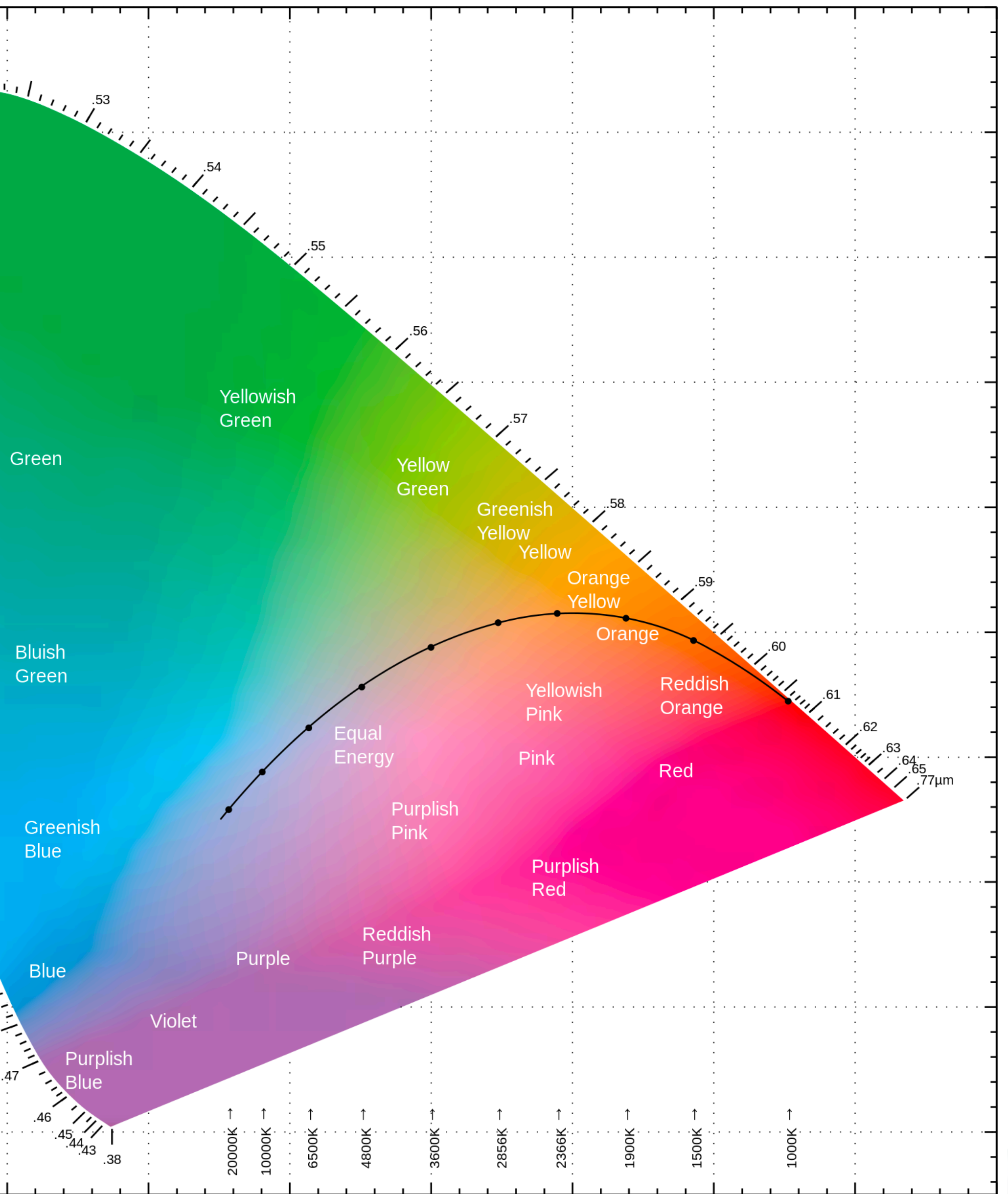
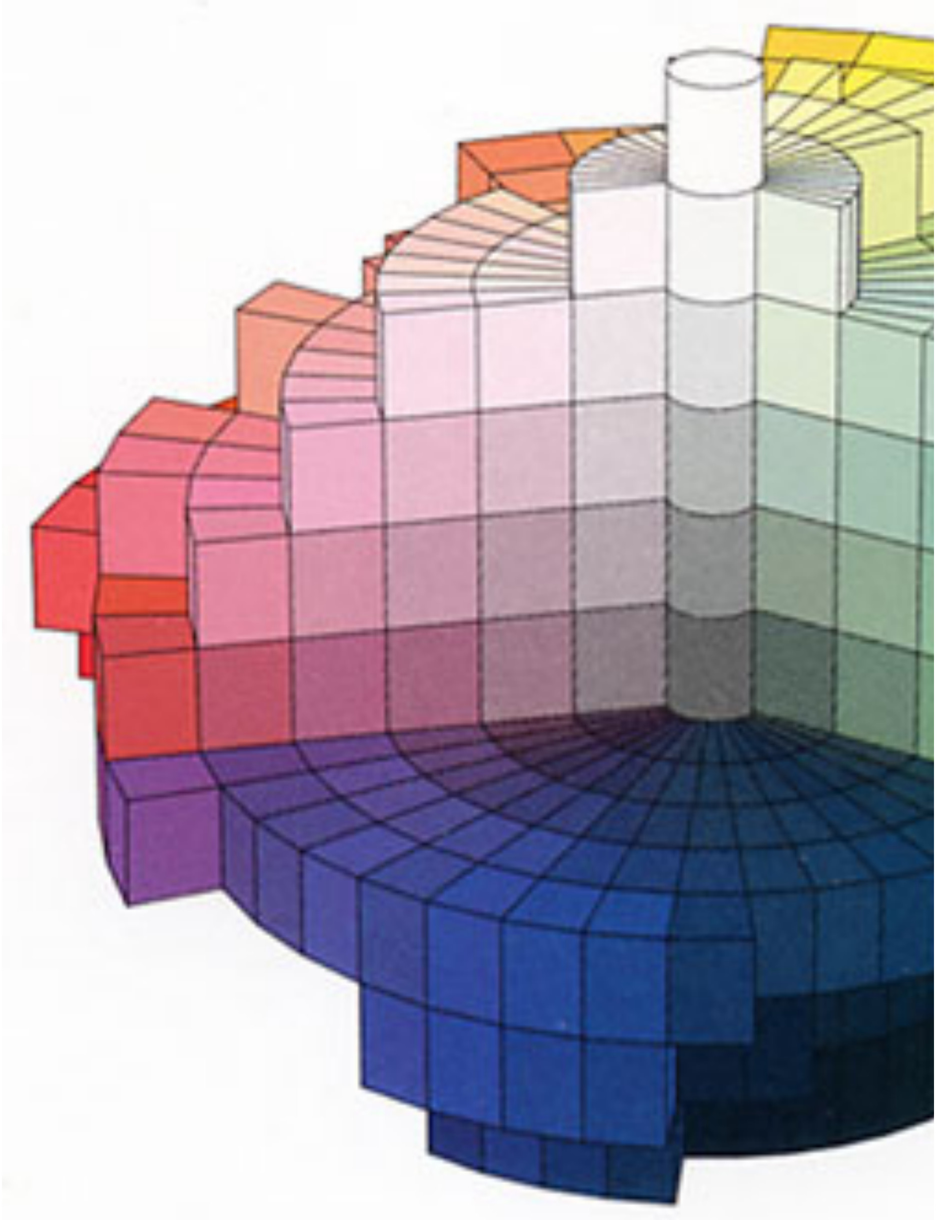
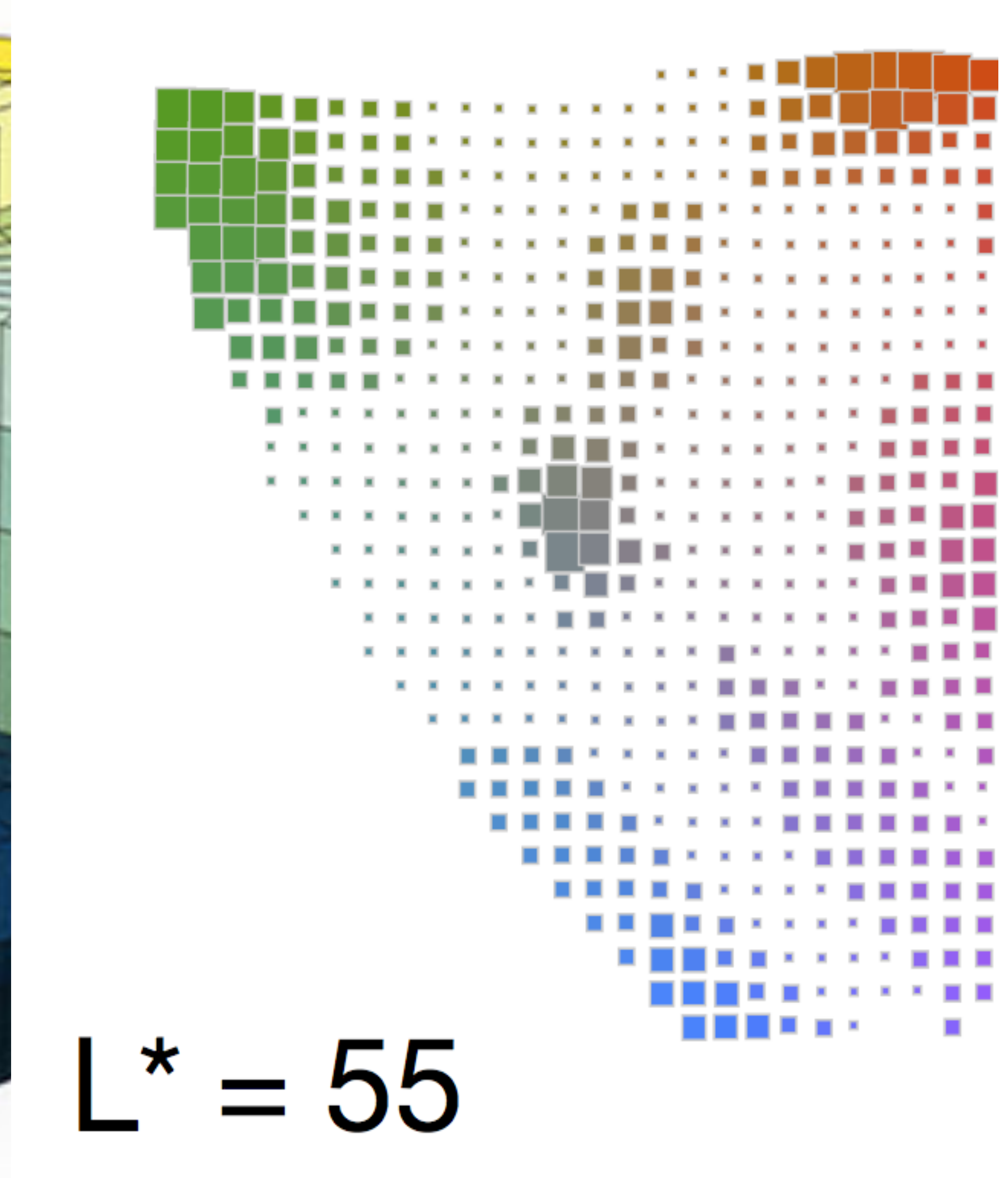
6.859: Interactive Data Visualization

