Color

DSC 106: Data Visualization

Sam Lau
UC San Diego

Join at
slido.com
#3972 640

Announcements

Lab 3 (JavaScript) out, checkoffs due 1/26.

Project 2 out, due on Friday 2/2.

In-person OH moved to HDSI 355 (not 1st floor!)

Sam's OH moved to 1pm on Thurs, not 2pm

FAQs:

1. When will Project 1 be graded? Aiming for Friday.

Project 2: Deceptive Visualization

Task: Create two static visualizations. One is **earnest**. One is **deceptive**.

Earnest = understandable, appropriate encodings, transparent

Deceptive = deliberately misleading, biased headings, not transparent.

Should be hard to tell which one is deceptive! Can't lie (e.g. change data values).

You will peer review 3 other students' submissions.

Quick Poll

1. Did you feel like you could get adequate OH help for Project 1?

Join at
slido.com
#3972 640

Quick Poll

1. Did you feel like you could get adequate OH help for Project 1?
2. Are you in favor of setting aside OH specifically for project questions?

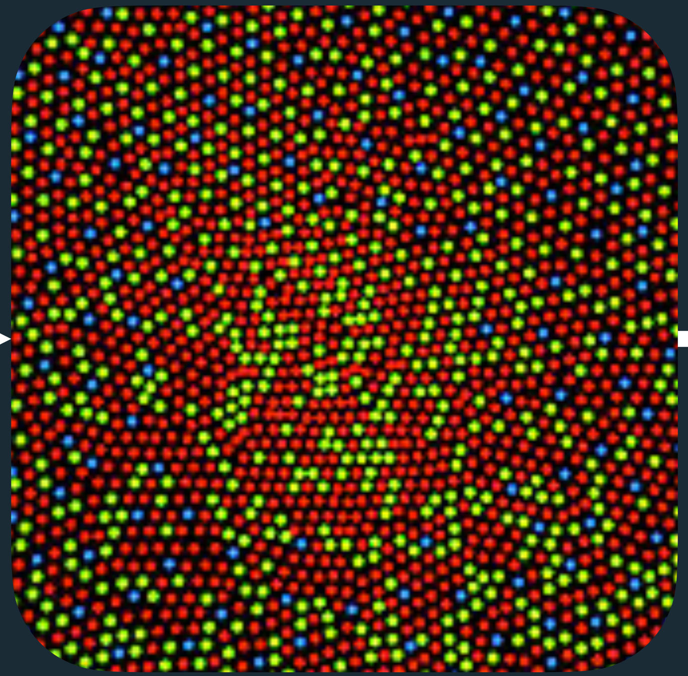
Join at
slido.com
#3972 640

Modeling Color Perception

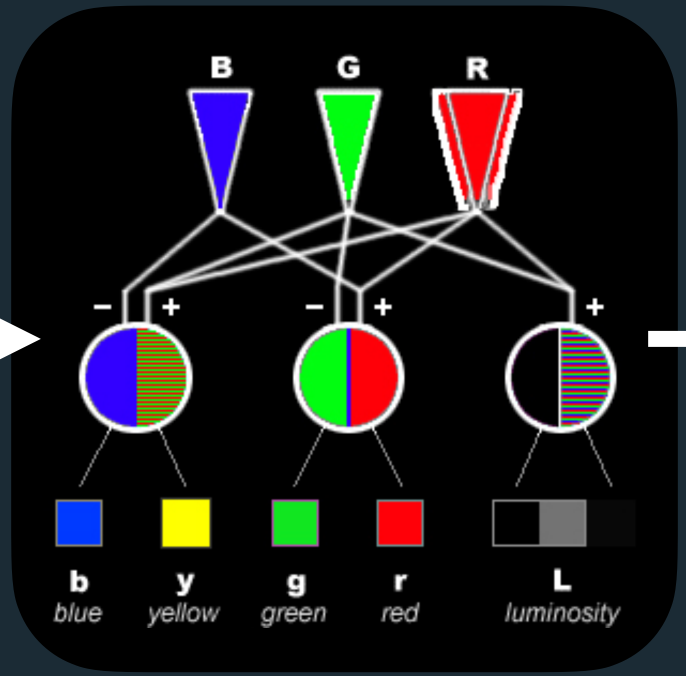
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response



Opponent Encoding

Perceptual Models

Appearance Models

“Teal”

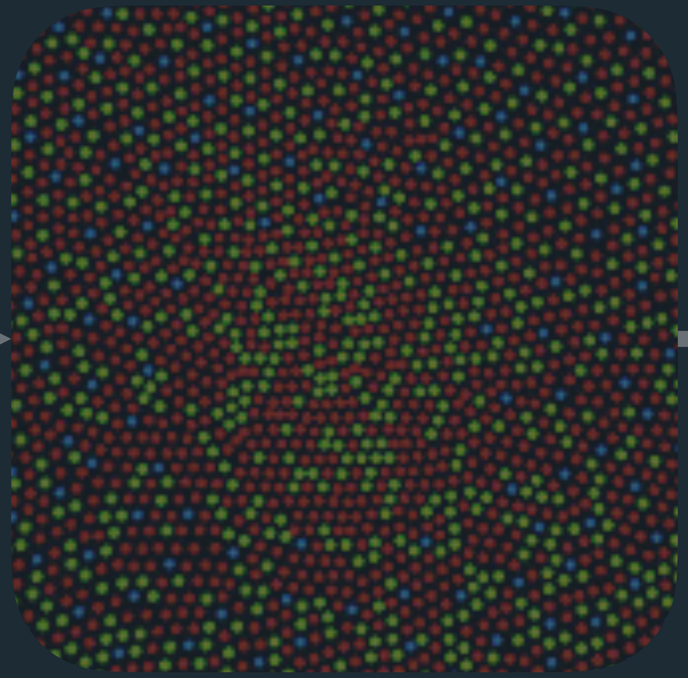
Cognitive Models

Modeling Color Perception

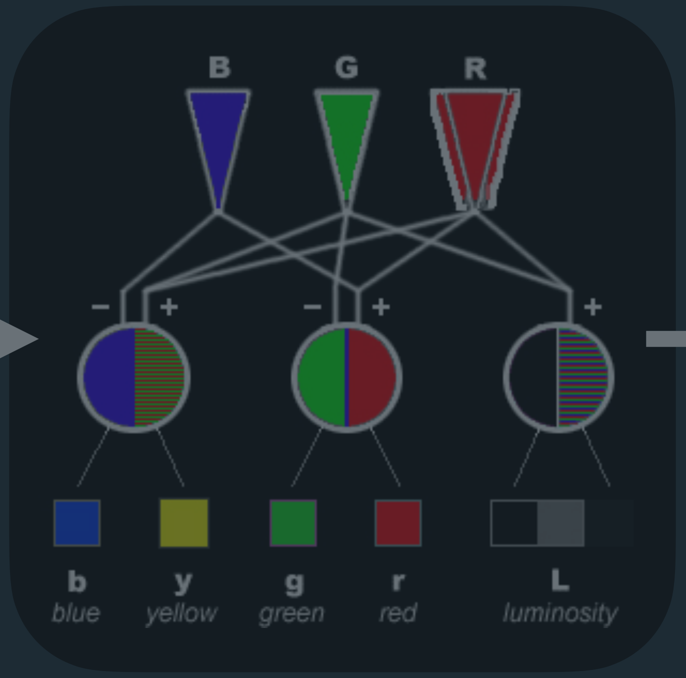
Low-Level | Abstraction | High-Level

Physical World | Visual System | Mental Models

Visible Light

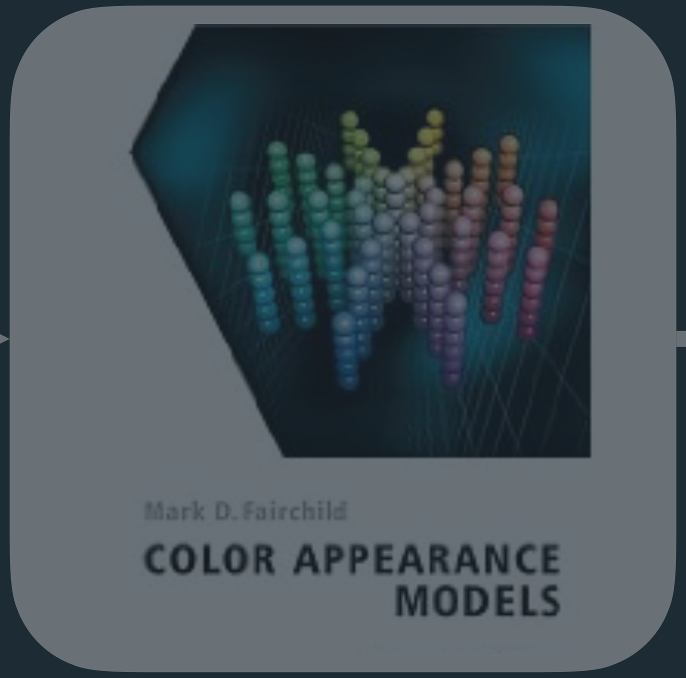


Cone Response



Opponent Encoding

Perceptual Models



Appearance Models

"Teal"

Cognitive Models

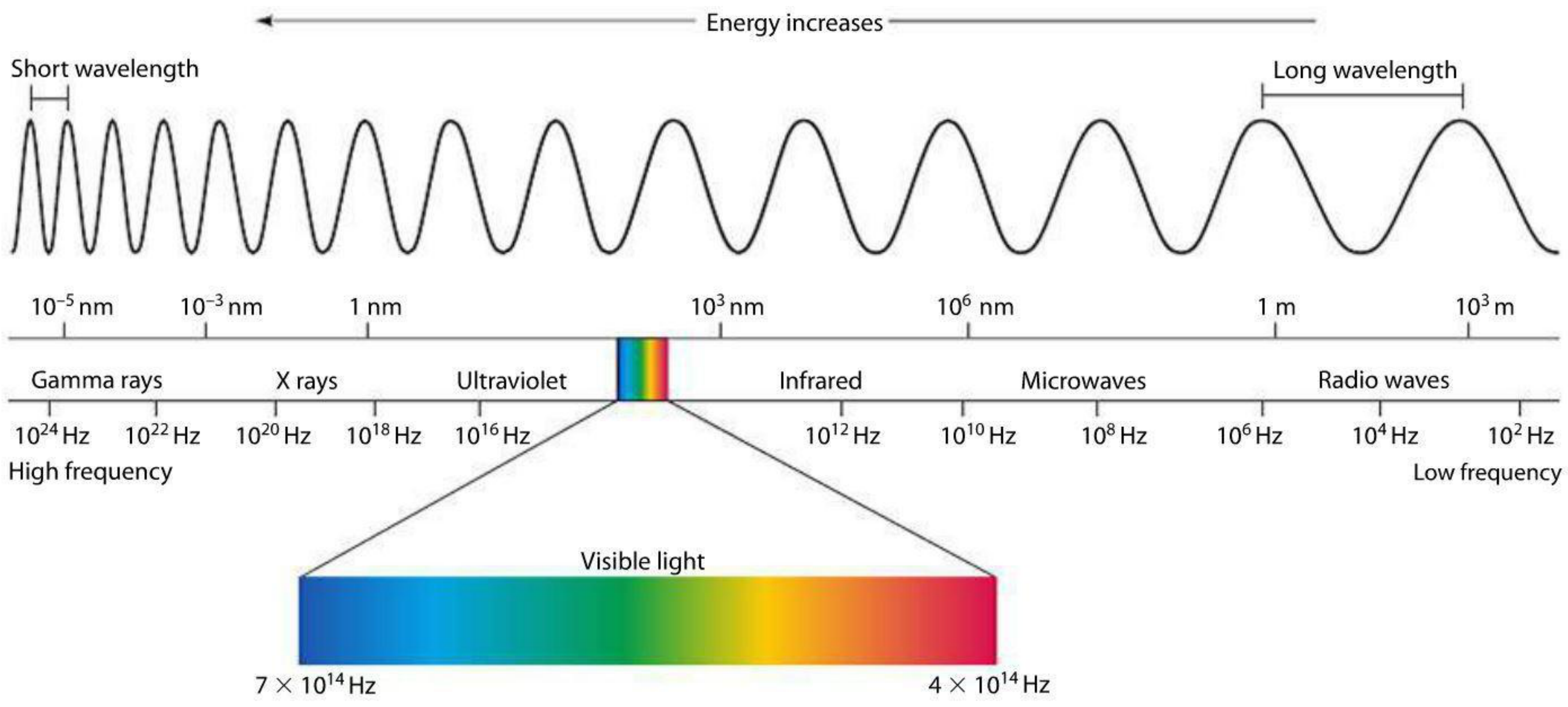
Visible Light

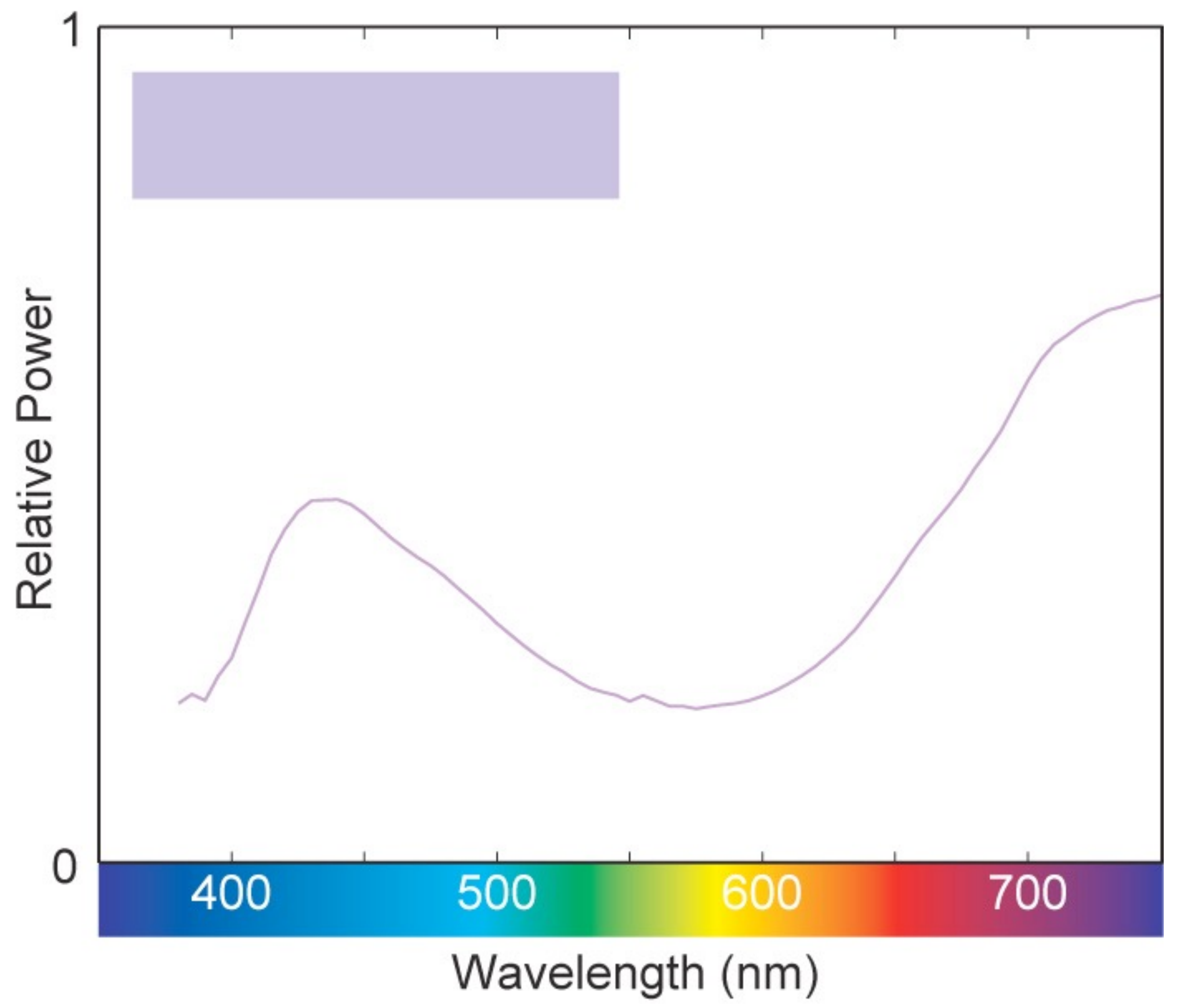
Light is an electromagnetic wave.

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]

Visible Light

Light is an electromagnetic wave.

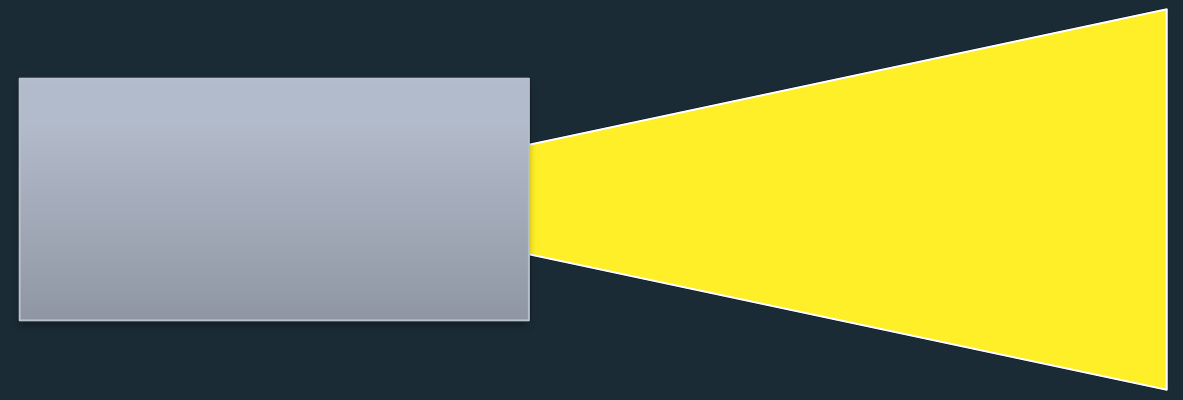
Wavelength (λ) between **370nm – 730nm**.

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

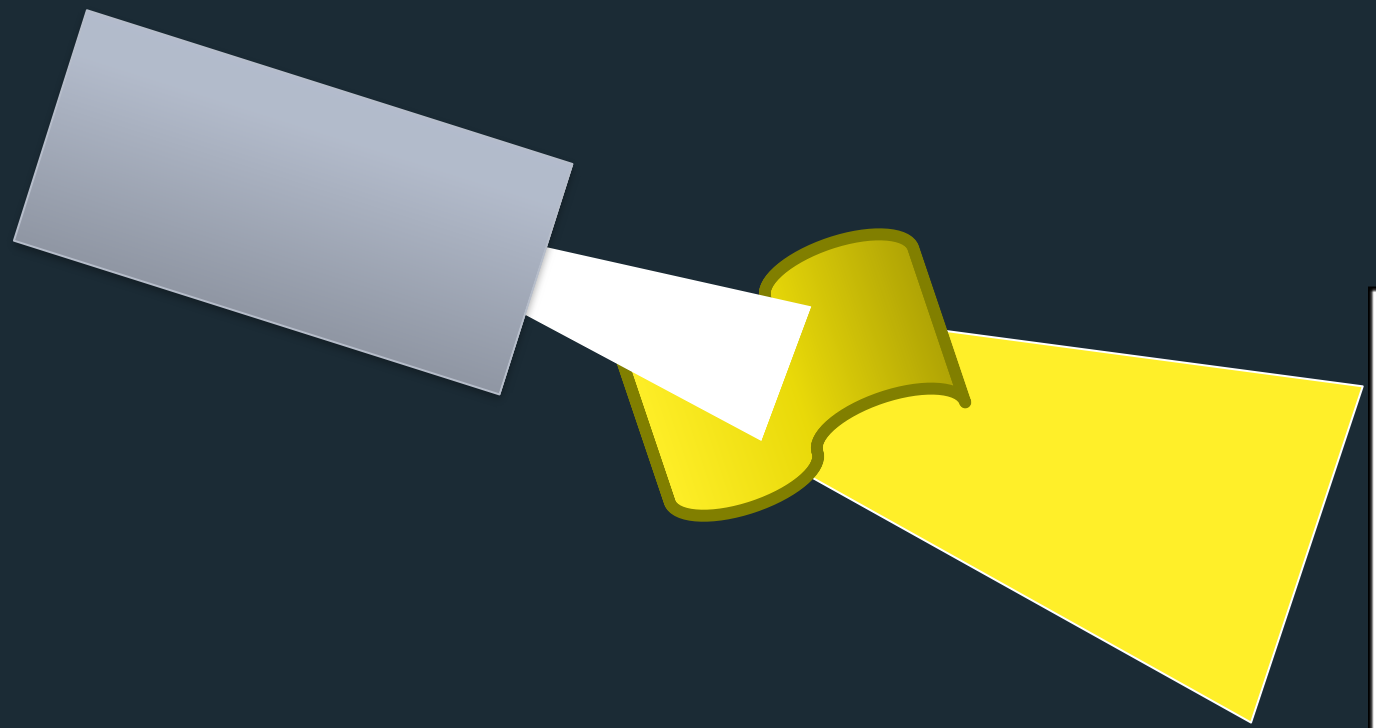
Area under the spectrum is ***intensity***: or how bright each wavelength is.

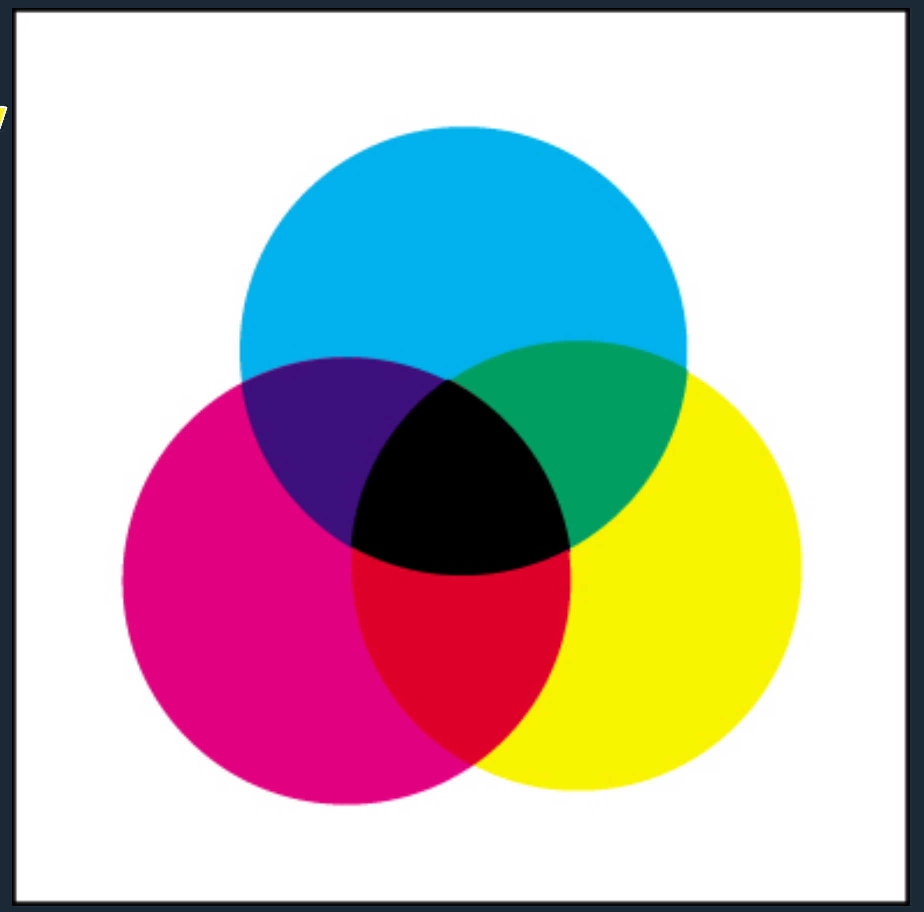
Additive: Perceived color is due to a combination of source lights (e.g., RGB).

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



Additive
(digital displays)





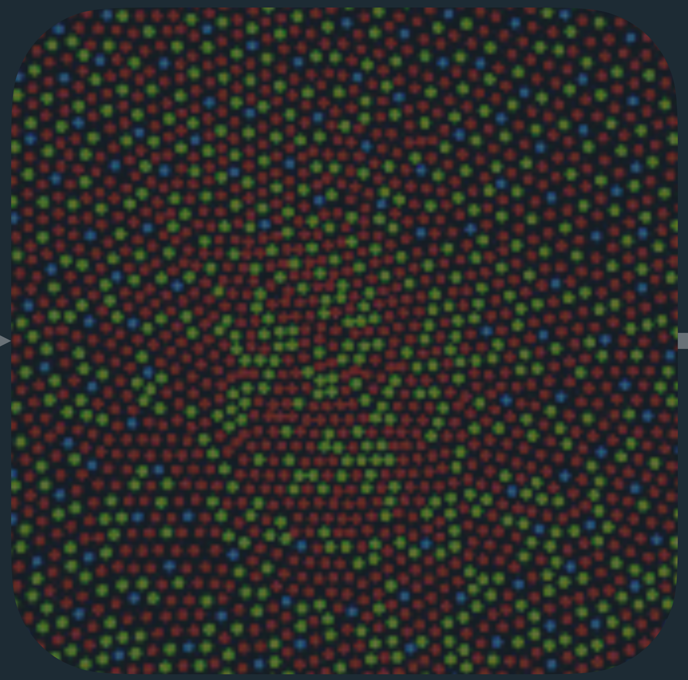
Subtractive
(print, e-paper)

Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

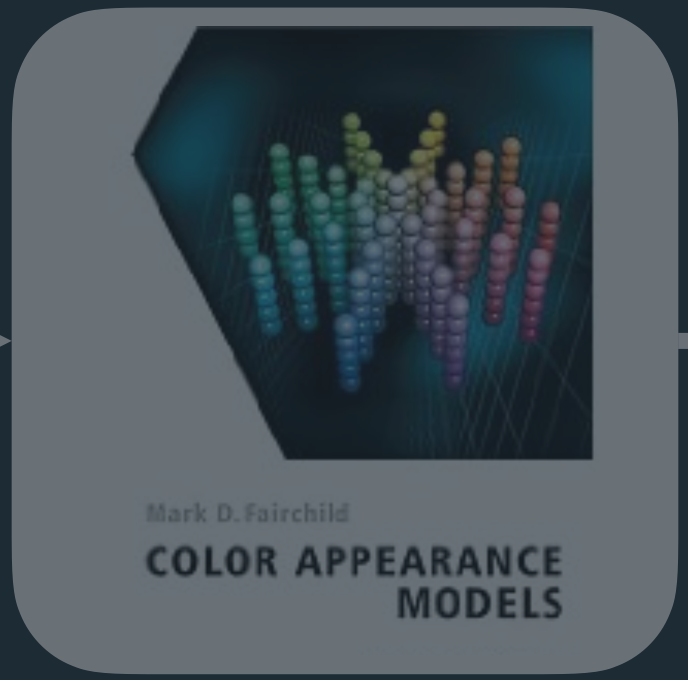
Visible Light



Cone Response

Opponent Encoding

Perceptual Models



Appearance Models

"Teal"

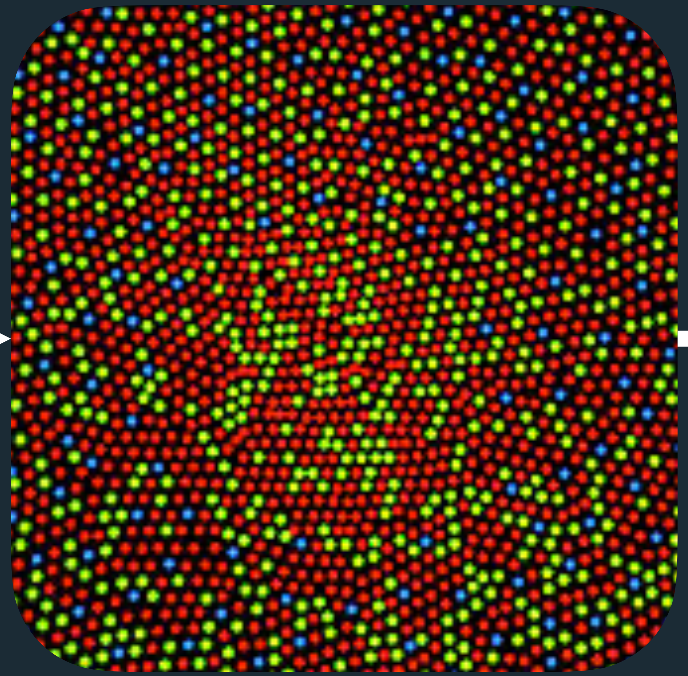
Cognitive Models

Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

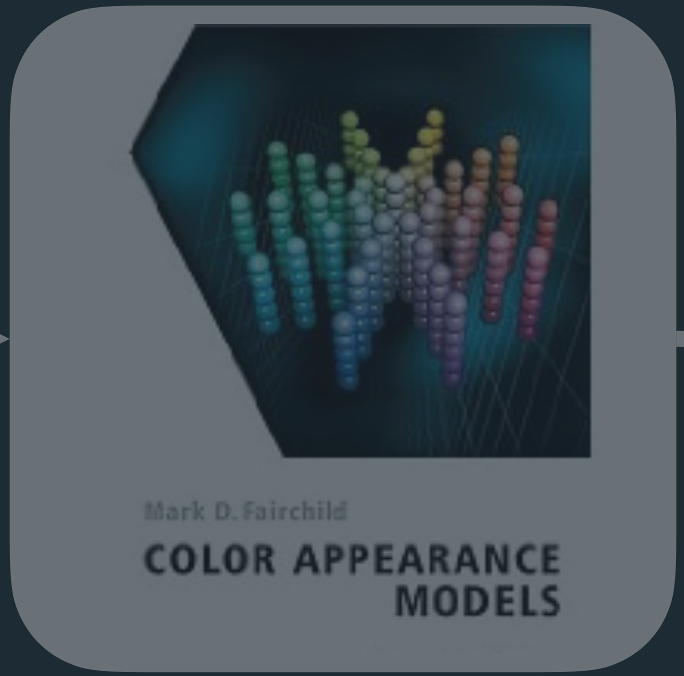
Visible Light



Cone Response

Opponent Encoding

Perceptual Models



Appearance Models

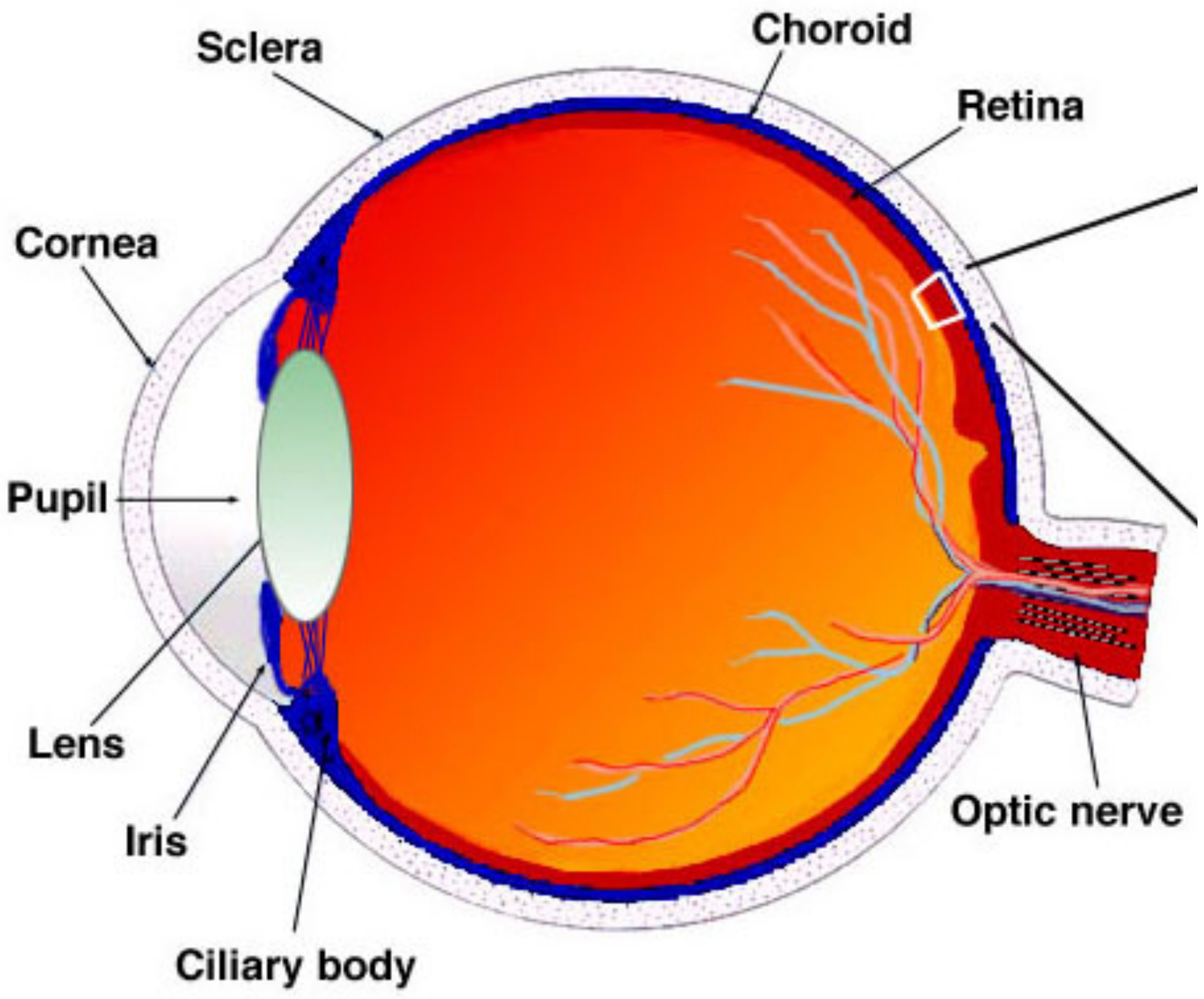
"Teal"

