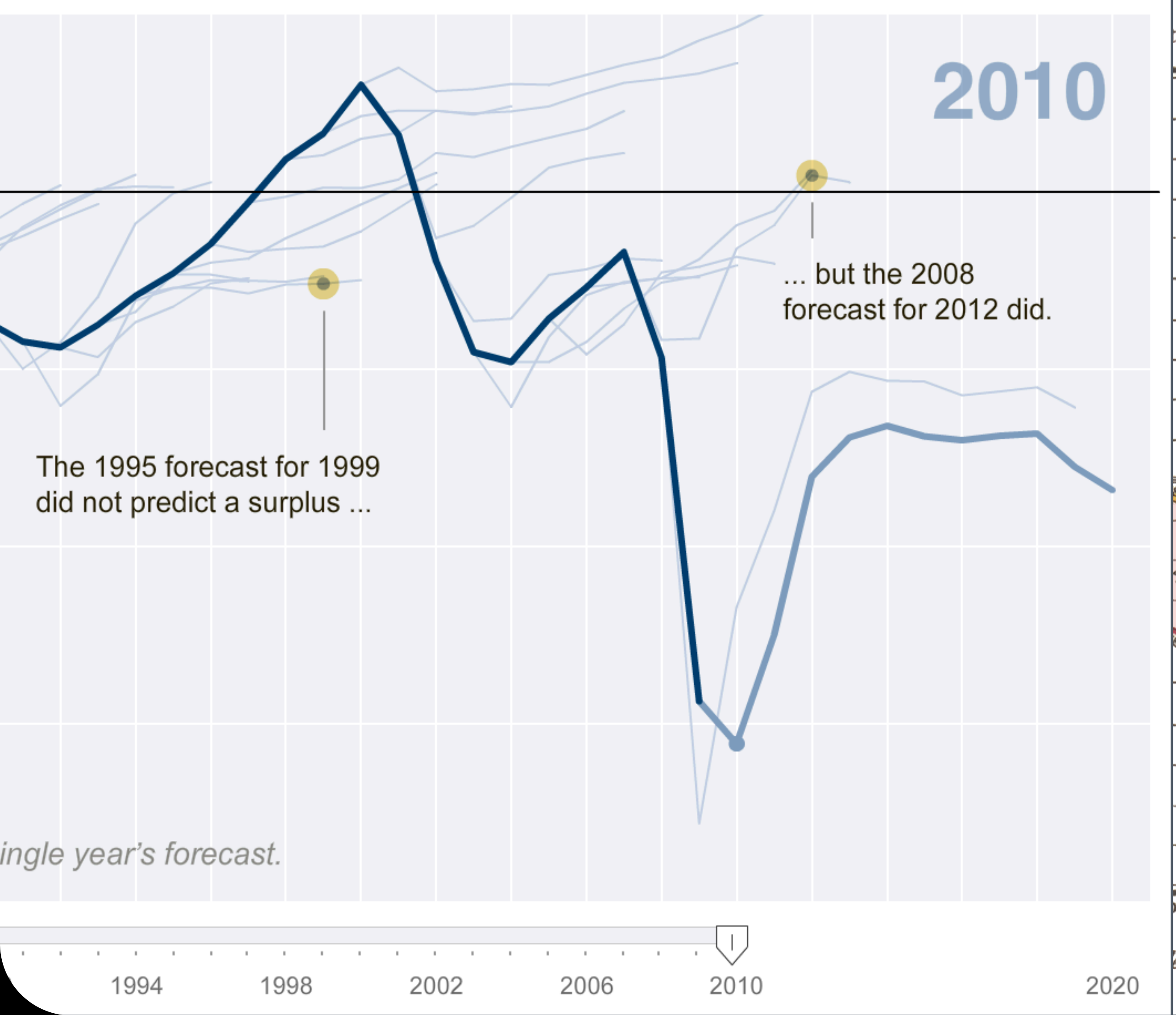
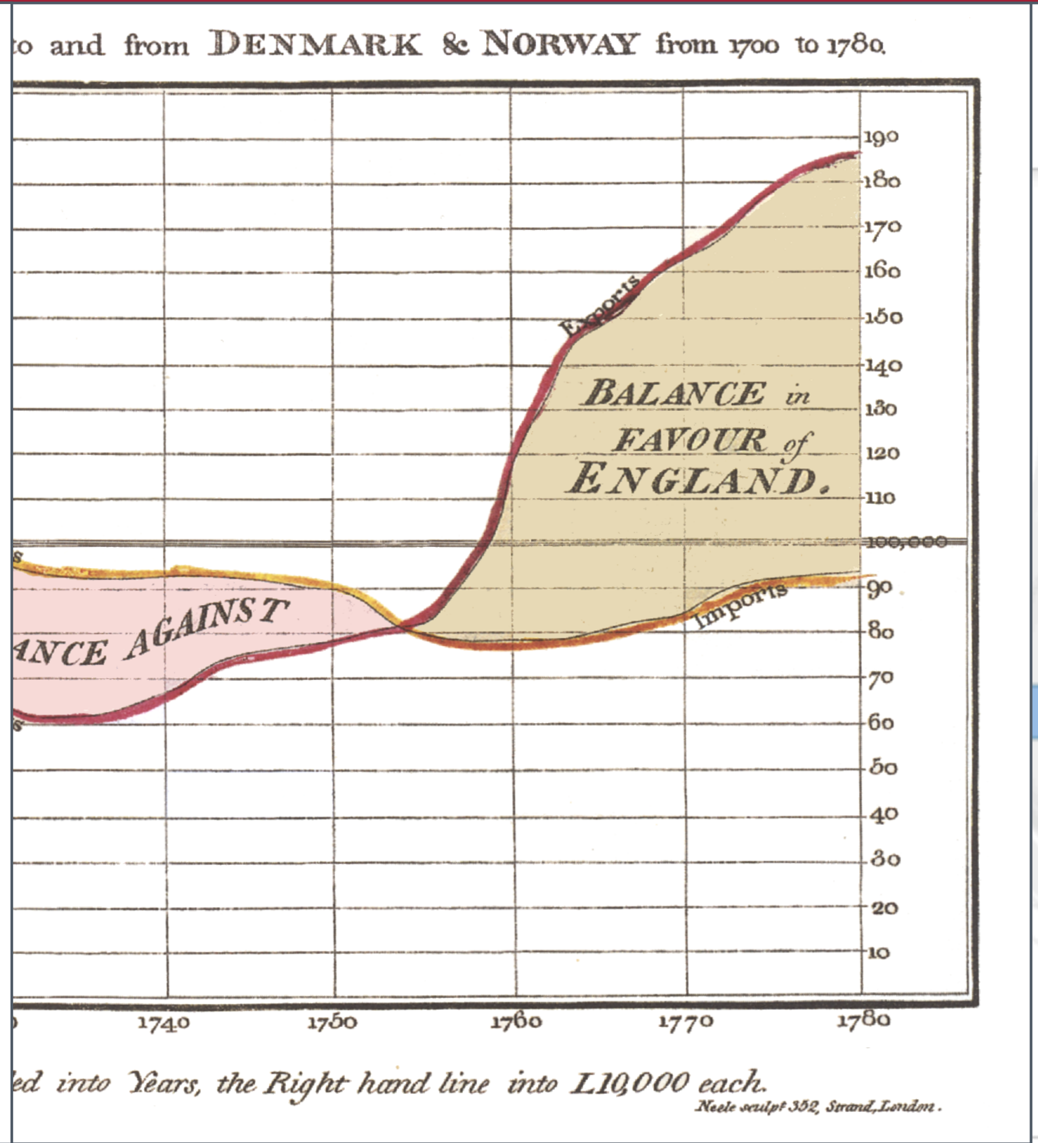
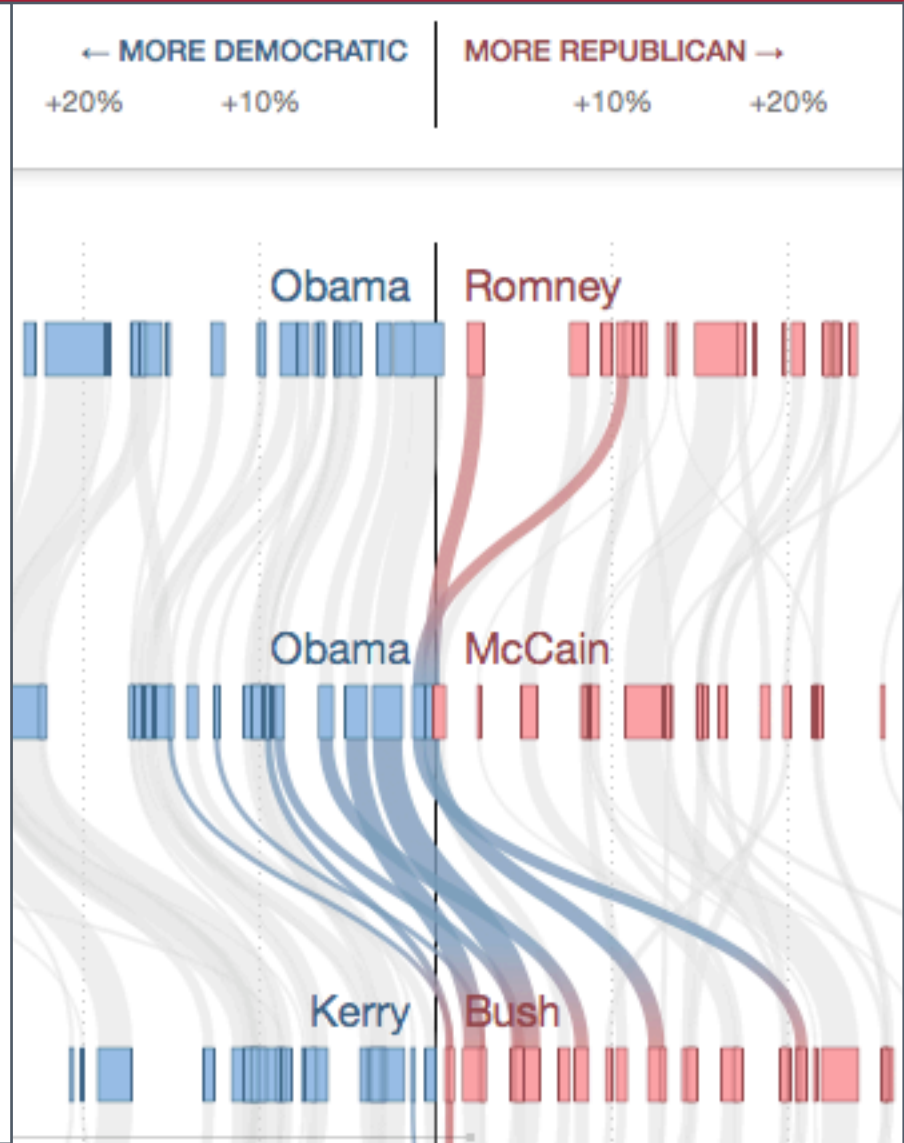
# 6.894: Interactive Data Visualization

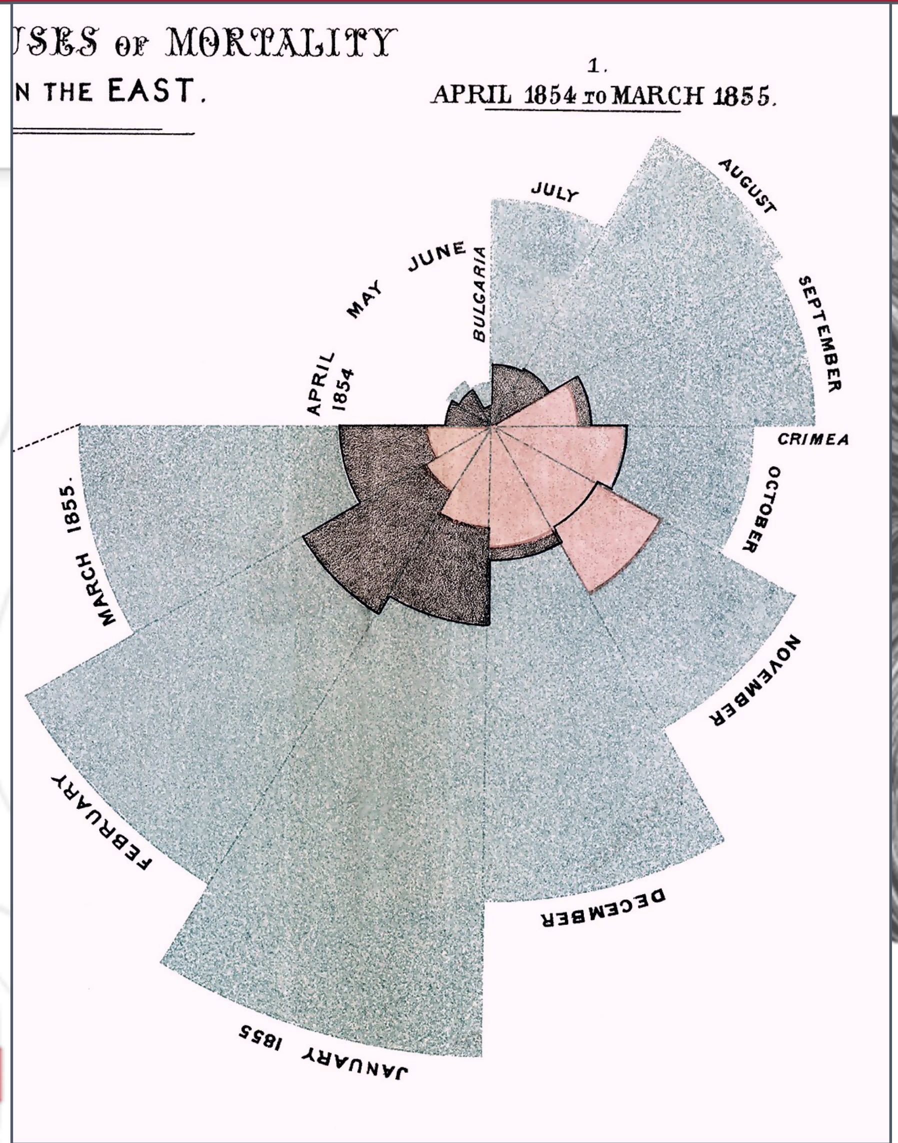
# **Color**

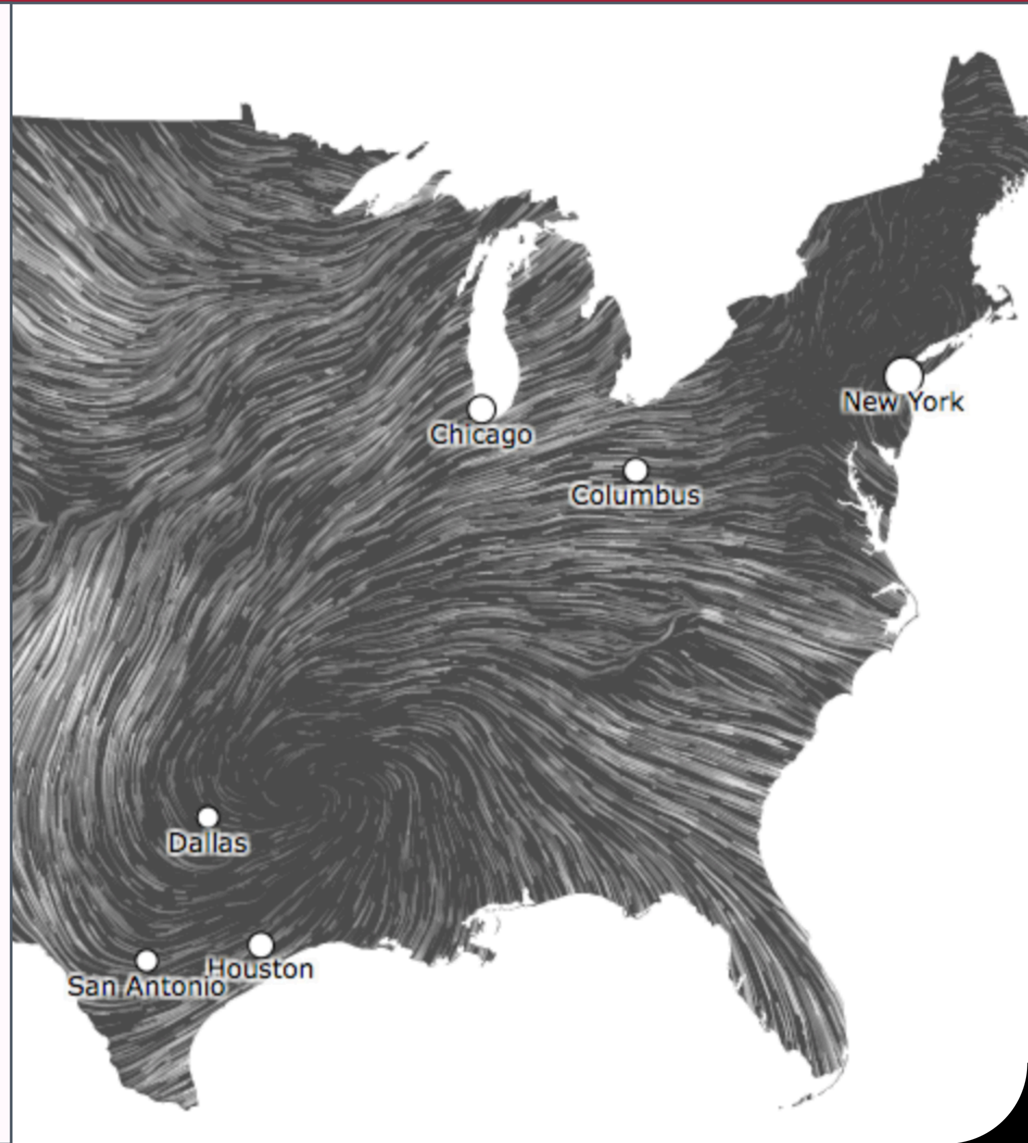
Arvind Satyanarayan



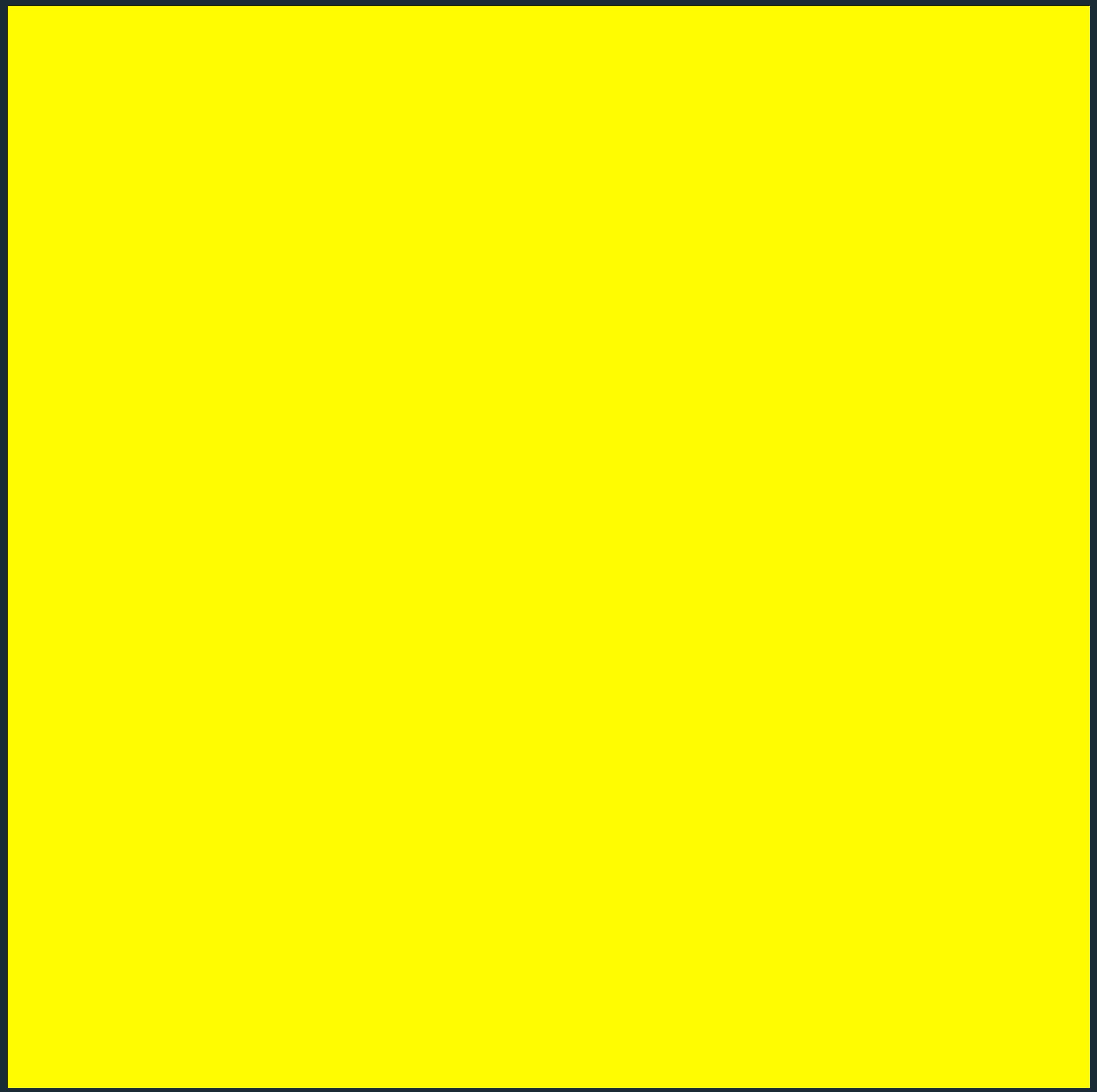



# What color is this?



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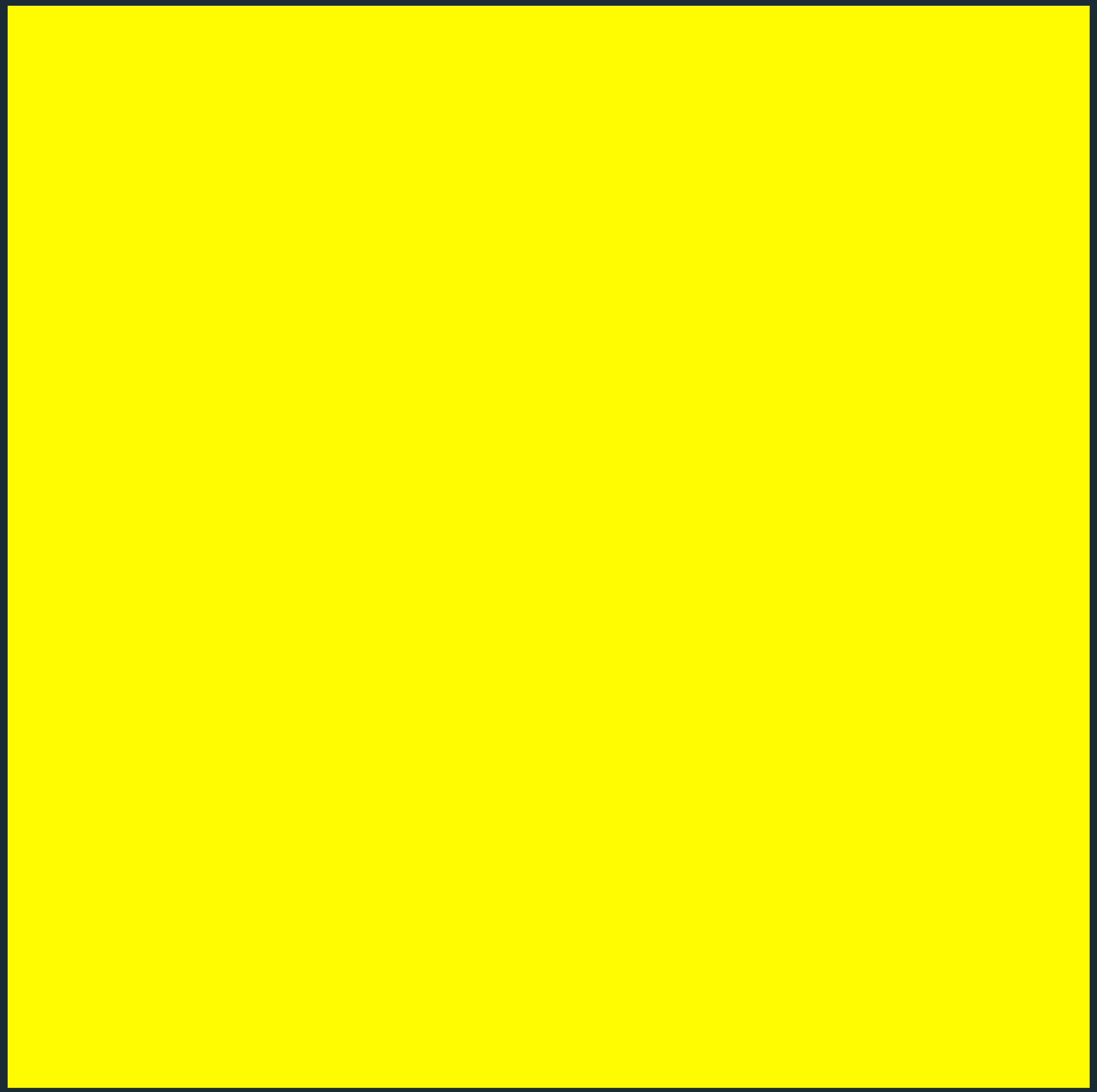
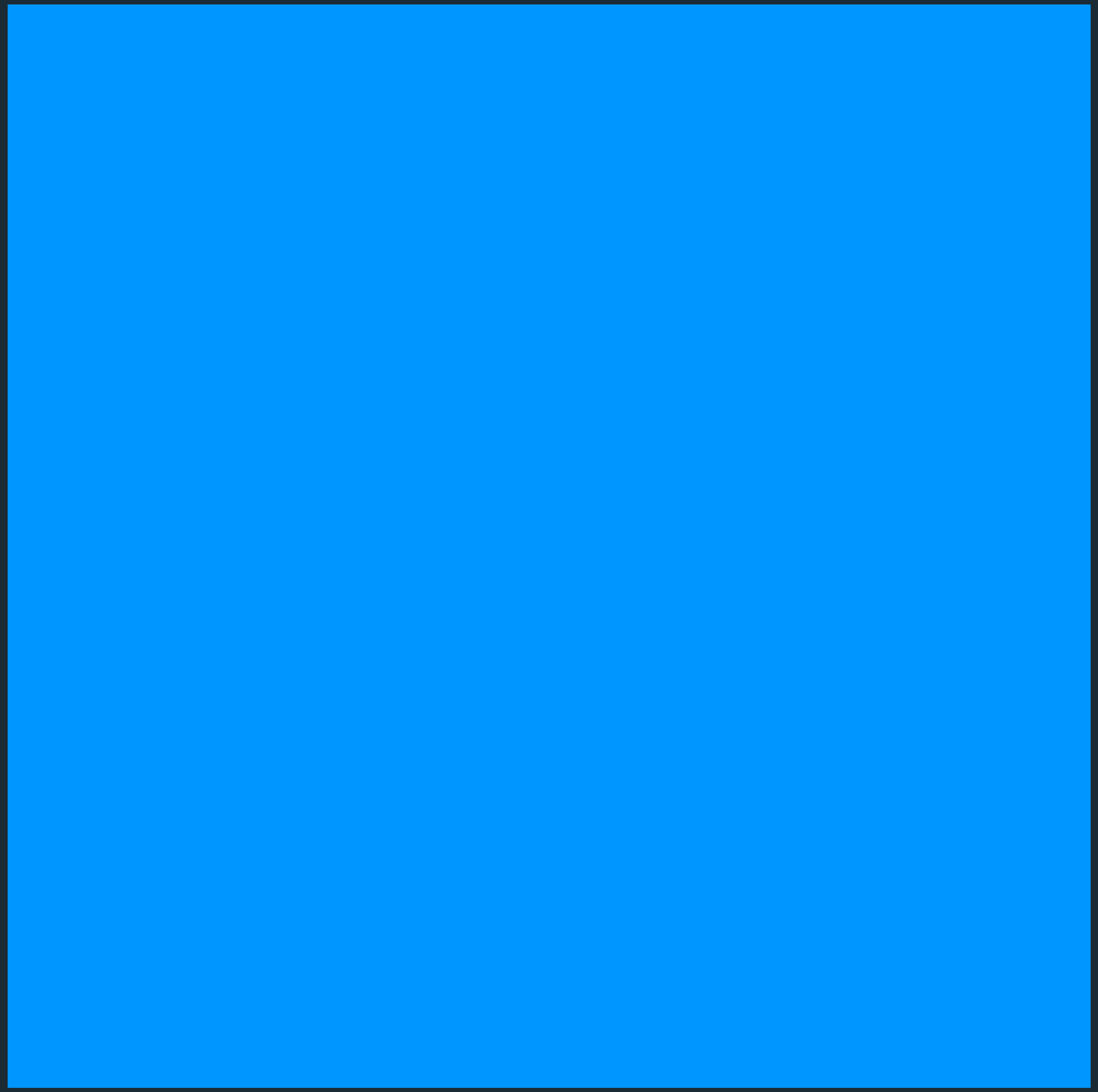


“Yellow”

# What color is this?



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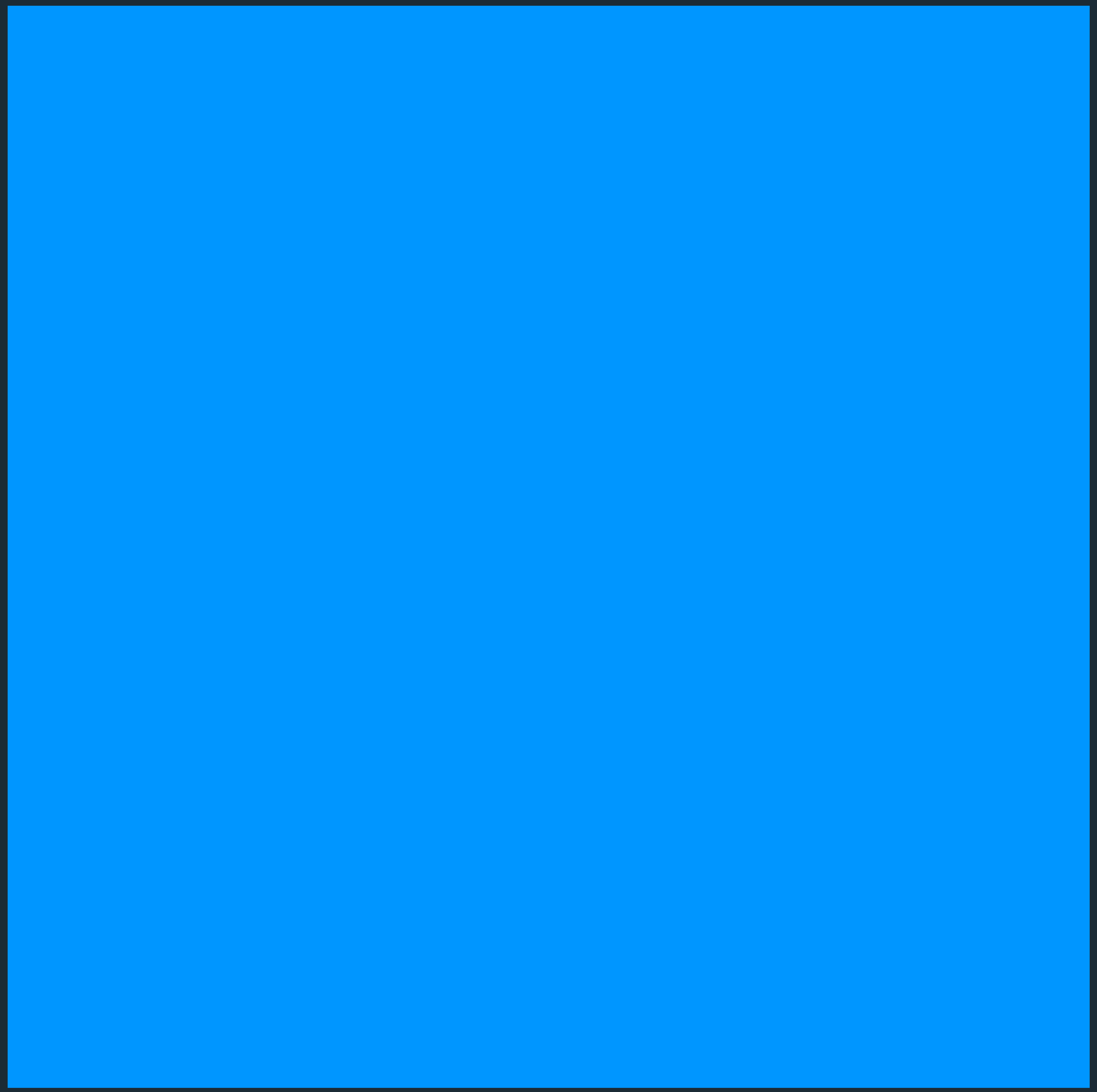
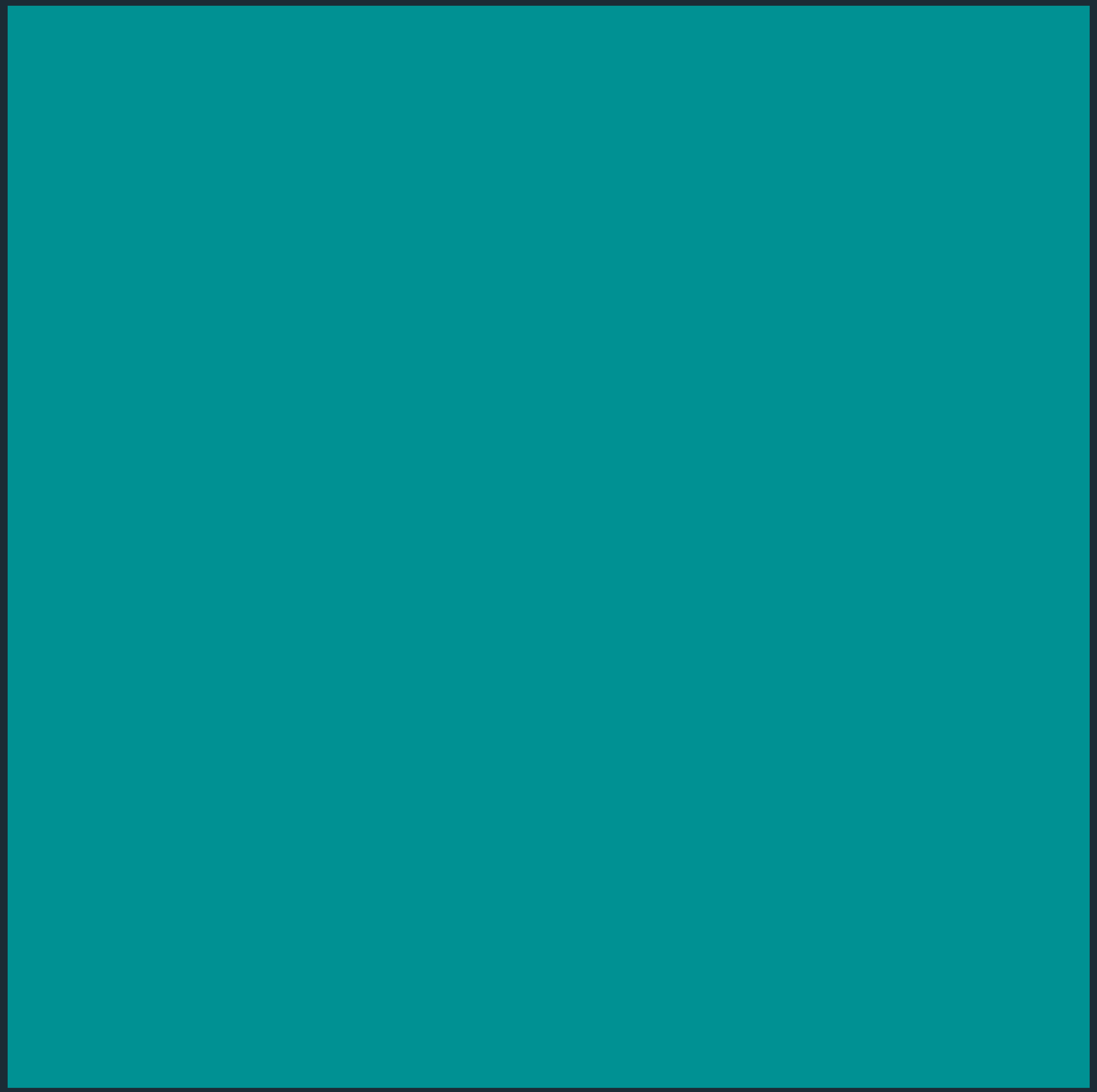


“Blue”

# What color is this?



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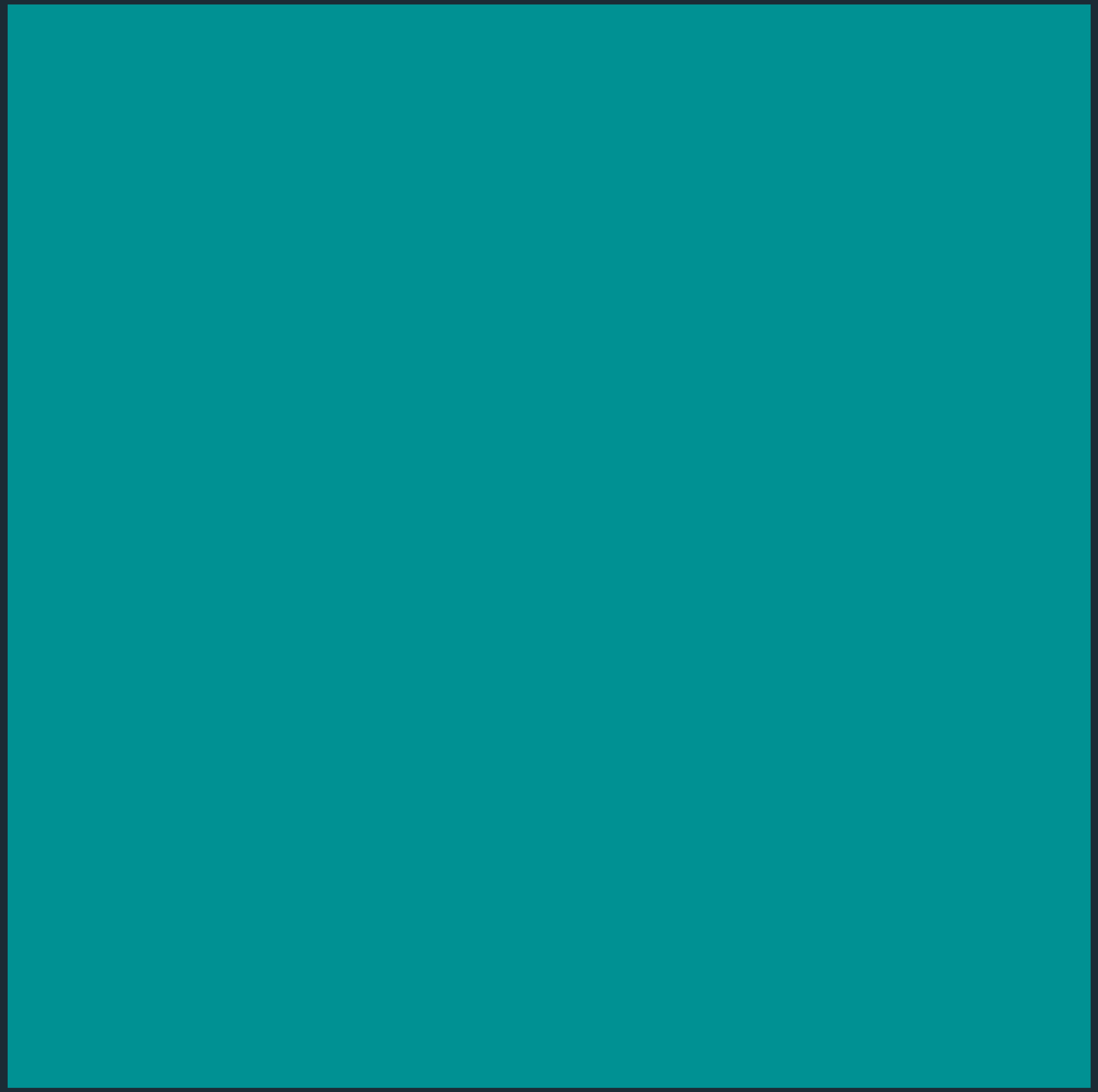


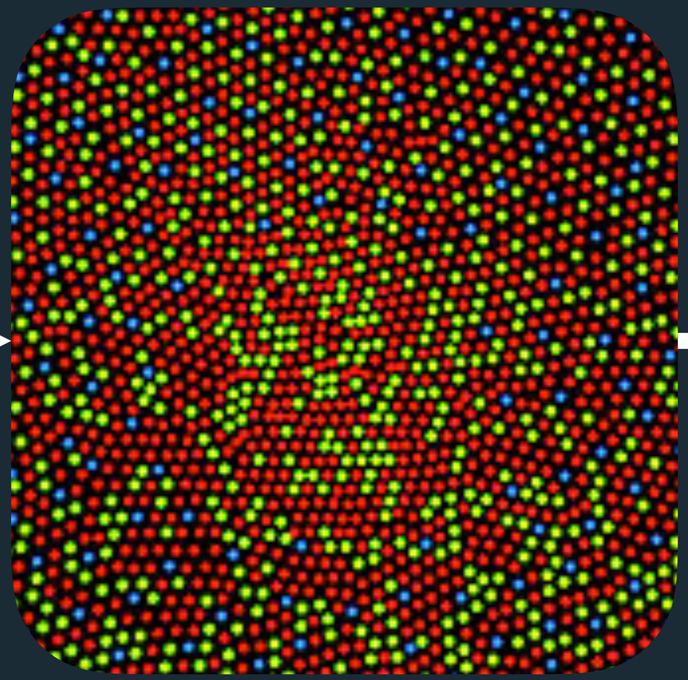
“Teal”? “Aqua”?