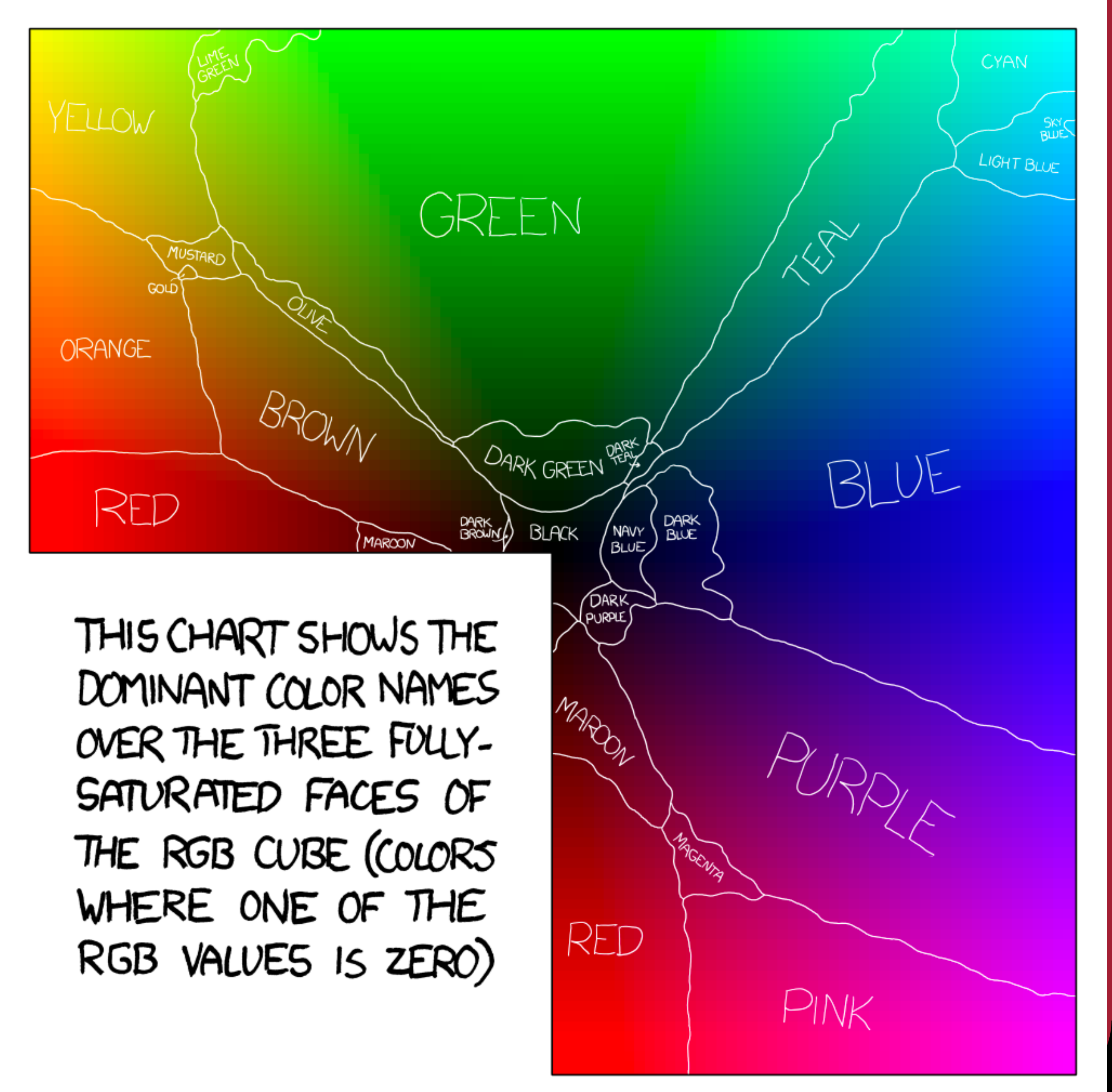
Color

Arvind Satyanarayan







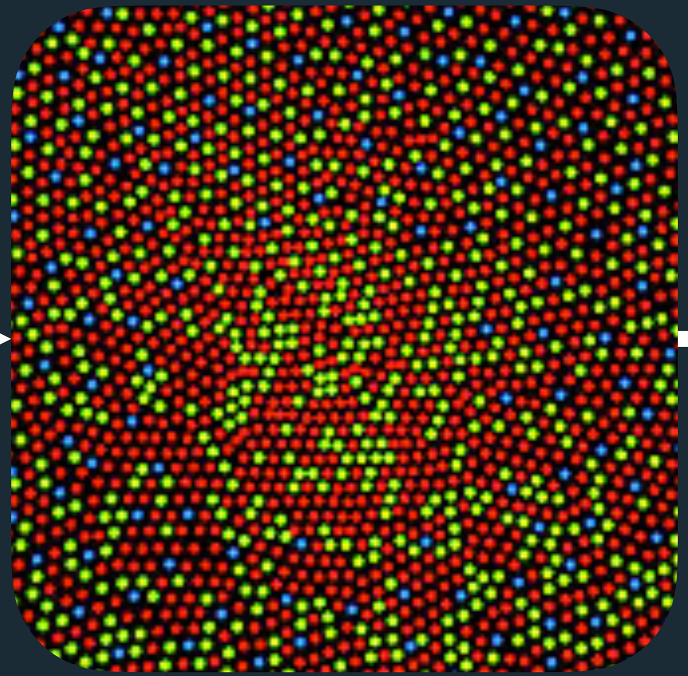


Modeling Color Perception

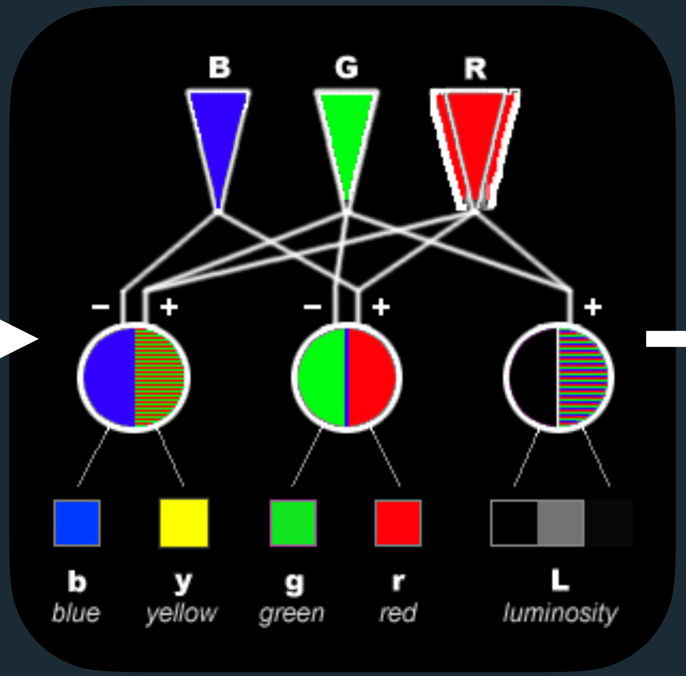
Low-Level Abstraction High-Level

Physical World | Visual System | Mental Models

Visible Light



Cone Response



Opponent Encoding

Perceptual Models

Appearance Models

"Teal"

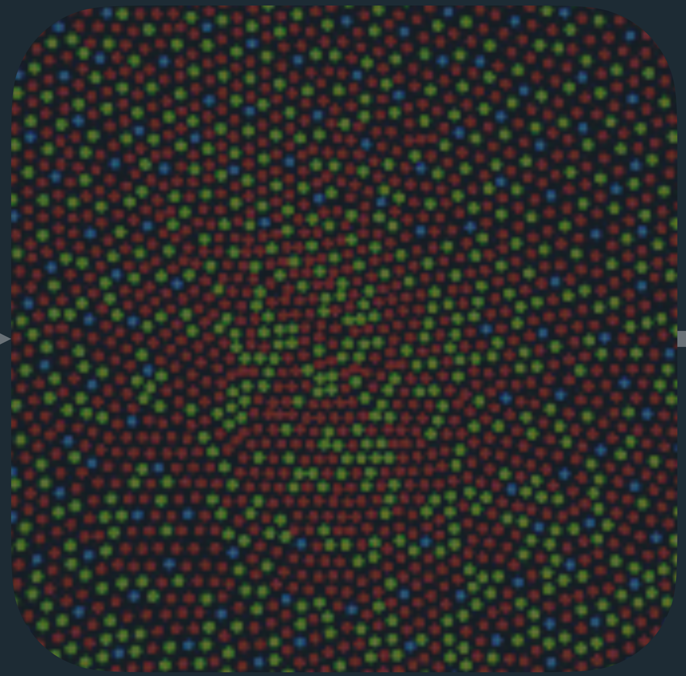
Cognitive Models

Modeling Color Perception

Low-Level — Abstraction — High-Level

Physical World — Visual System — Mental Models

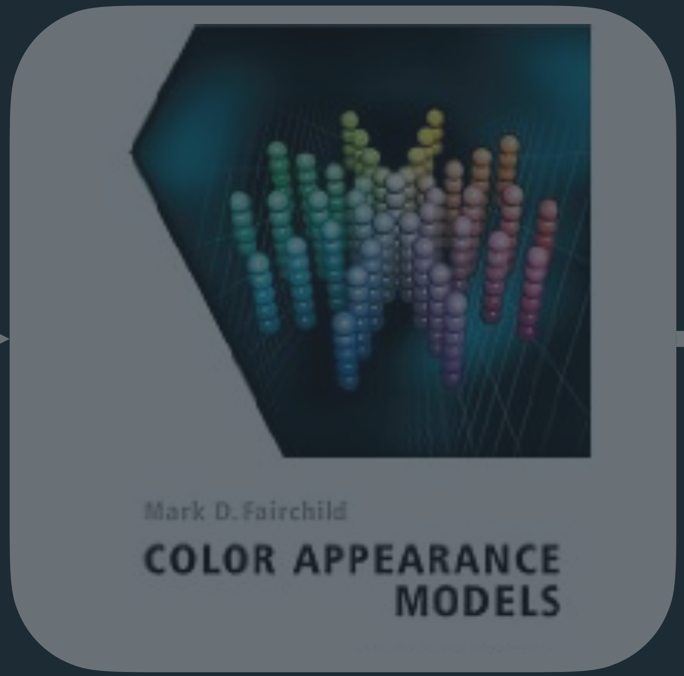
Visible Light



Cone Response

Opponent Encoding

Perceptual Models



Appearance Models

“Teal”

