Color

DSC 106: Data Visualization

Jared Wilber
UC San Diego

Announcements

Project 2 Peer Review - Thursday 5/2.

Lab 5 (D3) out, due 5/3.

Project 3 out, due on Friday 5/10.

I will email a group sign-up sheet for Project 3.

Be respectful on Ed - inflammatory messages will be sent to SAGE for Non-Academic misconduct.

Project 2 Peer Review

There is a spreadsheet assigning each students two peers.

You will review Project 2 for the given peers.

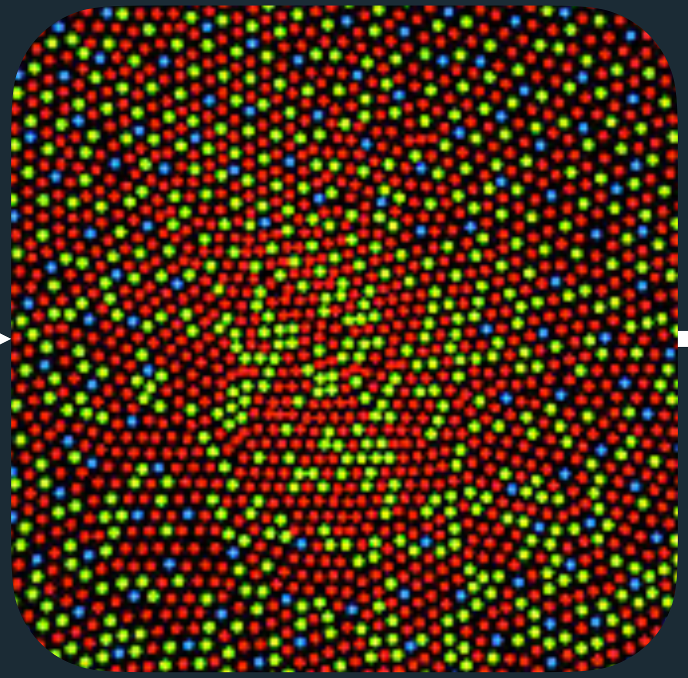
Color

Modeling Color Perception

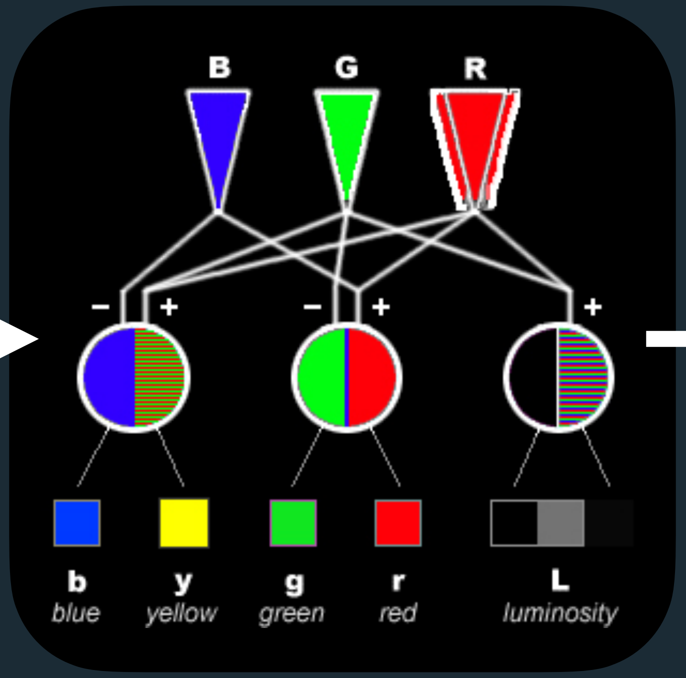
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response



Opponent Encoding

Perceptual Models

Appearance Models

"Teal"

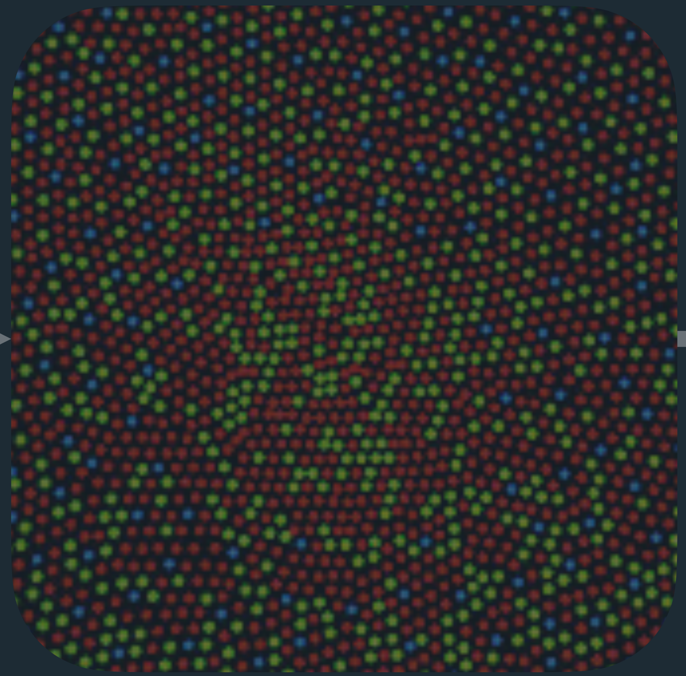
Cognitive Models

Modeling Color Perception

Low-Level Abstraction High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response

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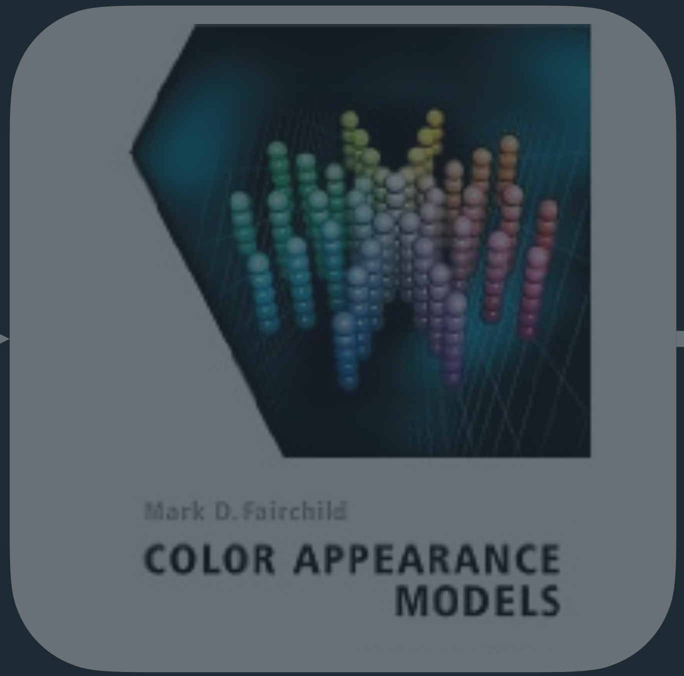


Appearance Models

"Teal"

Cognitive Models

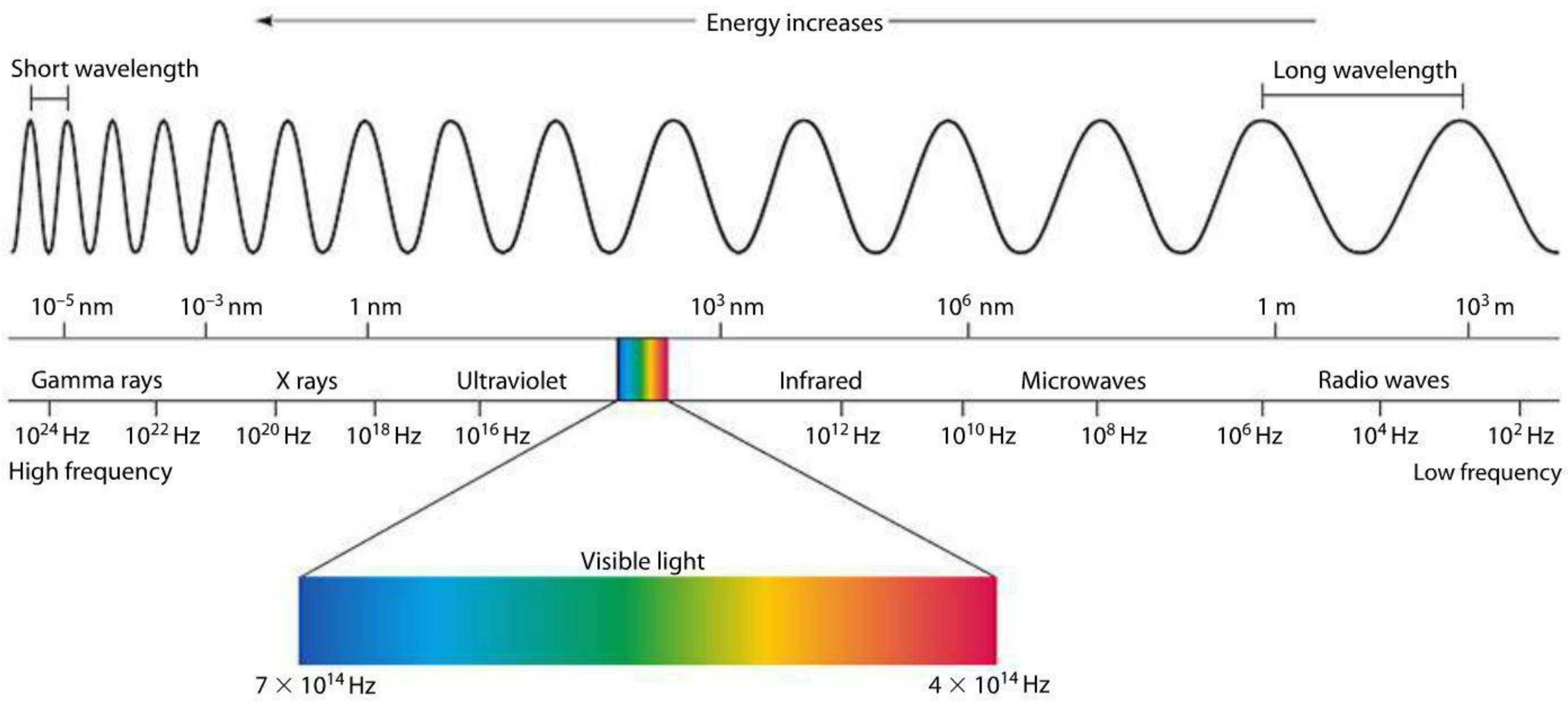
Visible Light

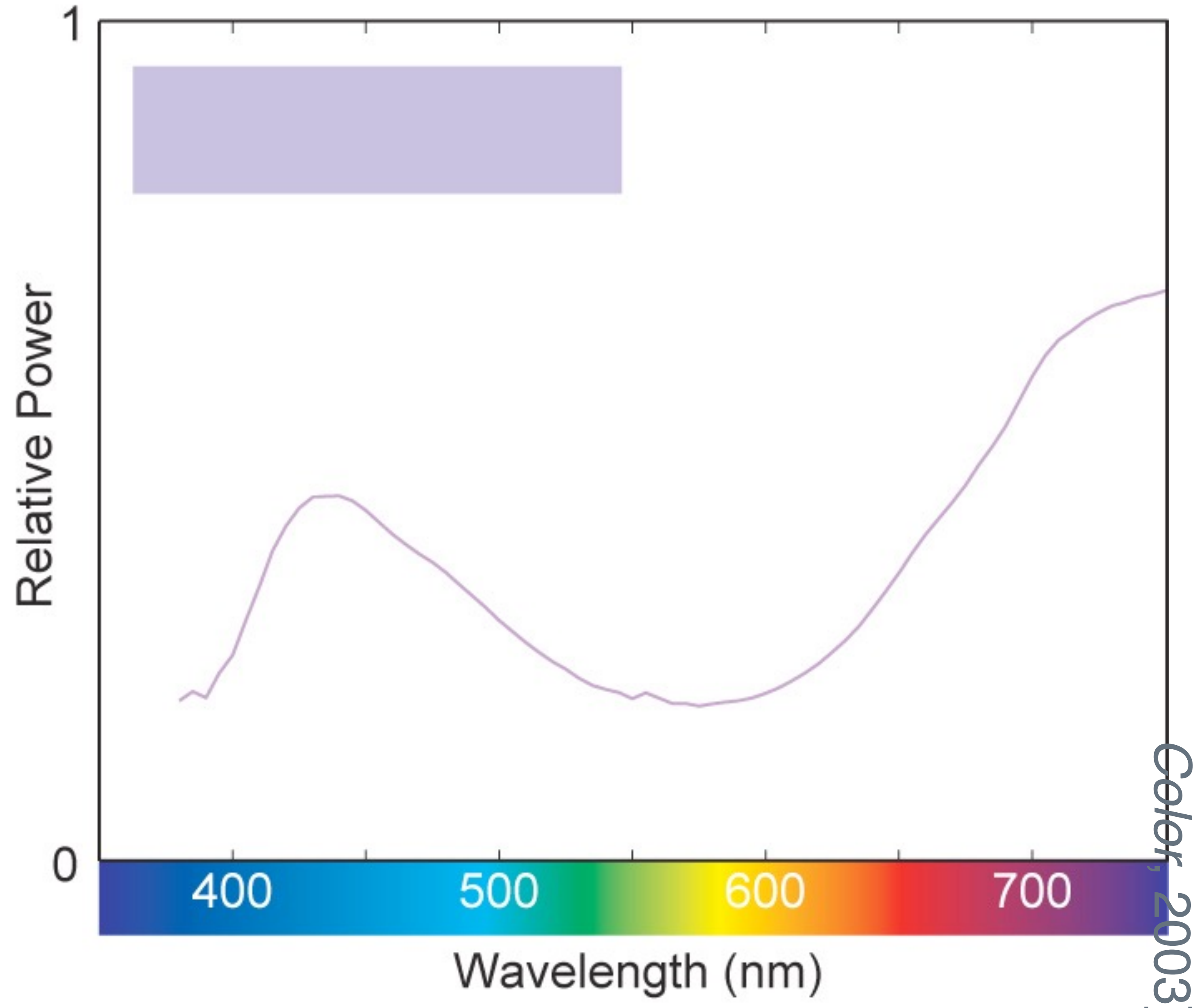
Light is an electromagnetic wave.

Wavelength (λ) between **370nm – 730nm**.

Color depends on the *spectral distribution function* (or ***spectrum***): distribution of “relative luminance” at each wavelength.

Area under the spectrum is ***intensity***: or how bright each wavelength is.





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

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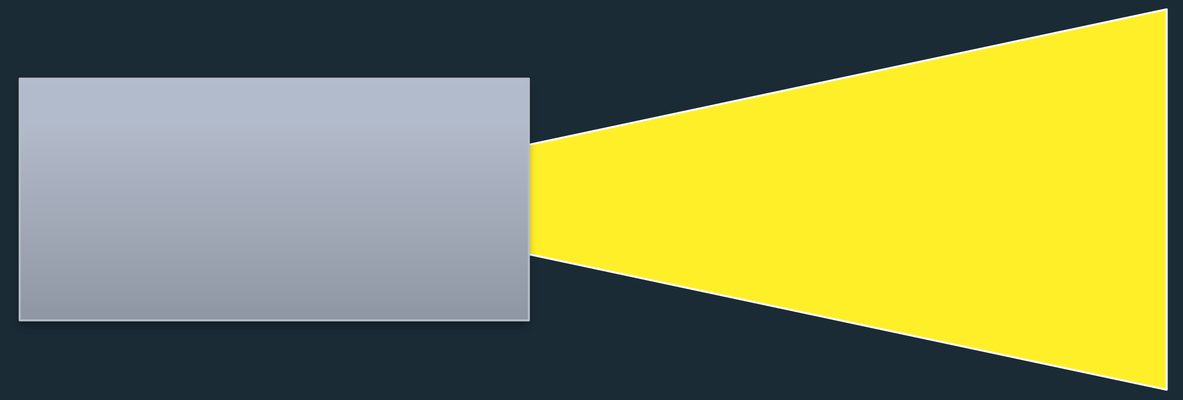
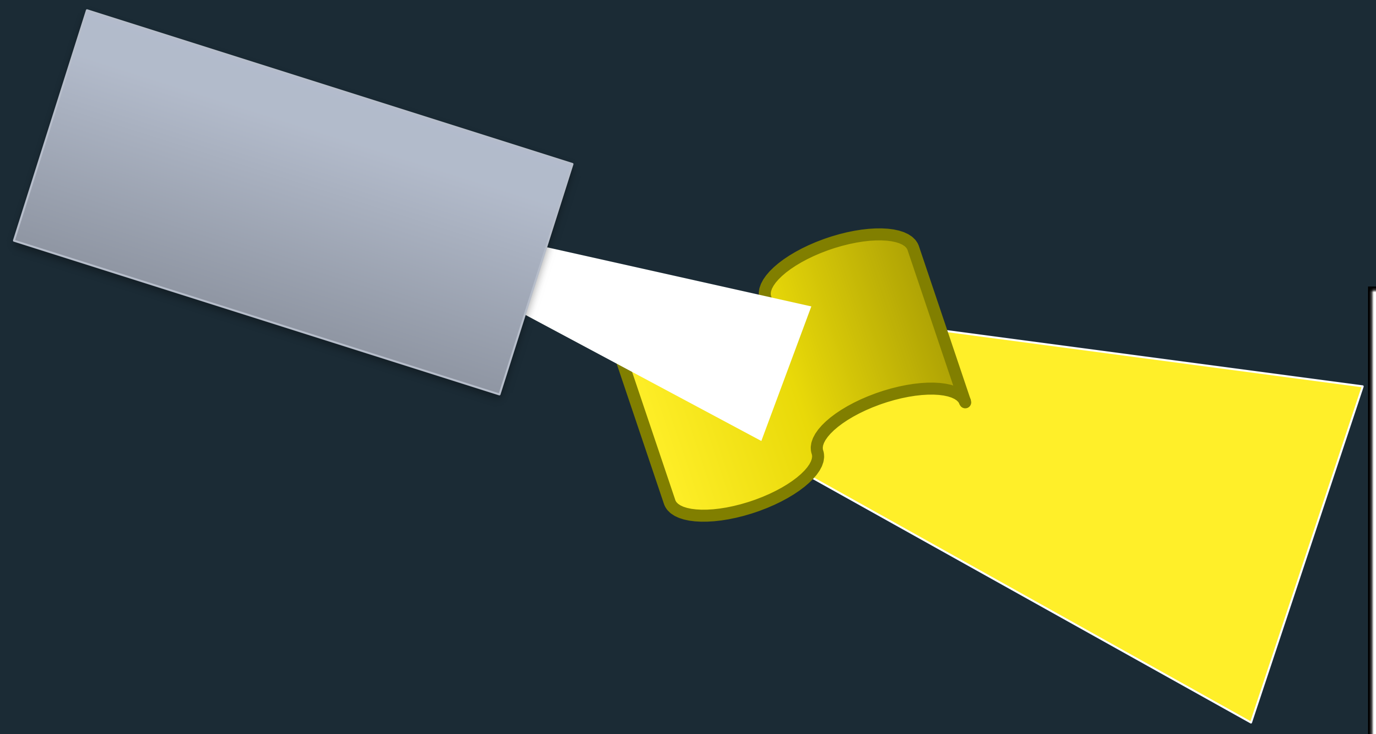
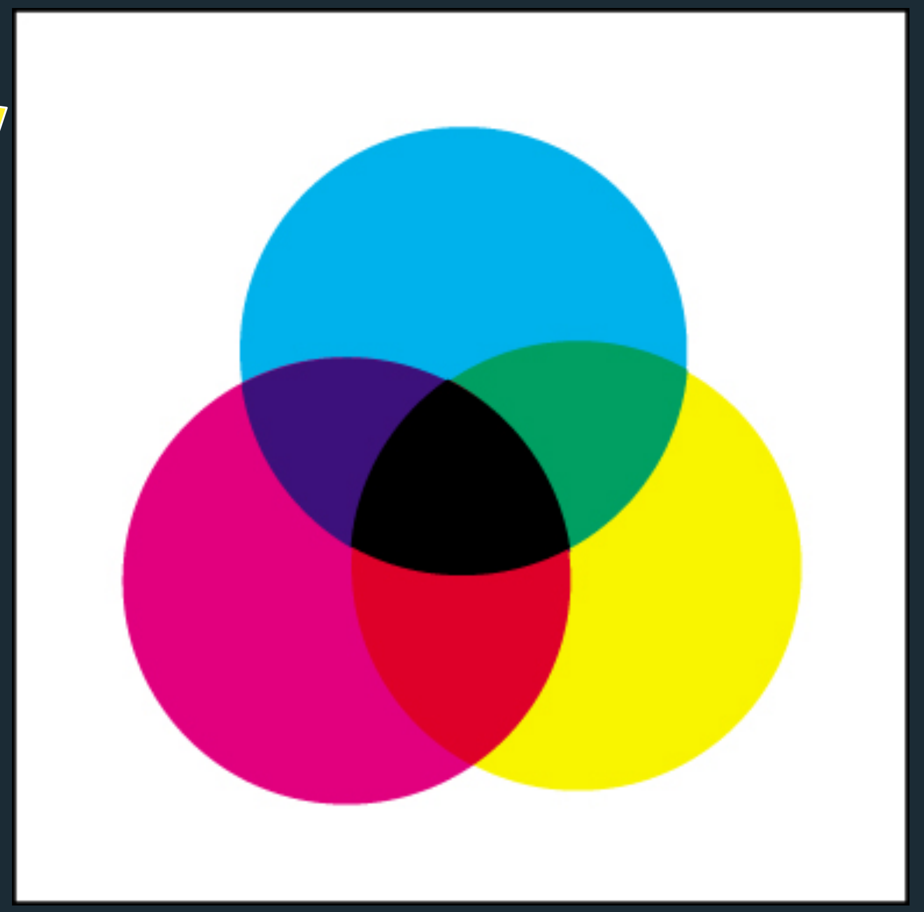
Additive: Perceived color is due to a combination of source lights (e.g., RGB).

Subtractive: Start from a white spotlight, and materials absorb specific λs (e.g., RYB or CMYK).



Additive
(digital displays)





Subtractive
(print, e-paper)

Modeling Color Perception

Low-Level — Abstraction — High-Level

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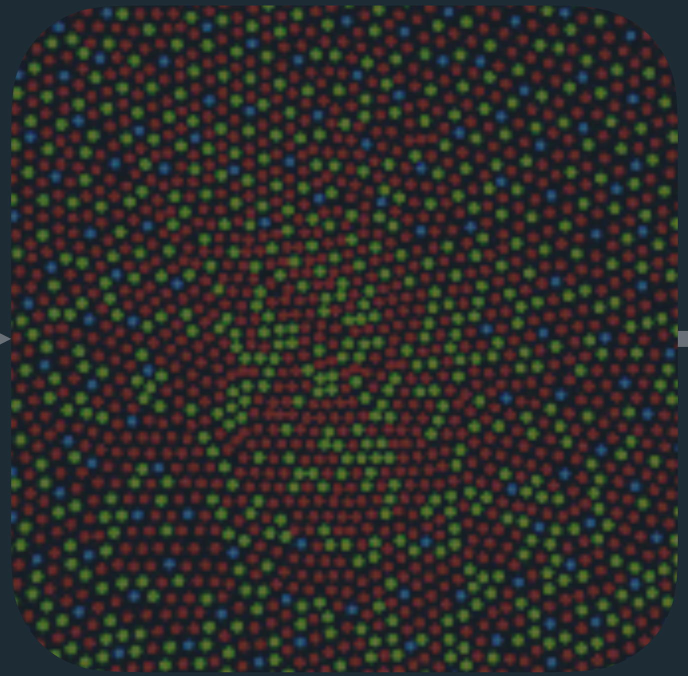
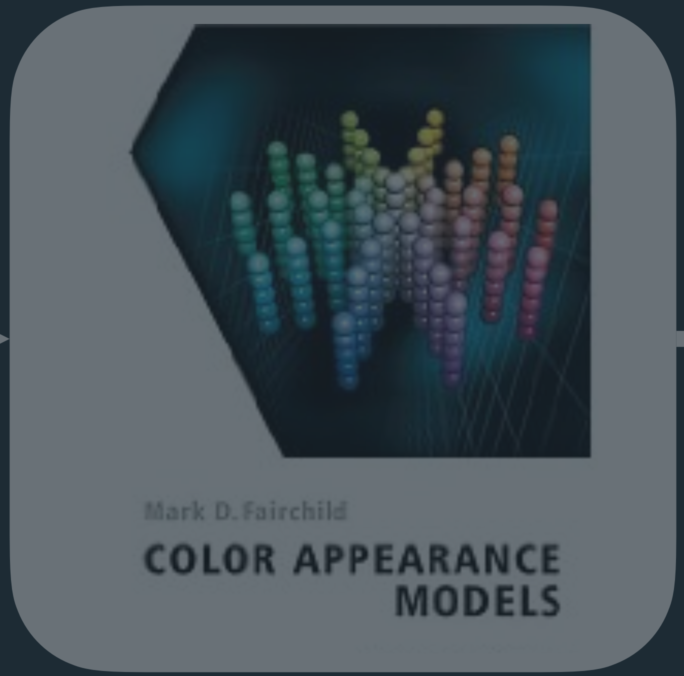
Visible Light



Cone Response

Opponent Encoding

Perceptual Models



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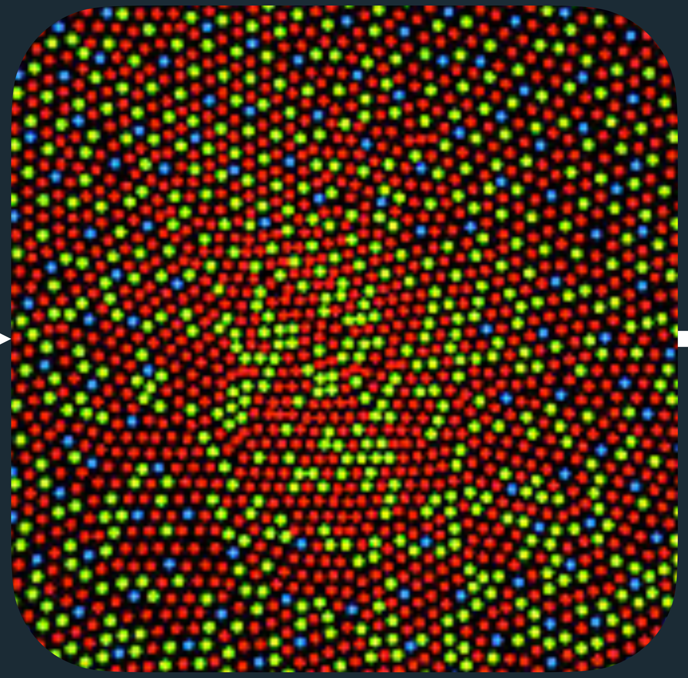

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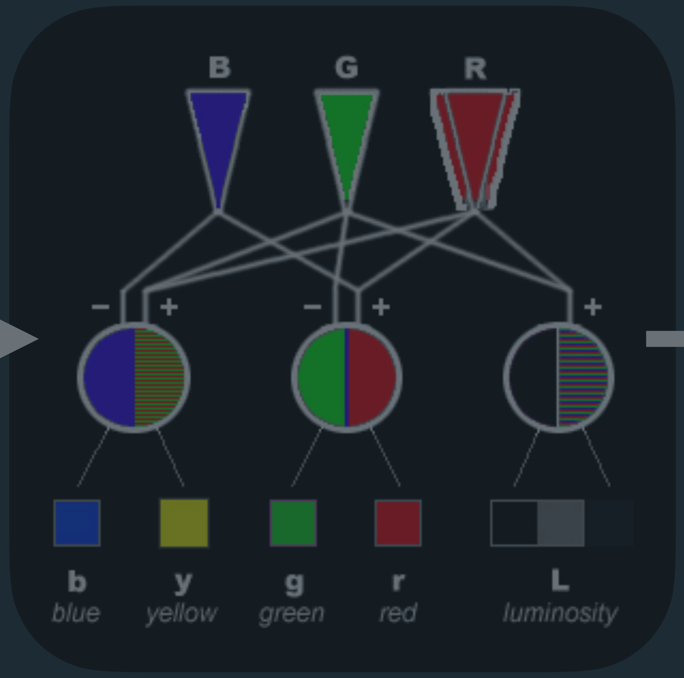

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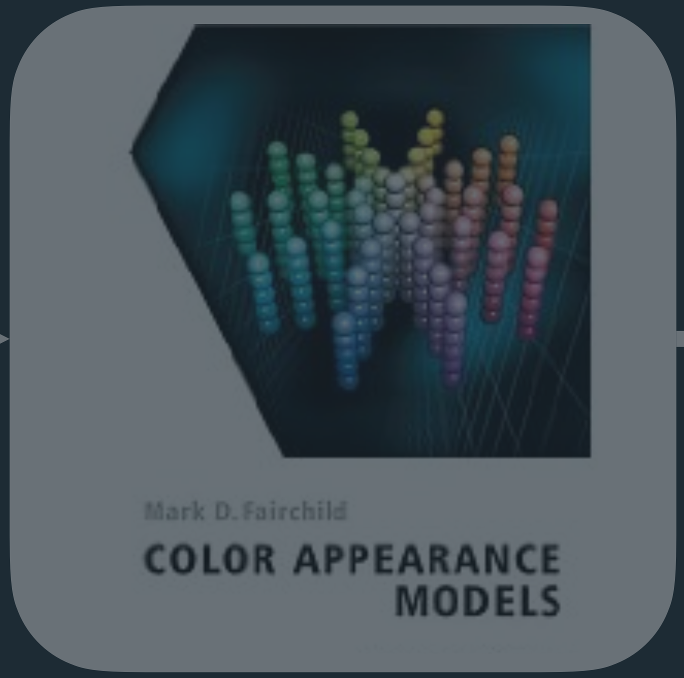