# Modeling Color Perception

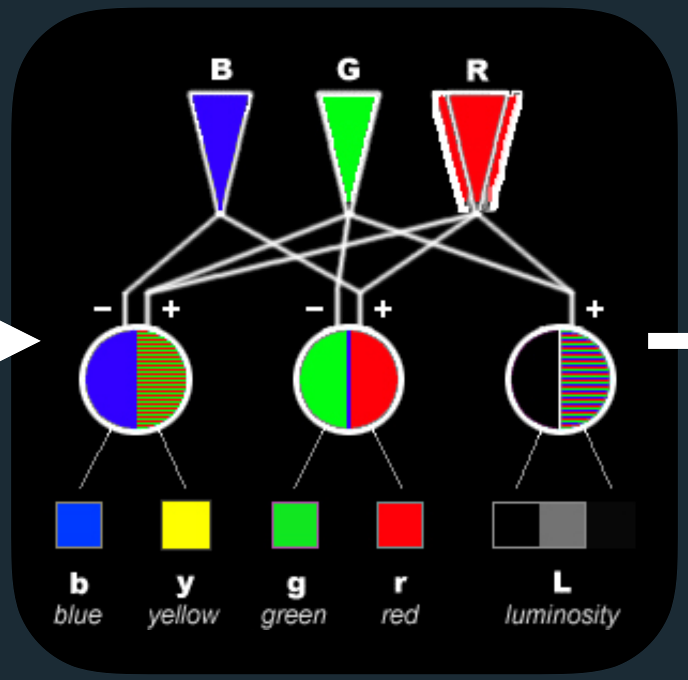
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response




Opponent Encoding

Perceptual Models


Appearance Models

**"Teal"**

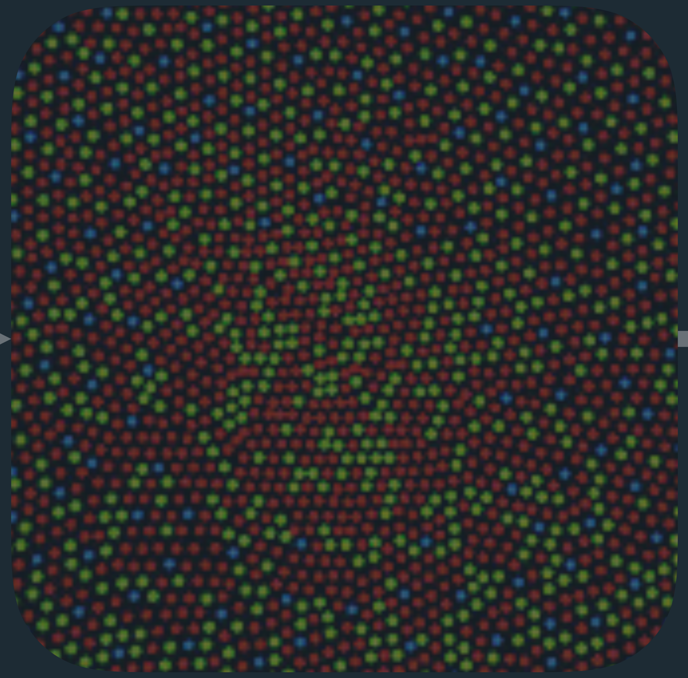
Cognitive Models

# Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light



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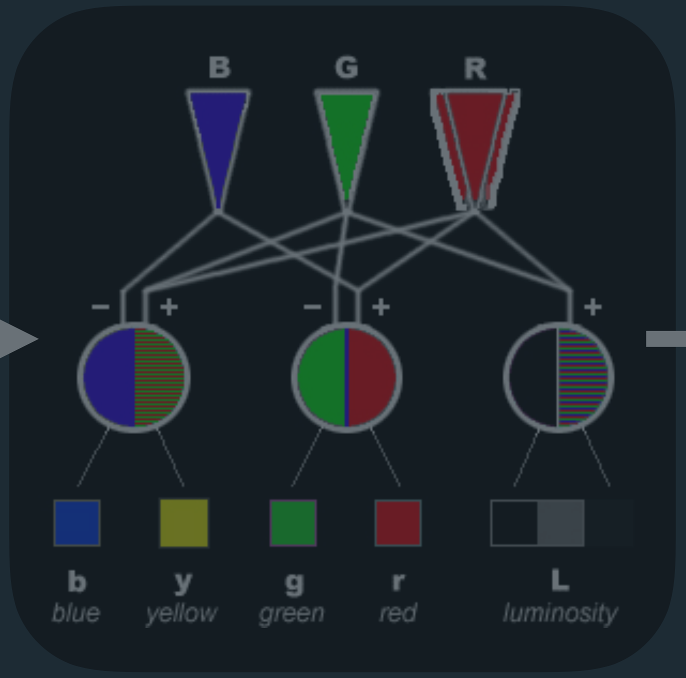
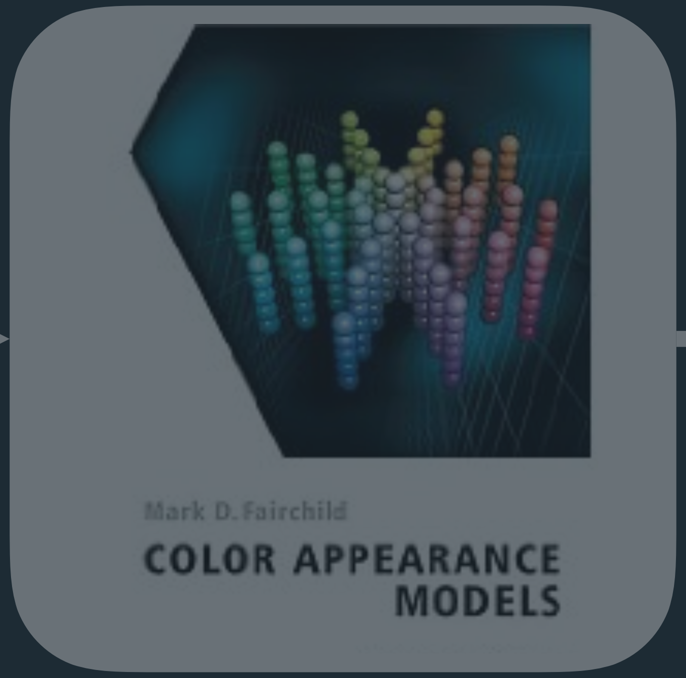



Opponent Encoding

Perceptual Models




Appearance Models

“Teal”

Cognitive Models

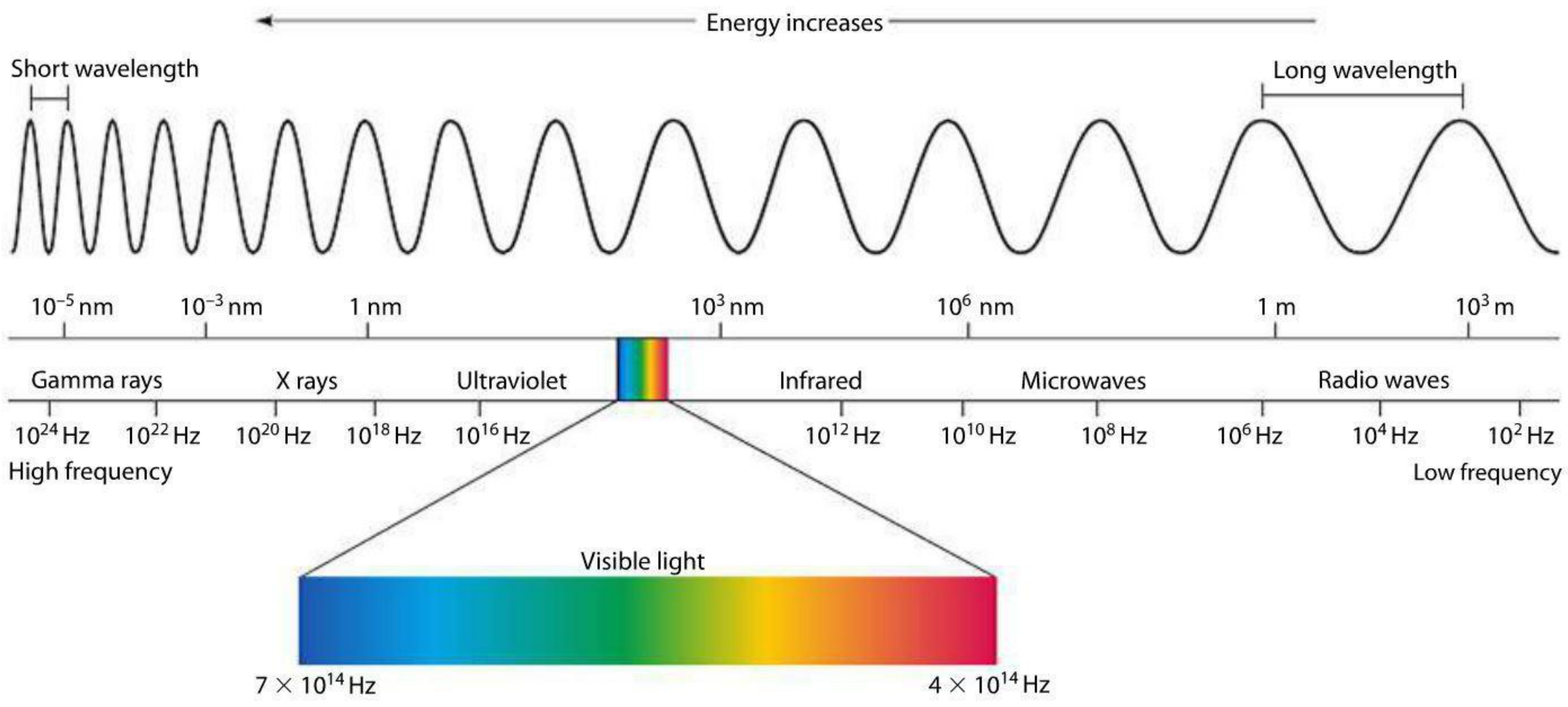
# Visible Light

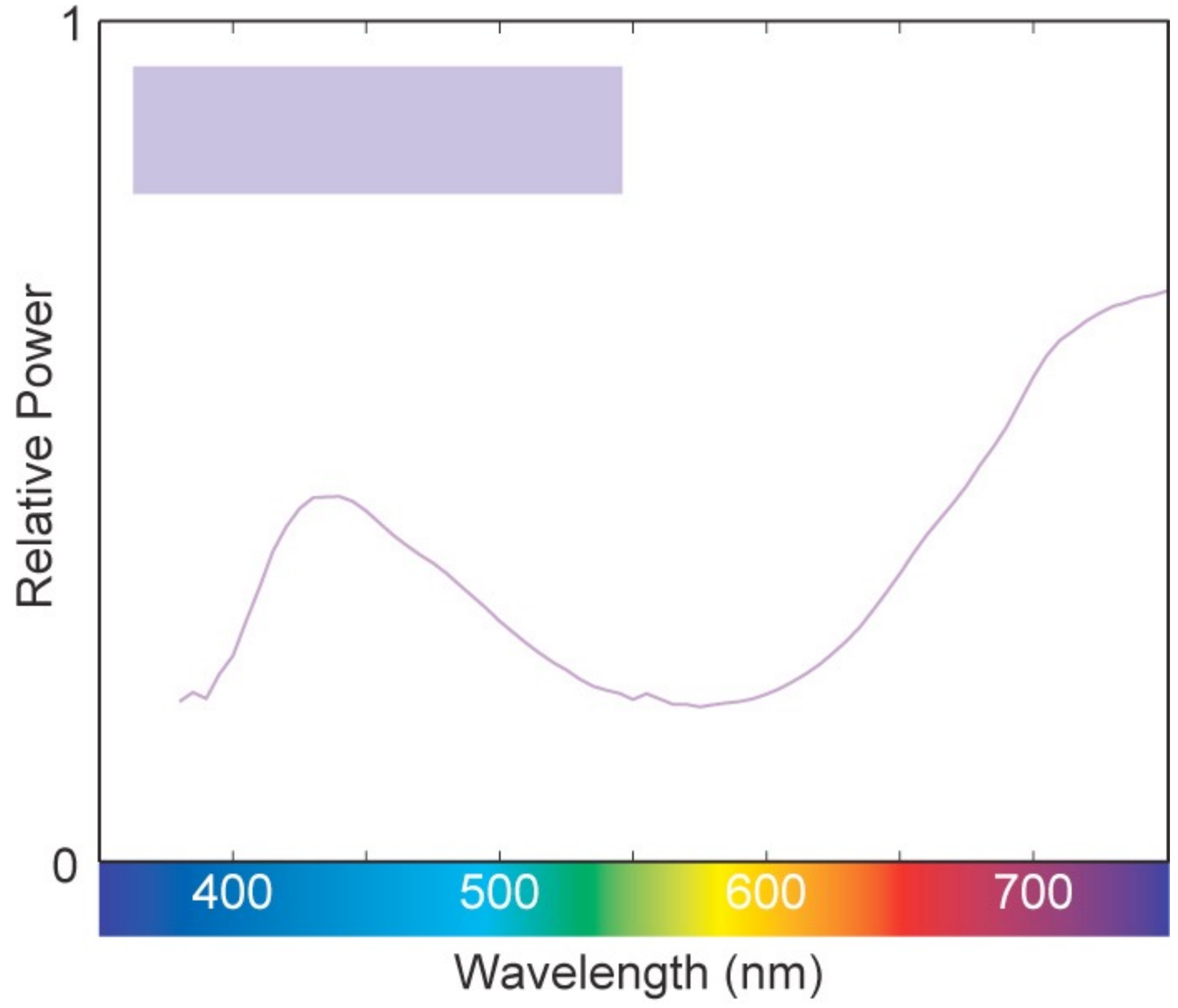
Light is an electromagnetic wave.

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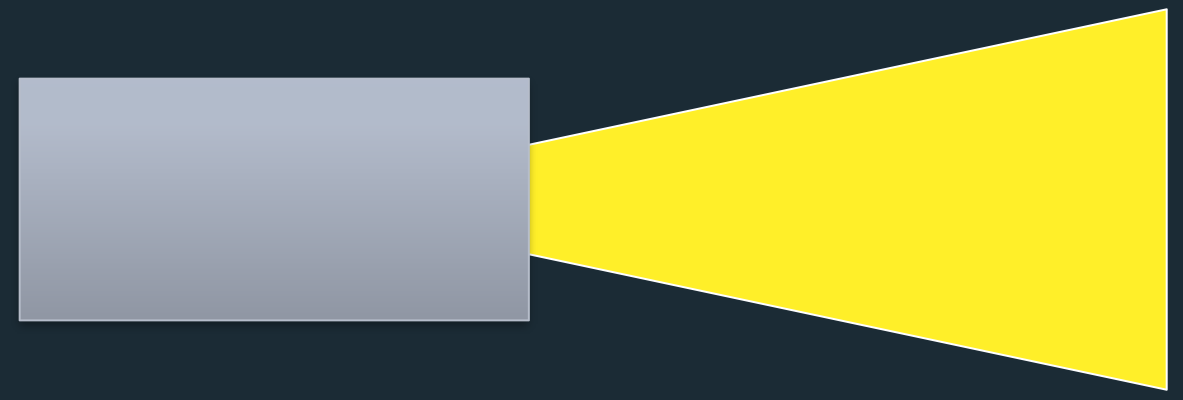
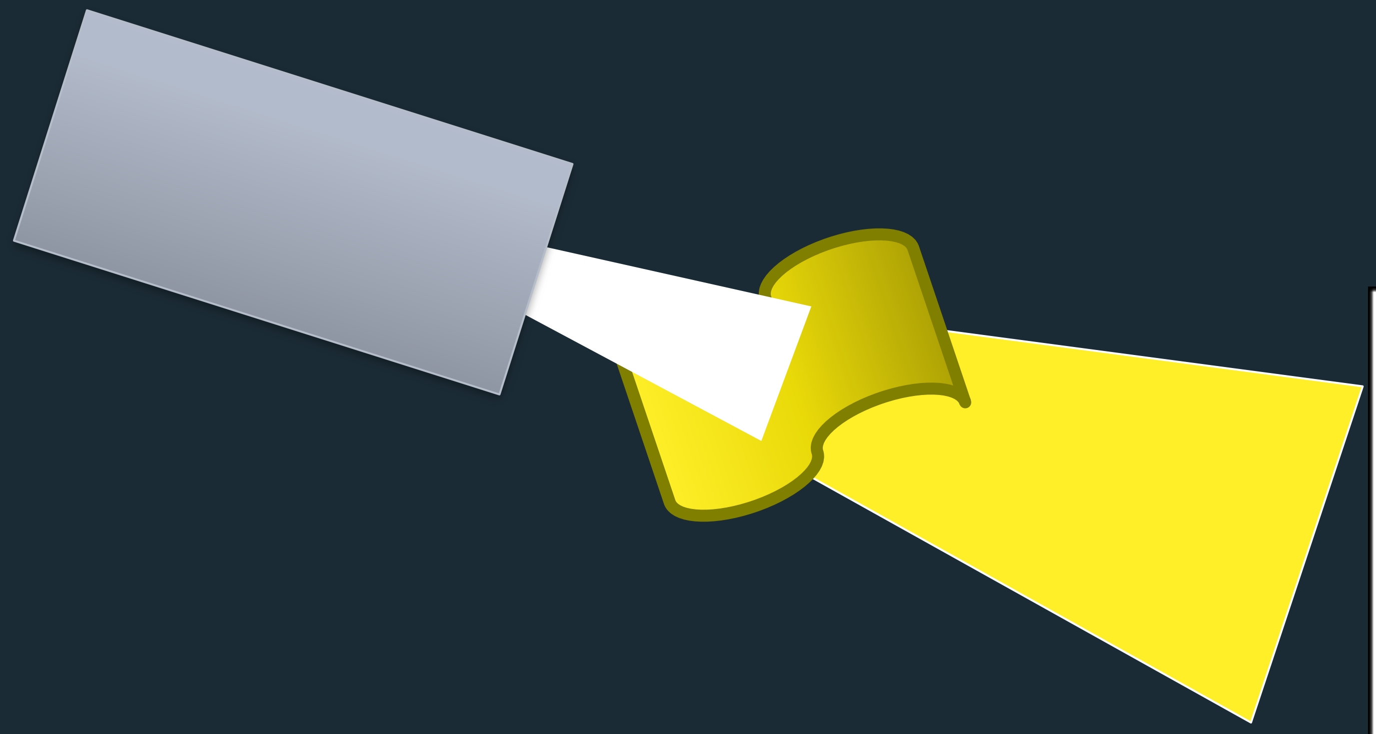
***Additive***: Perceived color is due to a combination of source lights (e.g., RGB).

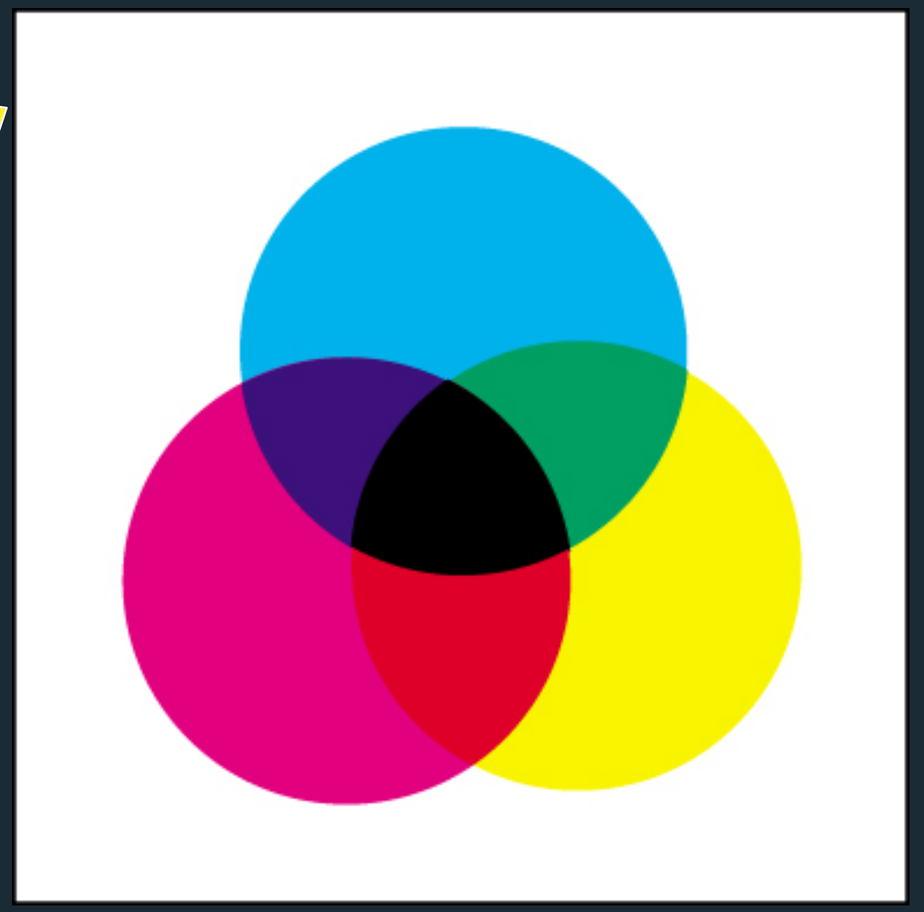
***Subtractive***: Start from a white spotlight, and materials absorb specific λs (e.g., RYB or CMYK).



**Additive**
(digital displays)



**Subtractive**
(print, e-paper)



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Low-Level — Abstraction — High-Level

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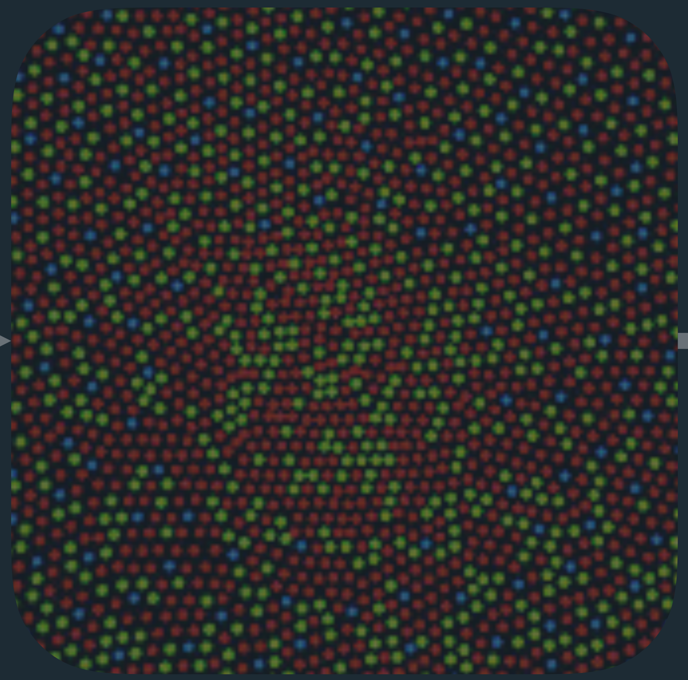

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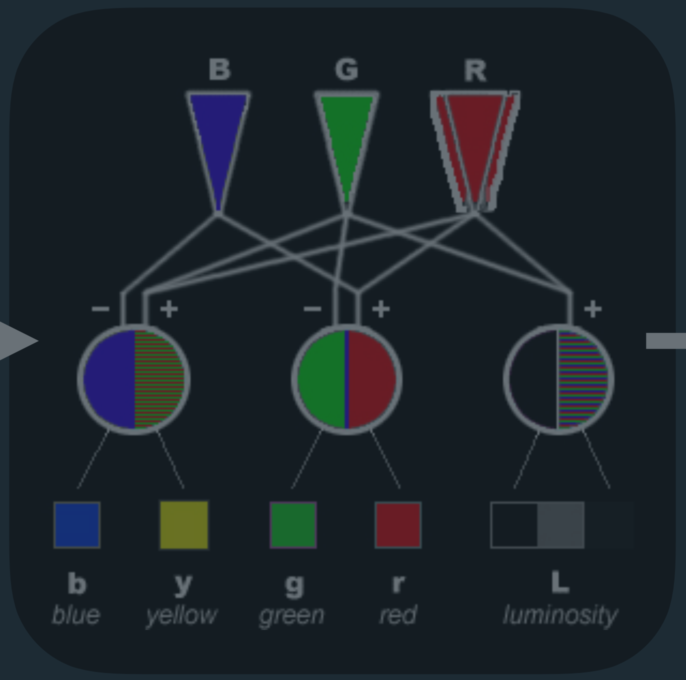
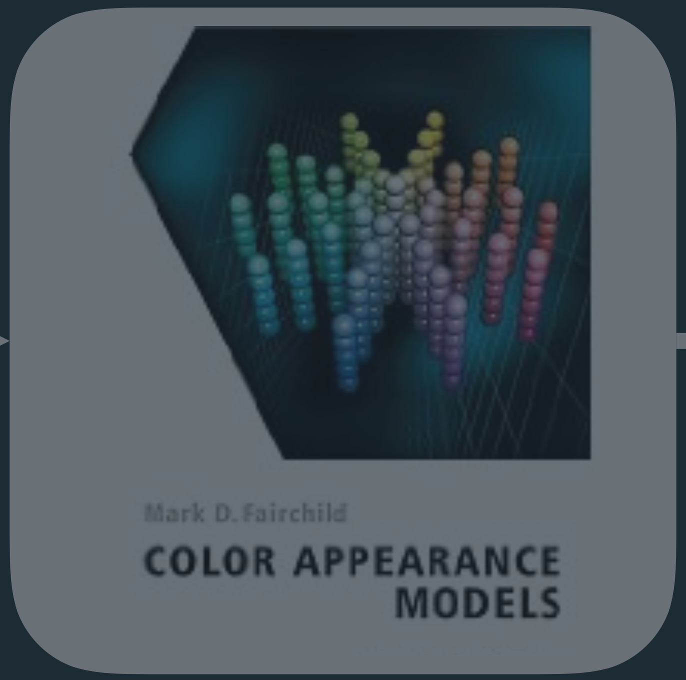



Opponent Encoding

Perceptual Models




Appearance Models

"Teal"

Cognitive Models

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Low-Level | Abstraction | High-Level

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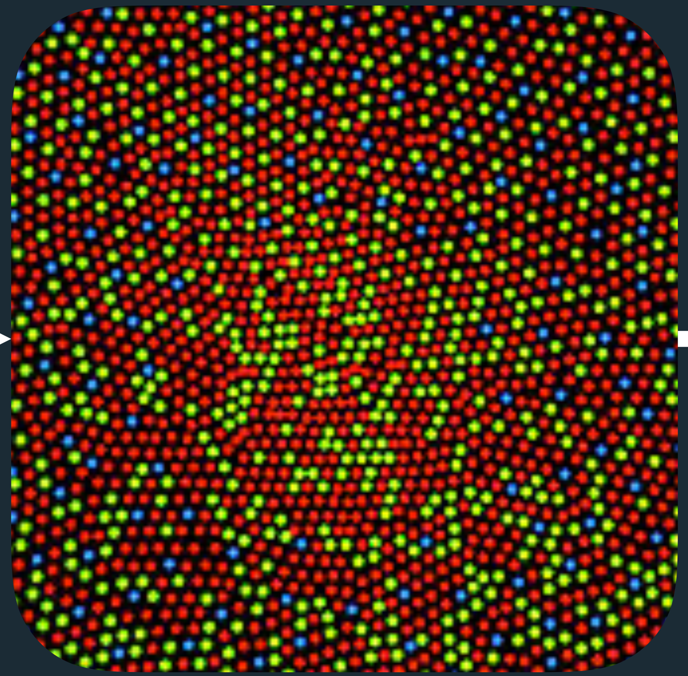

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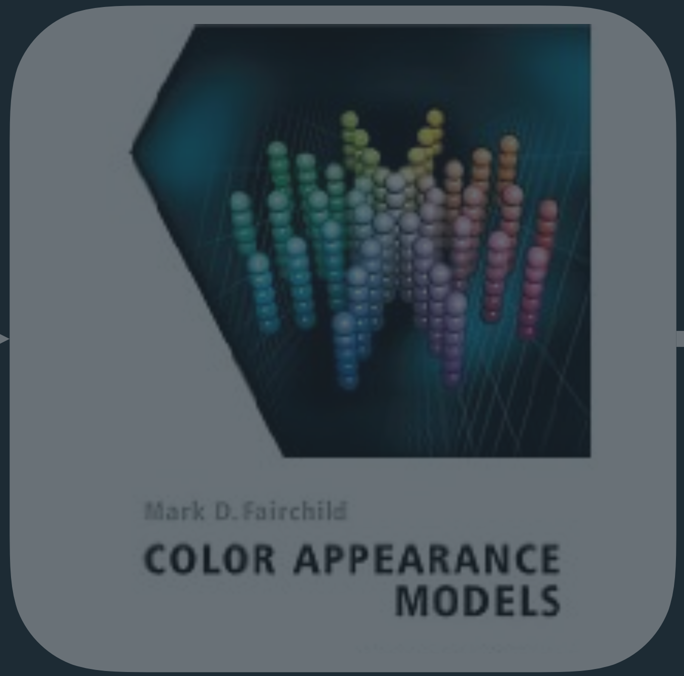



Appearance Models

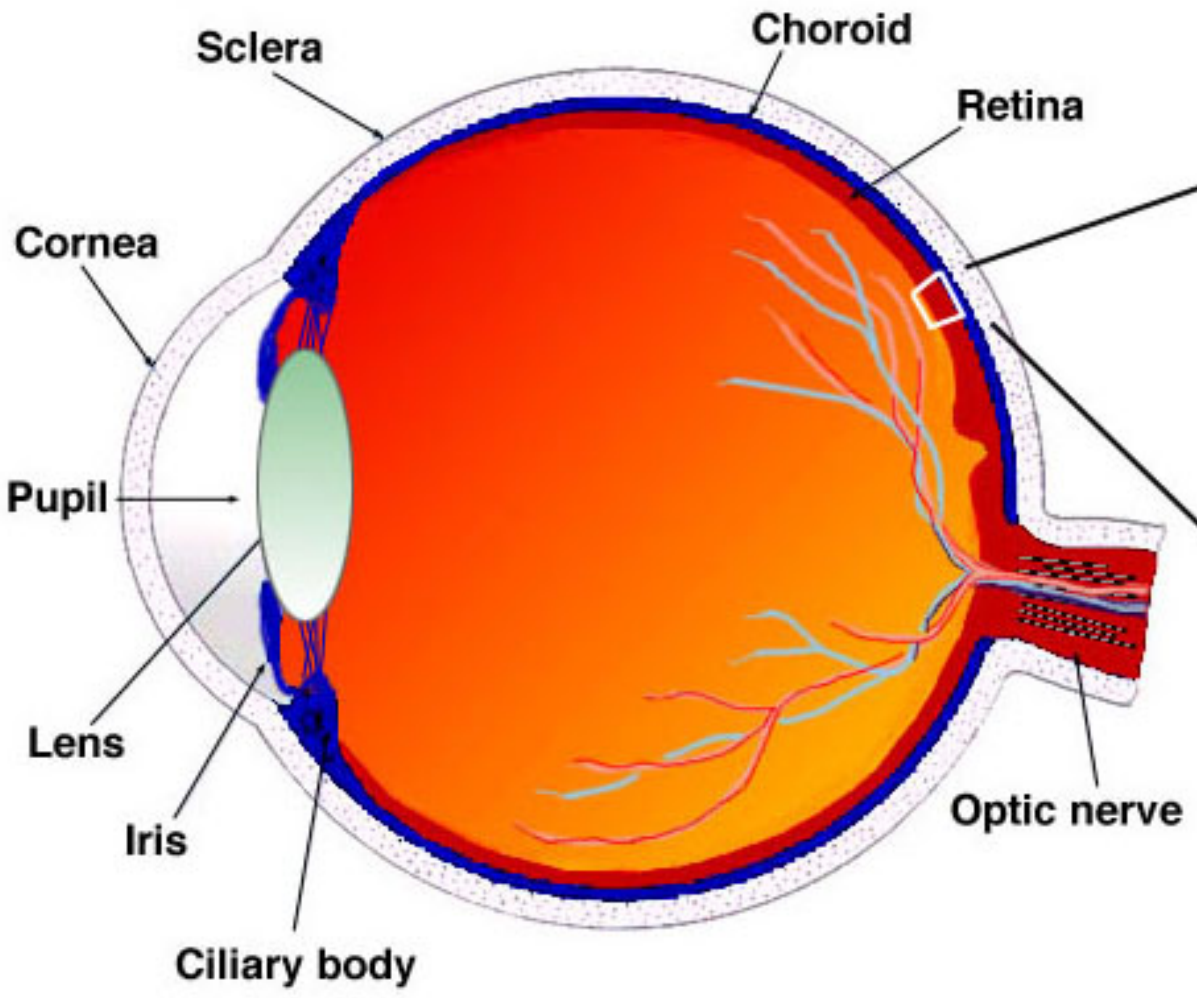
"Teal"

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*,]