Cognitive Models

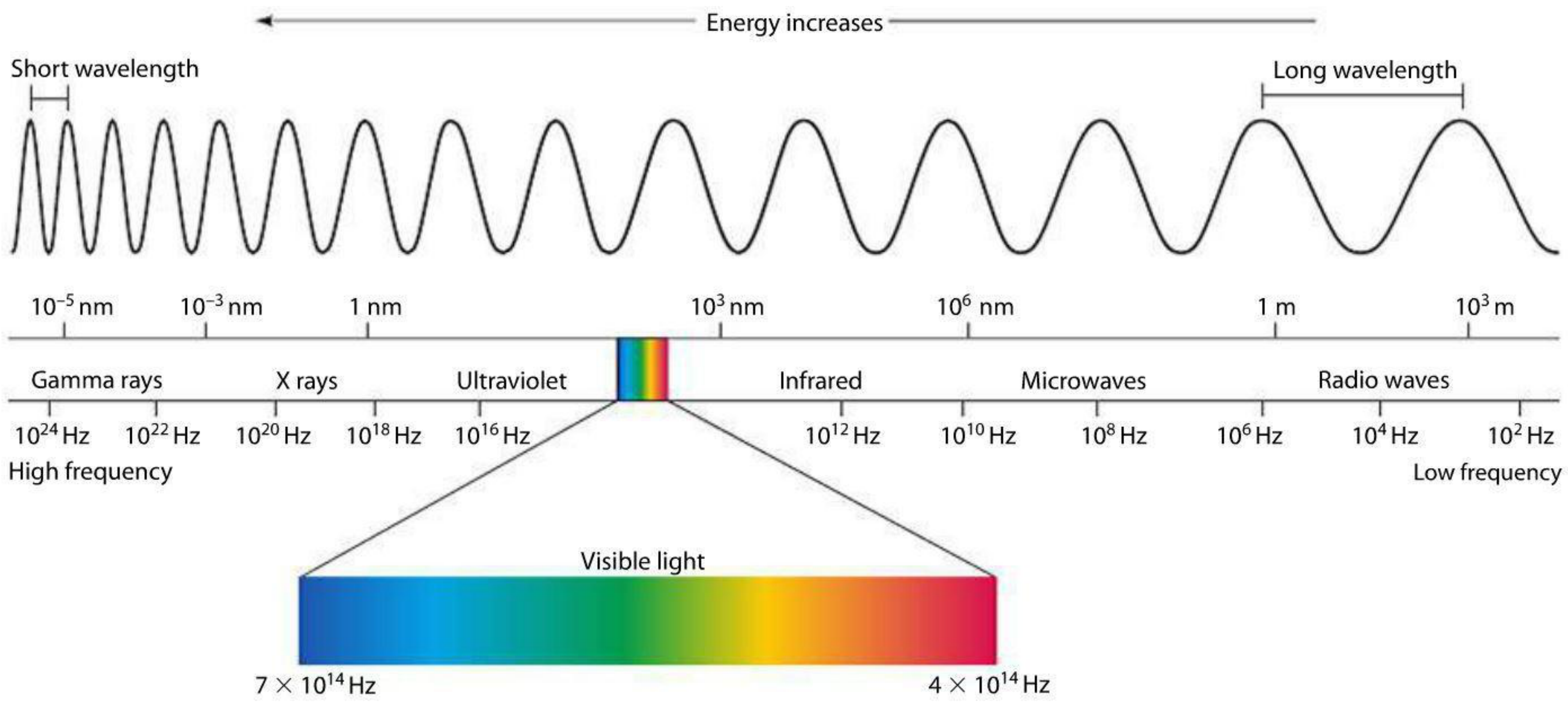
Visible Light

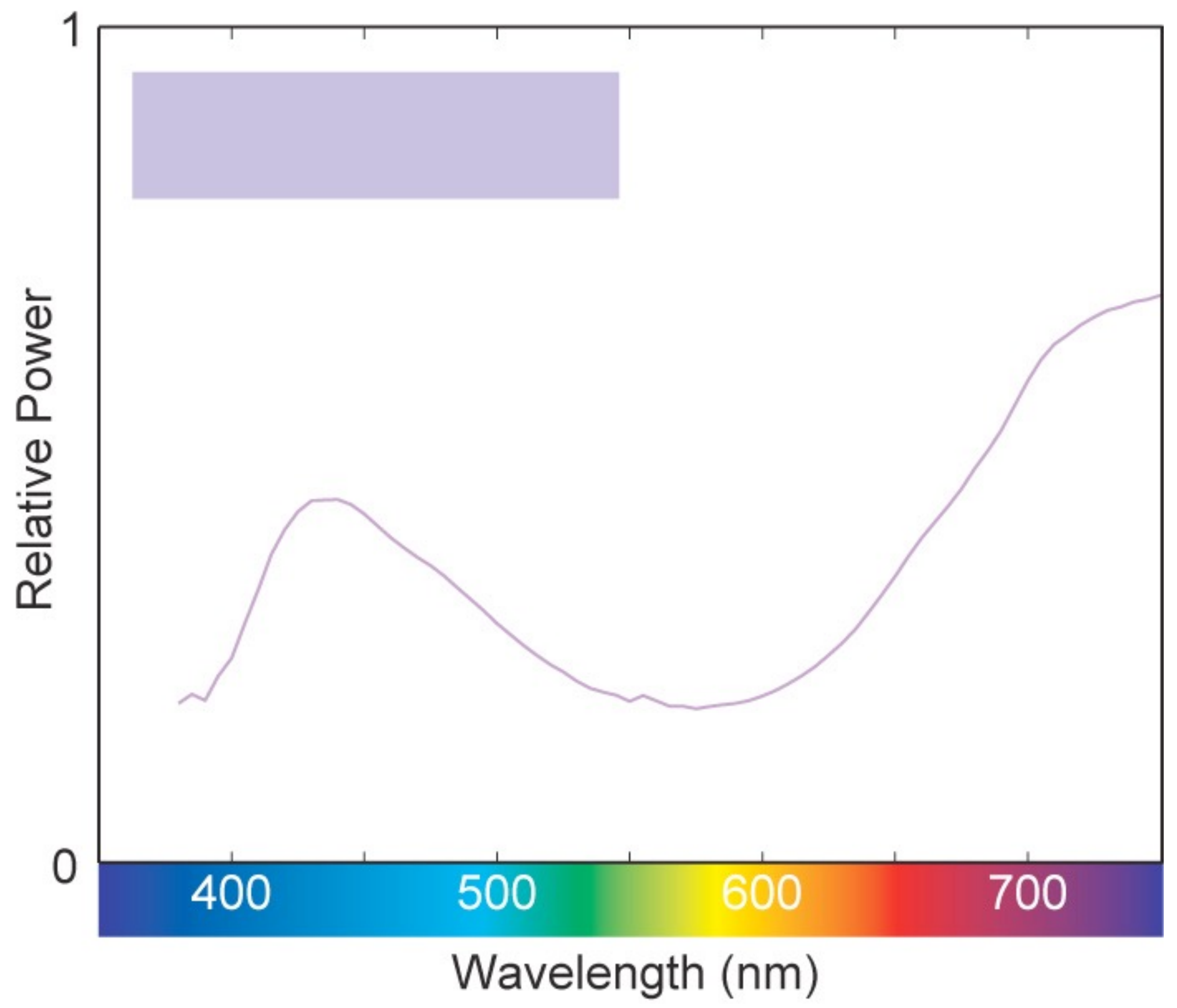
Light is an electromagnetic wave.

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]

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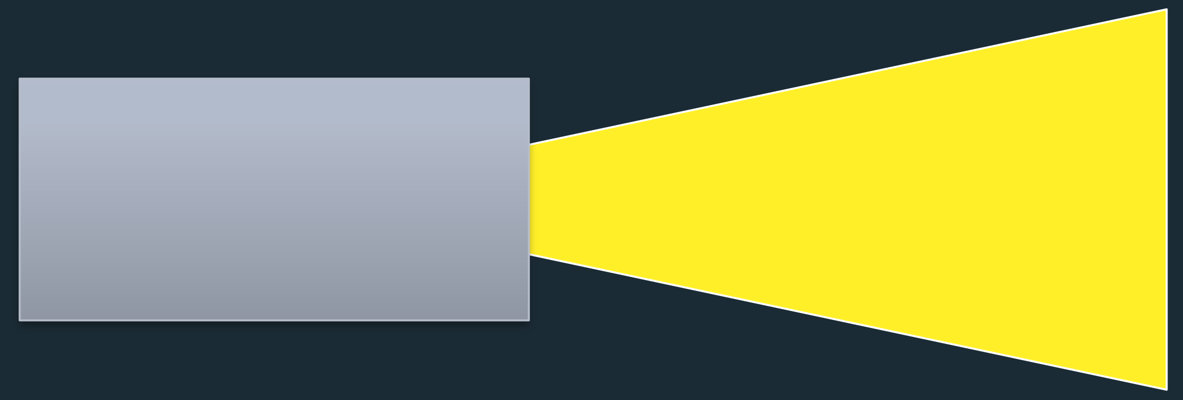
Wavelength (λ) between **370nm – 730nm**.

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

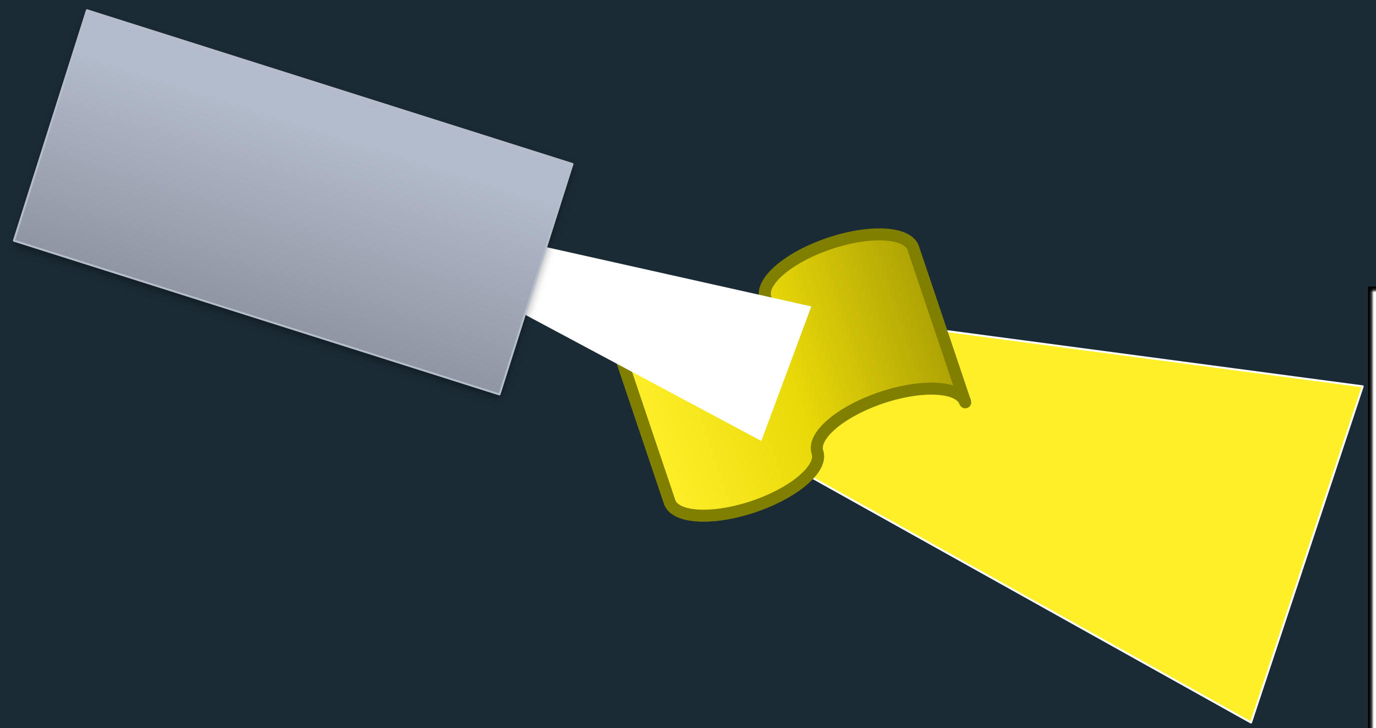
Area under the spectrum is ***intensity***: or how bright each wavelength is.

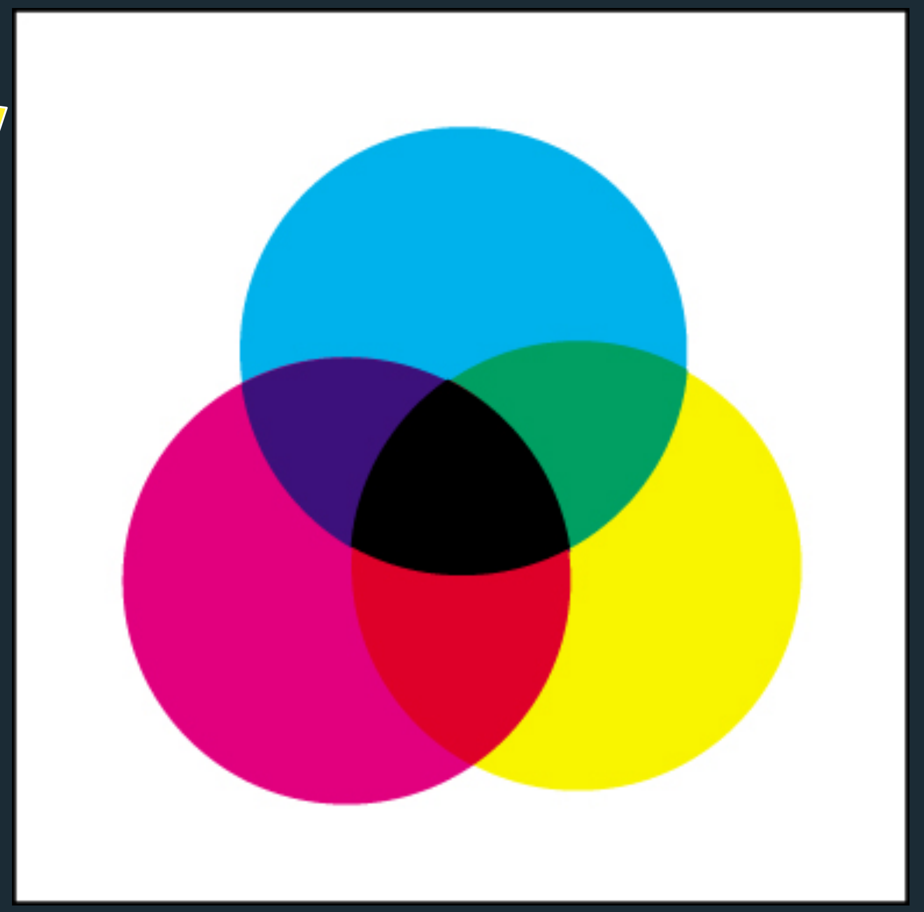
Additive: Perceived color is due to a combination of source lights (e.g., RGB).