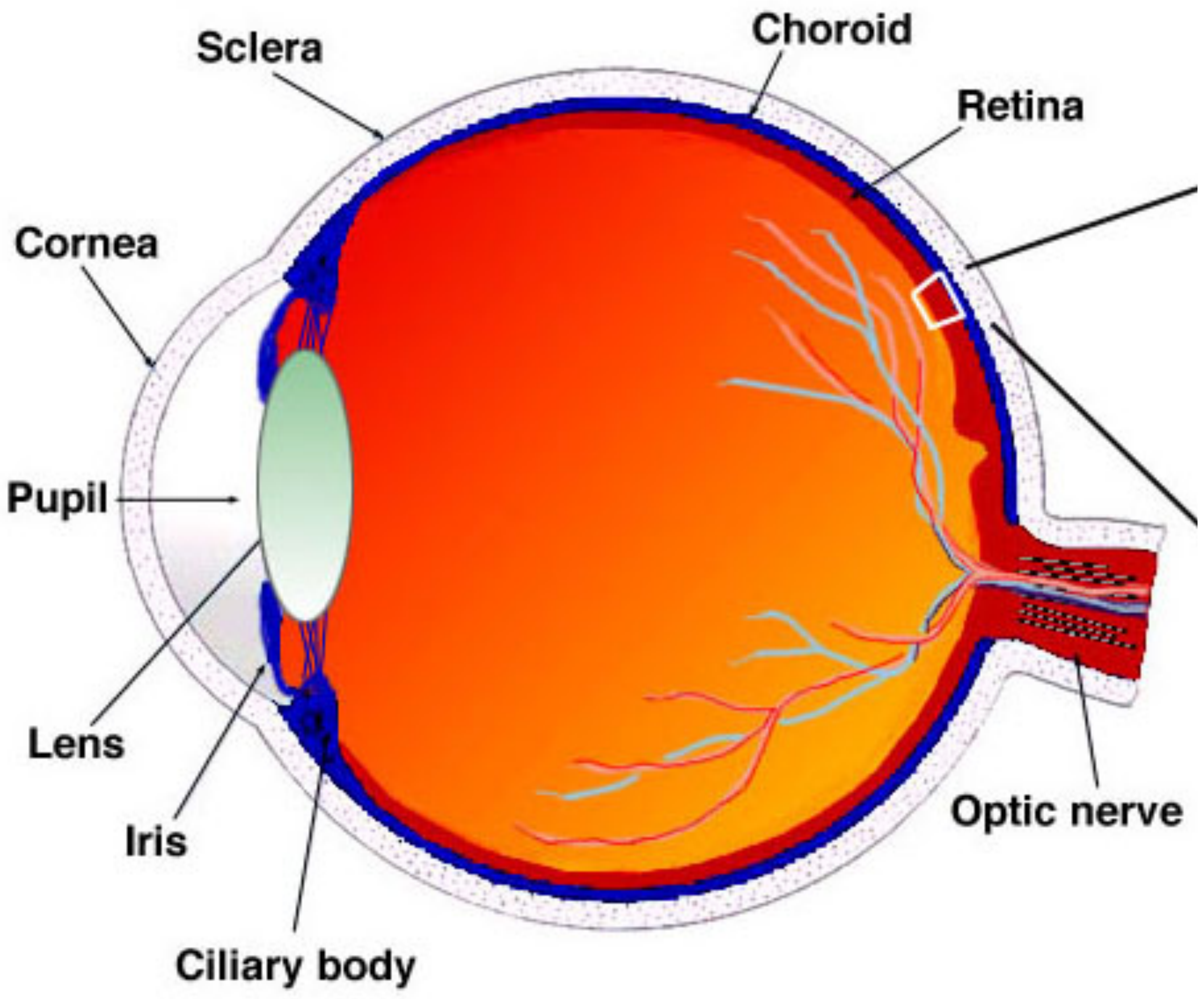
Appearance Models

Cognitive Models

The Retina

Photoreceptors on retina are responsible for vision:

rods – low-light levels, poor spatial acuity, little color vision



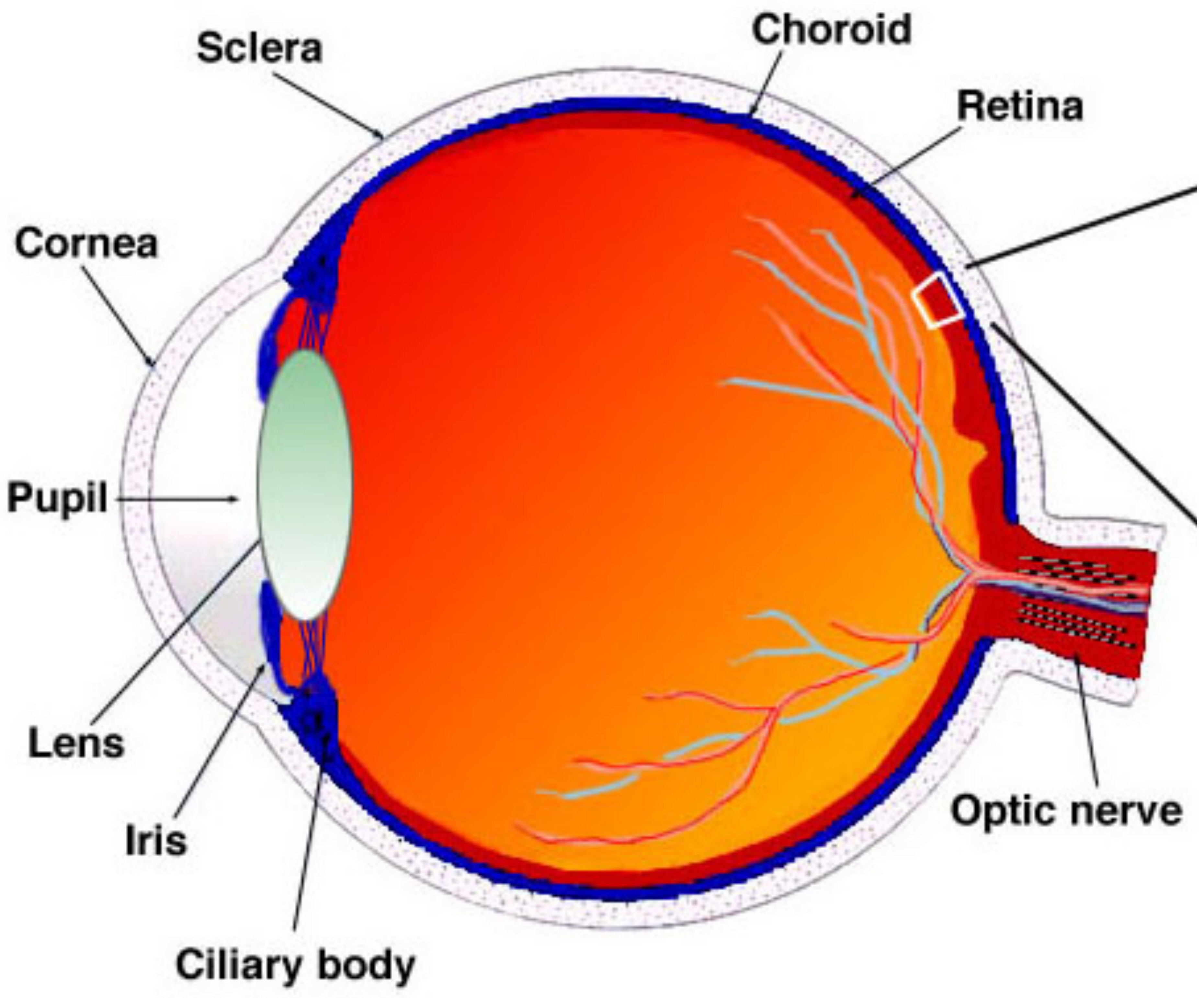
[Helga Kolb *Simple Anatomy of the Retina*]

The Retina

Photoreceptors on retina are responsible for vision:

rods – low-light levels, poor spatial acuity, little color vision

cones – sensitive to different wavelengths = color vision!
short, middle, long ~ blue, green, red



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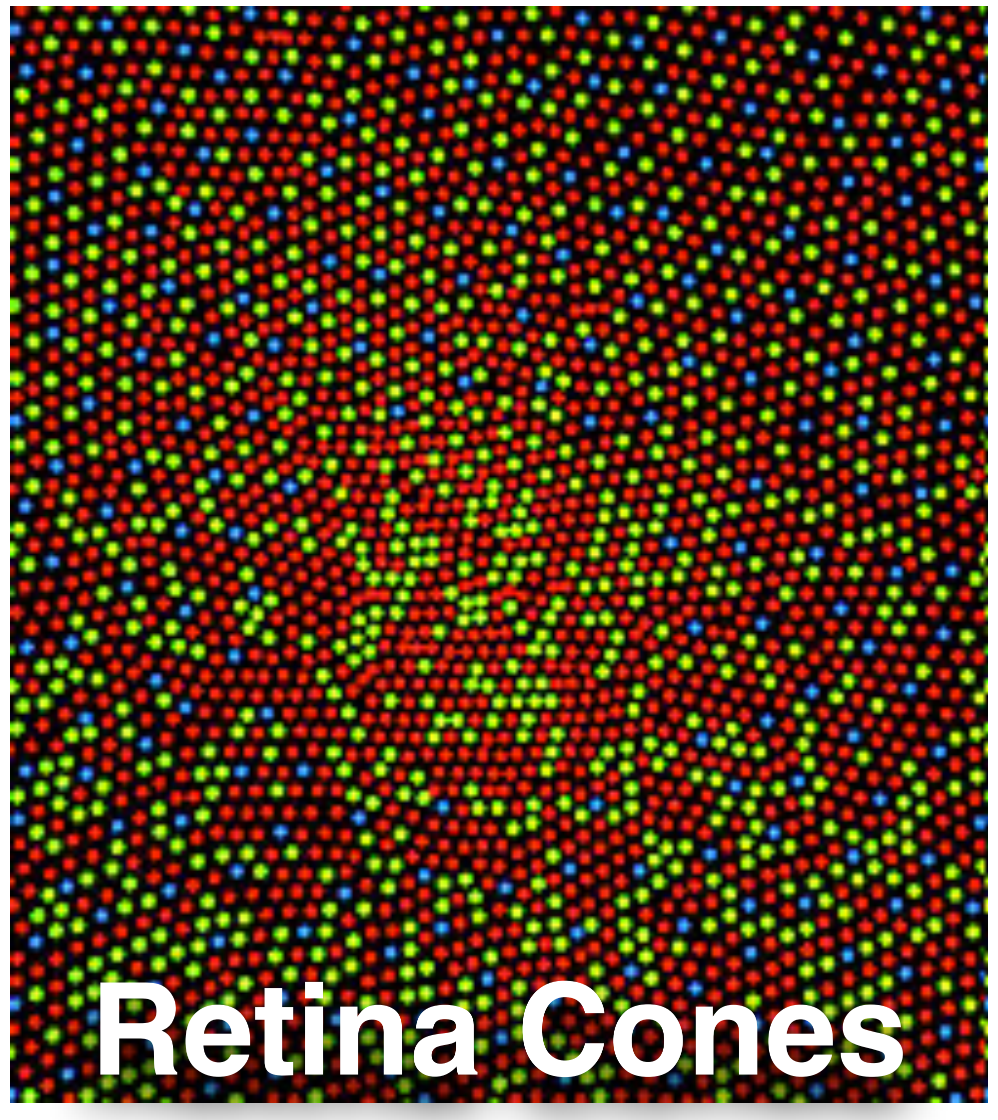
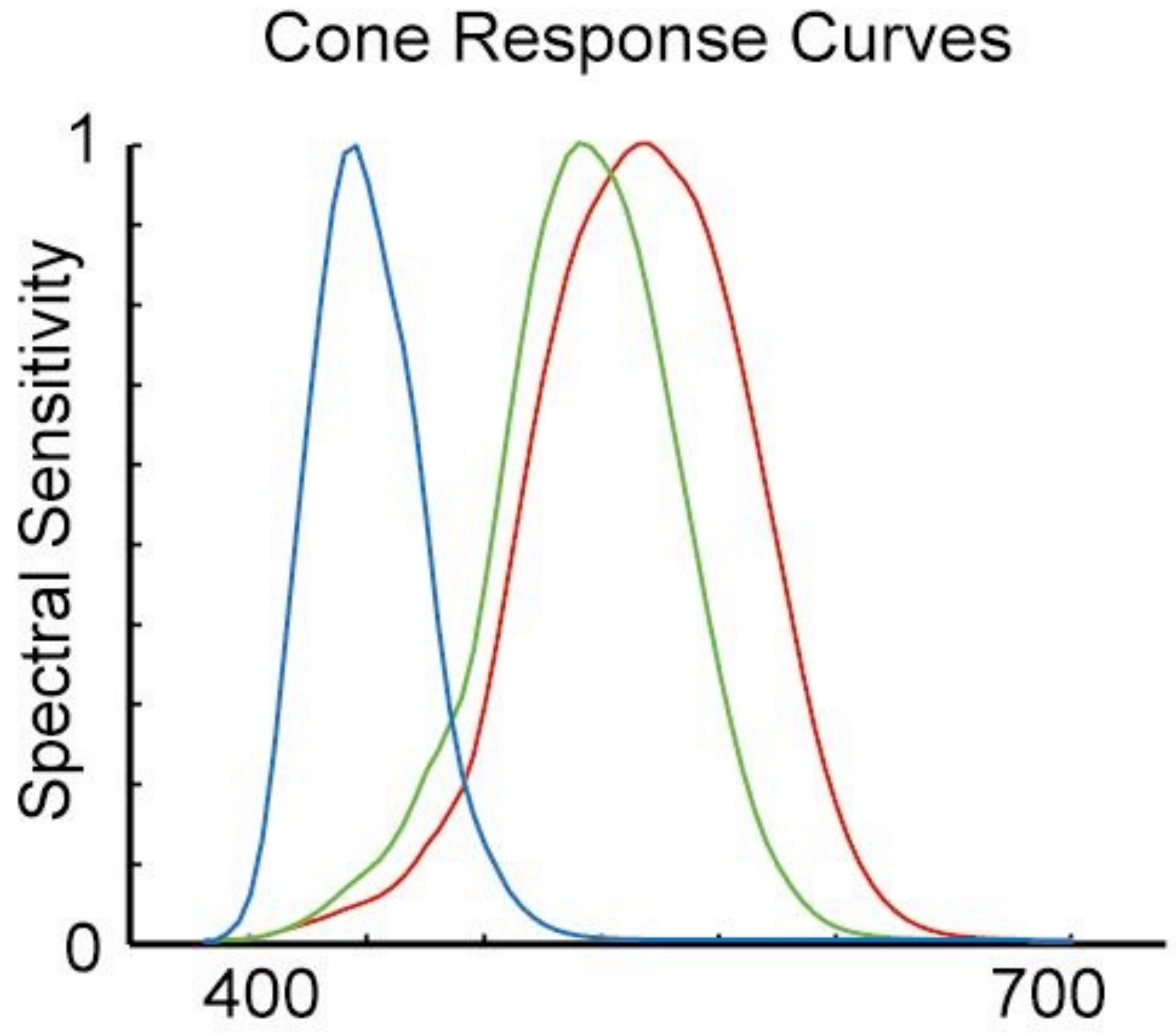
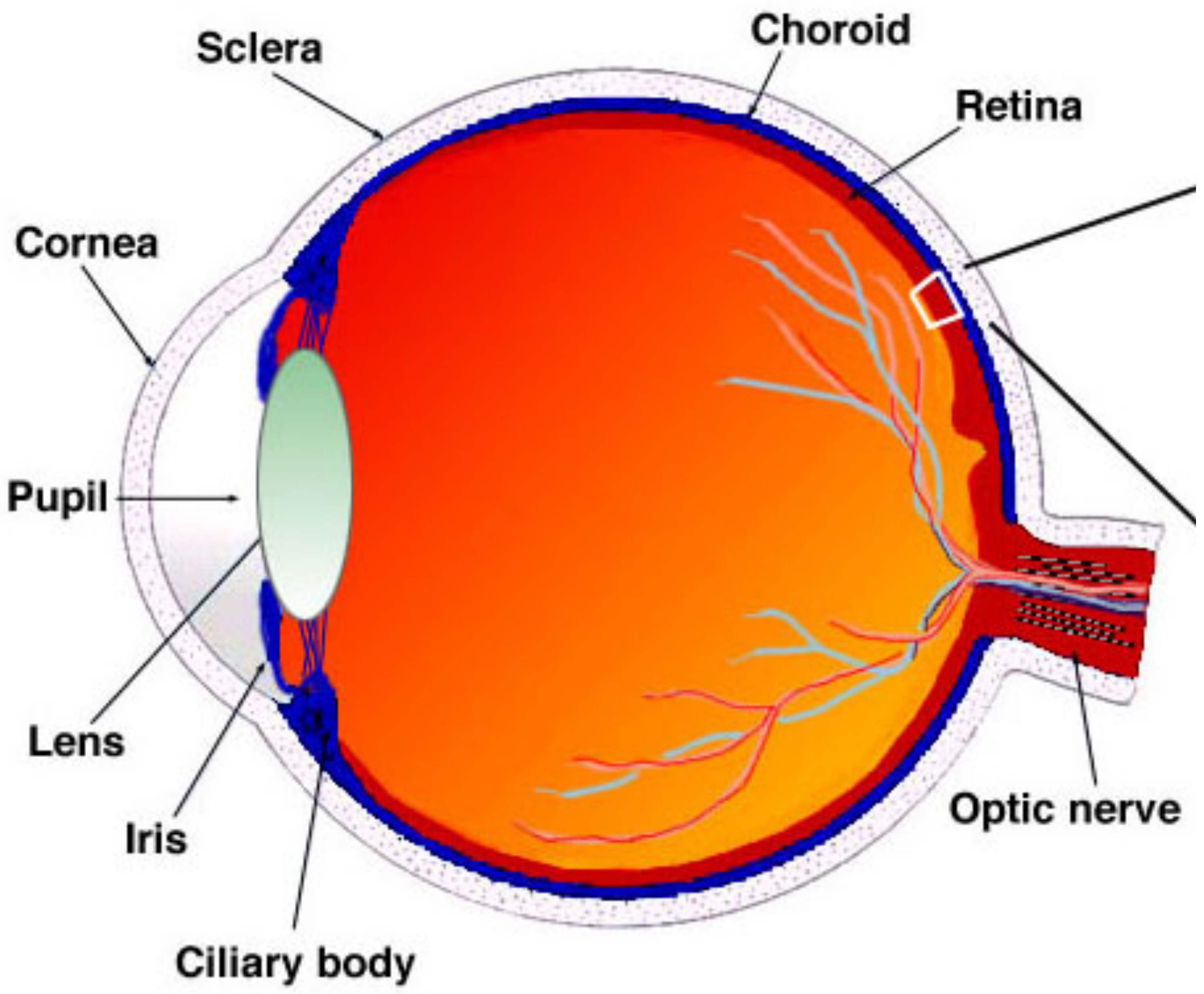




The Retina

Firefox and Chrome have built in simulators



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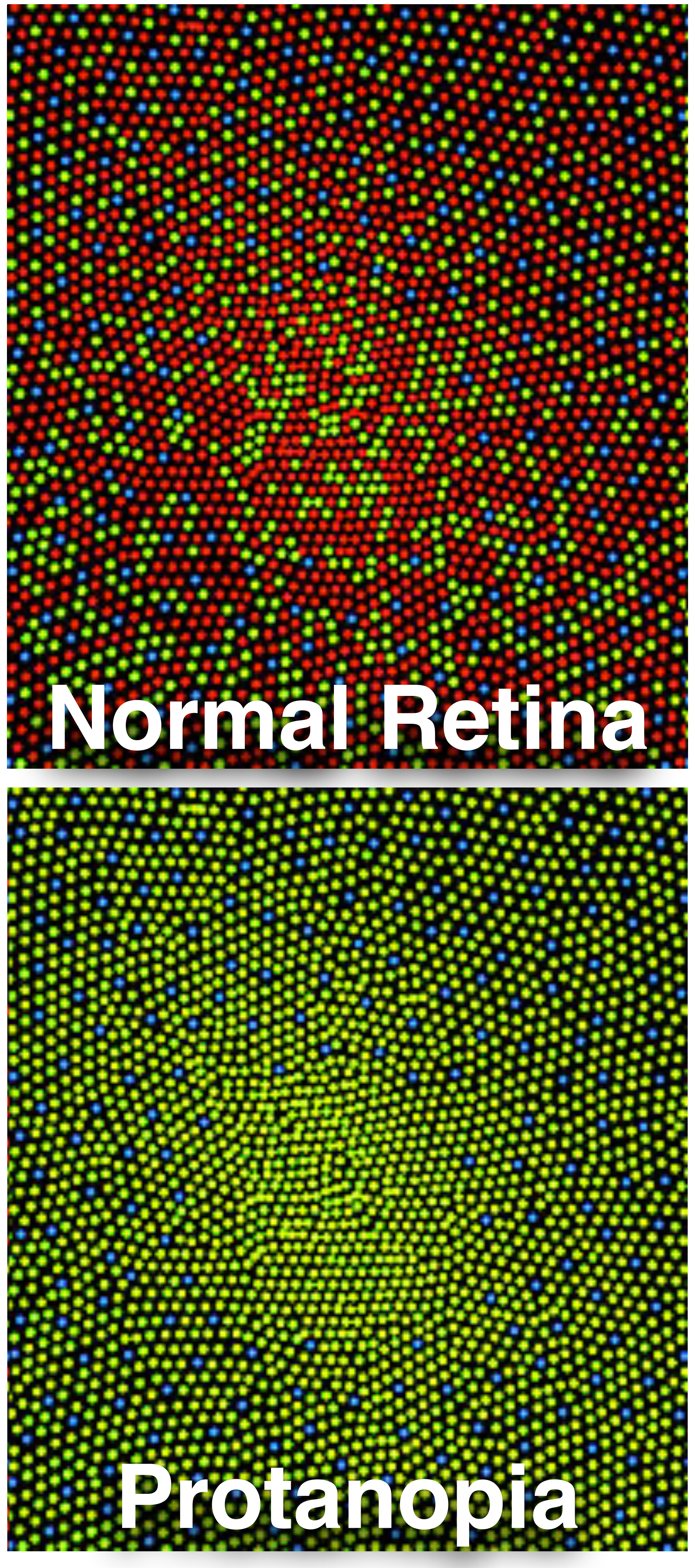

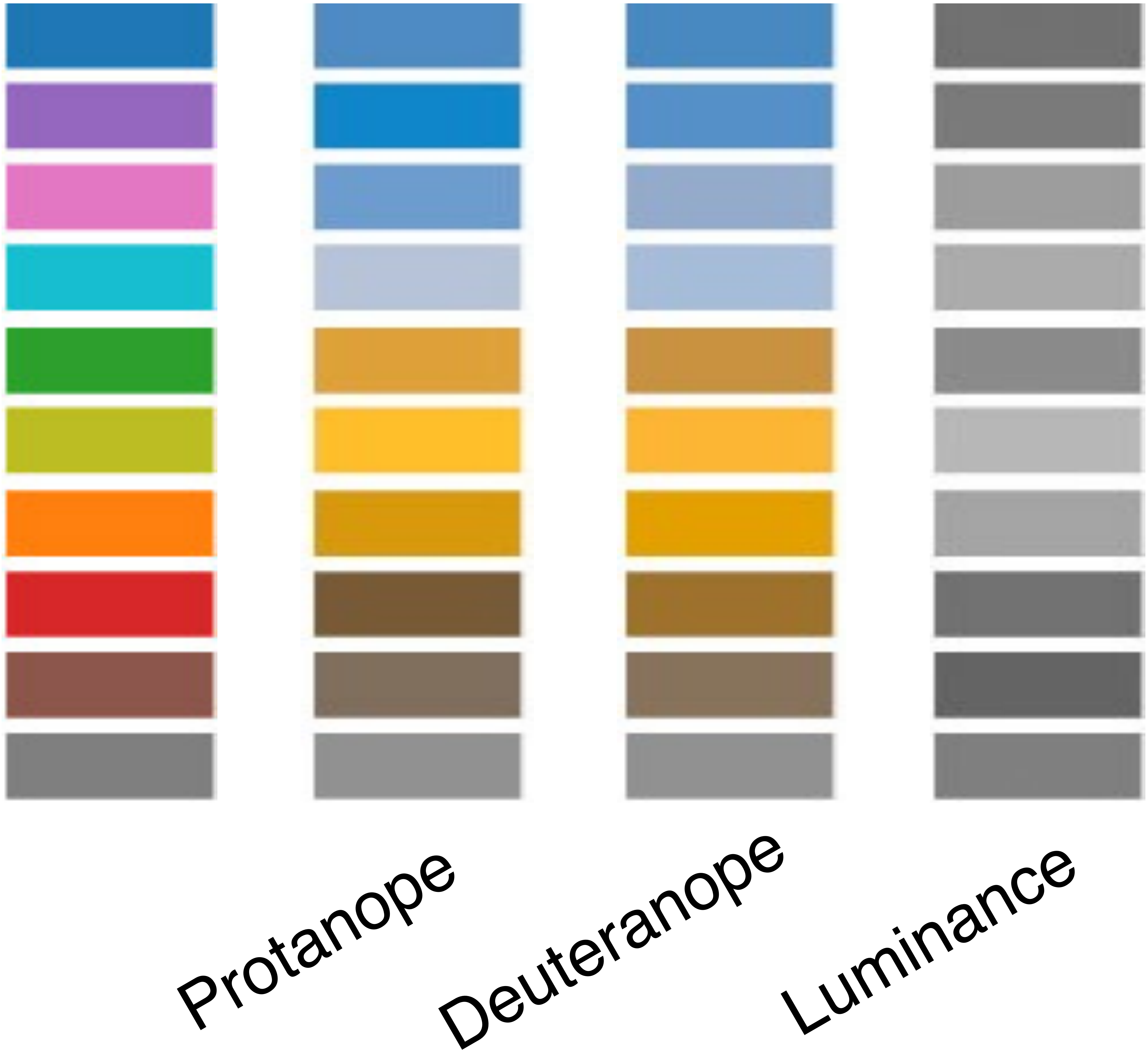

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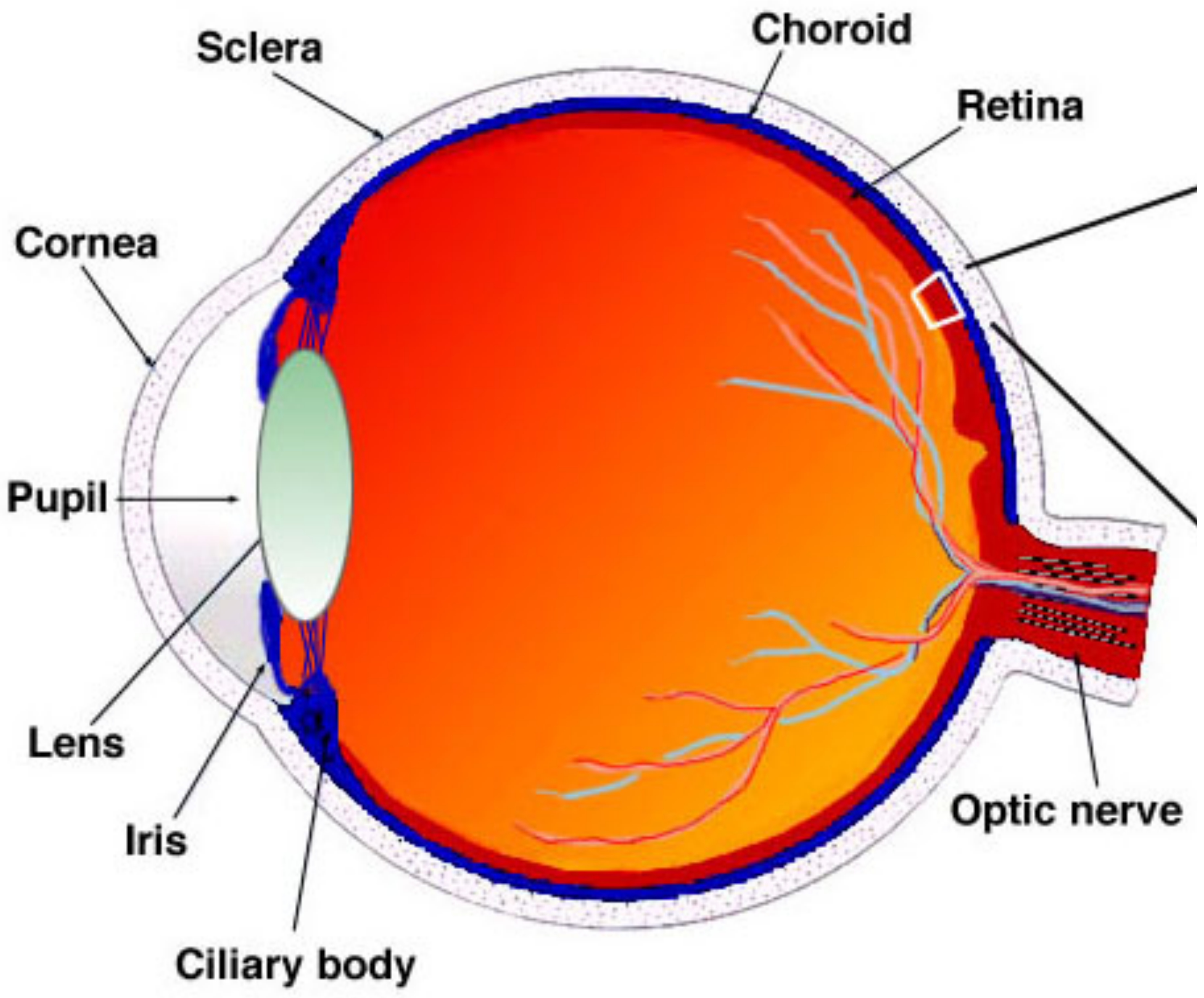
cones – sensitive to different wavelengths = color v

short, middle, long ~ blue, green, red



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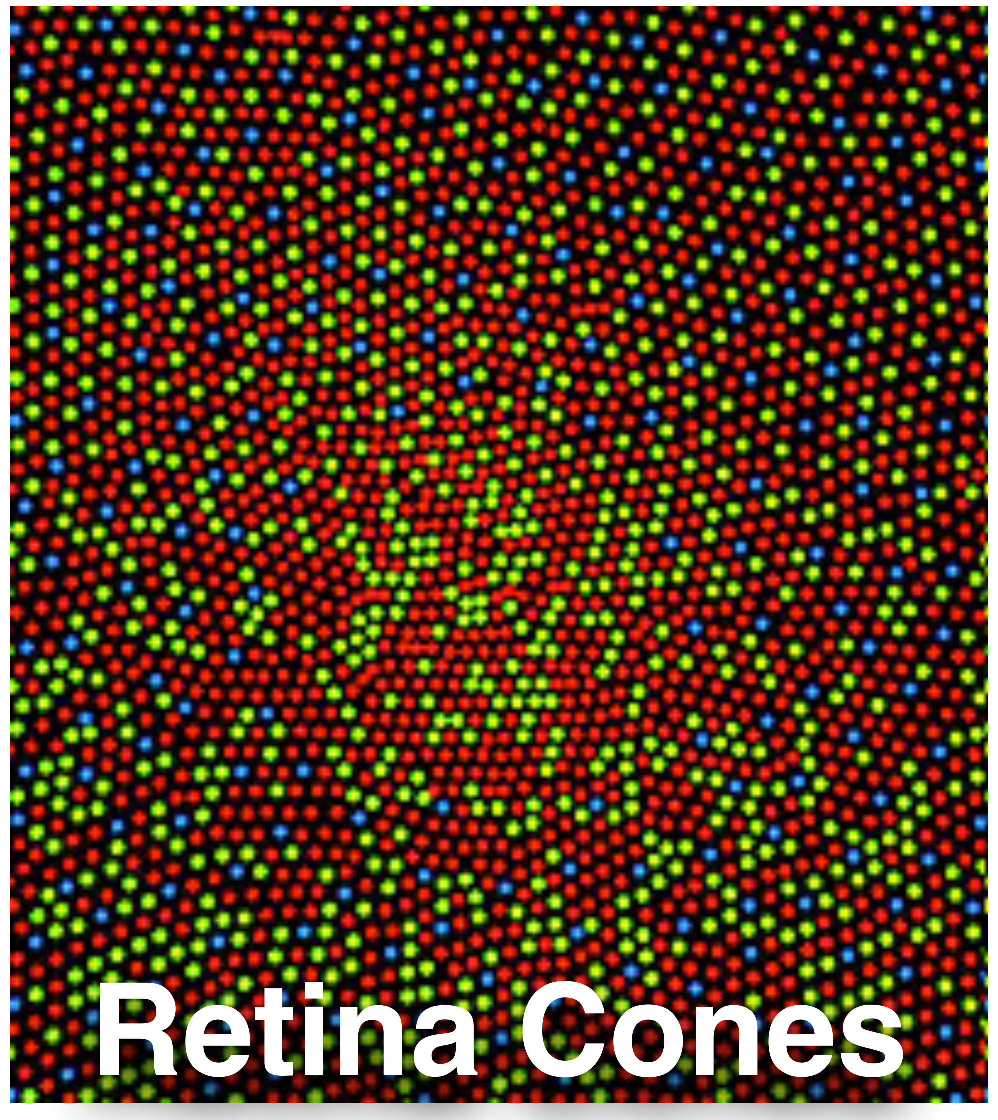