Cognitive Models

The Retina

Photoreceptors on retina are responsible for vision:

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



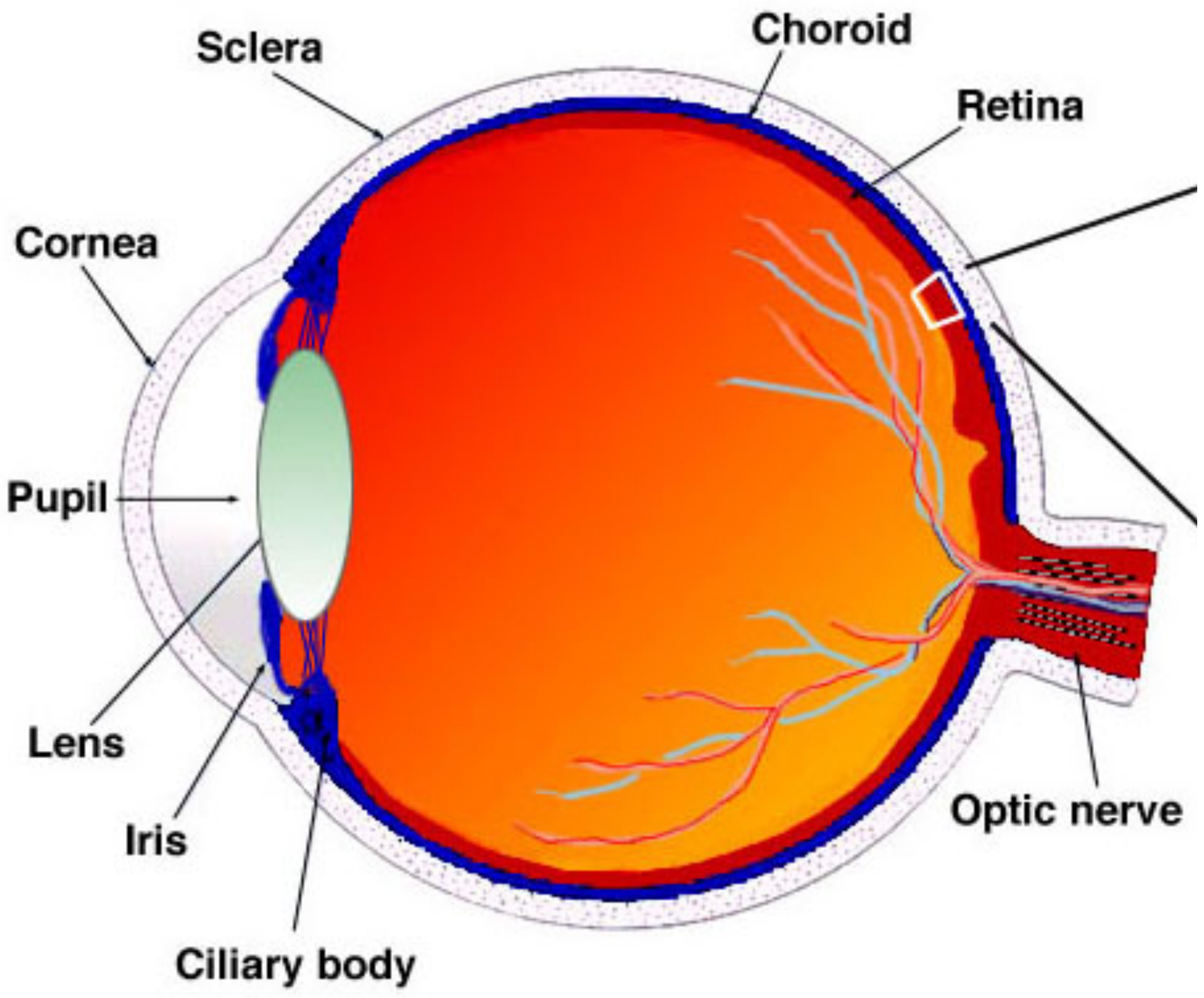
[Helga Kolb *Simple Anatomy of the Retina*,]

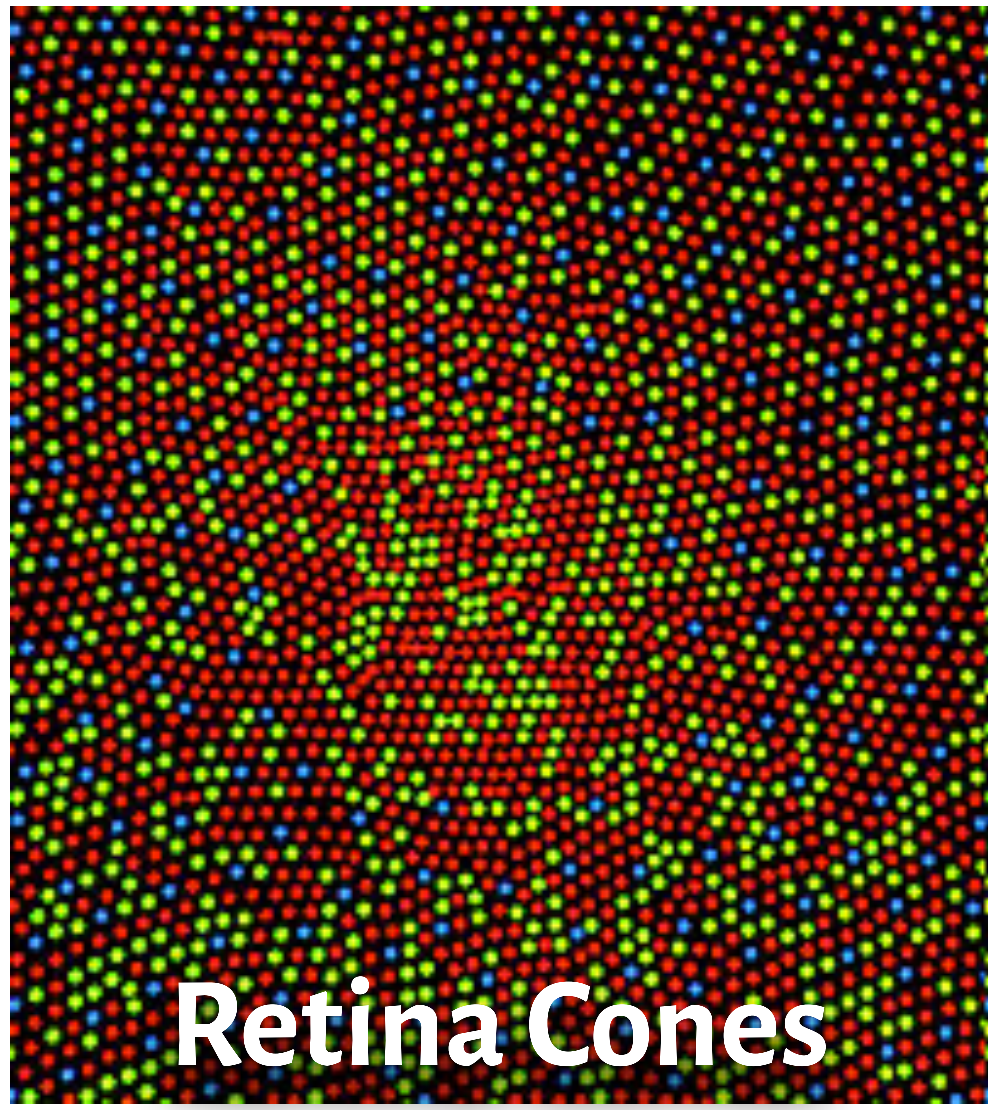
The Retina

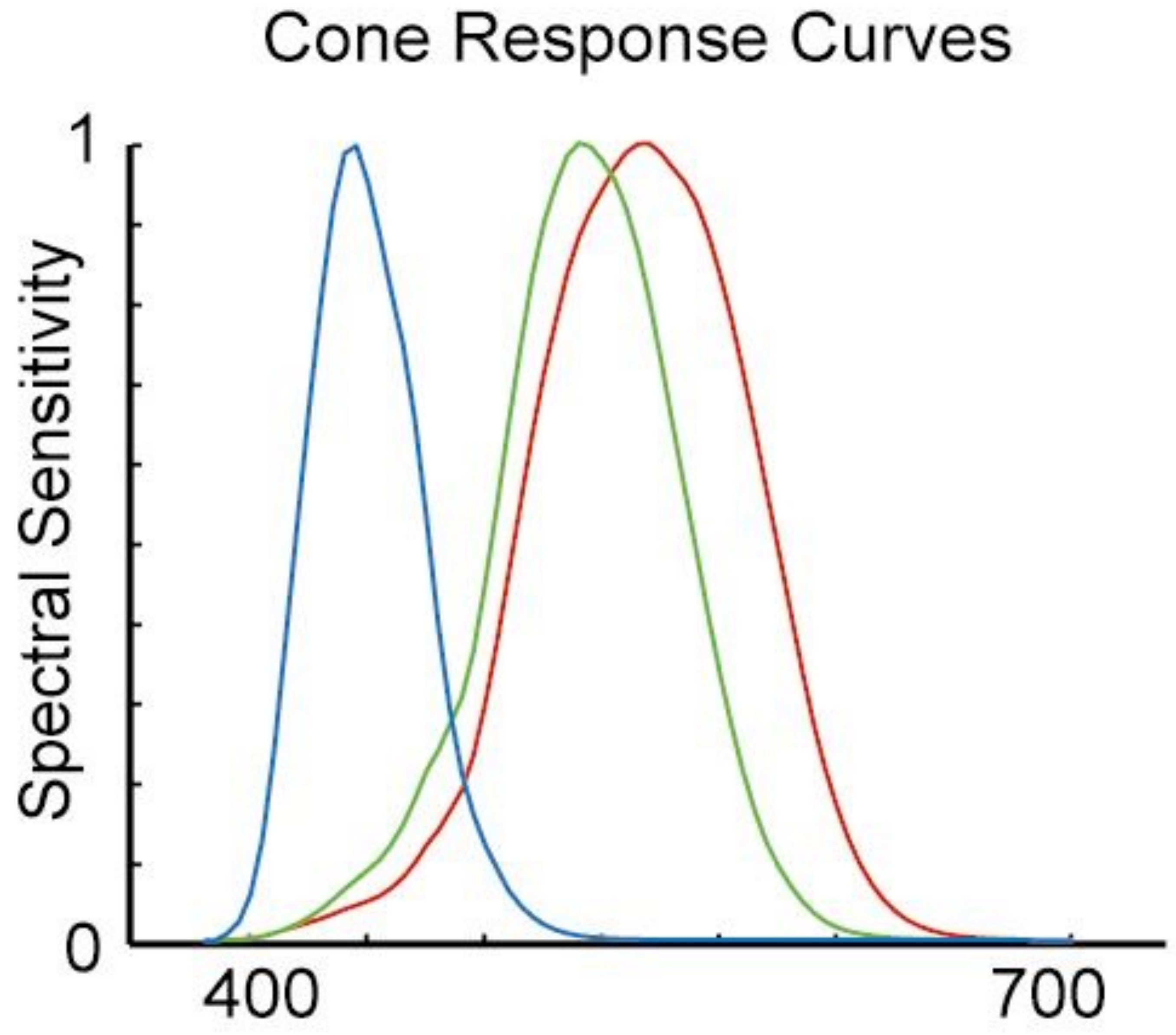
Photoreceptors on retina are responsible for vision:

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

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



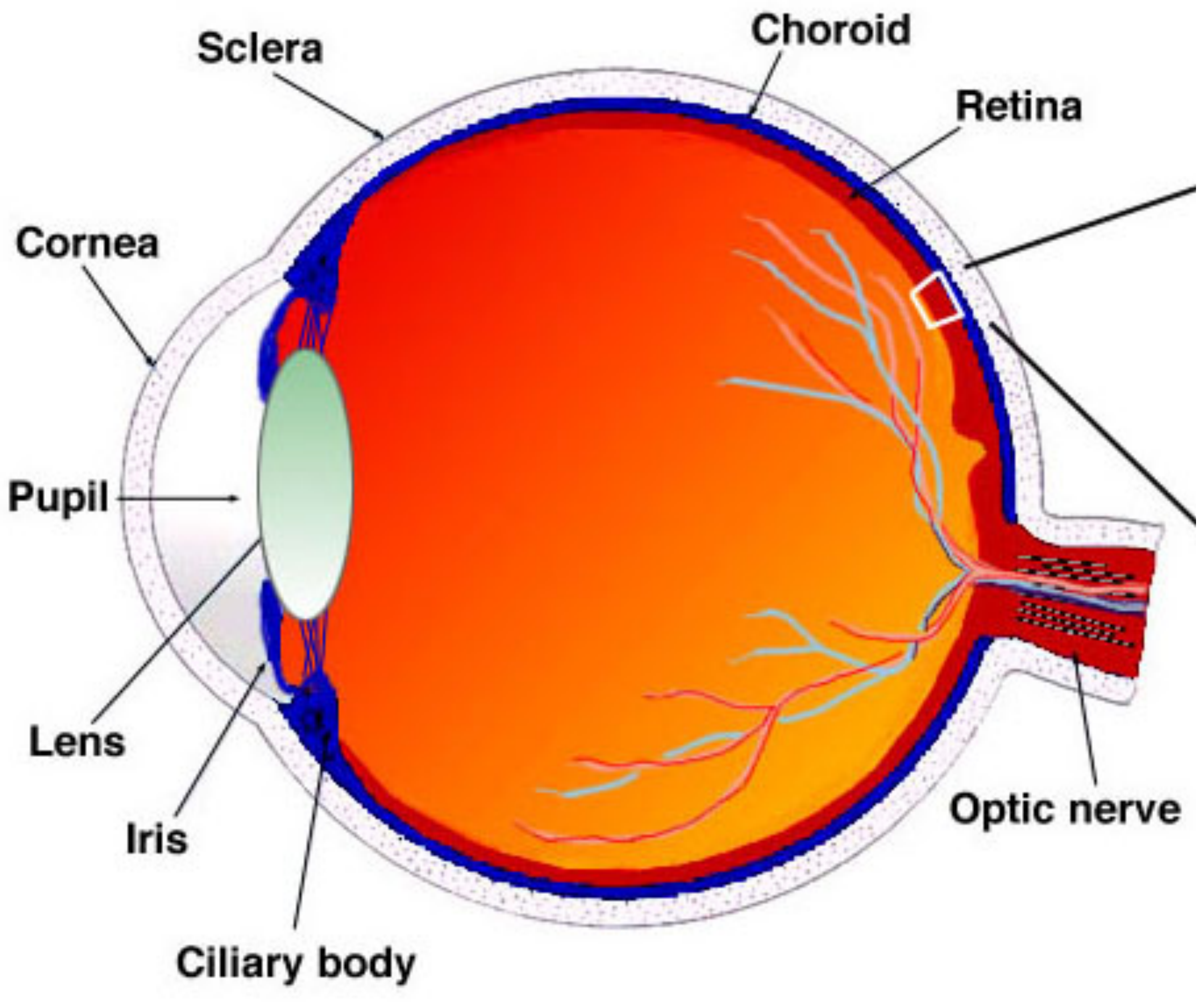




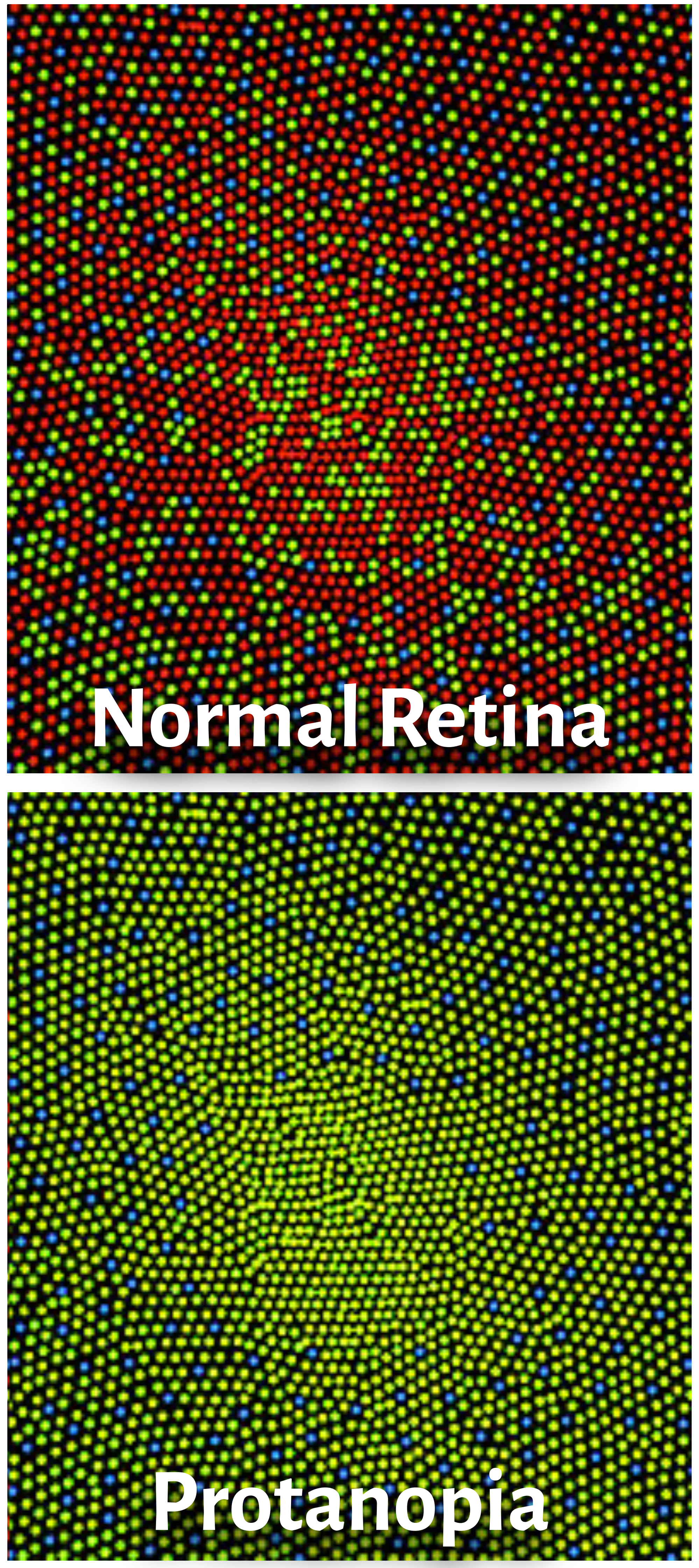
[Helga Kolb *Simple Anatomy of the Retina*,]

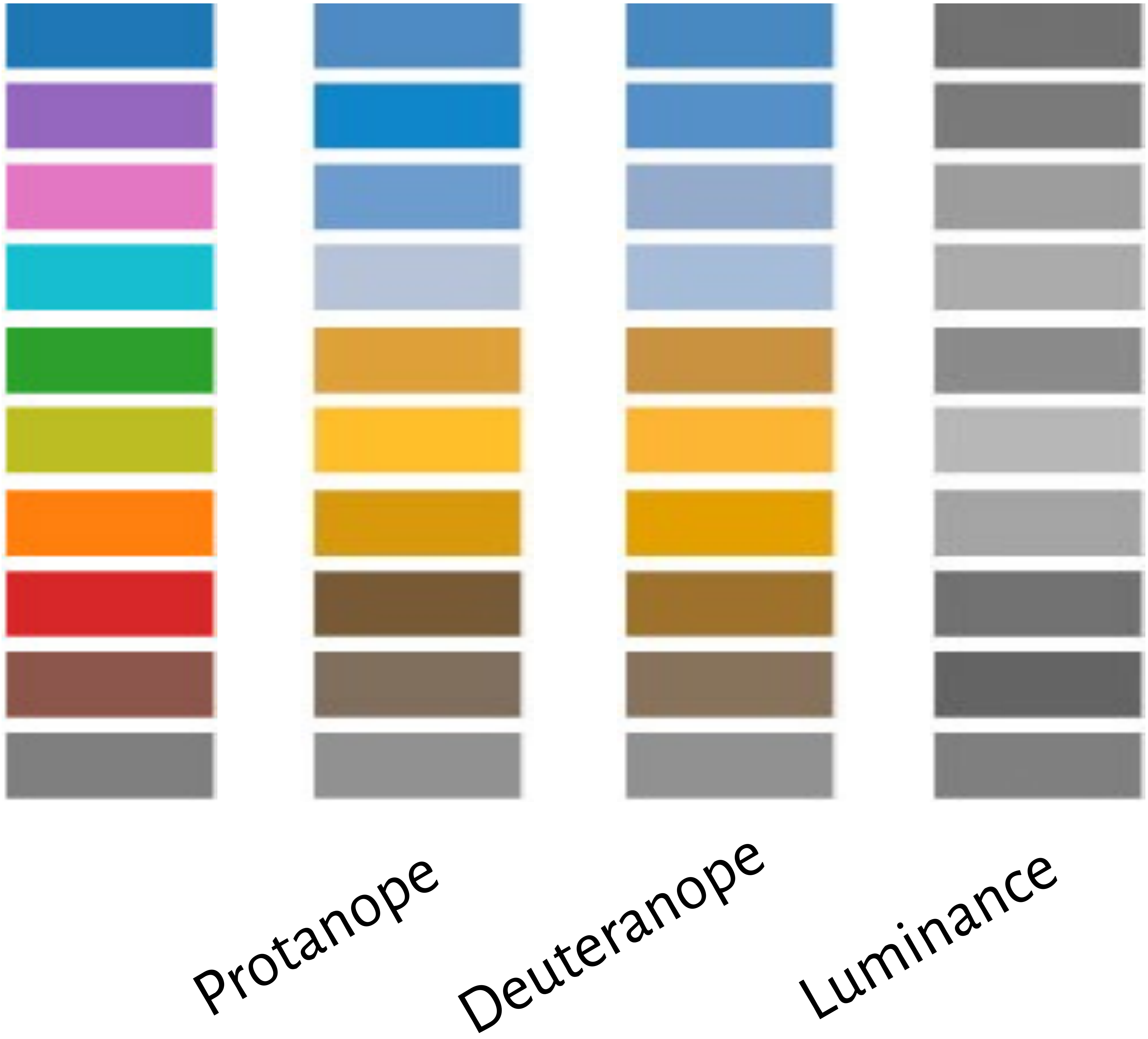
The Retina

Firefox and Chrome have built in simulators.



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

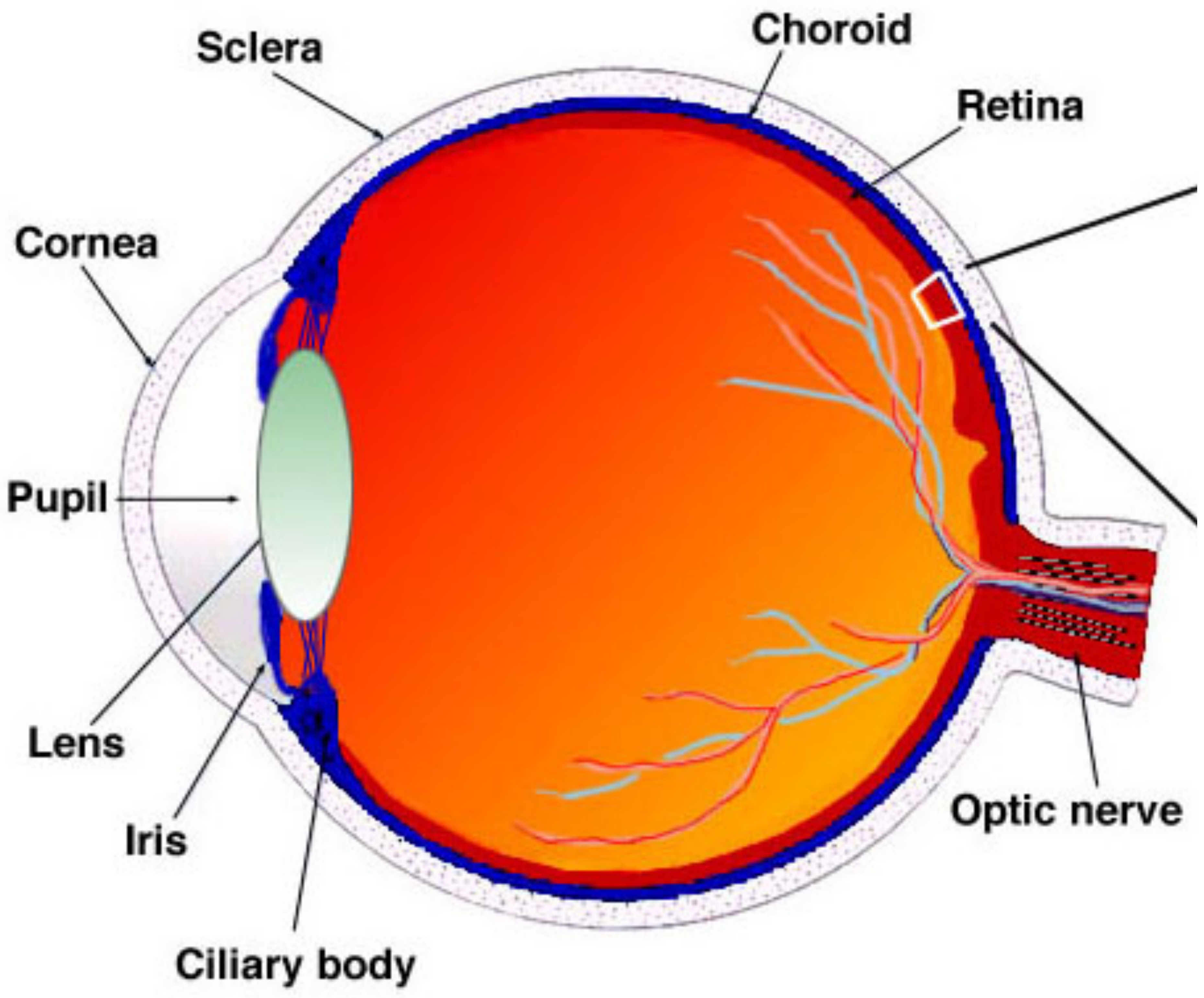


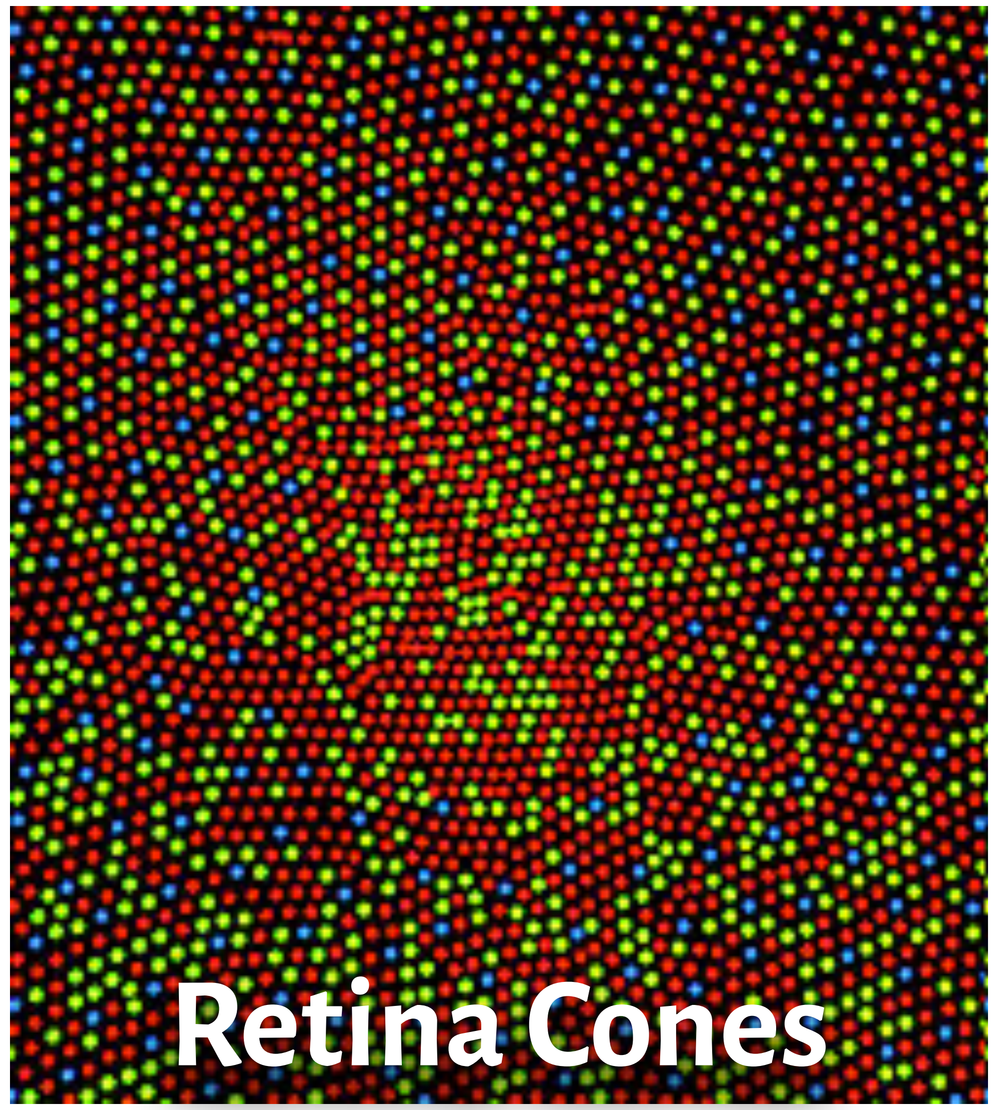


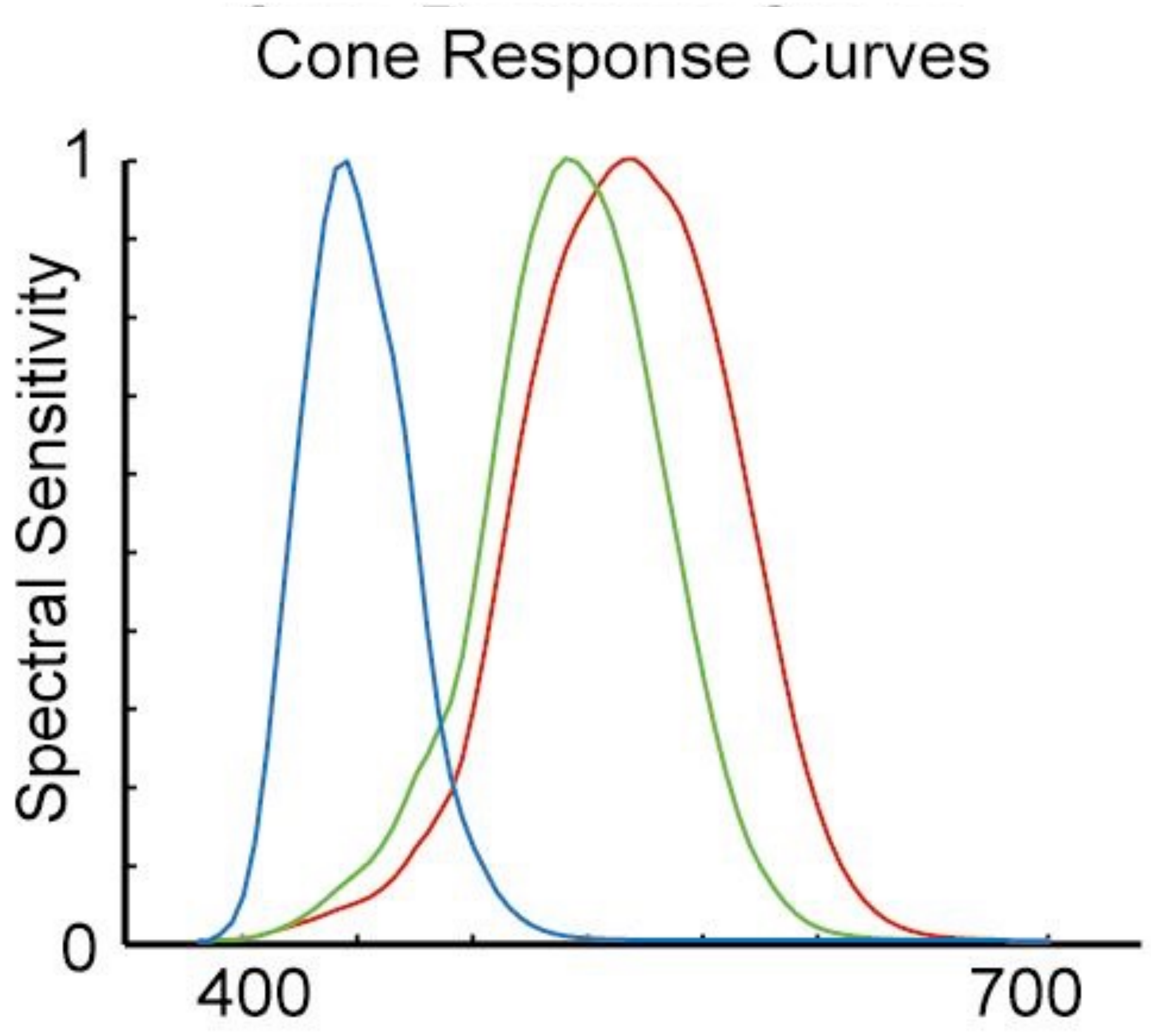
The Retina

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







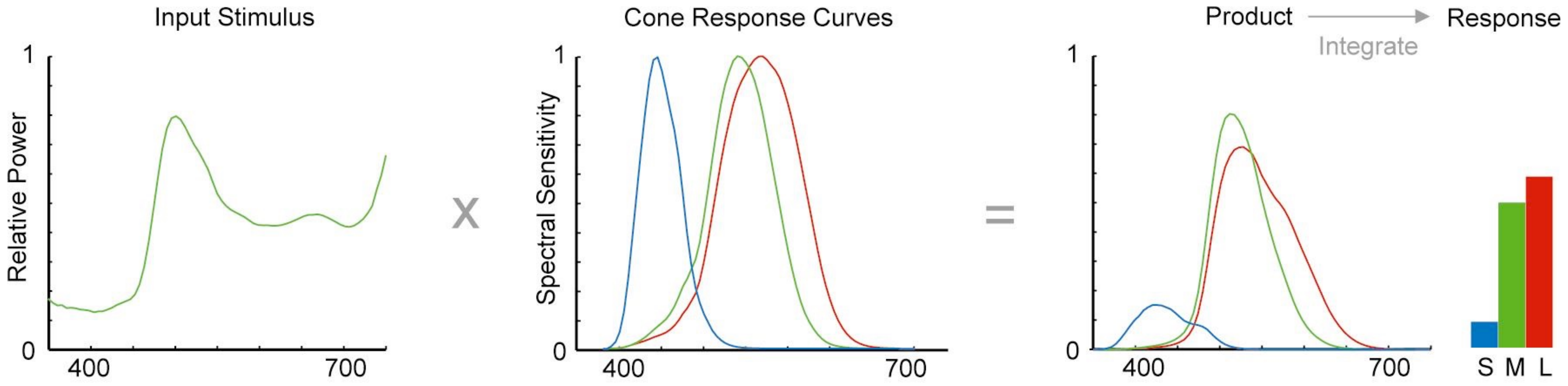
[Helga Kolb *Simple Anatomy of the Retina*,]