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



Additive
(digital displays)





Subtractive
(print, e-paper)

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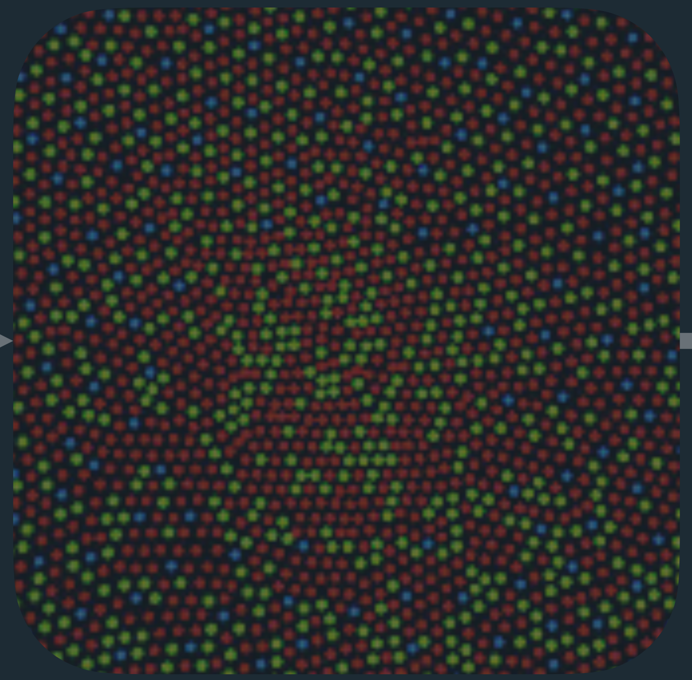

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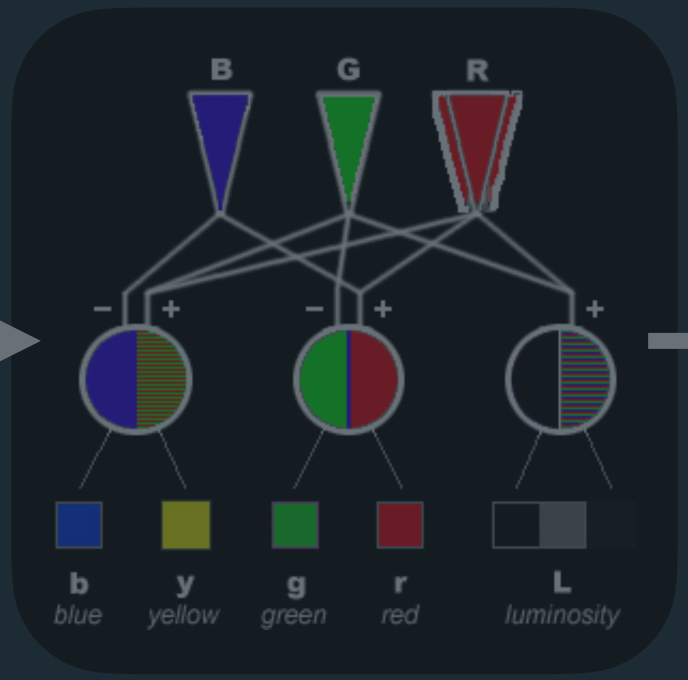
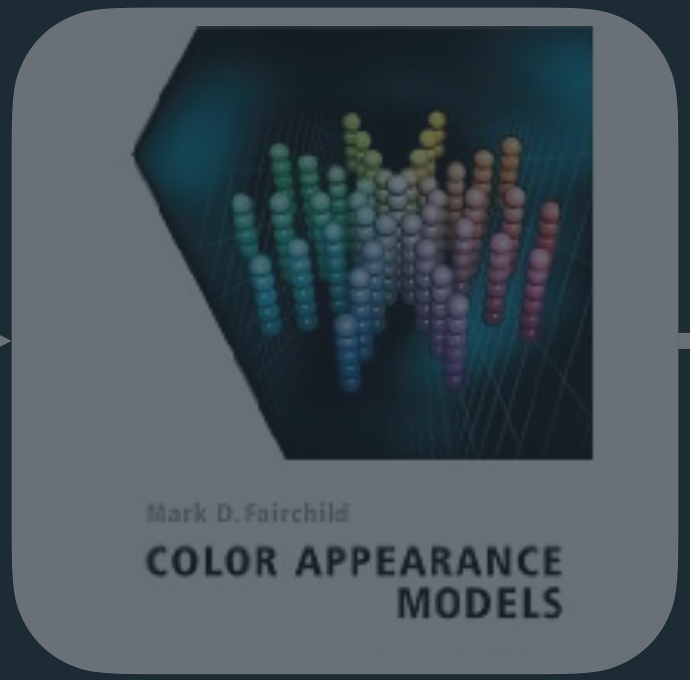


Opponent Encoding

Perceptual Models



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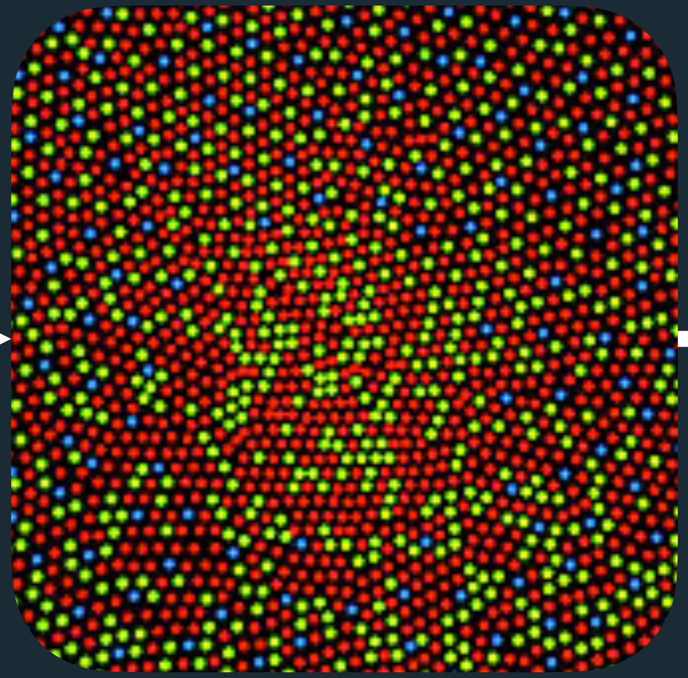

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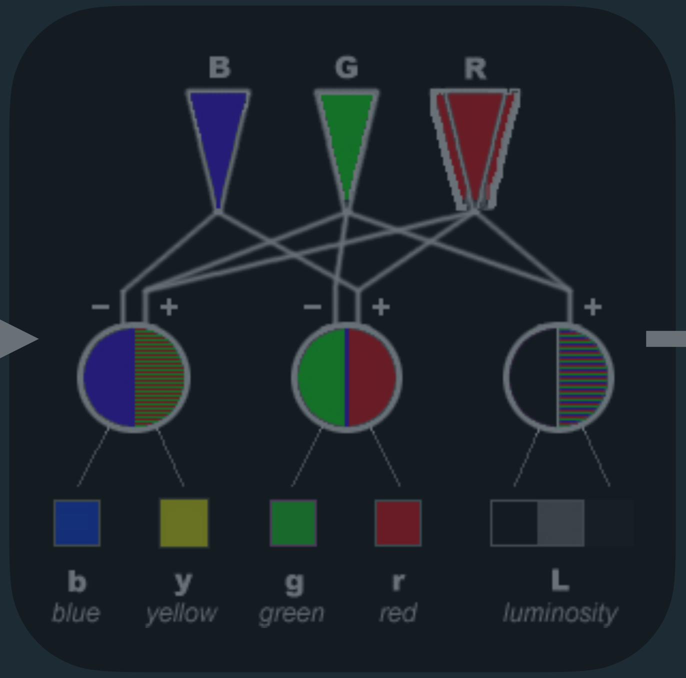

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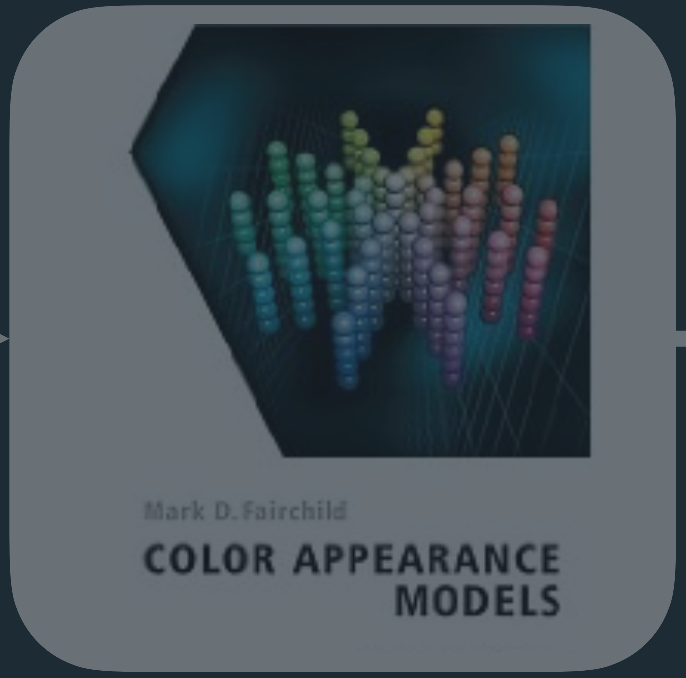

Appearance Models

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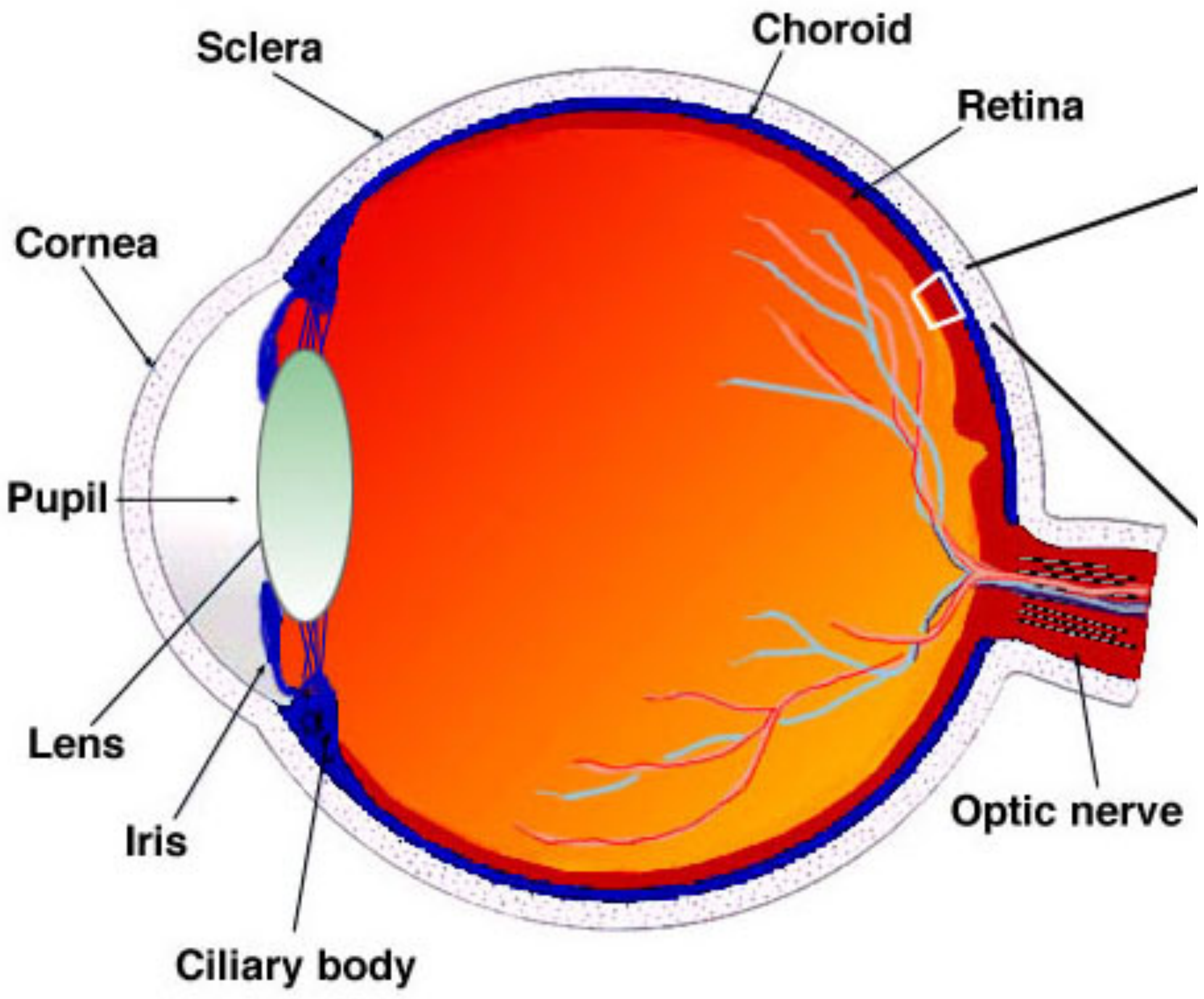
The Retina