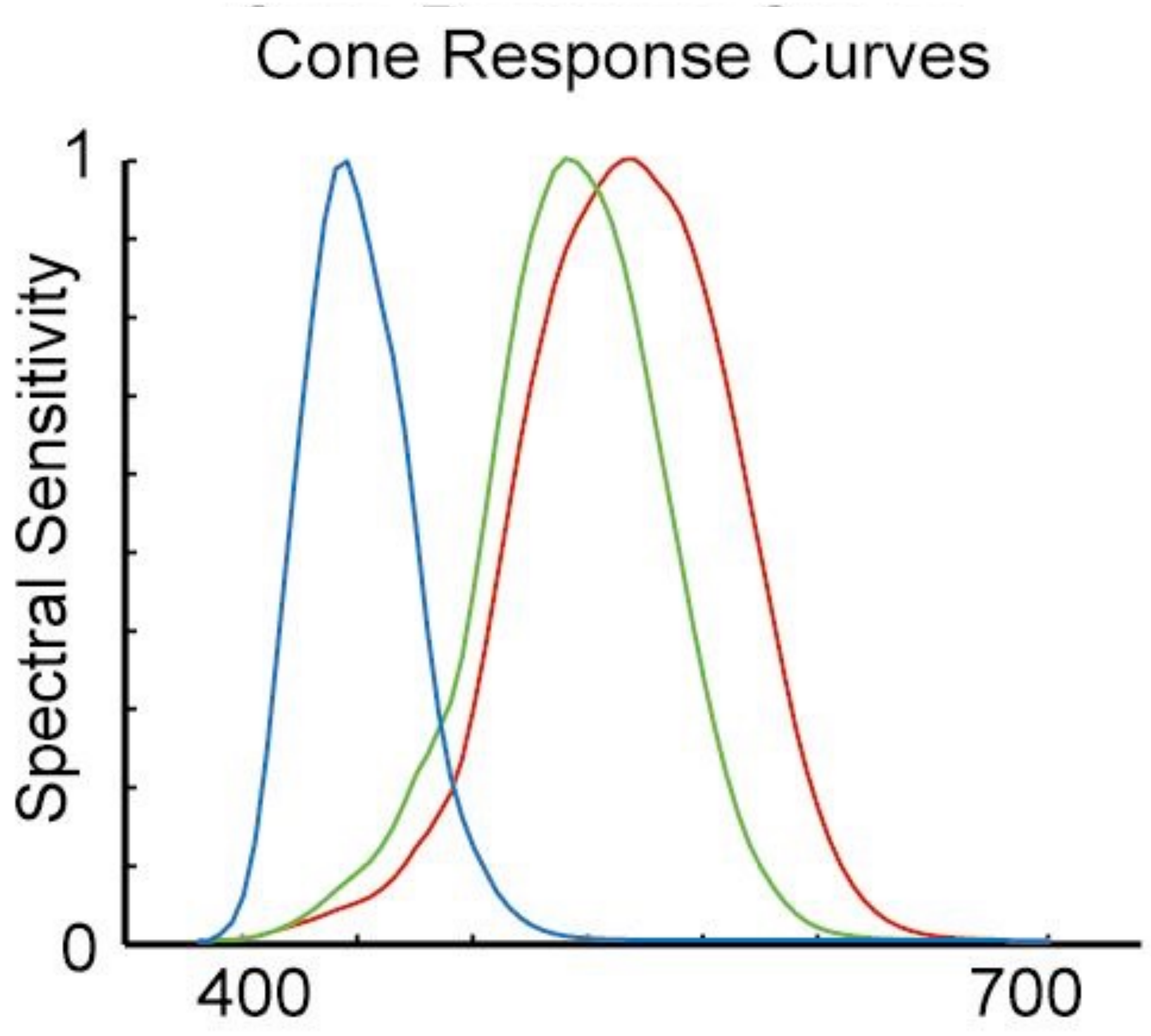

The Retina

Photoreceptors on retina are responsible for vision:

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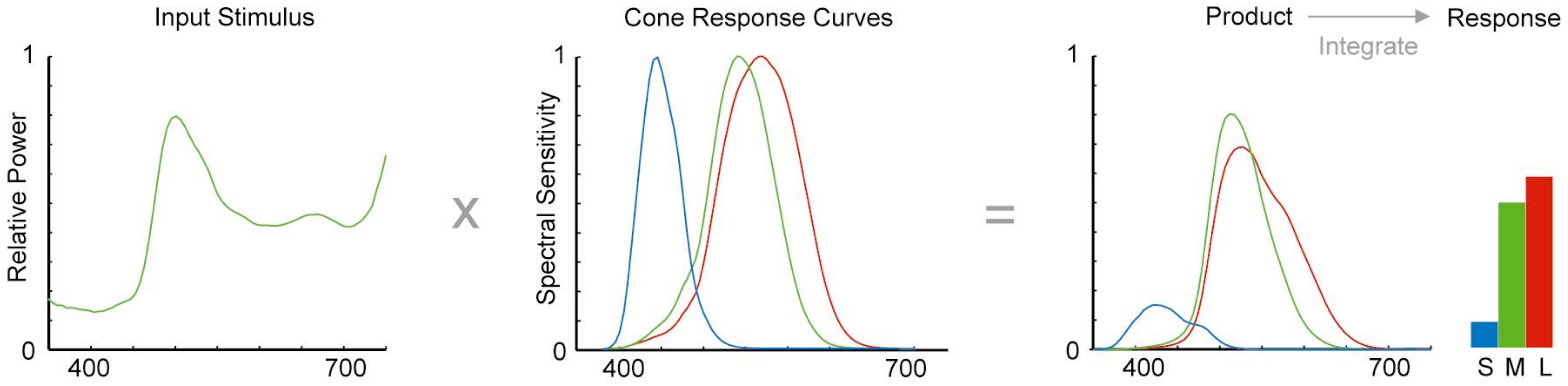
cones – sensitive to different wavelengths = color v

short, middle, long ~ blue, green, red

integrate against different input stimuli



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

tri-stimulus response – color can be modeled as 3 values.

The Retina

Photoreceptors on retina are responsible for vision:

rods – low-light levels, poor spatial acuity, little color

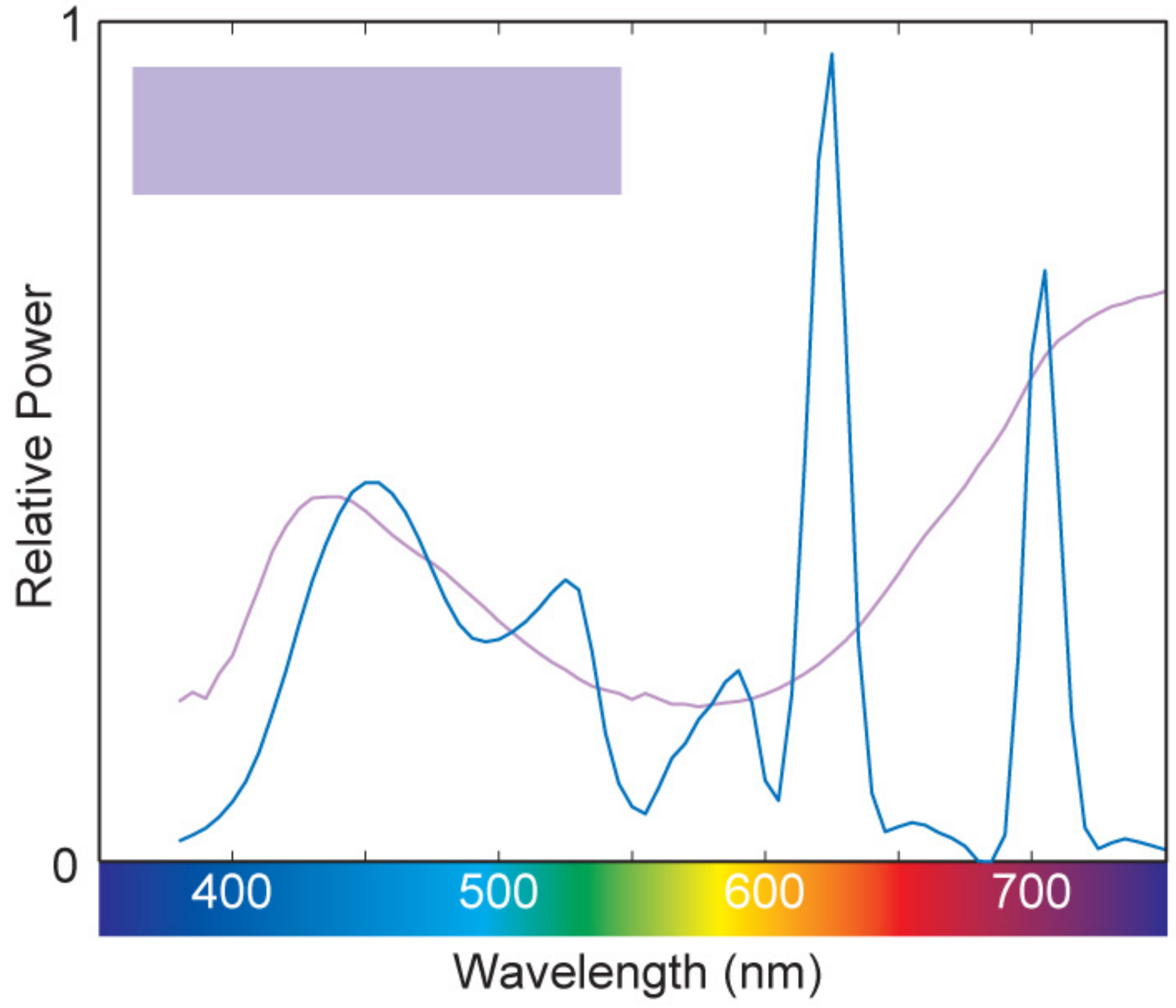
cones – sensitive to different wavelengths = color v

long, middle, short ~ red, green, blue

integrate against different input stimuli

tri-stimulus response – color can be modeled as 3 values.

metamers – spectra that stimulate the same LMS response are indistinguishable.

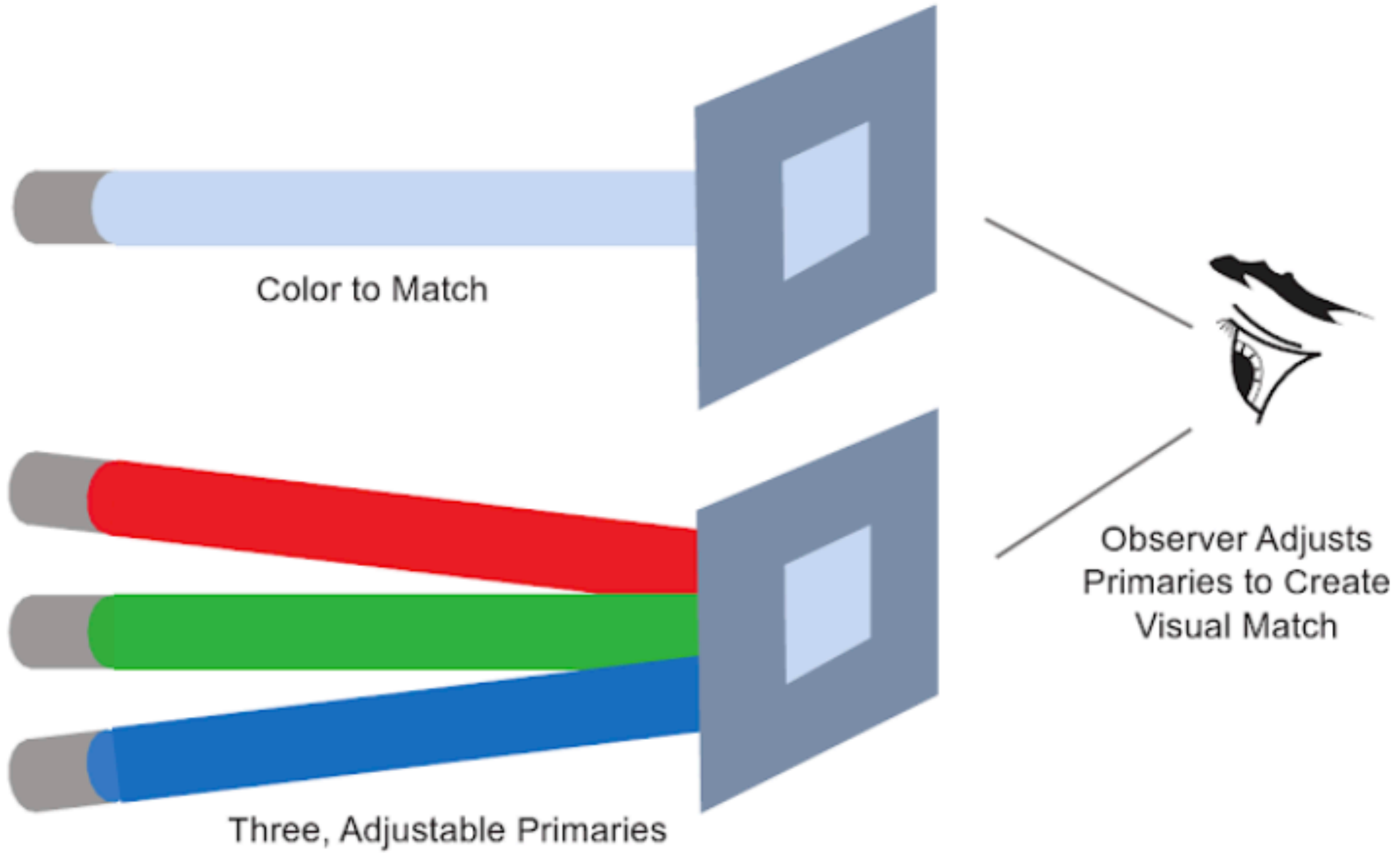


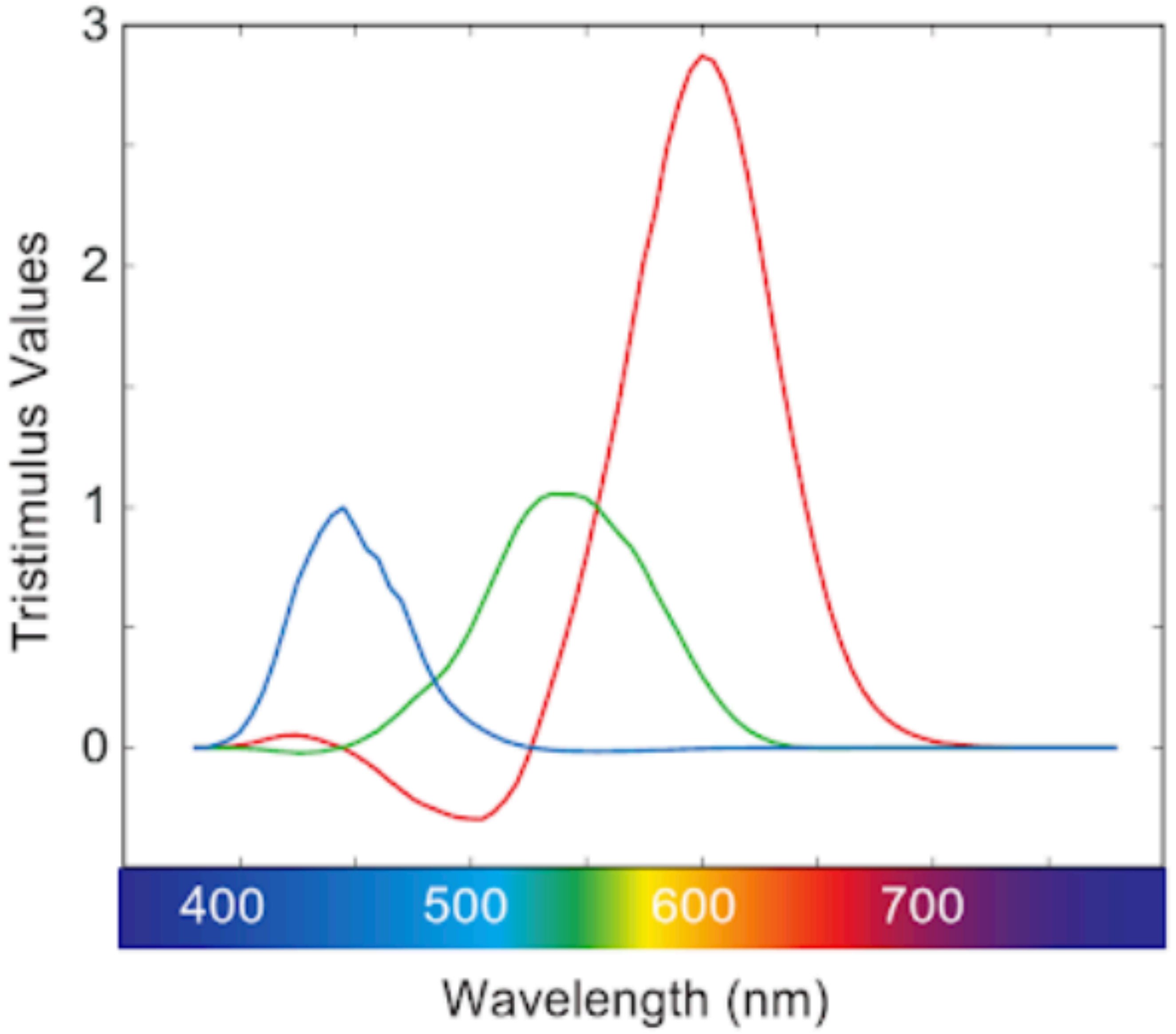
[Maureen Stone. *A Field Guide to Digital Color*, 2003]

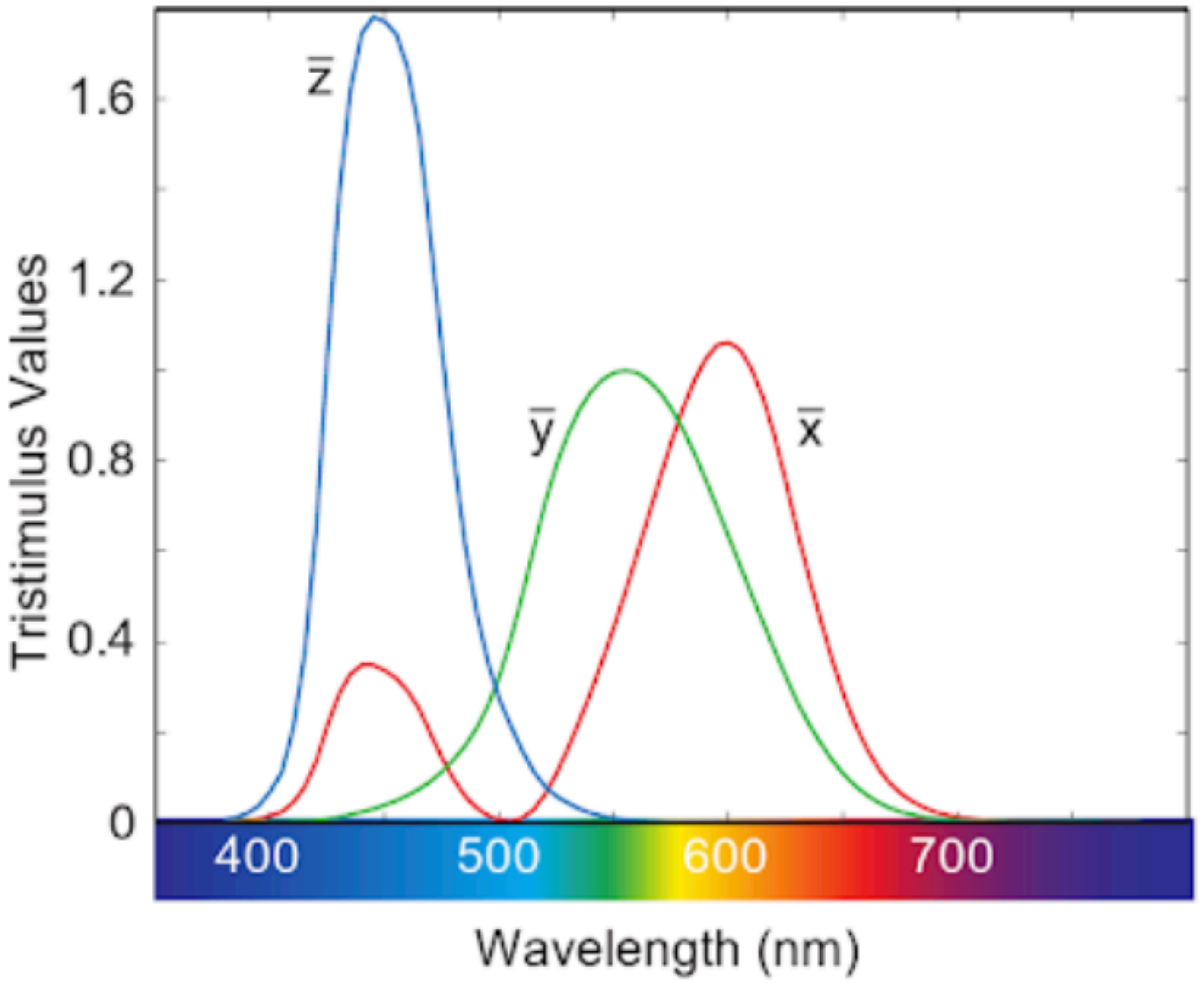
CIE XYZ

Color space standardized in 1931 to mathematically represent tri-stimulus response curves.

empirically determined







Red = 645nm
Green = 525nm
Blue = 444nm

mathematic transformation

No real lights can the x, y, z response curves.

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

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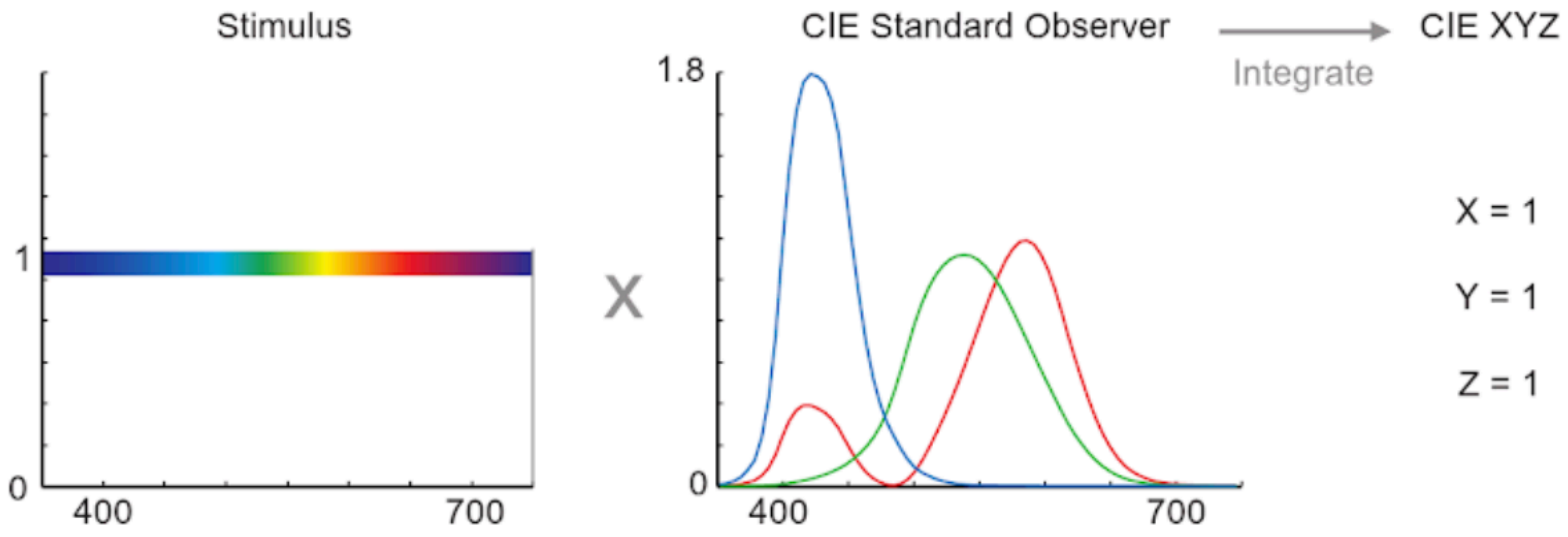