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
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

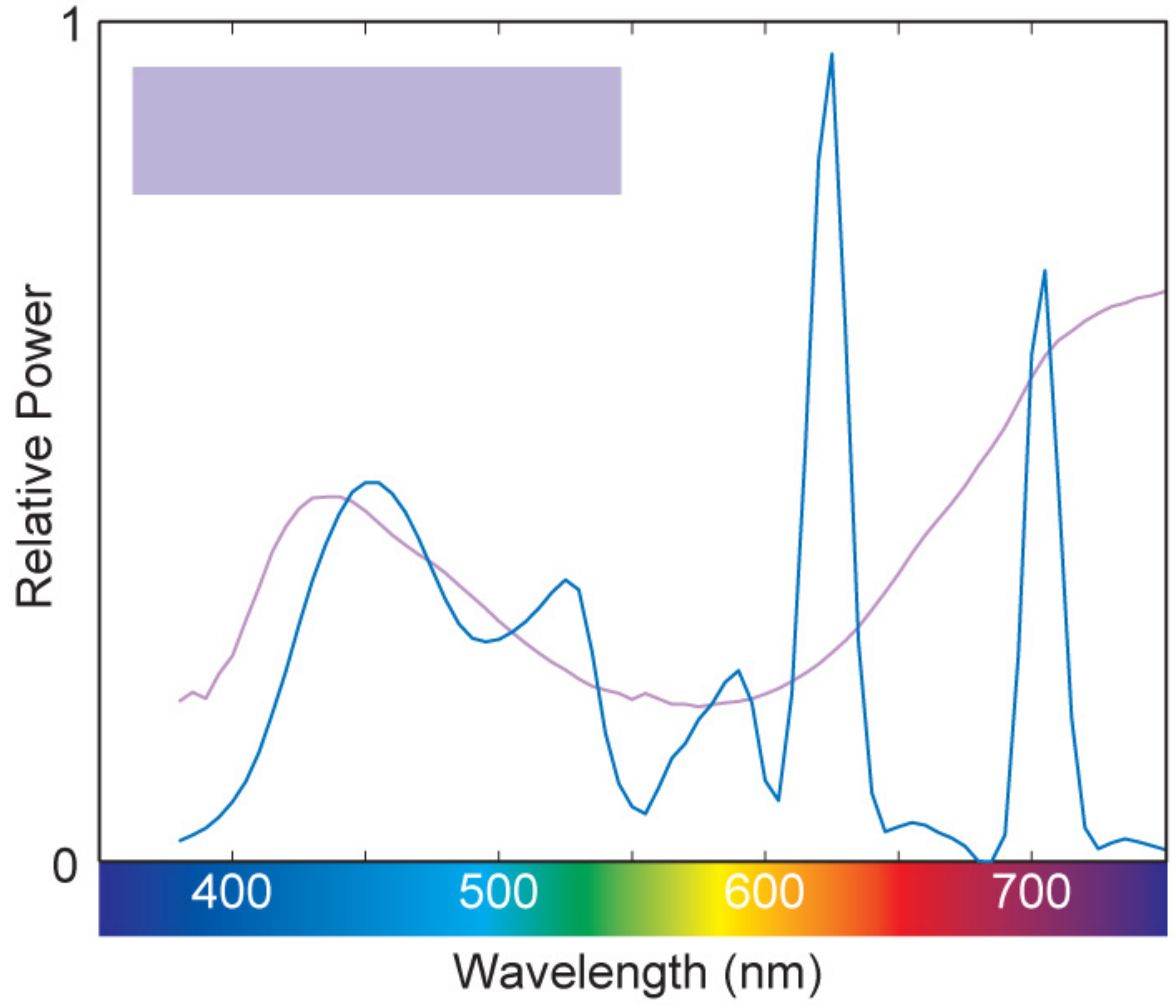
Photoreceptors on retina are responsible for vision:

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

cones – sensitive to different wavelengths = color vision!
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.

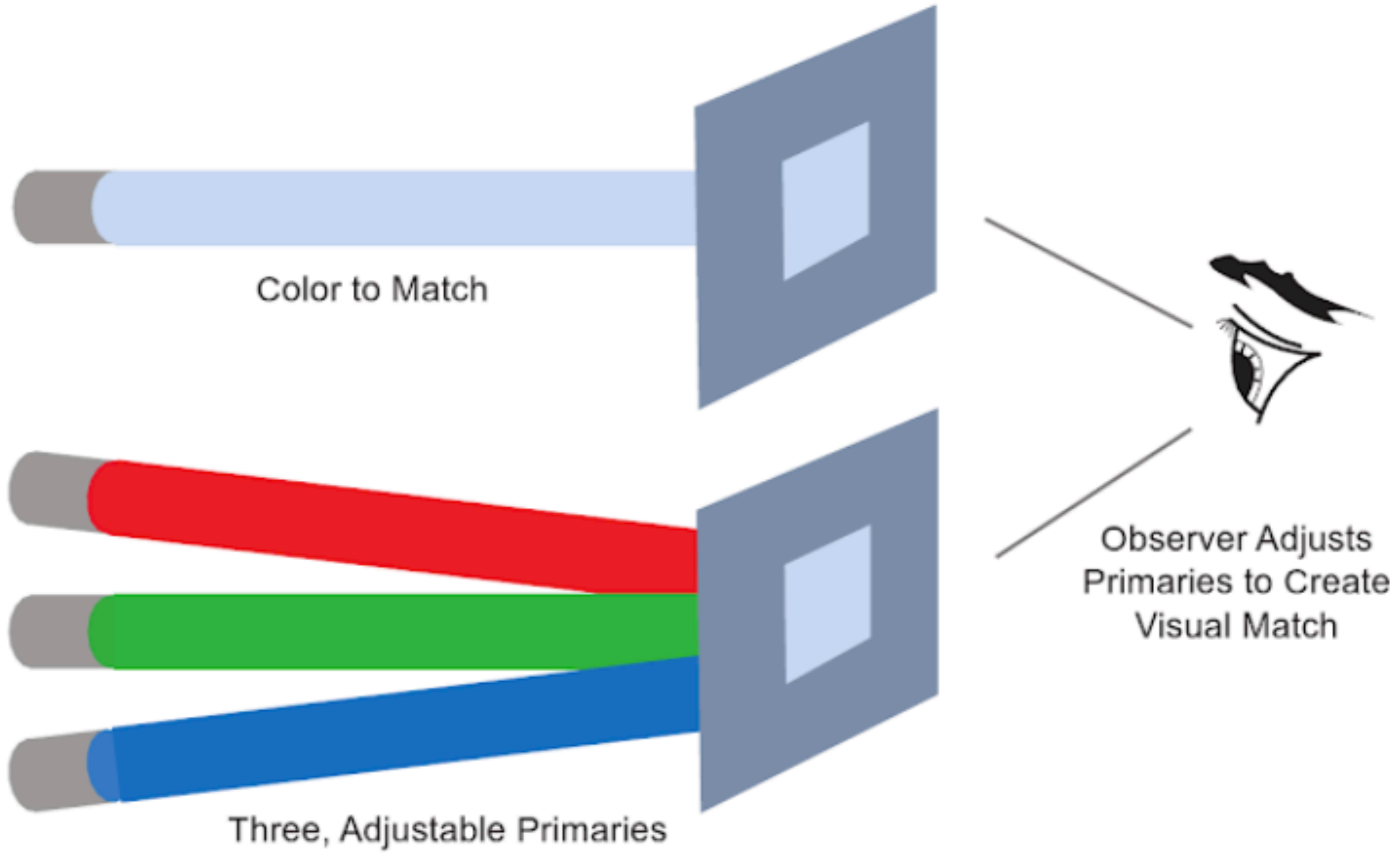


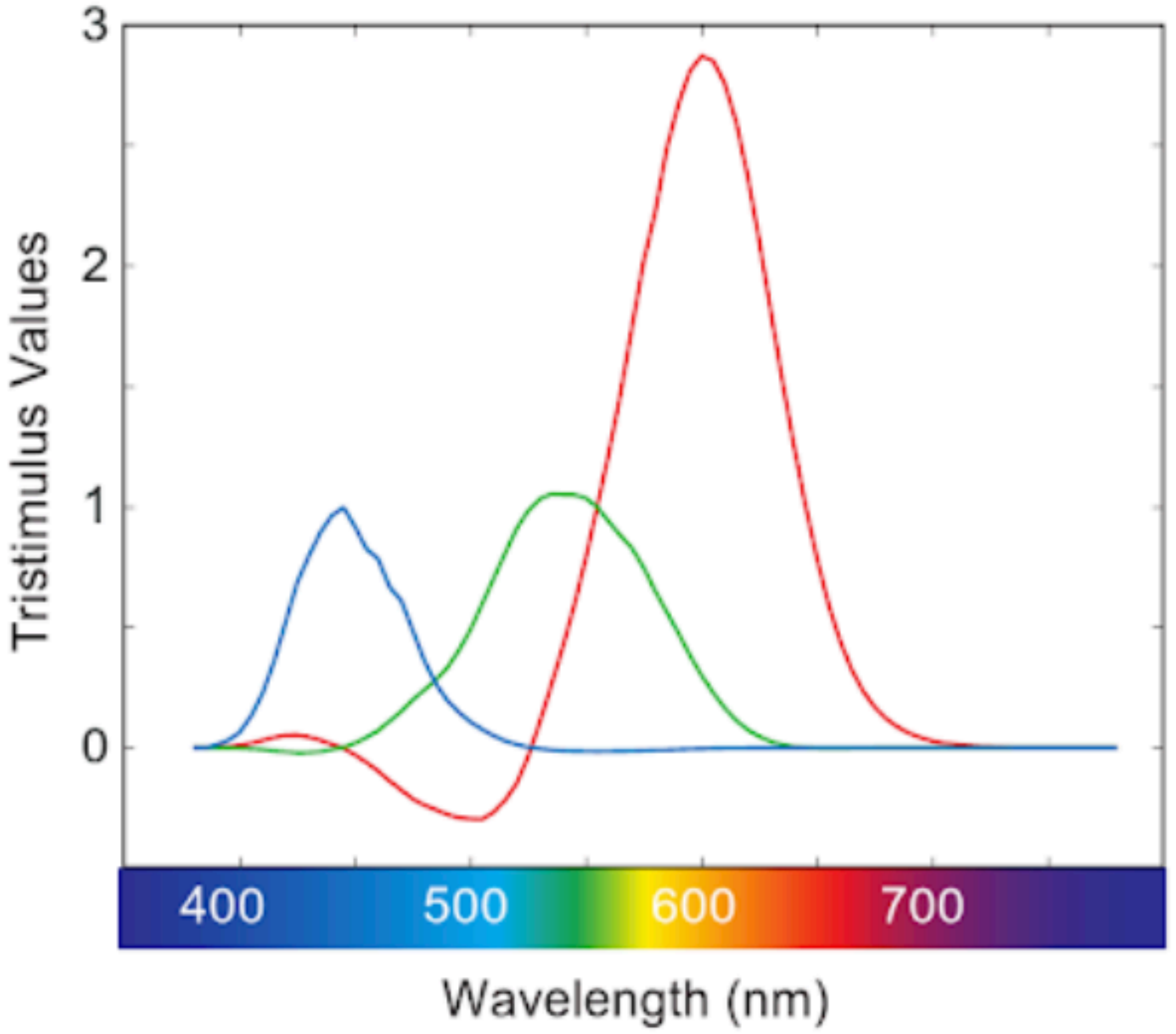
[Maureen Stone. *A Field Guide to Digital Color*, 2003]

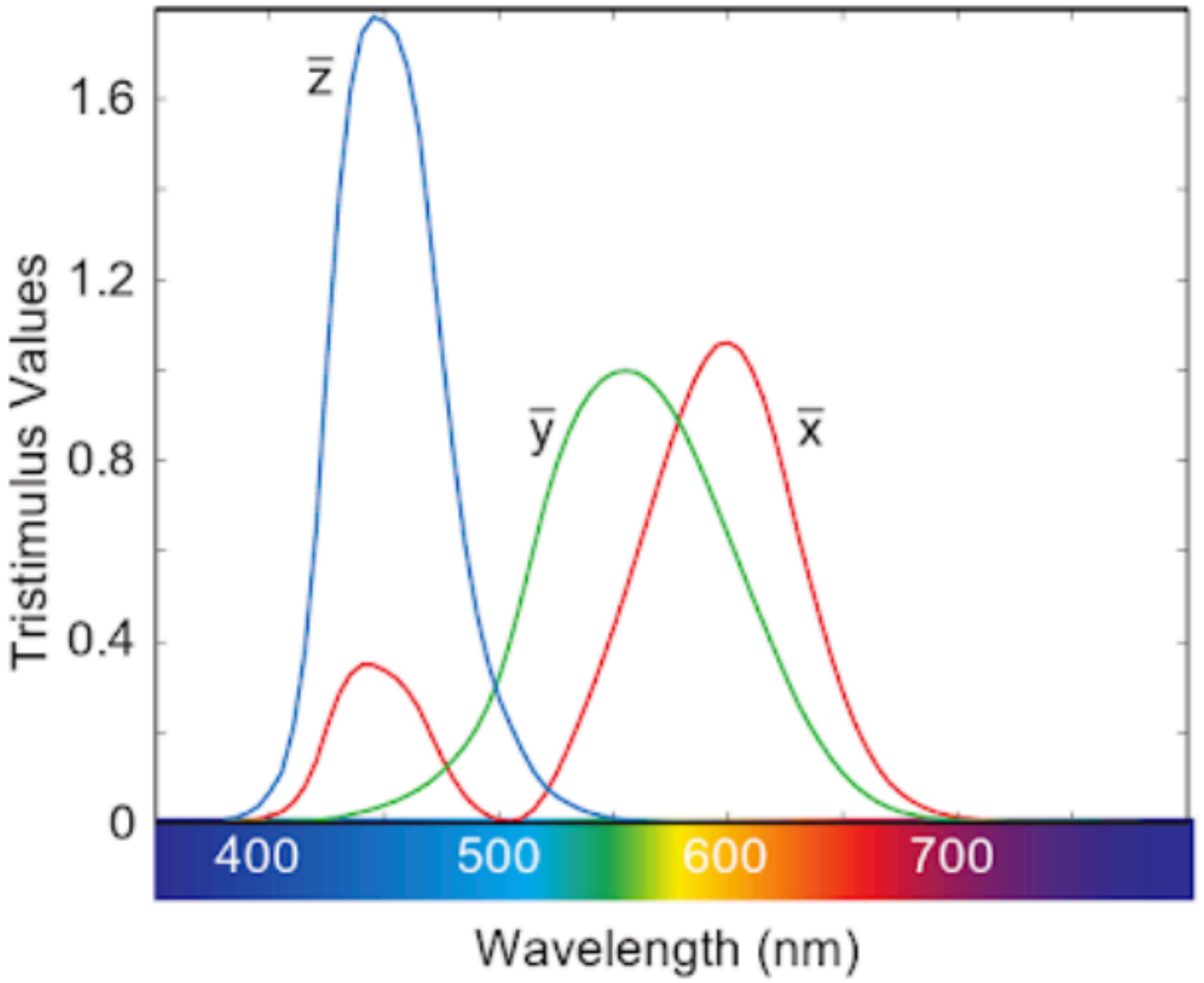
CIE XYZ

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

empirically determined







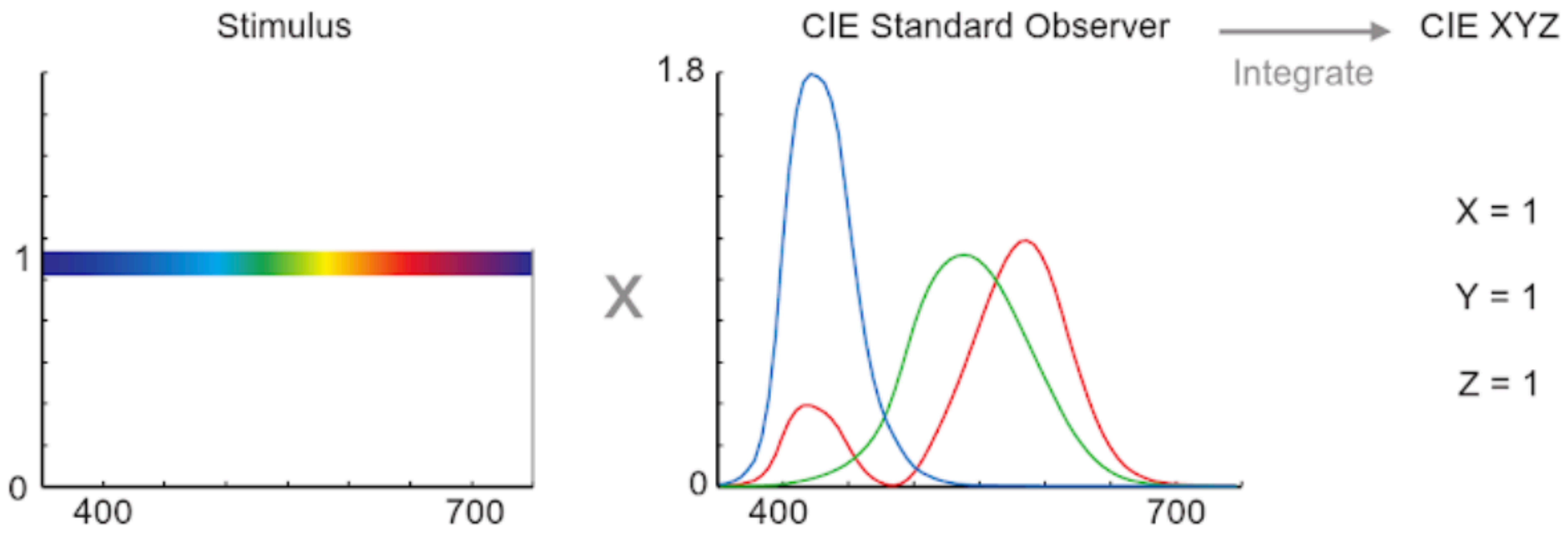
Red = 645nm
Green = 525nm
Blue = 444nm

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

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

CIE XYZ

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



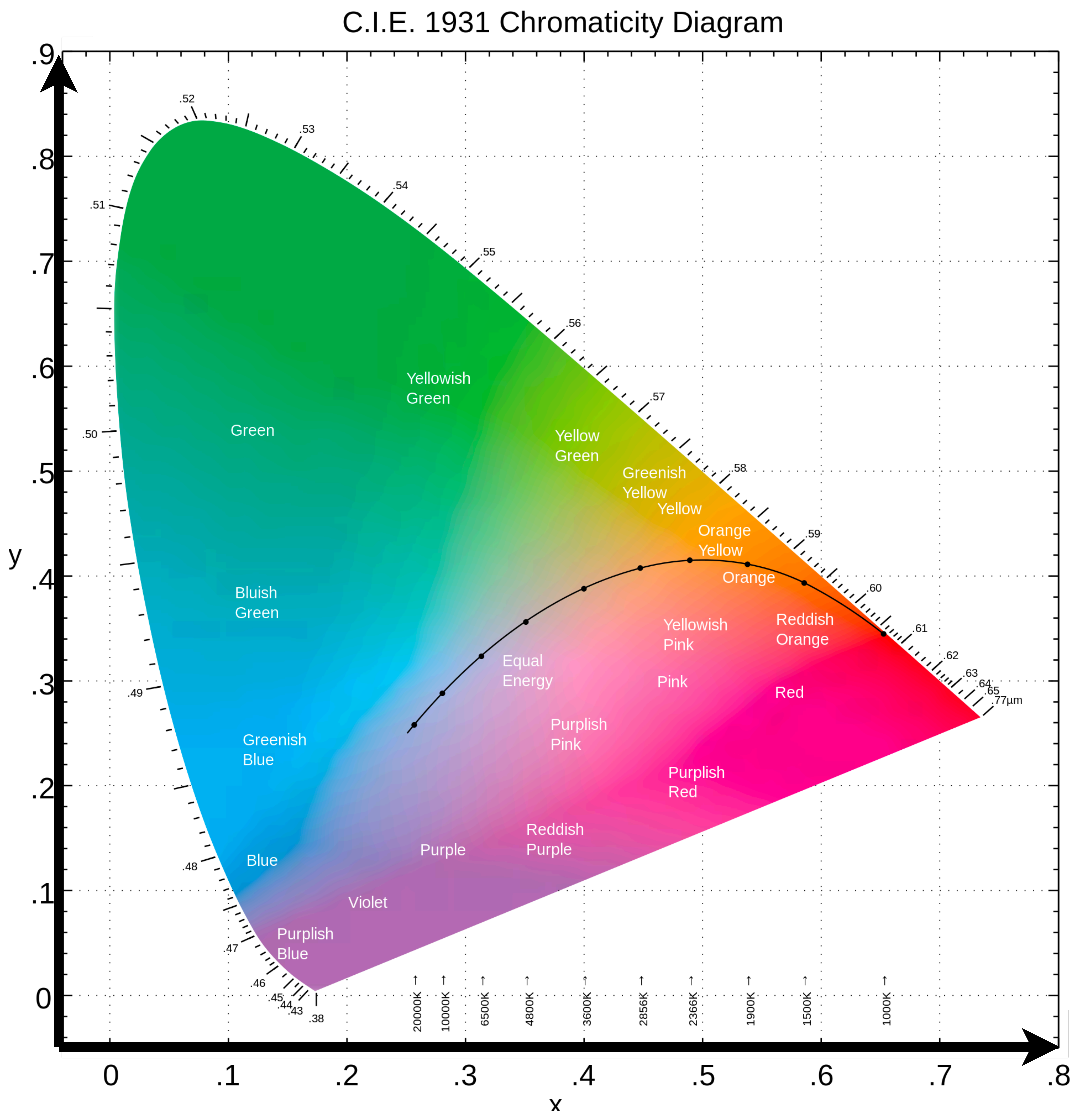
CIE XYZ Color Space

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

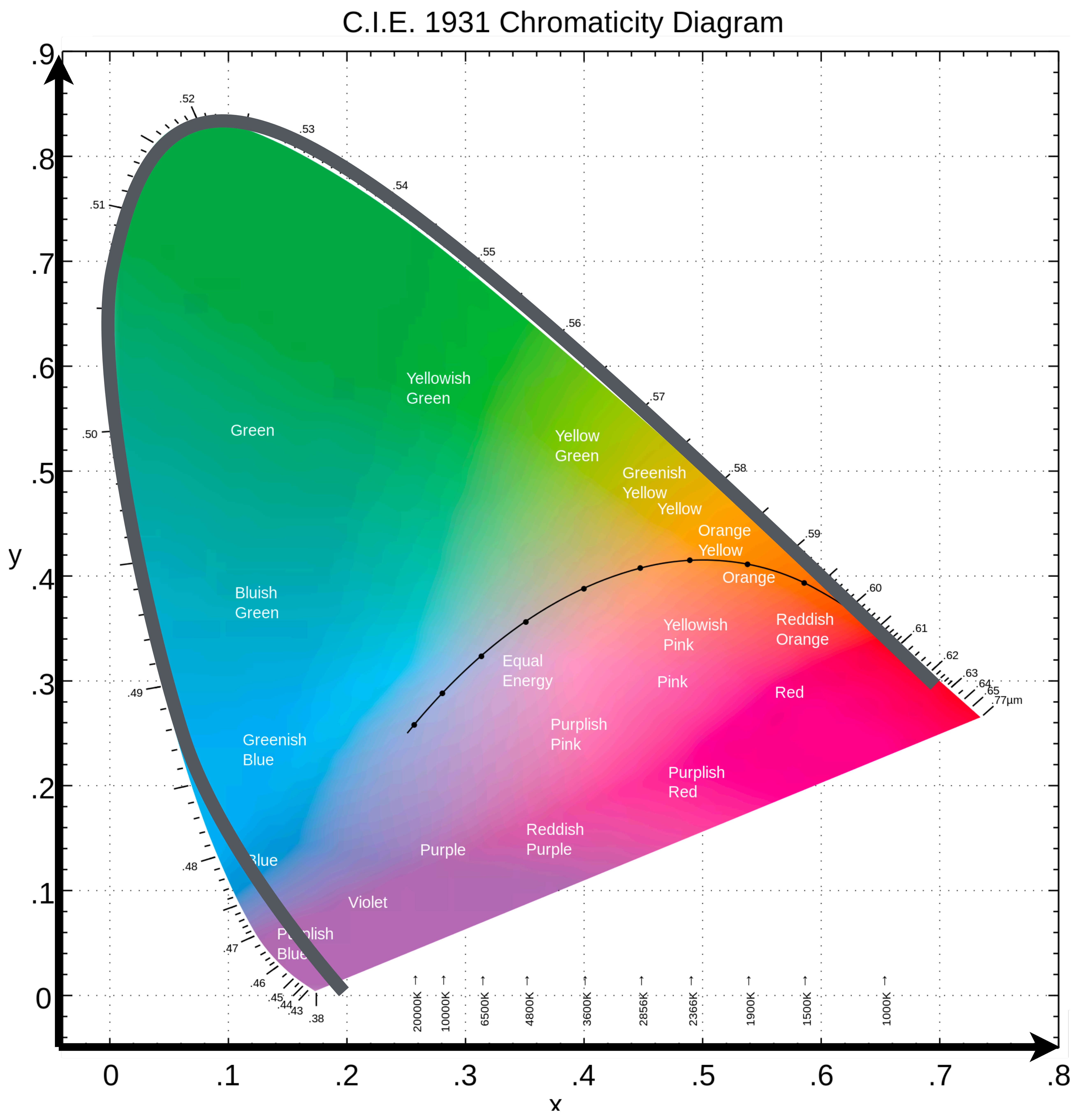
$$x = \frac{X}{X+Y+Z}$$

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

$$1 = x + y + z$$

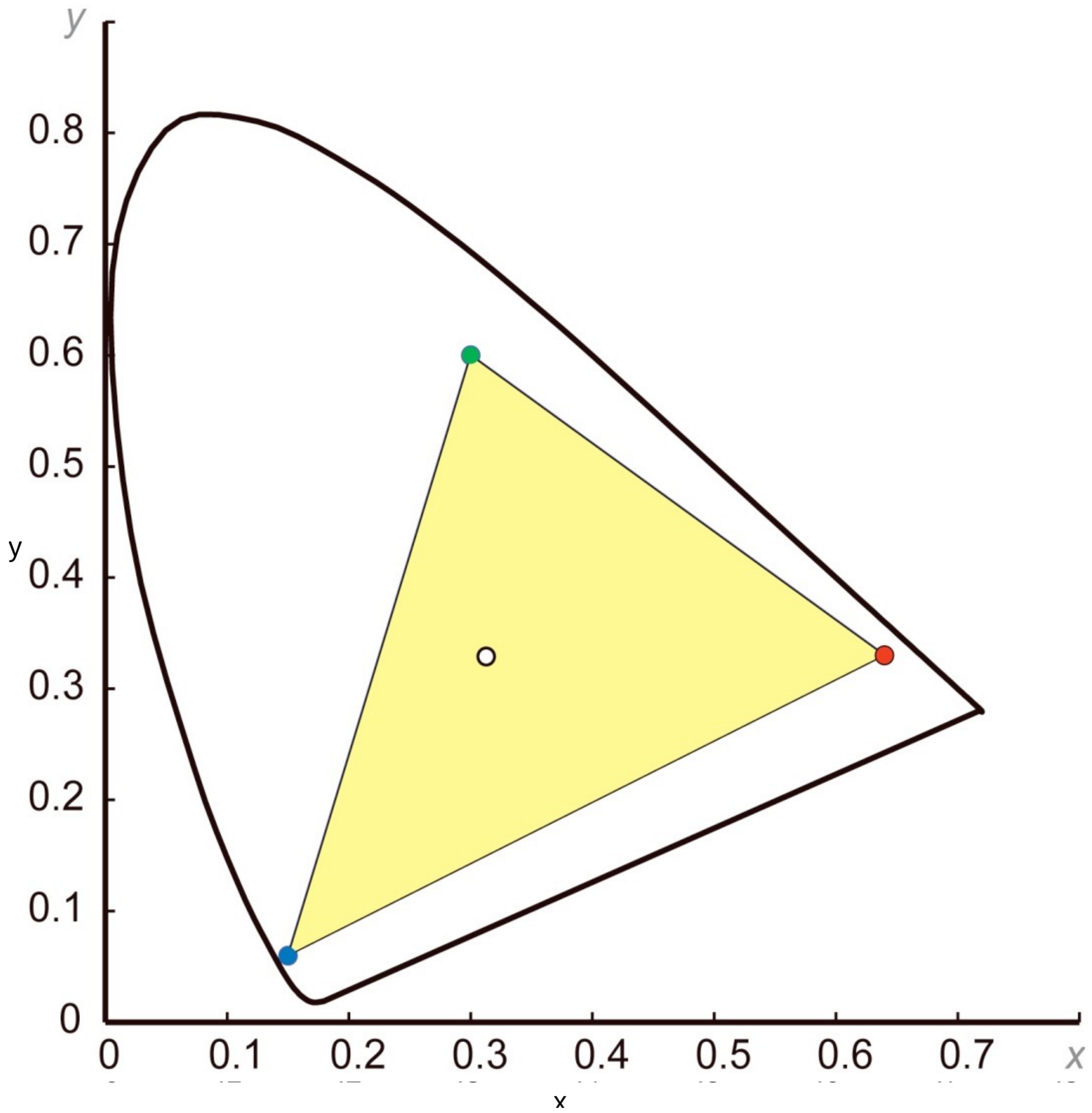
Spectral locus – set of pure colors (i.e., lasers of a single wavelength).

Slowly shifts from S → M → L.