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

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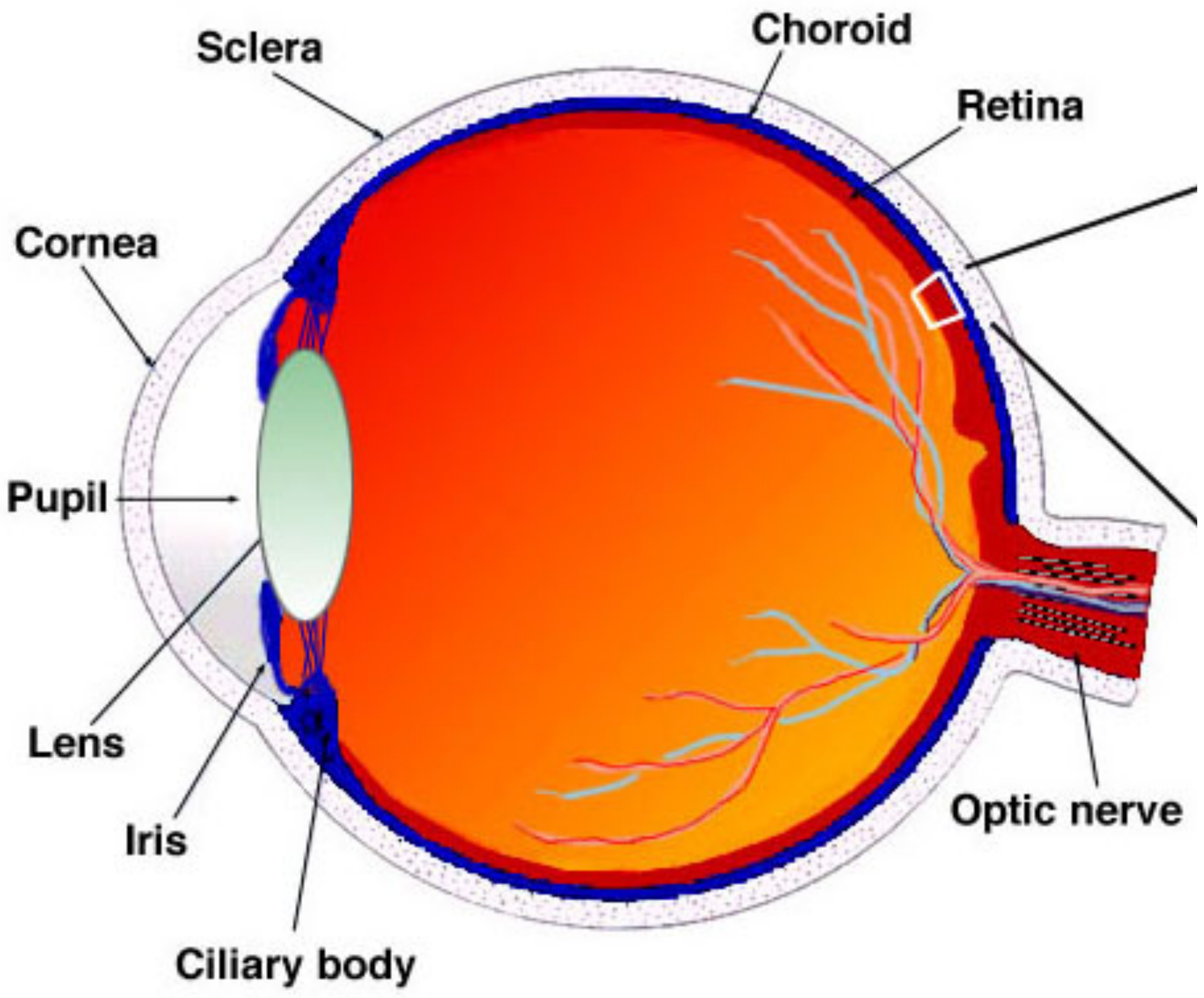
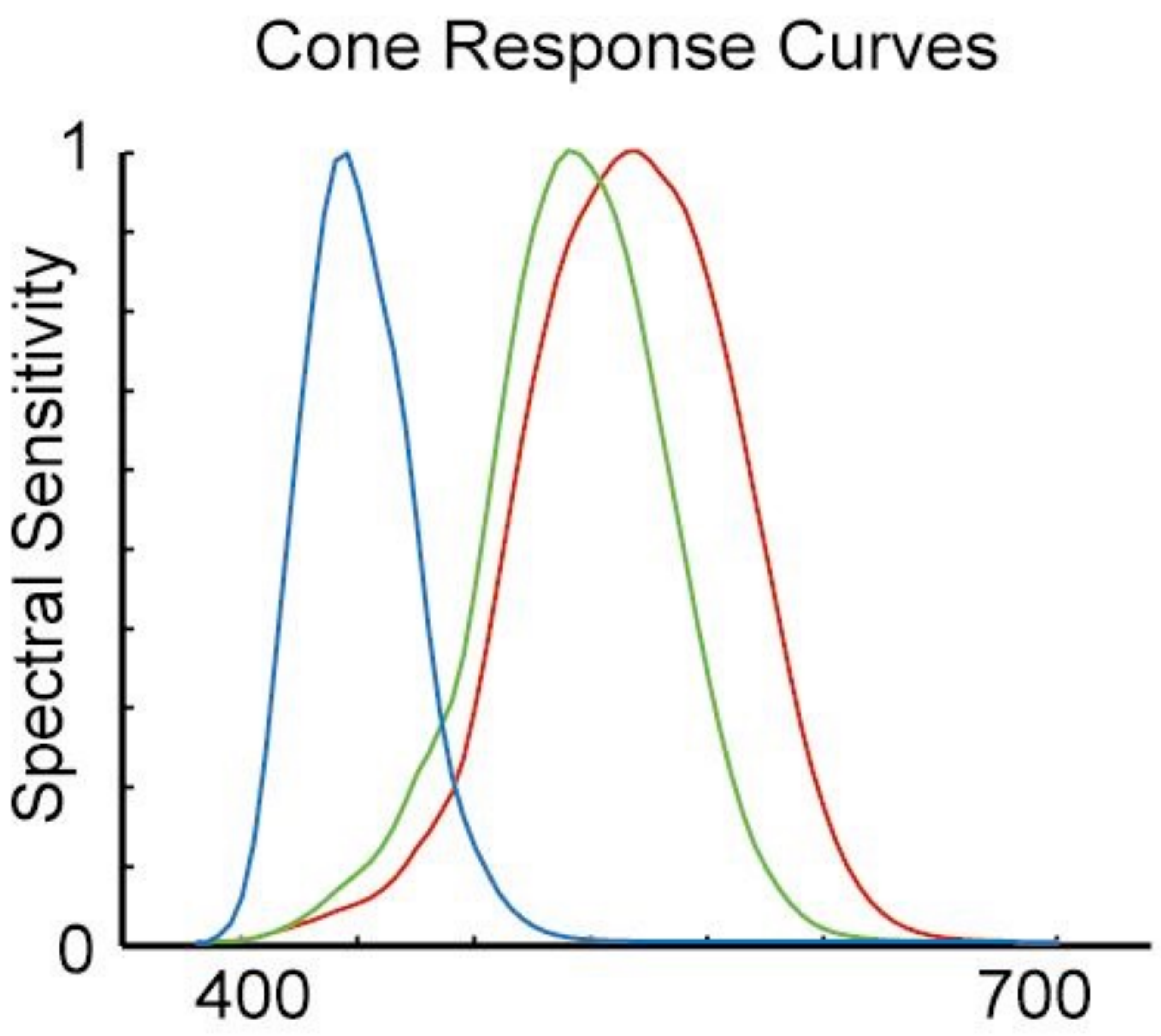
cones – sensitive to different wavelengths = color vision!
short, middle, long ~ blue, green, red

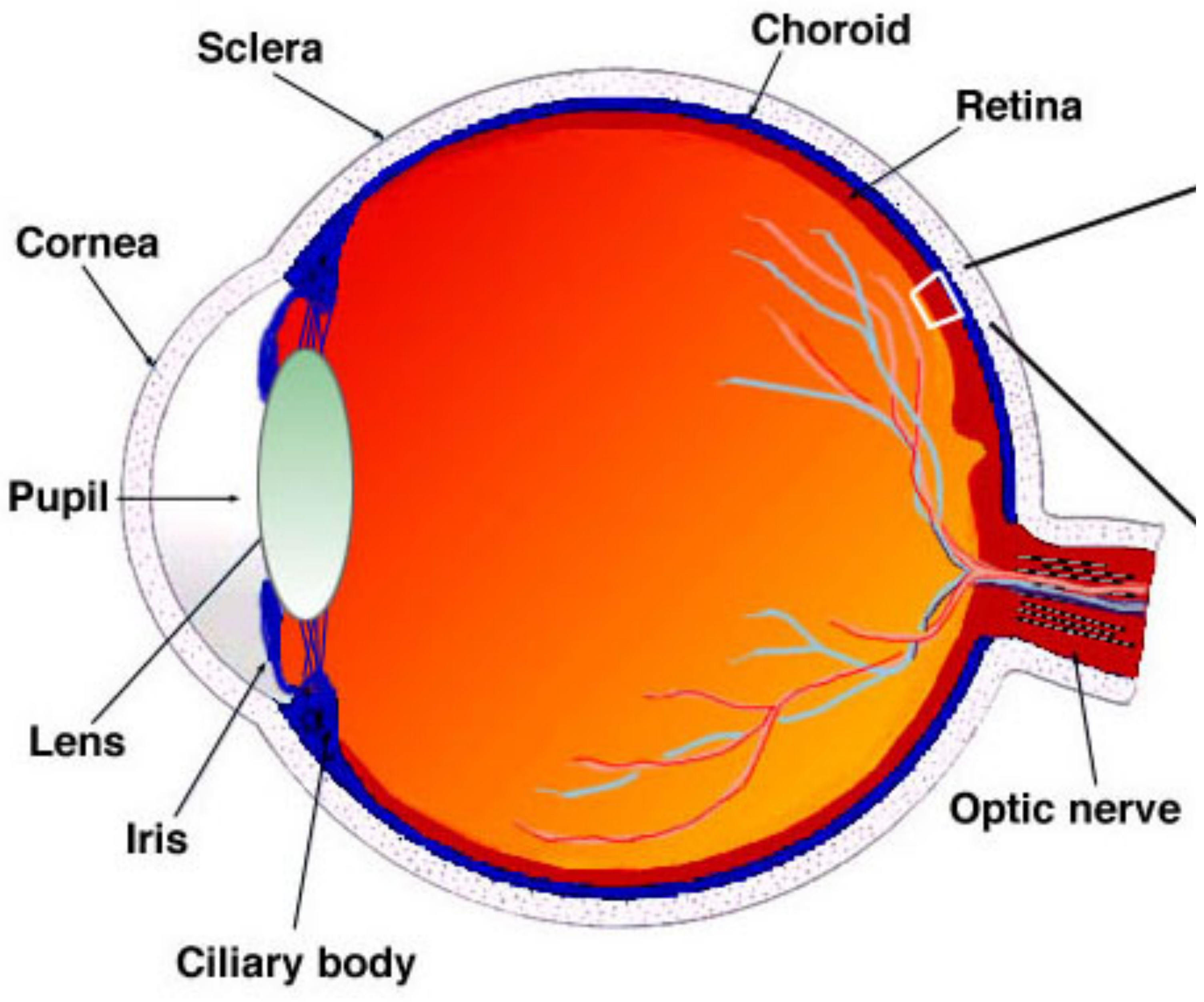




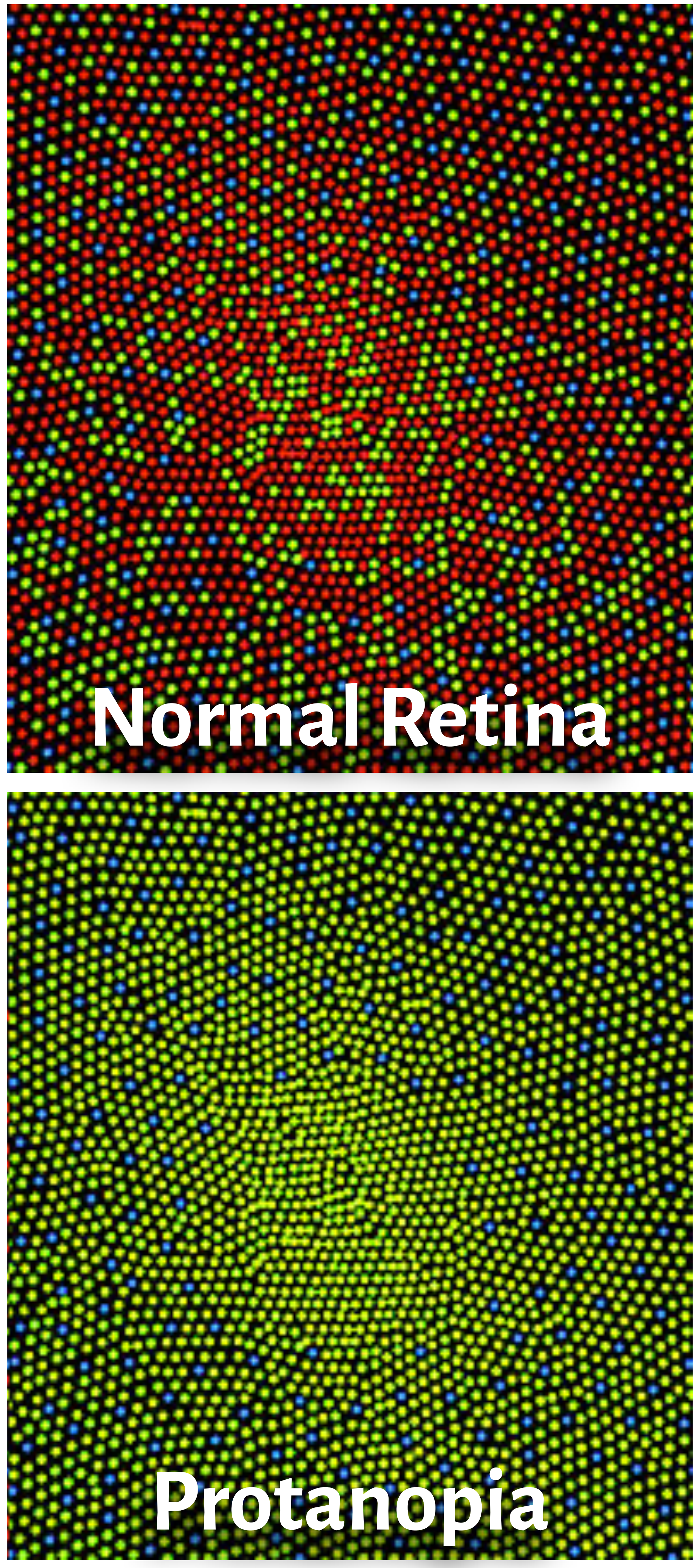
[Helga Kolb *Simple Anatomy of the Retina*,]