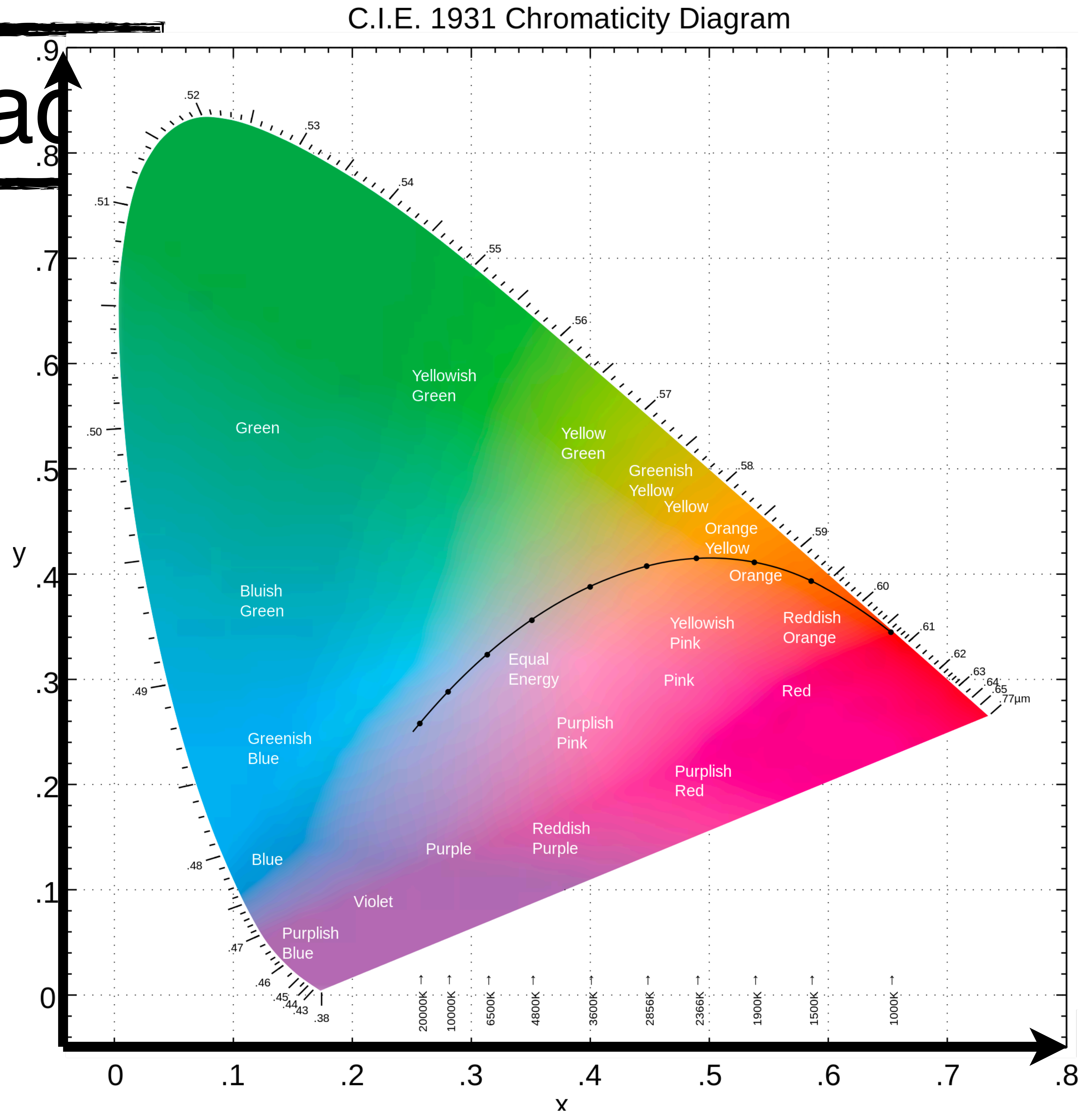
CIE XYZ Color Spac

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

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$1 = x + y + z$$



CIE XYZ Color Spac

$$x = \frac{X}{X+Y+Z}$$

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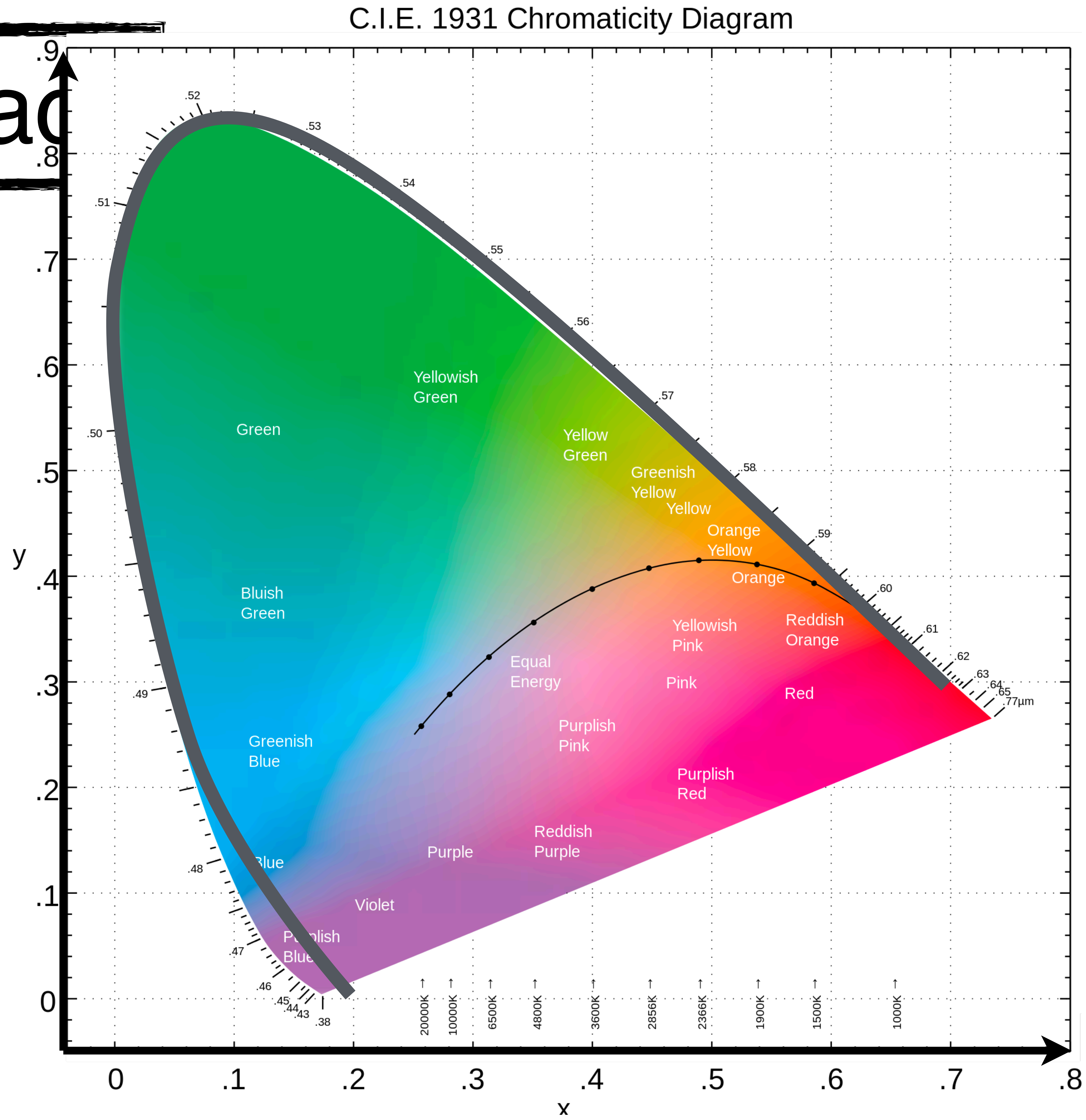
$$1 = x + y + z$$

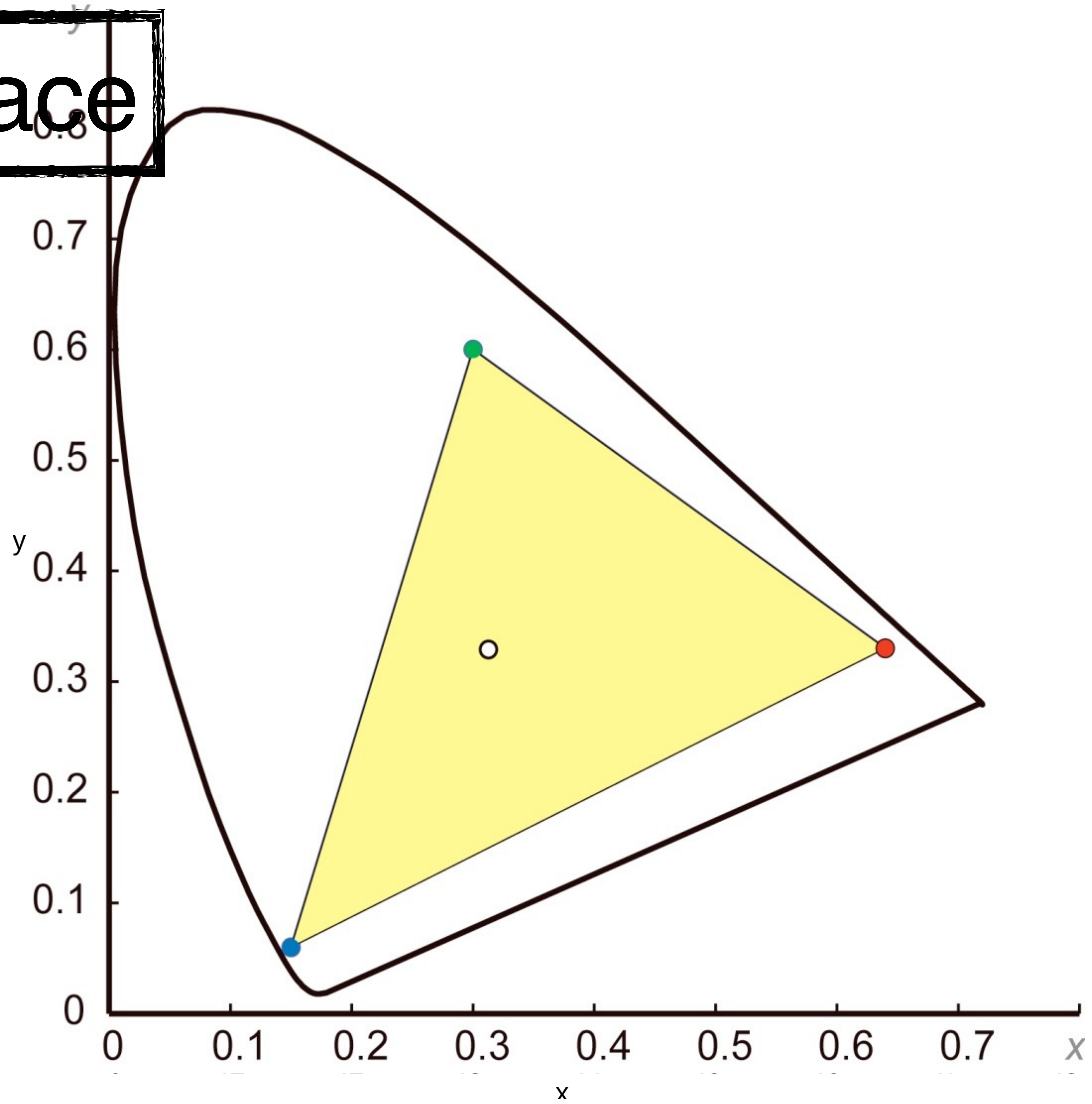
Spectral locus – set of pure colors (i.e., lasers of a single wavelength).

Slowly shifts from S → M → L.



CIE XYZ Color Space

Display gamut = portion of the color space that can be reproduced by a display.



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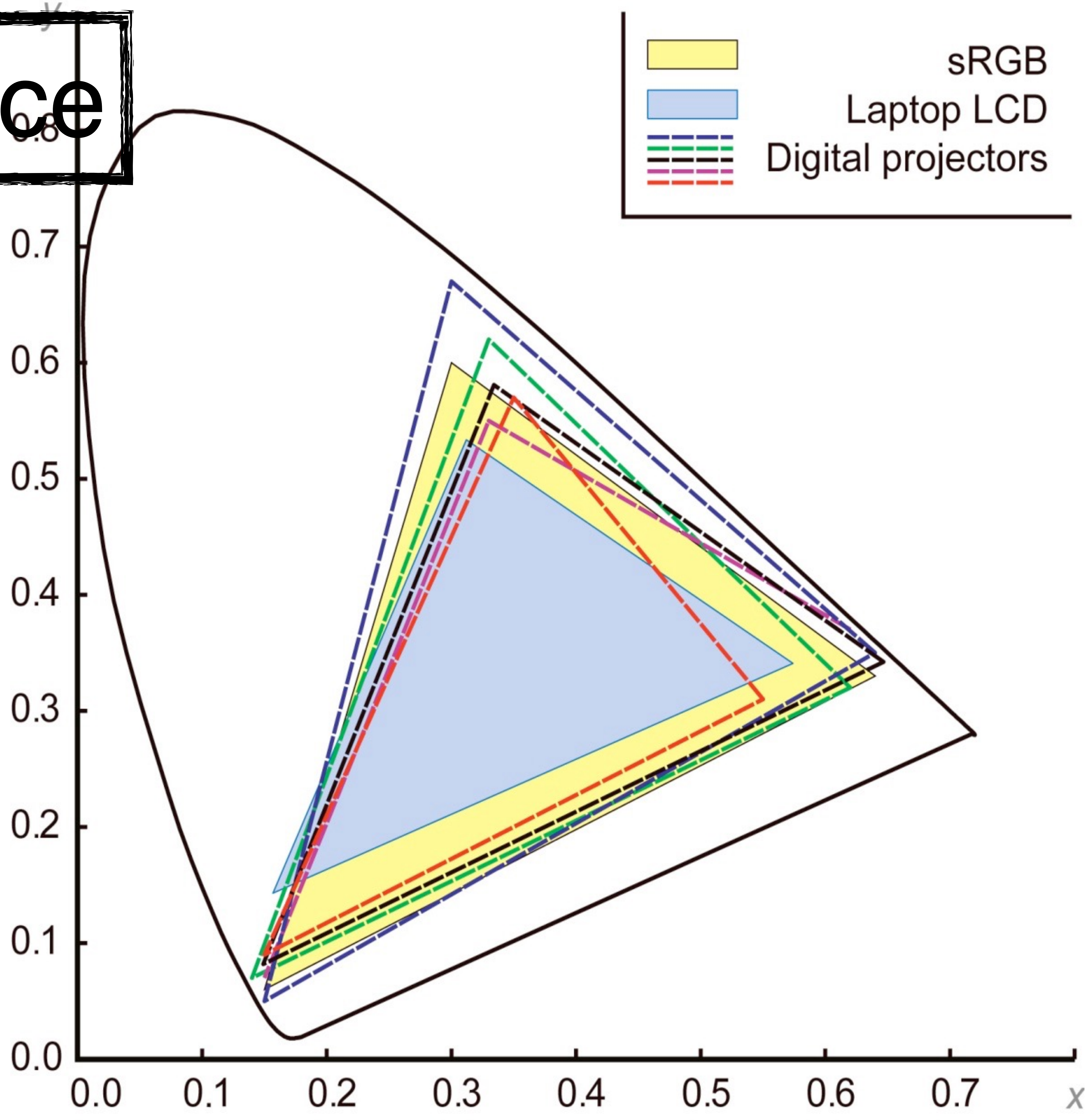
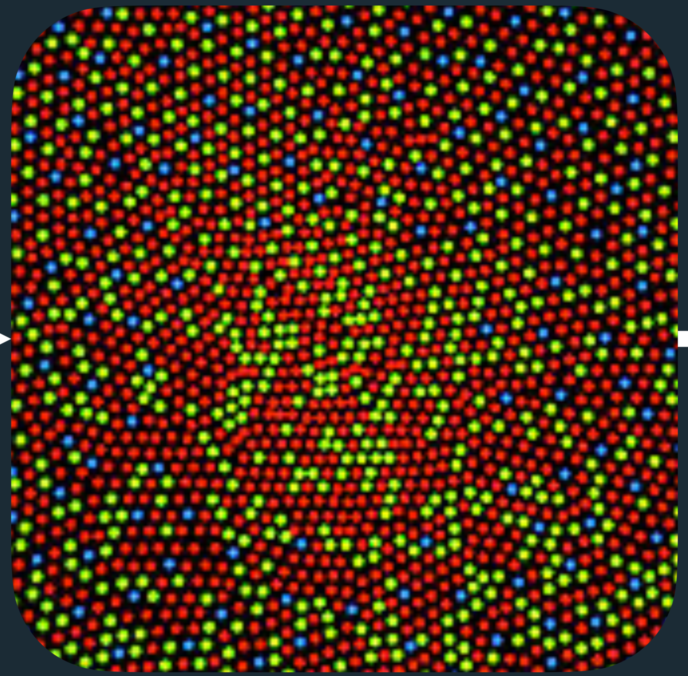


Modeling Color Perception

Low-Level Abstraction High-Level

Physical World | Visual System | Mental Models

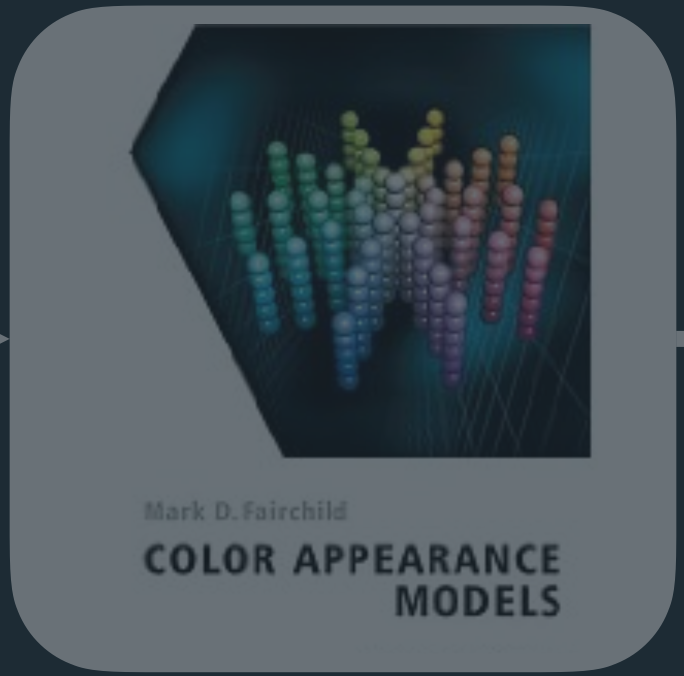
Visible Light



Cone Response

Opponent Encoding

Perceptual Models



Appearance Models

"Teal"

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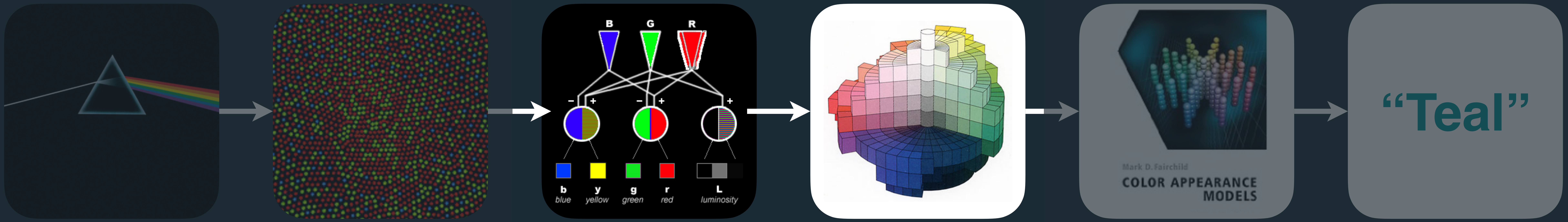
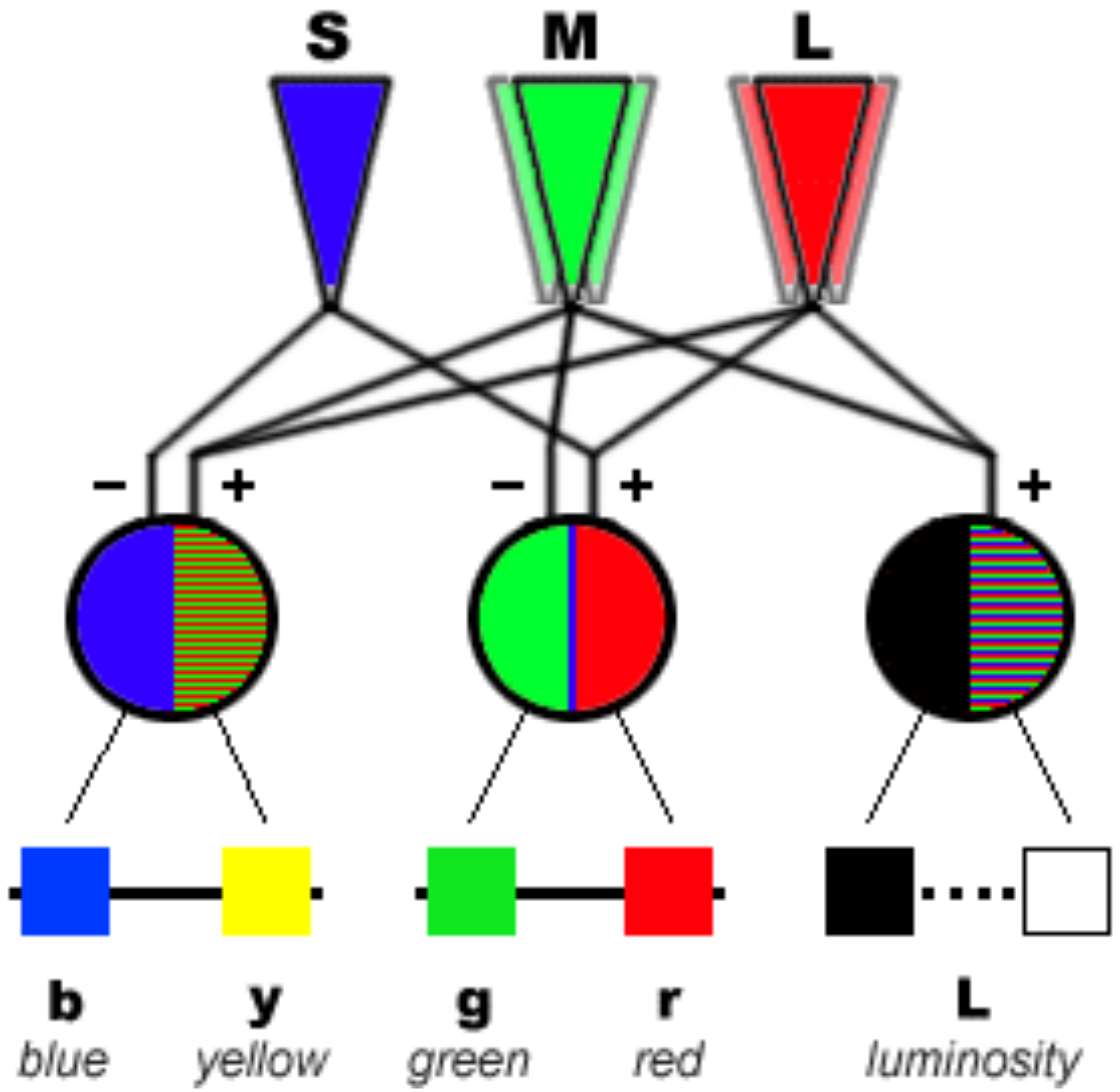
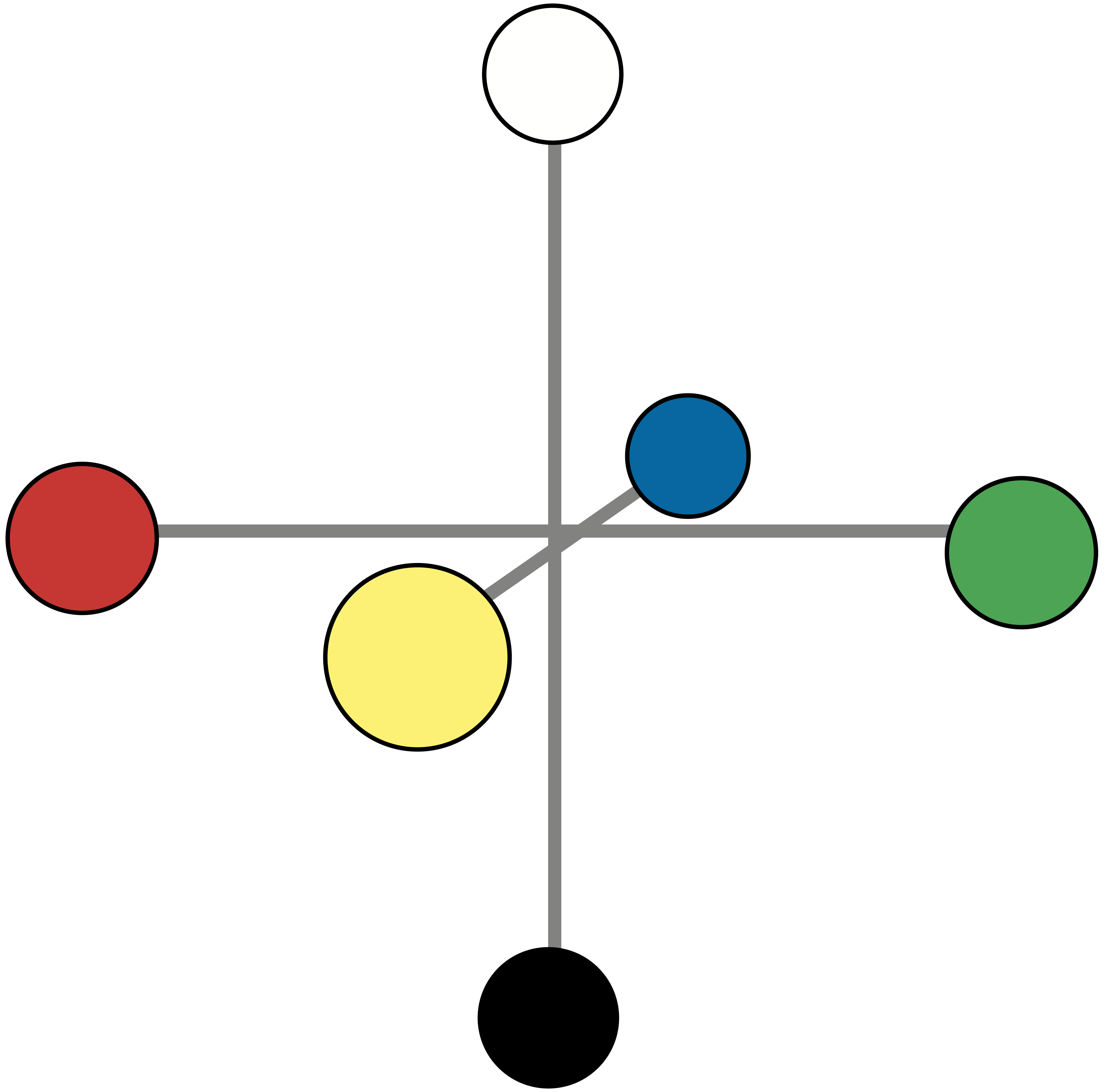


Visible Light	Cone Response	Opponent Encoding	Perceptual Models	Appearance Models	Cognitive Models

Opponent Encoding





Opponent Encoding Theory

Idea: our perception of color is controlled by two types of opposing pairs:

- **Red and Green**
- **Blue and Yellow**

There is also a third pair, which is **Black and White**, used to describe lightness (not strictly a color opposition but rather the presence versus absence of light).

How Opponent Encoding Theory Works

1. **Antagonistic Responses**: Within this system, when one color of a pair is stimulated, the response to the other color is inhibited. For example, if the red-sensitive cells are stimulated, the response of the green-sensitive cells is suppressed, and vice versa. This means you cannot perceive both red and green at the exact same spot and time.

How Opponent Encoding Theory Works

1. **Color Perception**: This theory helps explain certain aspects of color vision, such as why there are no "reddish greens" or "bluish yellows." These combinations are forbidden because the channels that process these colors work against each other rather than together.

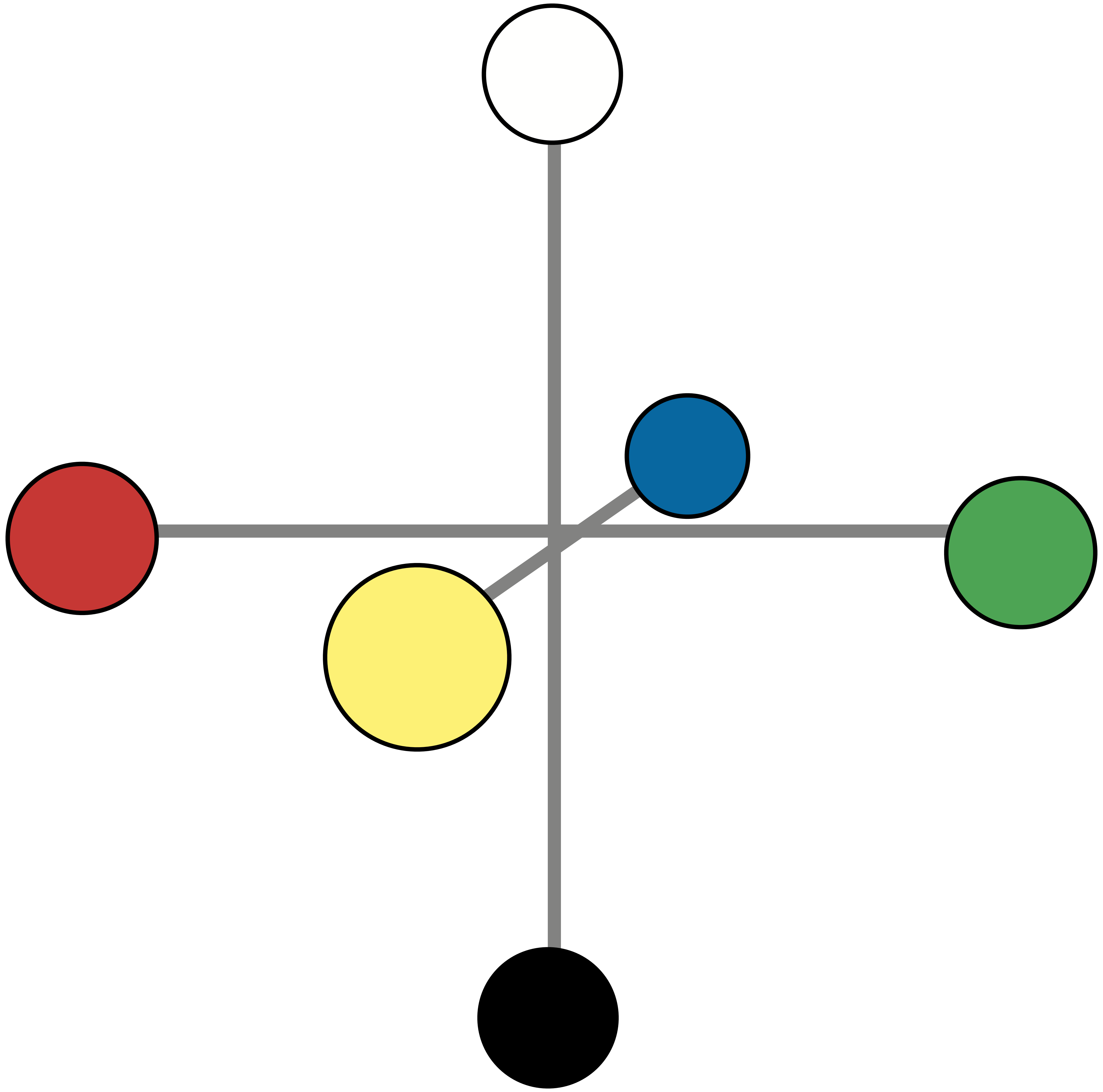
How Opponent Encoding Theory Works

1. **Afterimages and Color Fatigue**: Another phenomenon explained by this theory is the creation of afterimages. For example, if you stare at a red image for a while and then look at a white surface, you might see a green afterimage. This occurs because the red cells become "tired," and when you look away, the green cells (which were suppressed) now become more active, creating the perception of the opposite color.