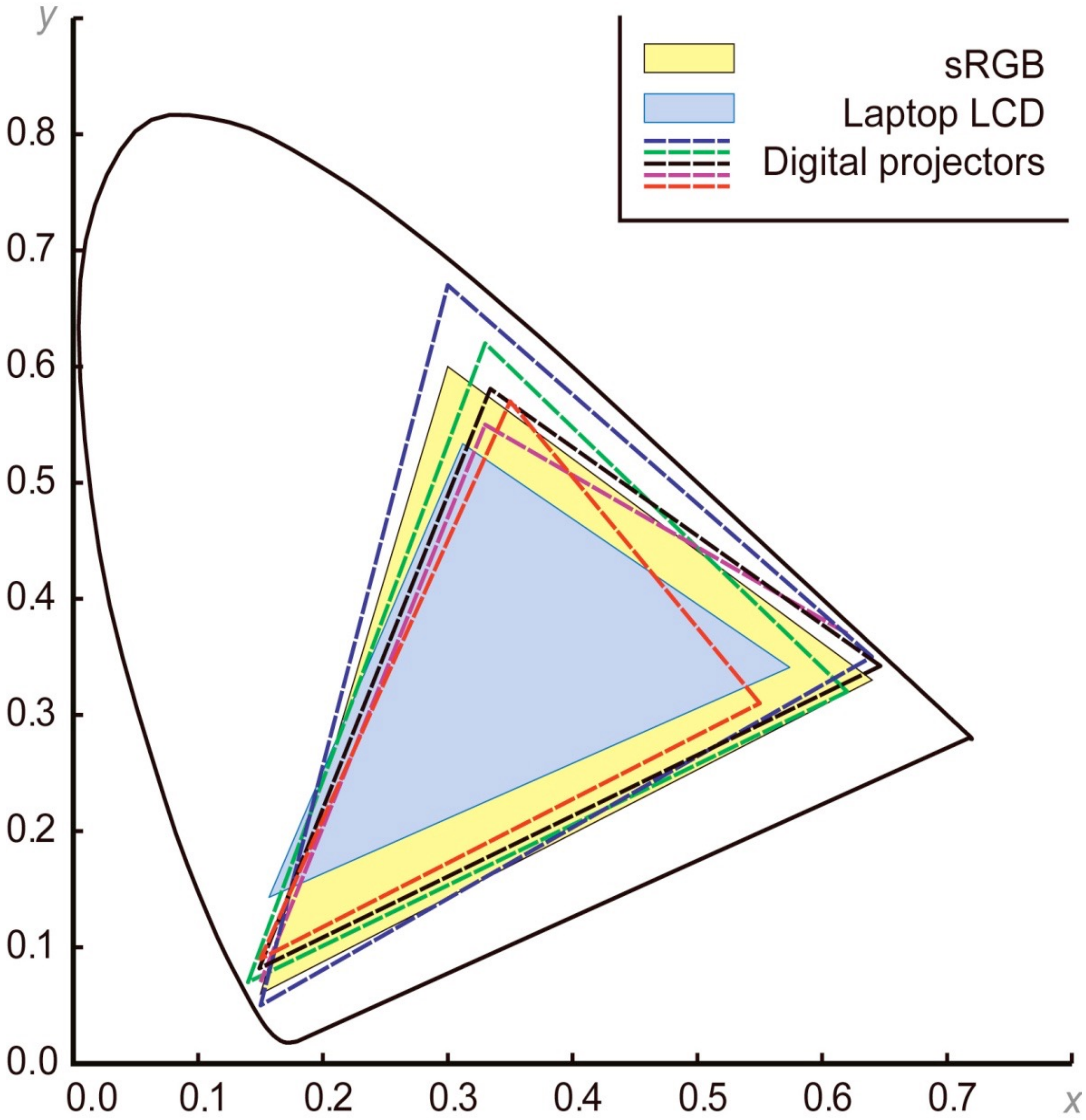
CIE XYZ Color Space

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



CIE XYZ Color Space

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



CIE XYZ Color Space

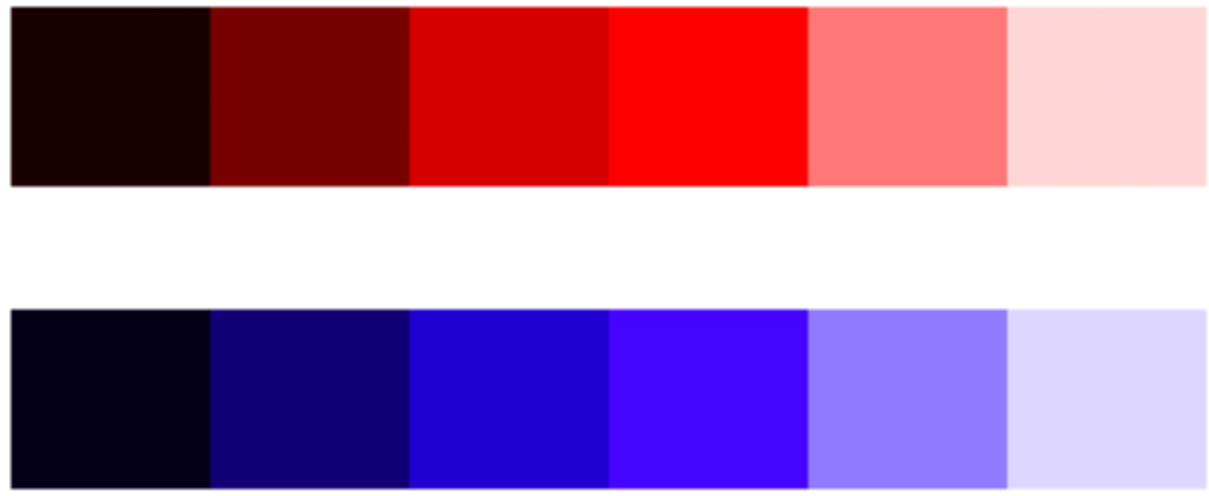
Display gamut = portion of the color space that can be reproduced by a display.

The angry rainbow in sRGB.

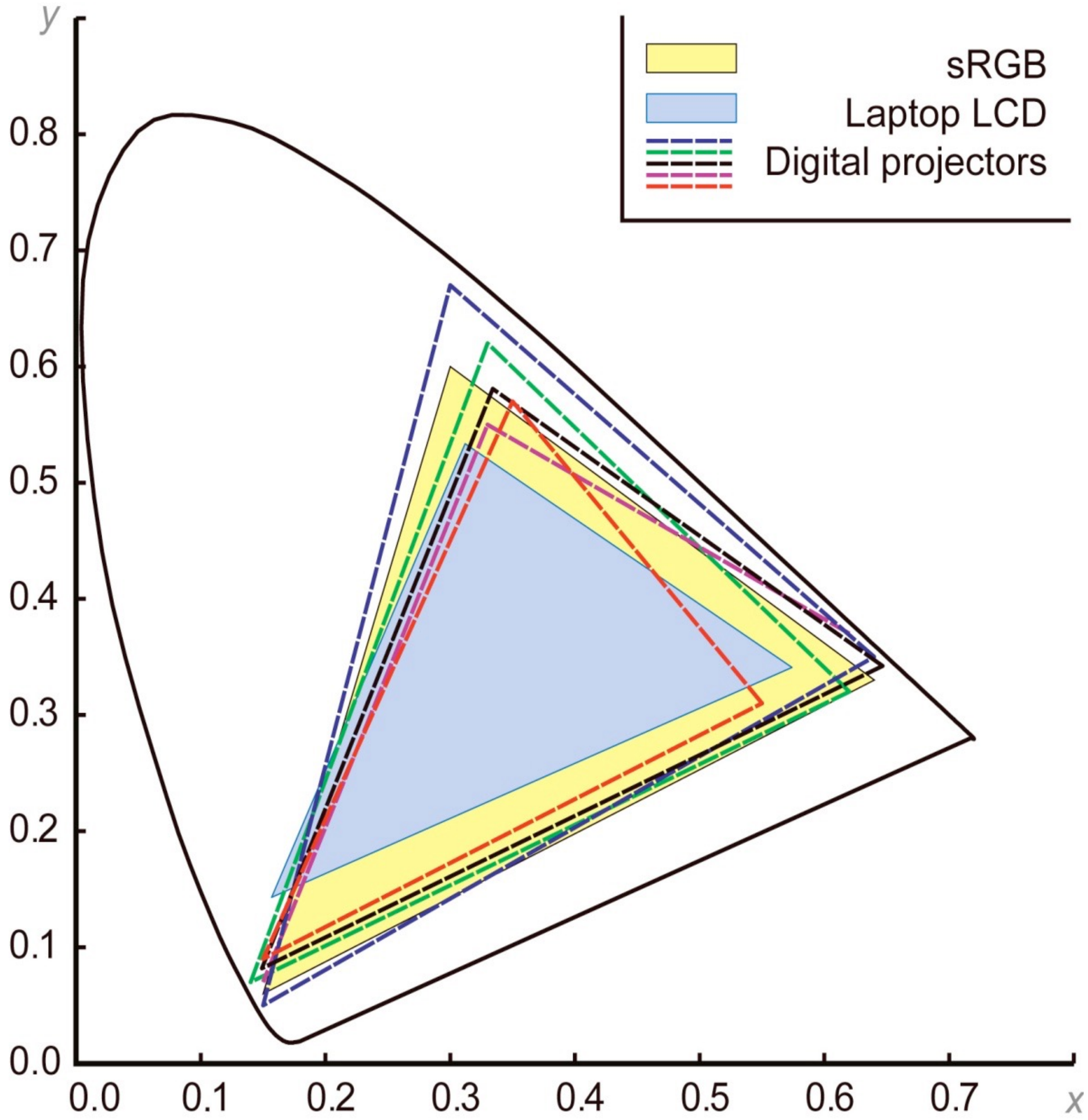
Corners of sRGB

Photoshop grayscale

No linear brightness gradient within a single hue.



[Gregor Aisch How to Avoid Equidistant HSV Colors.]

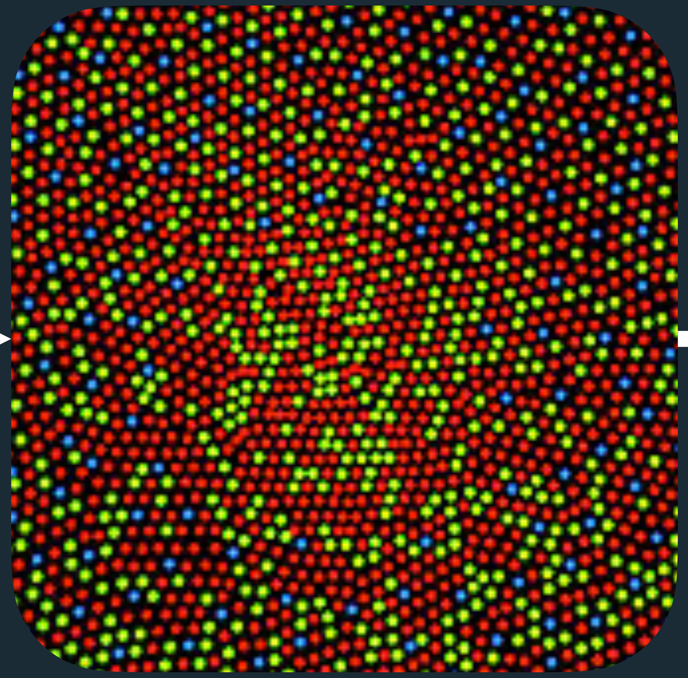


Modeling Color Perception

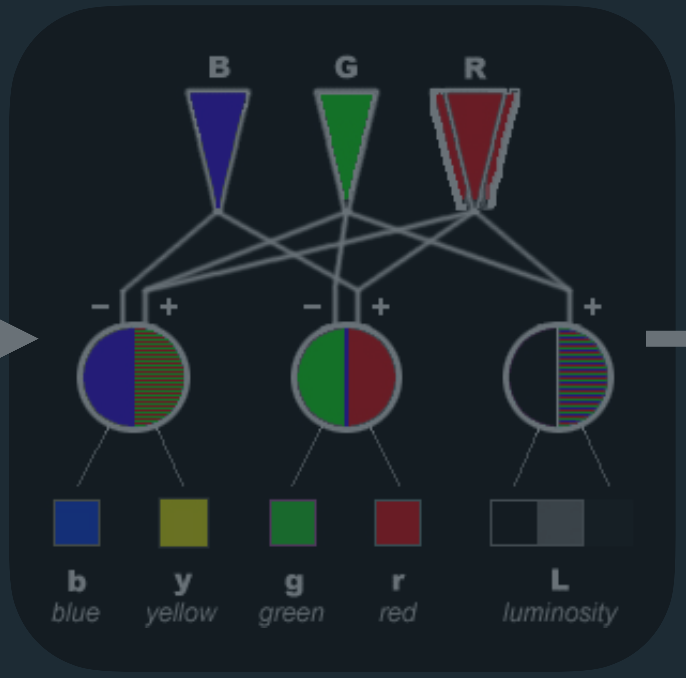
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light

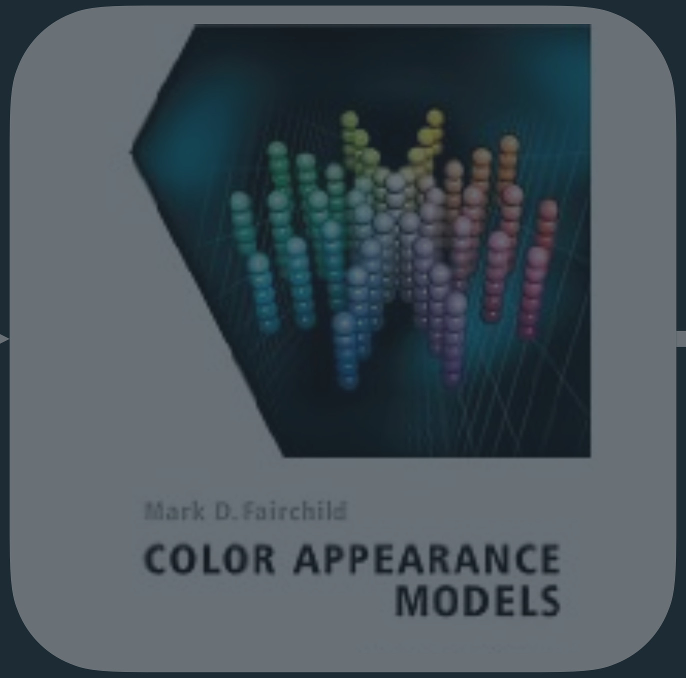


Cone Response



Opponent Encoding

Perceptual Models



Appearance Models

"Teal"

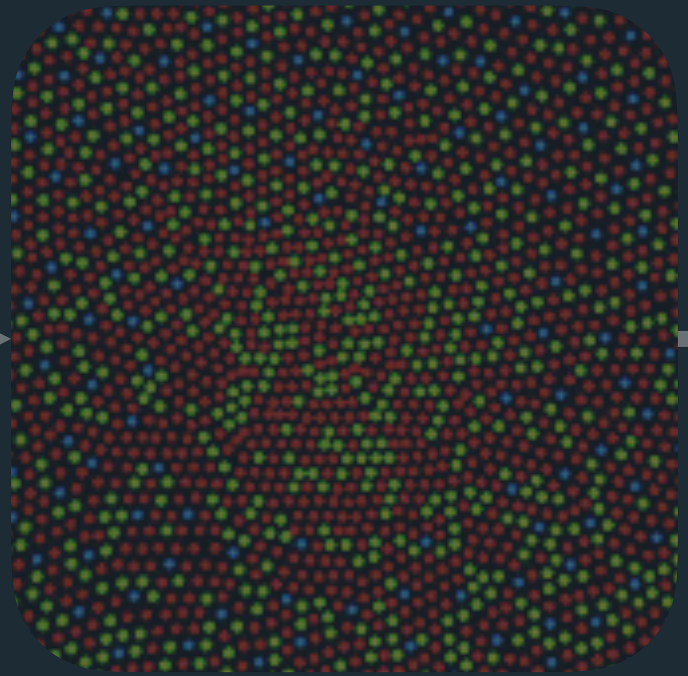
Cognitive Models

Modeling Color Perception

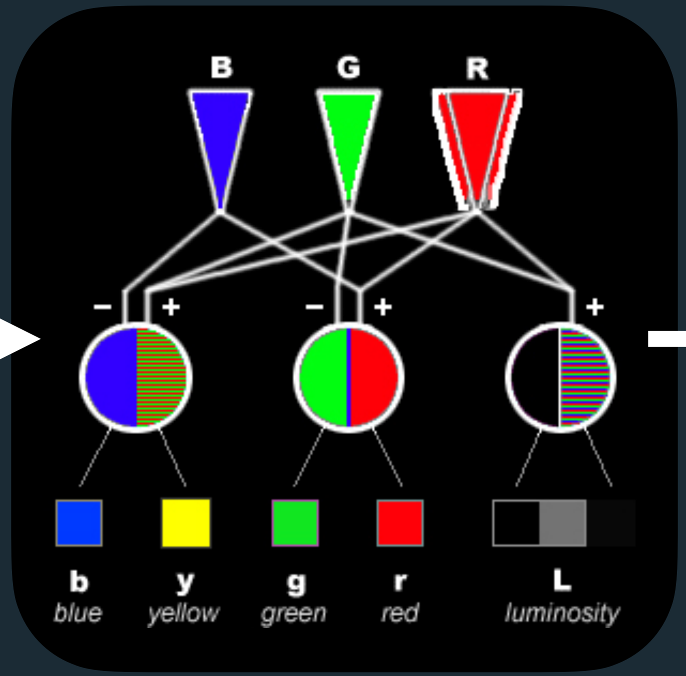
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light

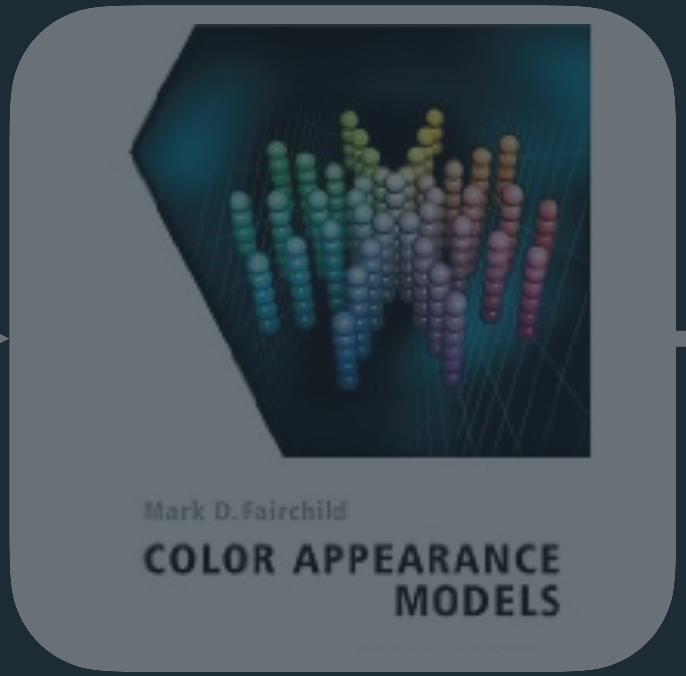


Cone Response



Opponent Encoding

Perceptual Models

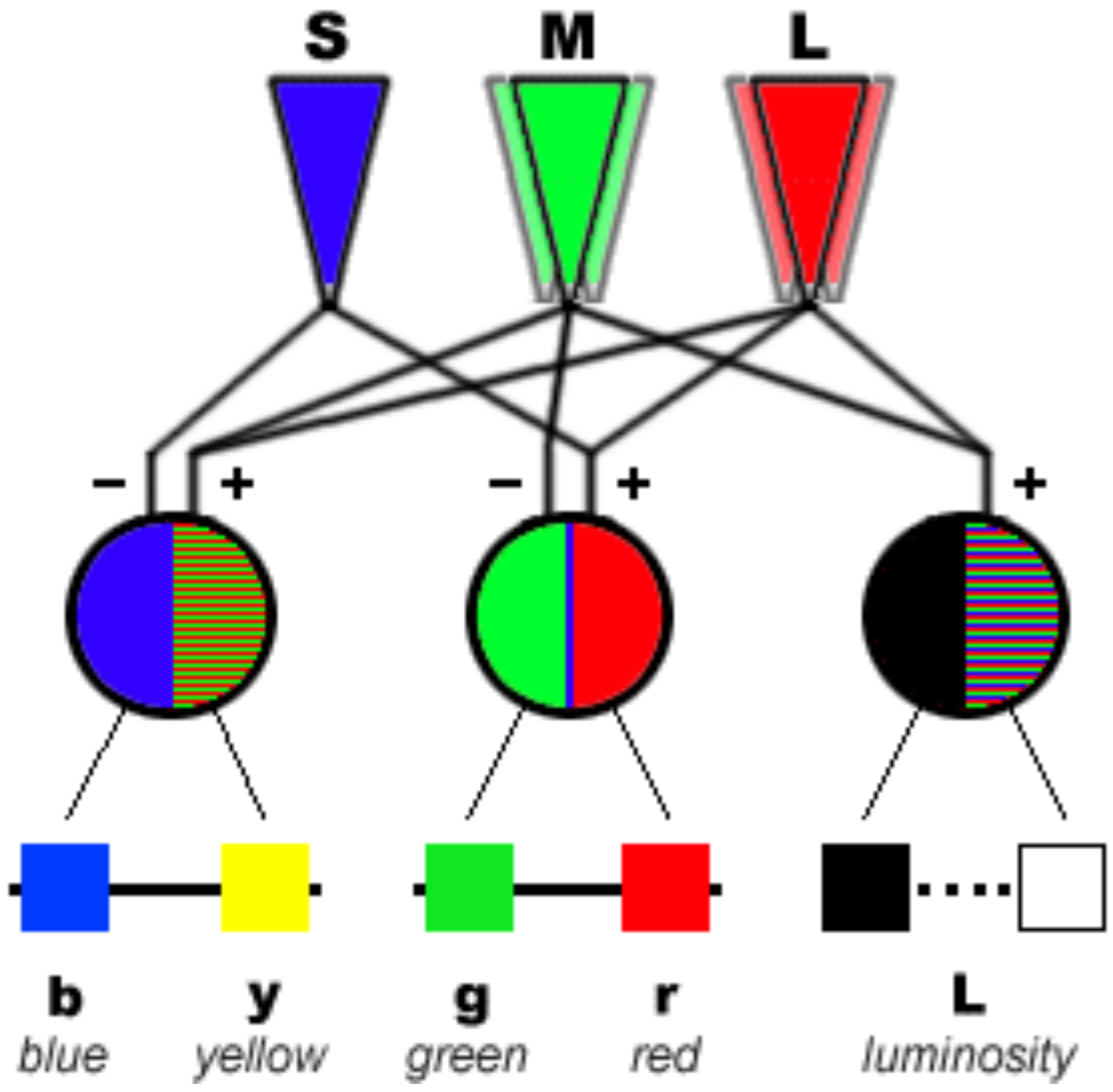


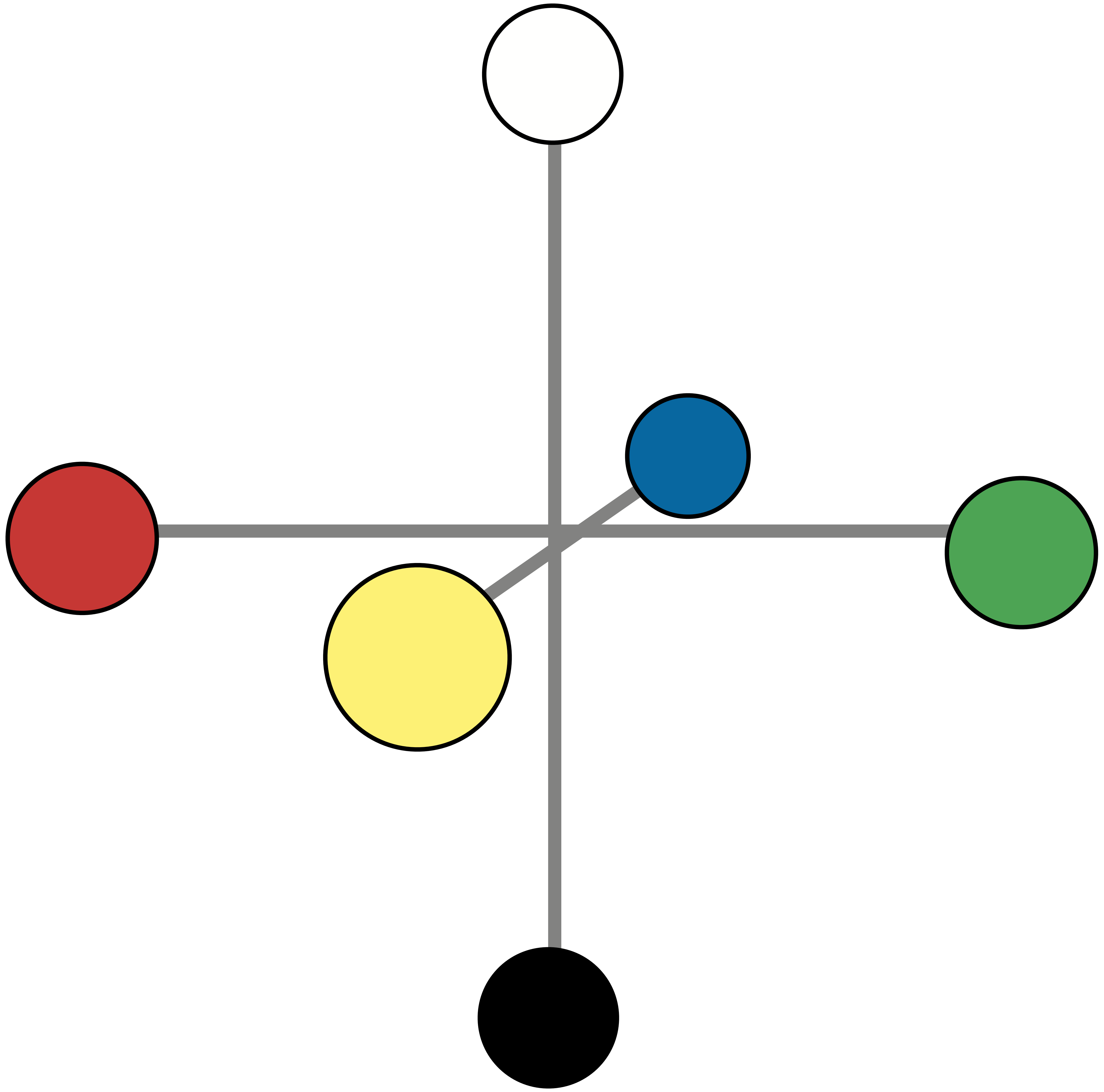
Appearance Models

"Teal"

Cognitive Models

Opponent Encoding

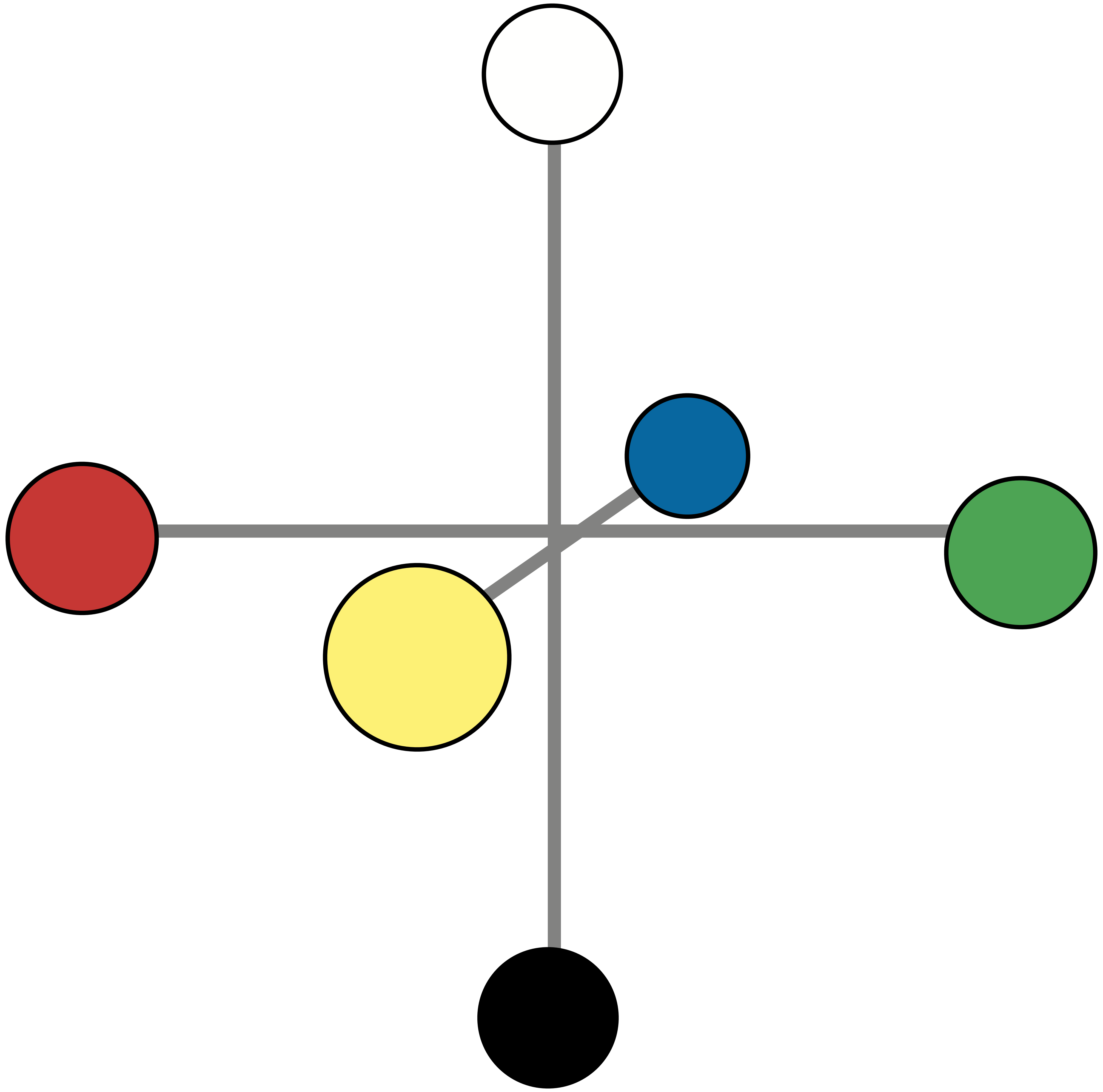




CIE LAB Color Space

Axes correspond to opponent signals:

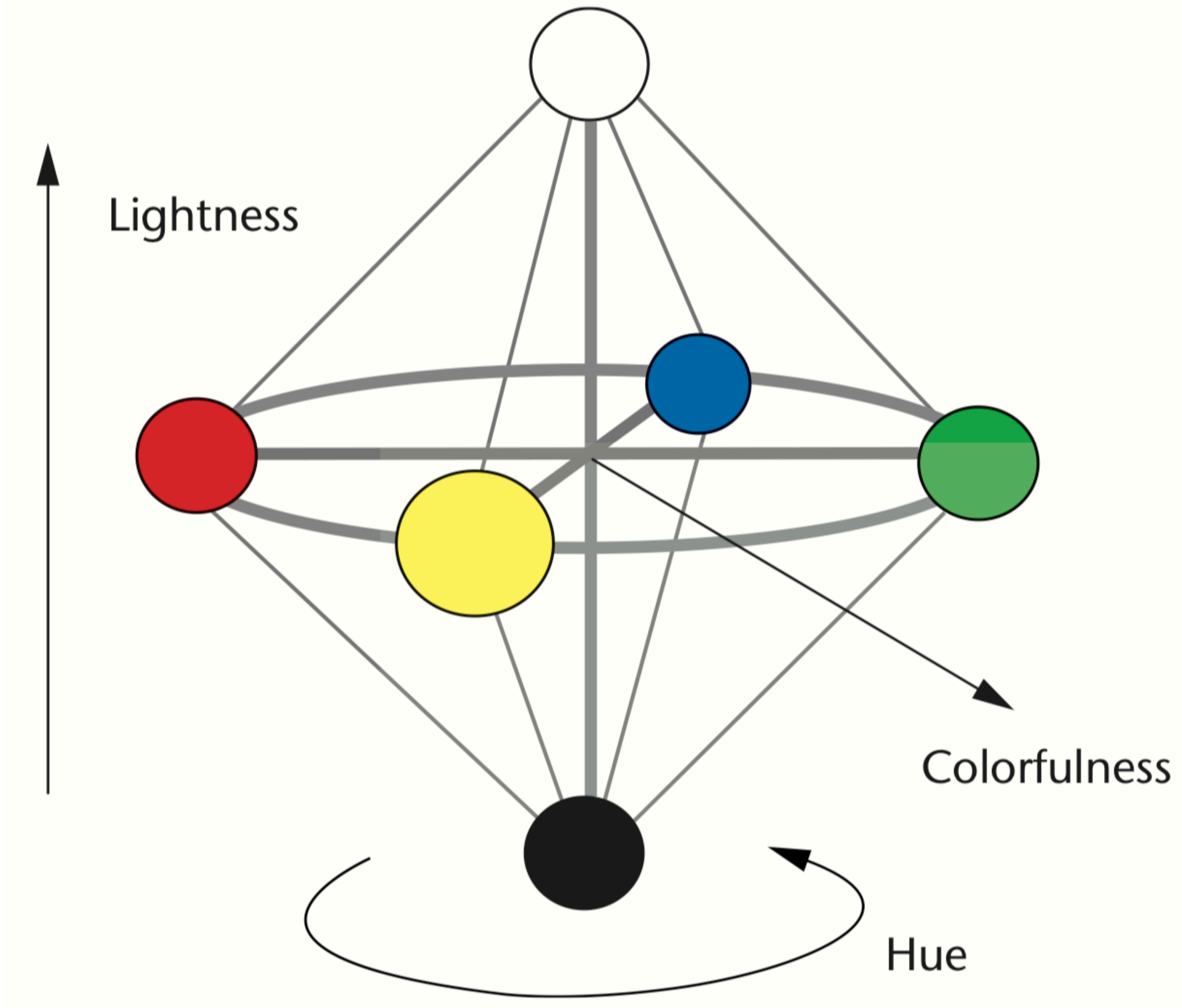
- L* = luminance
- a* = red-green contrast
- b* = yellow-blue contrast