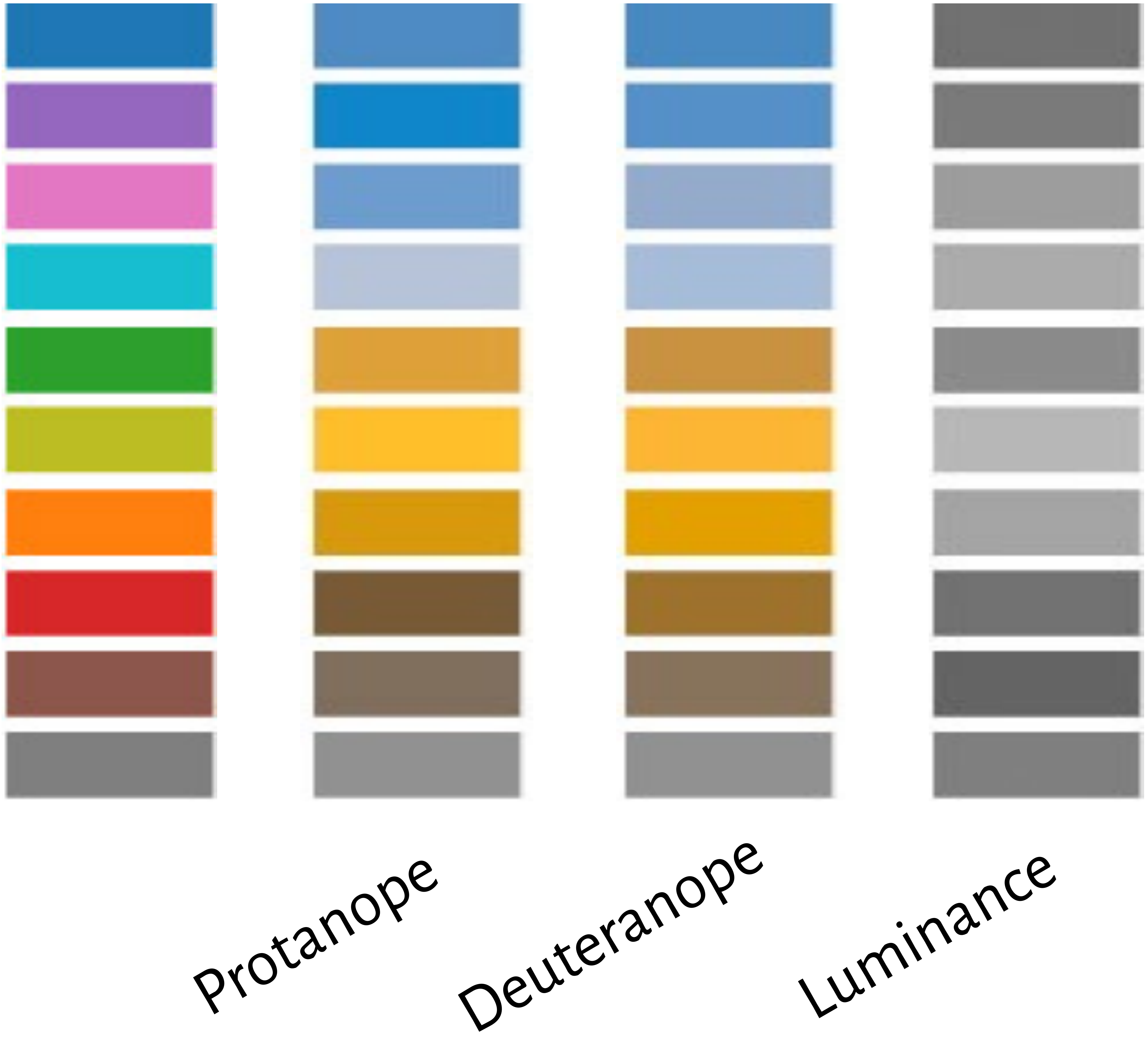
The Retina

Firefox and Chrome have built in simulators.



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





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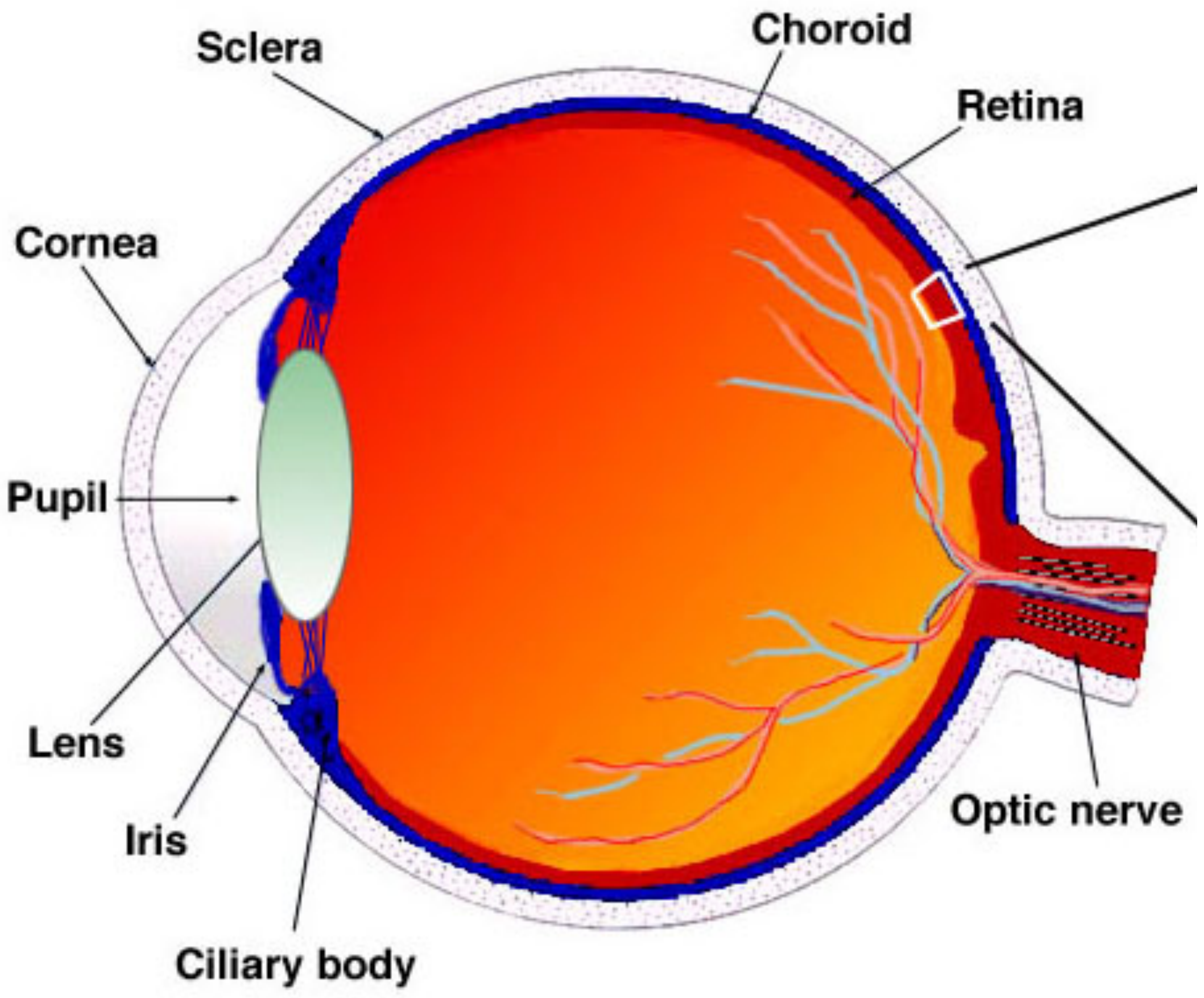