CIE LAB Color Space

Axes correspond to opponent signals:

L* = luminance
a* = red-green contrast
b* = yellow-blue contrast



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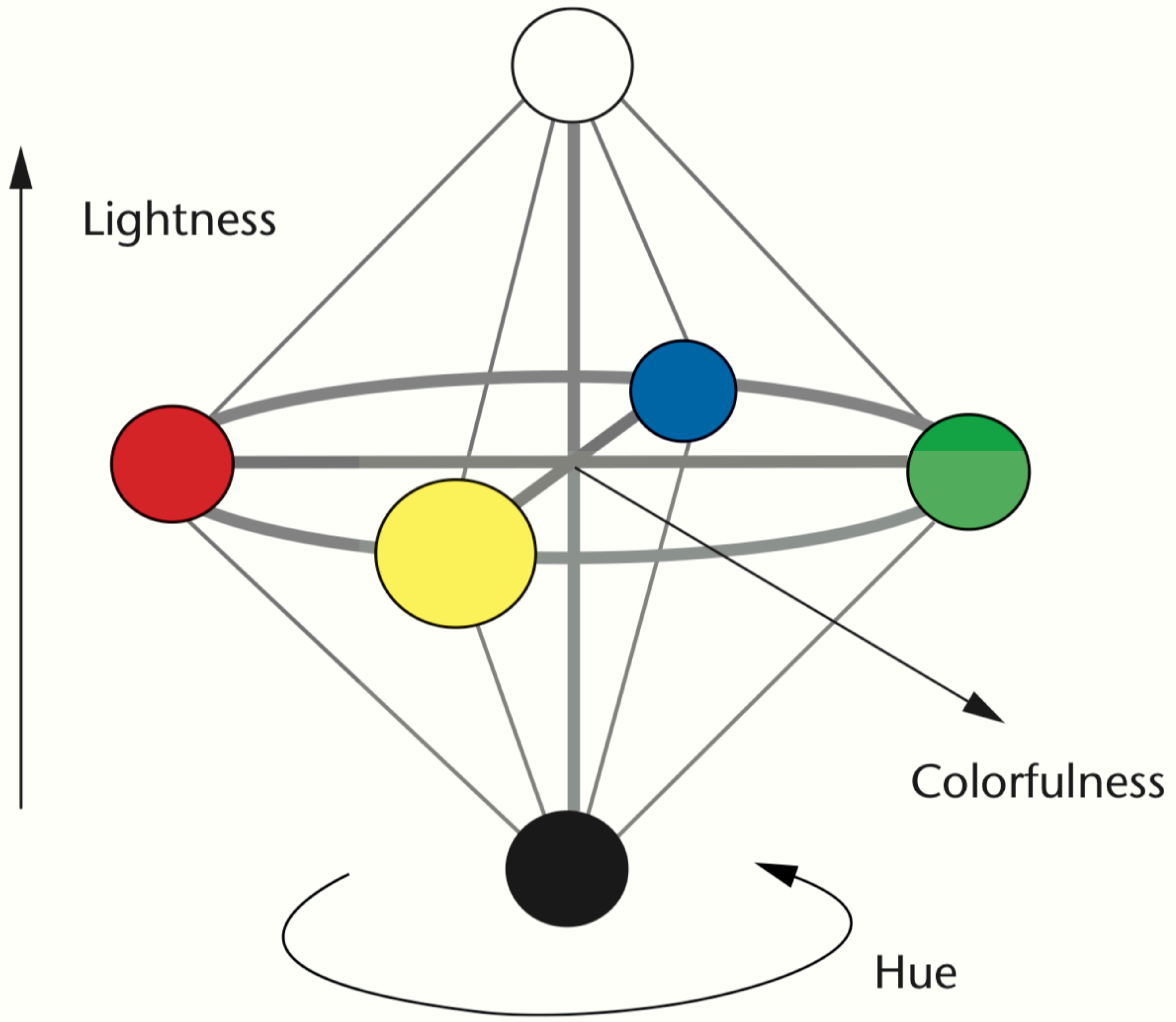


[Maureen Stone. *A Field Guide to Digital Color*, 2003]

CIE LAB Color Space

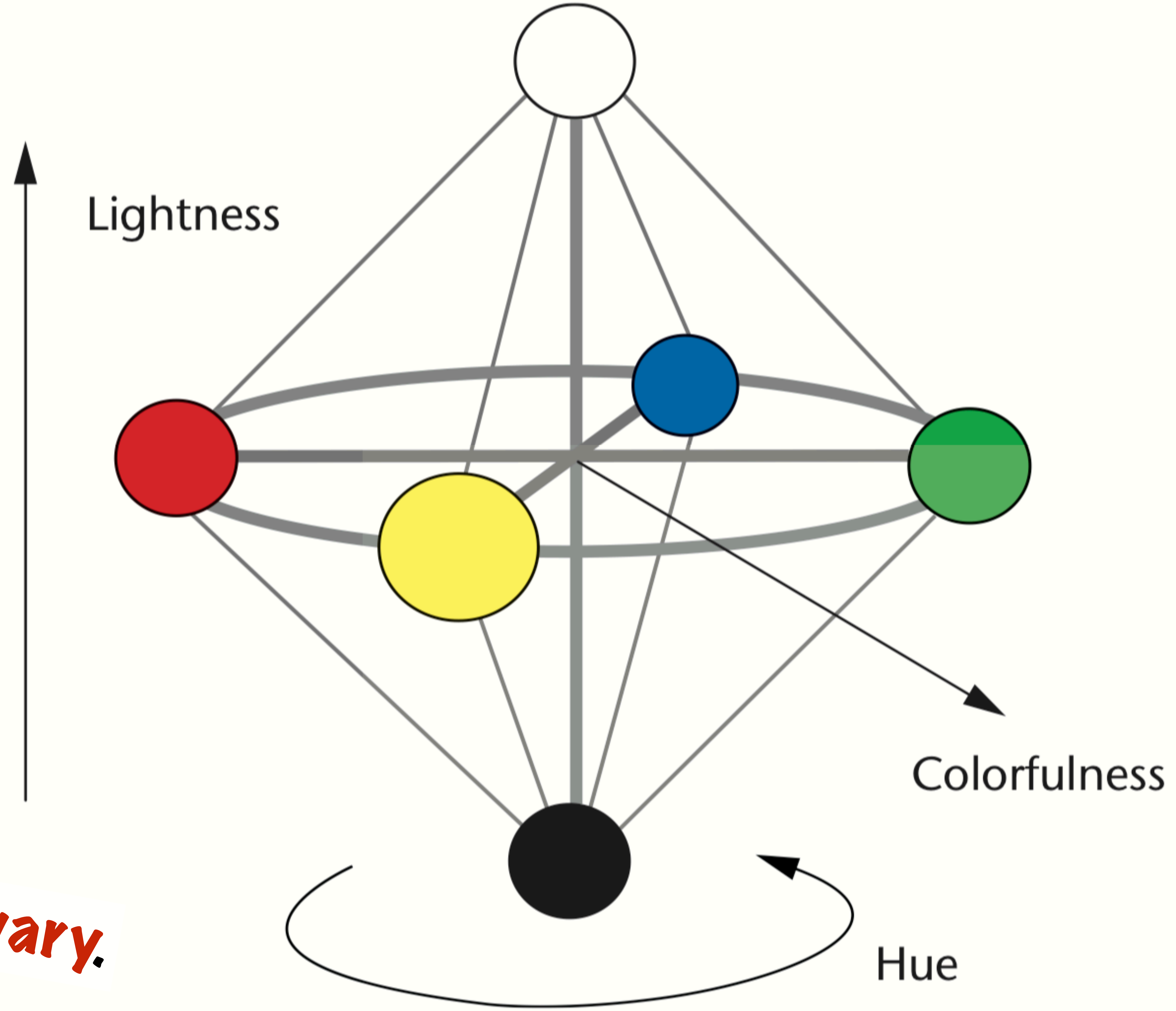
More perceptually uniform than sRGB.

Scaling of axes such that distance in color space is proportional to perceptual distance.

The angry rainbow in RGB.

Better. But still be wary.

A happier rainbow in LAB.



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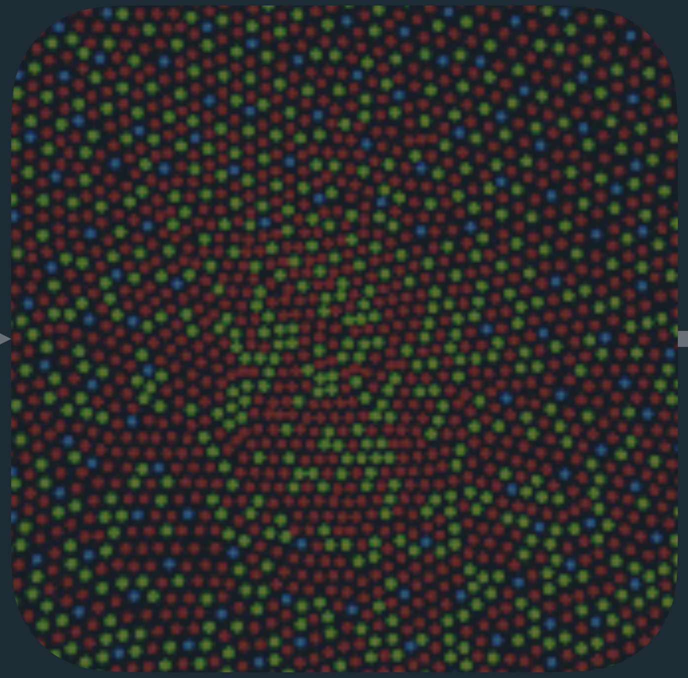

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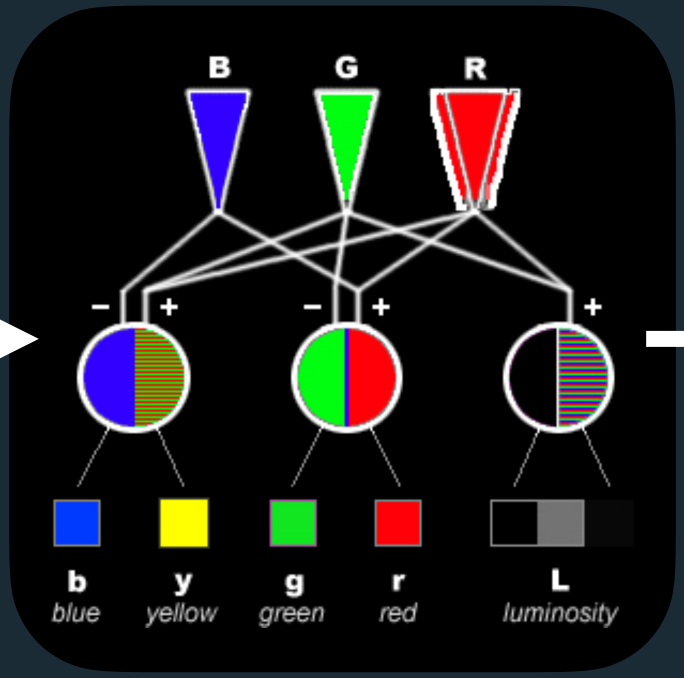
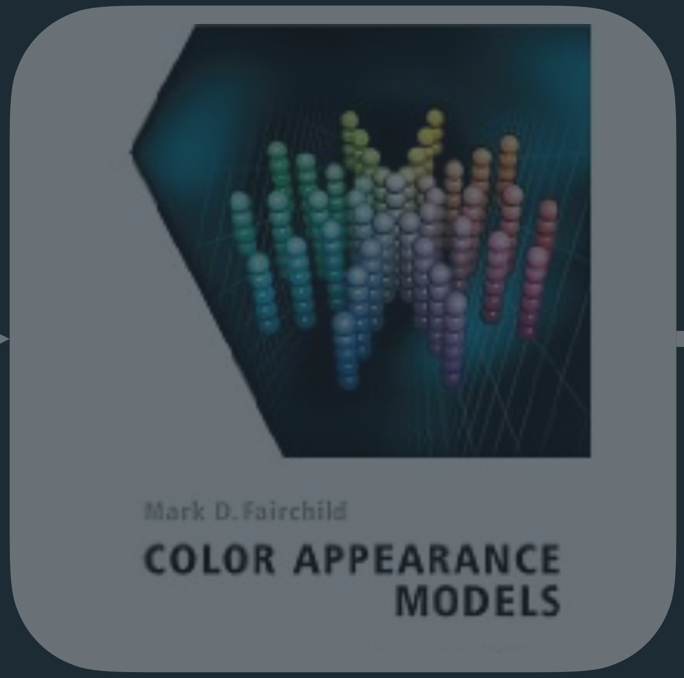


Opponent Encoding

Perceptual Models



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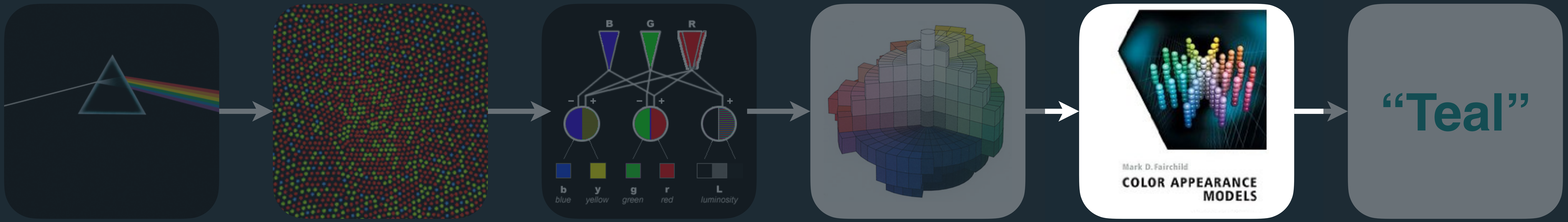
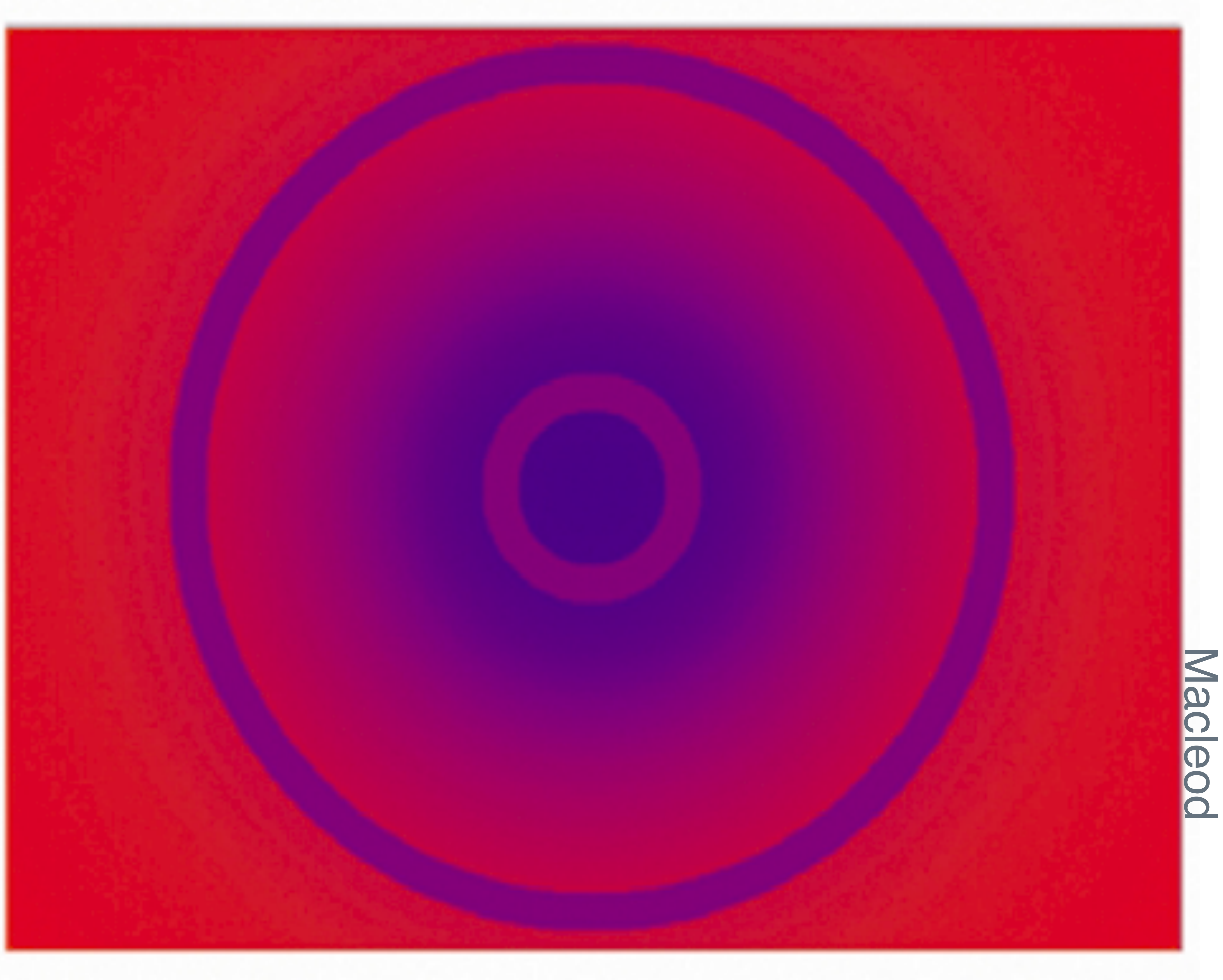


Visible Light | Cone Response | Opponent Encoding | Perceptual Models | Appearance Models | Cognitive Models

Simultaneous Contrast

When two colors are side-by-side, they interact and affect our perception

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



Donald Macleod

Simultaneous Contrast

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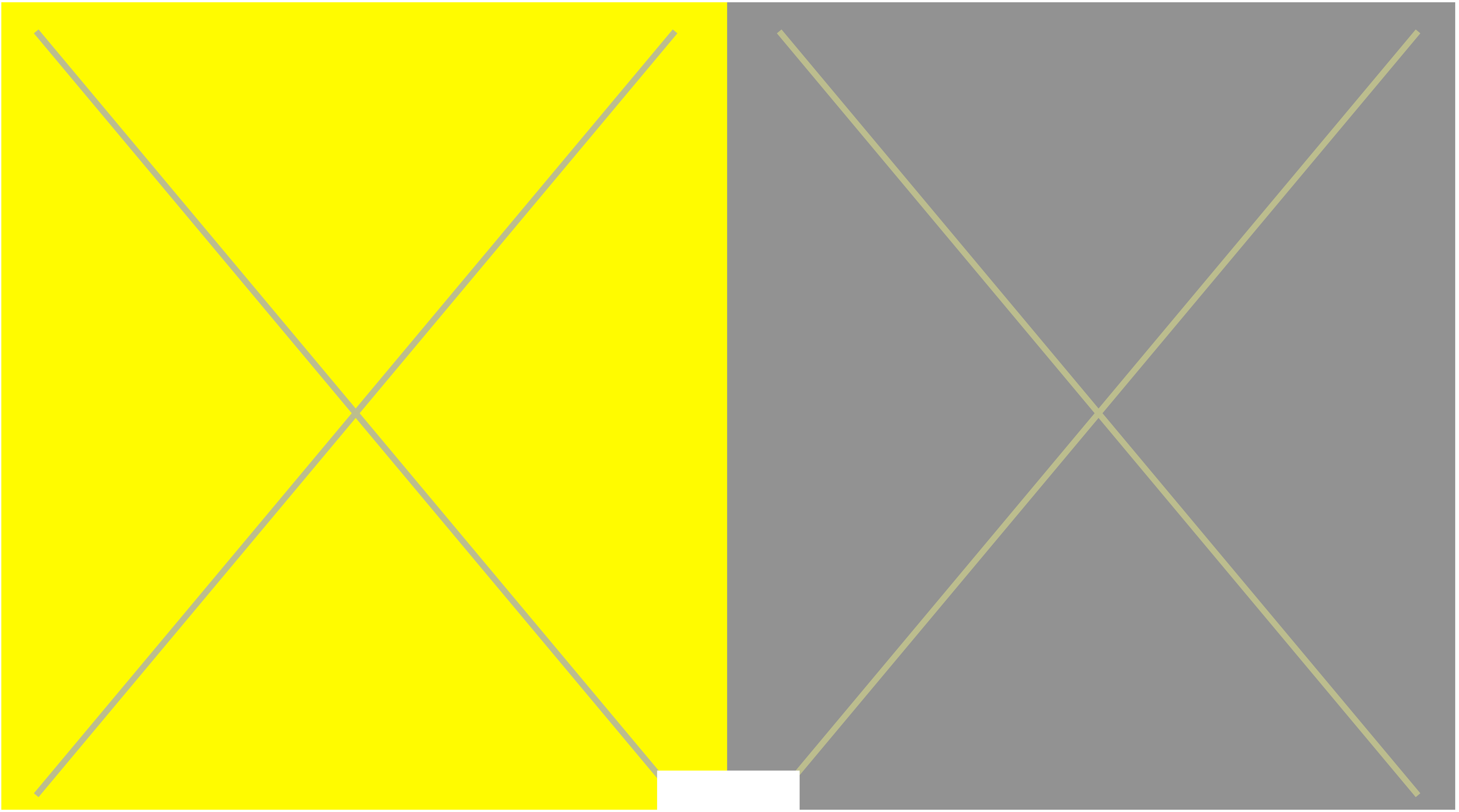

Josef Albers

Simultaneous Contrast

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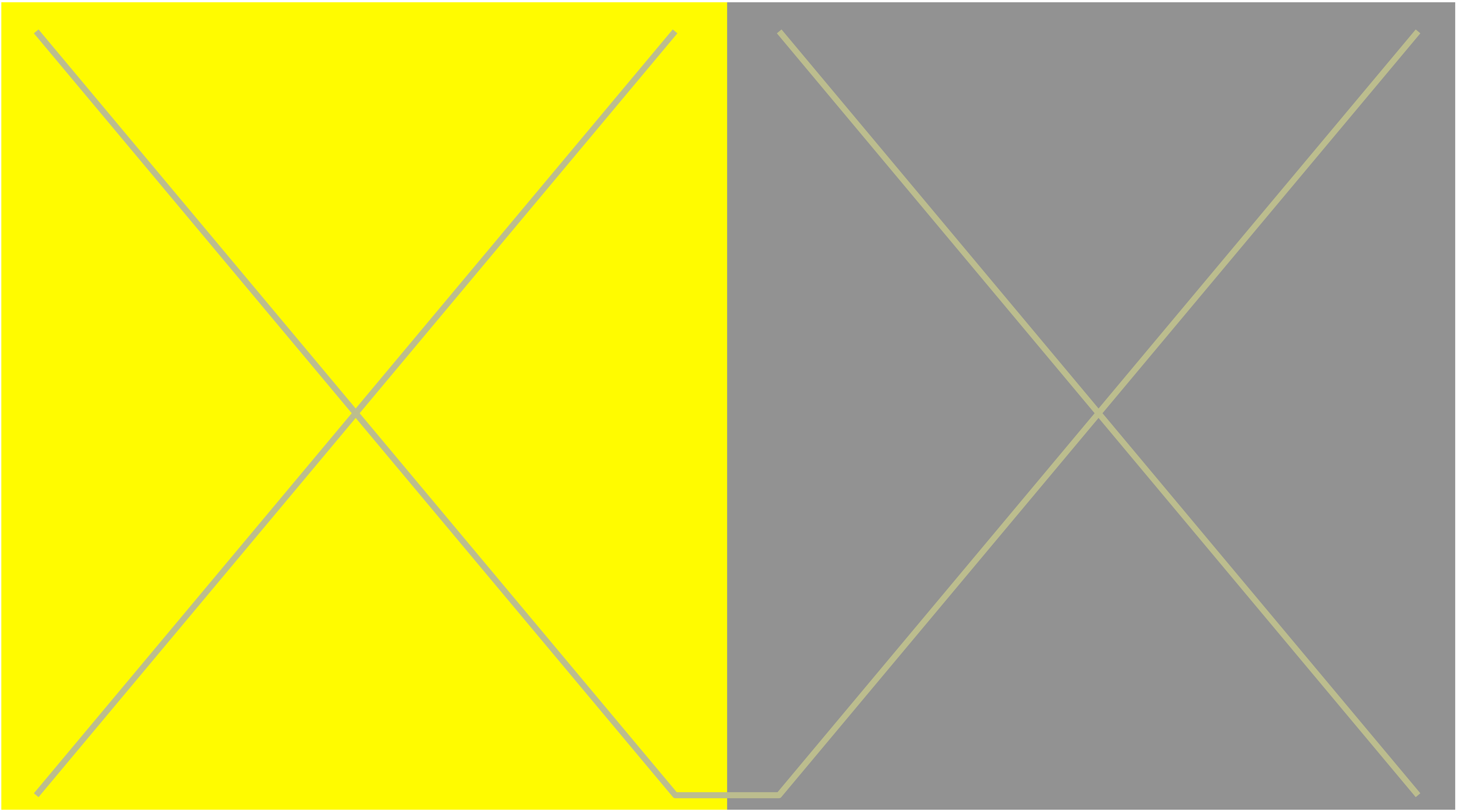

Josef Albers

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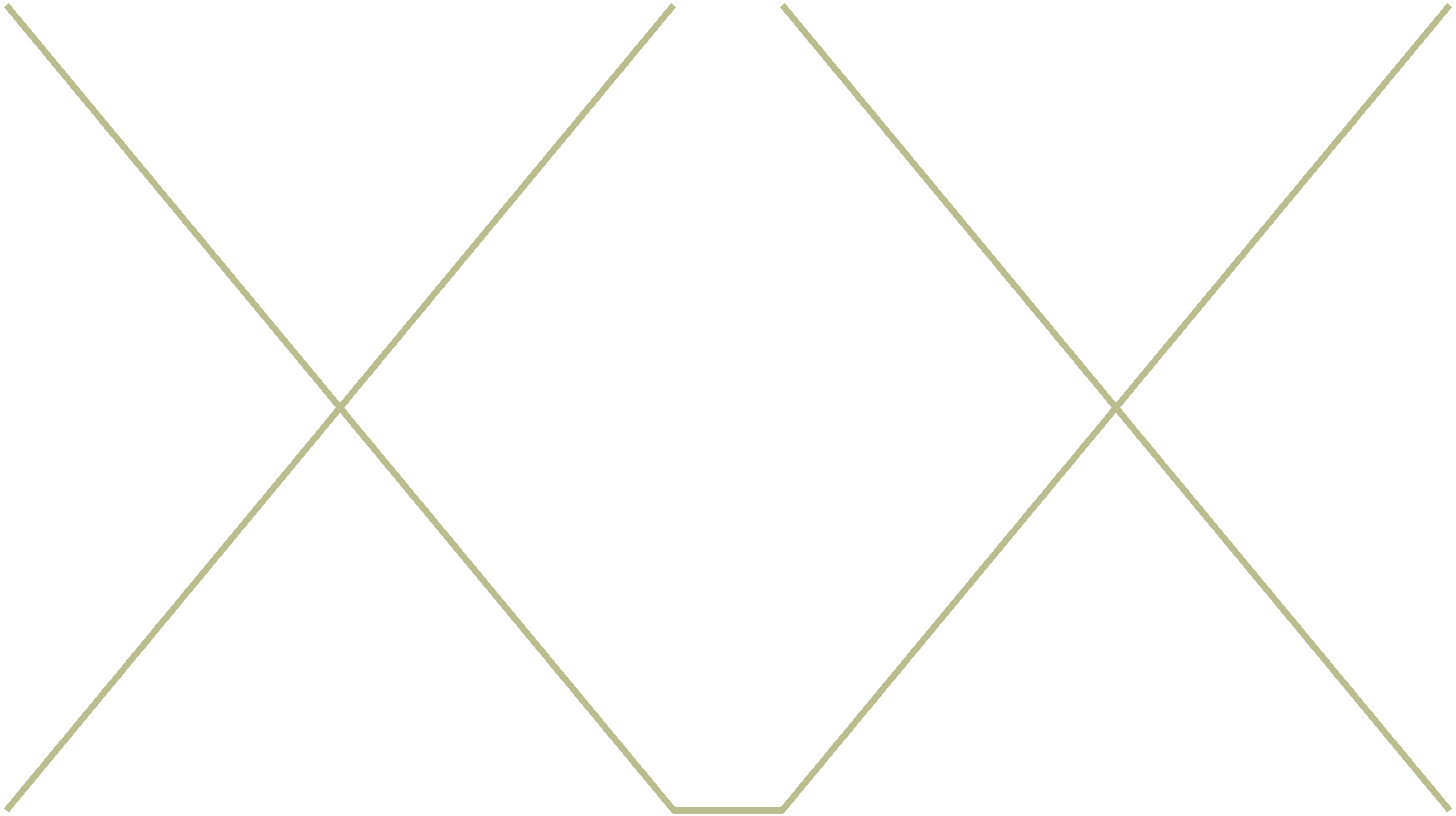
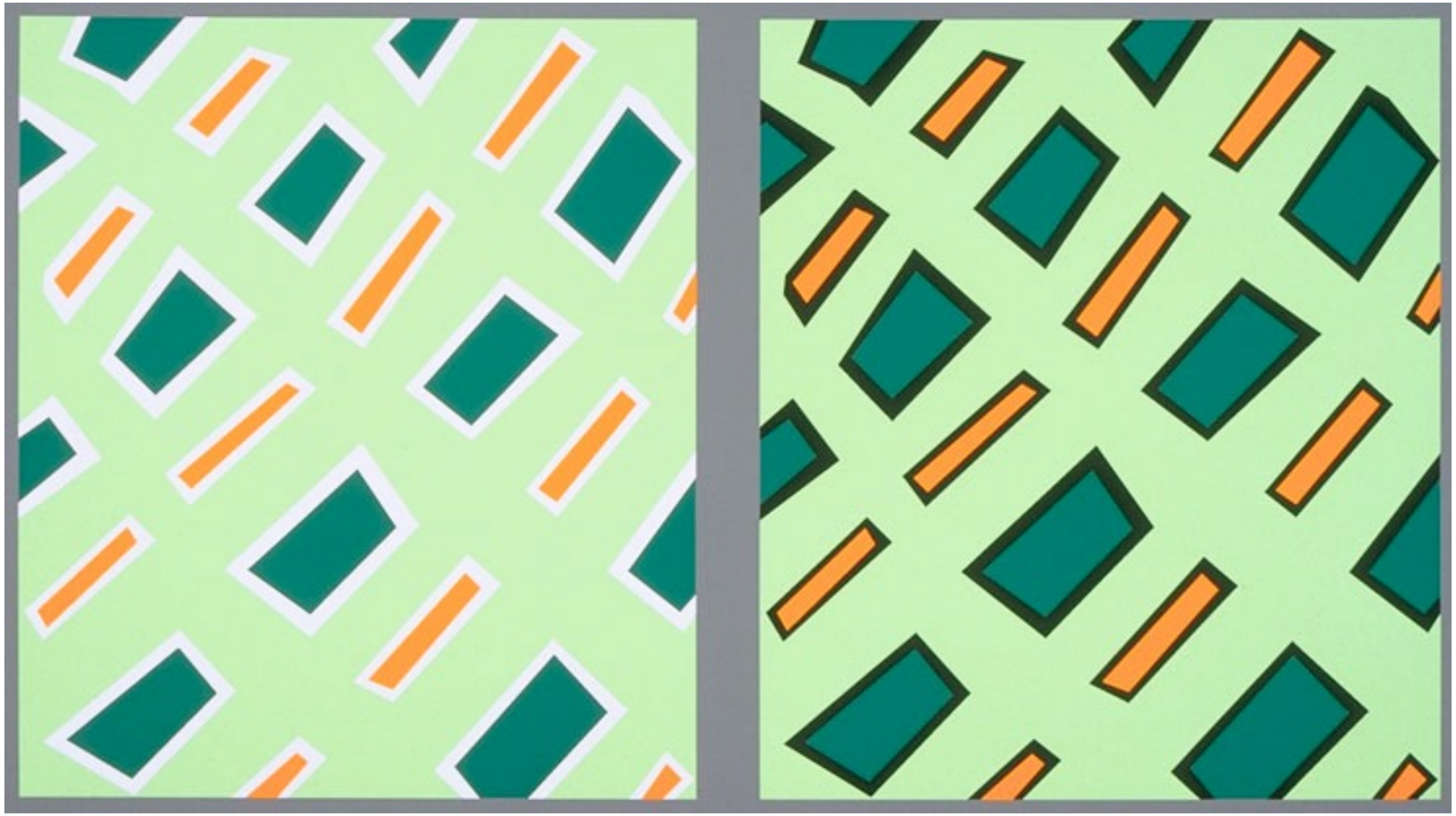


Josef Albers

Bezold Effect

Color appearance depends on adjacent colors

E.g., adding a dark border around a color can the color appear darker.



