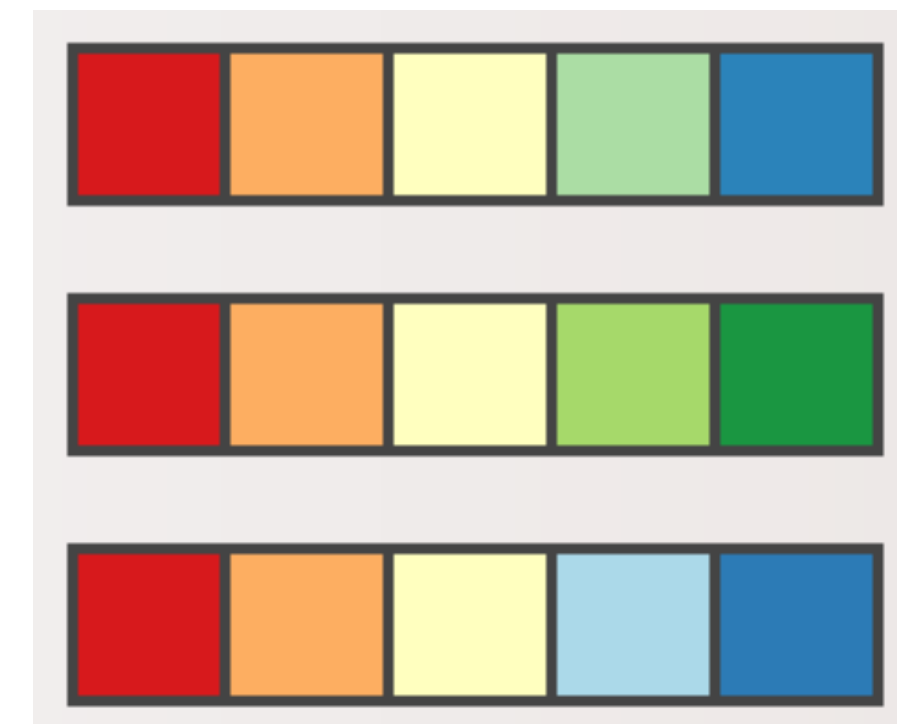
## Sequential Color Scale

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 with the URL `observablehq.com`. The navigation bar includes links for Platform, Solutions, Resources, and Pricing, along with Sign in and Sign up buttons. The main content area is titled "Color Schemes" and includes a sub-header "Including Every ColorBrewer Scale". A note states: "Click any `d3-scale-chromatic` scheme below to copy it to the clipboard." A dropdown menu for "Scheme size" is set to "continuous". The page lists two categories of color schemes: "Sequential (Single-Hue)" and "Sequential (Multi-Hue)".

**Sequential (Single-Hue)**

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

**Sequential (Multi-Hue)**

- BuGn
- BuPu
- GnBu
- OrRd
- PuBuGn

<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.