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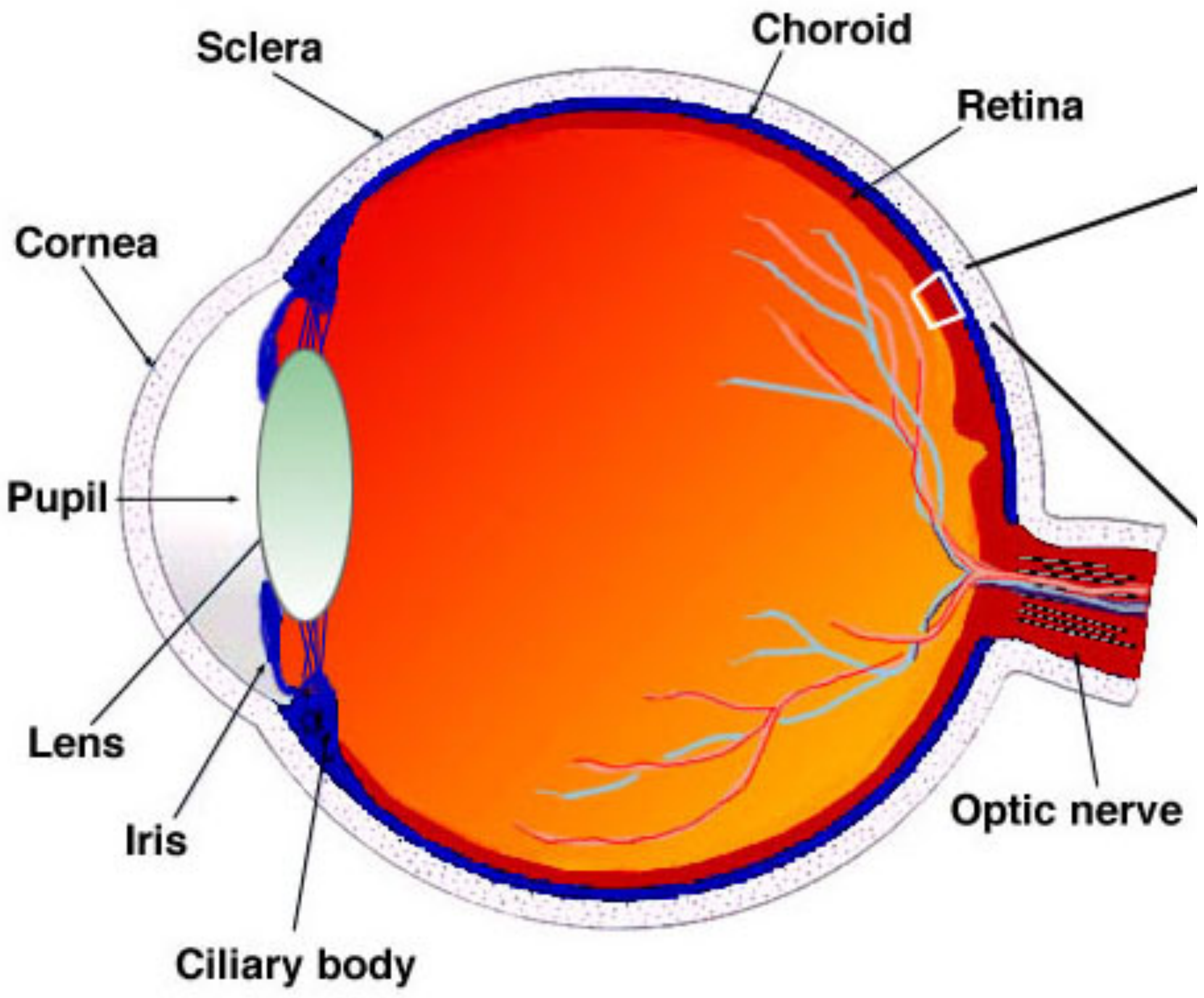
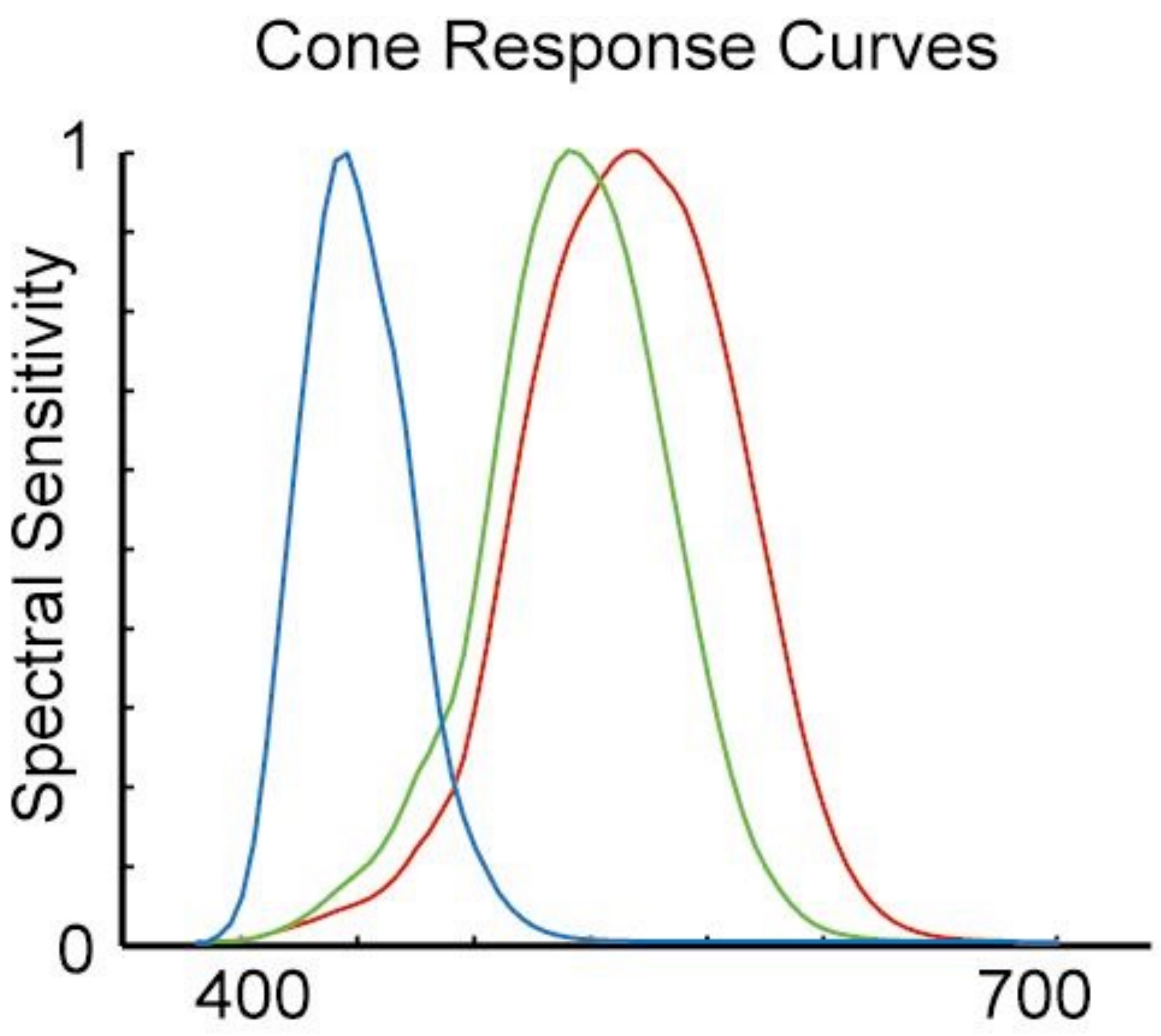
***cones*** – sensitive to different wavelengths = color vision!
long, middle, short ~ red, green, blue

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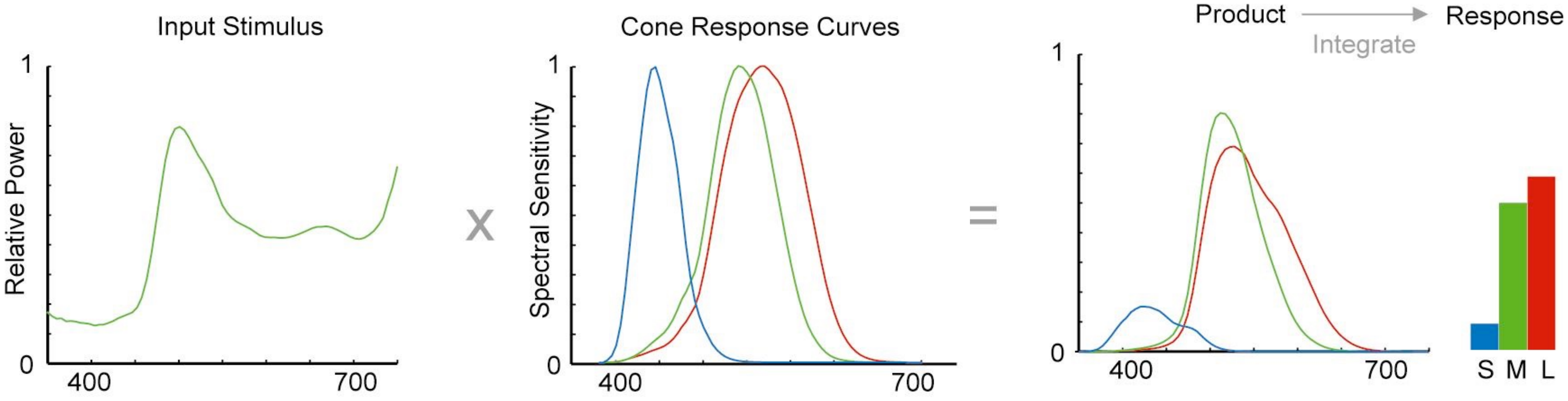


[Maureen Stone. *A Field Guide to Digital Color*, 2003]

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

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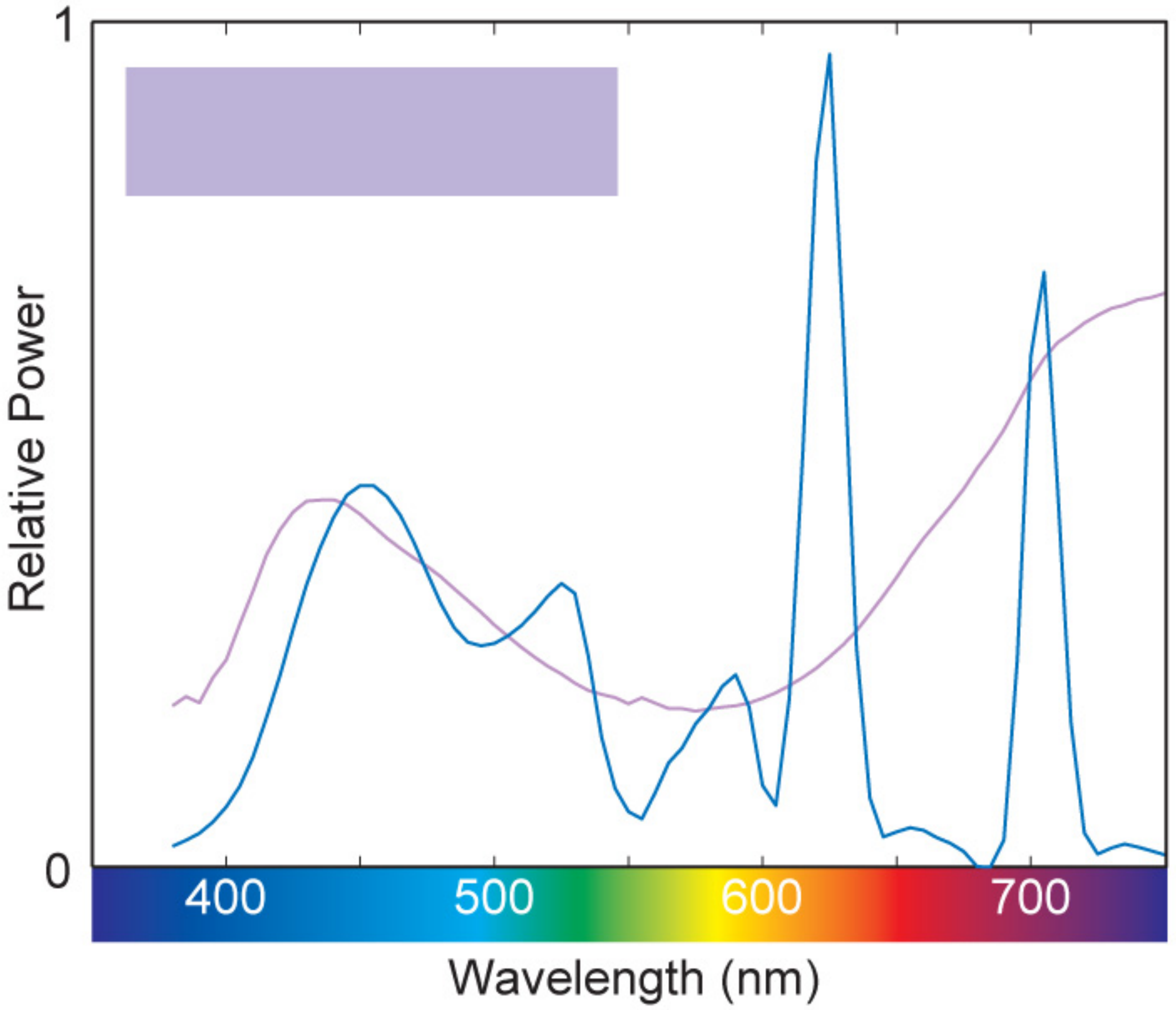
***tri-stimulus response*** – color can be modeled as 3 values.



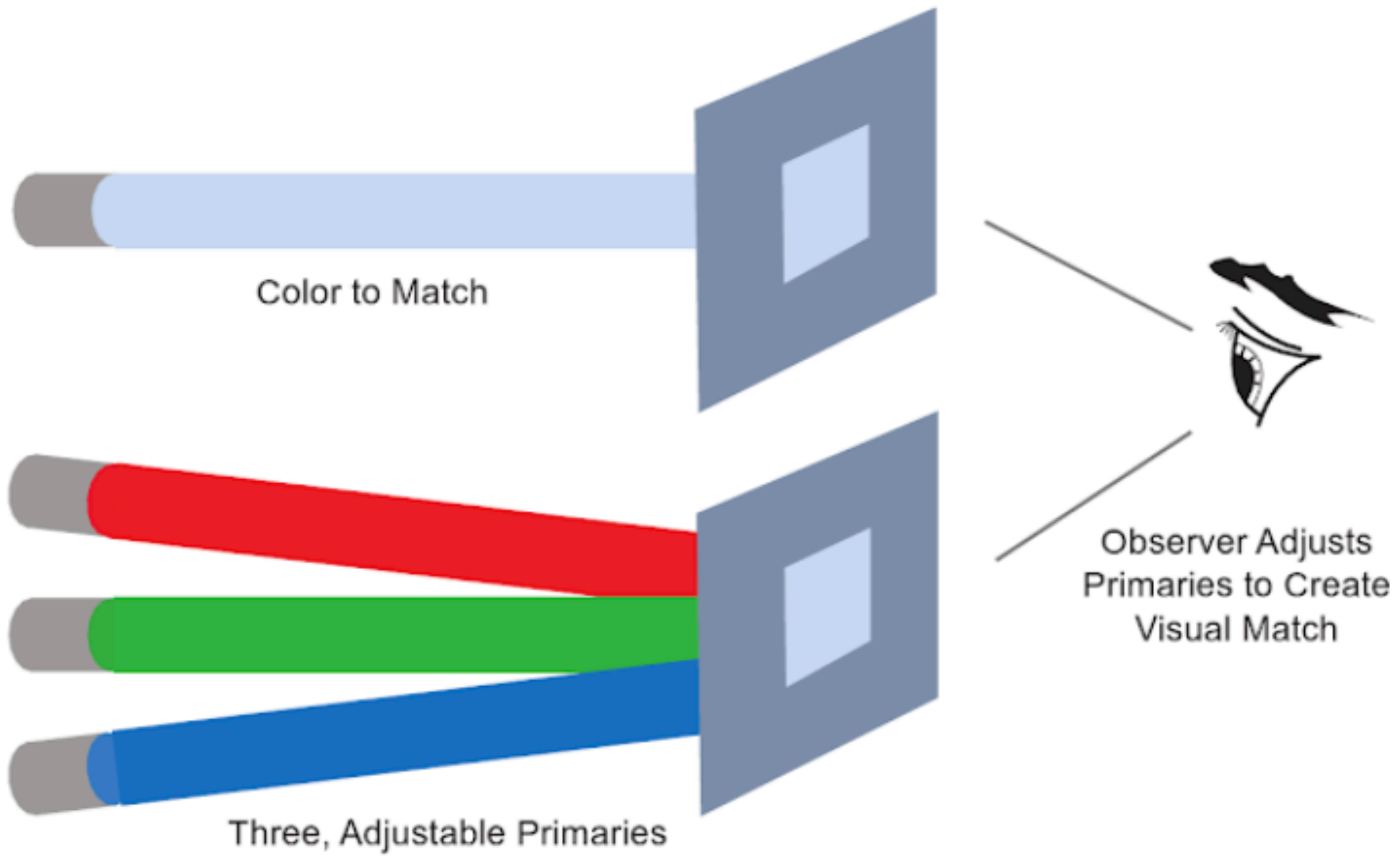

***metamers*** – spectra that stimulate the same LMS response are indistinguishable.

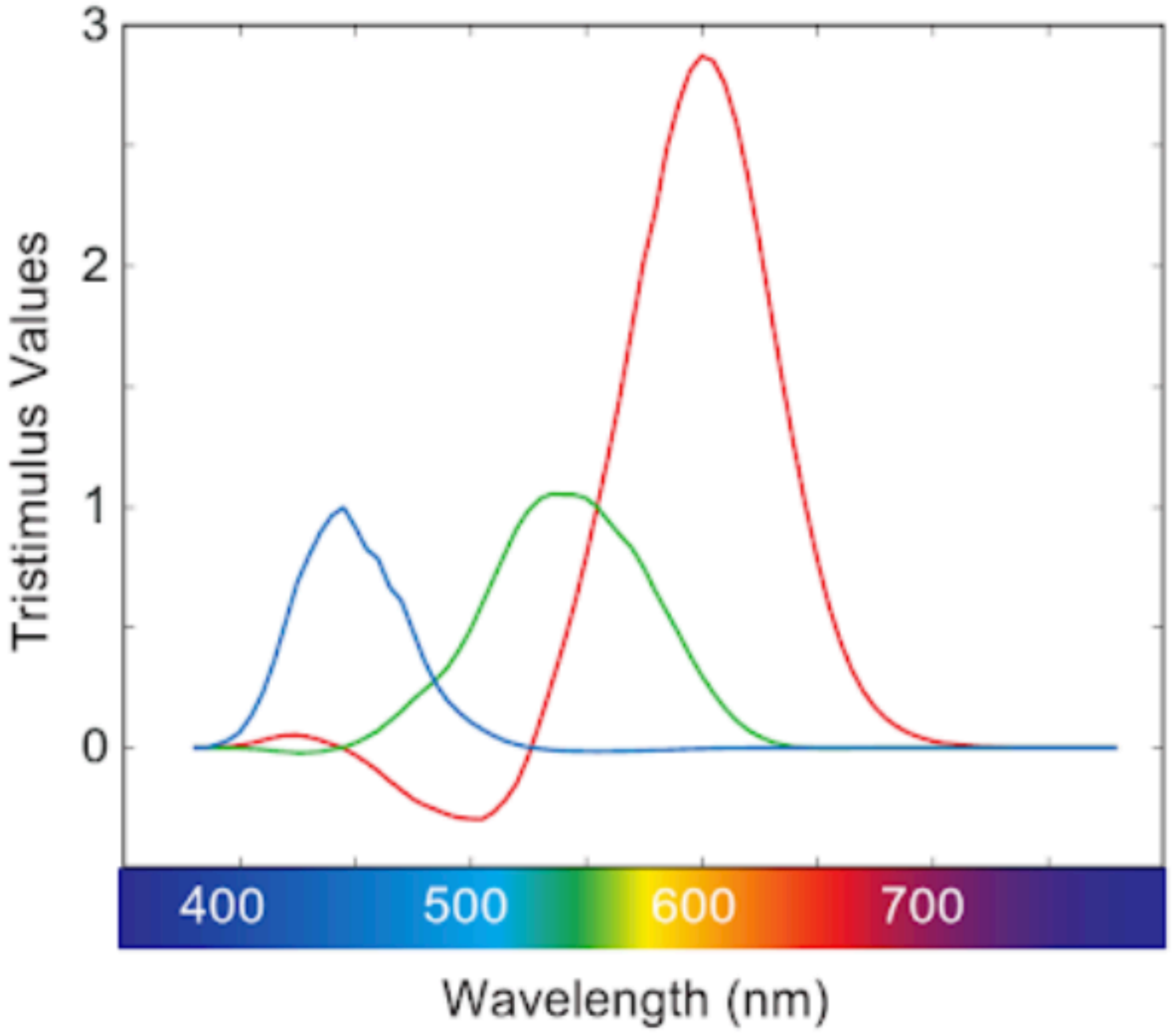
[Maureen Stone. *A Field Guide to Digital Color*, 2003]

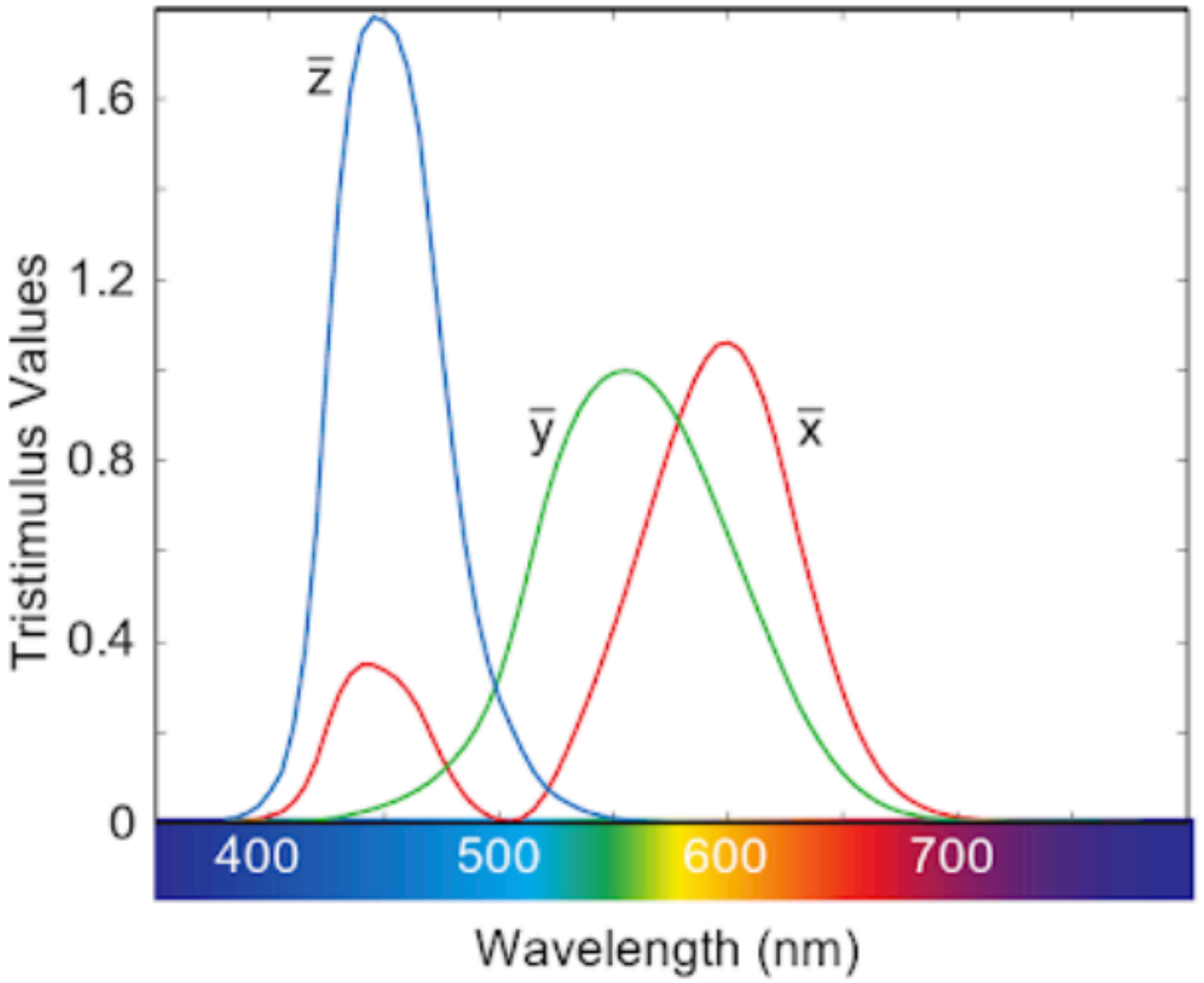
# CIE XYZ

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

*empirically determined*



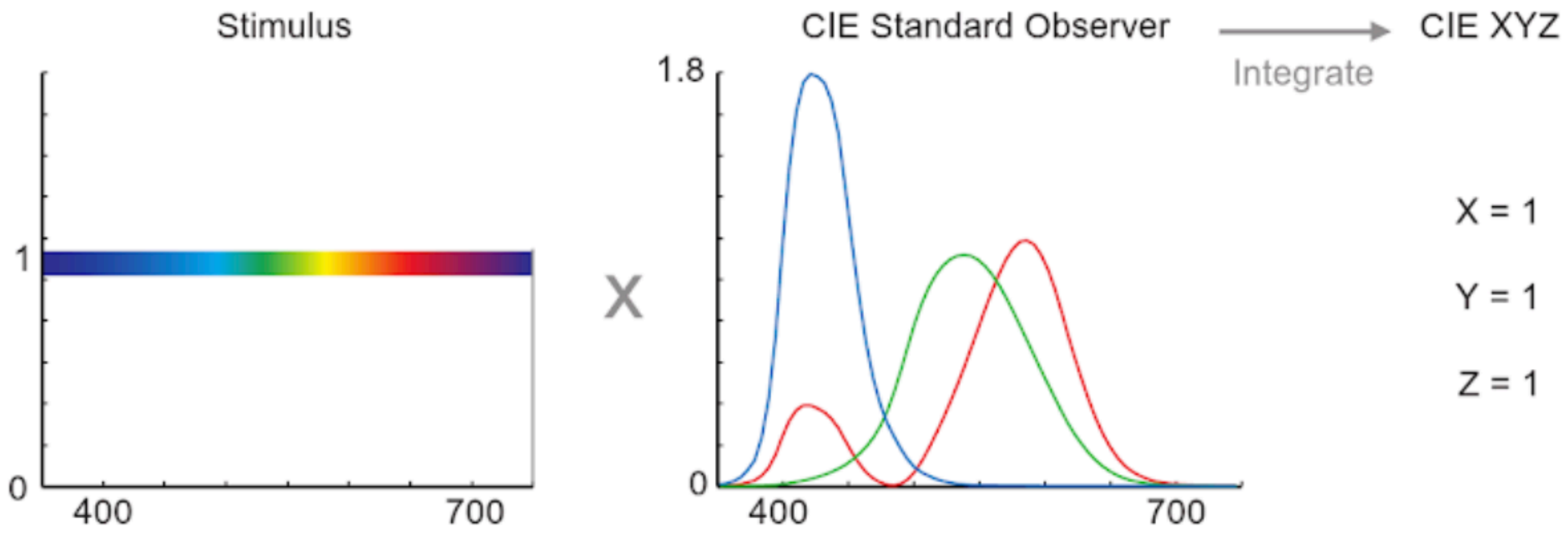




Red = 645nm
Green = 525nm
Blue = 444nm

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

# CIE XYZ

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



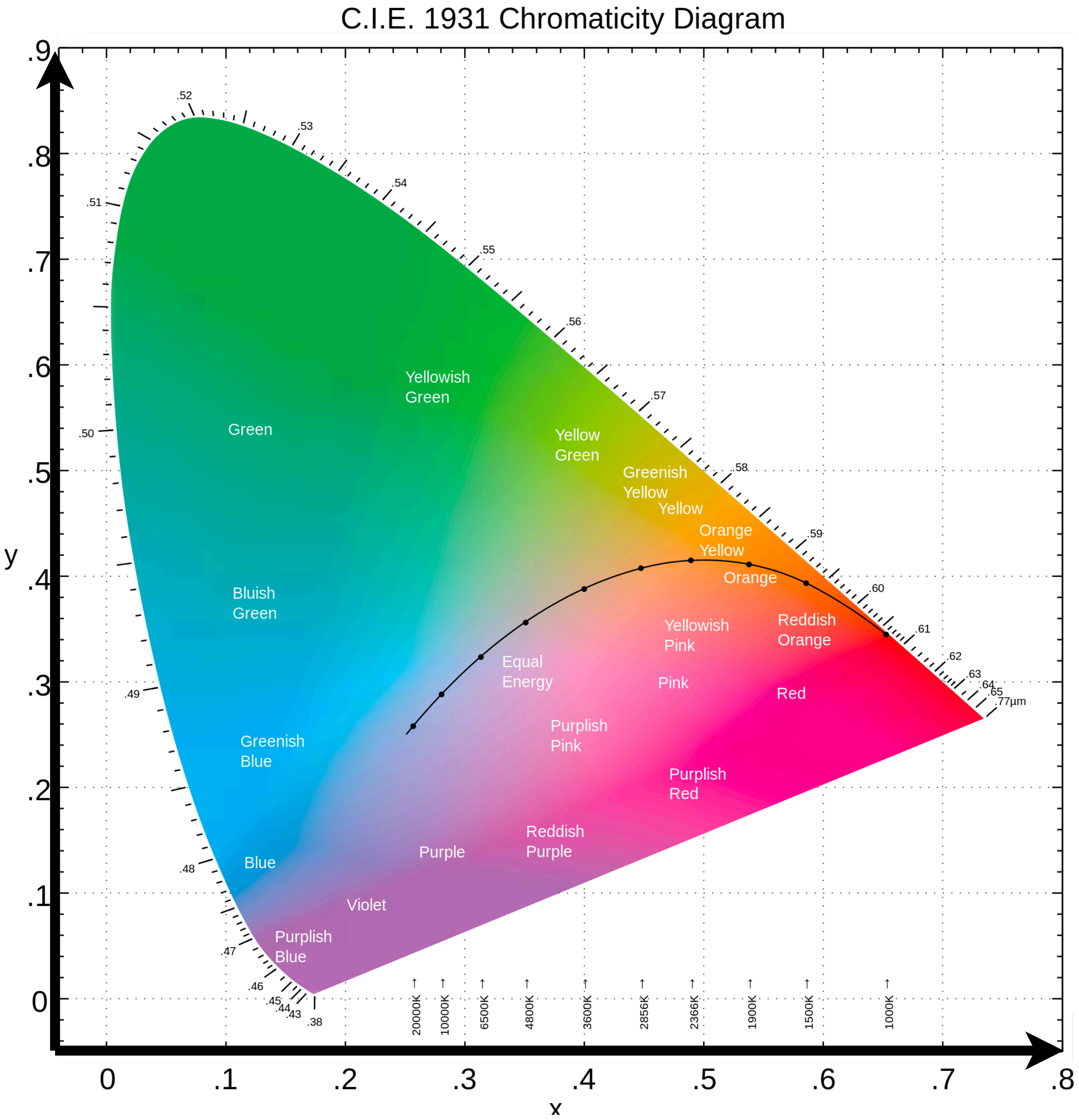
# CIE XYZ Color Space

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 Space

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

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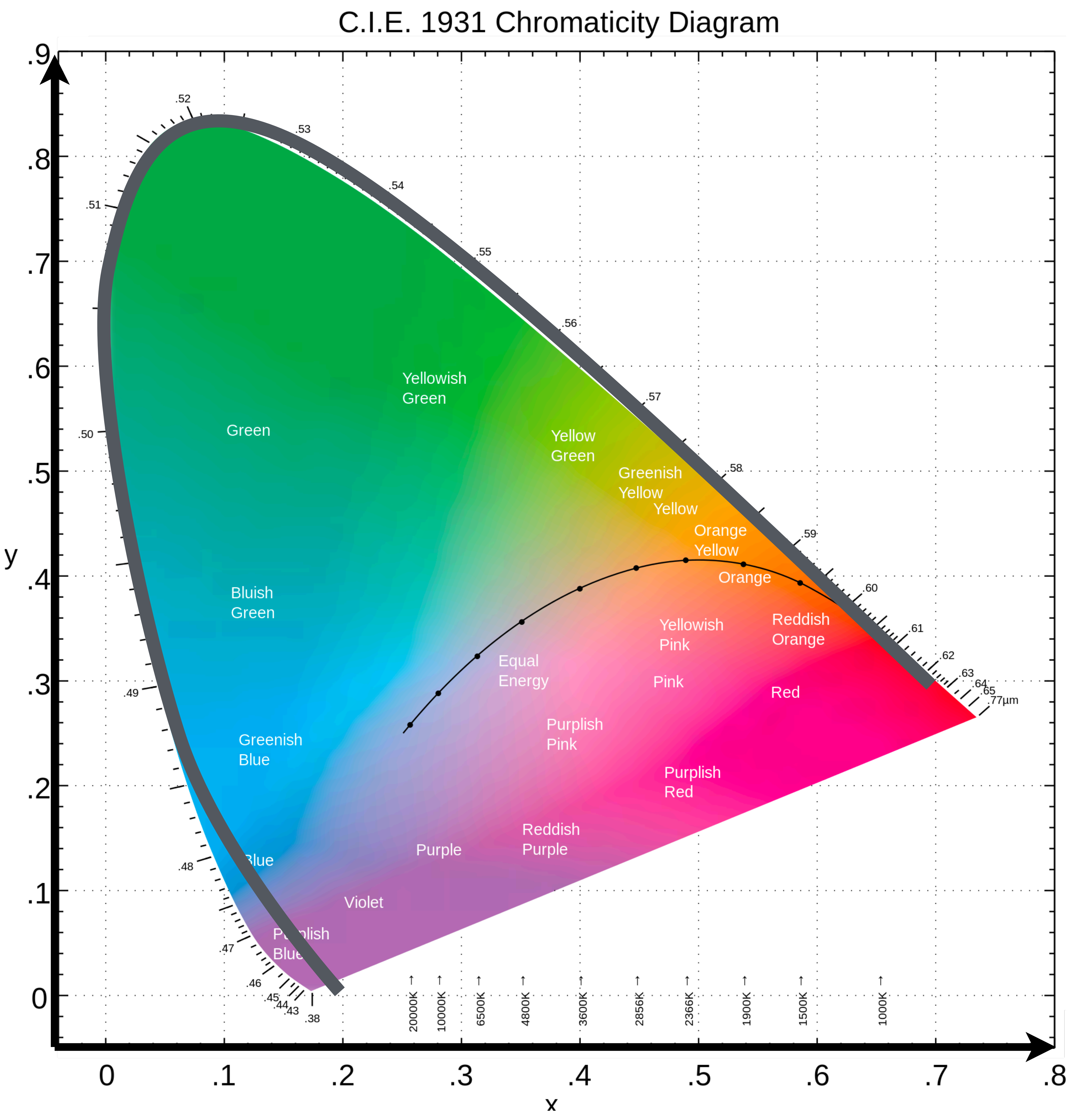
***Spectral locus*** – set of pure colors (i.e., lasers of a single wavelength).

Slowly shifts from S → M → L.



# CIE XYZ Color Space

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

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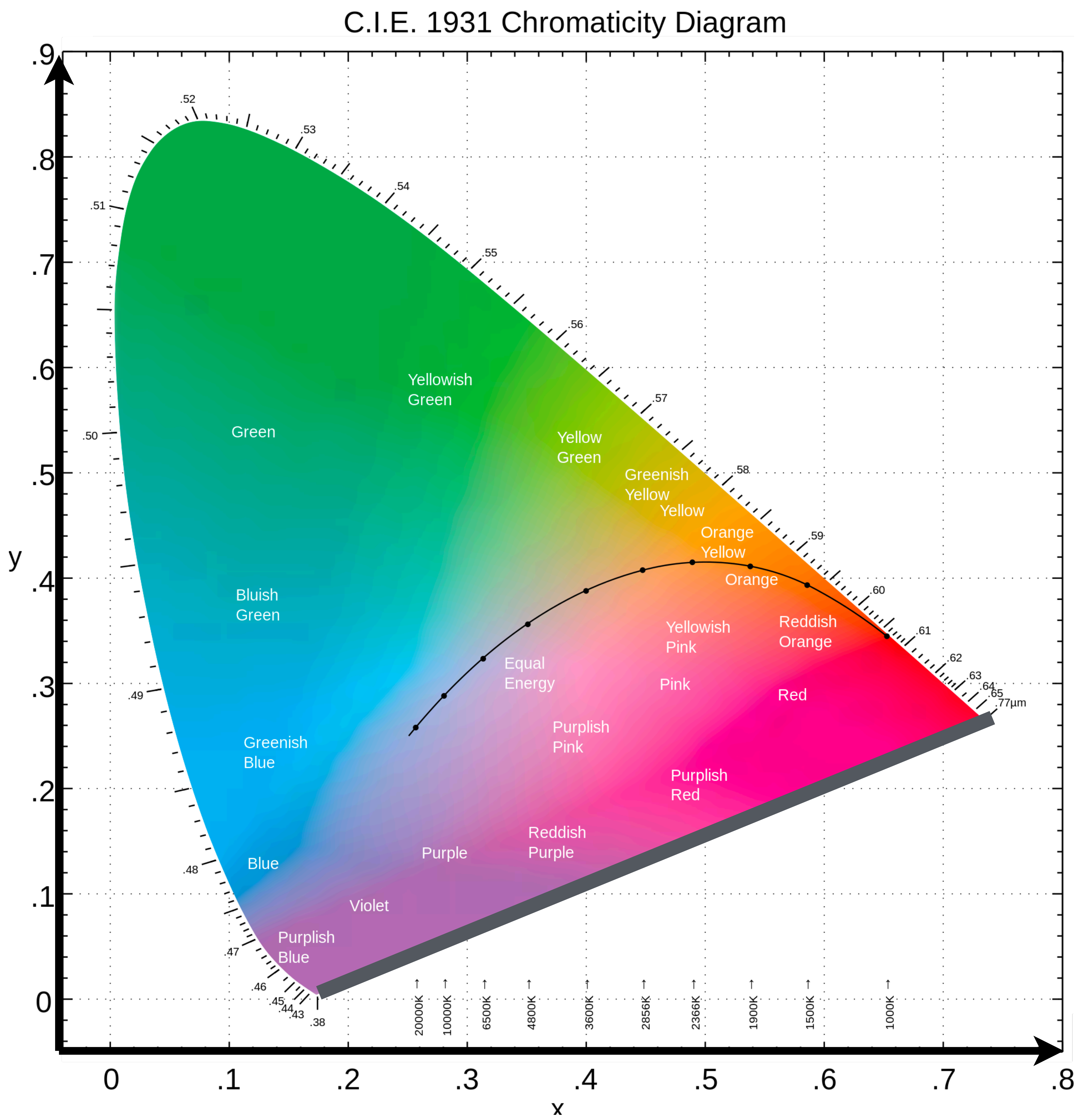
$$1 = x + y + z$$

***Purple line*** – not possible to recreate with a monochromatic light source.

Mixture of spectral violet + red (i.e., short and long wavelengths).