Chromatic Adaptation

Our ability to adjust to color perception based on illumination

Jason Su

Chromatic Adaptation

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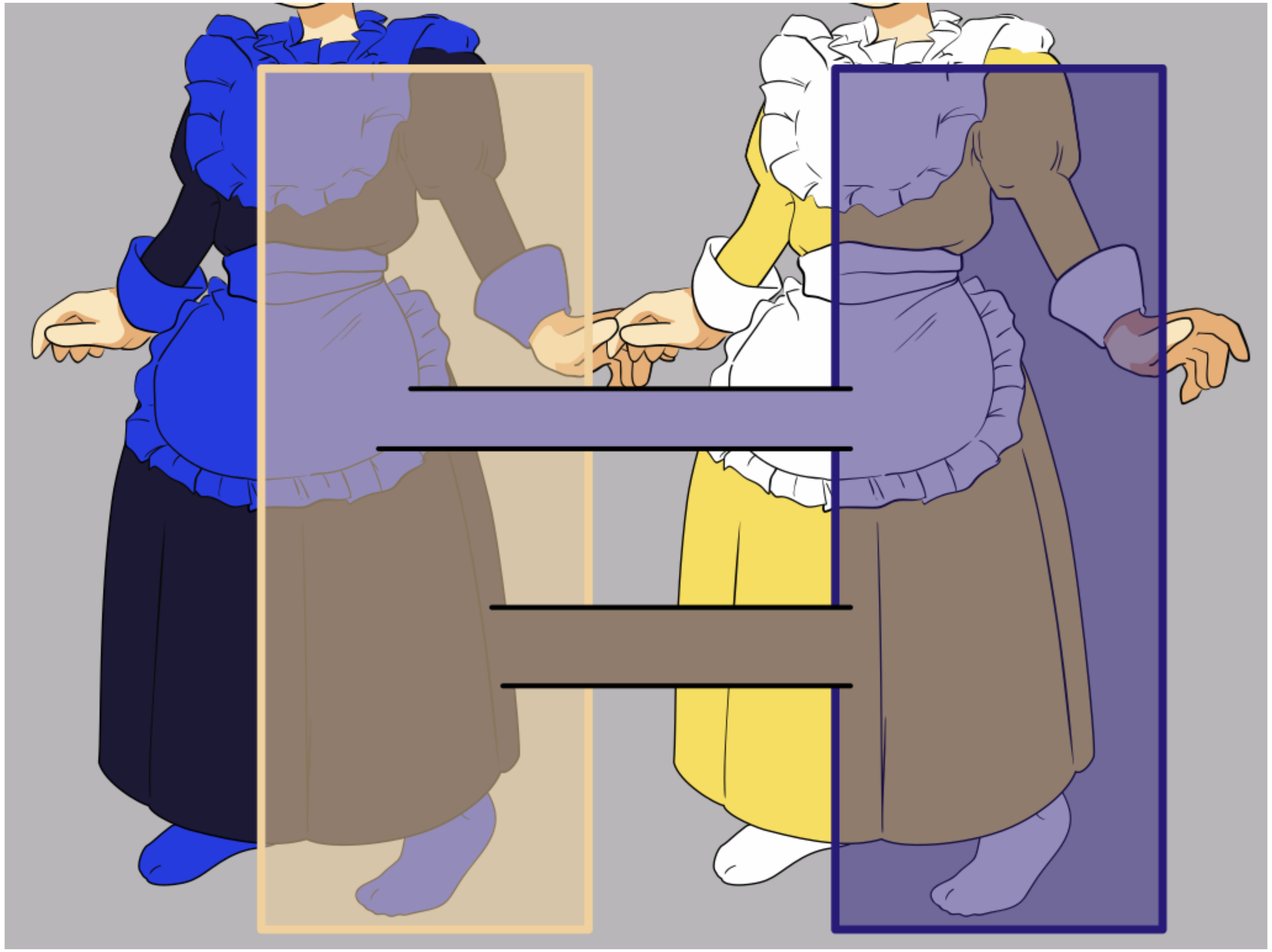
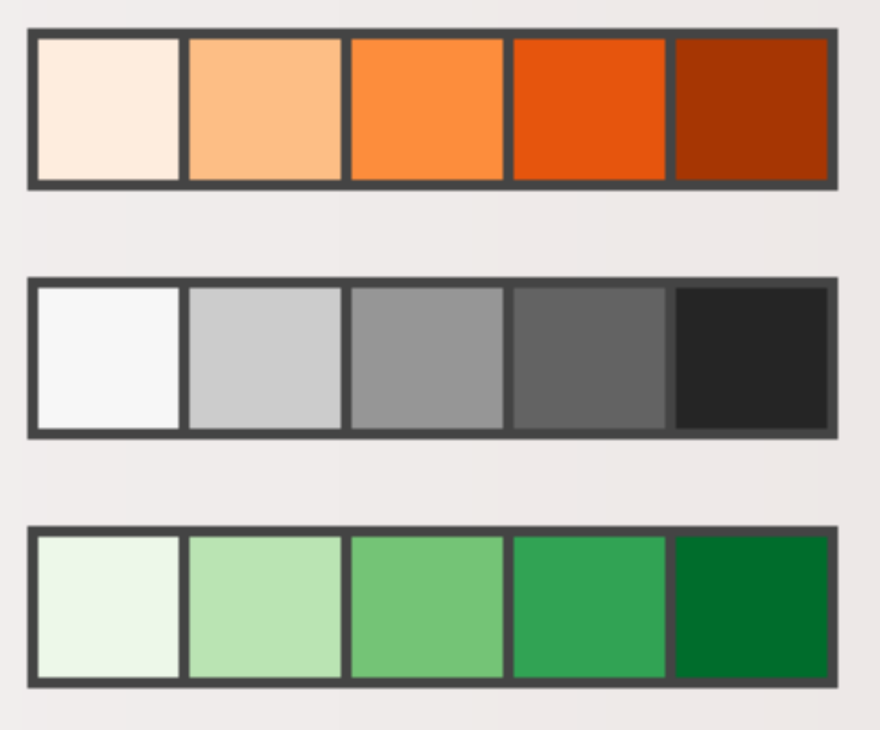


Quantitative Color Encoding

Sequential Color Scale

Ramp in luminance, possibly also hue.

Typically higher values map to darker colors.

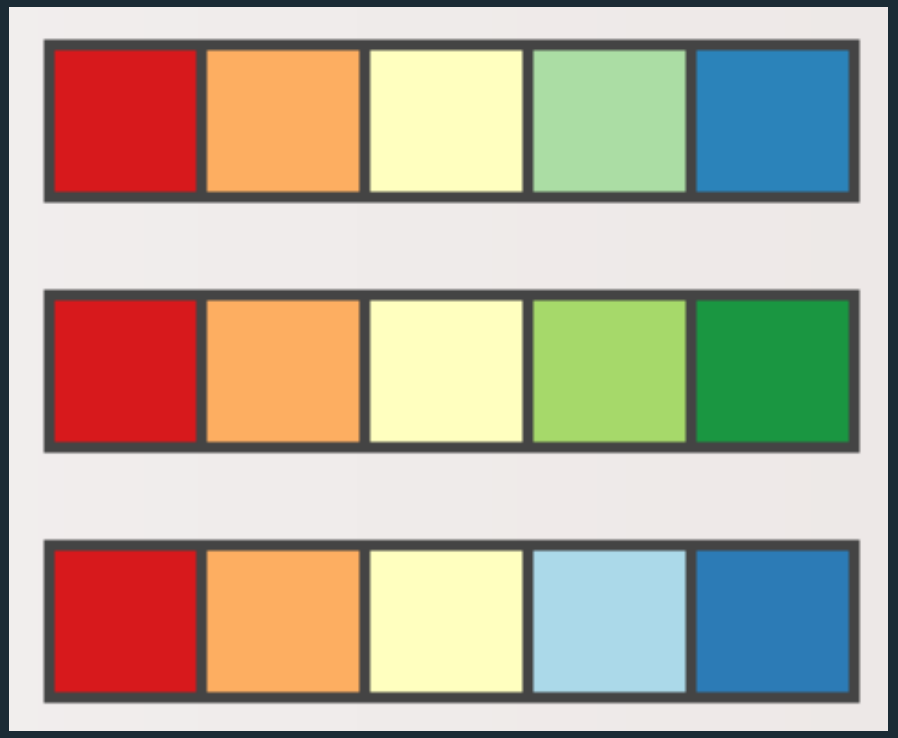


Diverging Color Scale

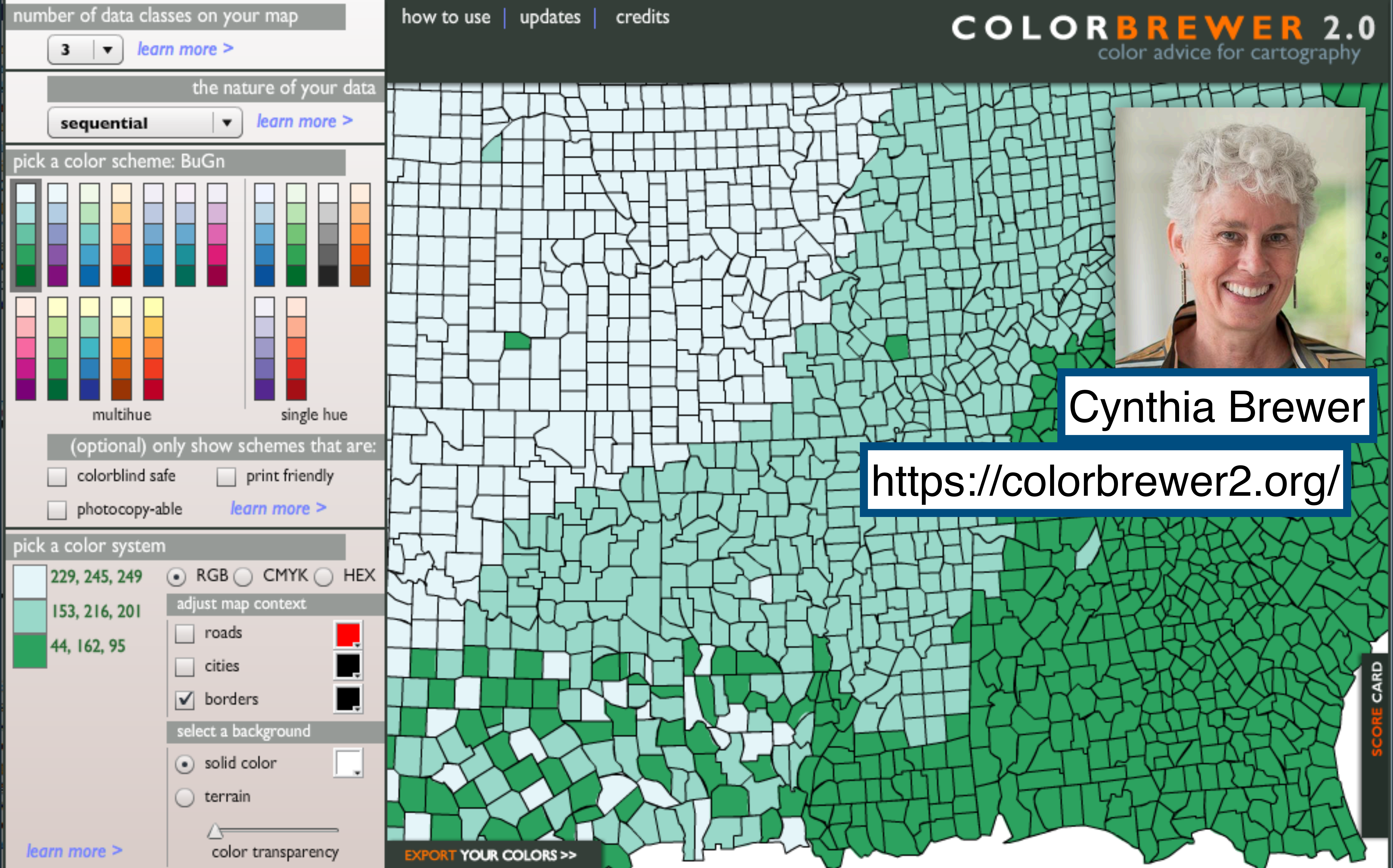
Useful when data has a meaningful “midpoint.”

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

Use saturated colors for endpoints.



Limit number of steps in color to 3–9



Cynthia Brewer

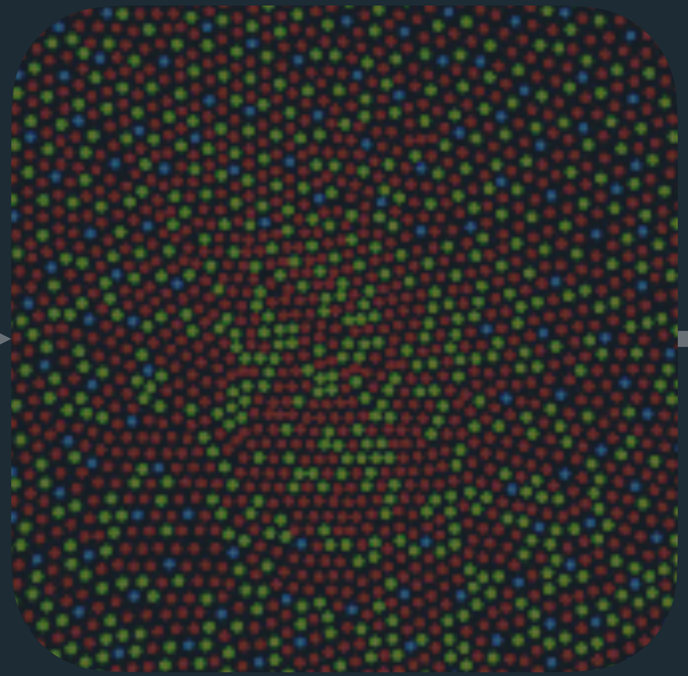
https://colorbrewer2.org/

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”

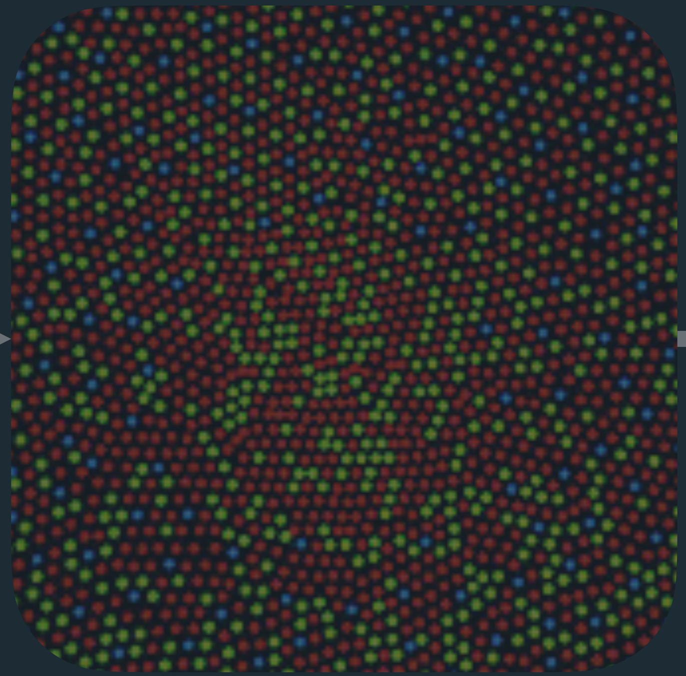
Cognitive Models

Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World — Visual System — Mental Models

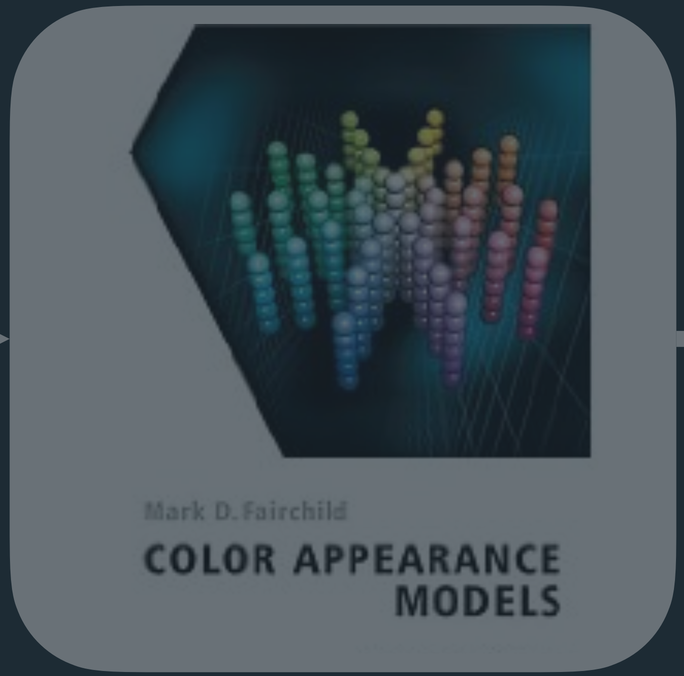
Visible Light



Cone Response

Opponent Encoding

Perceptual Models

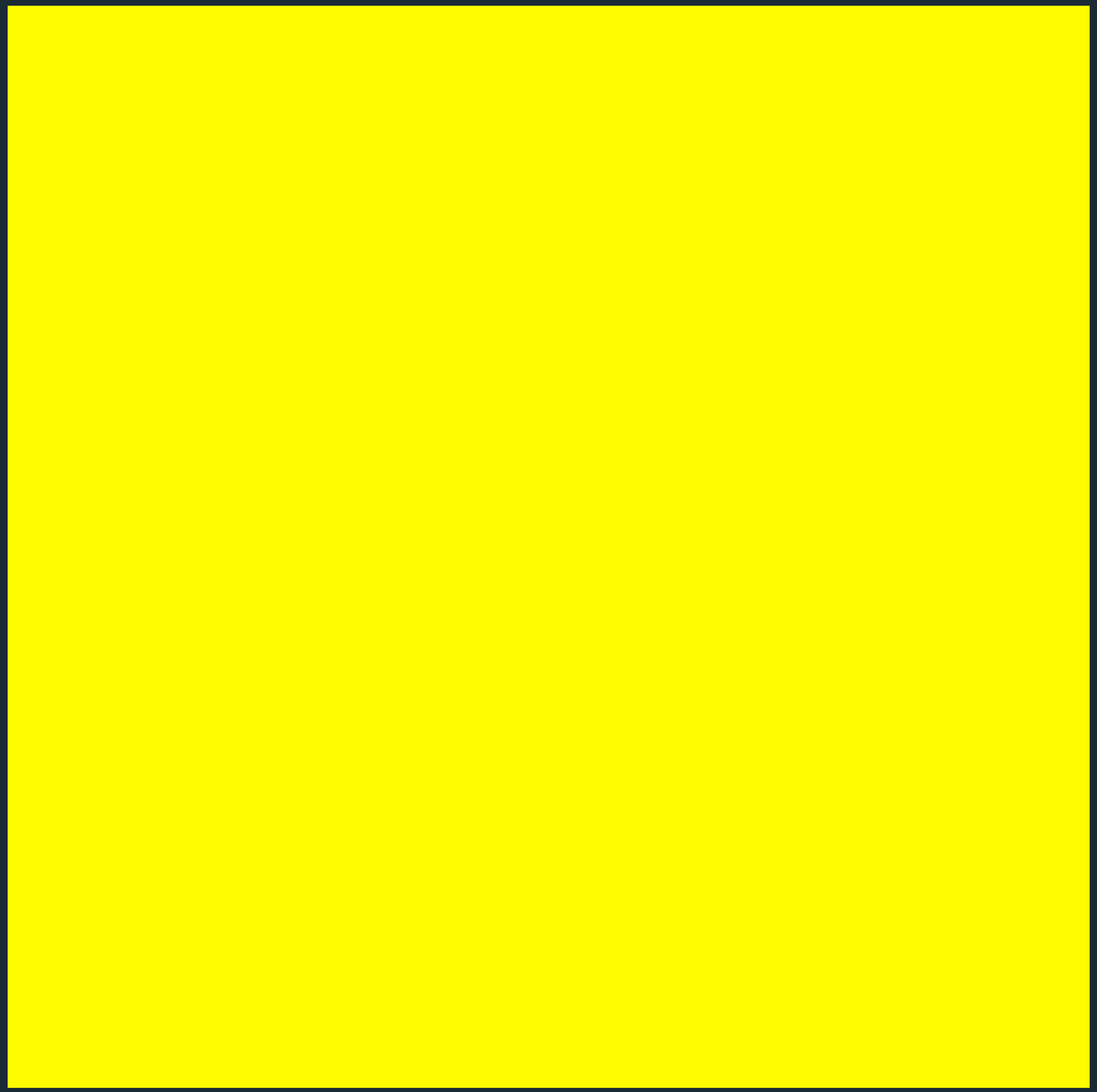


Appearance Models

“Teal”

Cognitive Models

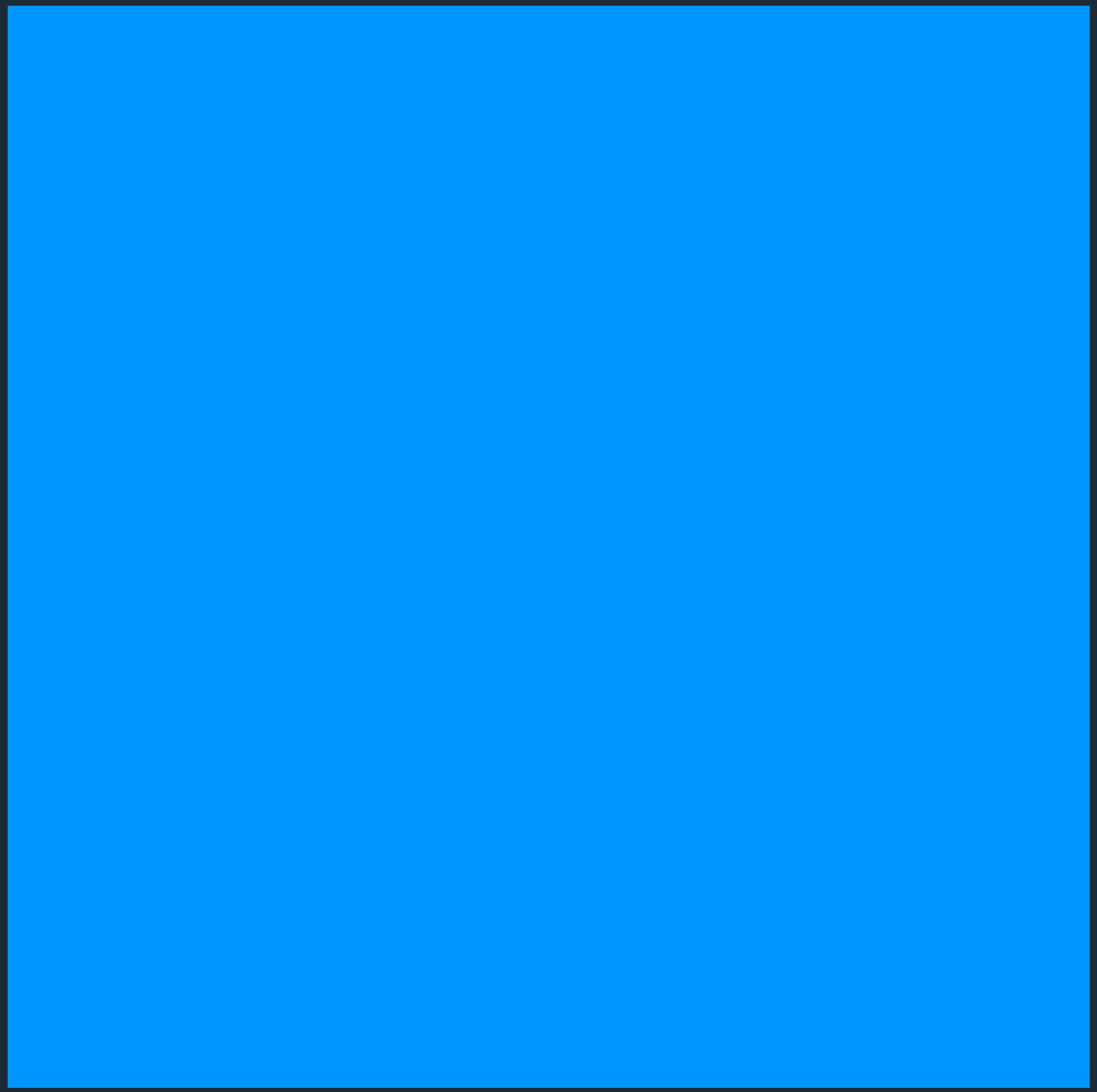
What color is this?



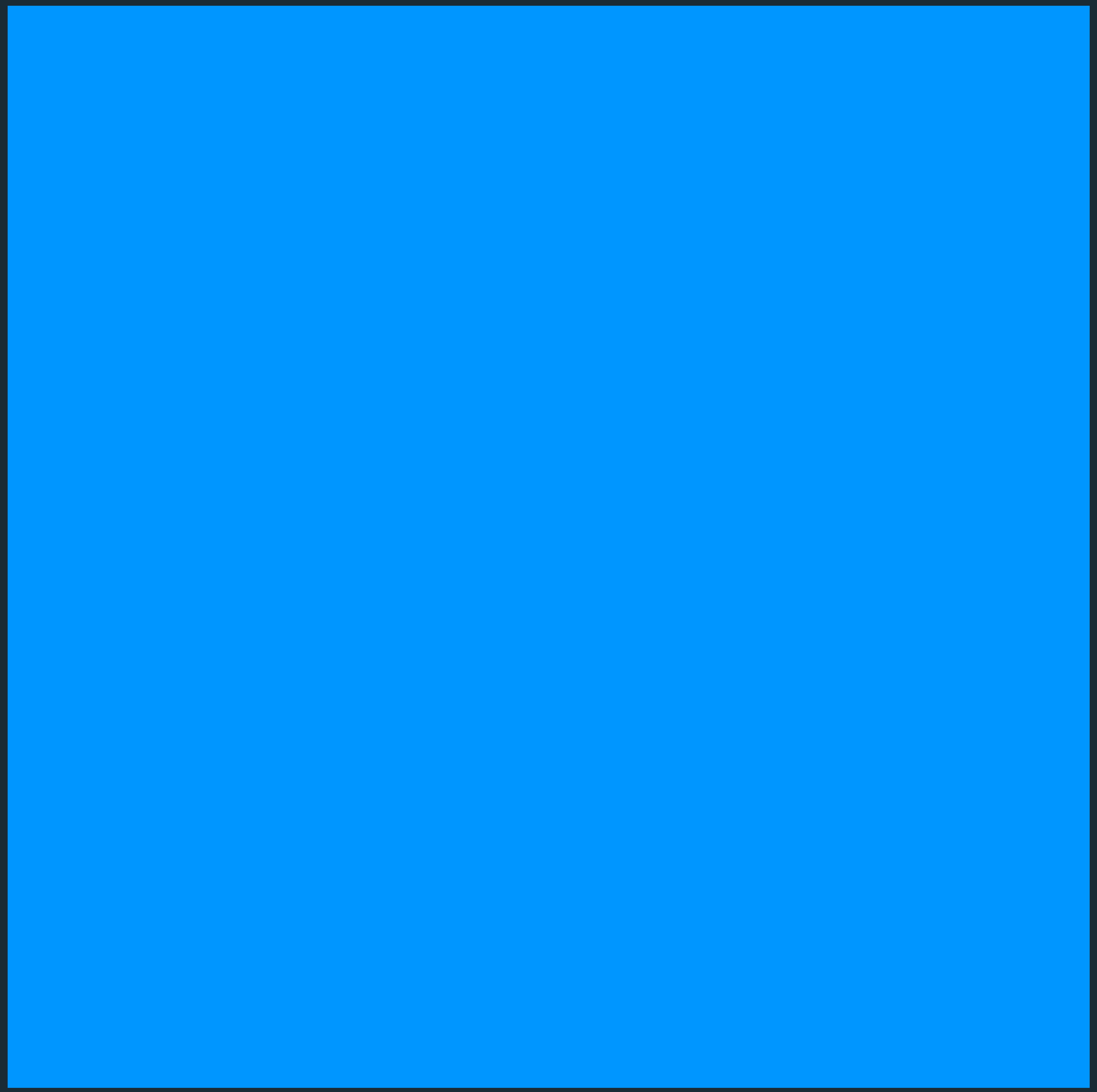
What color is this?

"Yellow"

What color is this?