CIE LAB Color Space

Axes correspond to opponent signals:

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



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

CIE LAB Color Space

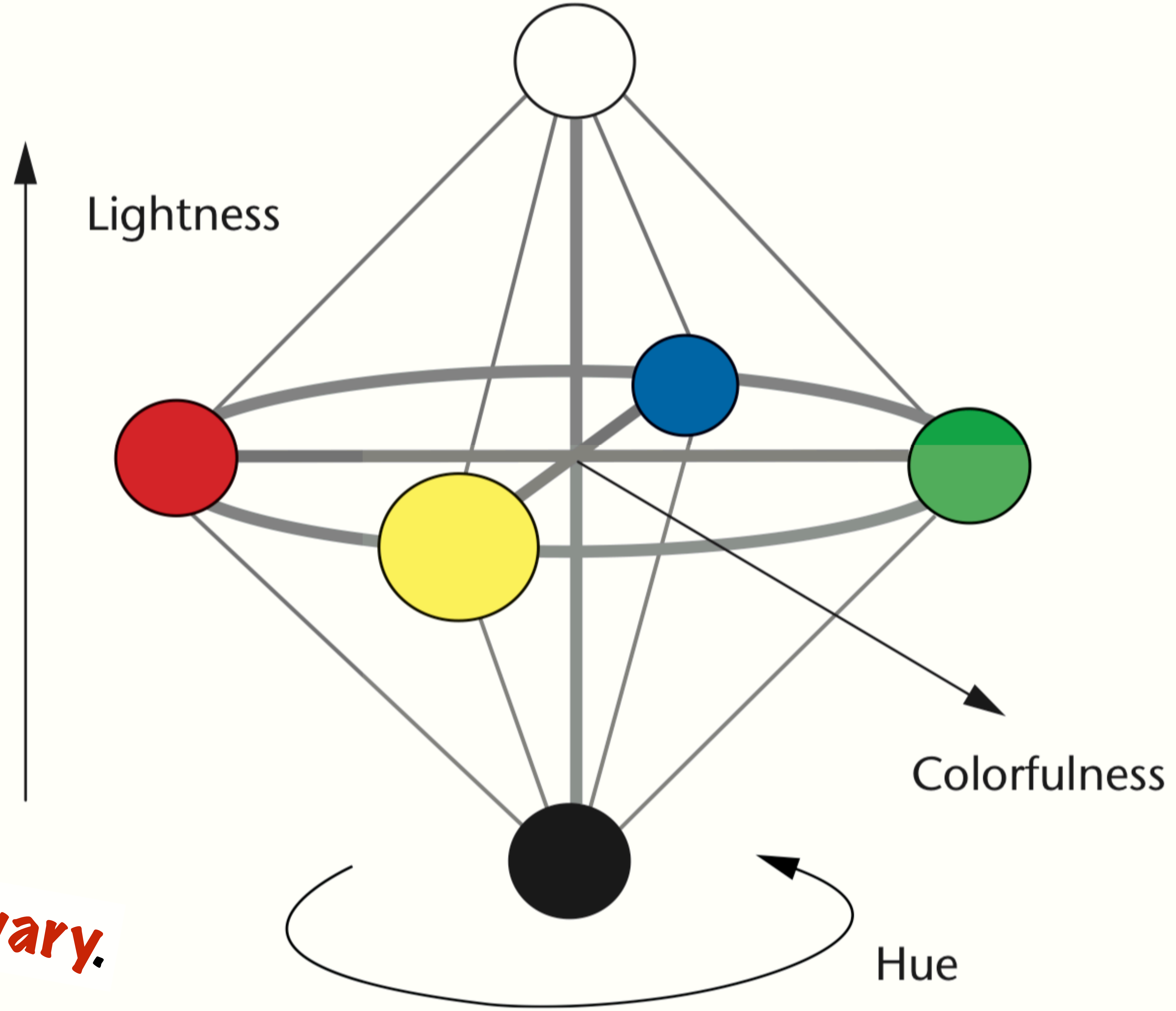
More perceptually uniform than sRGB.

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

The angry rainbow in sRGB.

Better. But still be wary.

A happier rainbow in LAB.



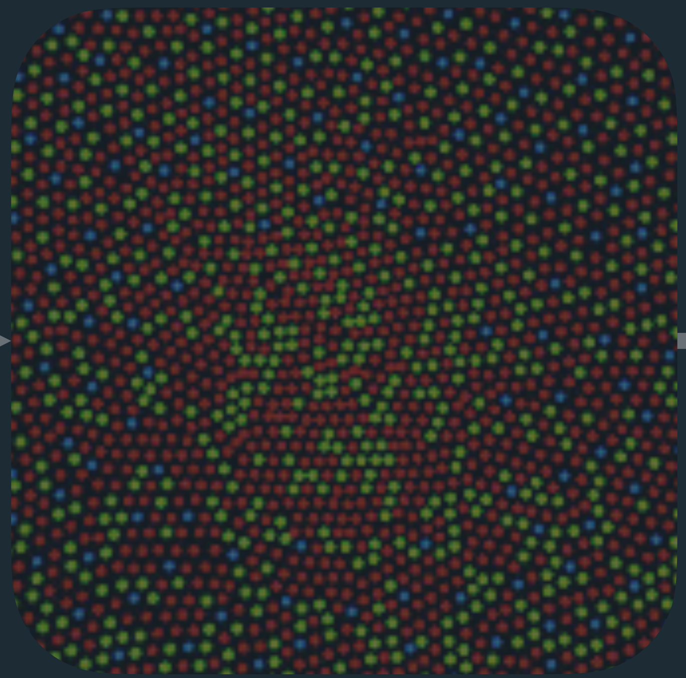
[Maureen Stone. *A Field Guide to Digital Color*, 2003]

Modeling Color Perception

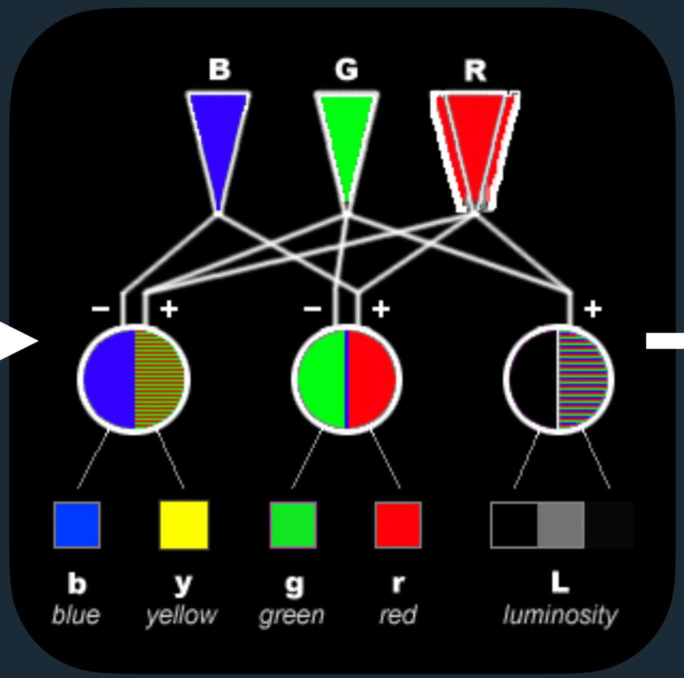
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light

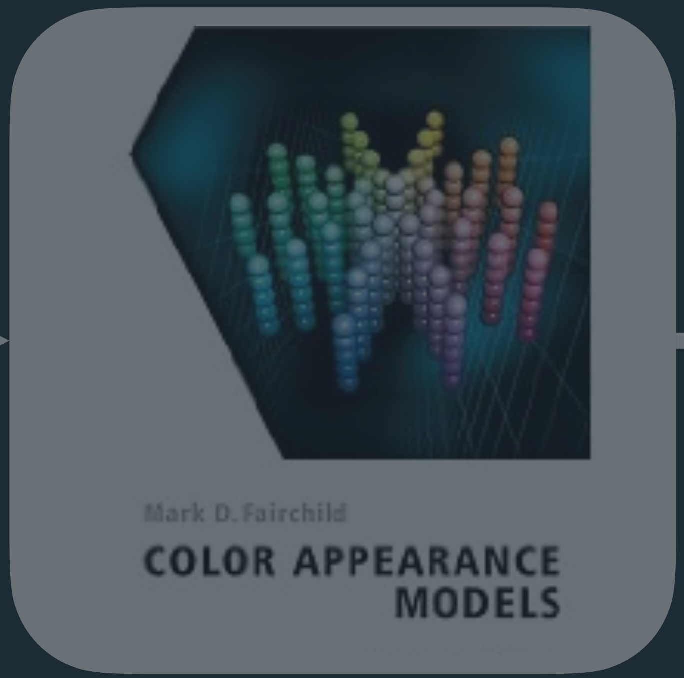


Cone Response



Opponent Encoding

Perceptual Models



Appearance Models

"Teal"

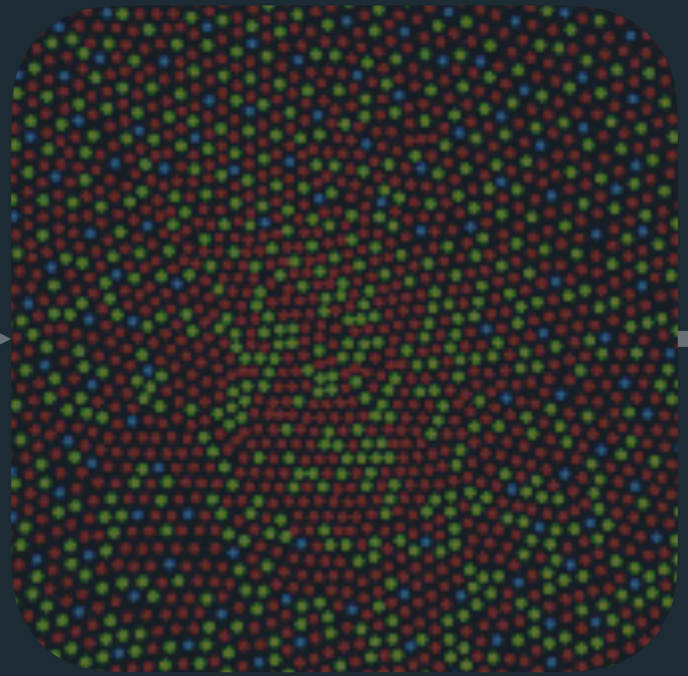
Cognitive Models

Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response

Opponent Encoding

Perceptual Models

Appearance Models

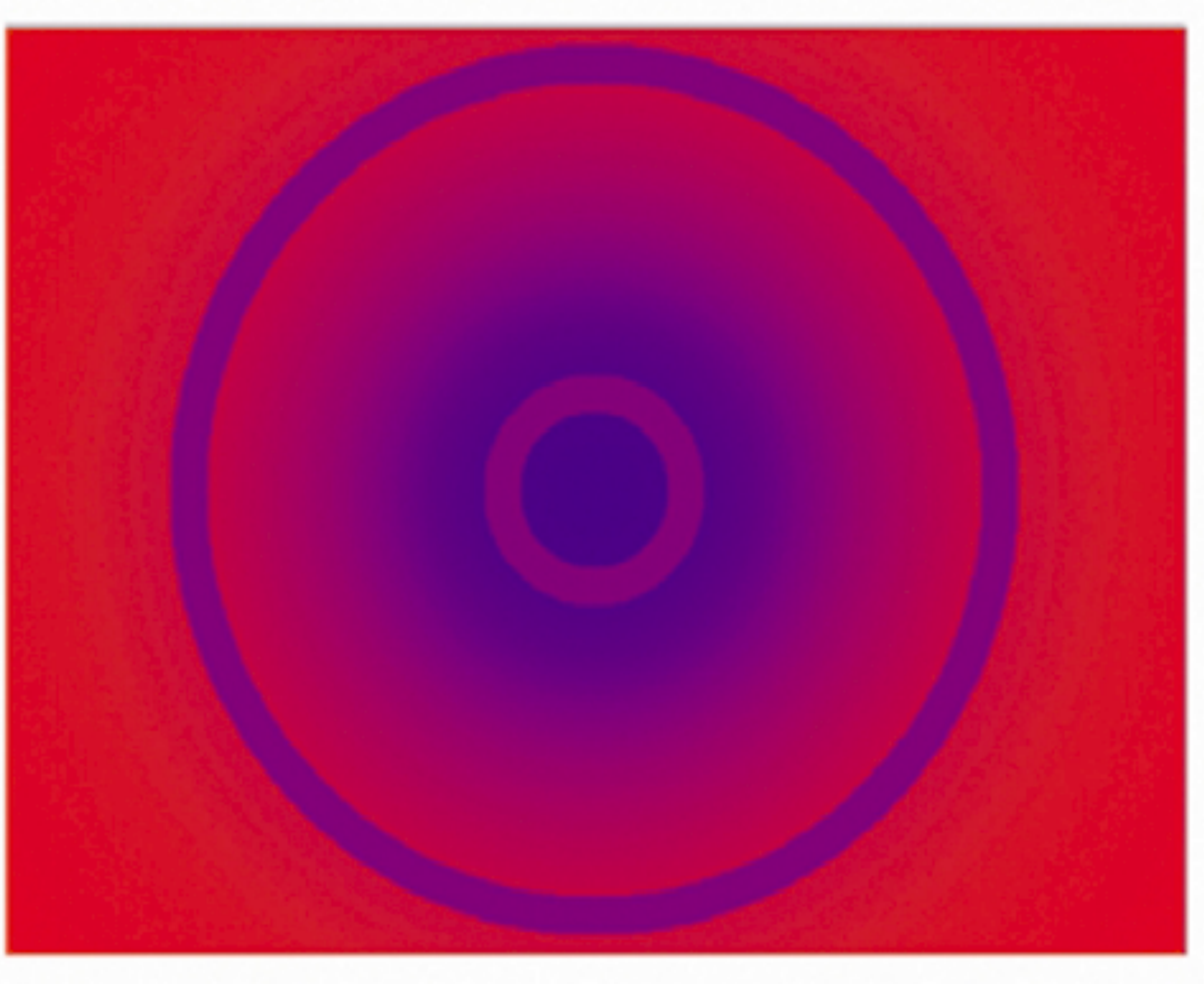
“Teal”

Cognitive Models

Simultaneous Contrast

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

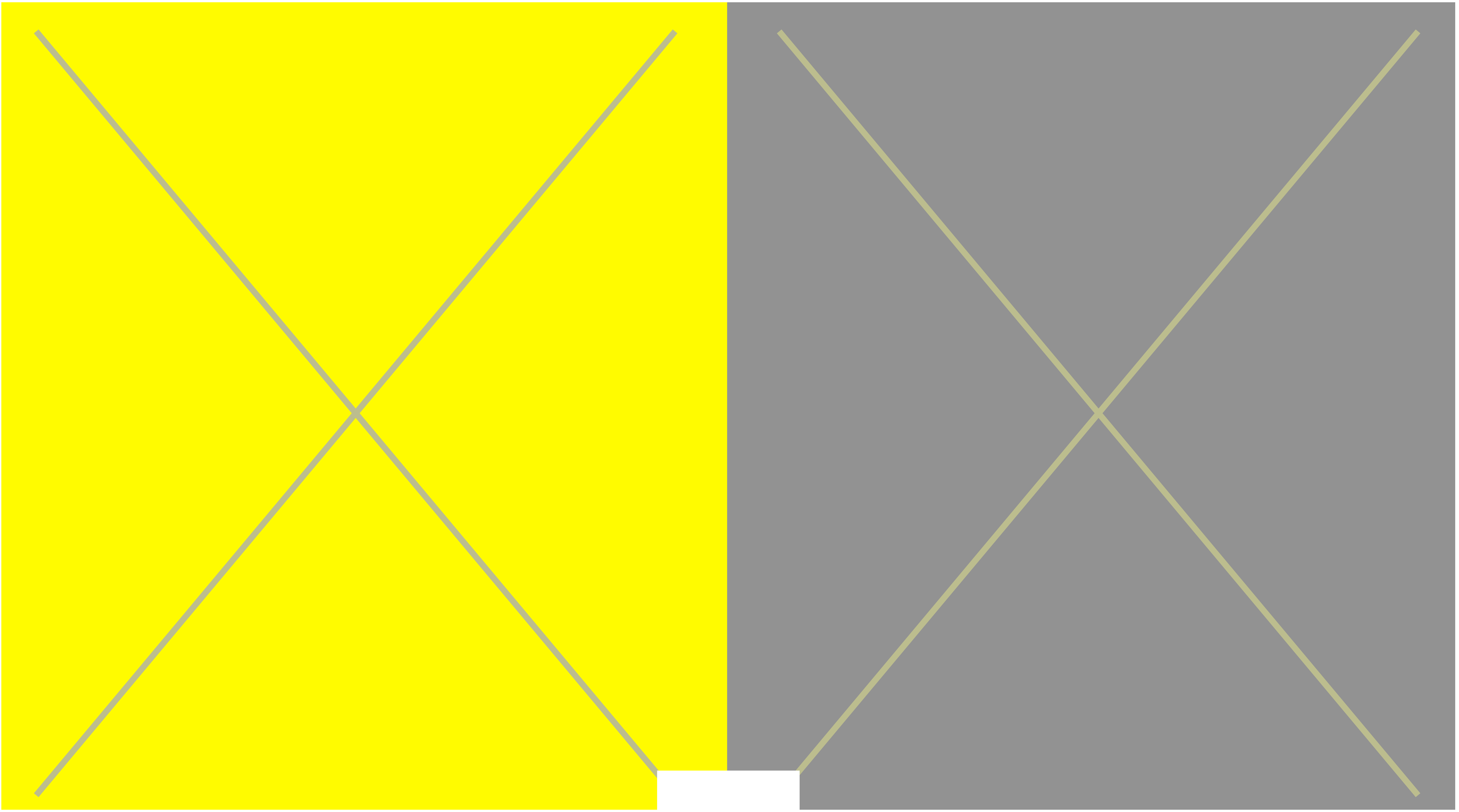
The inner and outer thin rings are,
in fact, the same physical purple!



Donald Macleod

Simultaneous Contrast

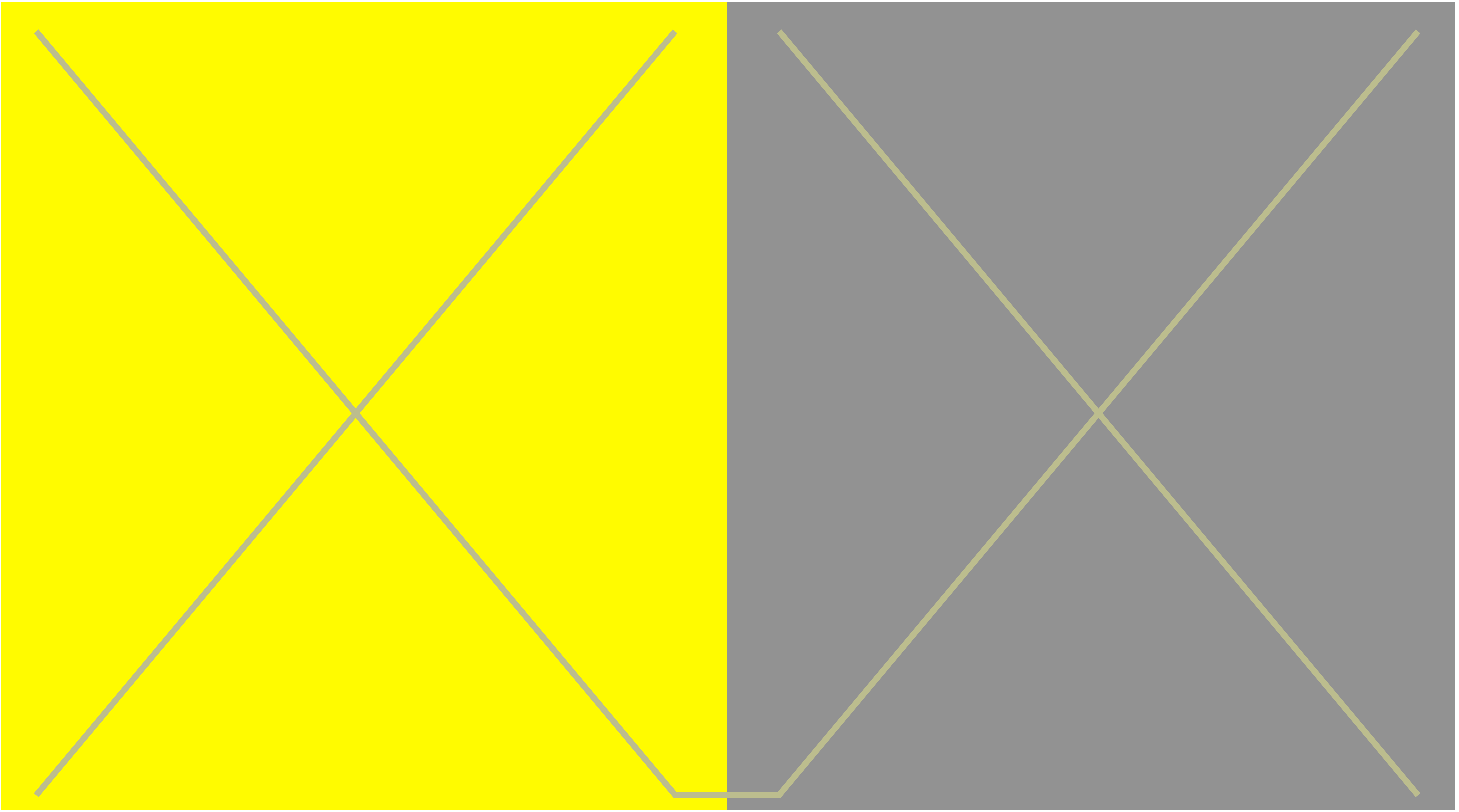
When two colors are side-by-side,
they interact and affect our perception



Josef Albers

Simultaneous Contrast

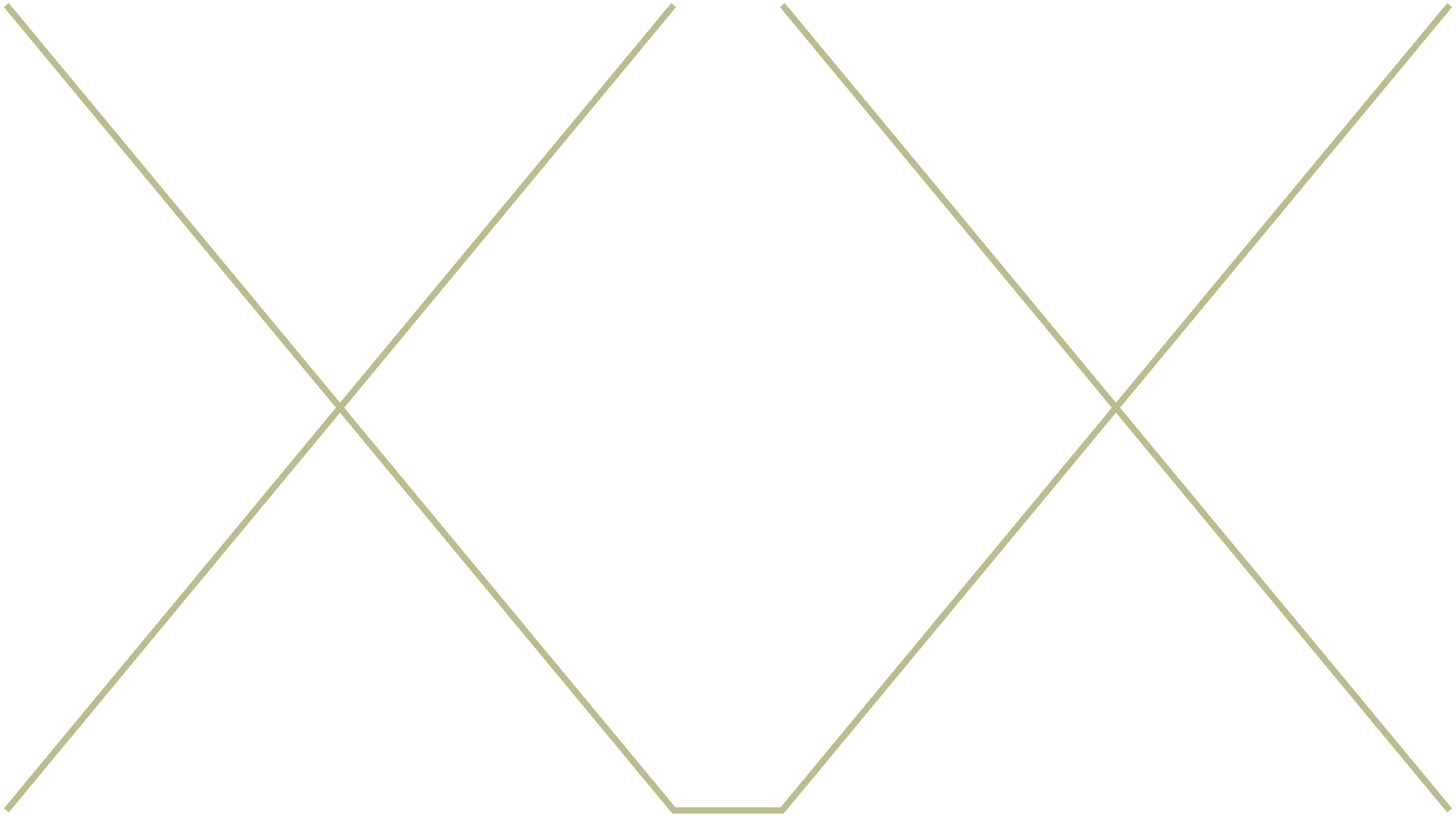
When two colors are side-by-side,
they interact and affect our perception



Josef Albers

Simultaneous Contrast

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

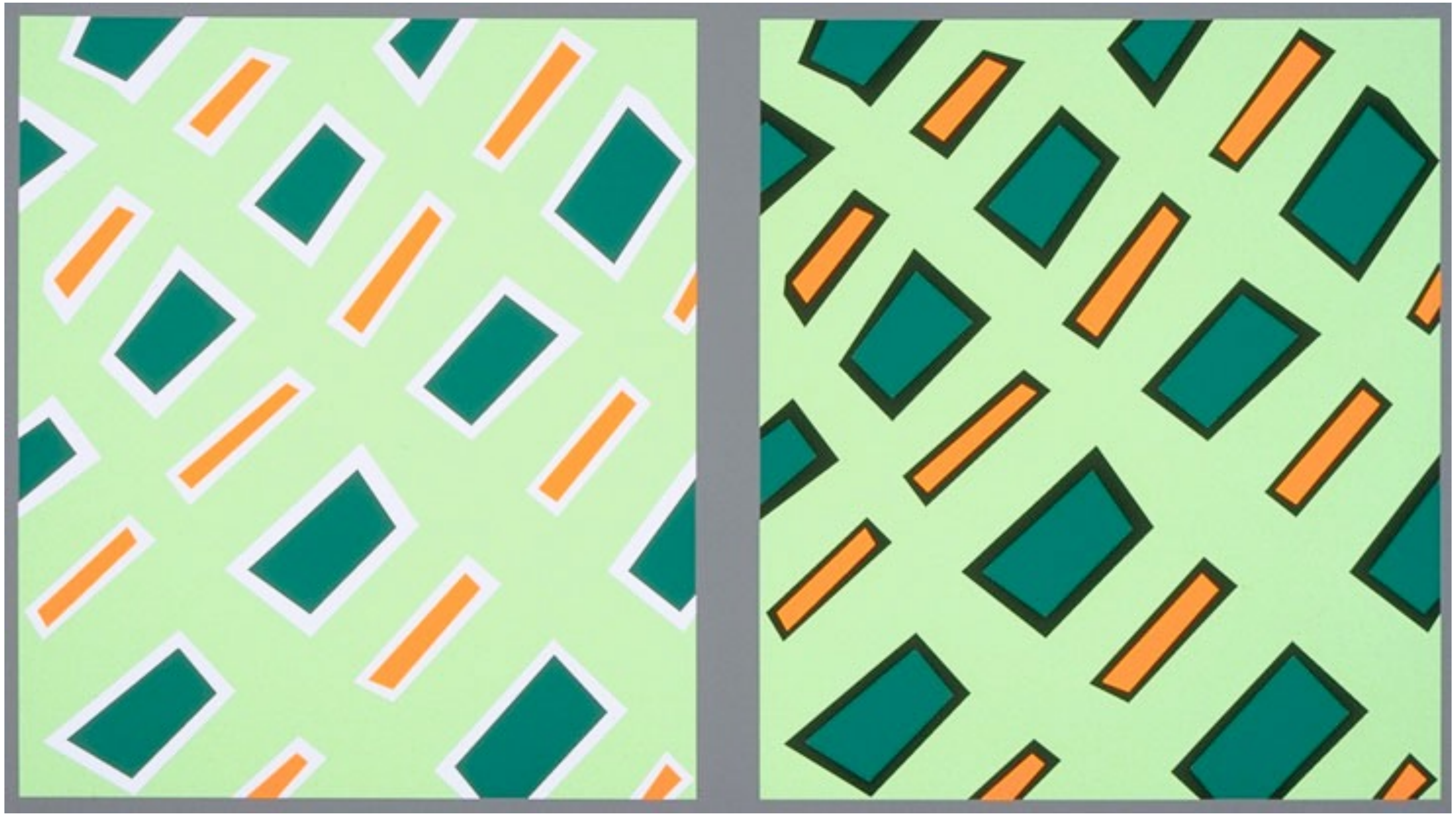


Josef Albers

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

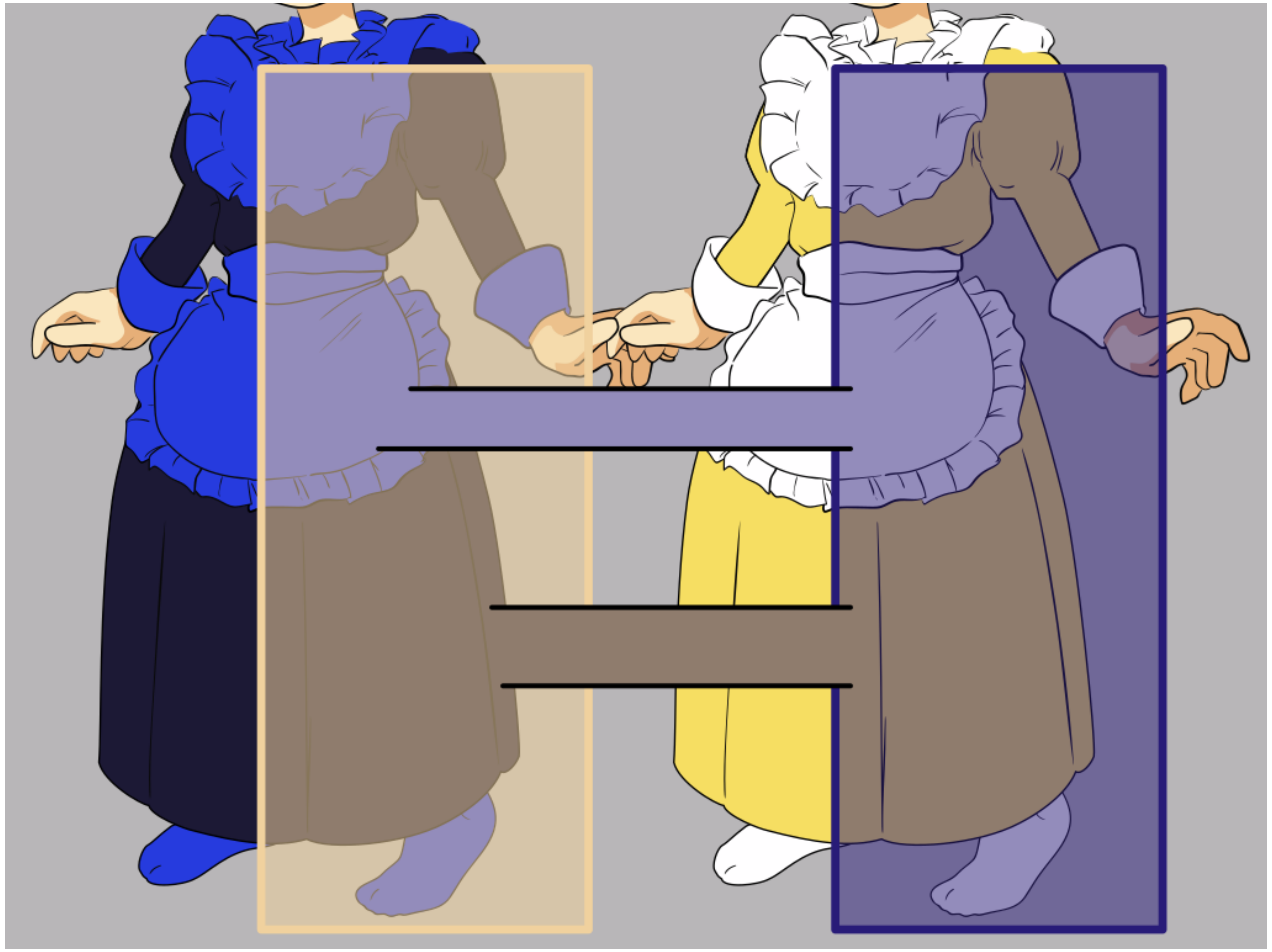
Chromatic Adaptation

Our ability to adjust to color perception based on illumination

Jason Su

Chromatic Adaptation

Our ability to adjust to color perception based on illumination

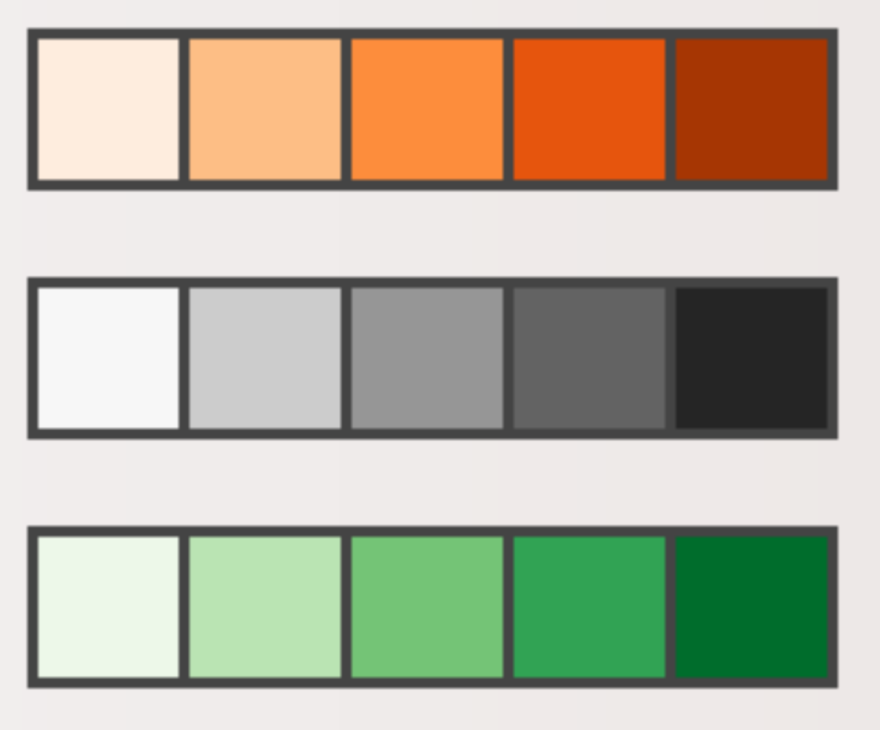


Quantitative Color Encoding

Sequential Color Scale

Ramp in luminance, possibly also hue.