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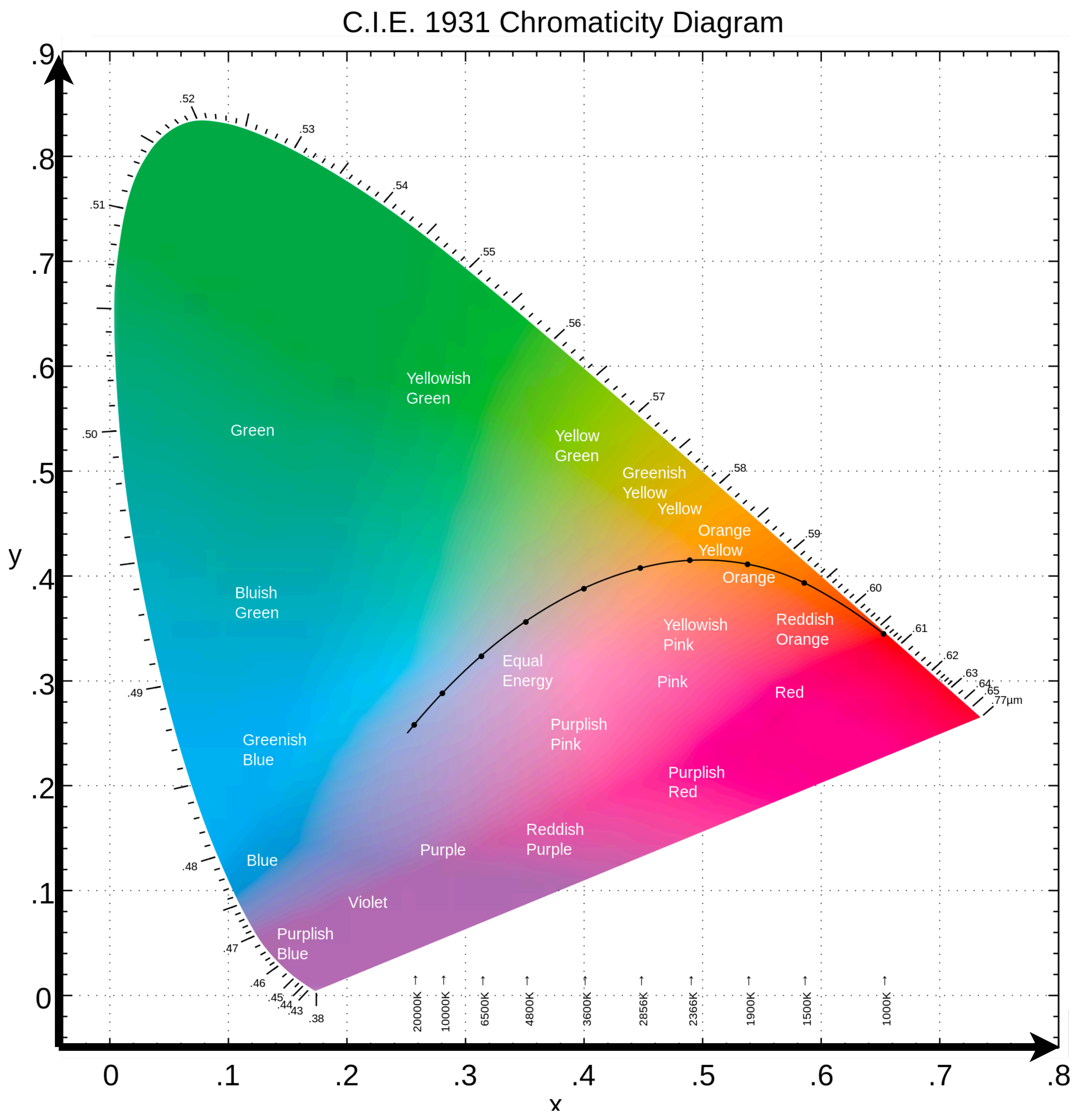
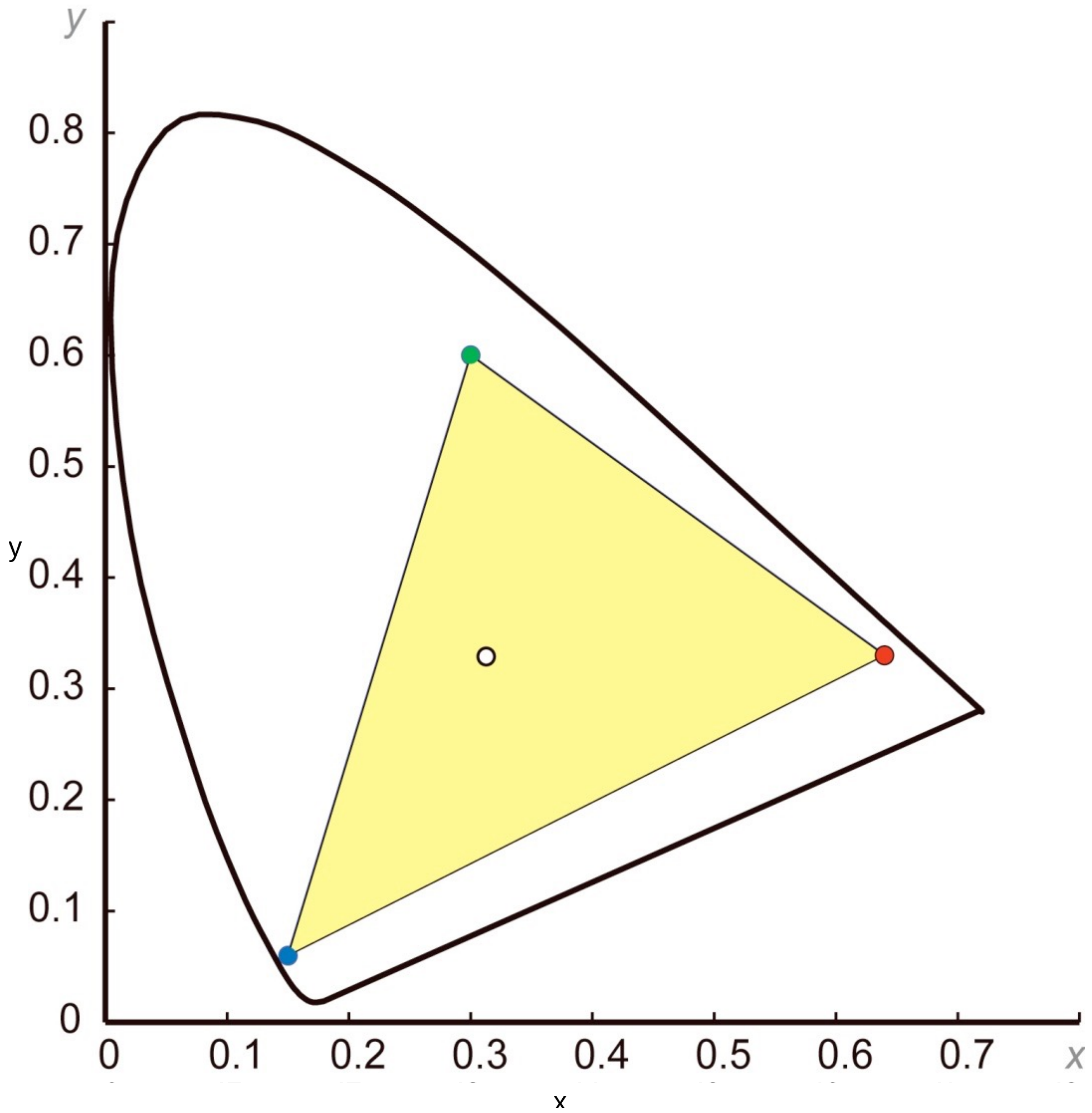
***Straight line*** = mixture of two light sources.



# CIE XYZ Color Space

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



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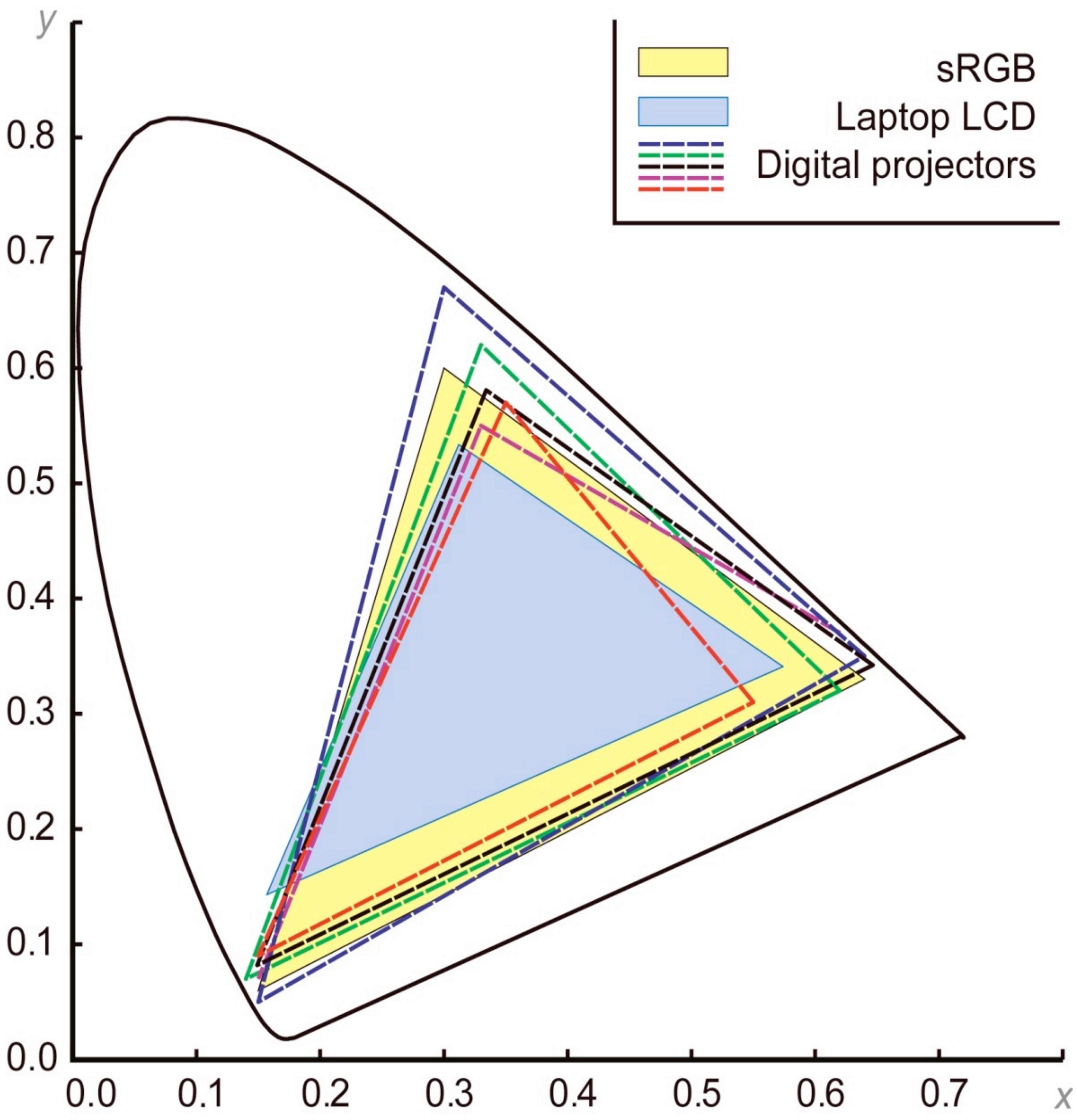


# CIE XYZ Color Space

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

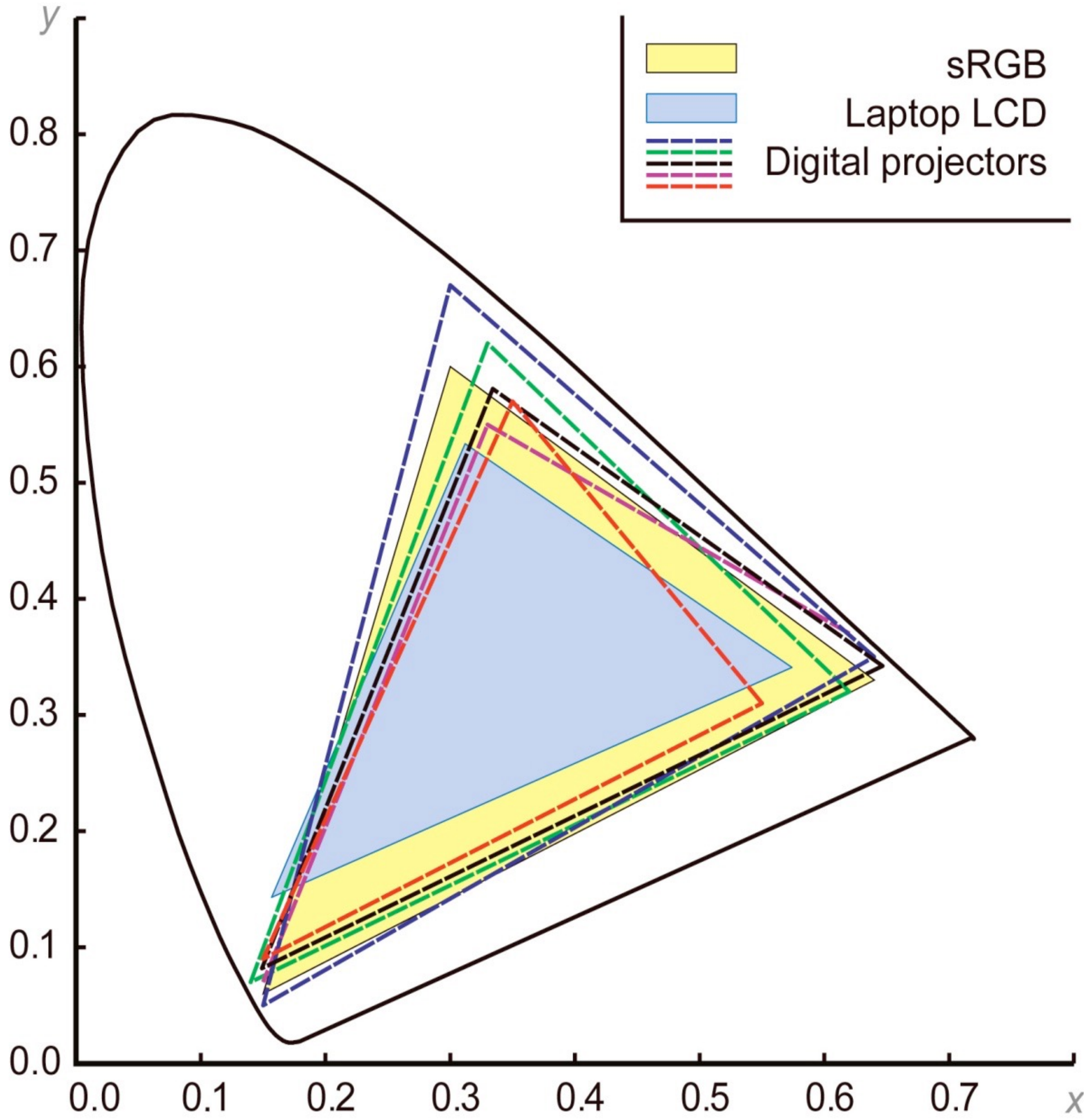
The angry rainbow in sRGB.

Corners of sRGB

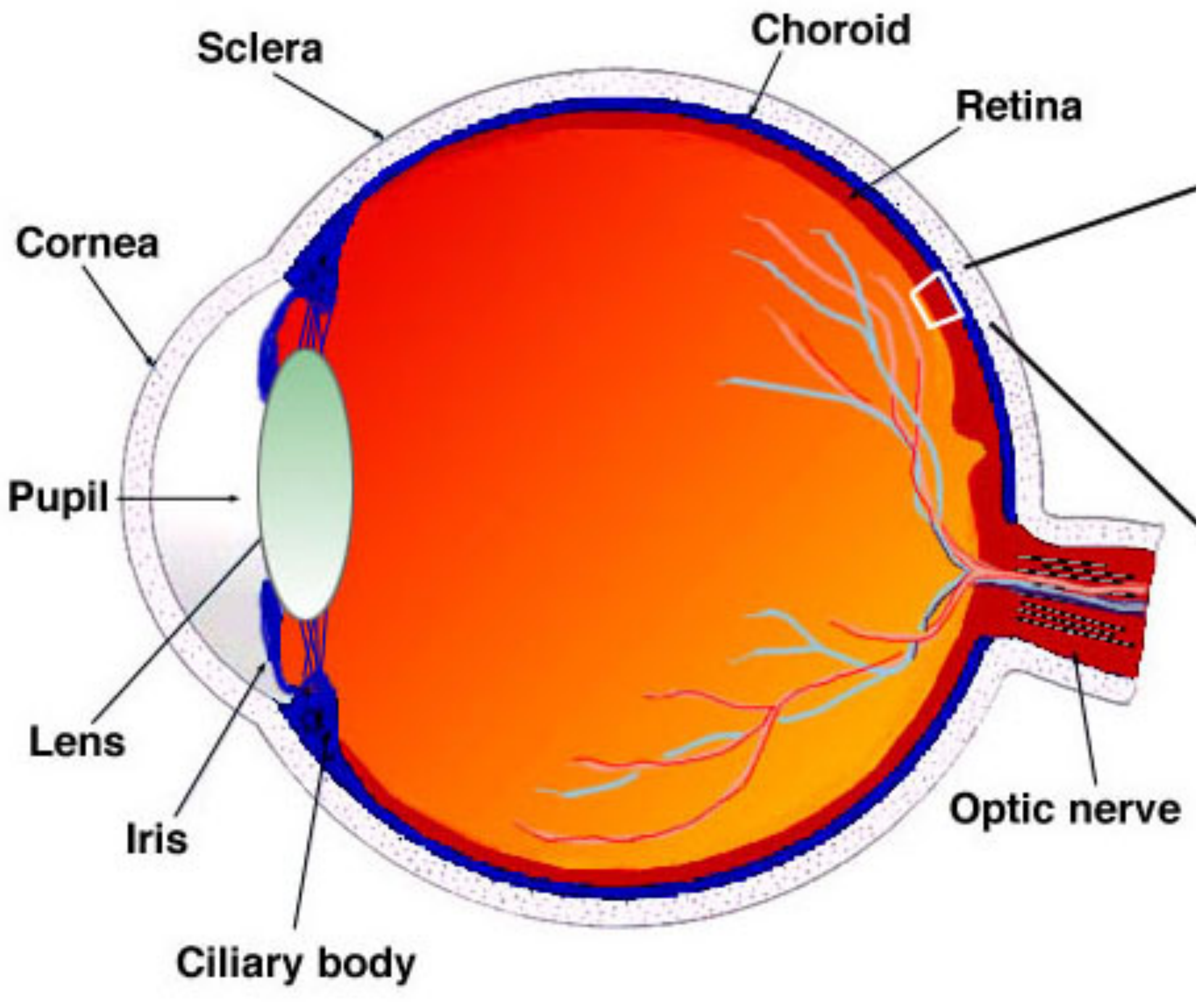
Photoshop grayscale

No linear brightness gradient within a single hue.

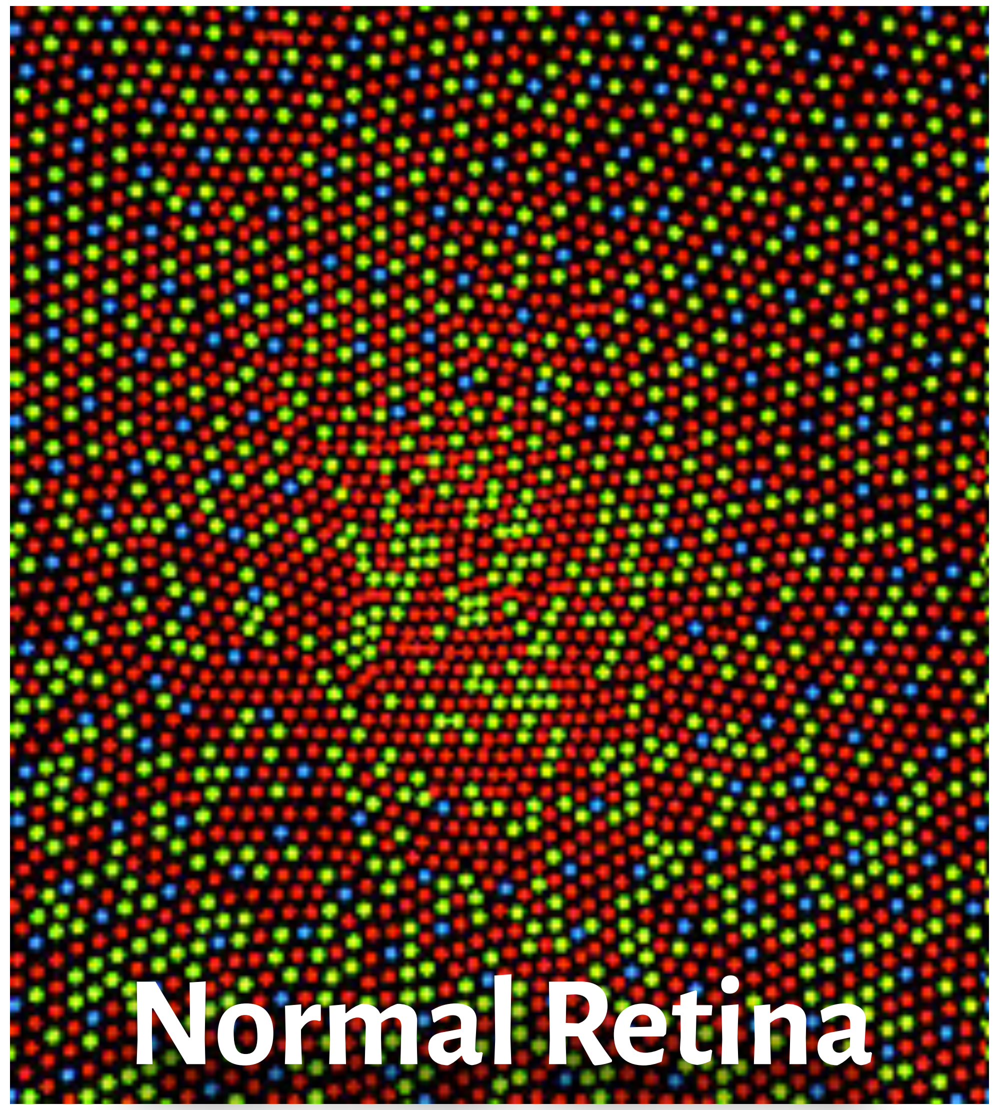
[Gregor Aisch How to Avoid Equidistant HSV Colors.]

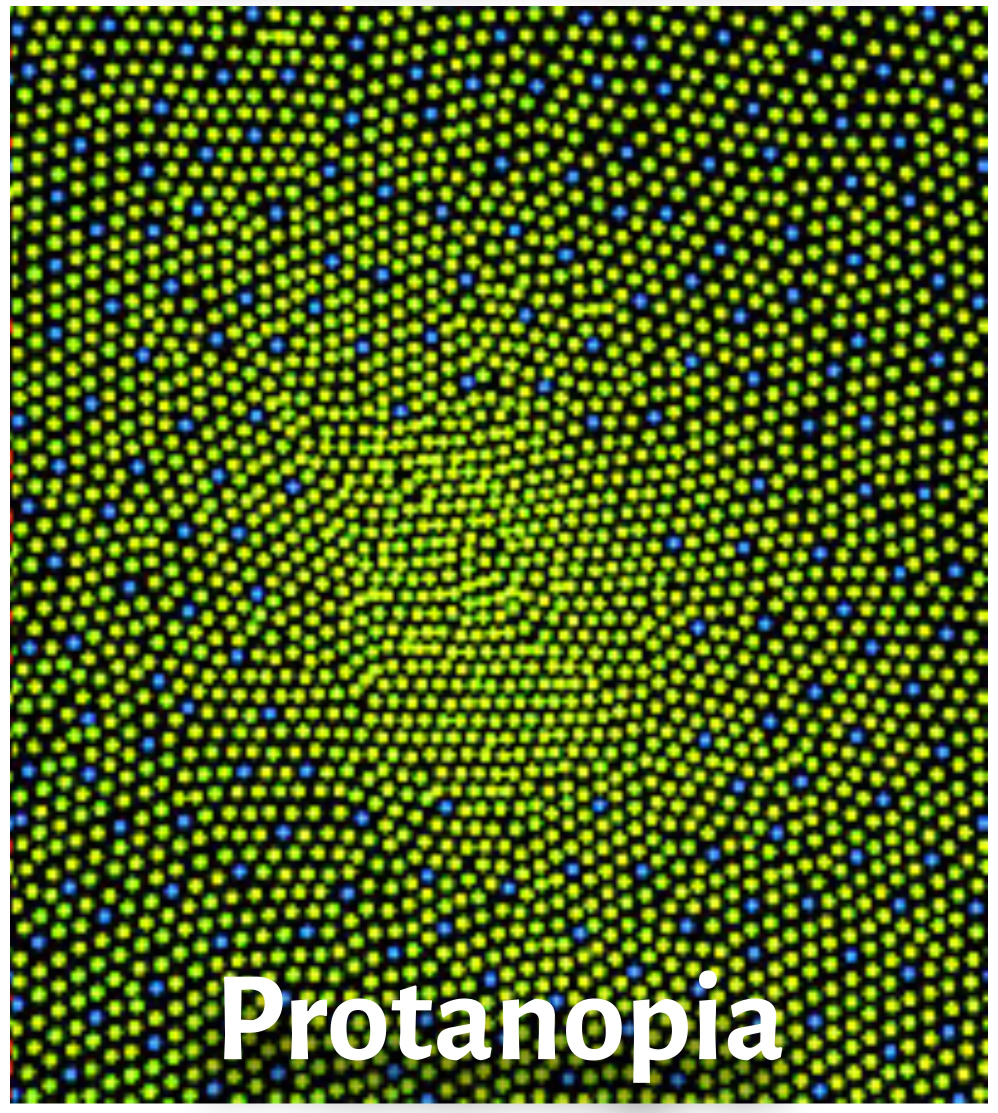


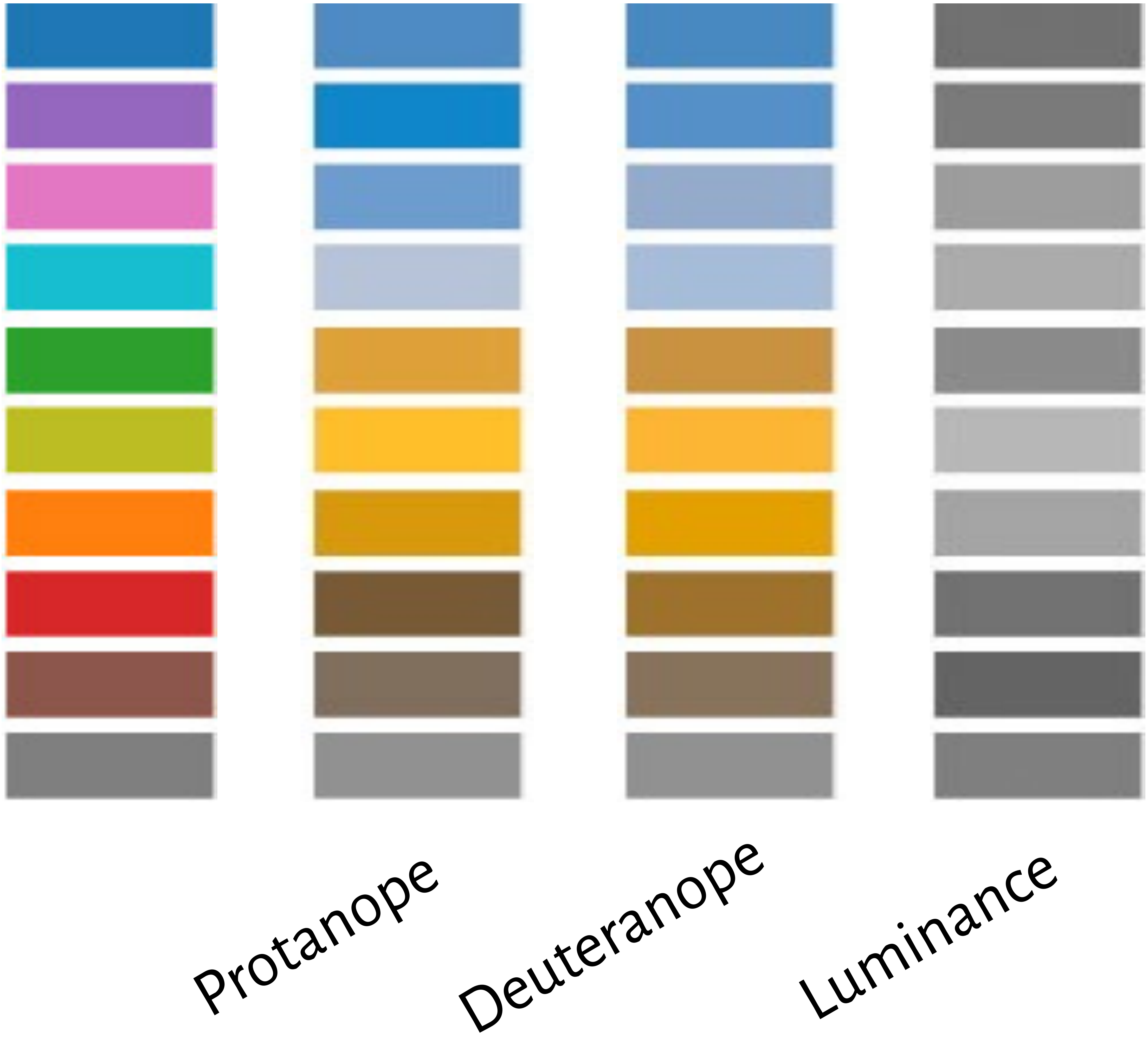
# The Retina




[Helga Kolb *Simple Anatomy of the Retina*.]



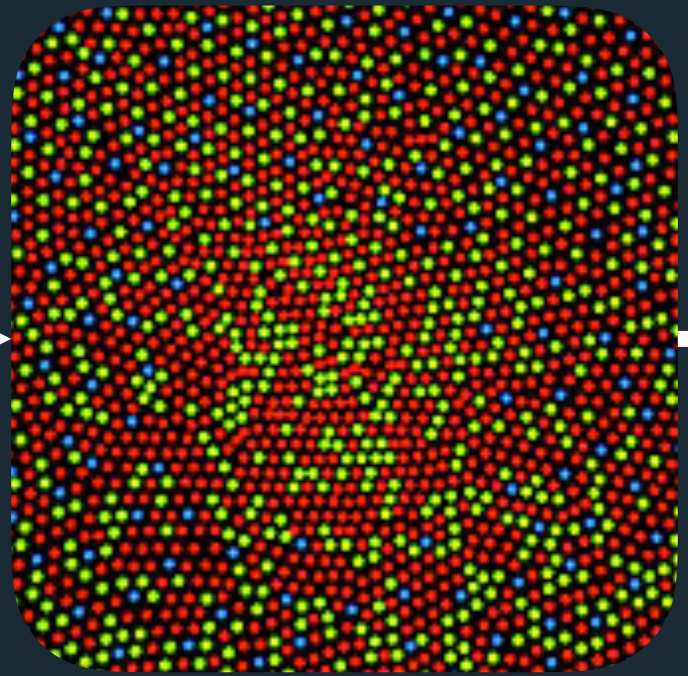



# Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

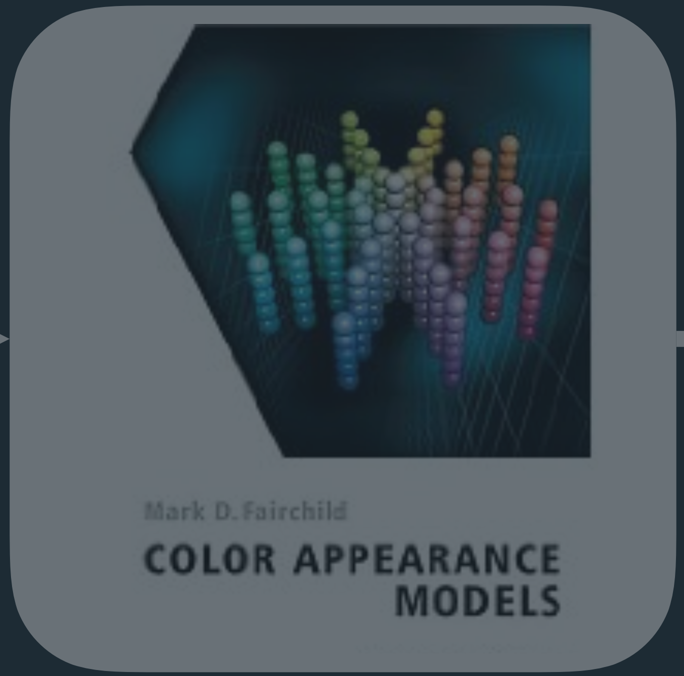
Visible Light



Cone Response


Opponent Encoding

Perceptual Models




Appearance Models

"Teal"

Cognitive Models

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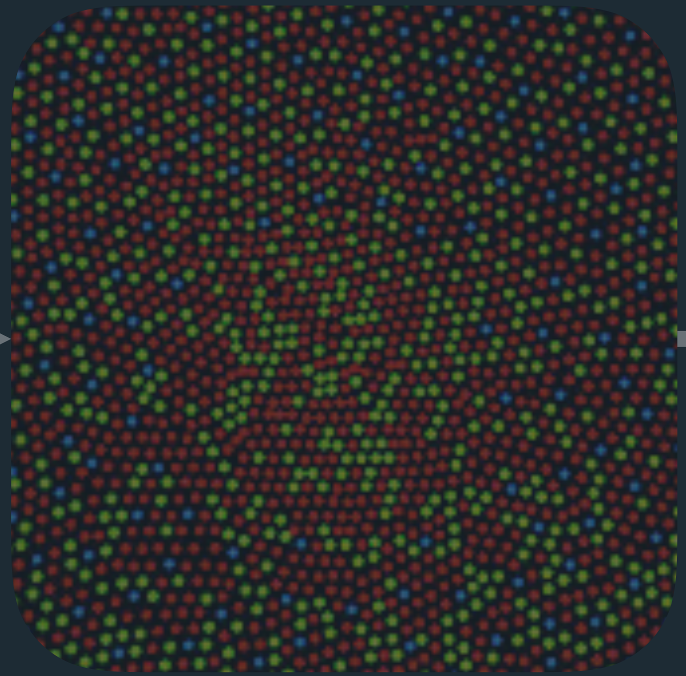

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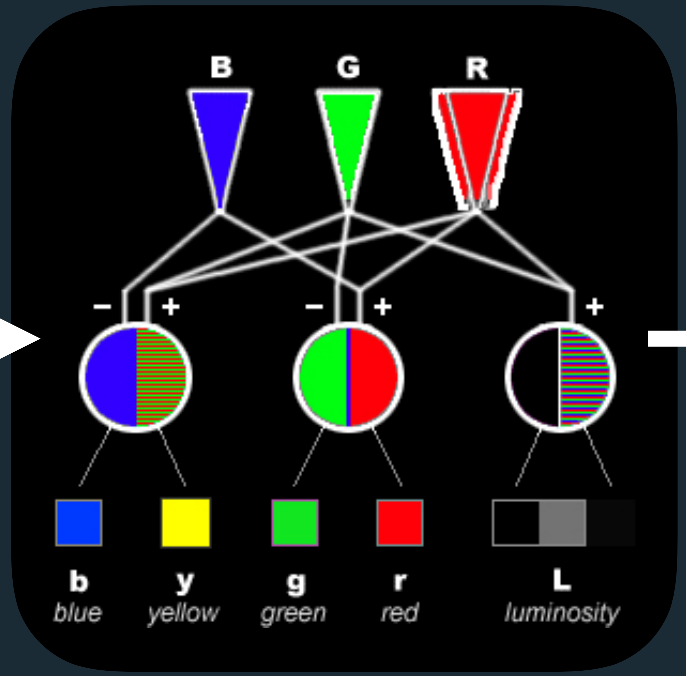