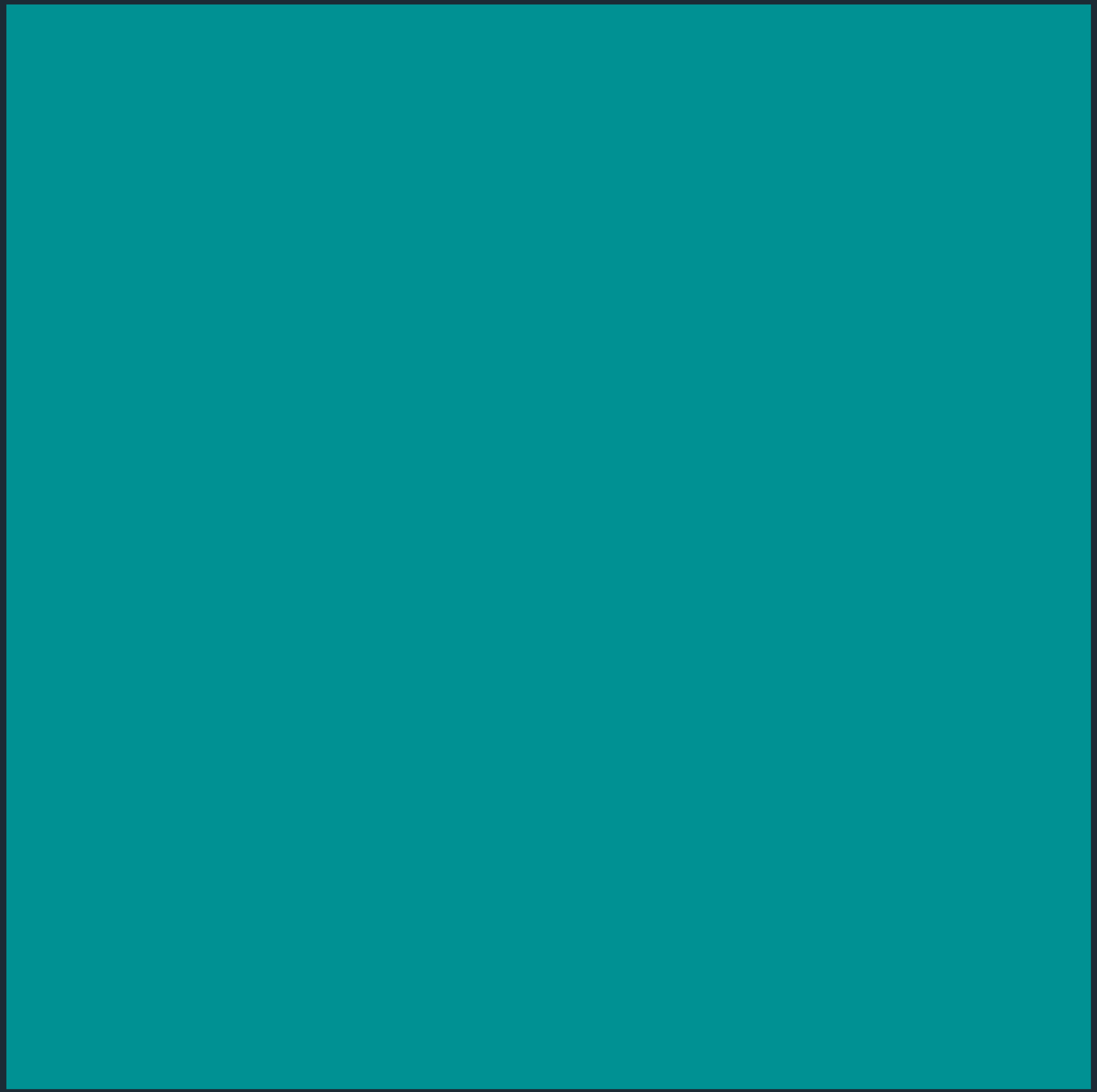


What color is this?



“Blue”

What color is this?



Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?

Berlin & Kay, *Basic Color Terms*. 1969.

- Surveyed speakers from 20 languages.
- Literature from 69 languages.

World Color Survey. 1976.

- 110 languages (including tribal), 25 speakers each.
- Analysis published in 2009.

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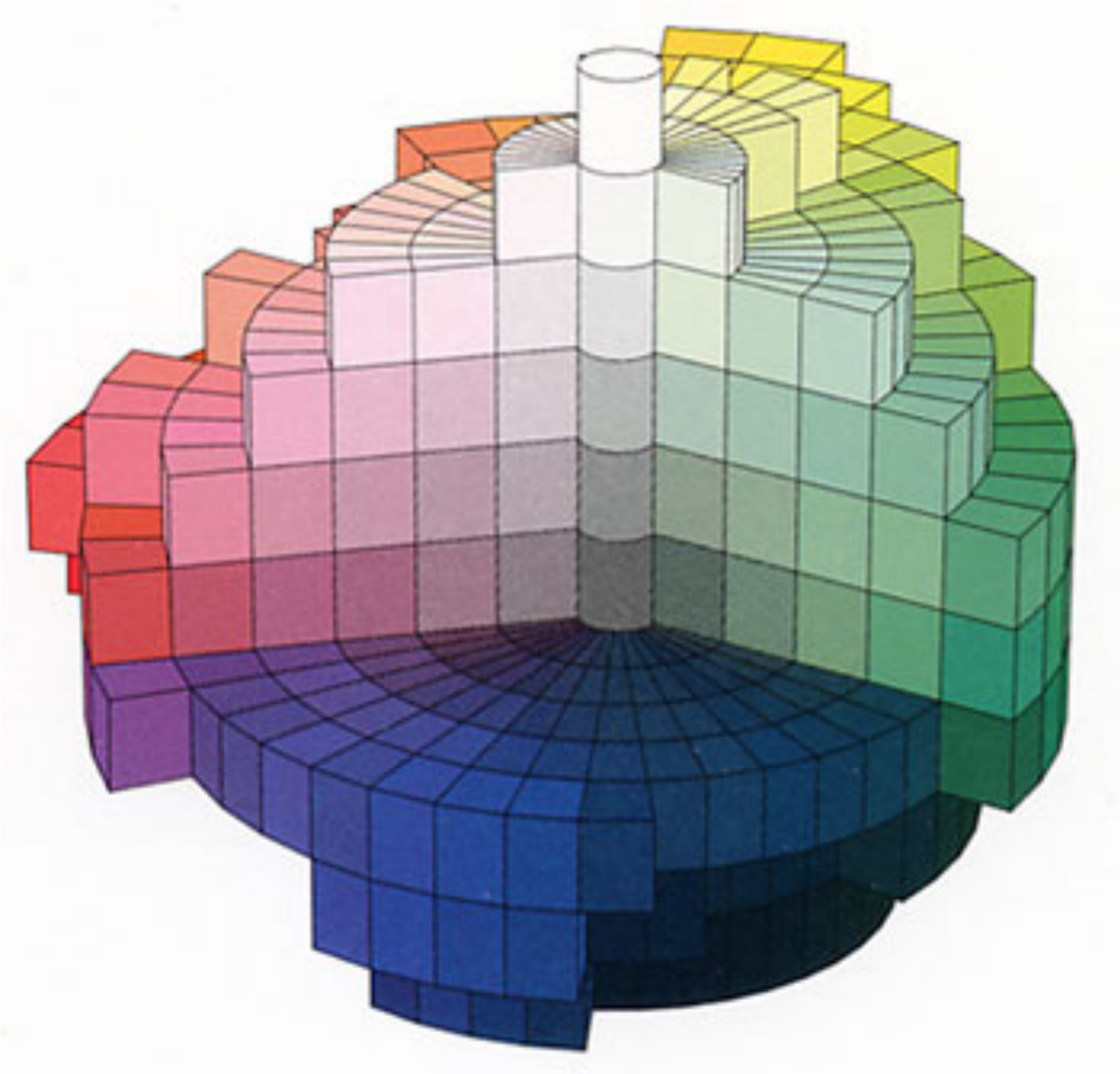

Name 320 Munsell color chips. (Shares perceptual properties with CIE LAB, but predates it.)

Color Naming

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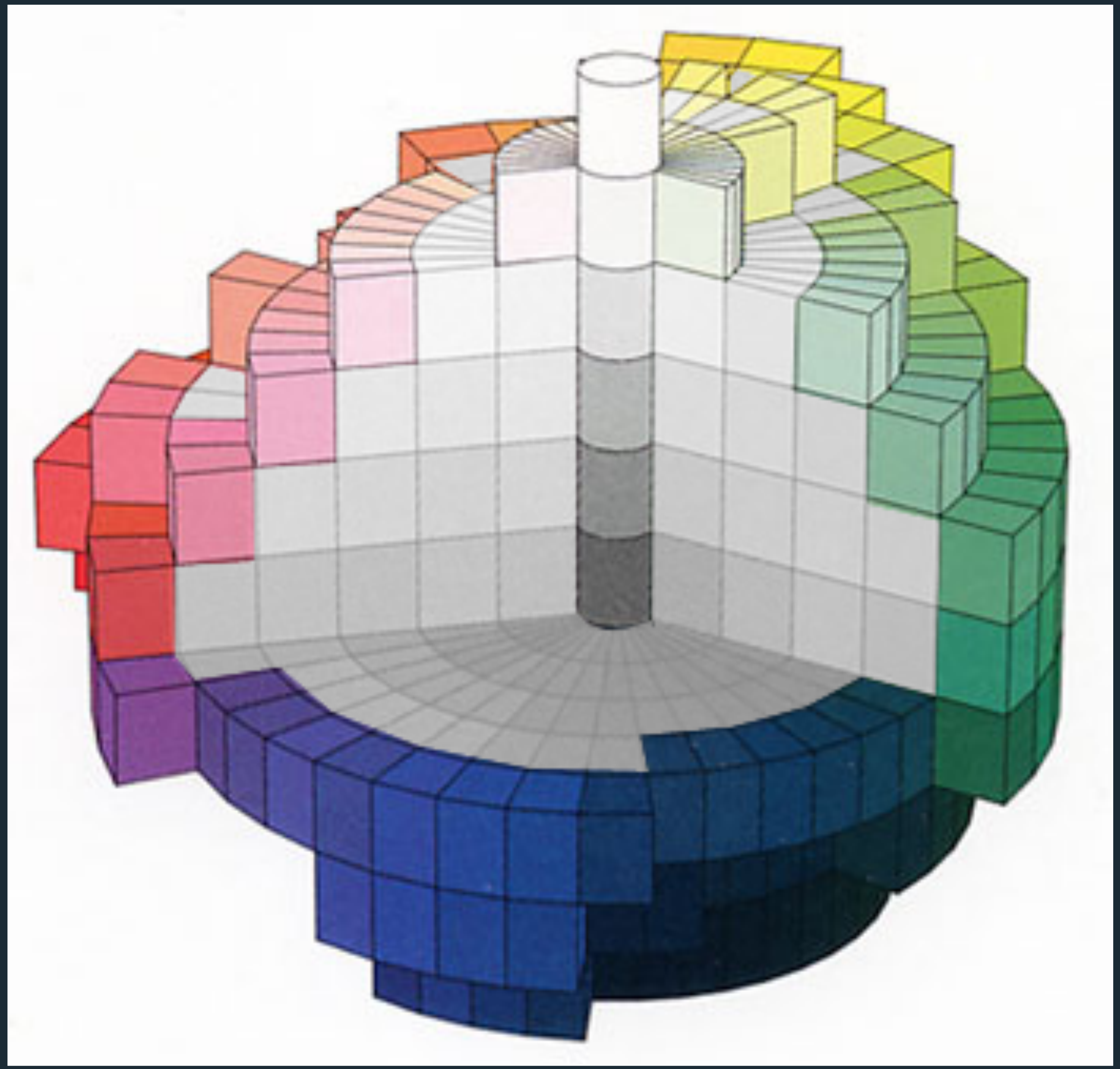


+10 achromatic chips

Color Naming

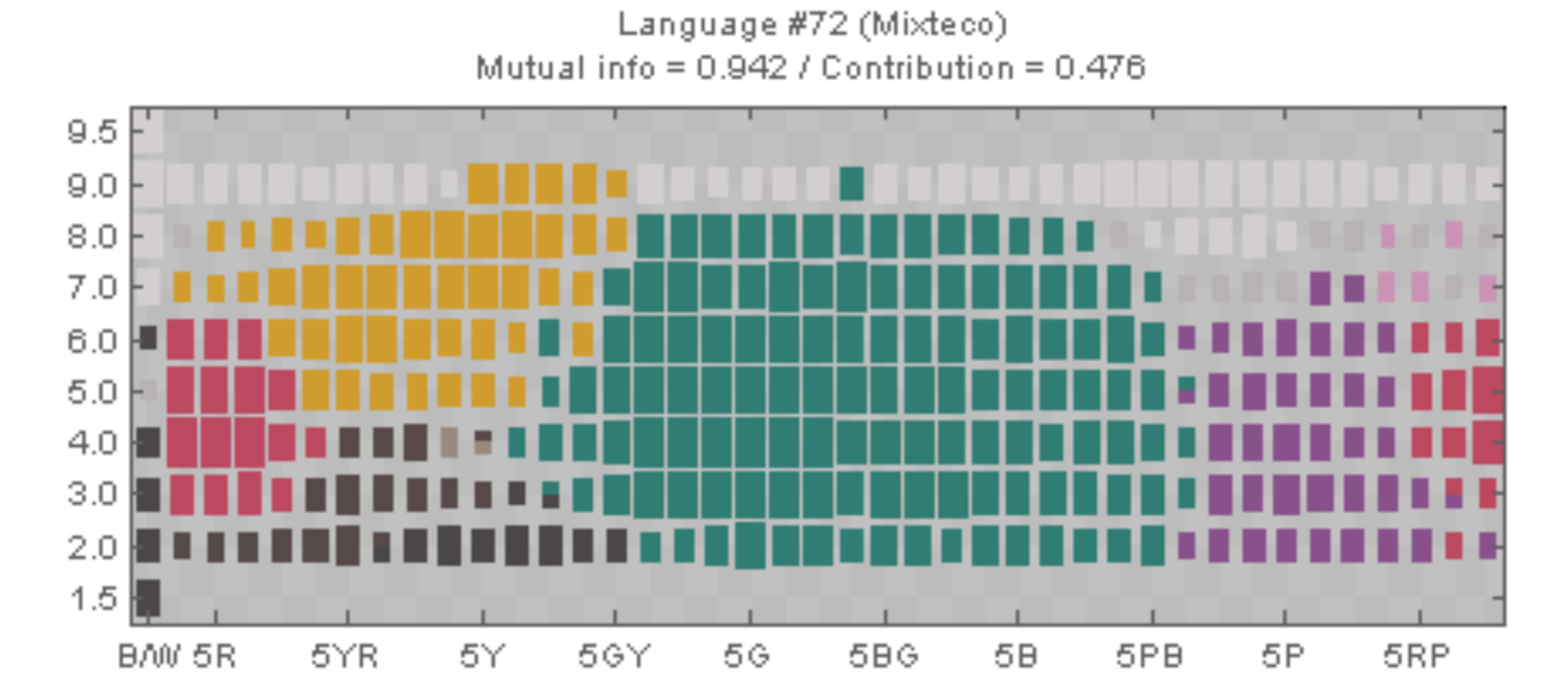
Is color naming universal? Do languages evolve color terms in similar ways?

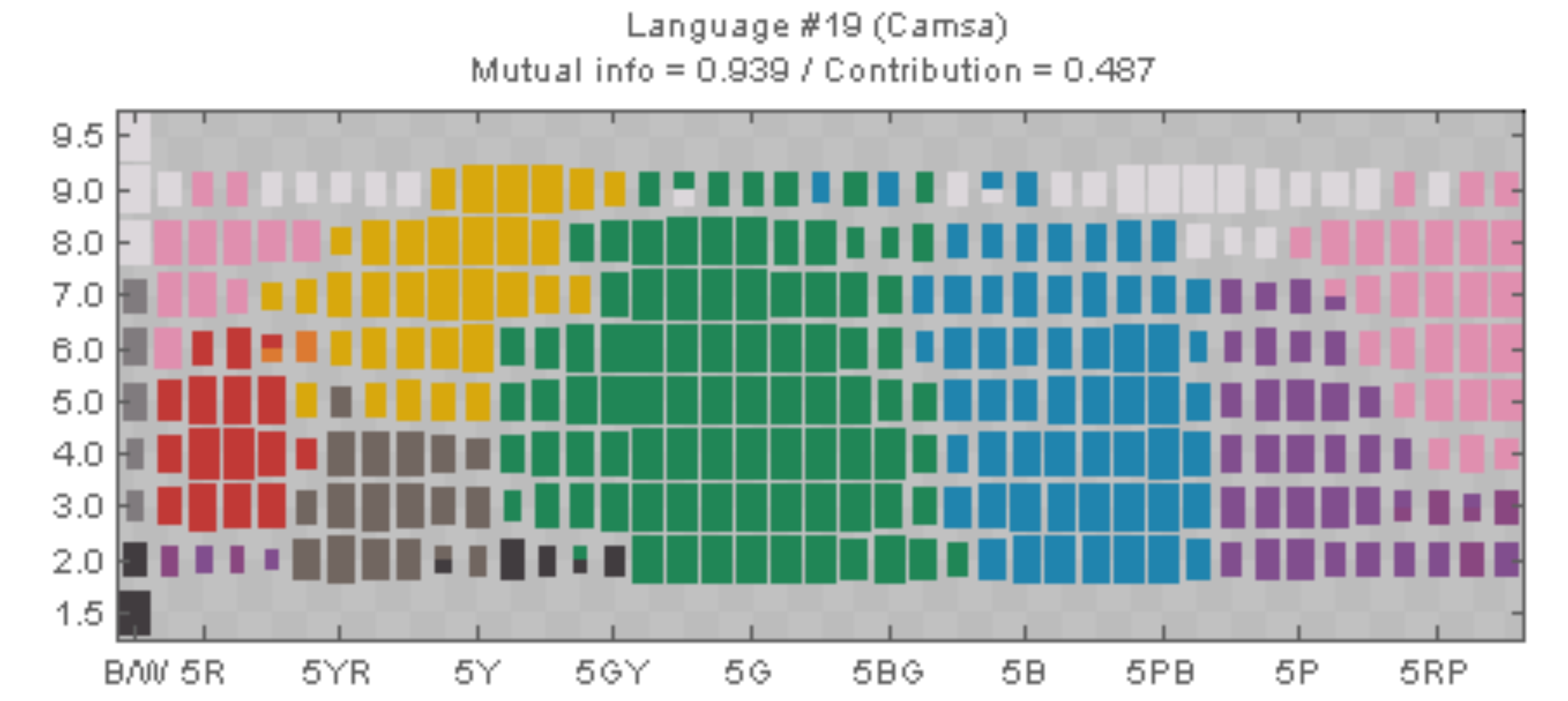
WCS stimulus array. For each basic color term (*t*) participants named, they were asked:

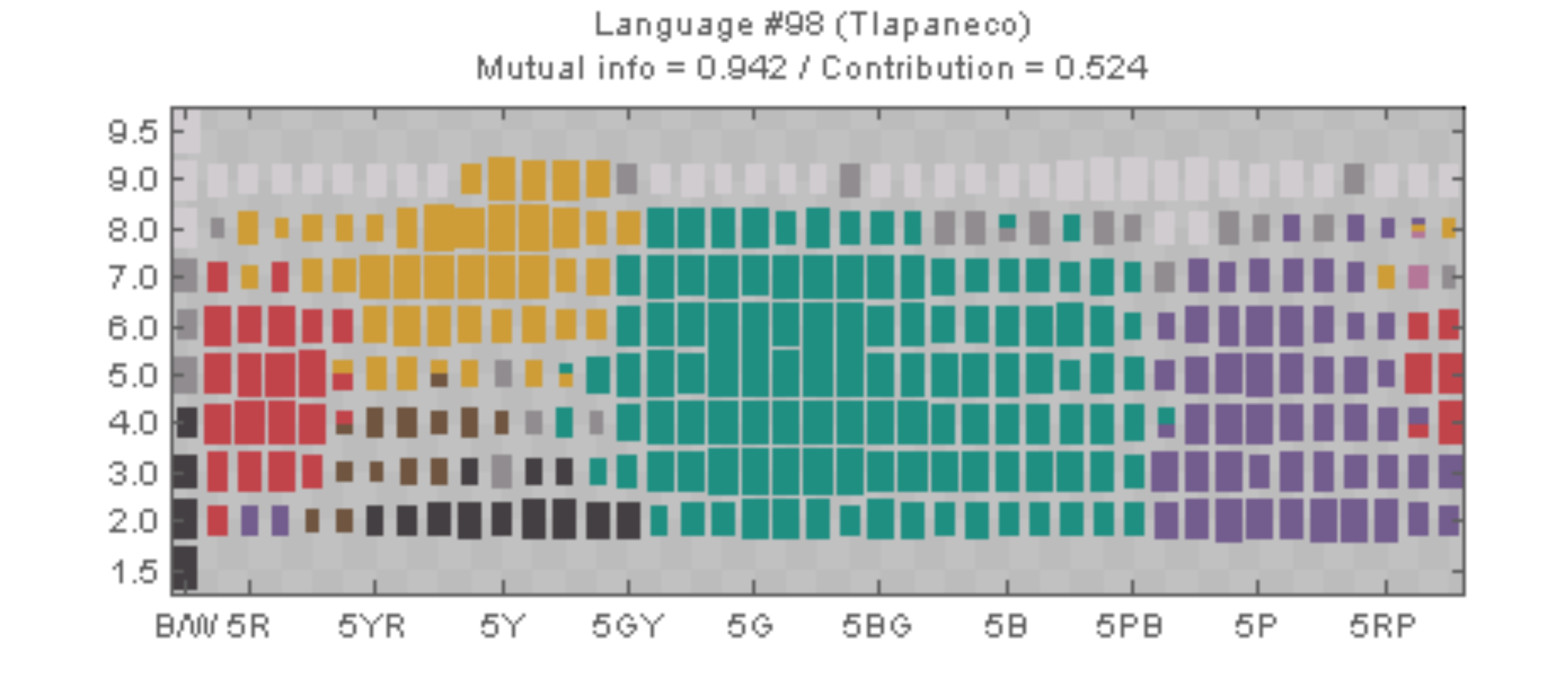
1. Mark all chips that you would call *t*.
2. Which chip is the best example(s) of *t*.

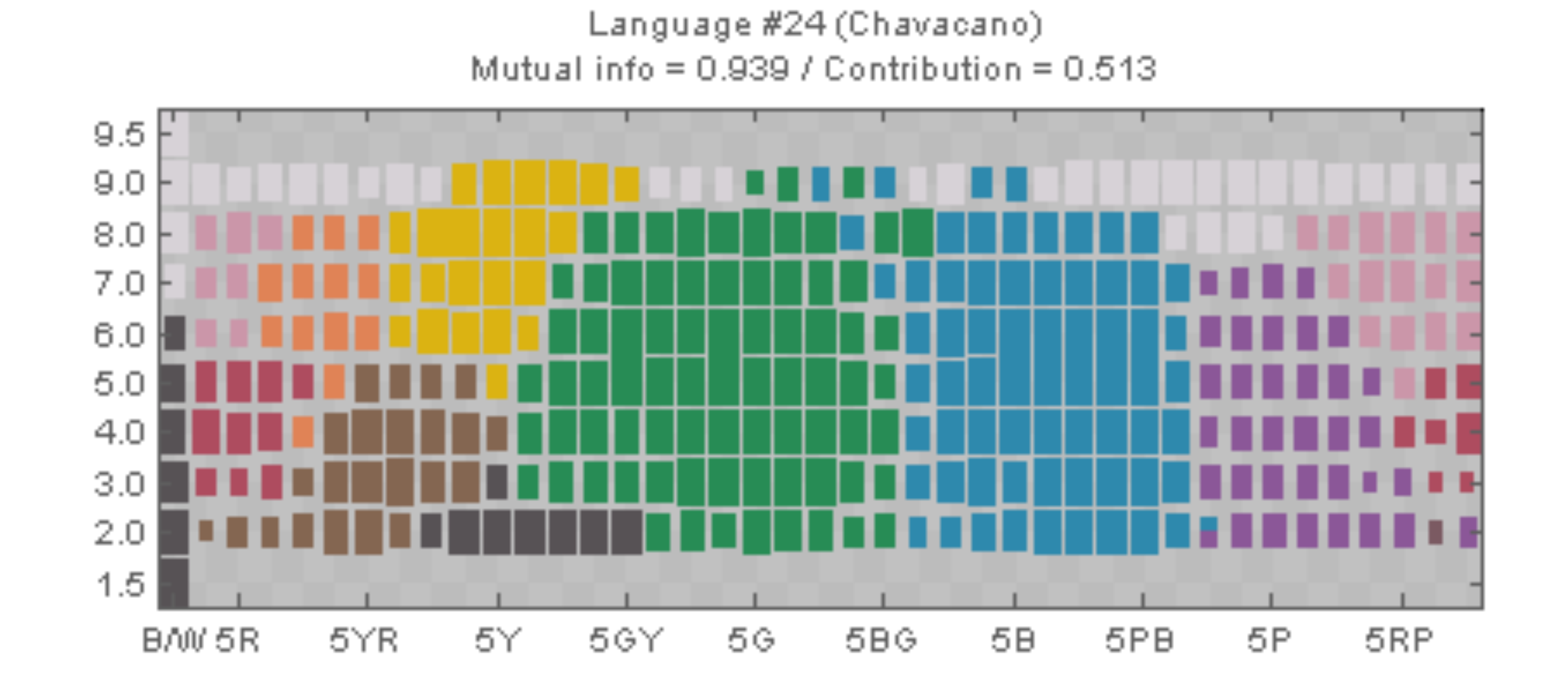
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?



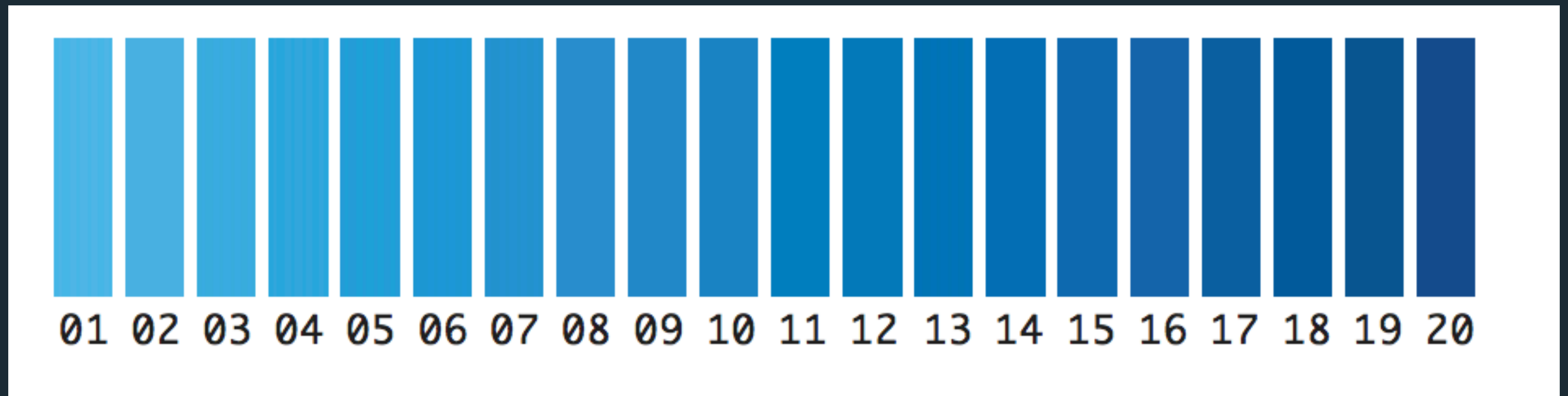






Color Naming

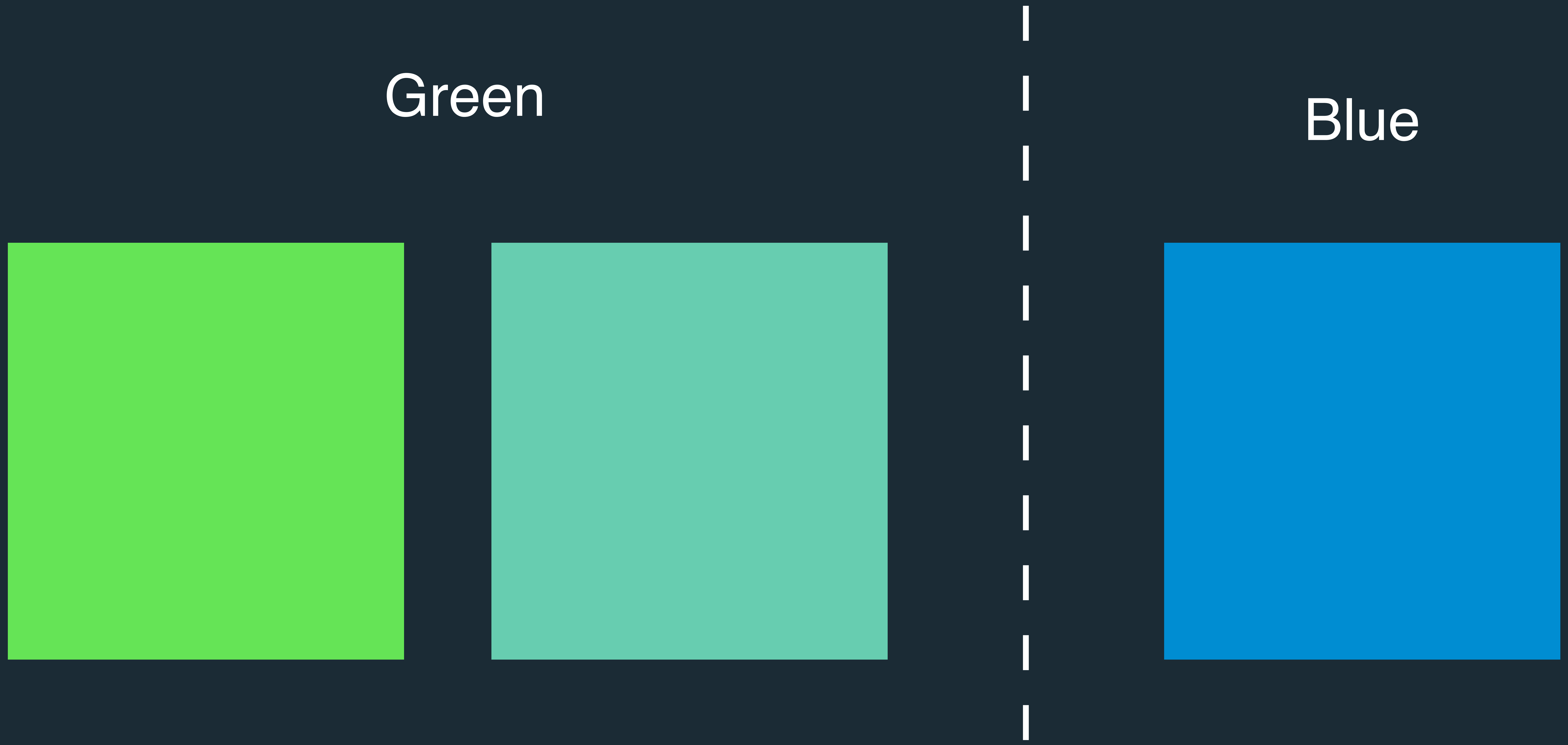
Is color naming universal? Do languages evolve color terms in similar ways?