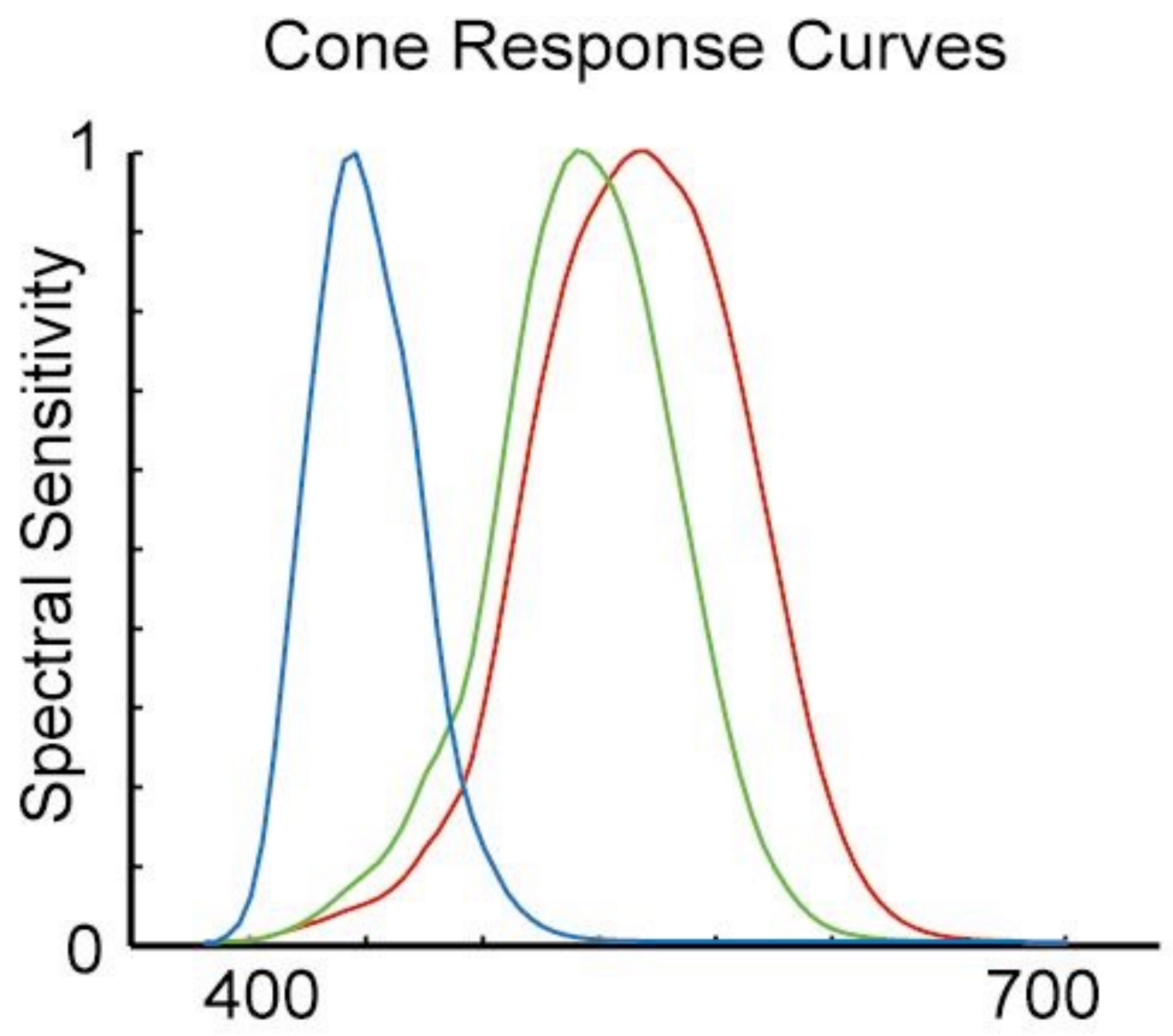

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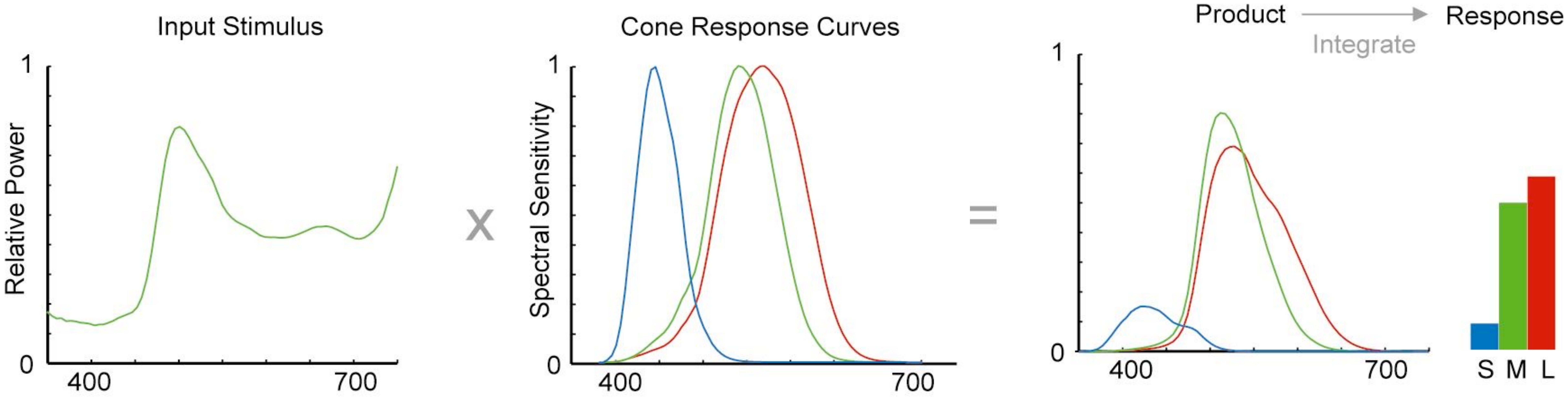
integrate against different input stimuli



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

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

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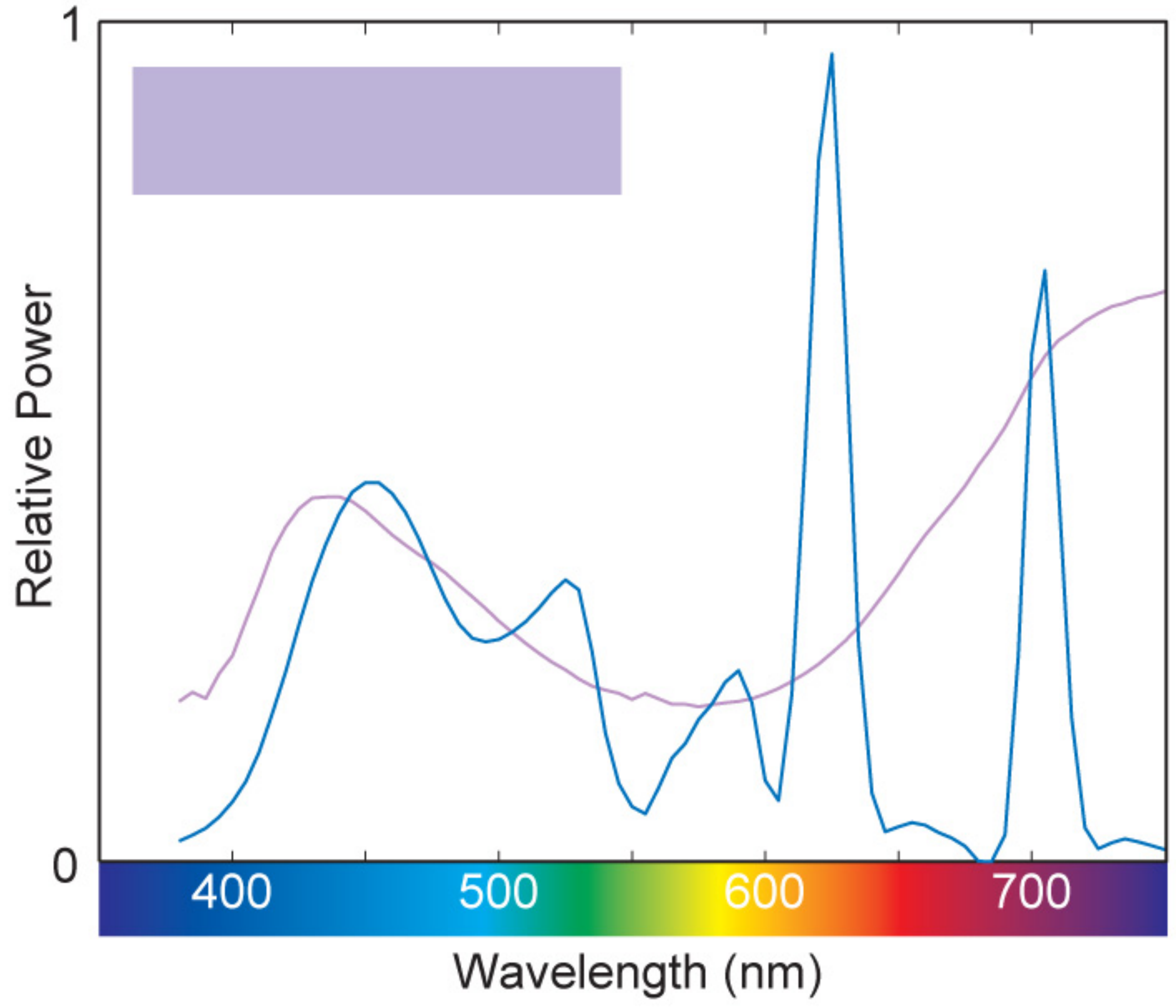
tri-stimulus response – color can be modeled as 3 values.

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

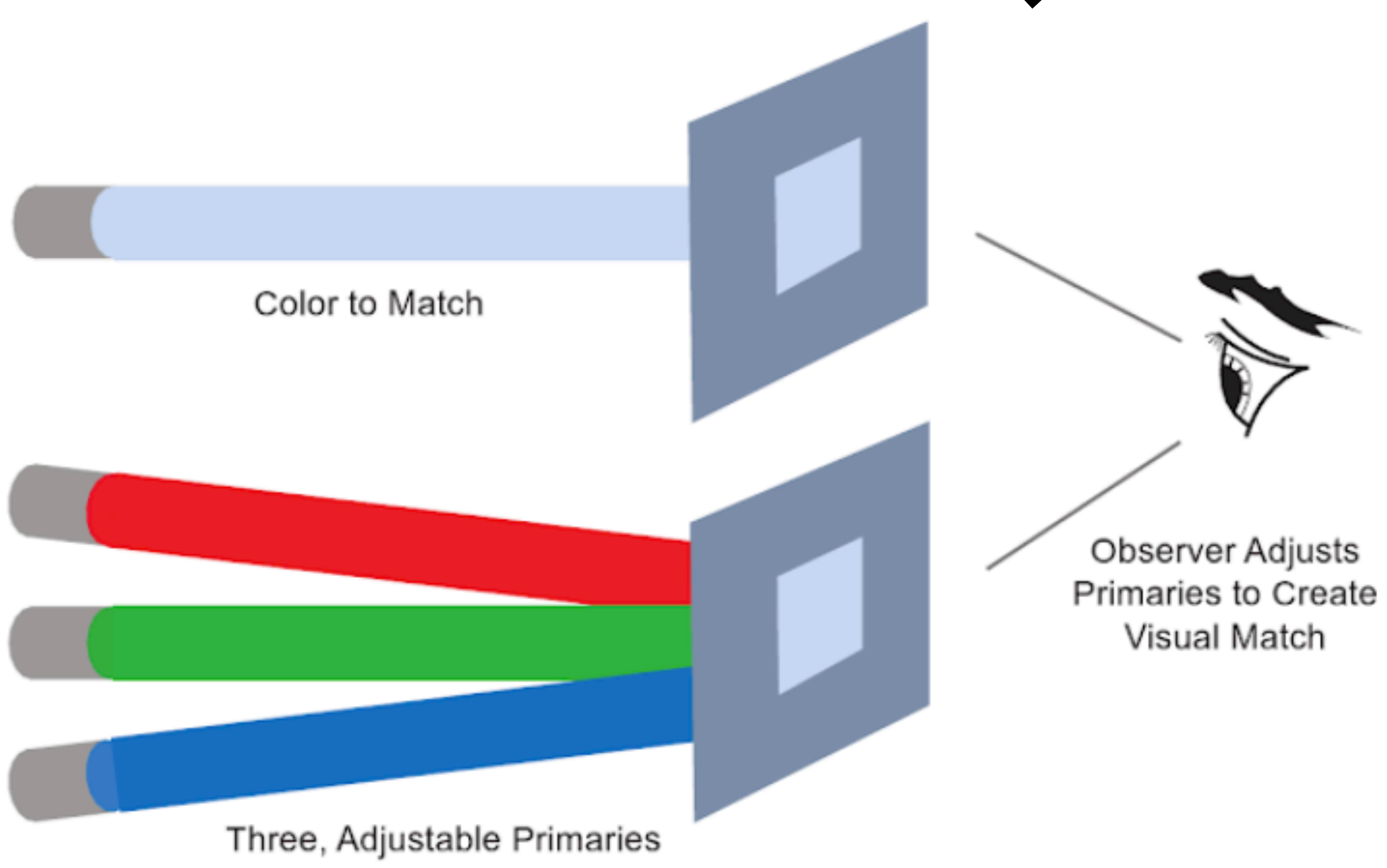


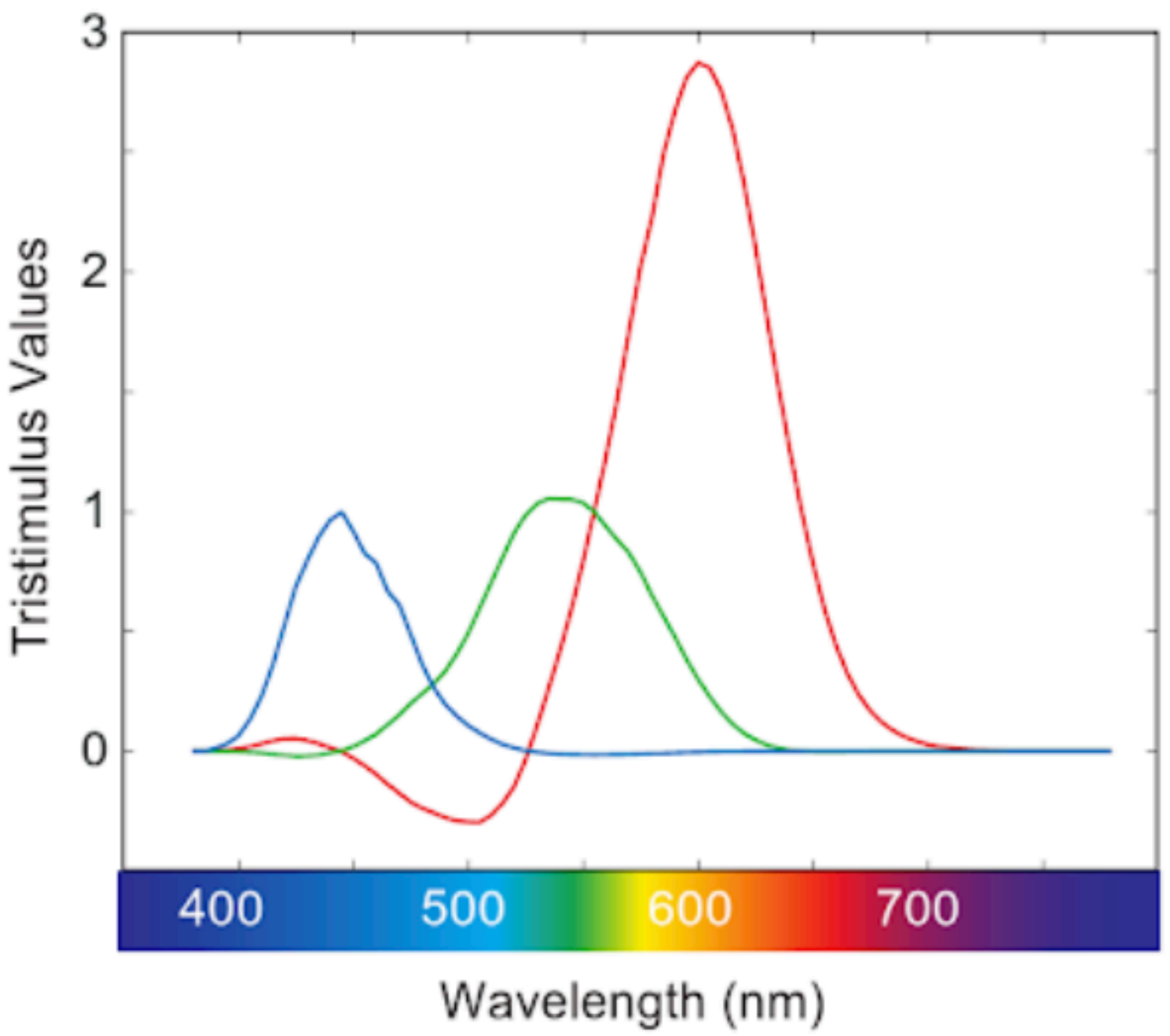
[Maureen Stone. *A Field Guide to Digital Color*, 2003]