Typically higher values map to darker colors.

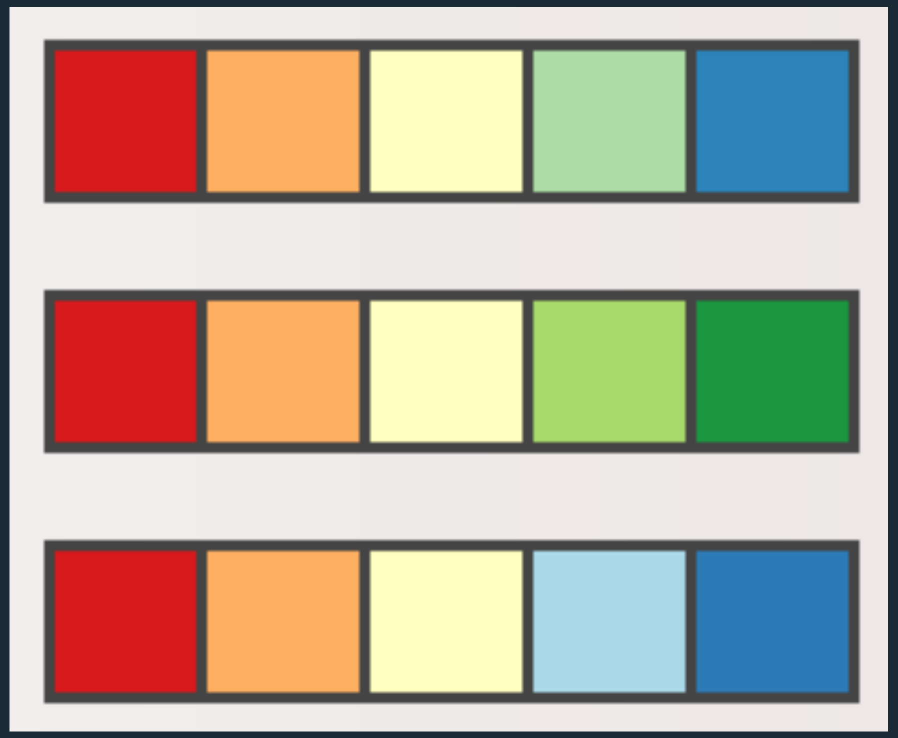


Diverging Color Scale

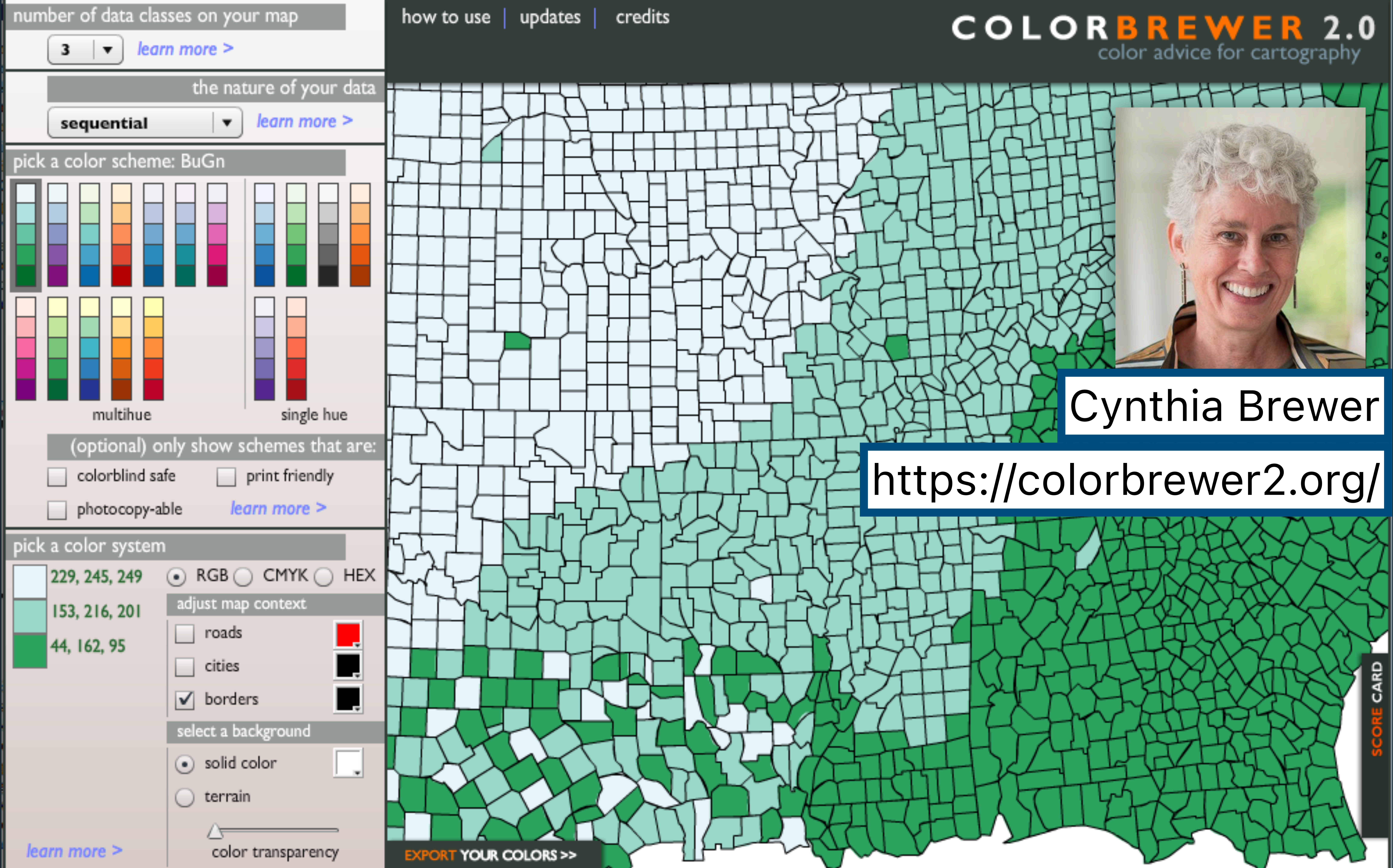
Useful when data has a meaningful "midpoint."

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

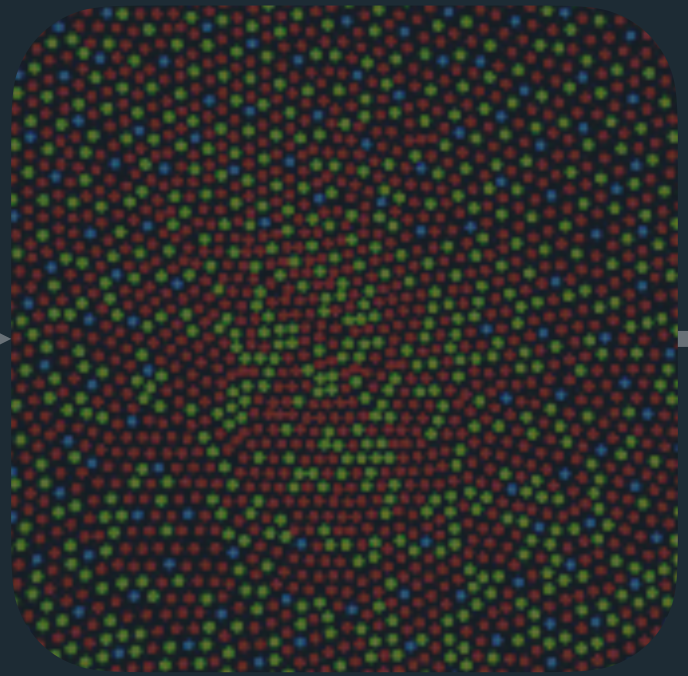
Low-Level Abstraction High-Level

Physical World

Visual System

Mental Models

Visible Light



Cone Response

Opponent Encoding

Perceptual Models

Appearance Models

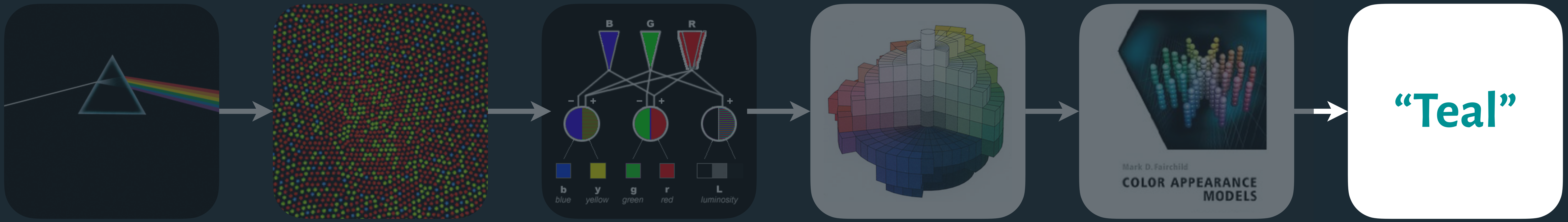
"Teal"

Cognitive Models

Modeling Color Perception

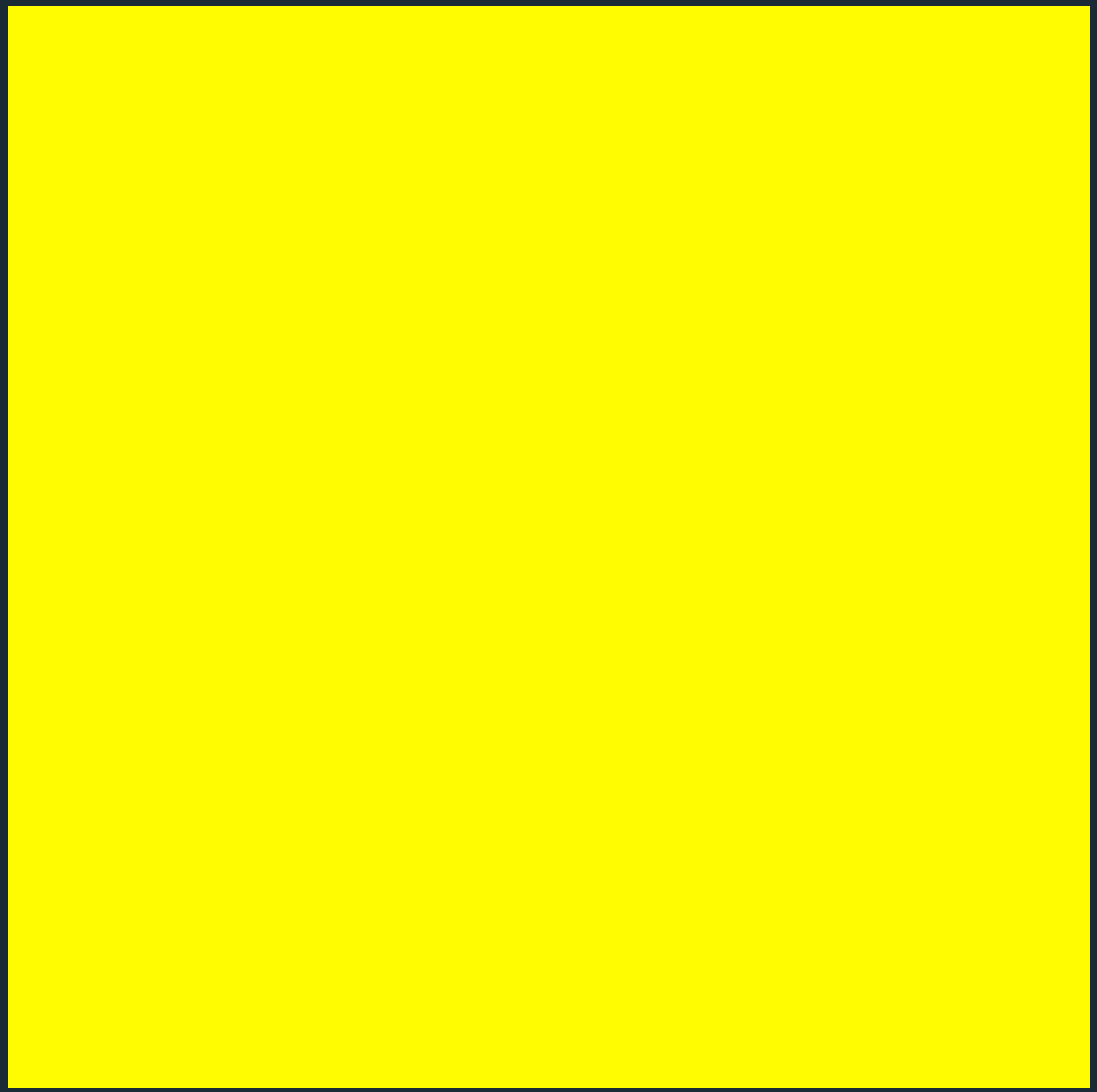
Low-Level | Abstraction | High-Level

Physical World | Visual System | Mental Models

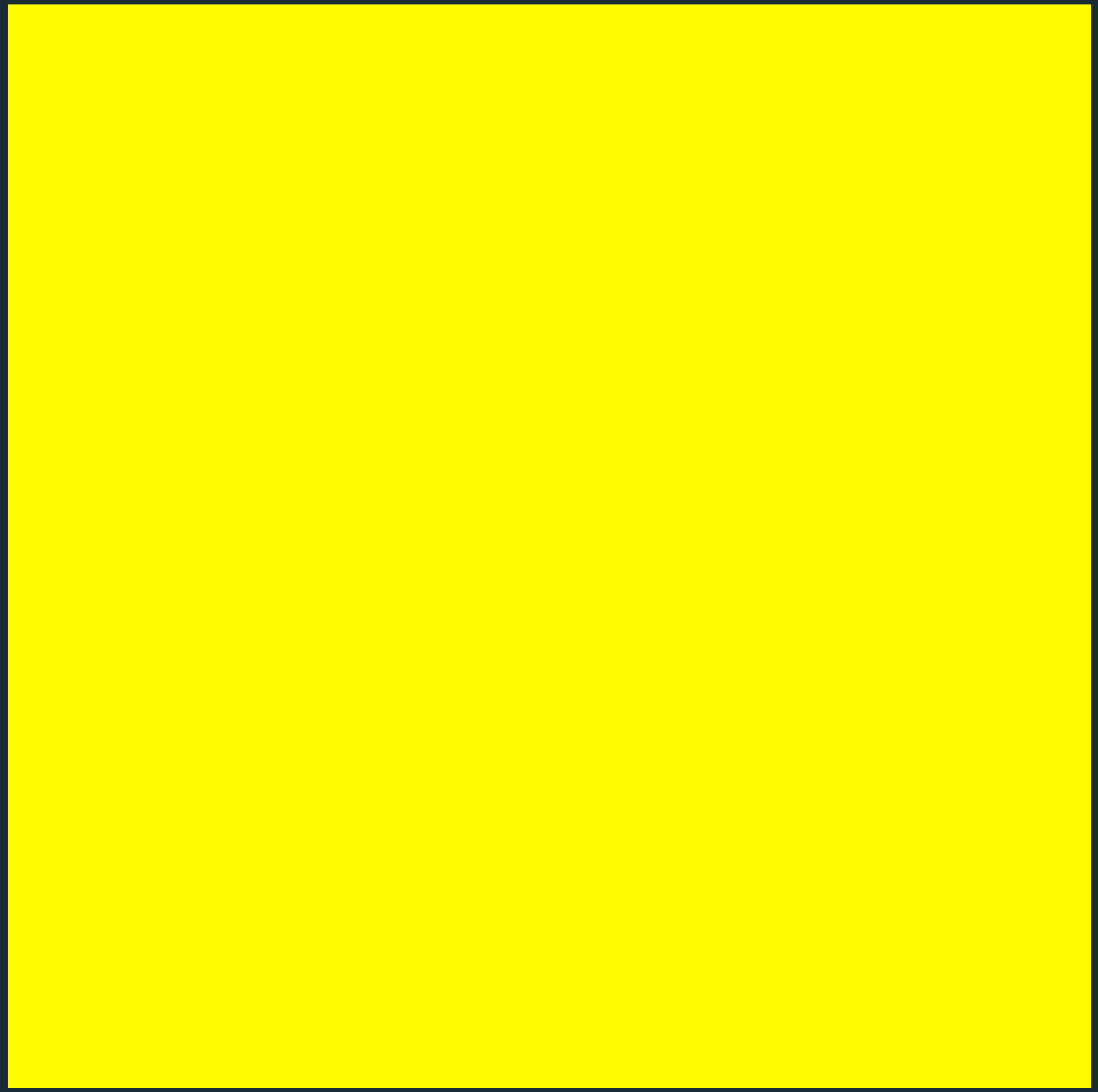


Visible Light → Cone Response → Opponent Encoding → Perceptual Models → Appearance Models → Cognitive Models

What color is this?

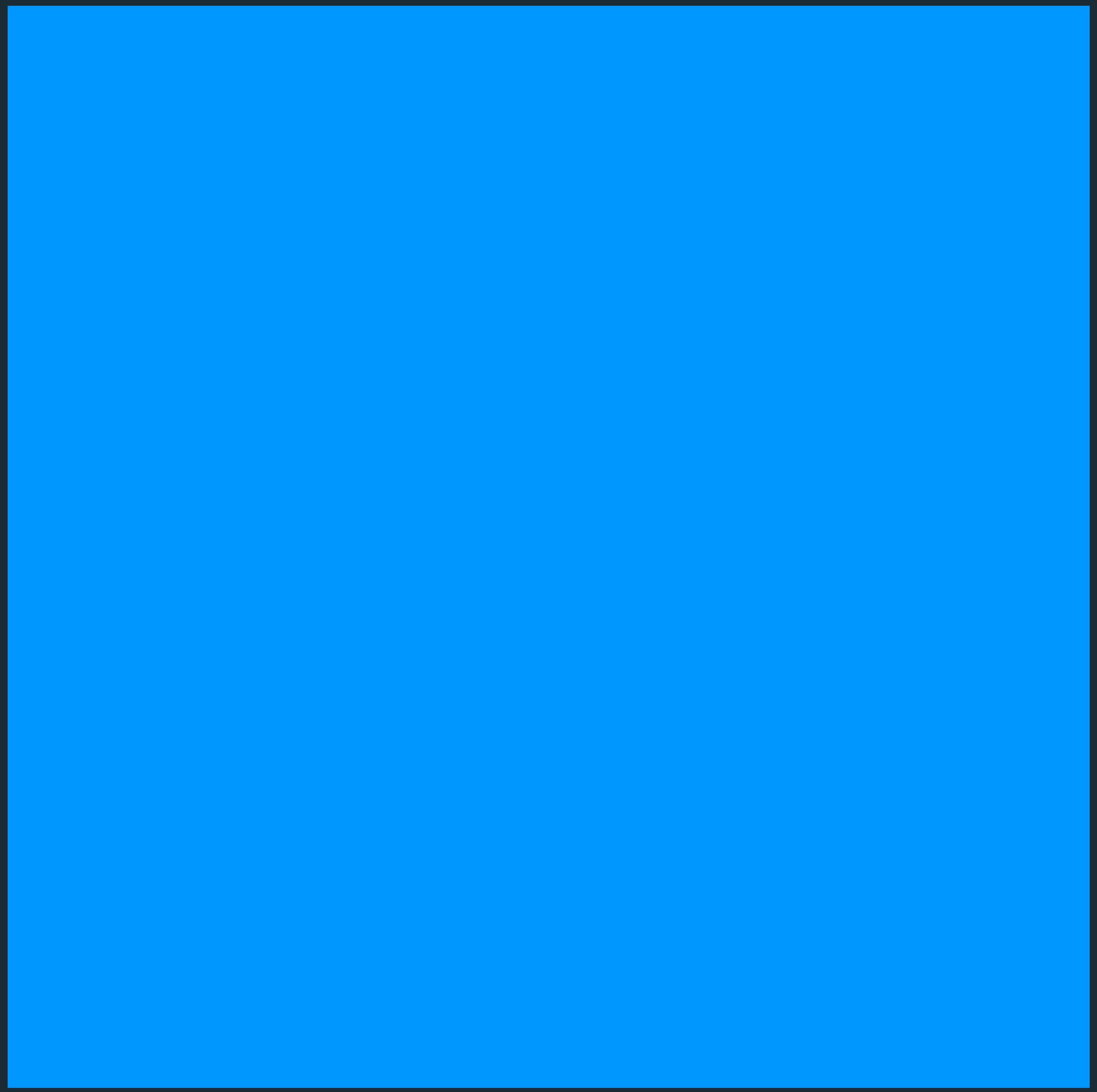


What color is this?

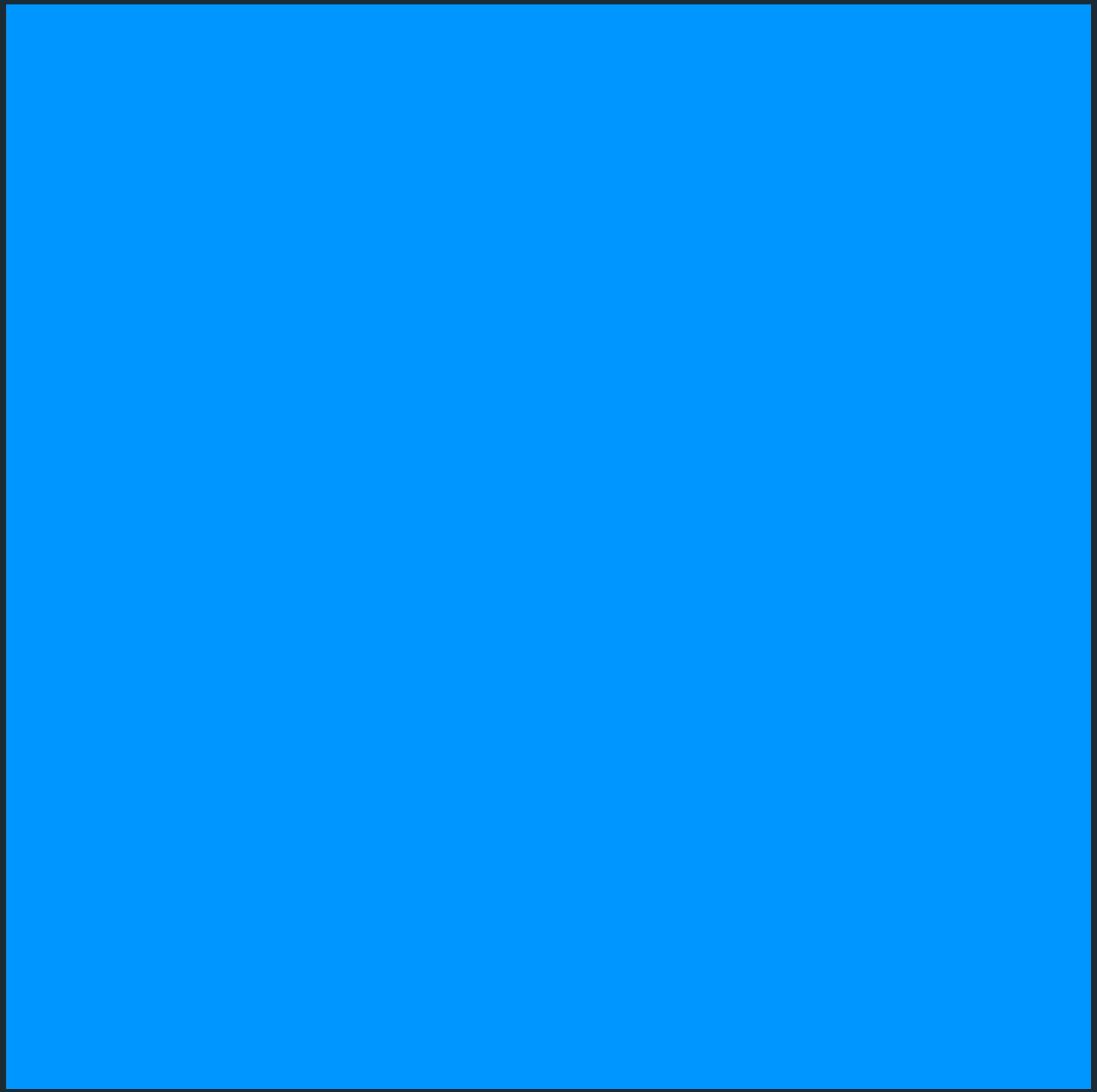


“Yellow”

What color is this?

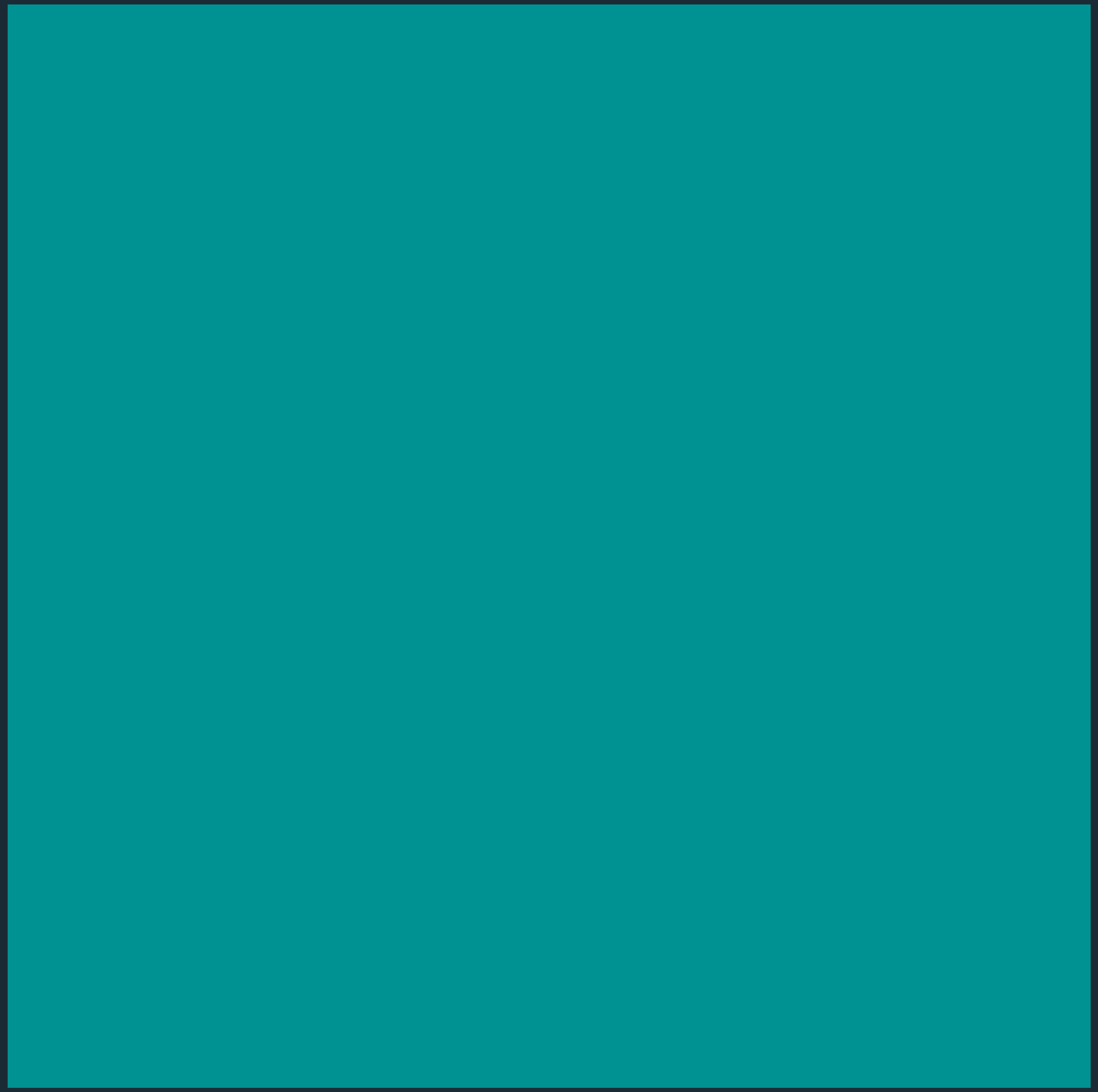


What color is this?



“Blue”

What color is this?



Join at
slido.com
#3972 640

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.