Winawer et al, 2007.

- Russian makes obligatory distinction between lighter blues (“goluboy”) and darker blues (“siniy”).
- Russian speakers **were faster** at discriminating 2 colors if they fell into different categories (1 siniy, 1 goluboy) than if they were both from the same category (both siniy, or both goluboy).

Color Naming Effects Perception



Color Naming Effects Perception

Minimize overlap and ambiguity of colors.

Select semantically resonant colors.

[Lin et al., EuroVis

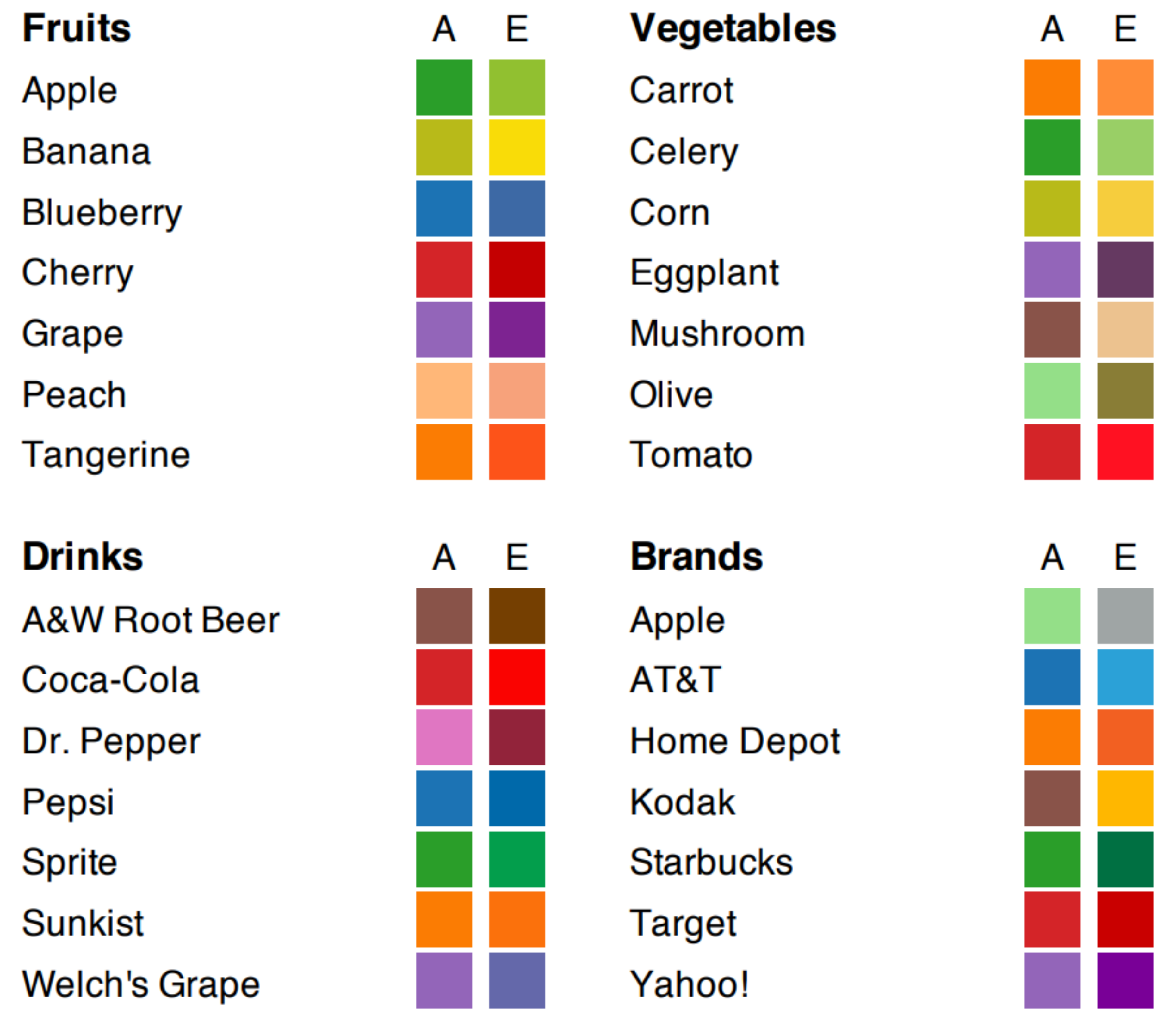
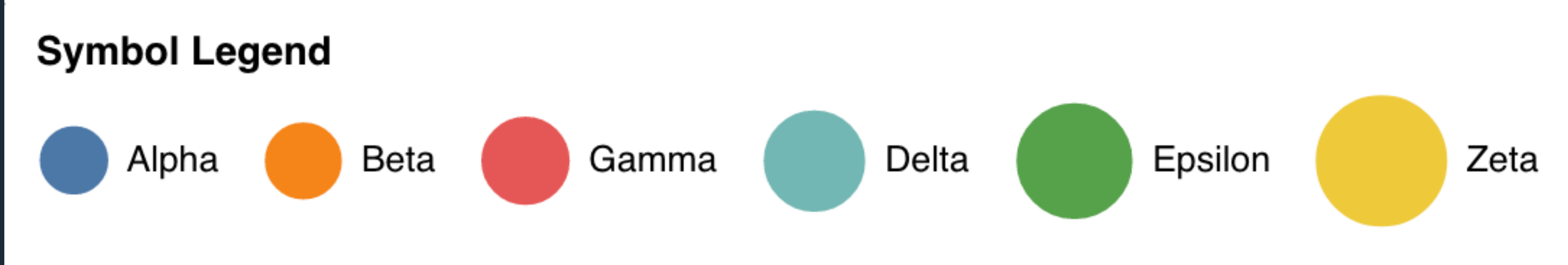


Figure 6: *Color assignments for categorical values in Experiment 1. (A = Algorithm, E = Expert)*

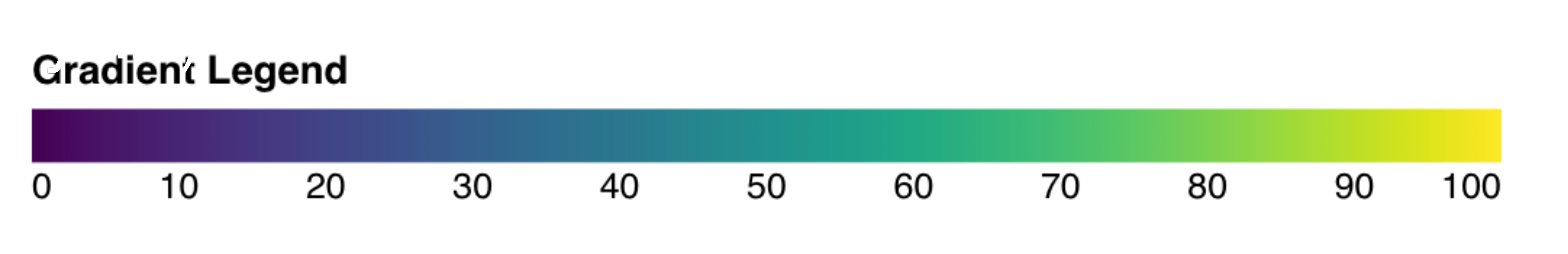
https://github.com/StanfordHCI/semantic-colors

Putting it together: Designing colormaps

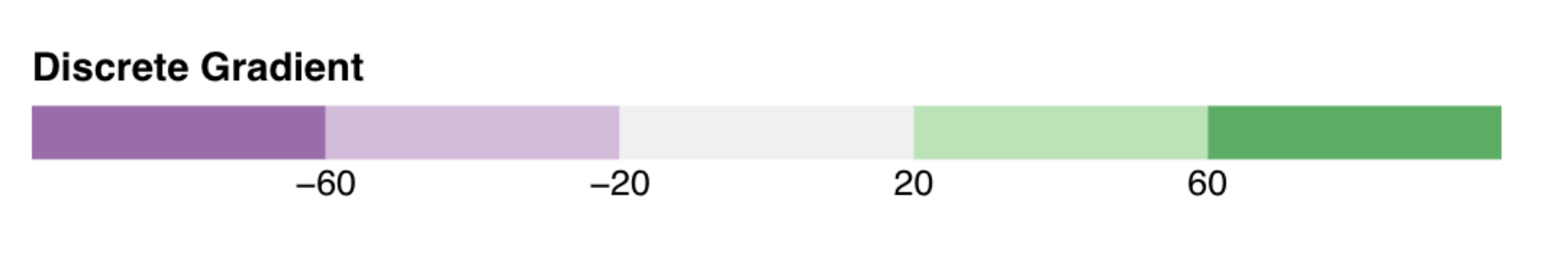
Discrete (binary, categorical)



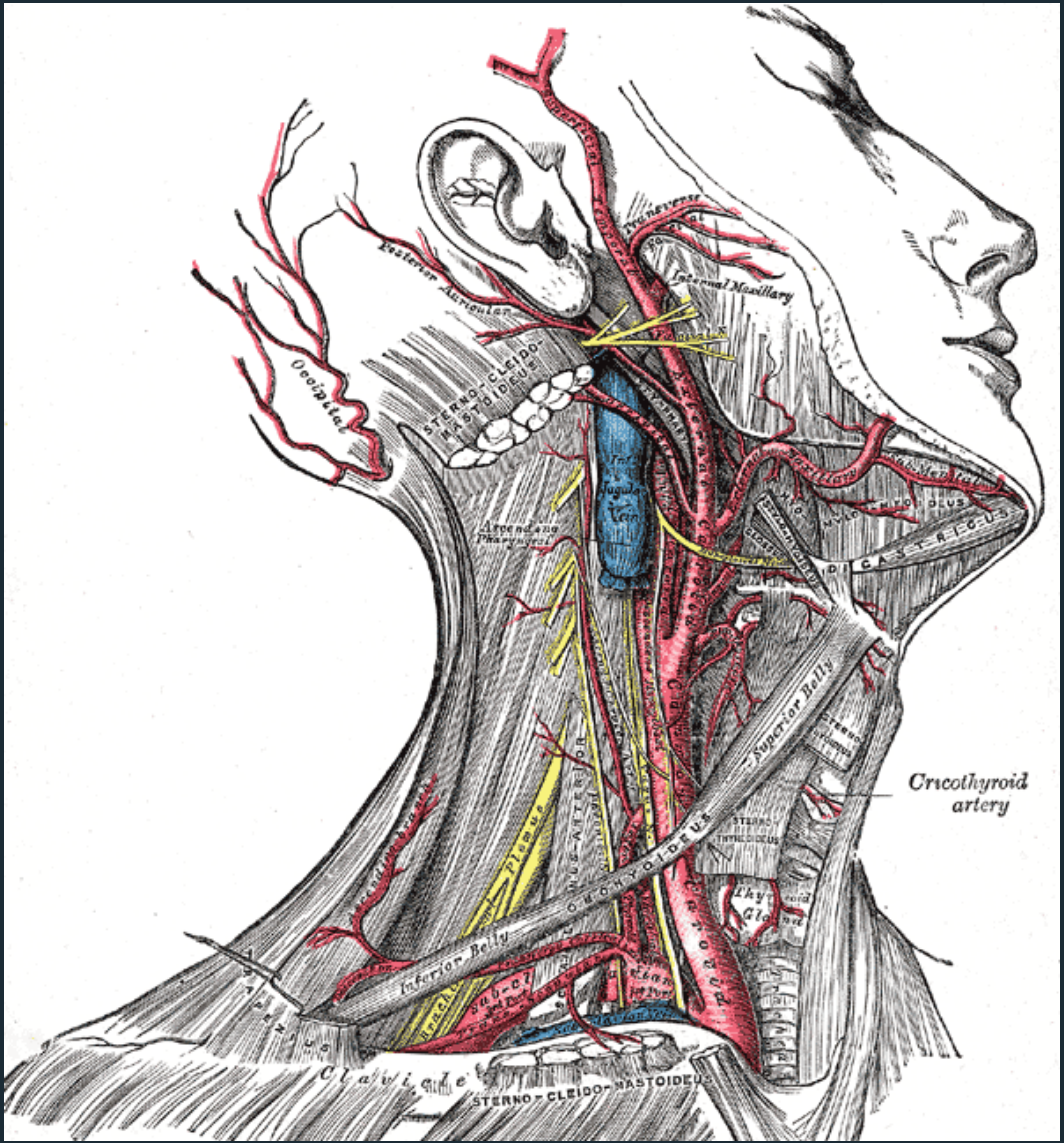
Continuous (sequential, diverging,



Discretized Continuous



Categorical Color


Occipital
Posterior Auricular
Internal Maxillary
STERNO-CLEIDO-MASTOIDEUS
Int. Jugular Vein
Superior Belly
Inferior Belly
Clavicle
STERNO-CLEIDO-MASTOIDEUS
Cricothyroid
artery

Color Naming Effects 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%

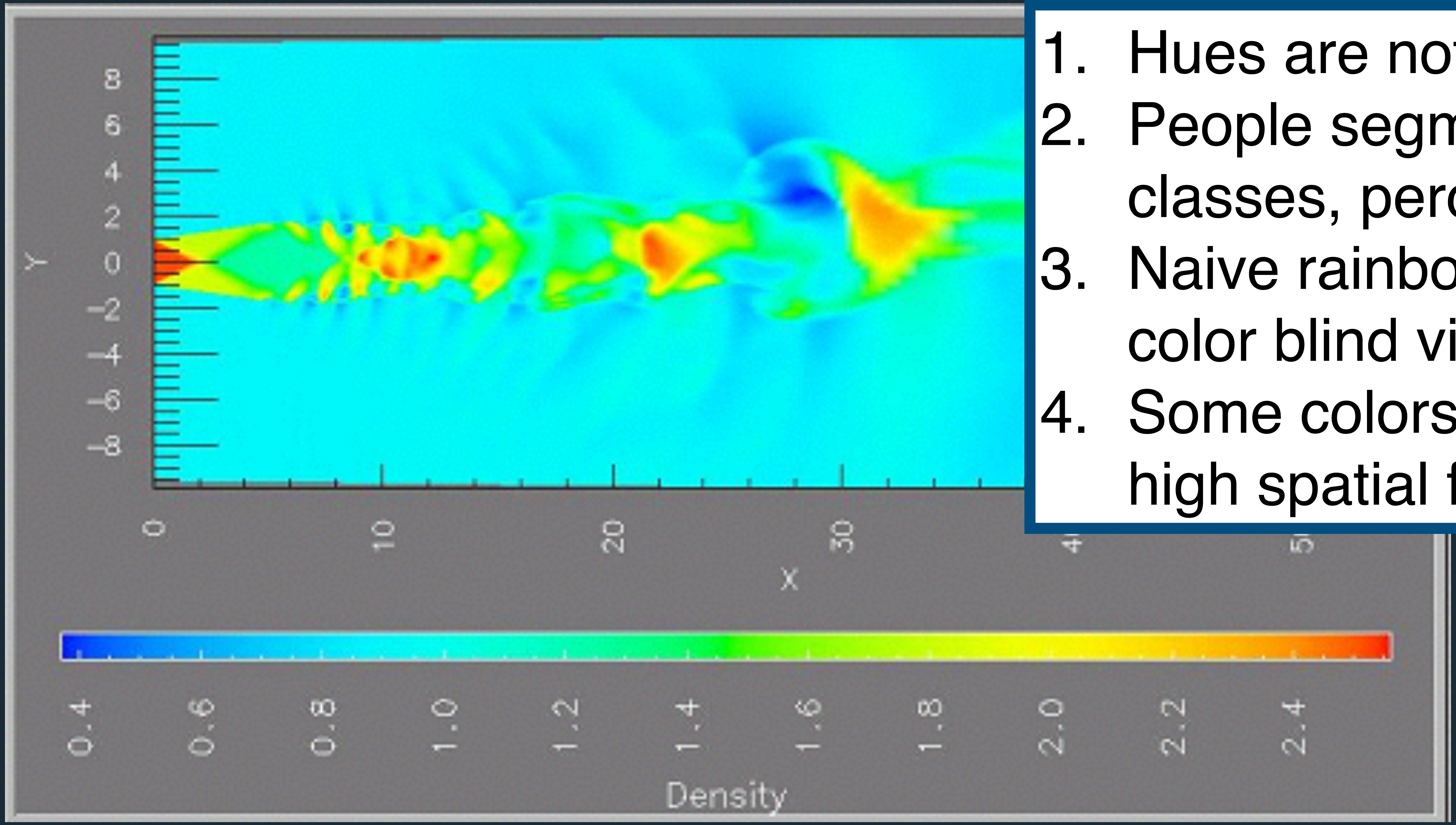
Tableau-10 *Average 0.96* .52

[Heer and Stone, CHI 20

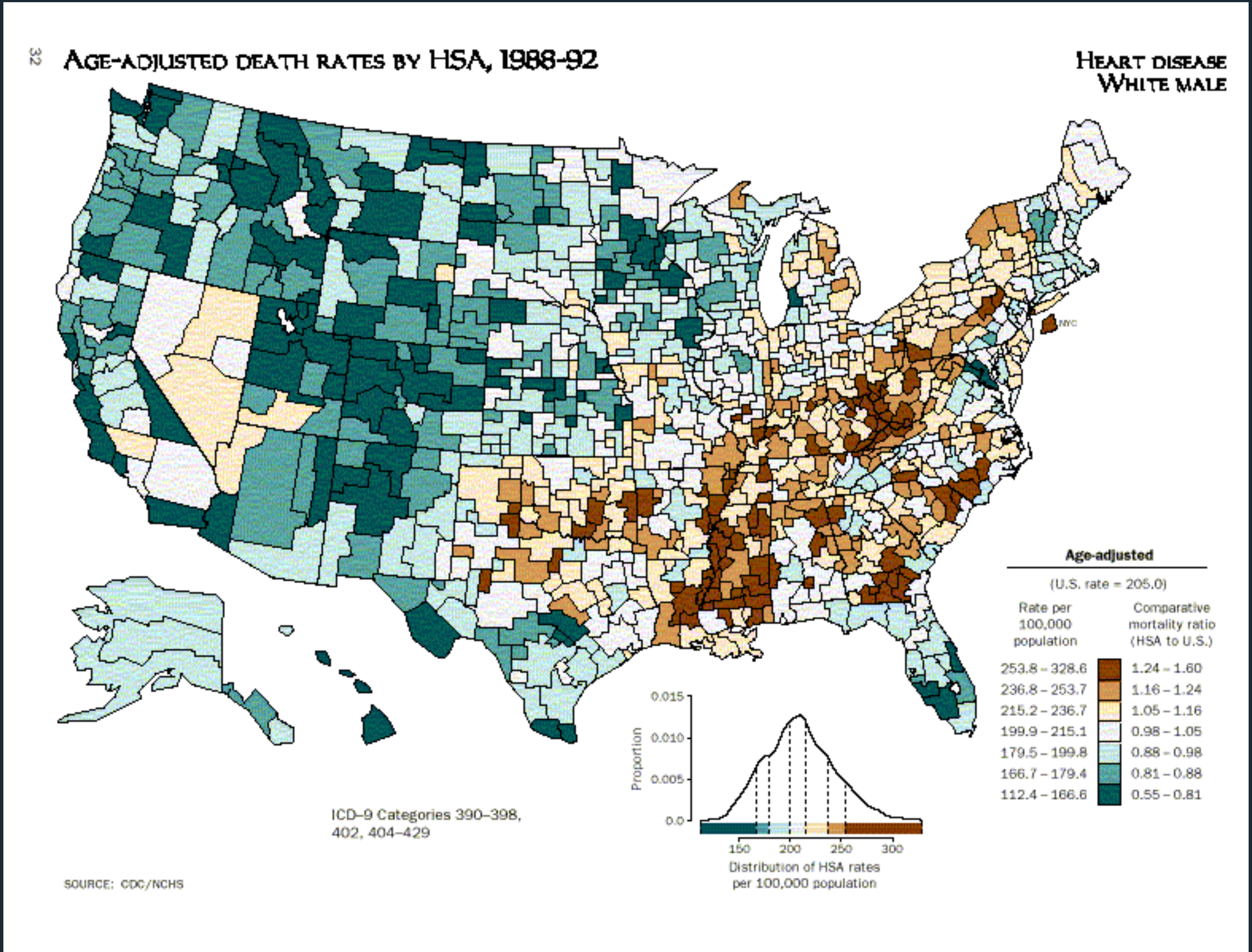
http://vis.stanford.edu/color-names/analyzer/

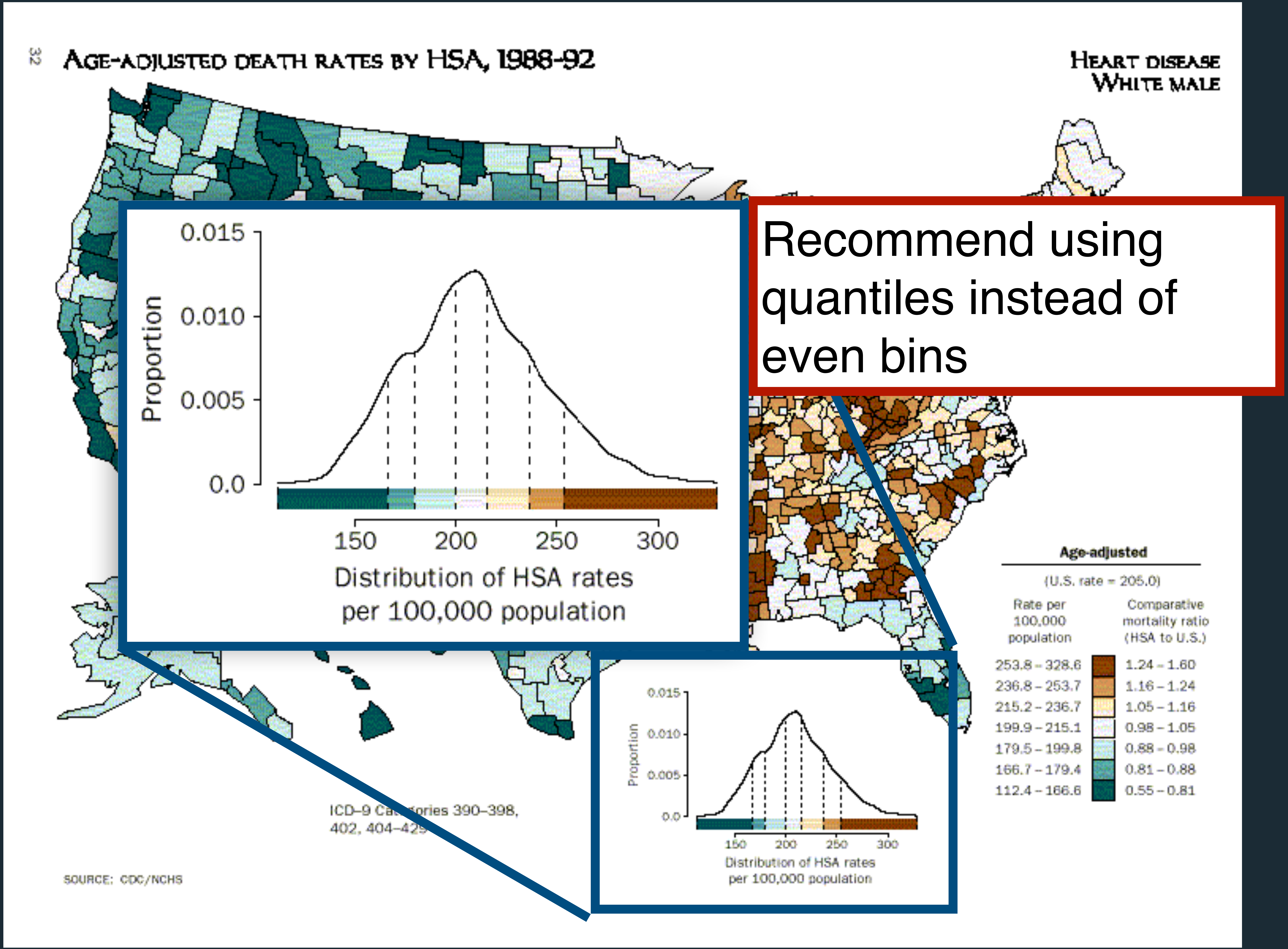
Quantitative Color

Be Wary 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


32
Age-adjusted death rates by HSA, 1988-92
Heart disease
White male
NYC
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
Proportion
0.015
0.010
0.005
0.0
150
200
250
300
Distribution of HSA rates per 100,000 population
ICD–9 Categories 390–398, 402, 404–429
SOURCE: CDC/NCHS

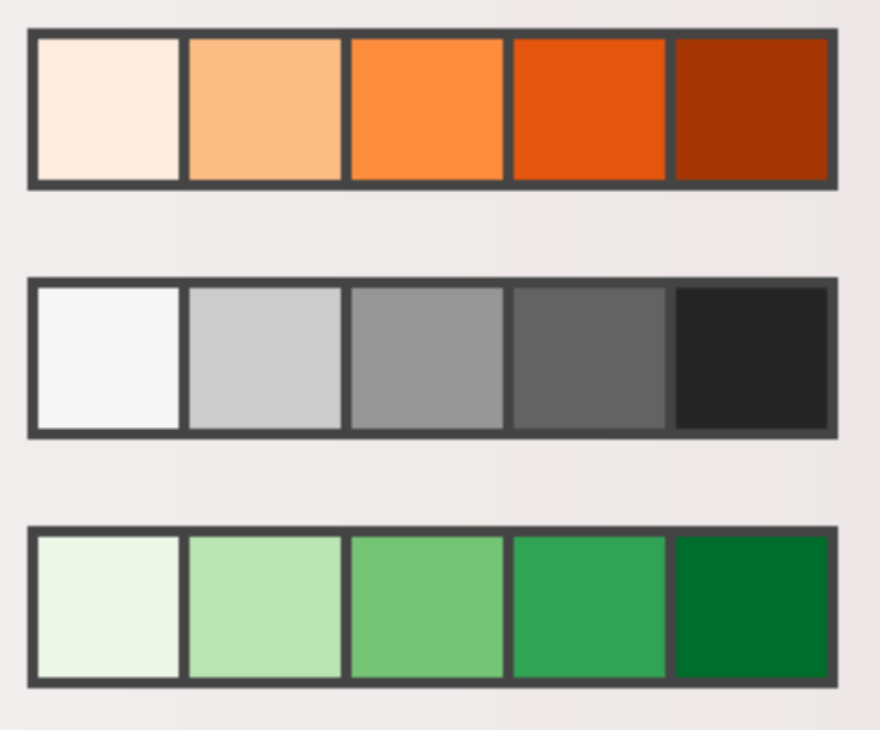


Recommend using quantiles instead of even bins

Quantitative Color Encoding

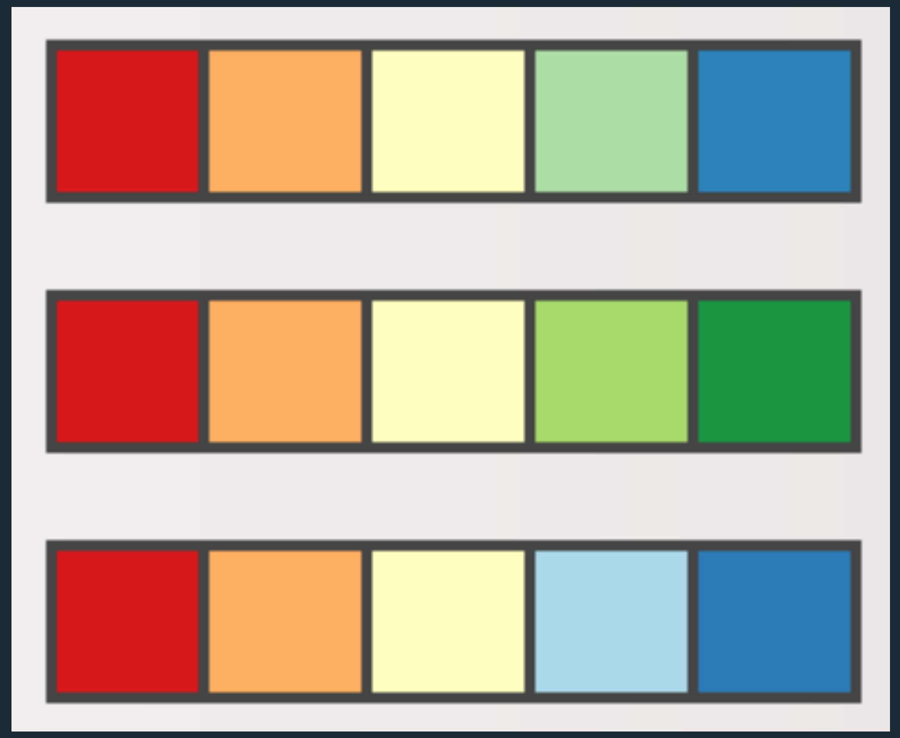
Sequential Color Scale

- 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 3–9

Summary

Use **only a few** colors (~6 ideally).

Colors should be **distinctive** and **named**.

Strive for color **harmony** (natural colors?).

Use/respect **cultural conventions**; appreciate symbolism.

Get it right in **black and white**.

Respect the **color blind**.

Take advantage of **perceptual color spaces**.