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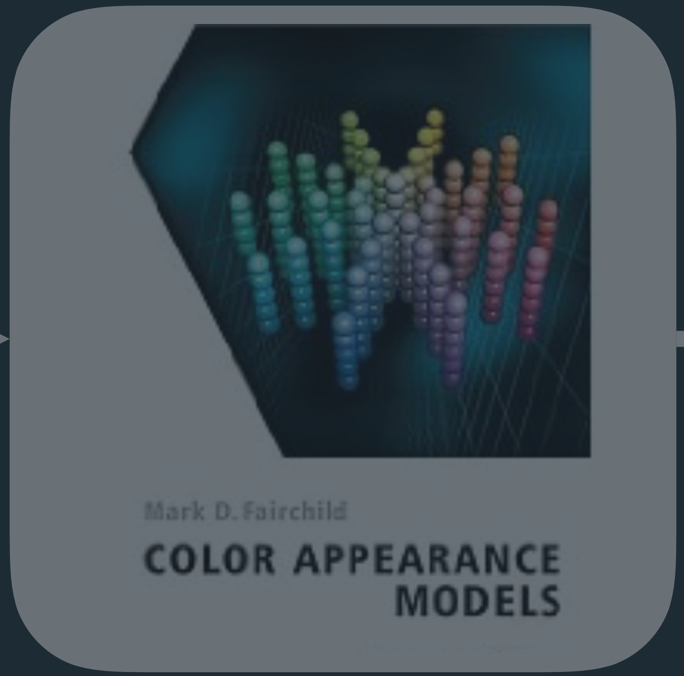


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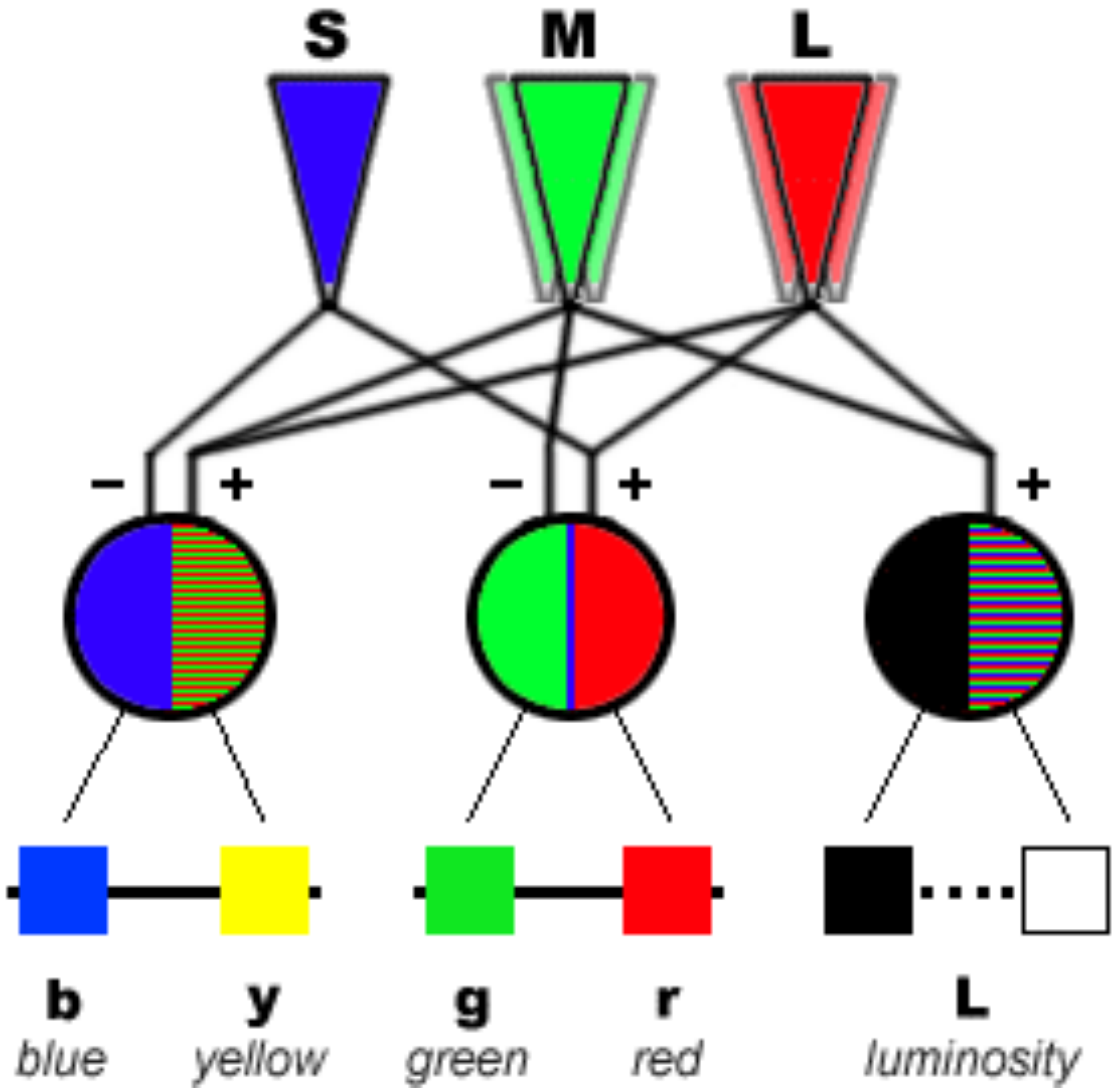
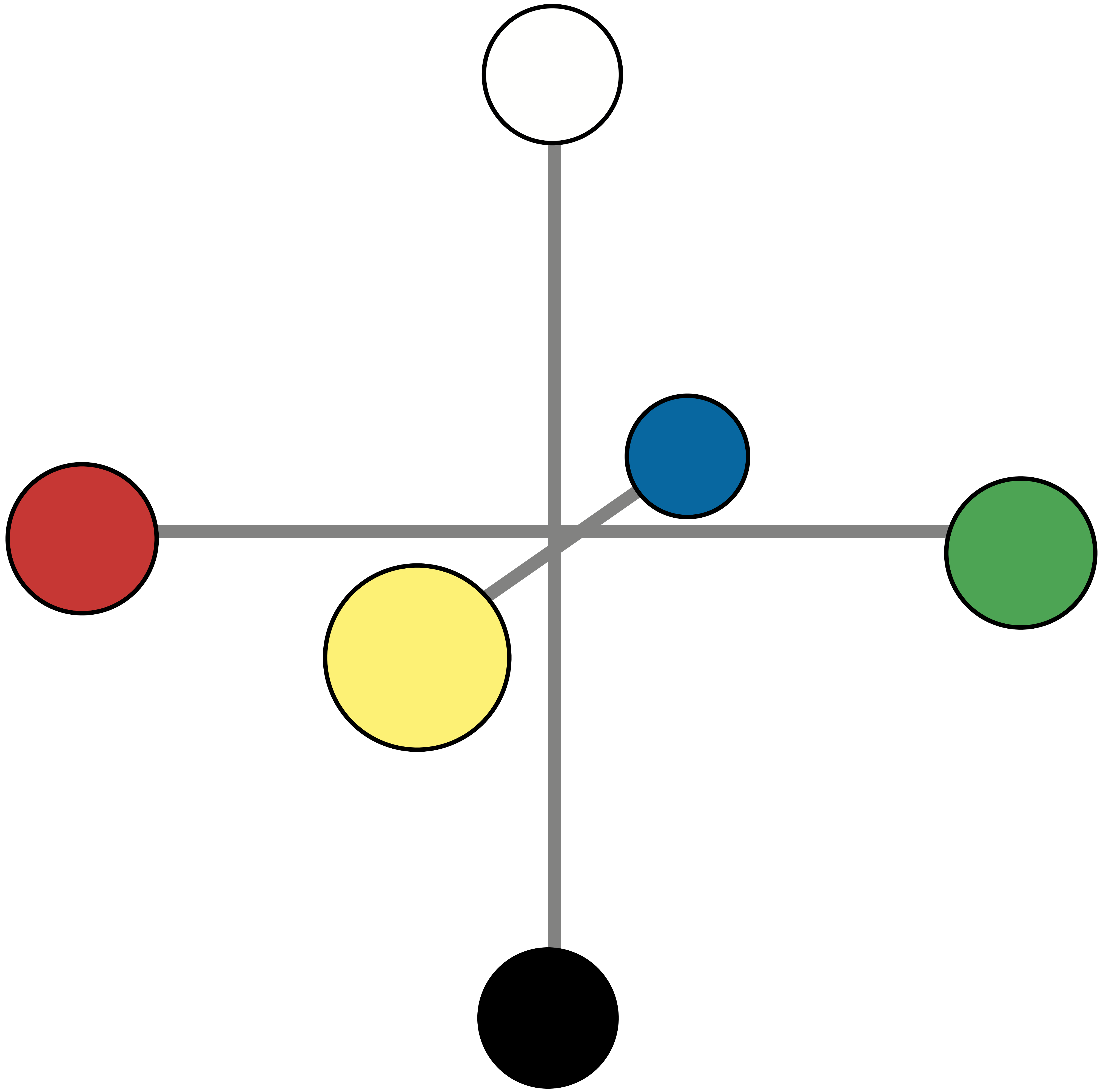


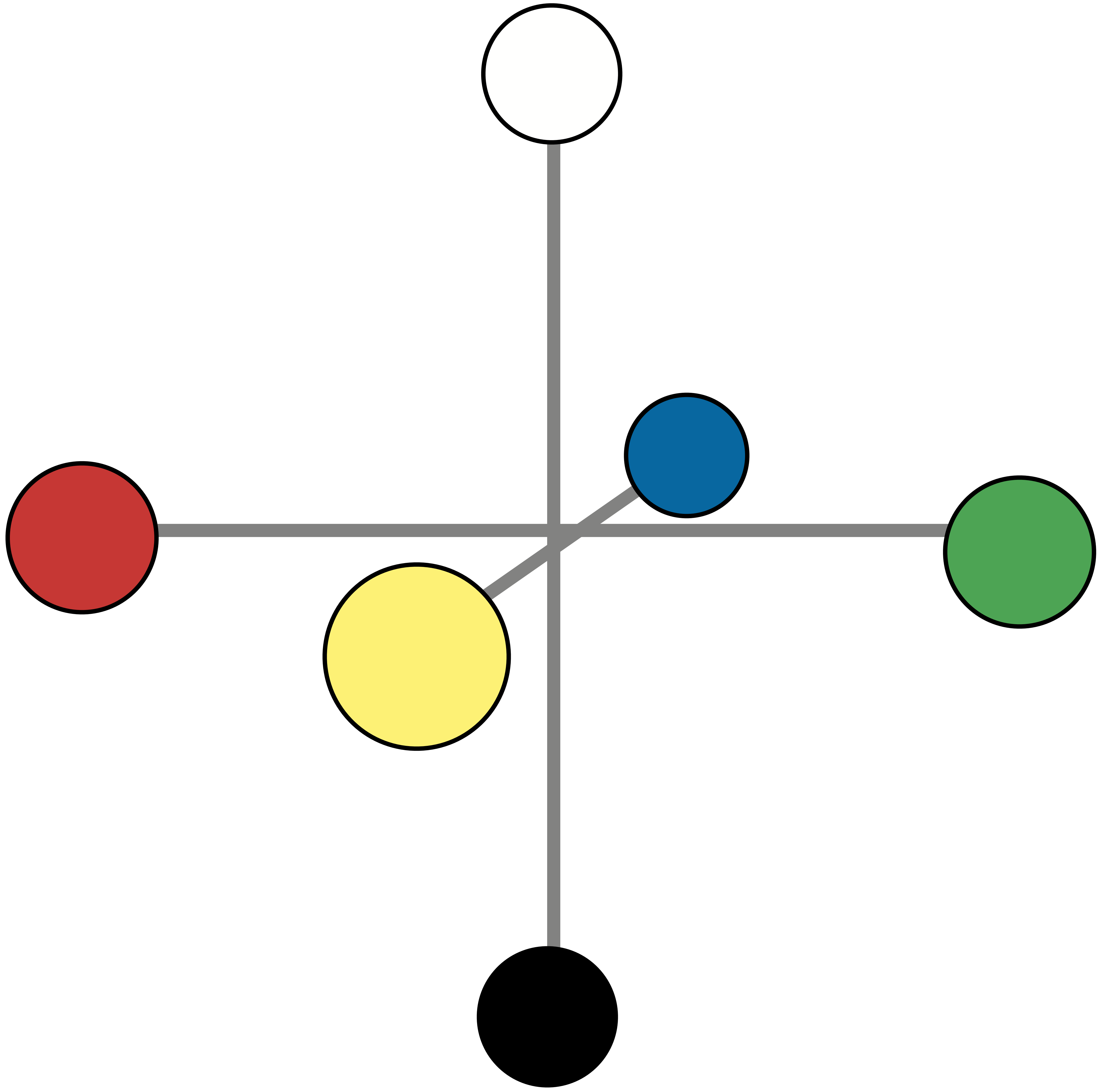
# CIE LAB Color Space

Axes correspond to opponent signals:

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

More perceptually uniform than sRGB.

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



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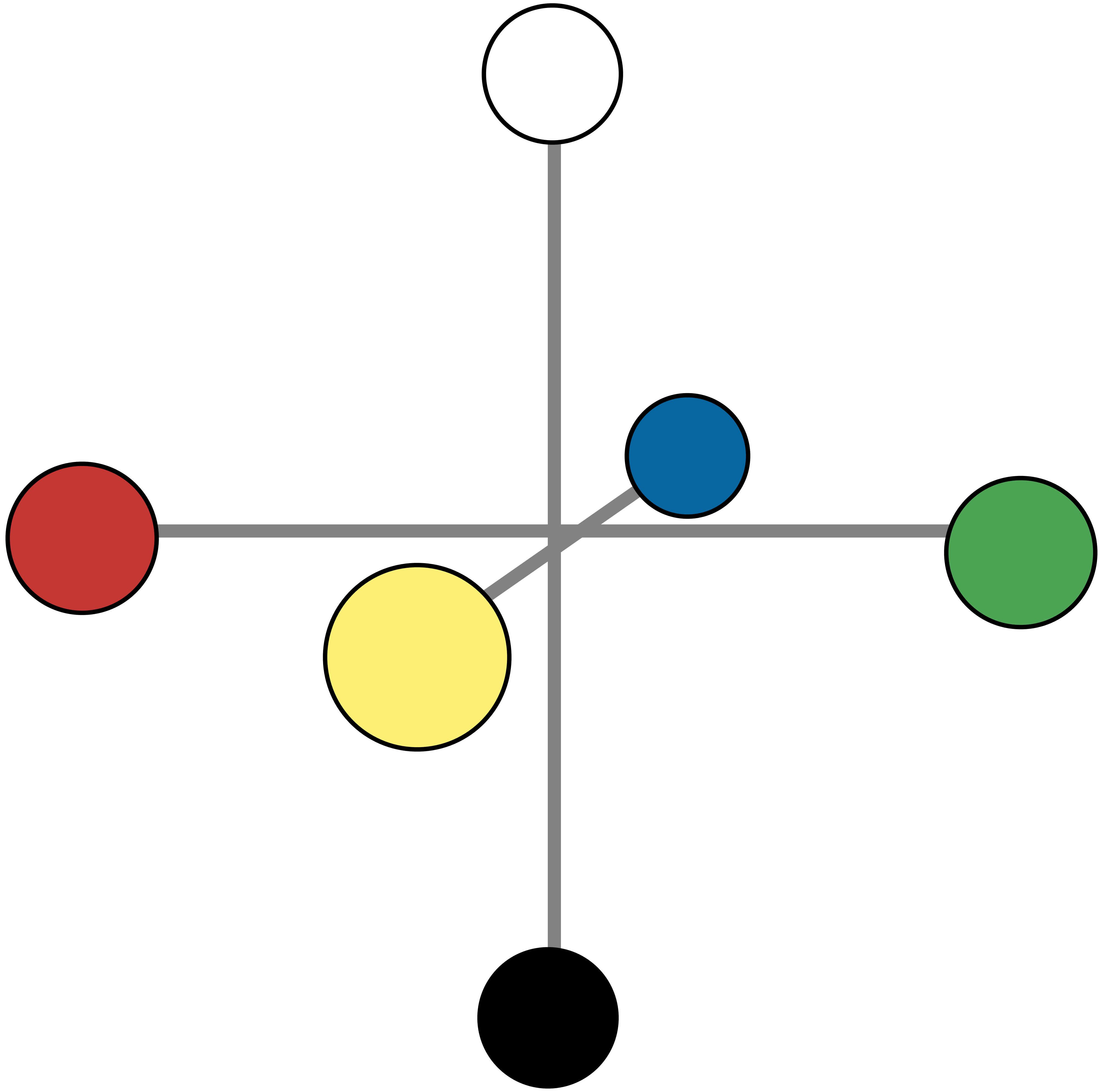

The angry rainbow in sRGB.

A happier rainbow in LAB.

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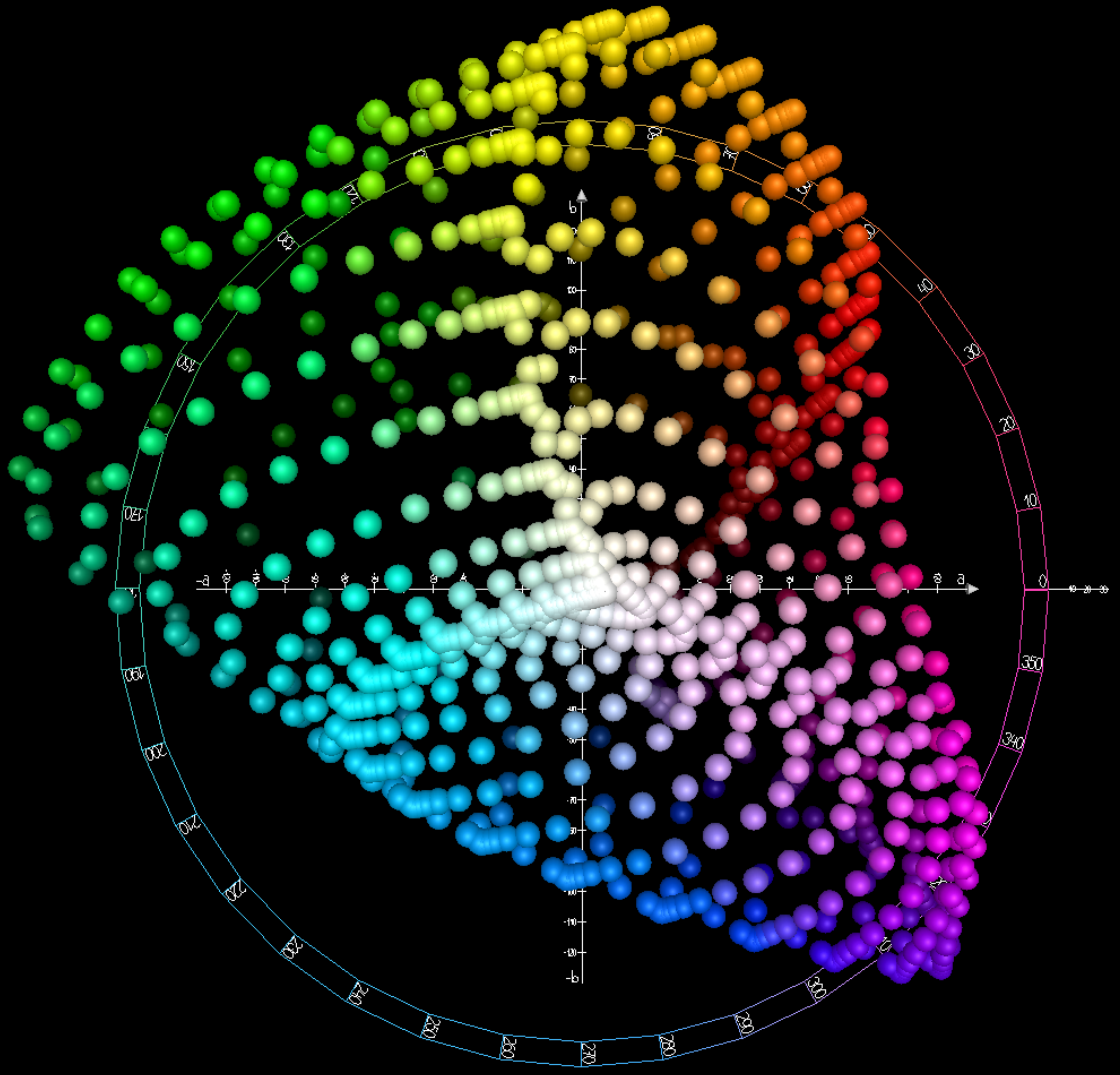

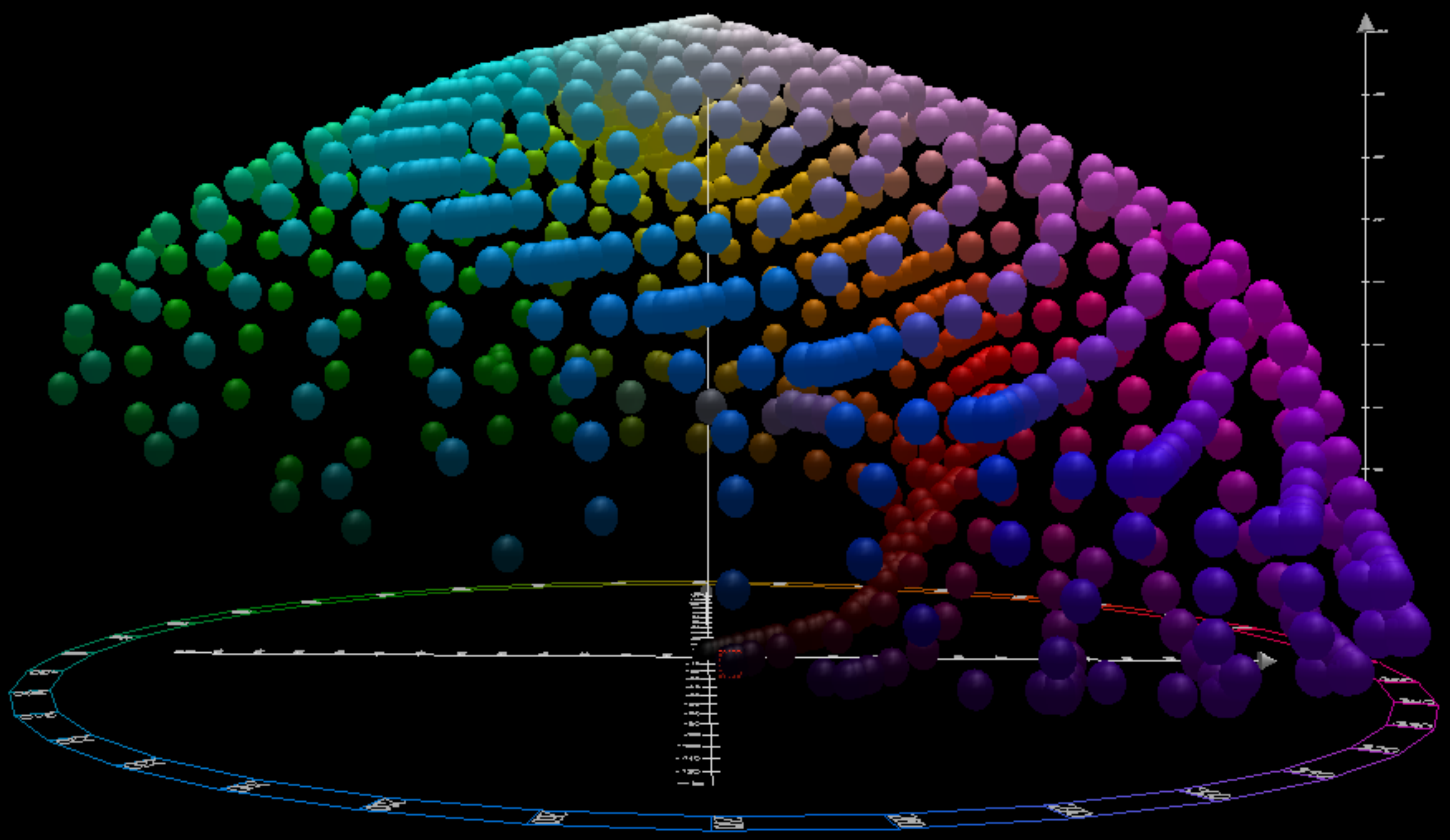

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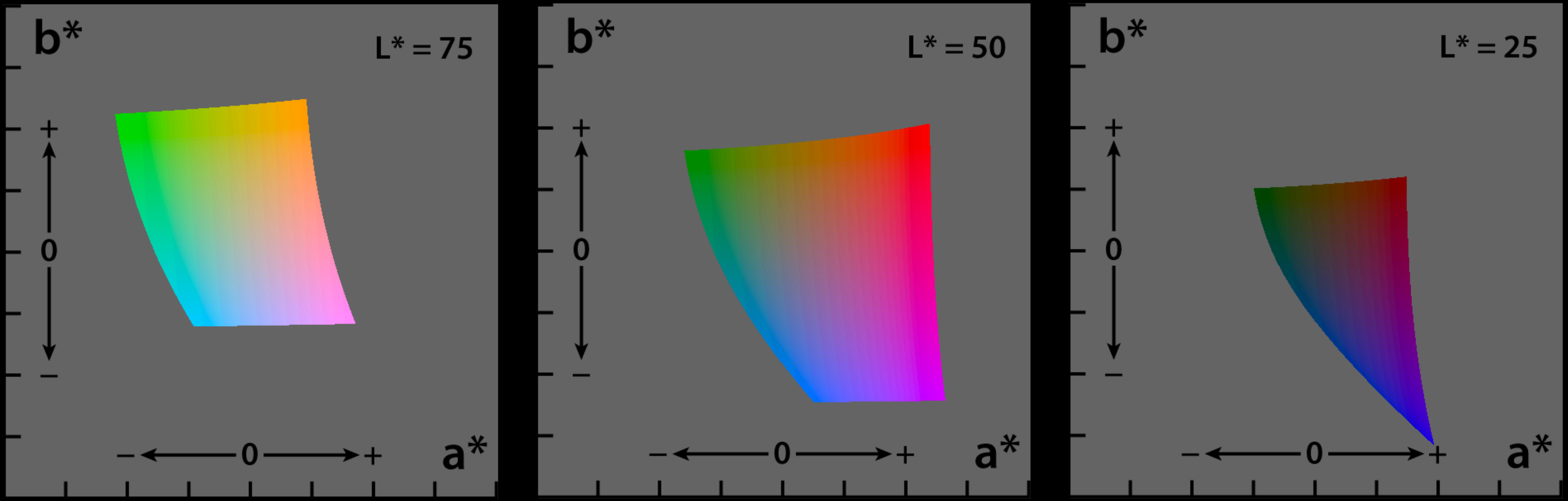
Embedding the sRGB gamut:



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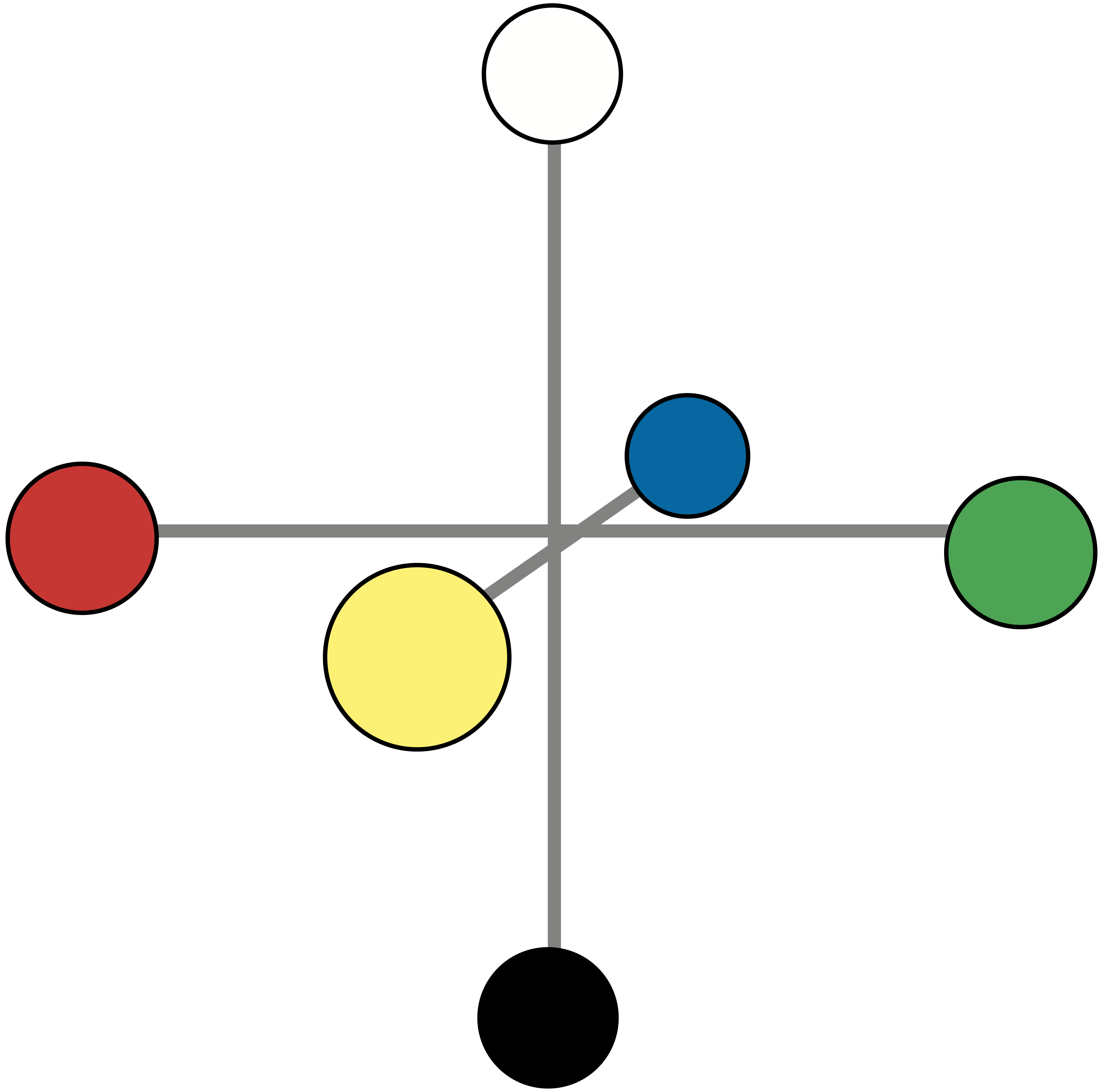

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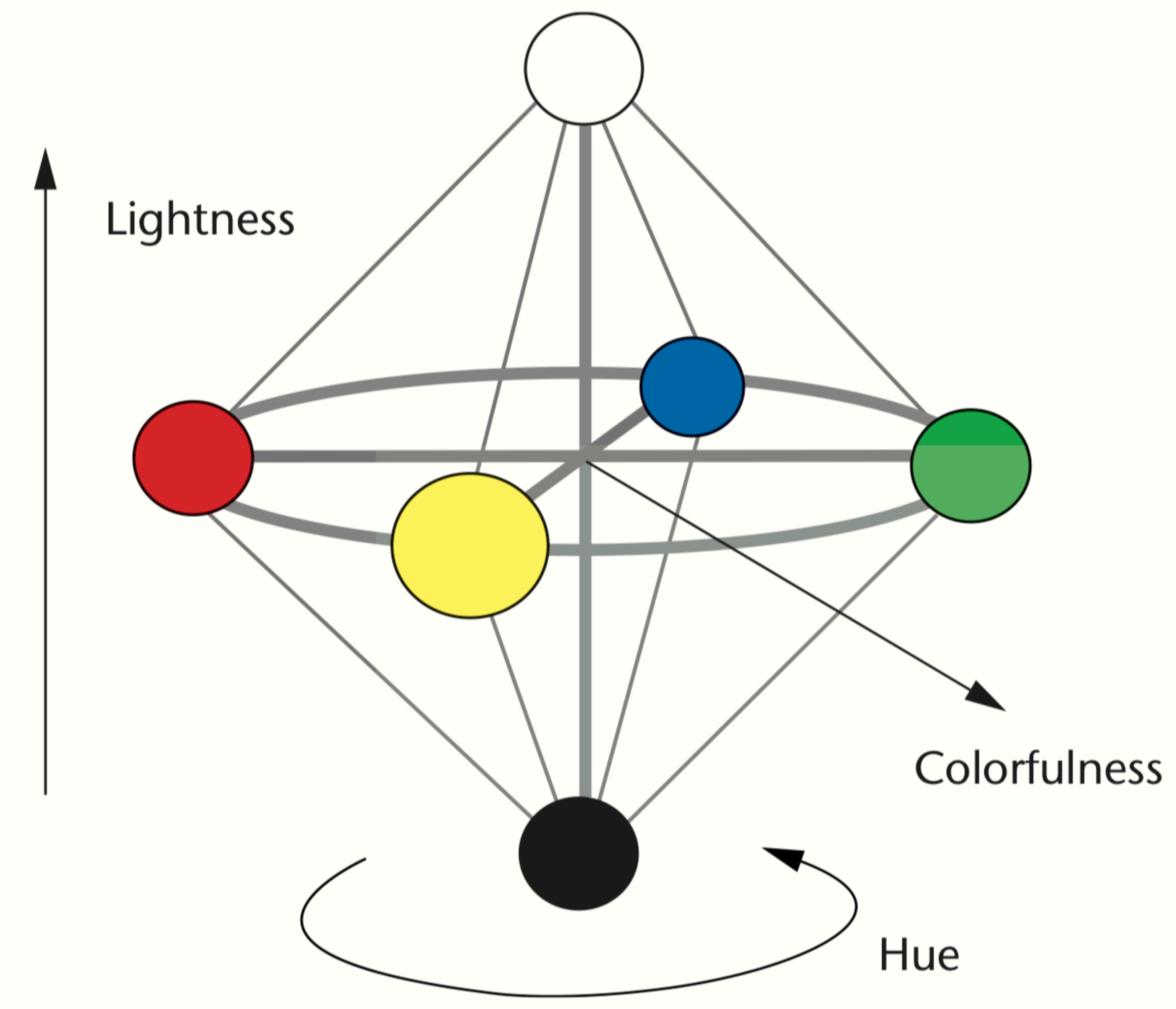
More perceptually uniform than sRGB.

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




The angry rainbow in sRGB.

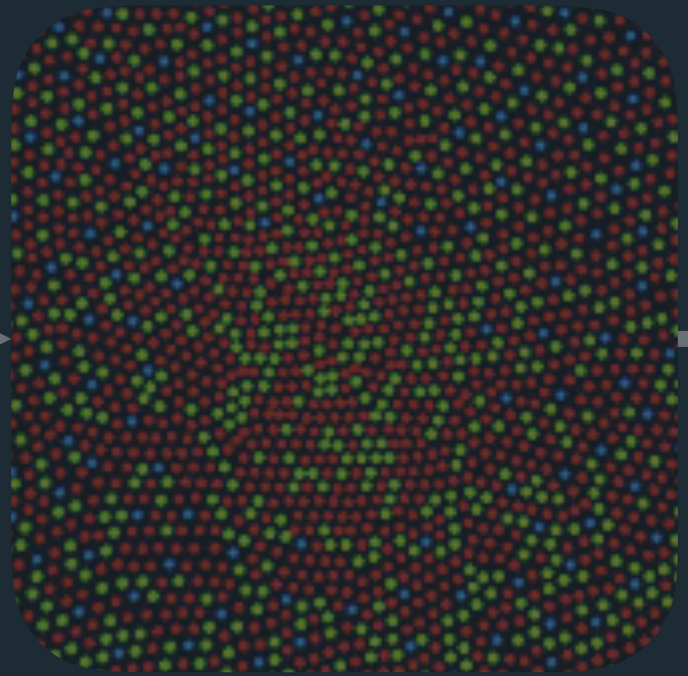
A happier rainbow in LAB.