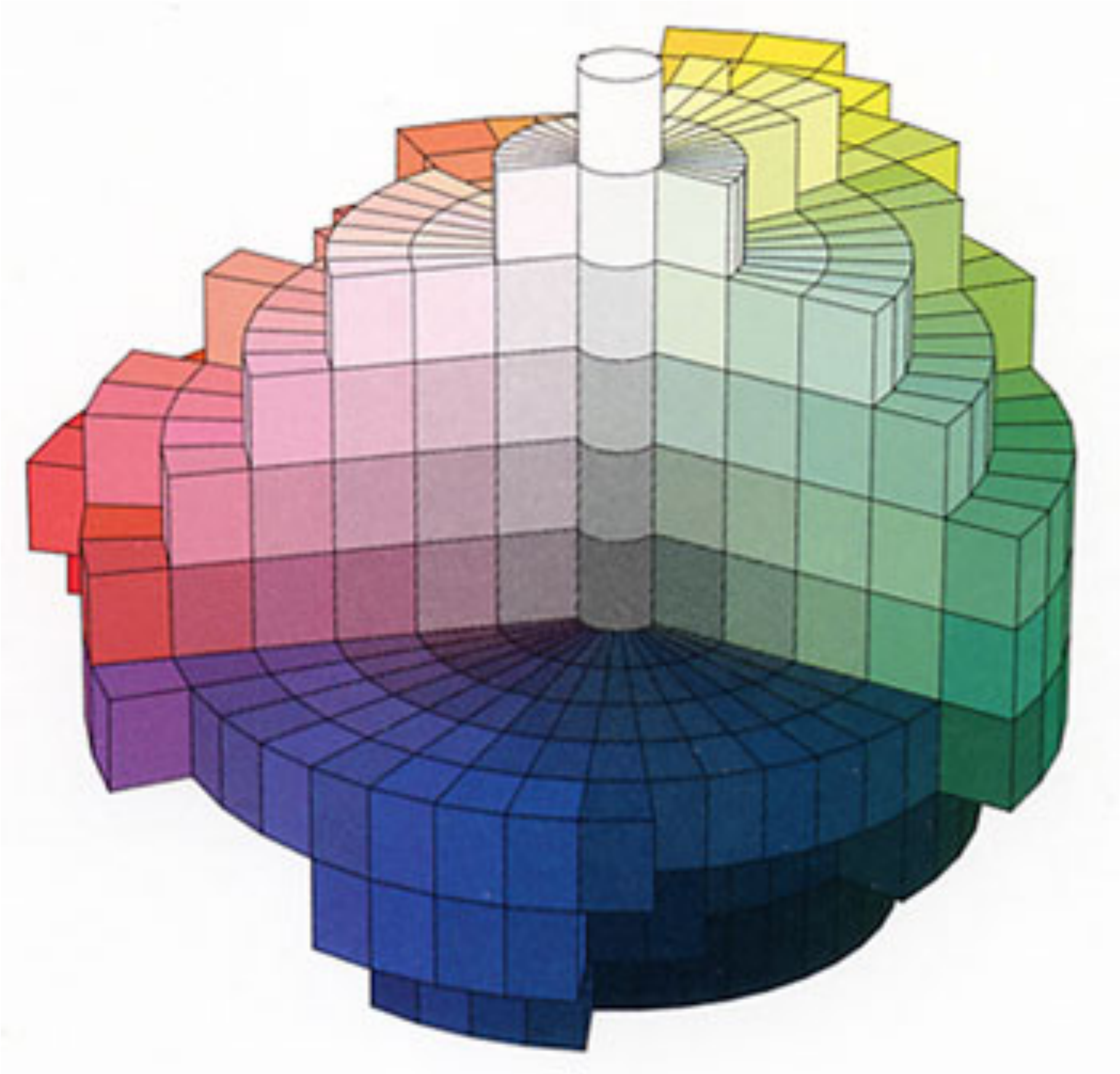
110 languages (including tribal), 25 speakers each.
Analysis published in 2009.

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.



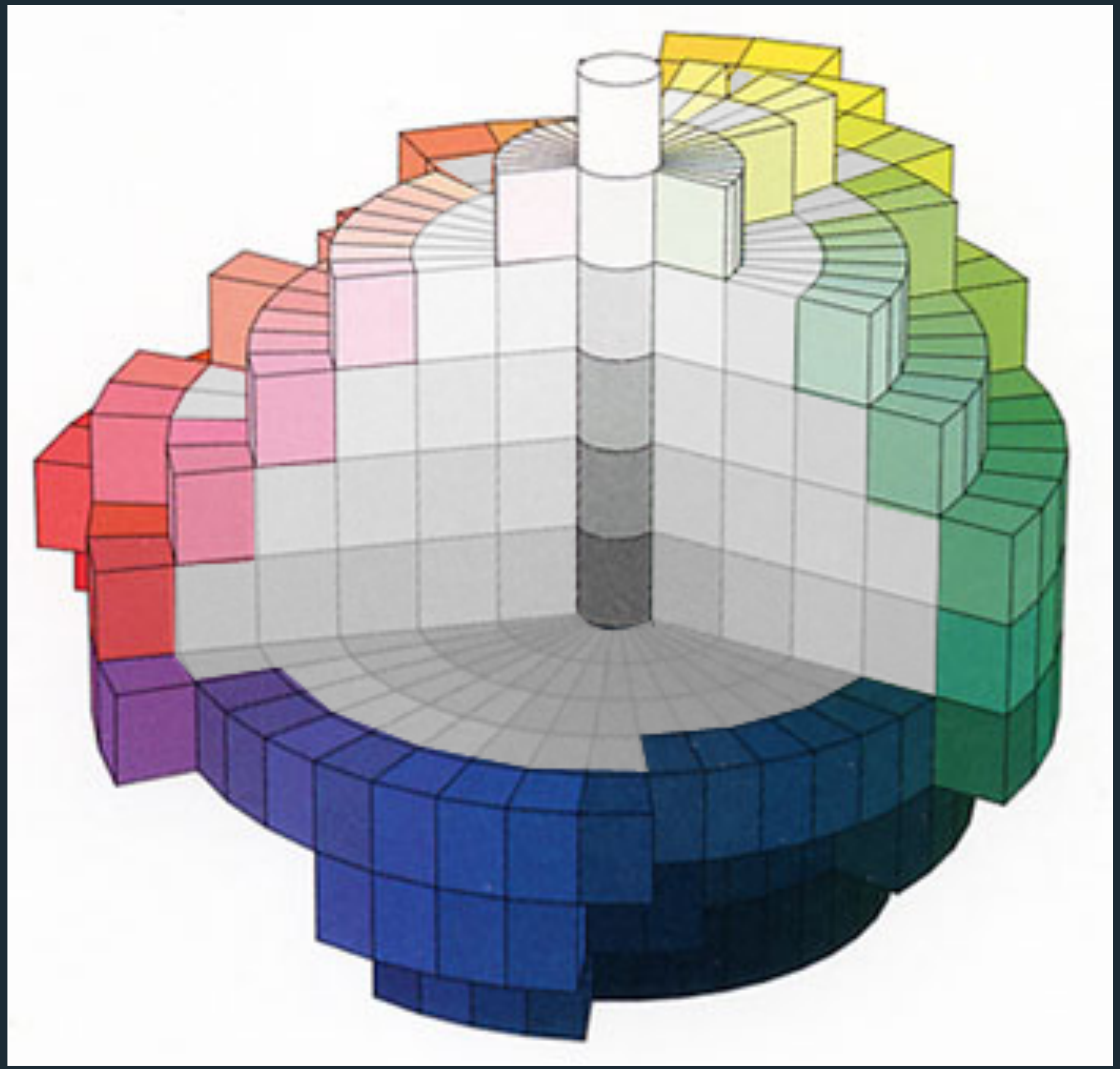
Name 320 Munsell color chips.
(Shares perceptual properties with CIE LAB, but predates it.)

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.



+10 achromatic chips

Color Naming

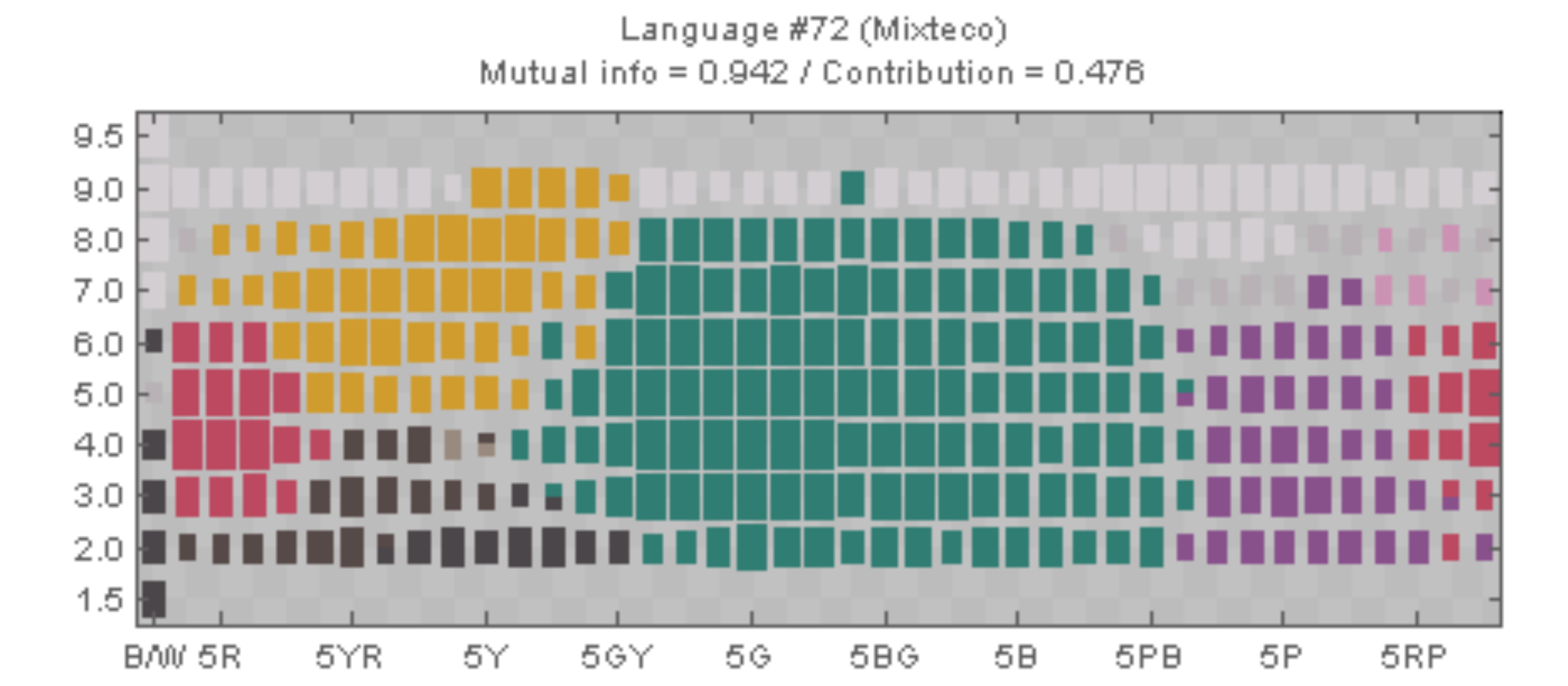
Is color naming universal? Do languages evolve color terms in similar ways?

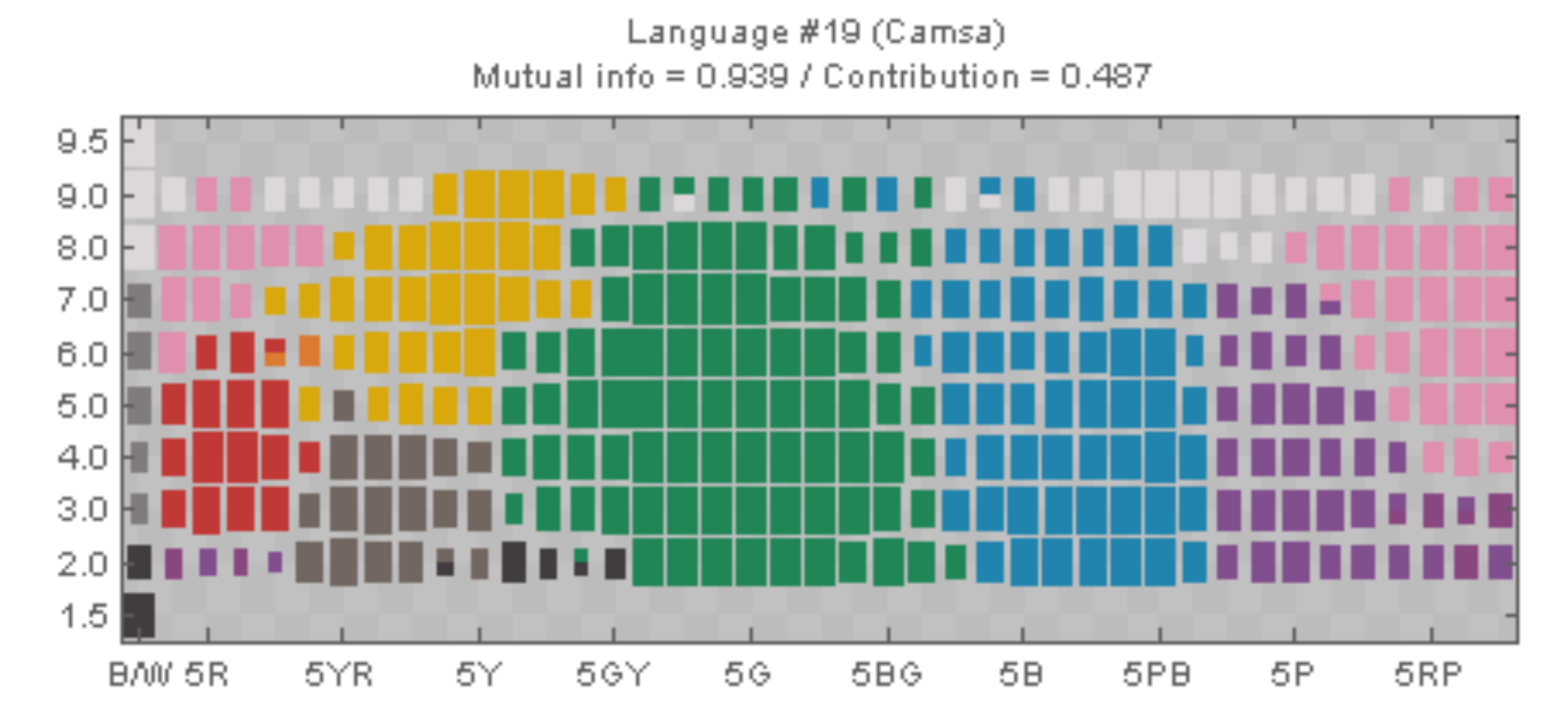
WCS stimulus array. For each basic color term (*t*) participants named, they were asked:

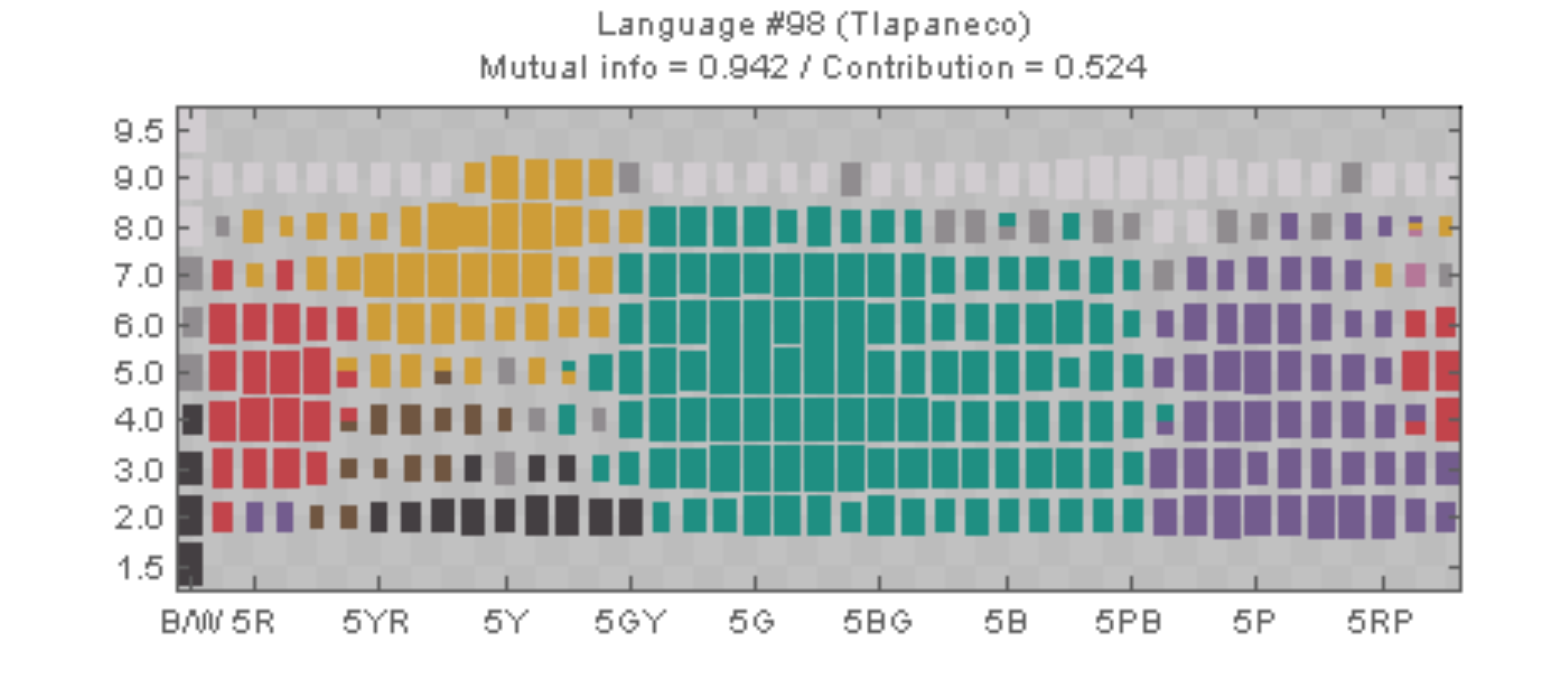
1. Mark all chips that you would call *t*.
2. Which chip is the best example(s) of *t*.

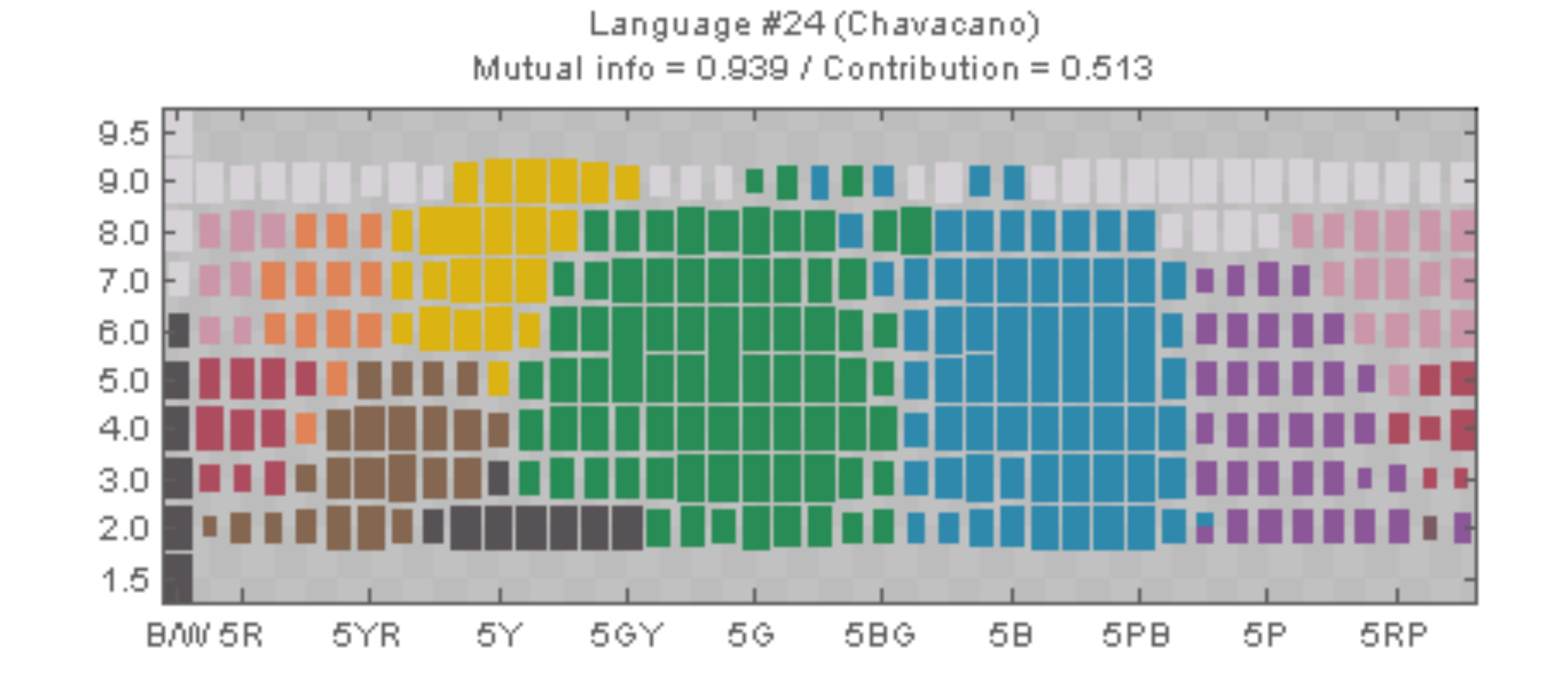
Color Naming

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







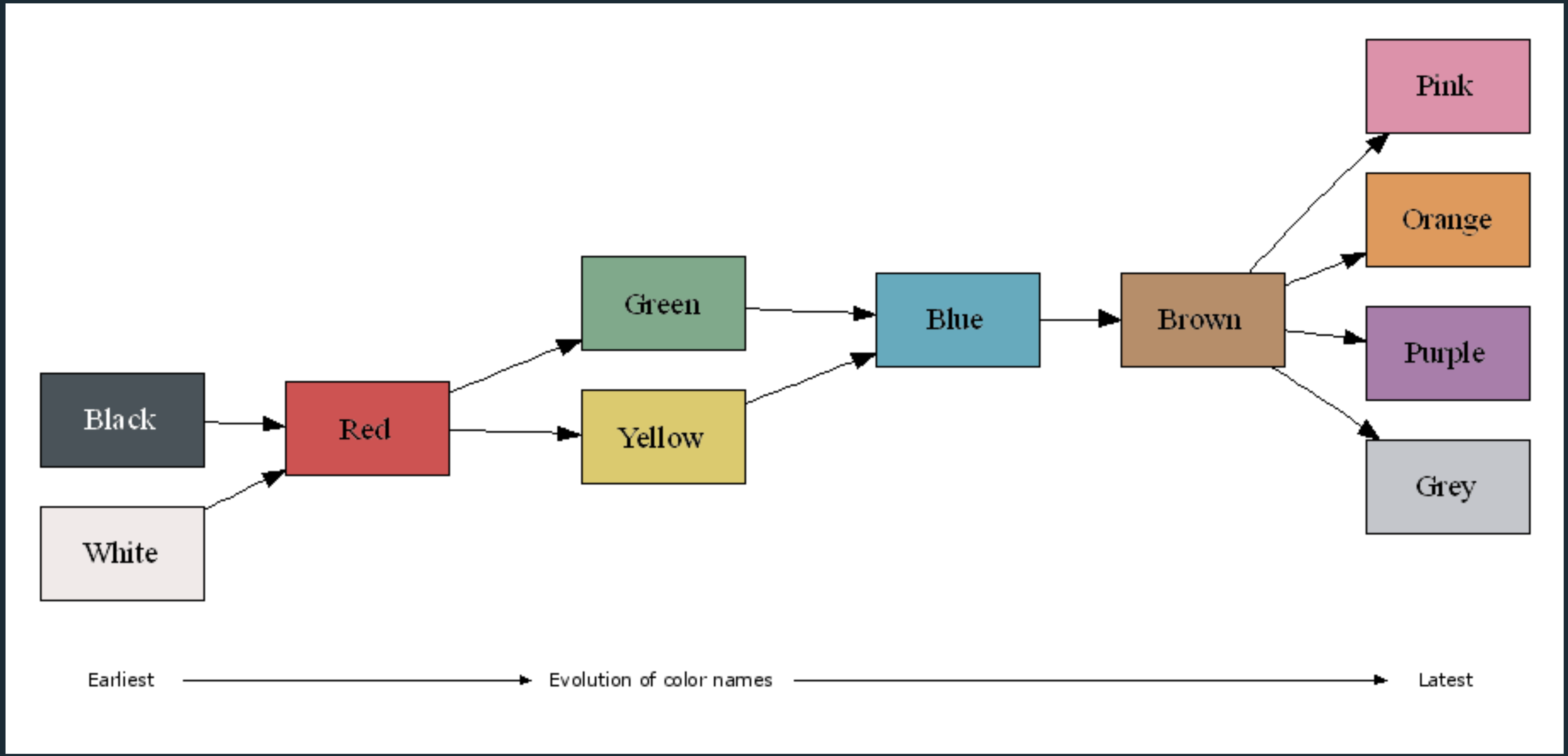


Color Naming

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

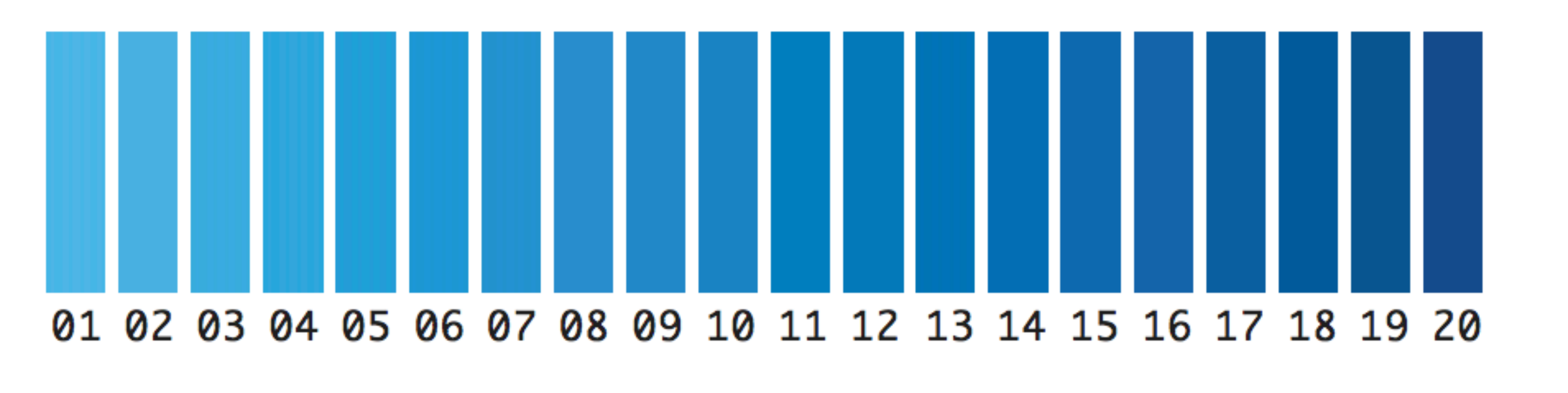
Basic color terms recur across languages:

- 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?

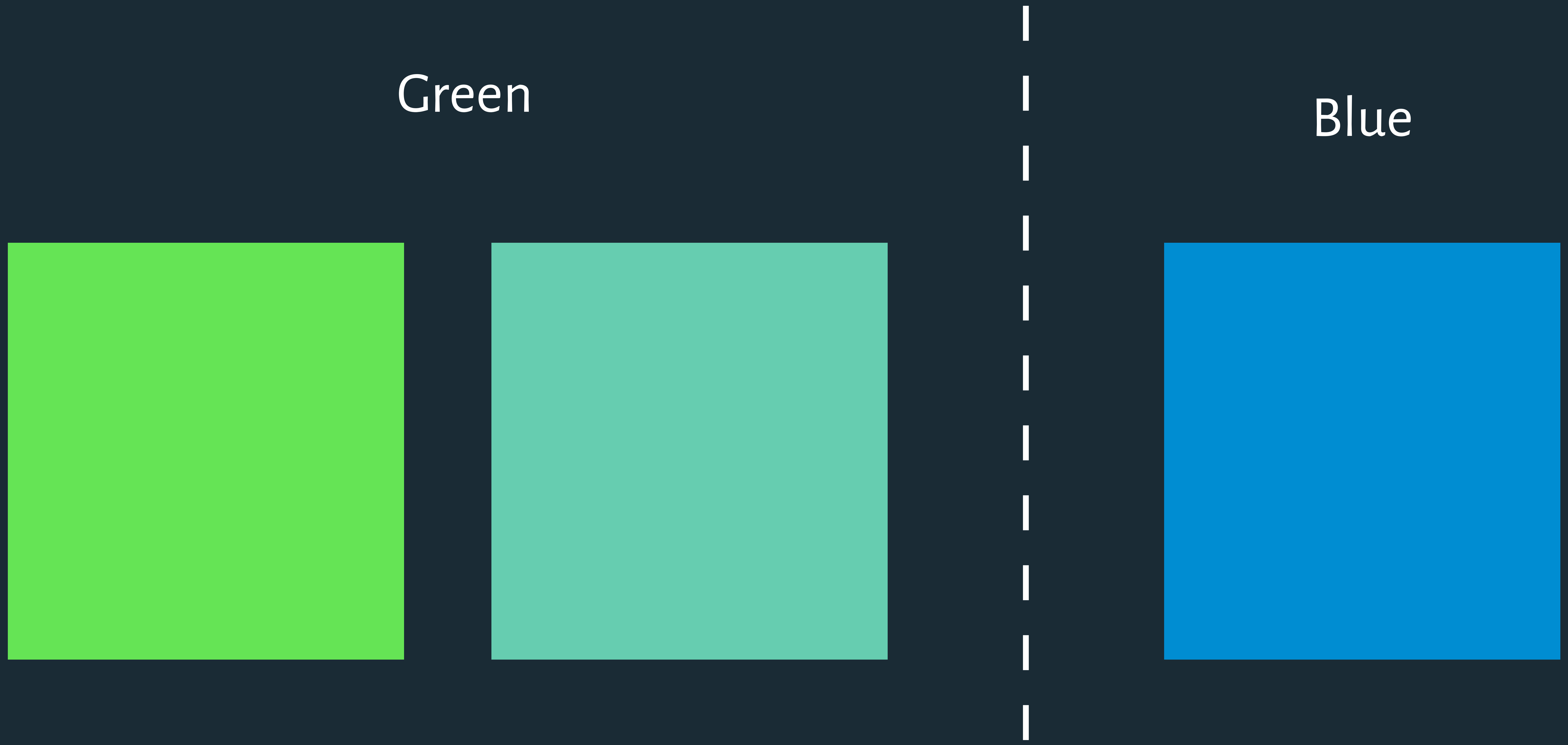


Winawer et al, 2007.

Russian makes obligatory distinction between lighter blues ("goluboy") and darker blues ("siniy").

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.

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/

[Heer and Stone, CHI 2012]

Color Naming Effects Perception

Minimize overlap and ambiguity of colors.

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

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

[Heer and Stone, CHI 2012]

Color Naming Effects Perception

Minimize overlap and ambiguity of colors.

Select semantically resonant colors.

[Lin et al., EuroVis 2013]

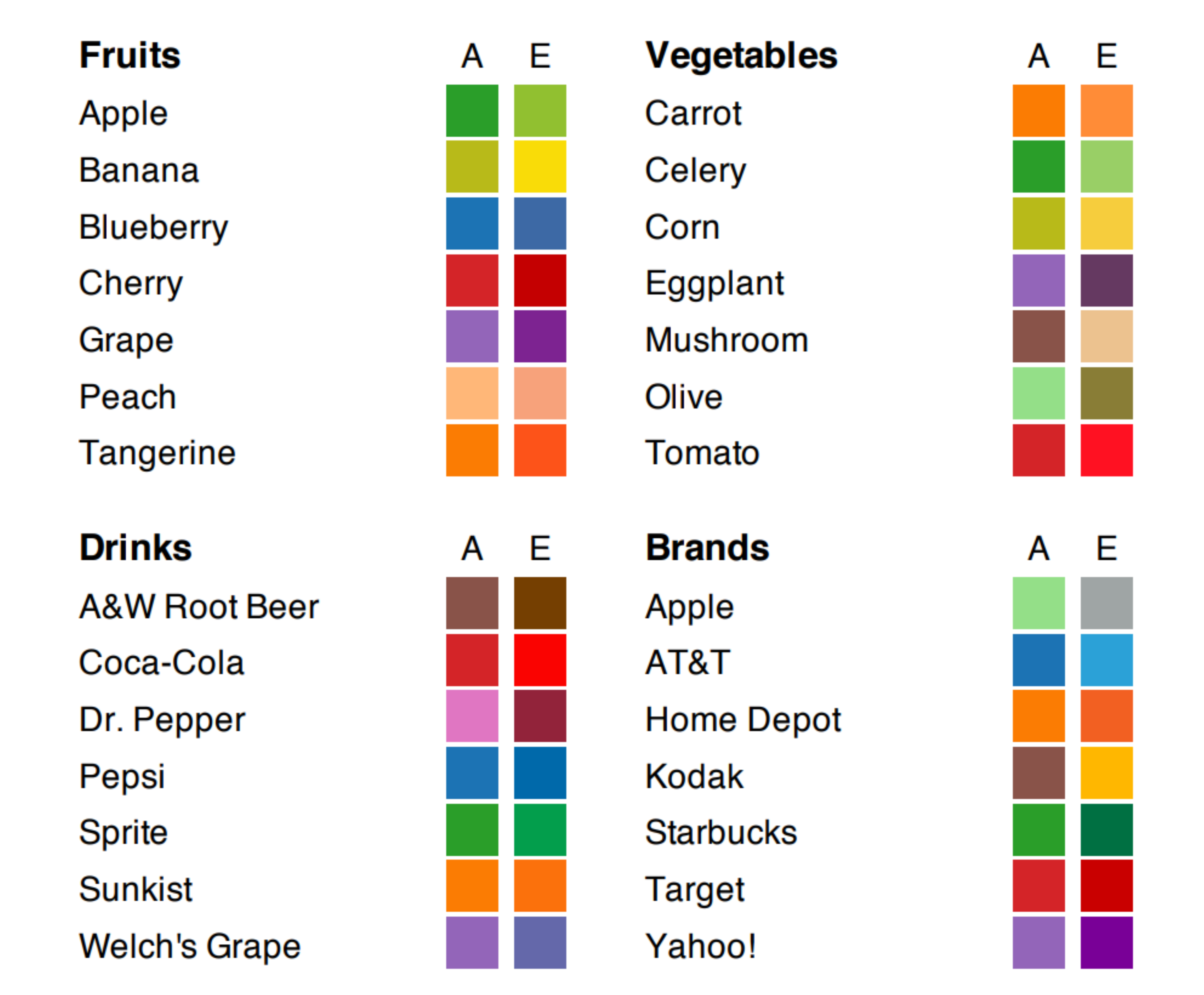
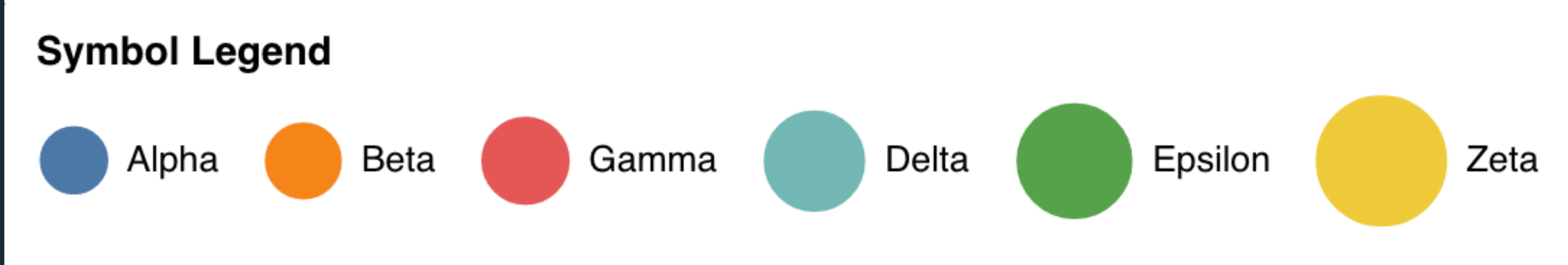


Figure 6: *Color assignments for categorical values in Experiment 1. (A = Algorithm, E = Expert)*

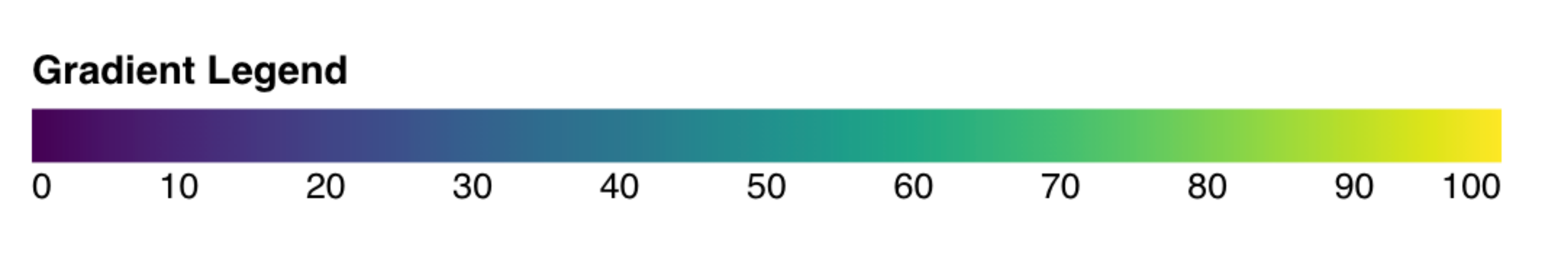
https://github.com/StanfordHCI/semantic-colors

Putting it together: Designing colormaps

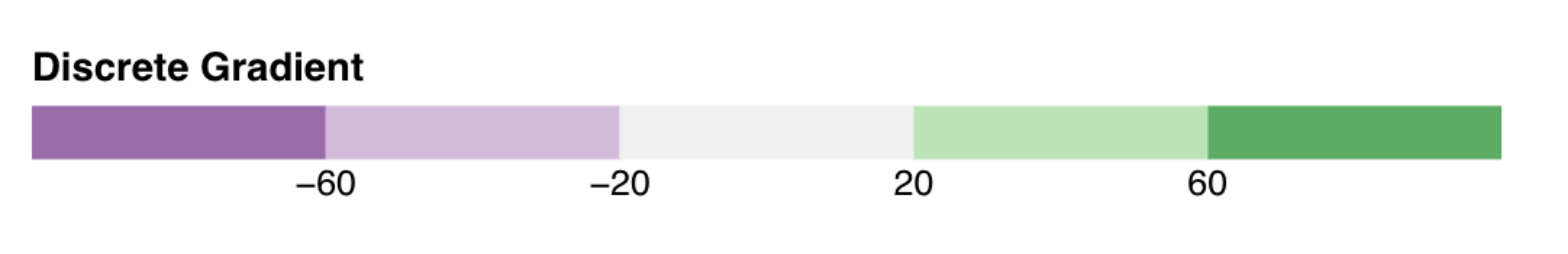
Discrete (binary, categorical)



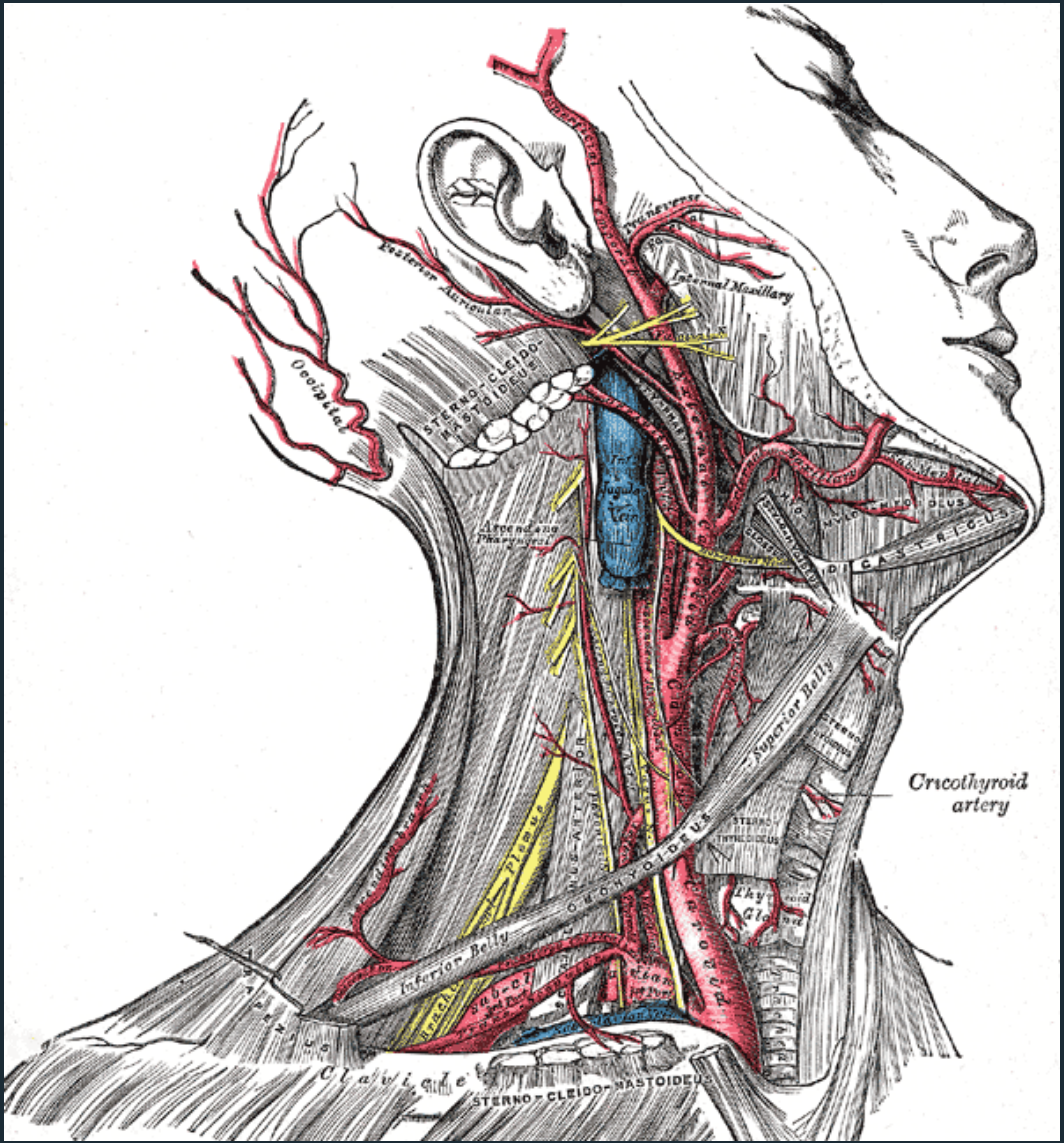
Continuous (sequential, diverging, cyclic)



Discretized Continuous



Categorical Color


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%

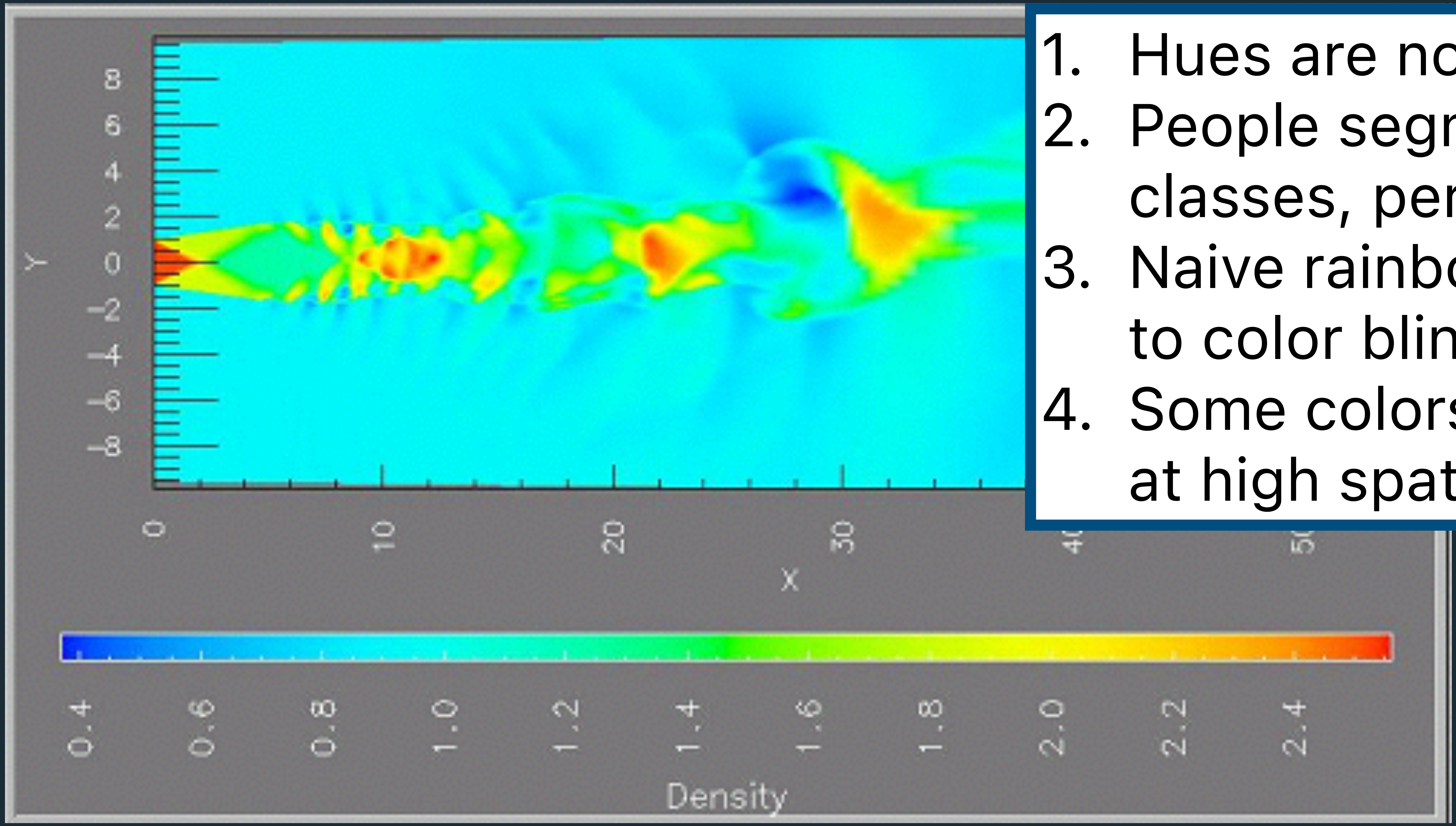
Tableau-10 *Average* *0.96* .52

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

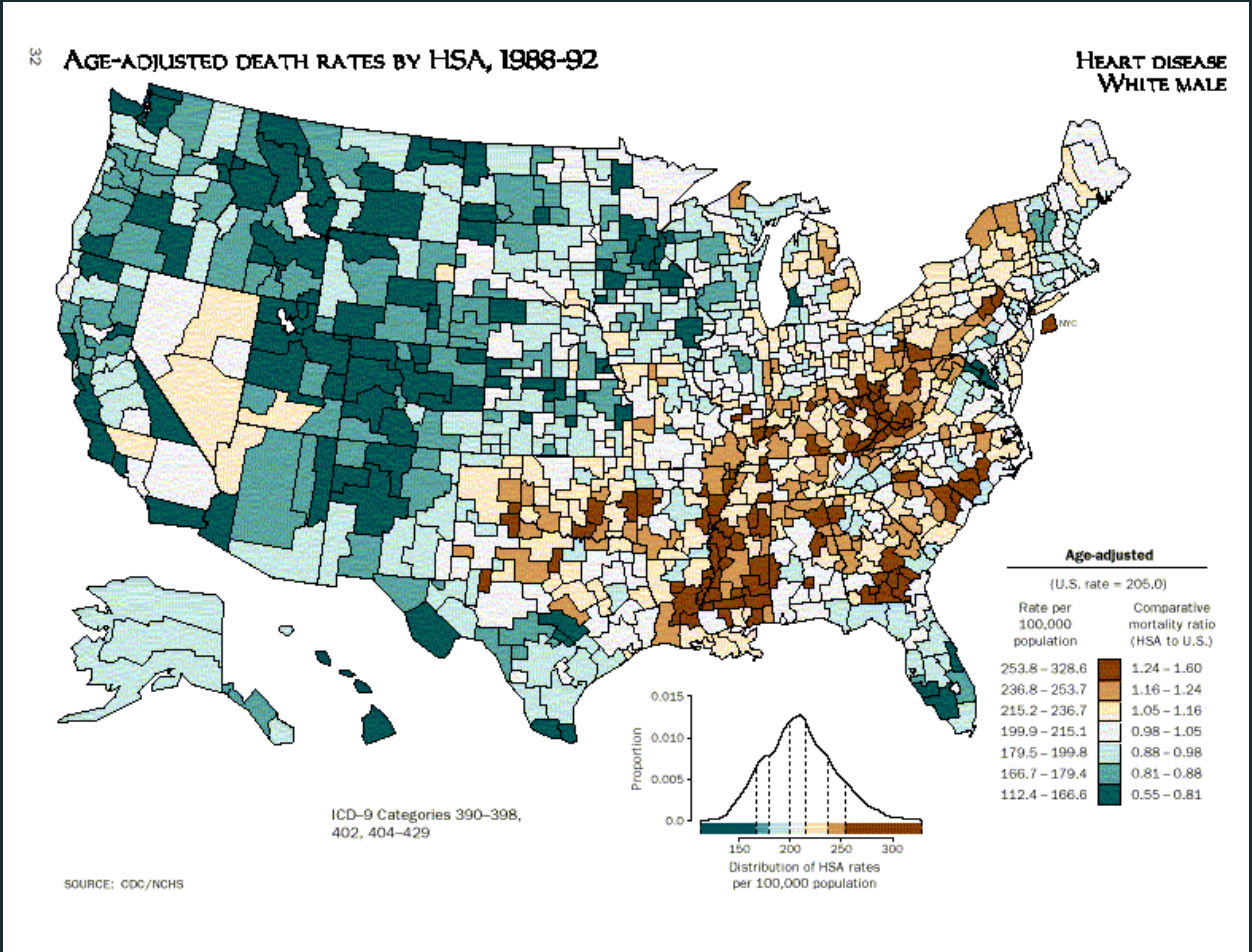
[Heer and Stone, CHI 2012]

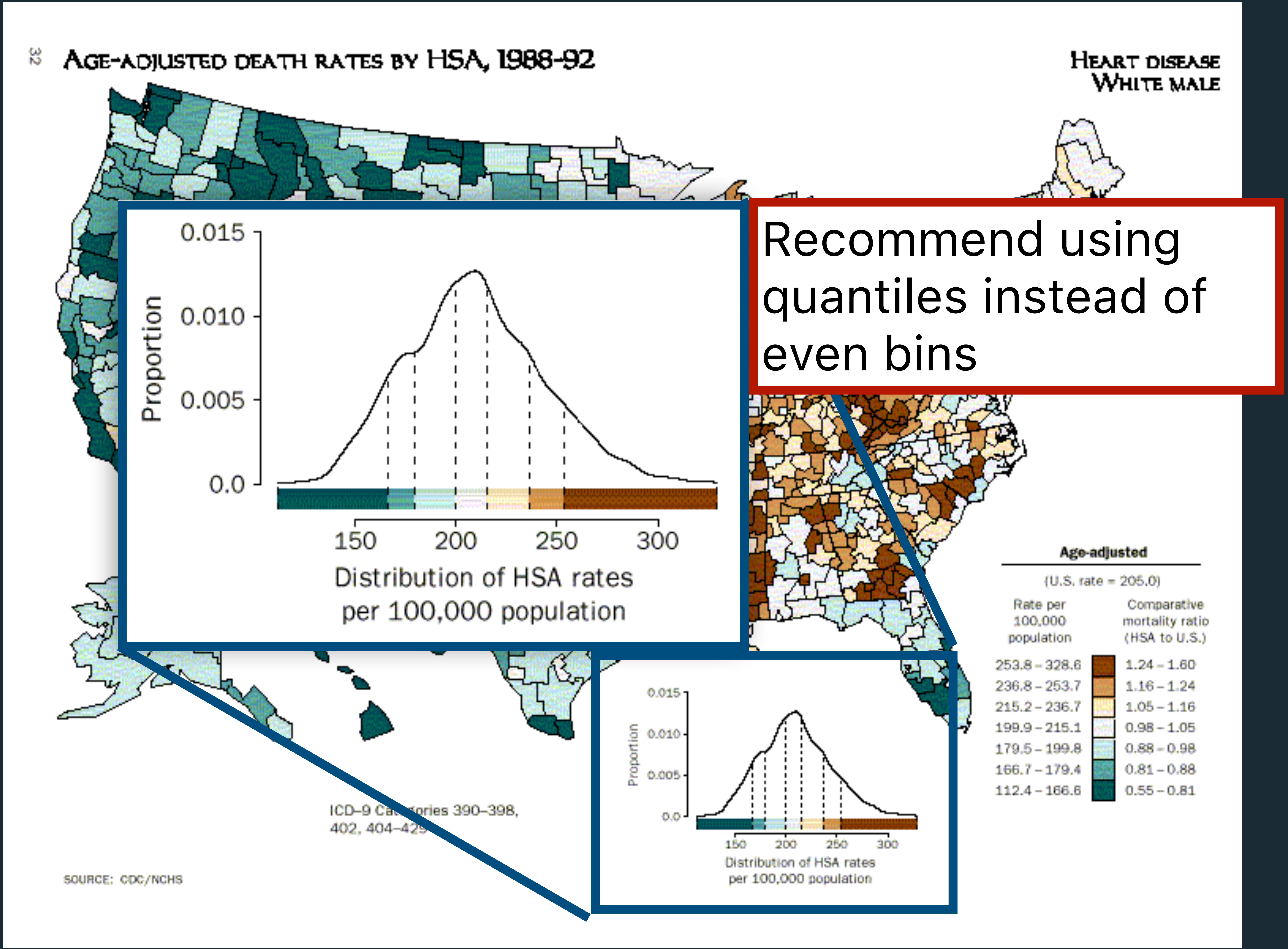
Quantitative Color

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



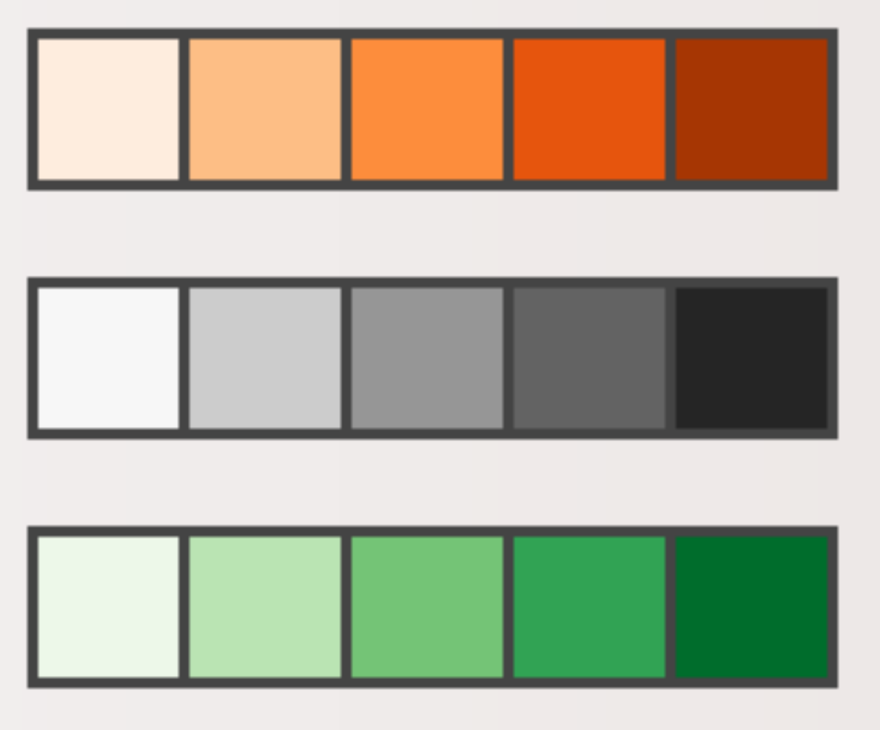
Recommend using quantiles instead of even bins

Quantitative Color Encoding

Sequential Color Scale

Ramp in luminance, possibly also hue.

Typically higher values map to darker colors.

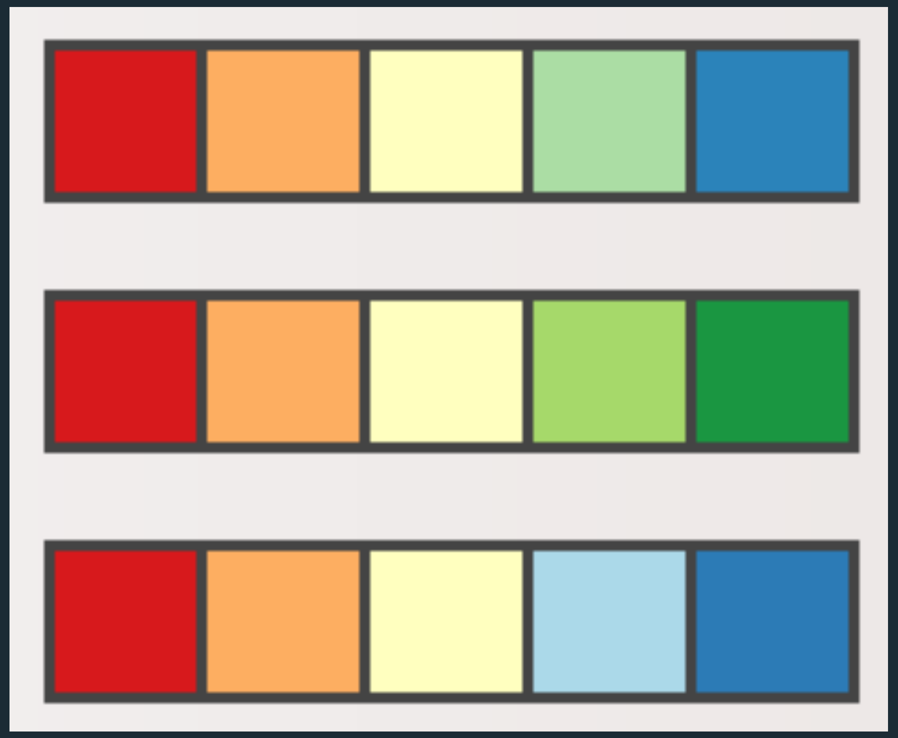


Diverging Color Scale

Useful when data has a meaningful “midpoint.”

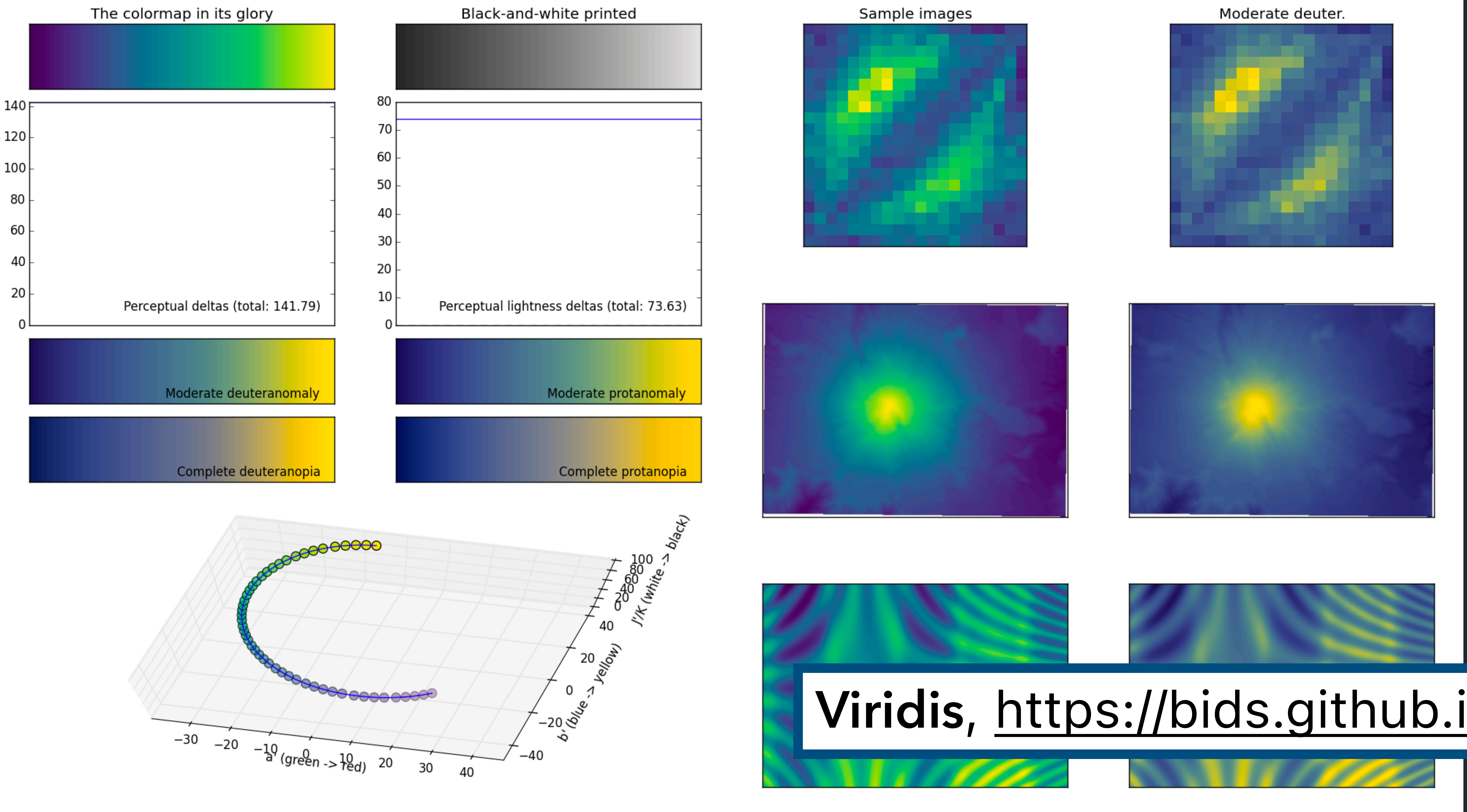
Use neutral color (e.g., gray) for midpoint.

Use saturated colors for endpoints.



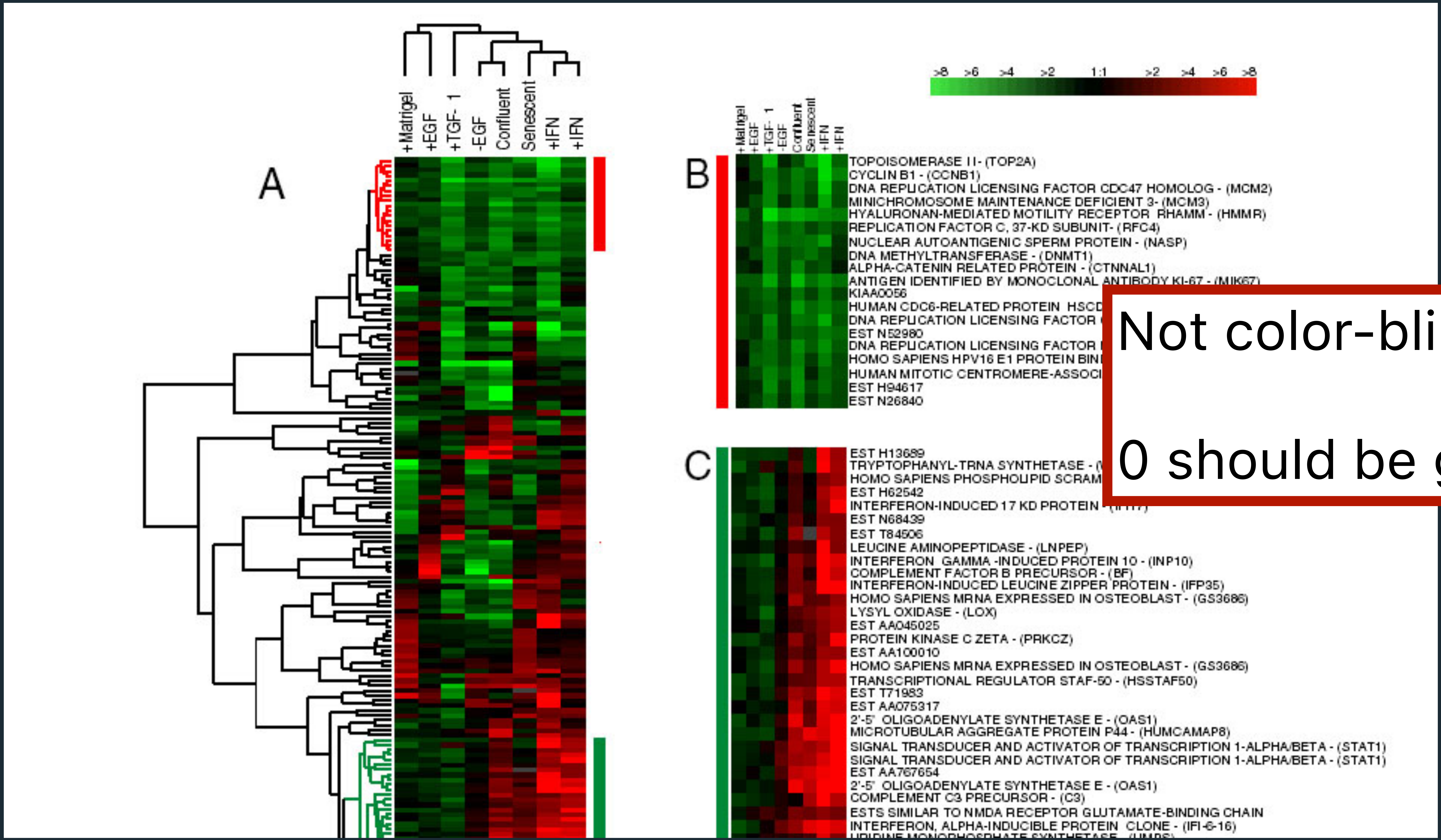
Limit number of steps in color to 3–9

Sequential Scales: Multi-Hue



Viridis, https://bids.github.io/colormap/

Diverging Color Schemes



Not color-blind friendly!

0 should be gray, not black

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**.