# Modeling Color Perception

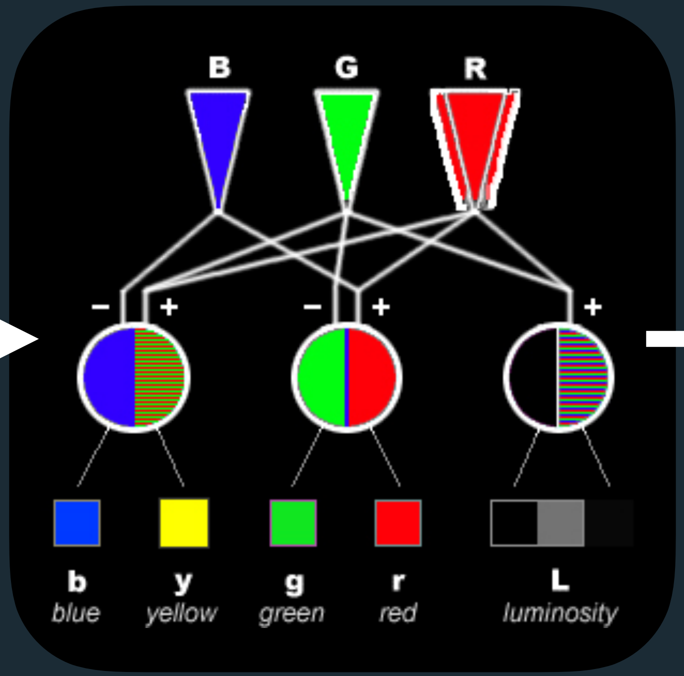
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light

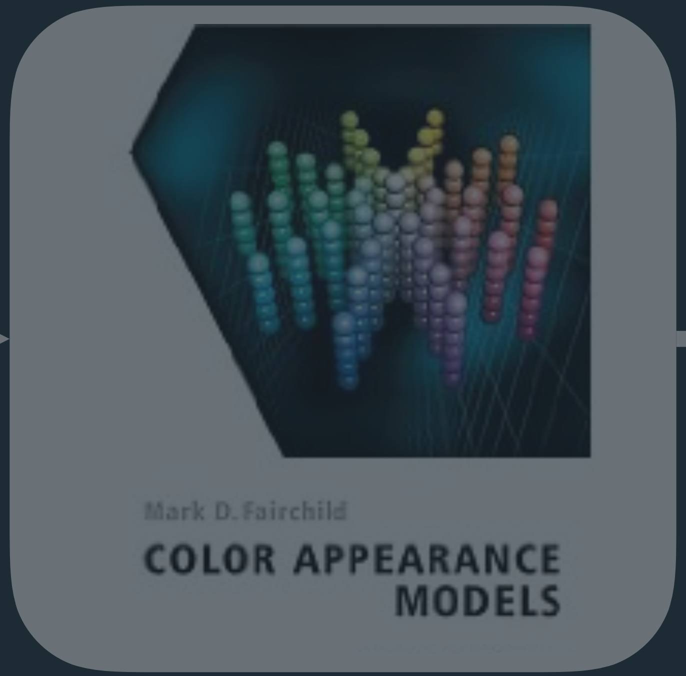


Cone Response




Opponent Encoding

Perceptual Models




Appearance Models

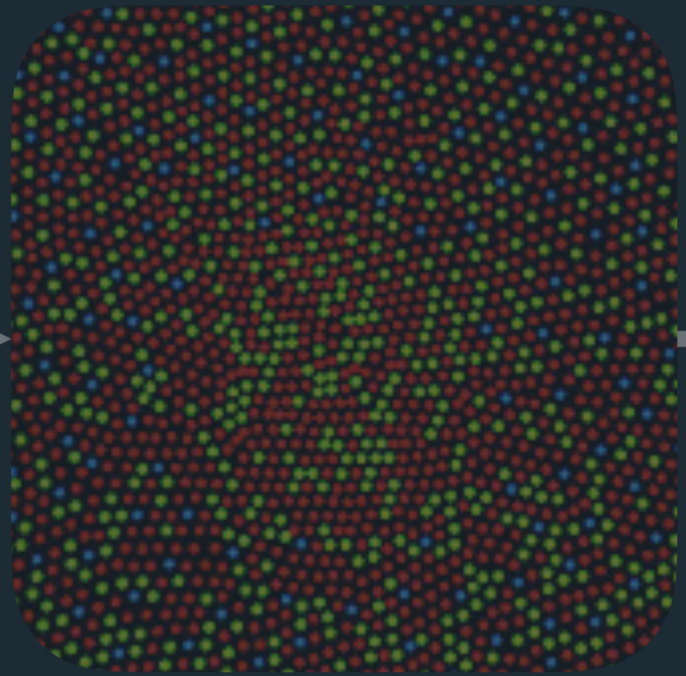
“Teal”

Cognitive Models

# Modeling Color Perception

Low-Level Abstraction High-Level

Physical World Visual System Mental Models





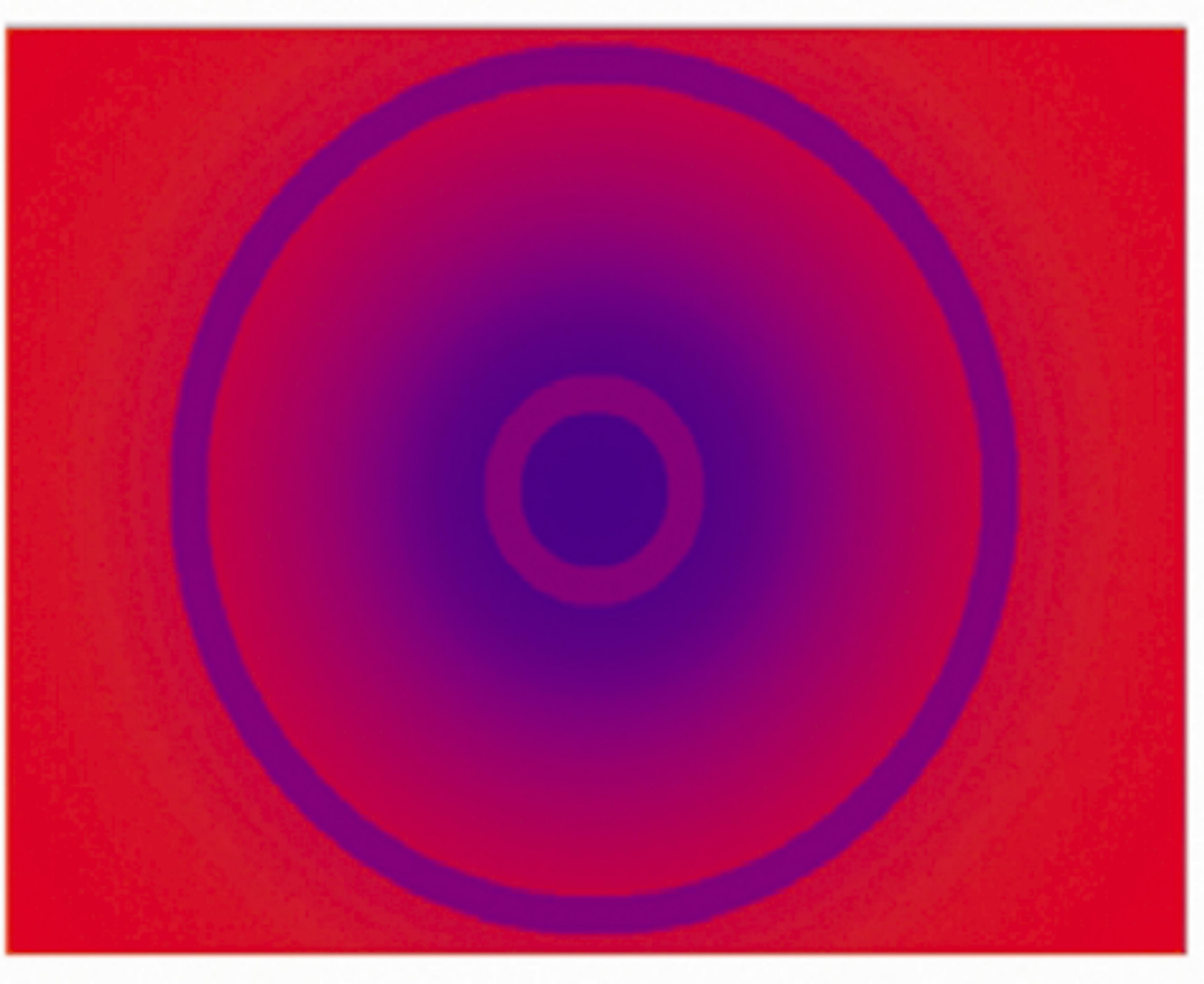
"Teal"

| 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

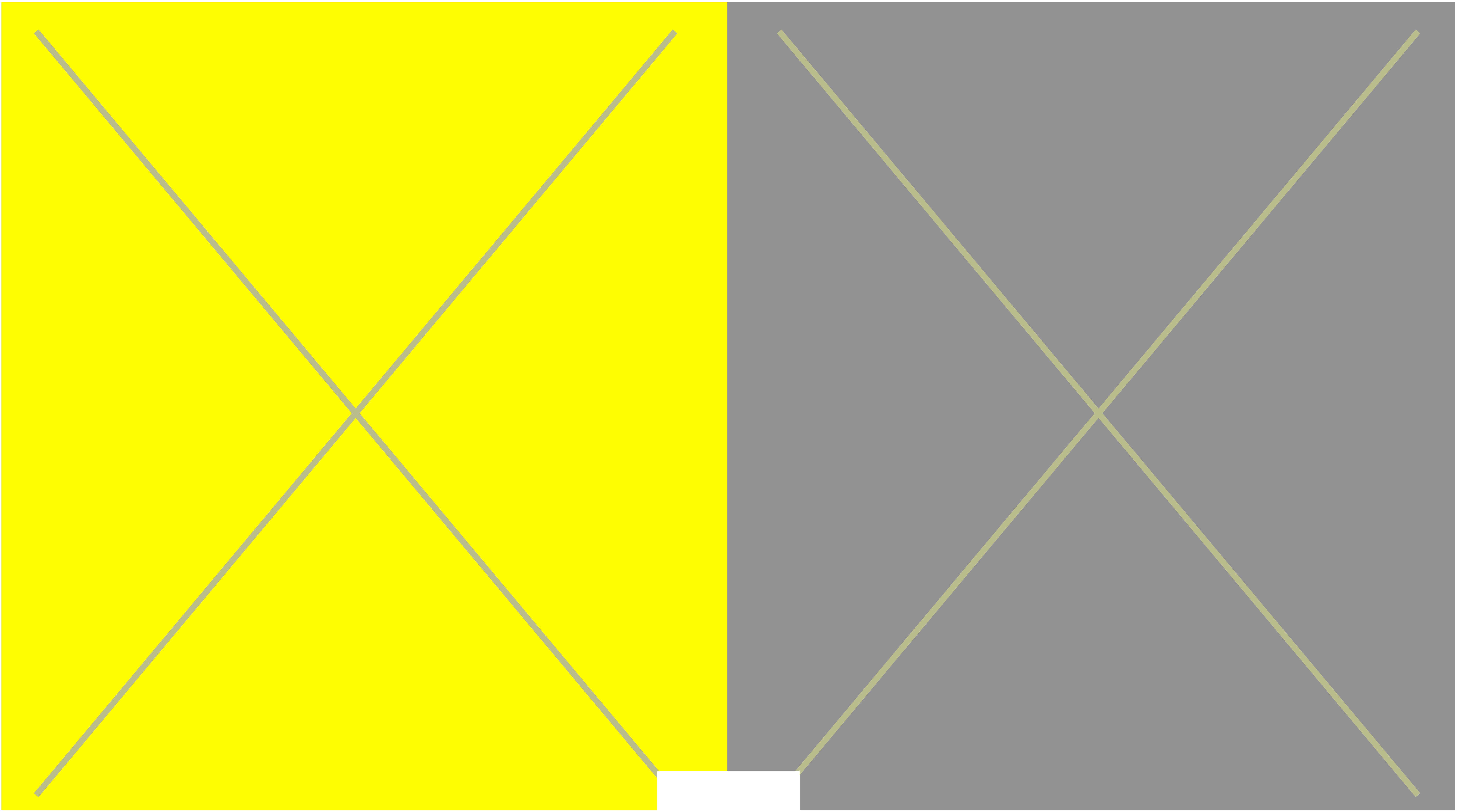
The inner and outer thin rings are,
in fact, the same physical purple!



Donald Macleod

# Simultaneous Contrast

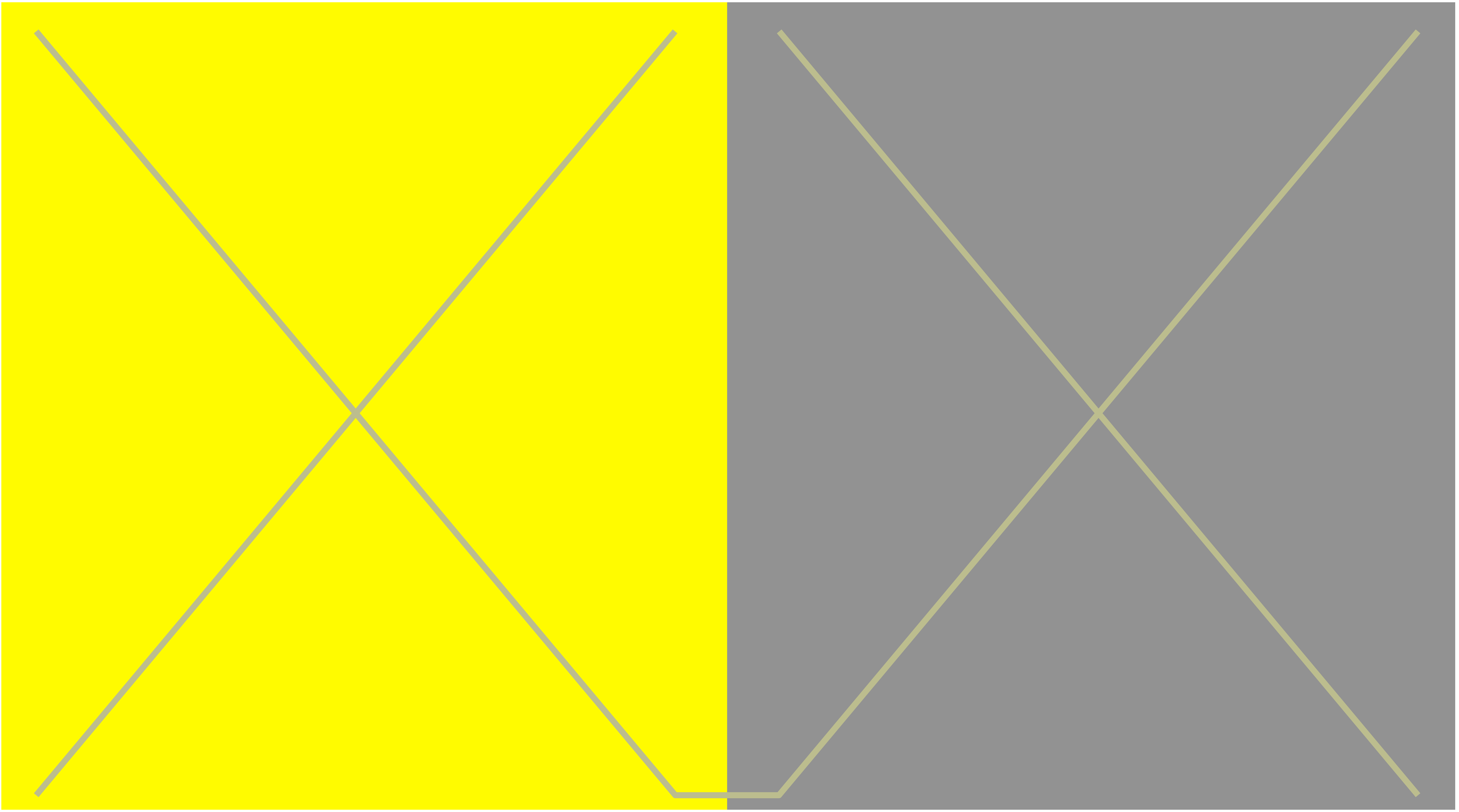
When two colors are side-by-side,
they interact and affect our perception



Josef Albers

# Simultaneous Contrast

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



Josef Albers

# Simultaneous Contrast

When two colors are side-by-side,
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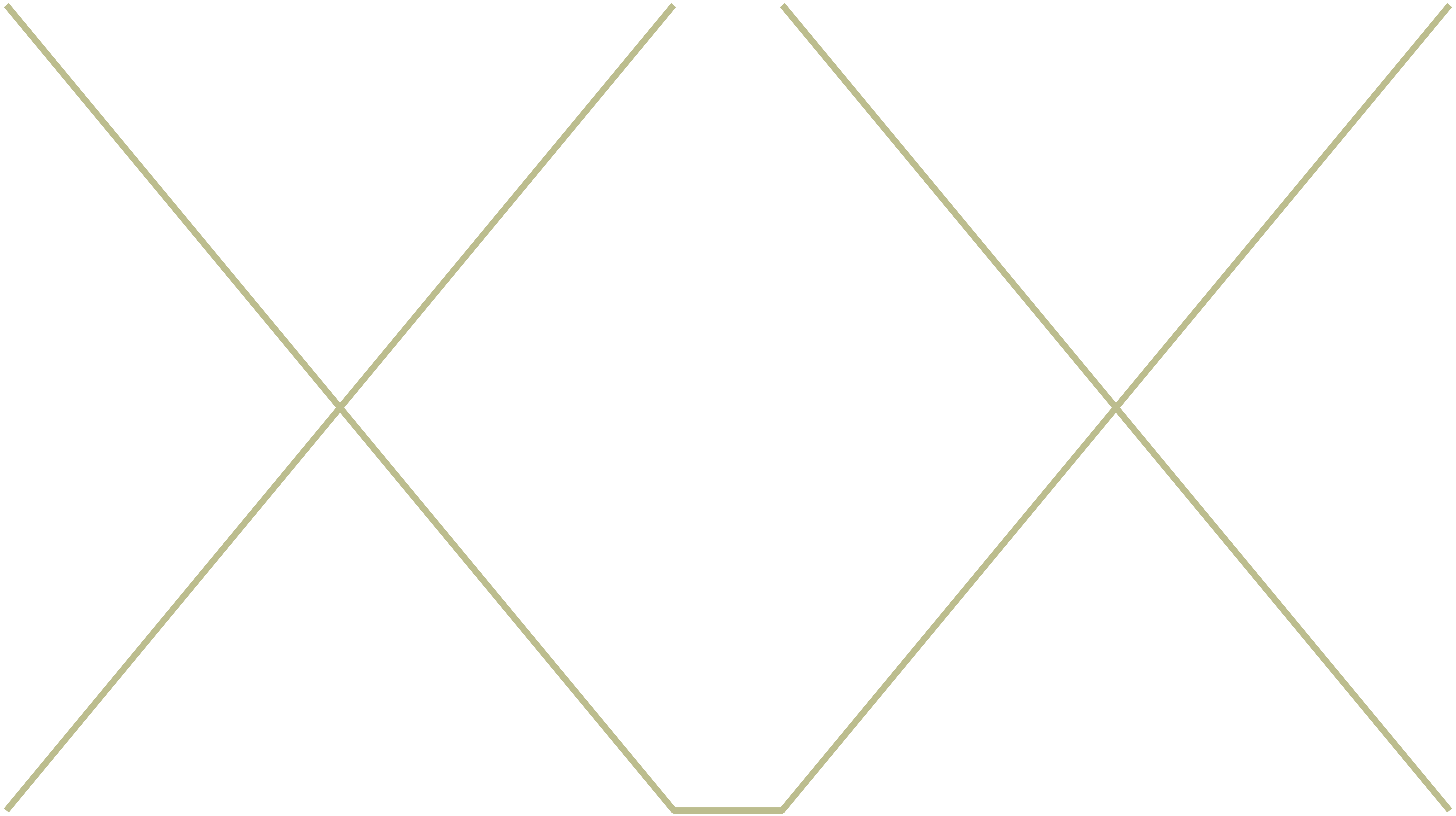
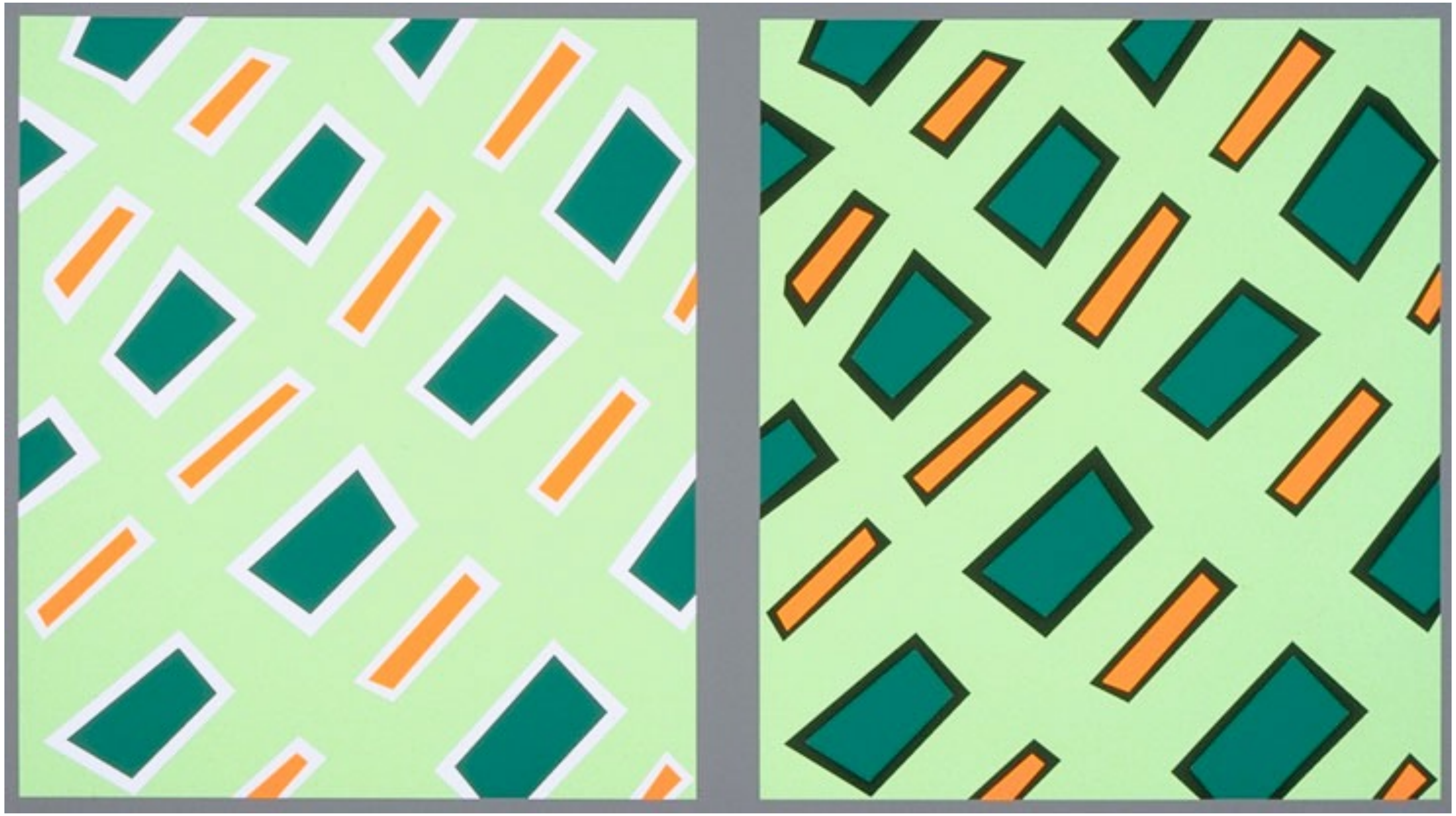


Josef Albers

# 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

Our ability to adjust to color perception based on illumination

Jason Su

# Chromatic Adaptation

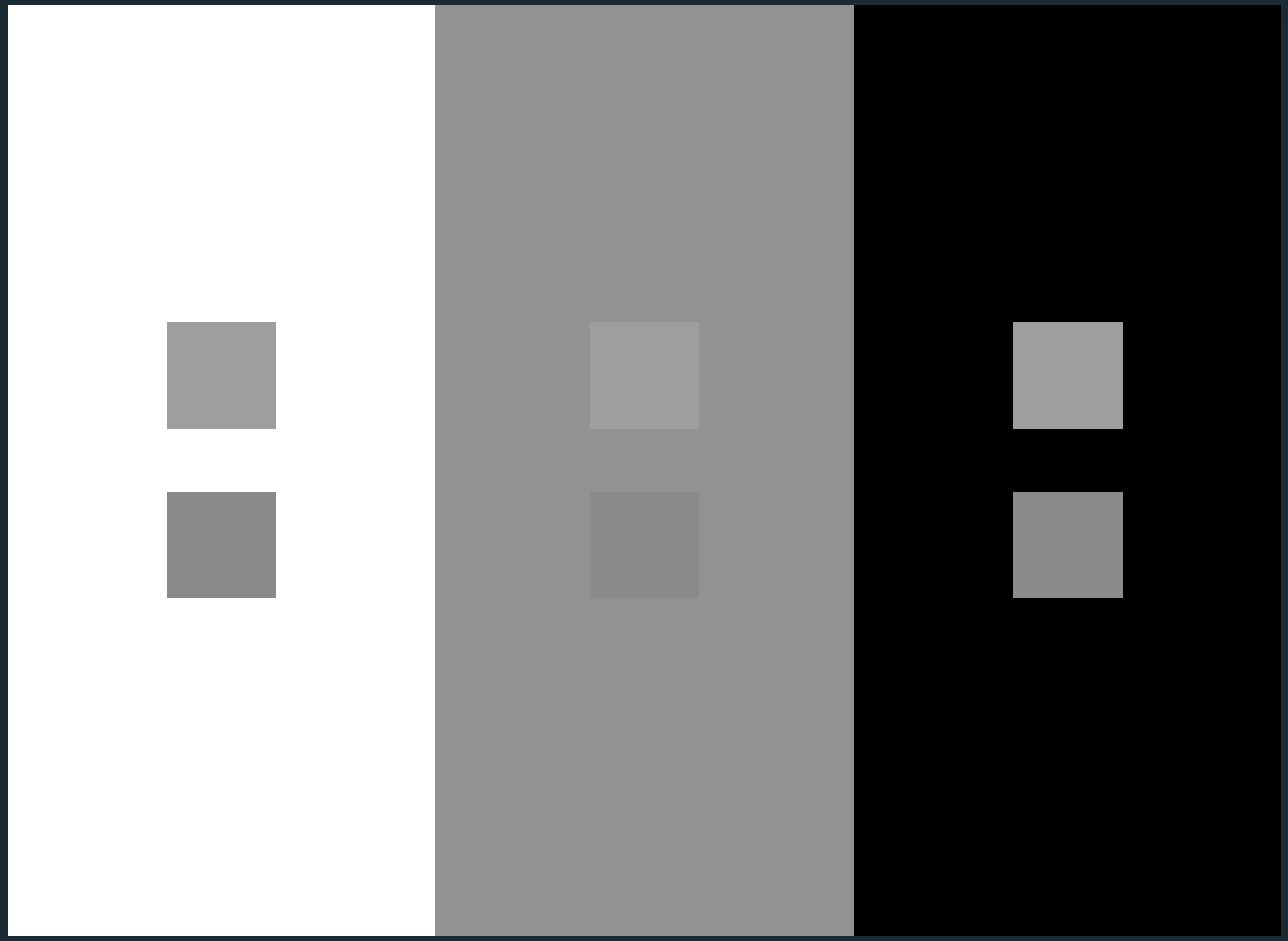
Our ability to adjust to color perception based on illumination

# Chromatic Adaptation

Our ability to adjust to color perception based on illumination

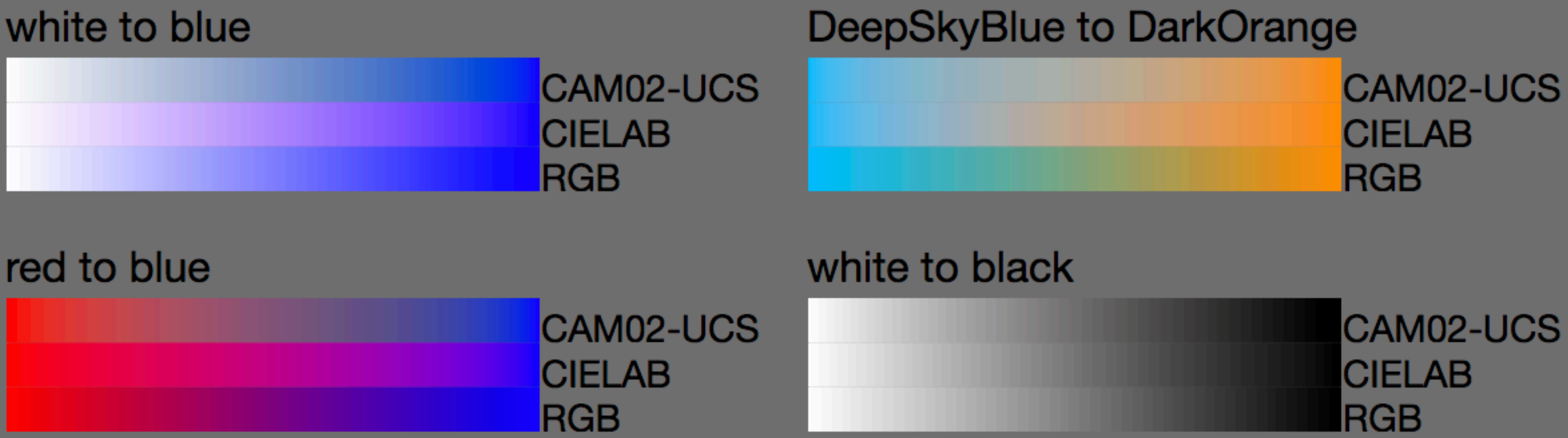
# Chromatic Adaptation

Perceived difference depends on background.



# Color Appearance Models

If we have a perceptually-uniform color space, can we predict how we perceive colors?

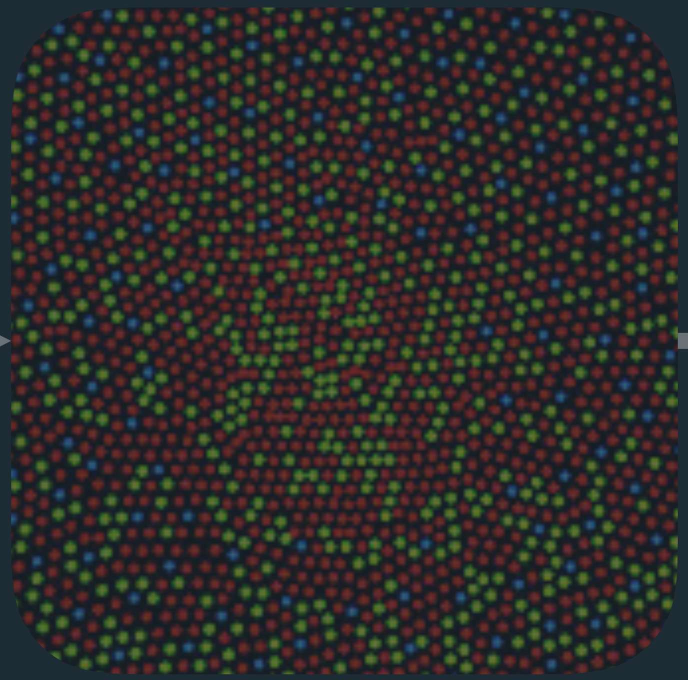


# Modeling Color Perception

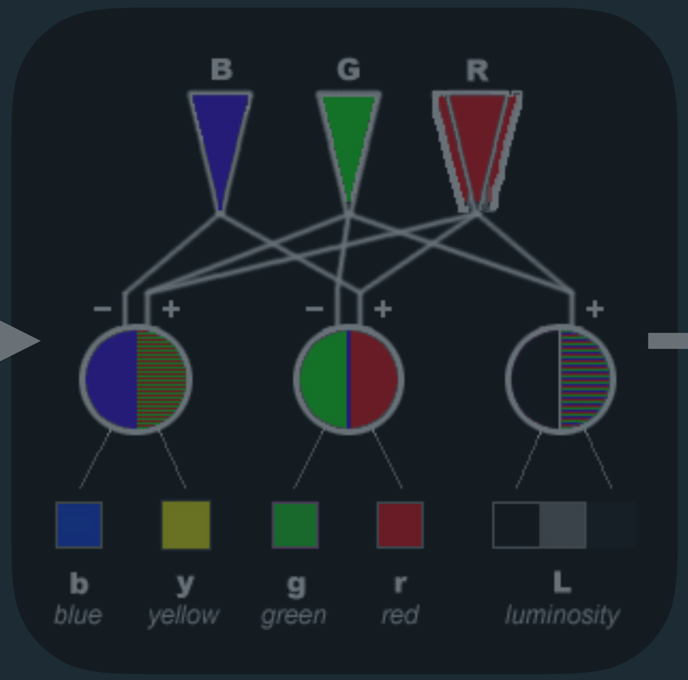
Low-Level Abstraction High-Level

Physical World Visual System Mental Models

Visible Light



Cone Response




Opponent Encoding

Perceptual Models


Appearance Models

"Teal"

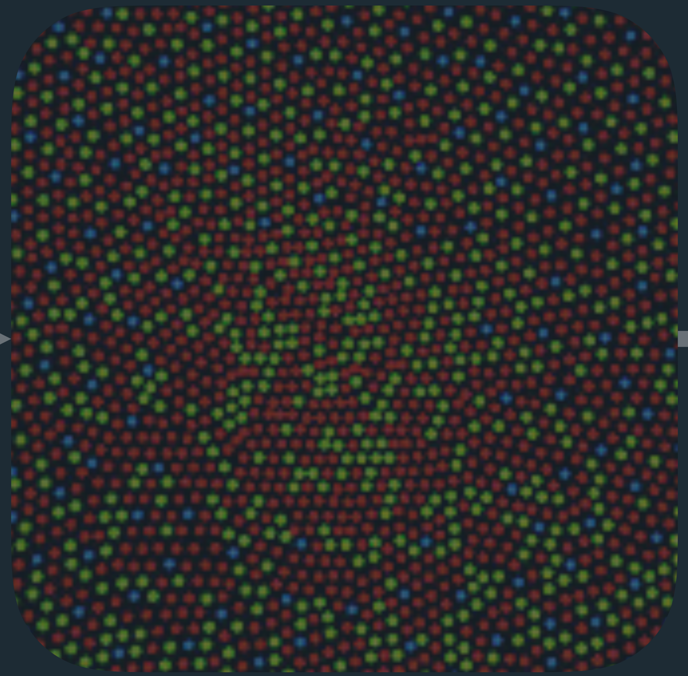
Cognitive Models

# Modeling Color Perception

Low-Level | Abstraction | High-Level

Physical World | Visual System | Mental Models

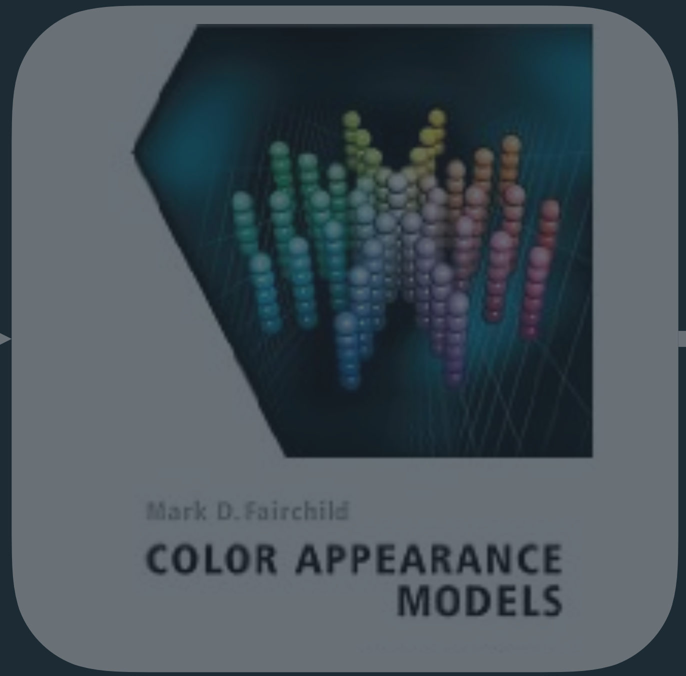
Visible Light



Cone Response


Opponent Encoding

Perceptual Models




Appearance Models

“Teal”

Cognitive Models

# 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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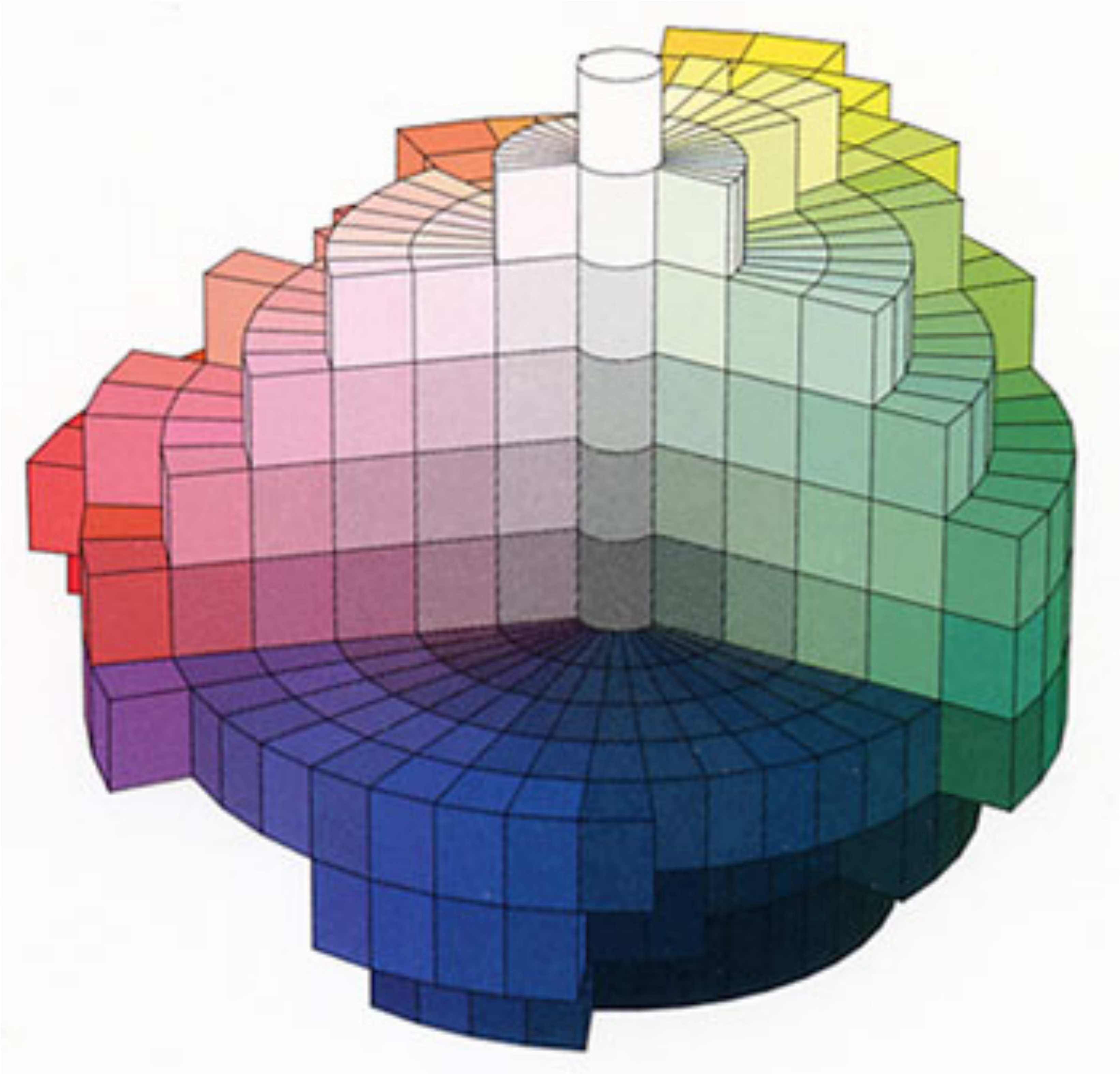

Name 320 Munsell color chips.
(Shares perceptual properties with CIE LAB, but predates it.)

# Color Naming

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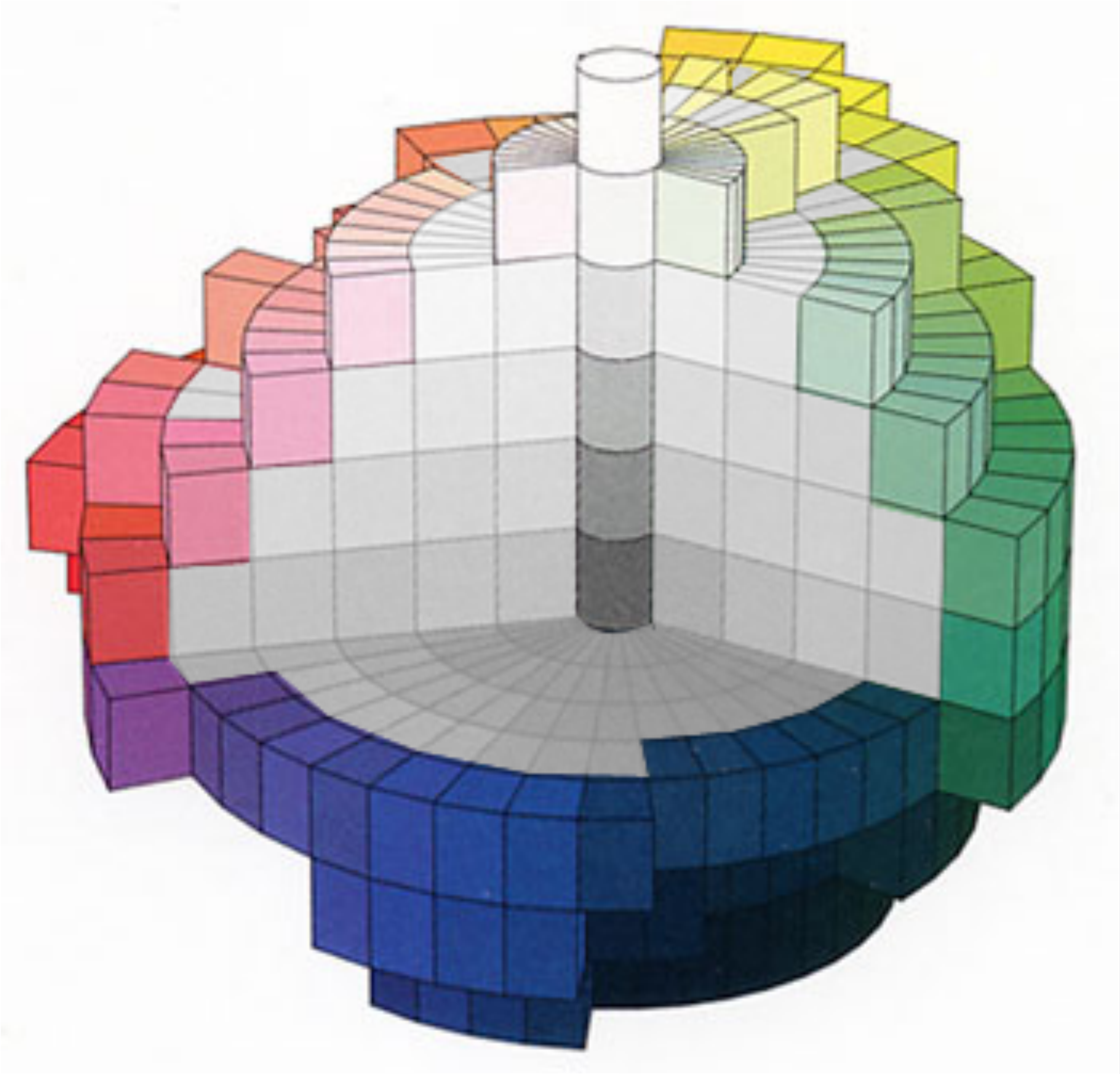


+10 achromatic chips

# Color Naming

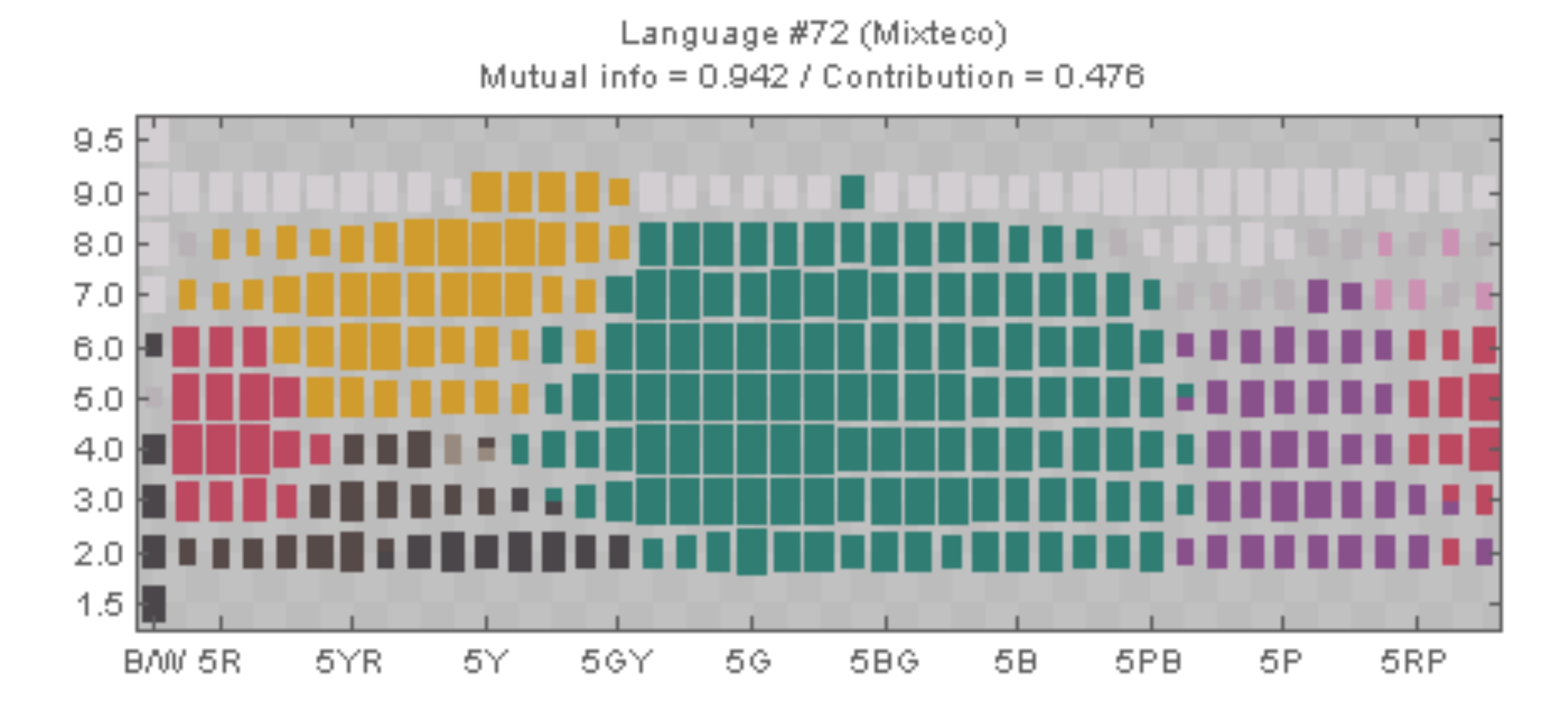
Is color naming universal? Do languages evolve color terms in similar ways?

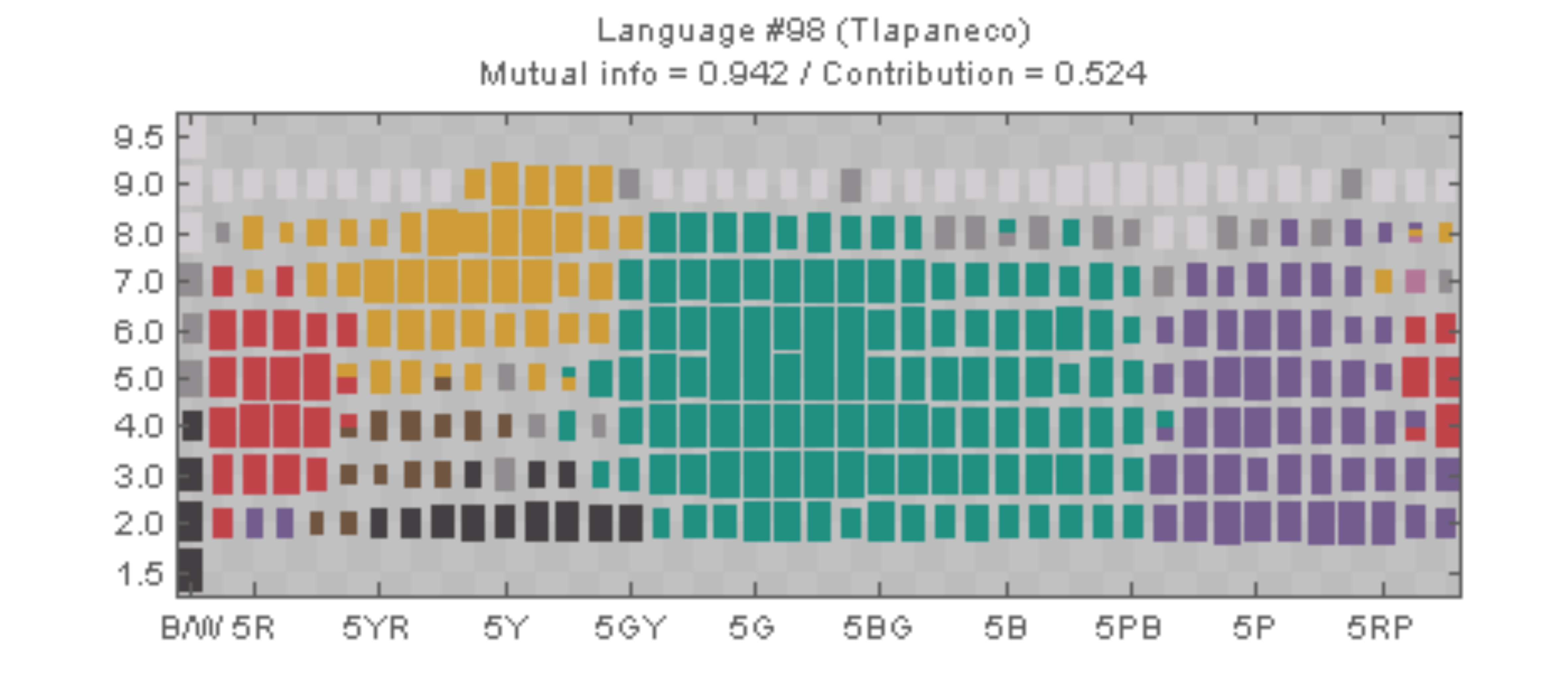

WCS stimulus array. For each basic color term ($t$) participants named, they were asked:

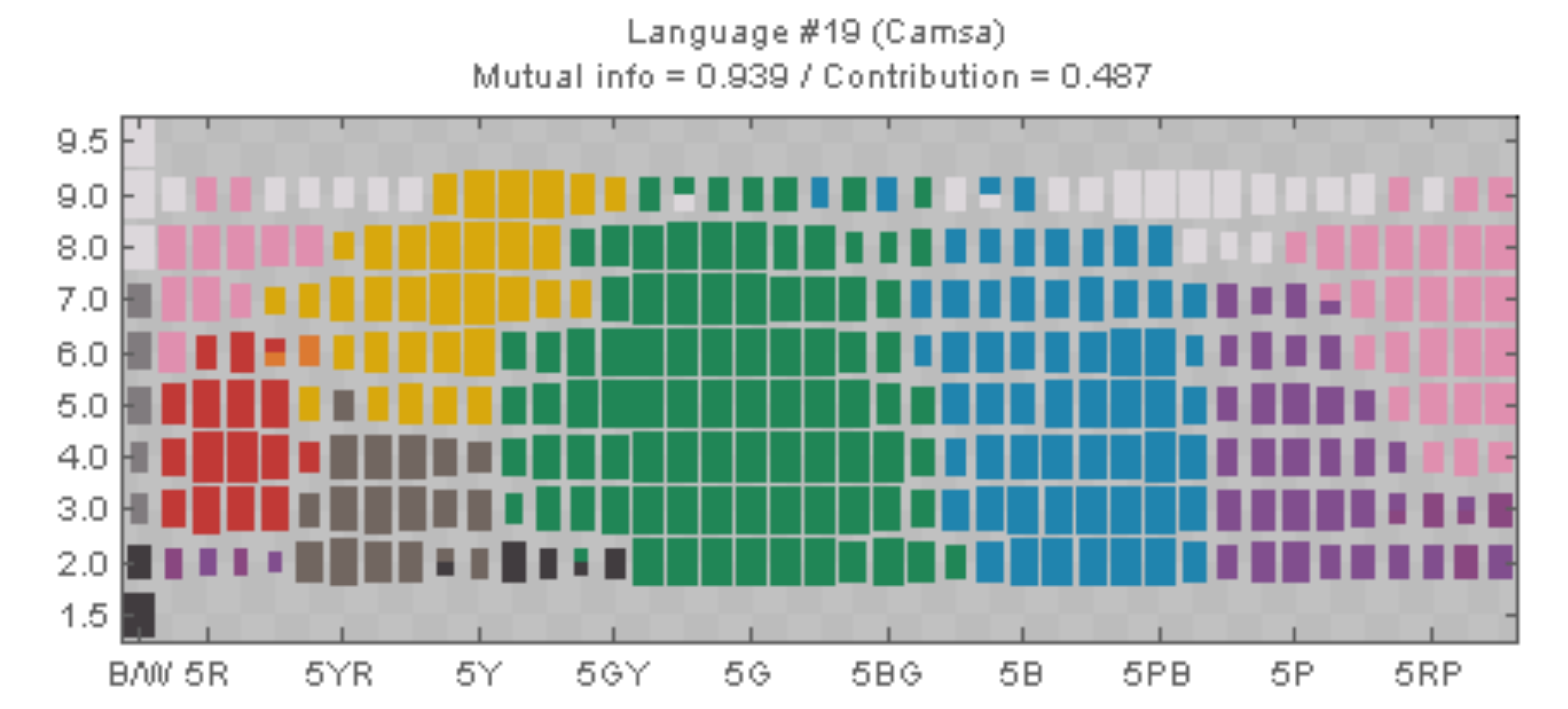
1. Mark all chips that you would call $t$.
2. Which chip is the best example(s) of $t$.

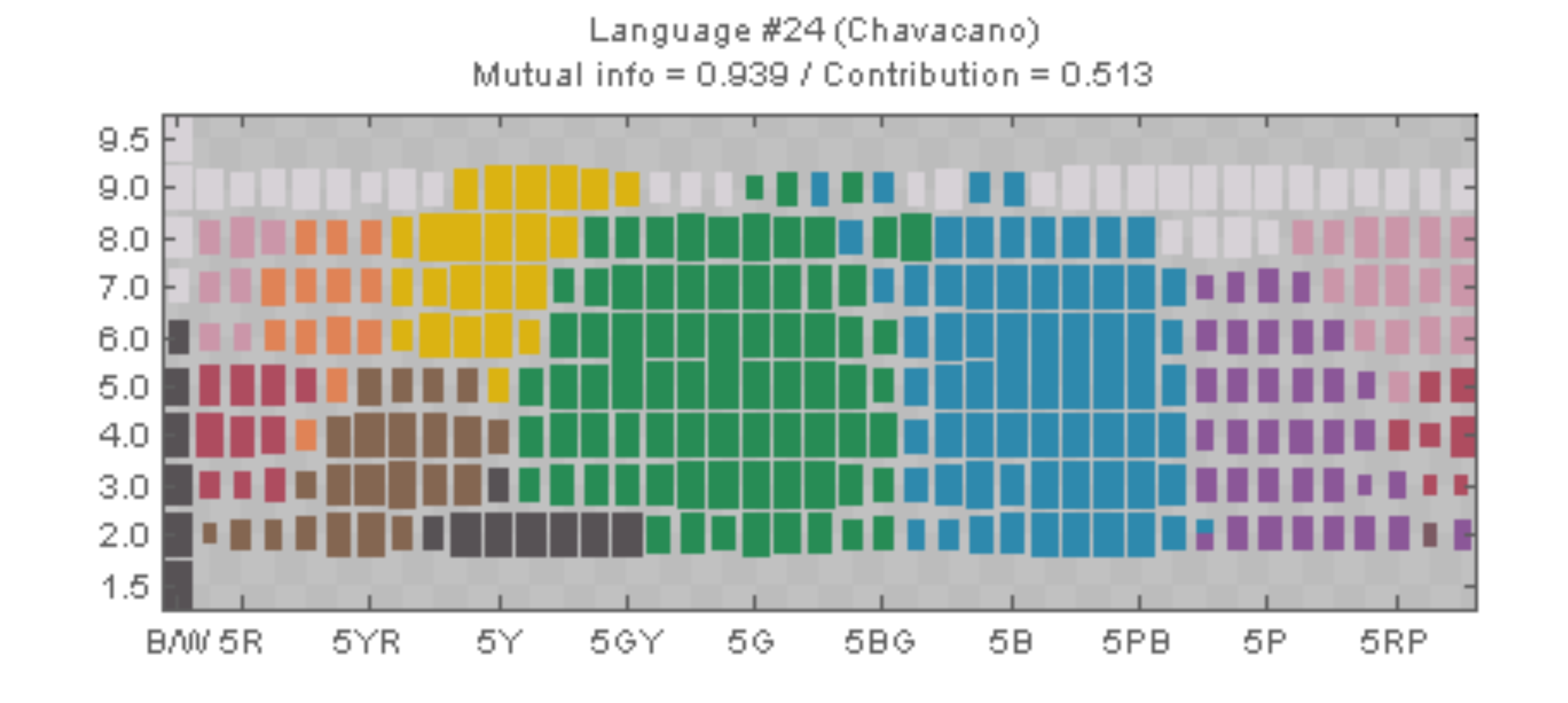
# Color Naming

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?

Basic color terms recur across languages:

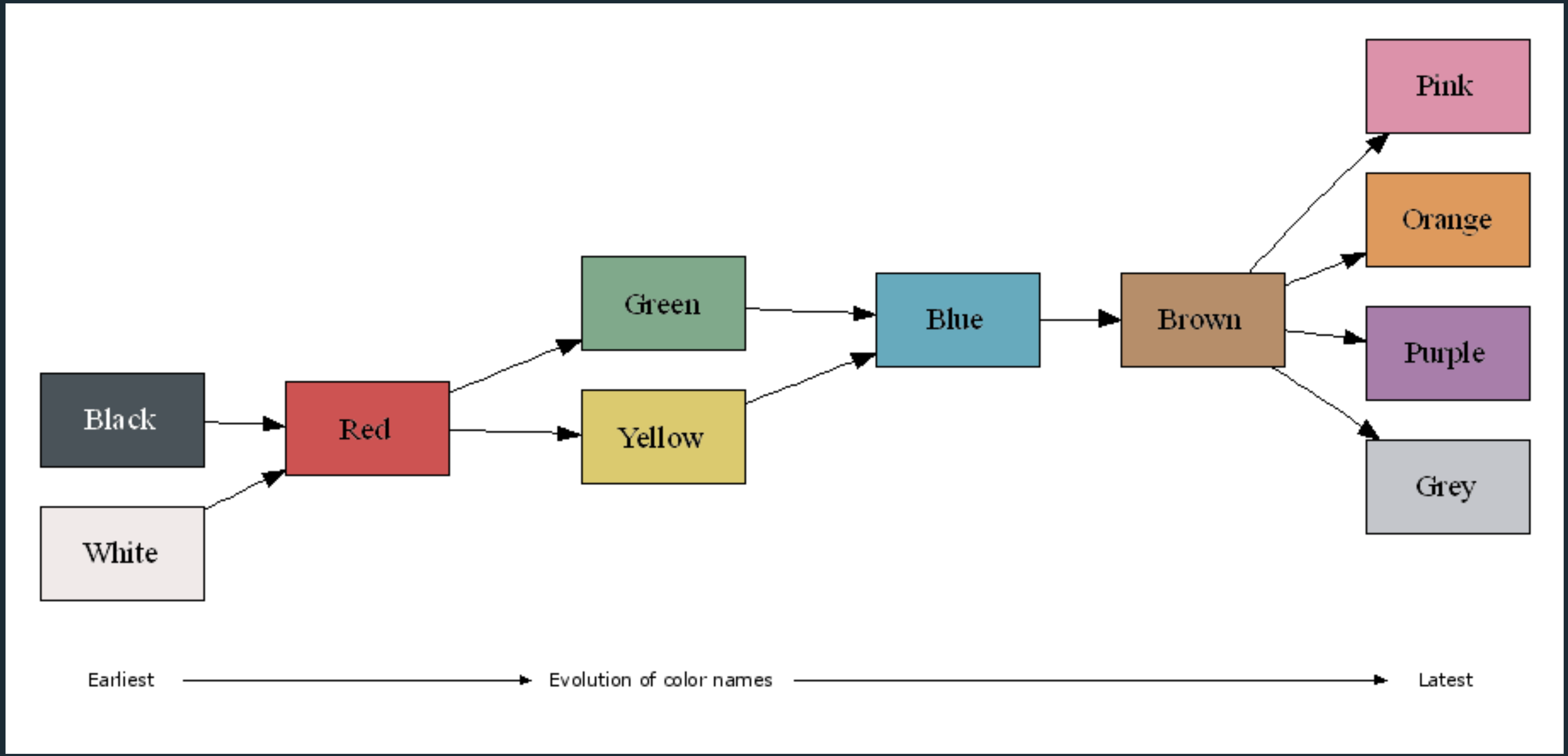
White Black Grey

Red Yellow

Green Blue

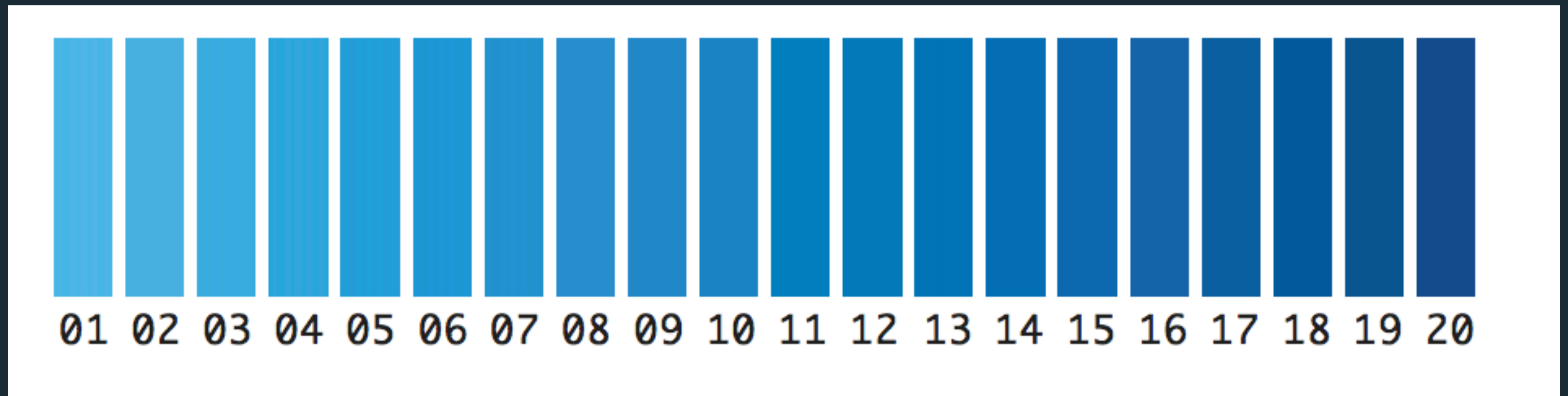
Pink Brown

Orange Purple



# 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”).
- How does this affect color perception?

# 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").

How does this affect color perception?

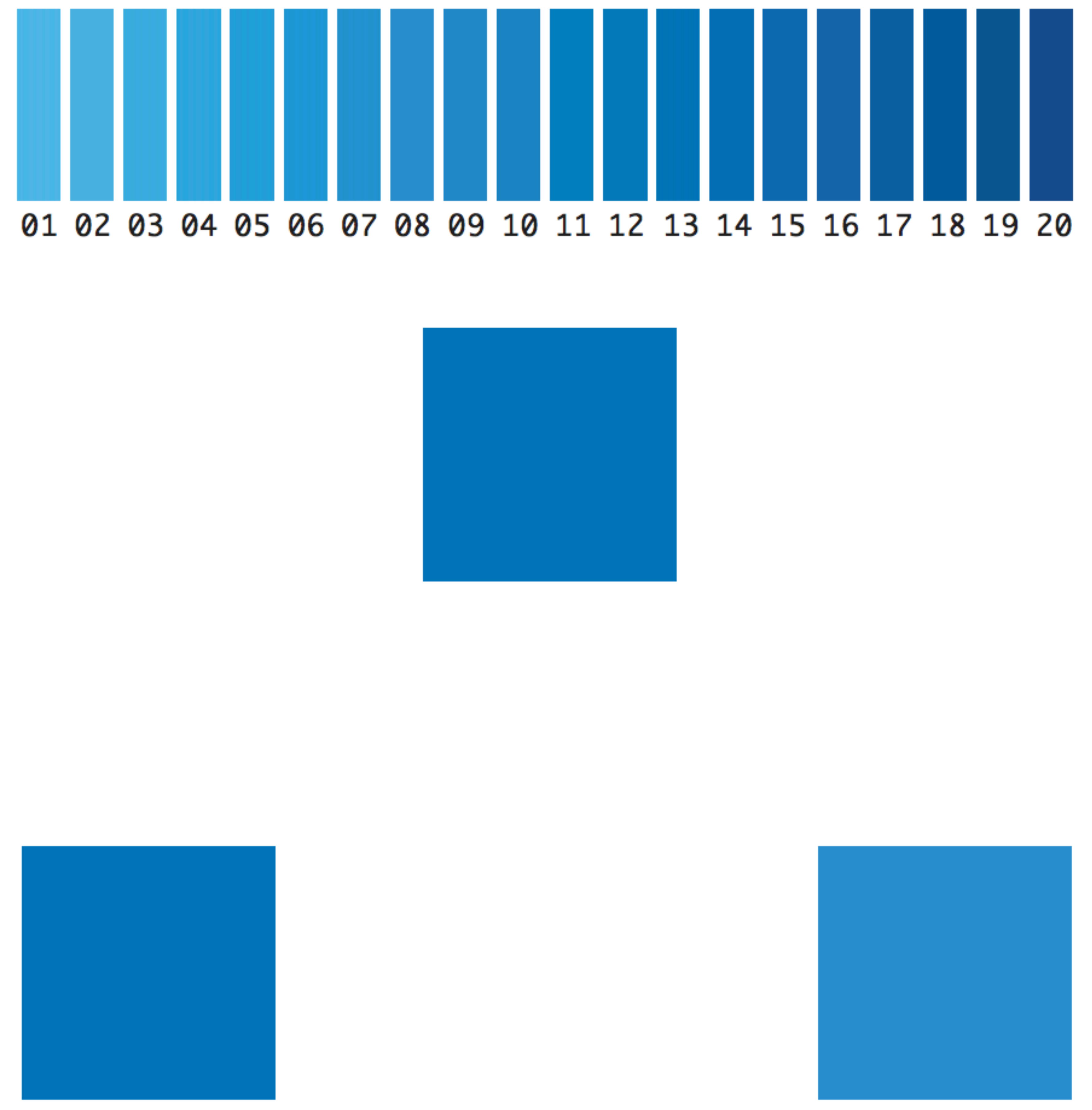



**Fig. 1.** The 20 blue colors used in this study are shown at the top of the figure. An example triad of color squares used in this study is shown at the bottom of the figure. Subjects were instructed to pick which one of the two bottom squares matched the color of the top square.

# Color Naming

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

Winawer et al, 2007.

- 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).

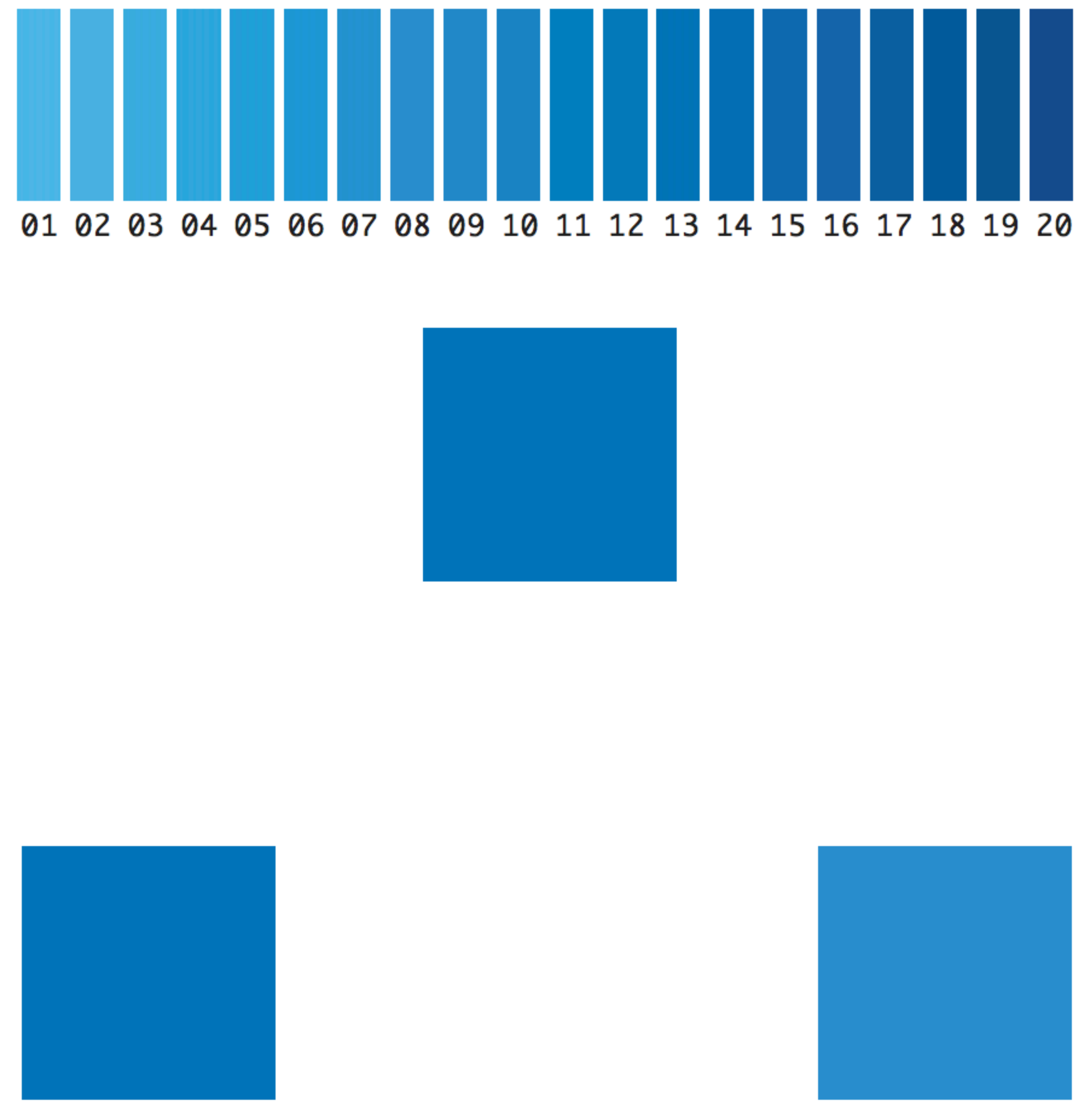


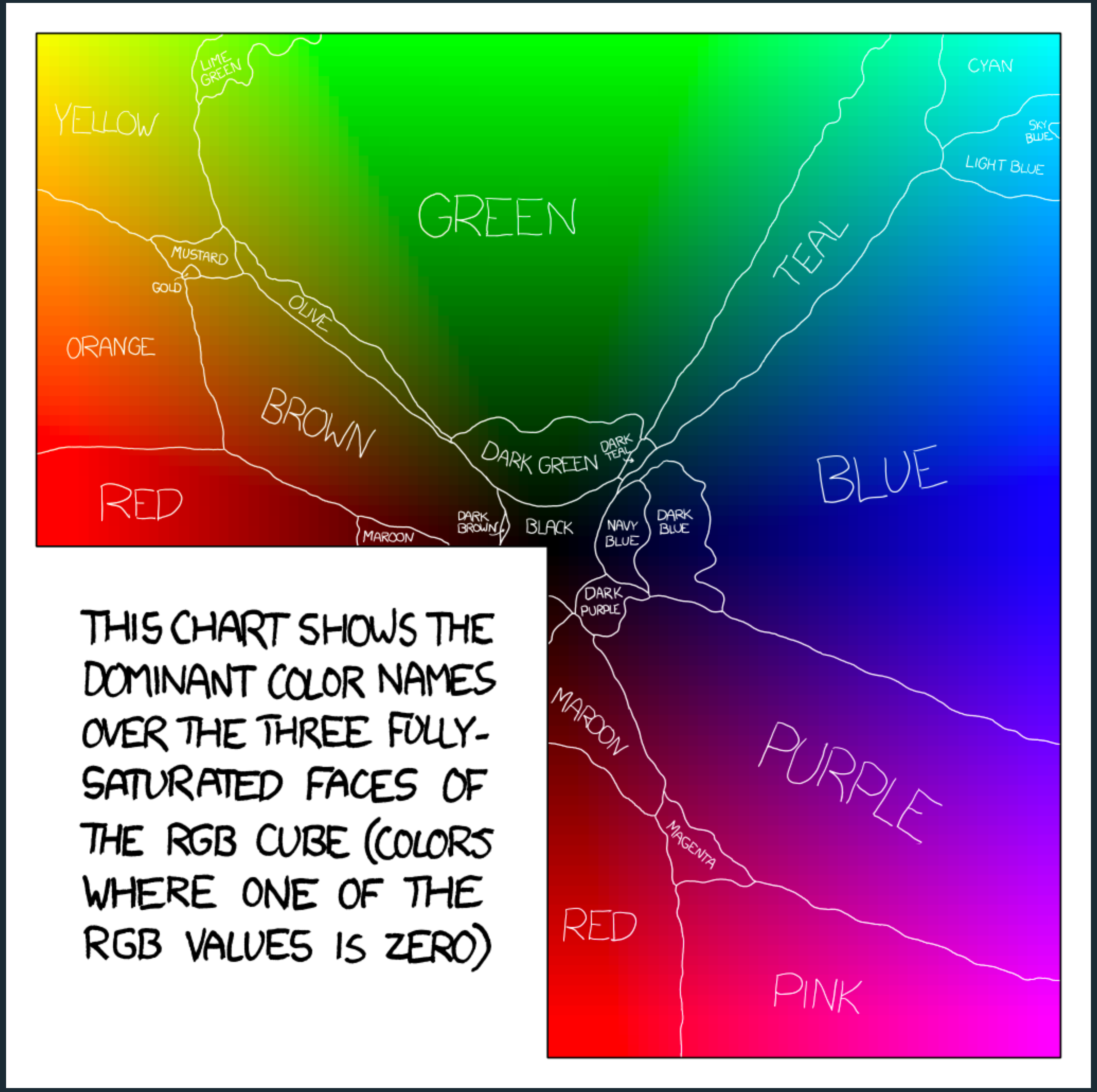

**Fig. 1.** The 20 blue colors used in this study are shown at the top of the figure. An example triad of color squares used in this study is shown at the bottom of the figure. Subjects were instructed to pick which one of the two bottom squares matched the color of the top square.

# Color Naming Models

[Heer and Stone, CHI 2012]

Modeled 3 million responses from the XKCD color survey.

P(color | name)



# Color Naming Models

[Heer and Stone, CHI 2012]

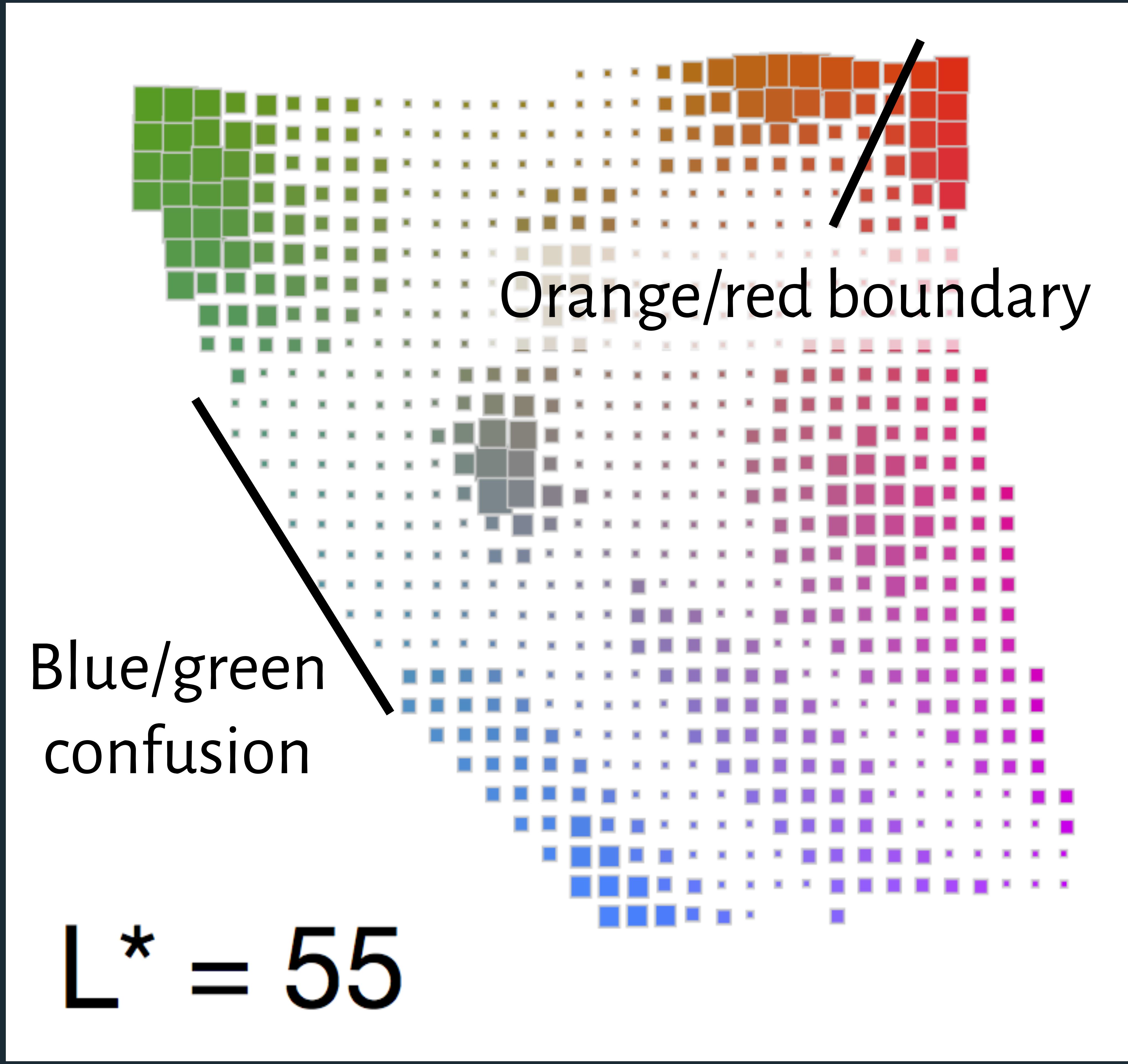
Modeled 3 million responses from the XKCD color survey.

P(color | name)

Metrics for:

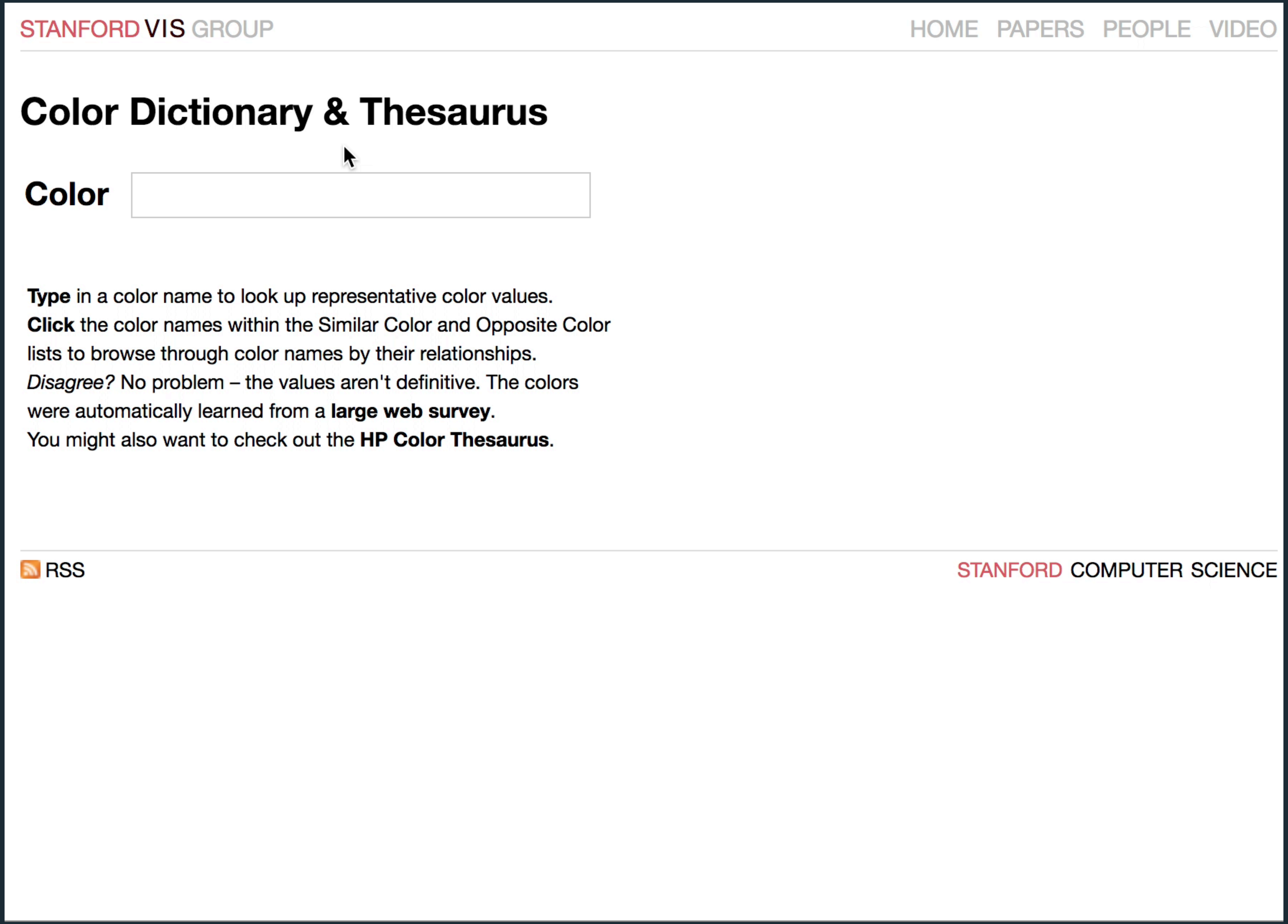
*color saliency* – how reliable is a color name?

*color name distance* – similarity between colors based on naming patterns.



# Color Naming Models

[Heer and Stone, CHI 2012]




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

# UNITED STATES FREQUENCY ALLOCATIONS

## THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND


ACTIVITY CODE

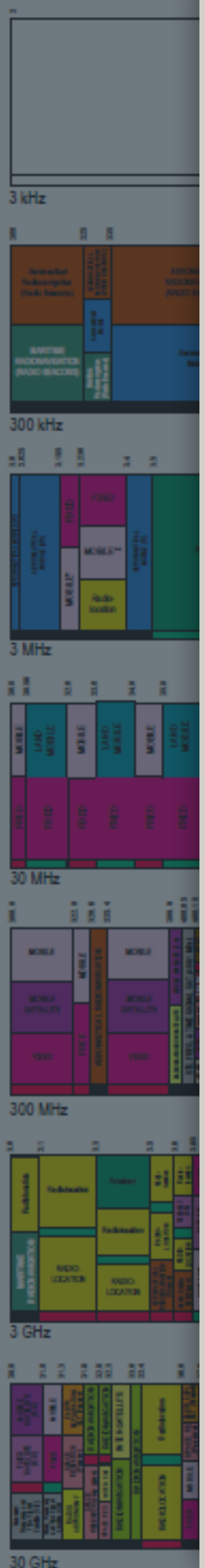

ALLOCATION USAGE DESIGNATION

| SERVICE | EXAMPLE | DESCRIPTION |
|---|---|---|


http://www.ntia.doc.gov/osmhome/allochrt.html

# UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM



## RADIO SERVICES COLOR LEGEND

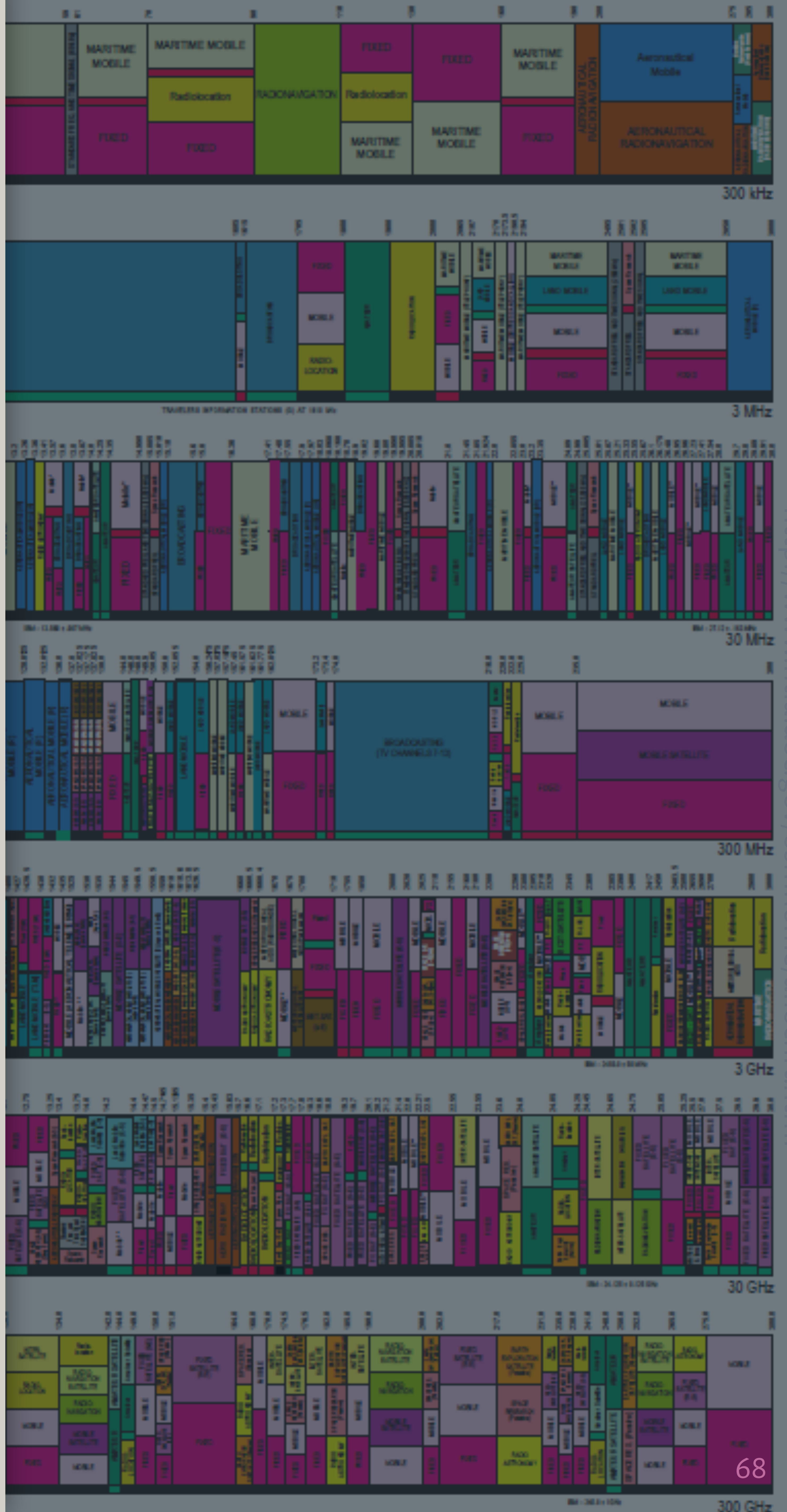
| | | |
|---|---|---|
| AERONAUTICAL MOBILE | INTER-SATELLITE | RADIO ASTRONOMY |
| AERONAUTICAL MOBILE SATELLITE | LAND MOBILE | RADIODETERMINATION SATELLITE |
| AERONAUTICAL RADIONAVIGATION | LAND MOBILE SATELLITE | RADIOLOCATION |
| AMATEUR | MARITIME MOBILE | RADIOLOCATION SATELLITE |
| AMATEUR SATELLITE | MARITIME MOBILE SATELLITE | RADIONAVIGATION |
| BROADCASTING | MARITIME RADIONAVIGATION | RADIONAVIGATION SATELLITE |
| BROADCASTING SATELLITE | METEOROLOGICAL AIDS | SPACE OPERATION |
| EARTH EXPLORATION SATELLITE | METEOROLOGICAL SATELLITE | SPACE RESEARCH |
| FIXED | MOBILE | STANDARD FREQUENCY AND TIME SIGNAL |
| FIXED SATELLITE | MOBILE SATELLITE | STANDARD FREQUENCY AND TIME SIGNAL SATELLITE |

## ACTIVITY CODE

GOVERNMENT EXCLUSIVE

GOVERNMENT/NON-GOVERNMENT SHARED

NON-GOVERNMENT EXCLUSIVE



# Color Naming Models

[Heer and Stone, CHI 2012]

Helpful for palette design:

- 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* | |

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

# Color Naming Models

[Heer and Stone, CHI 2012]

Helpful for palette design:

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* | |

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

# Color Naming Models

[Lin et al., EuroVis 2013]

Helpful for palette design:

- Minimize overlap and ambiguity of colors.
- Select semantically resonant colors.

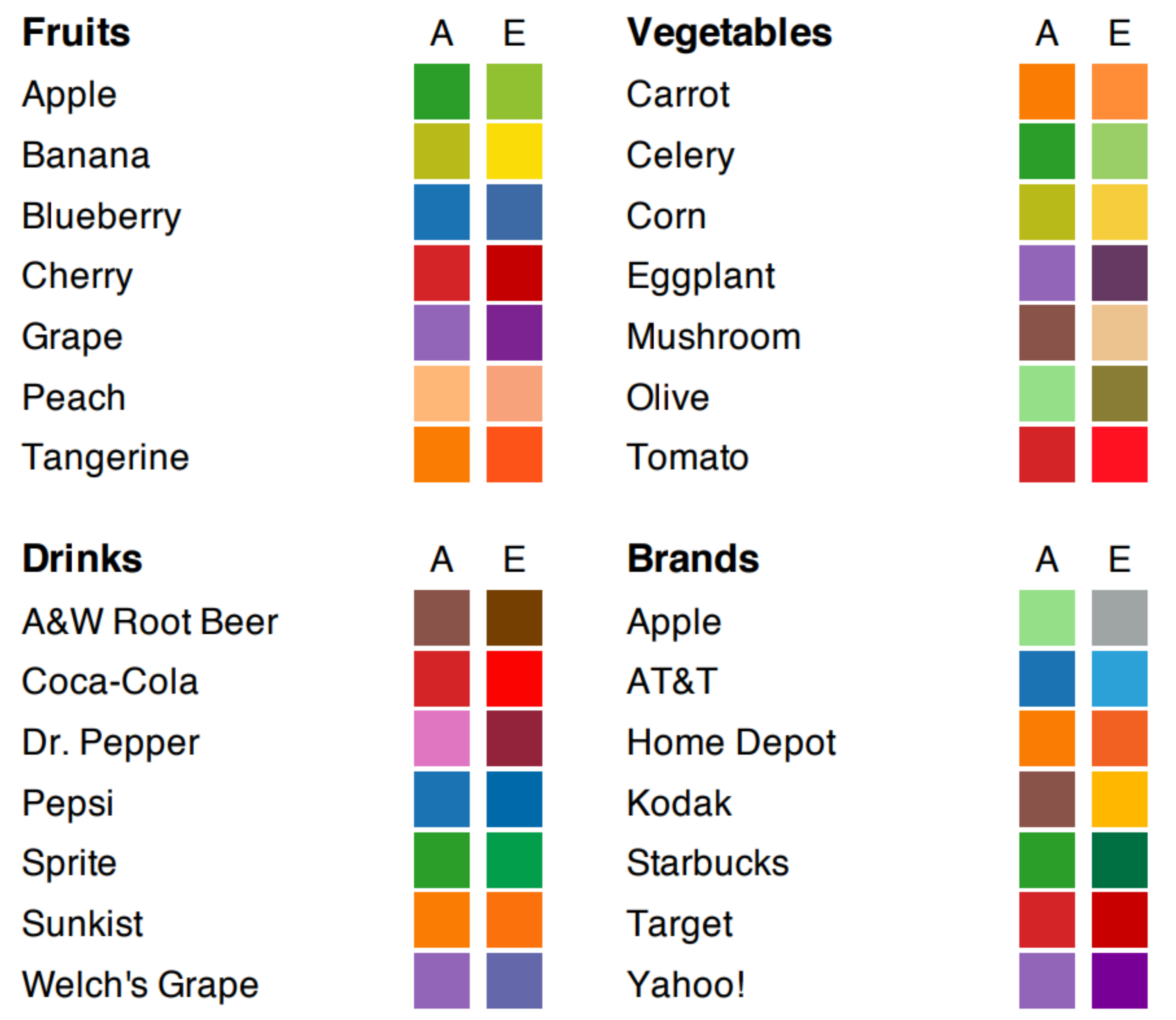
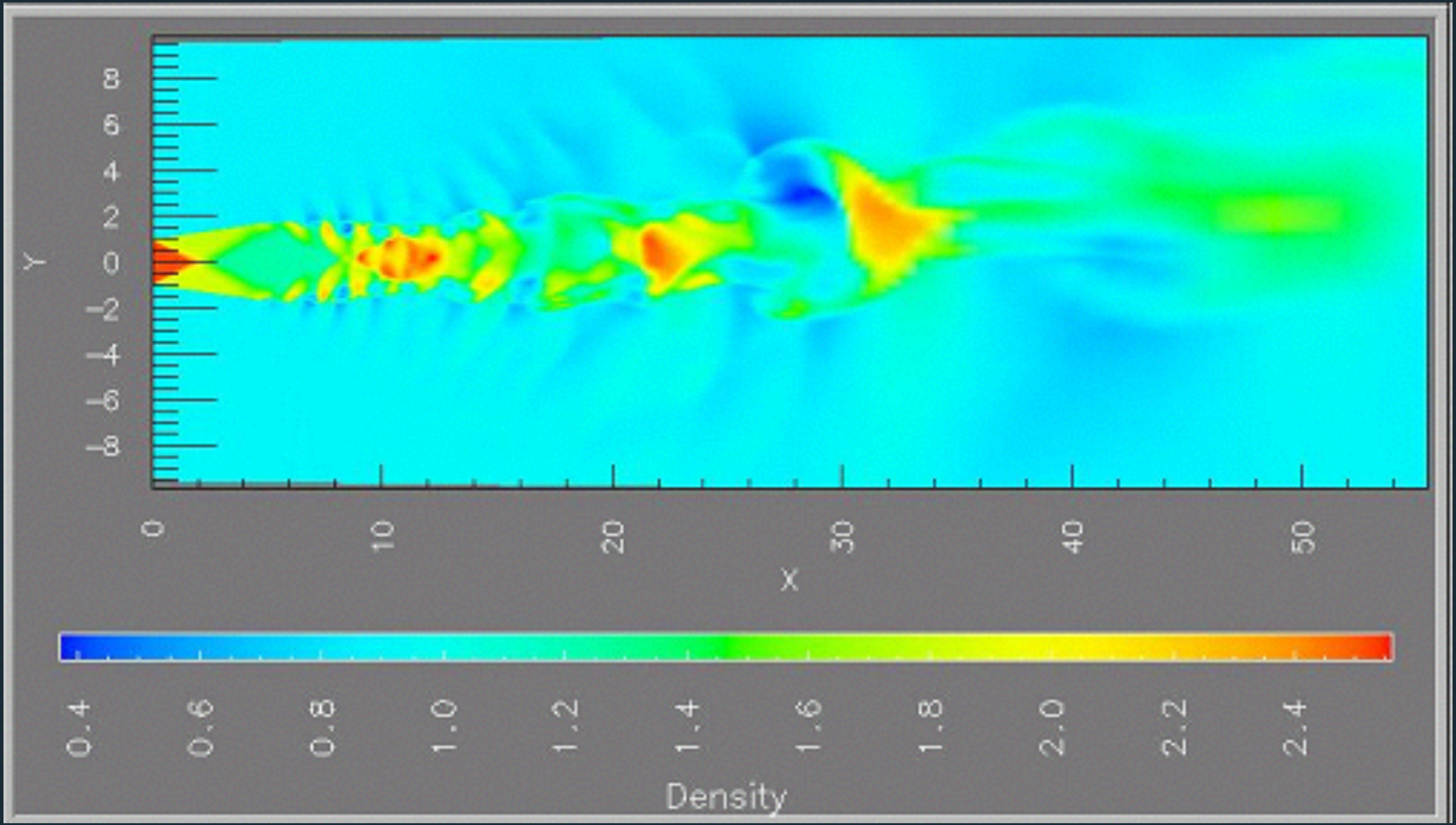


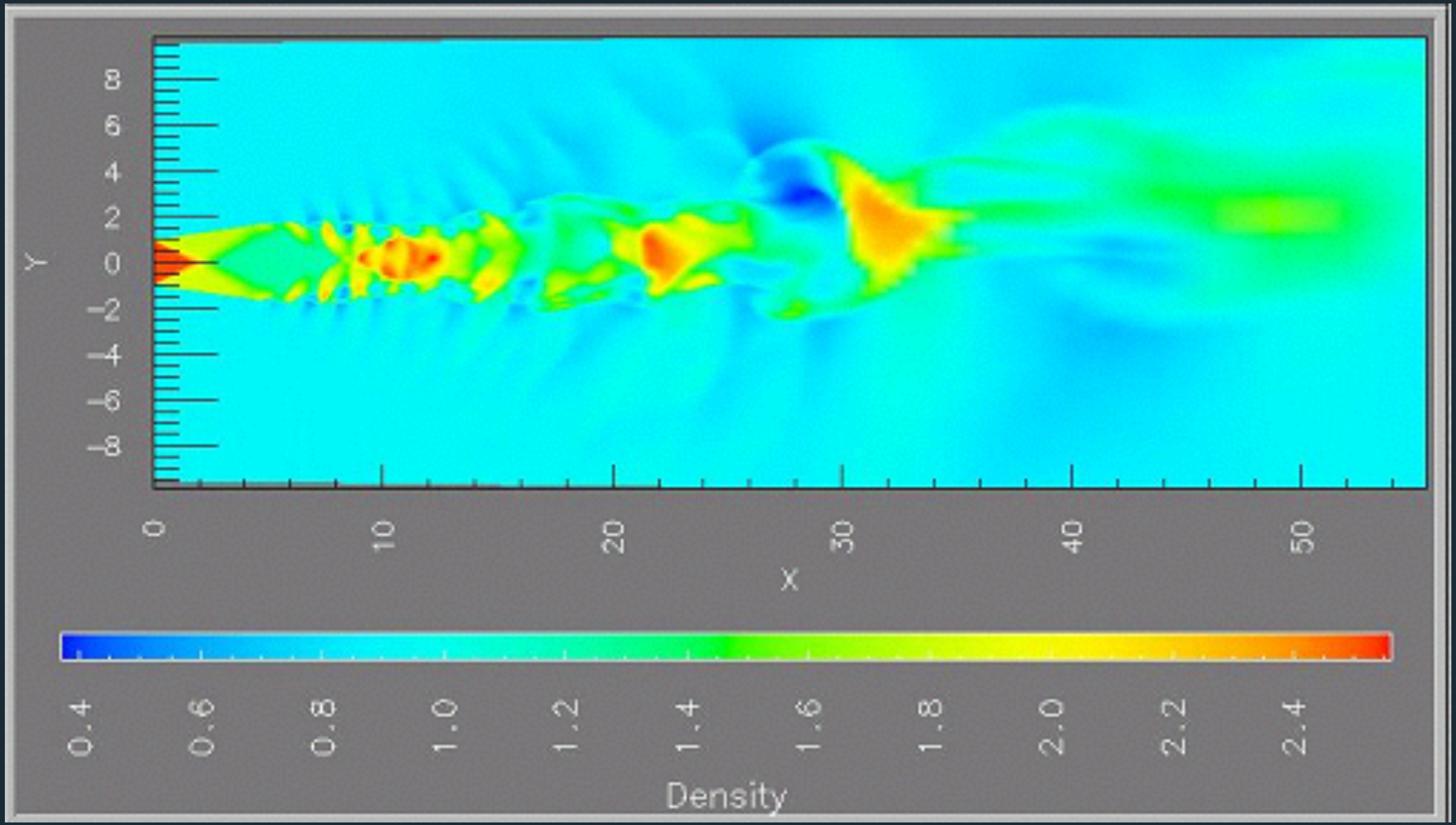

**Figure 6:** *Color assignments for categorical values in Experiment 1. (A = Algorithm, E = Expert)*

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


Y
8
6
4
2
0
−2
−4
−6
−8
0
10
20
30
40
50
X
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Density

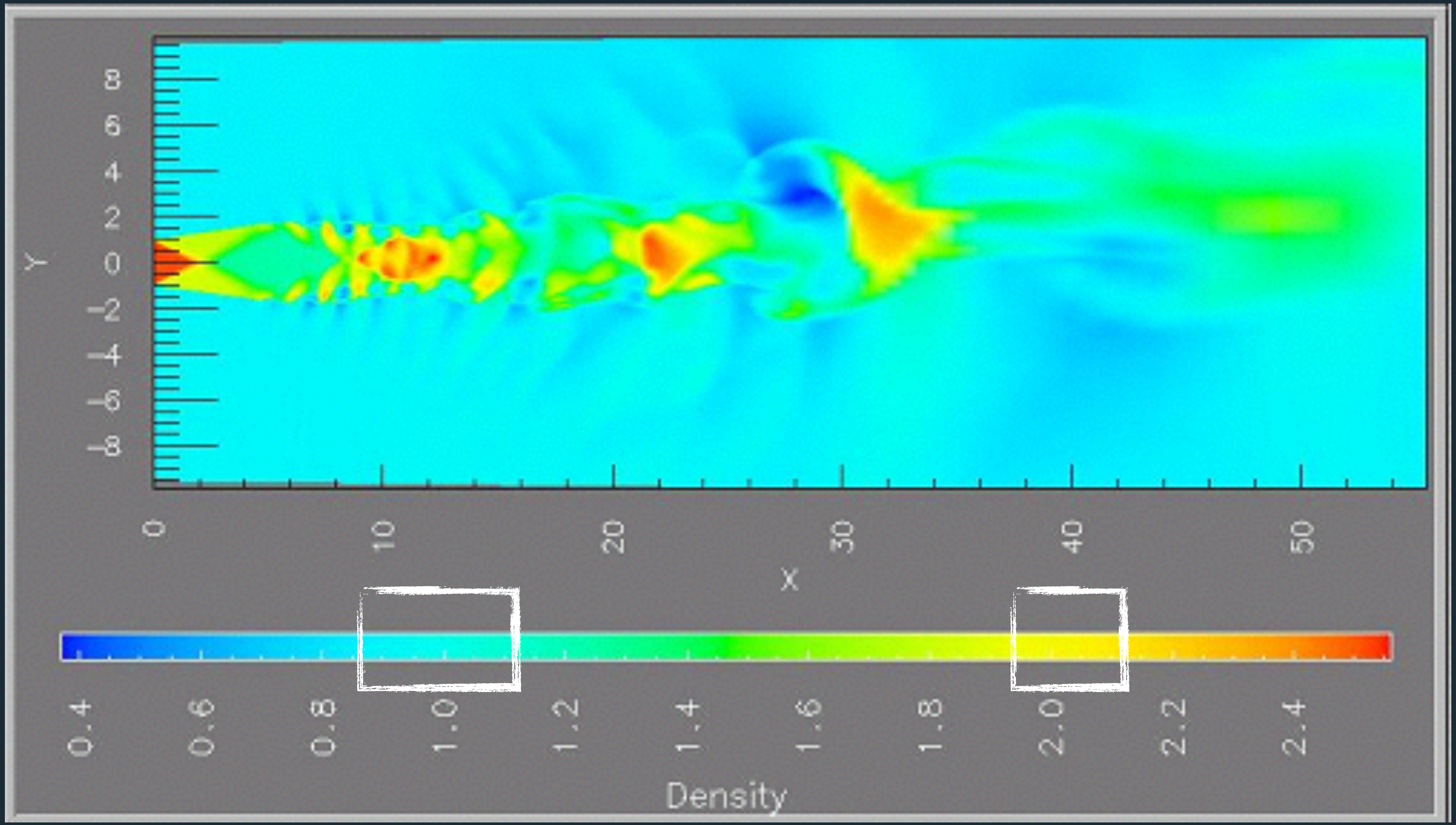
# Rainbow Color Maps: Danger!

1. Hues are not naturally ordered.



# Rainbow Color Maps: Danger!

1. Hues are not naturally ordered.
2. People segment colors into classes, leading to perceptual banding.
3. Naive rainbows are unfriendly to color blind viewers.

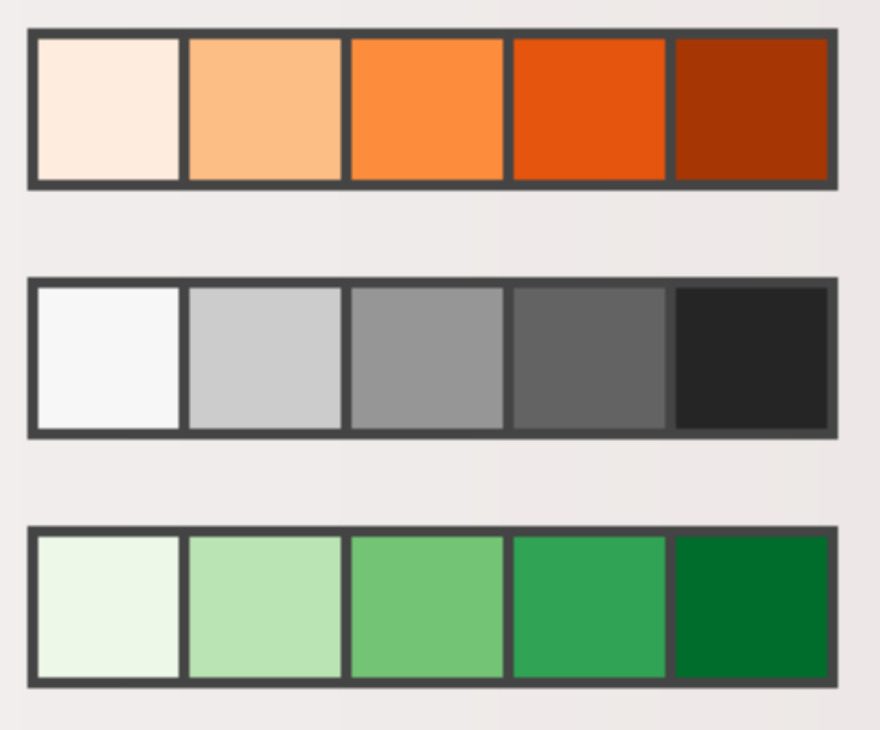


# Quantitative Color Encoding

**Sequential Color Scale**

Ramp in luminance, possibly also hue.

Typically higher values map to darker colors.

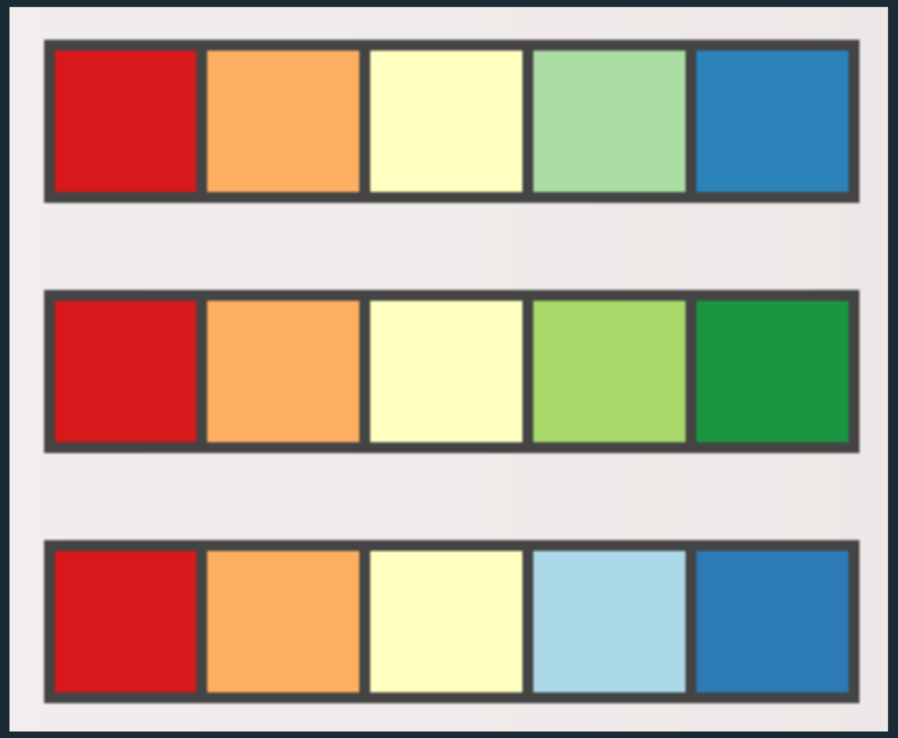


**Diverging Color Scale**

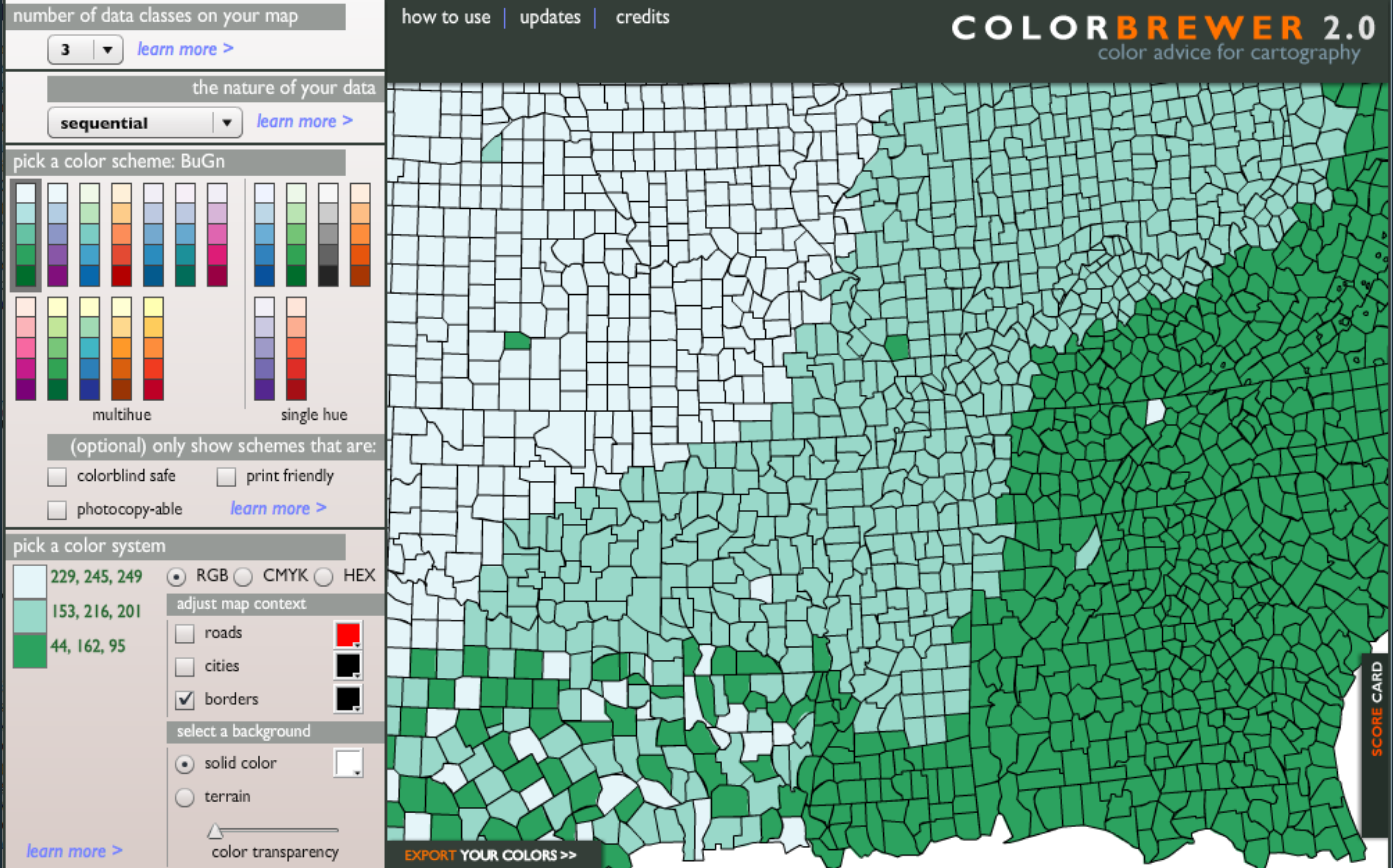
Useful when data has a meaningful “midpoint.”

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

Use saturated colors for endpoints.



**Limit number of steps in color to 3–9**


number of data classes on your map
3
learn more >
the nature of your data
sequential
learn more >
pick a color scheme: BuGn
multihue
single hue
(optional) only show schemes that are:
colorblind safe
print friendly
photocopy-able
learn more >
pick a color system
229, 245, 249
153, 216, 201
44, 162, 95
RGB
CMYK
HEX
adjust map context
roads
cities
borders
select a background
solid color
terrain
color transparency
learn more >
how to use | updates | credits
COLORBREWER 2.0
color advice for cartography
SCORE CARD
EXPORT YOUR COLORS >>