CIE XYZ

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

empirically determined





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

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

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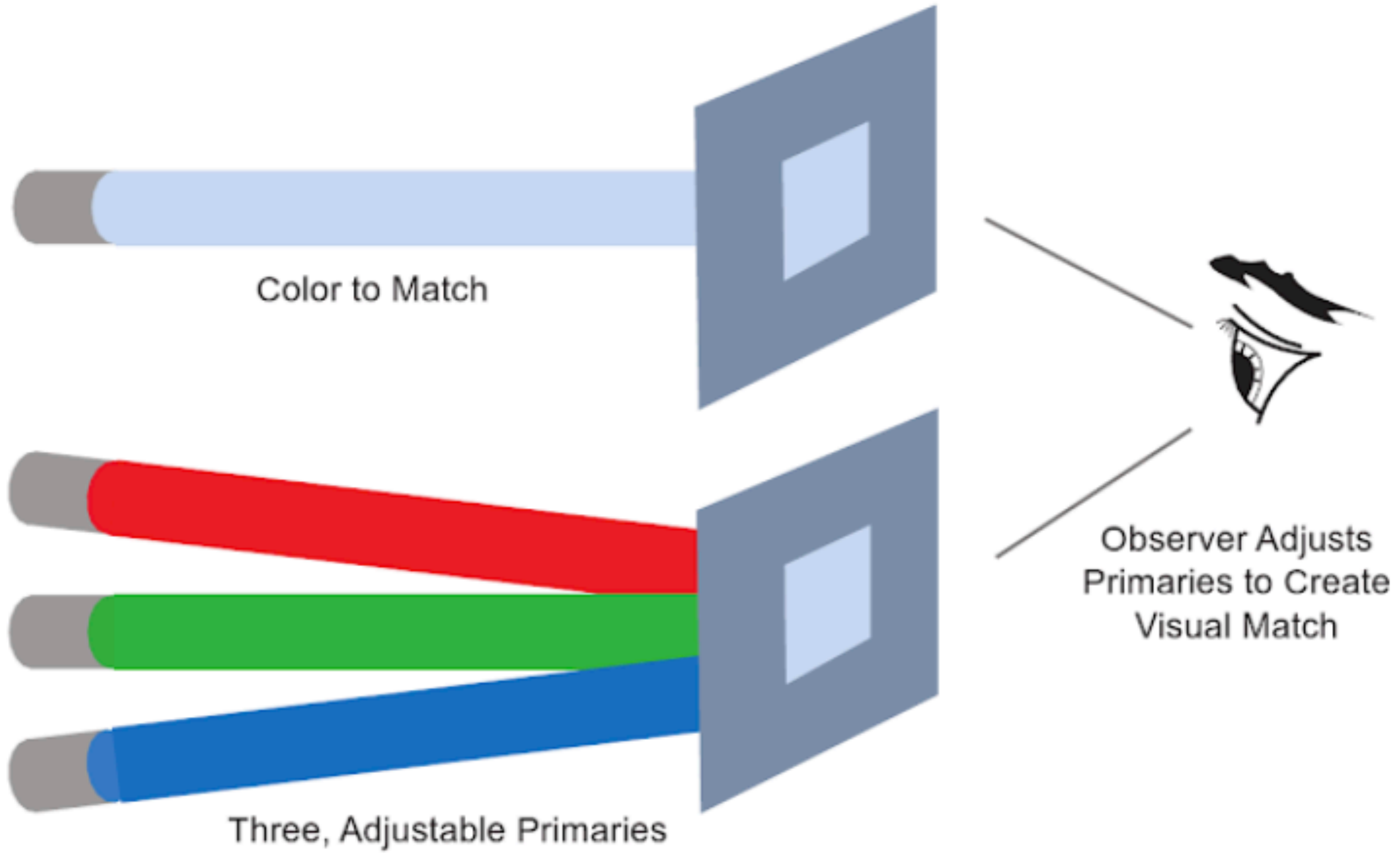

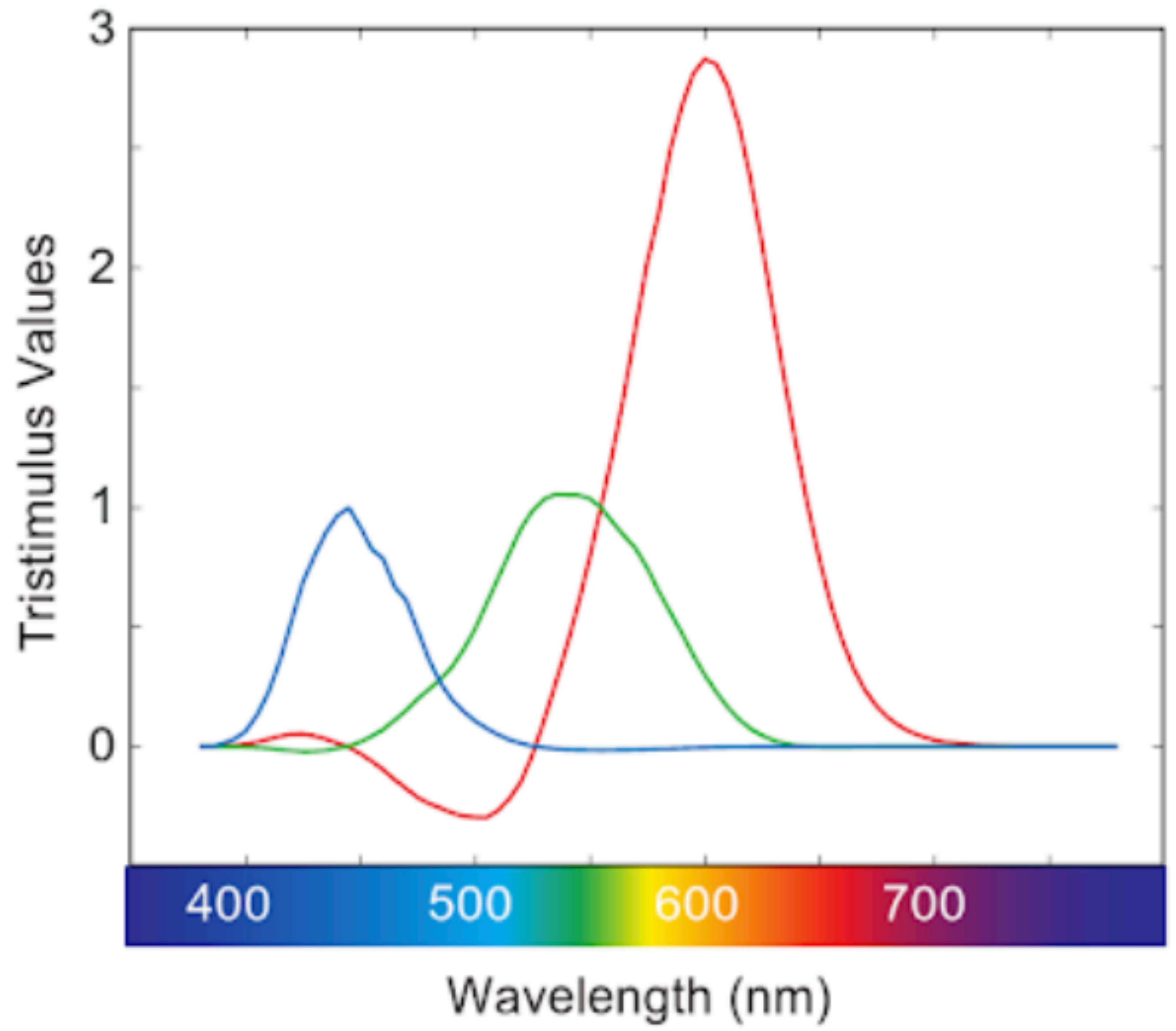

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What's odd about these curves?

Raise your hand

Post in the chat

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

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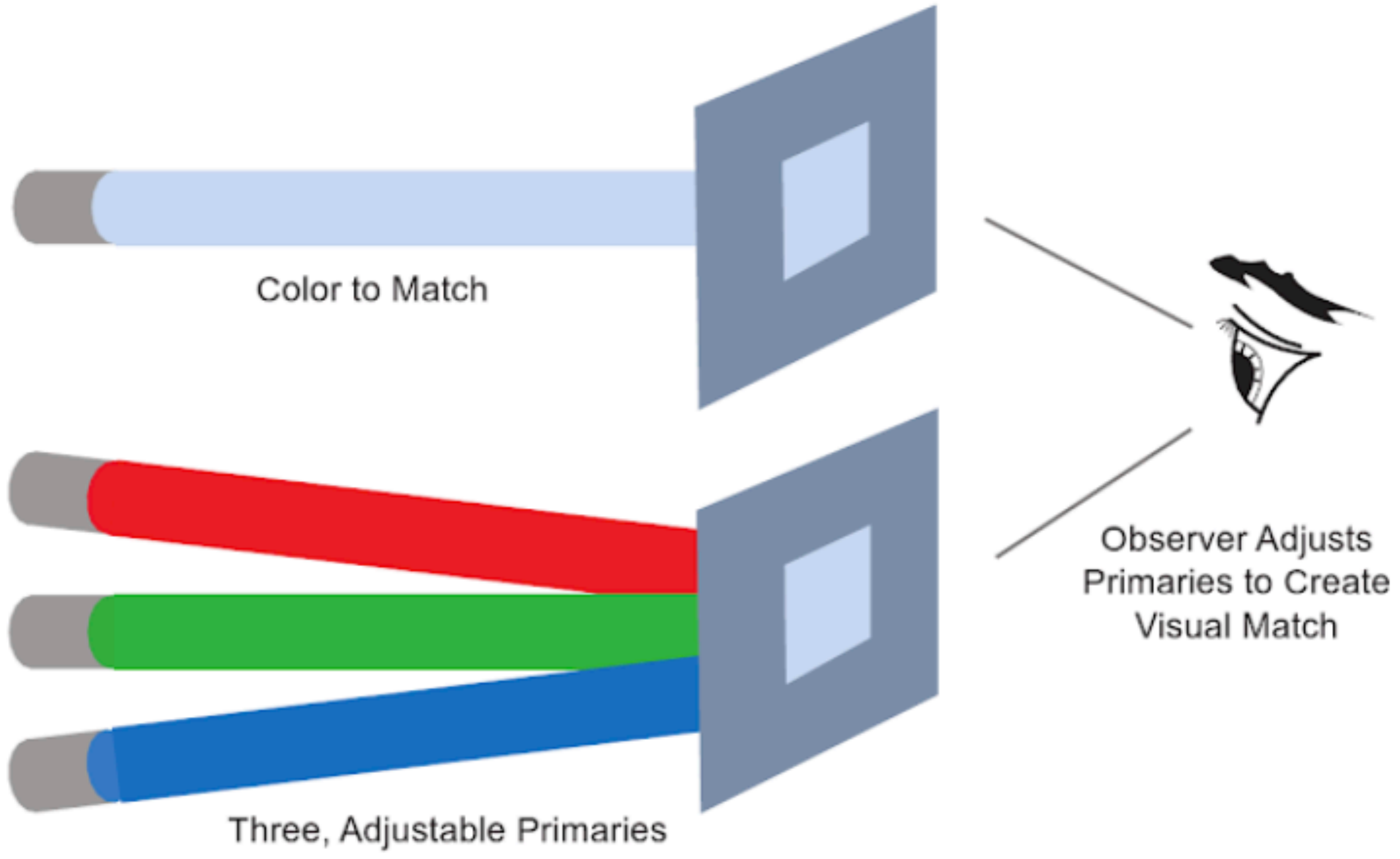

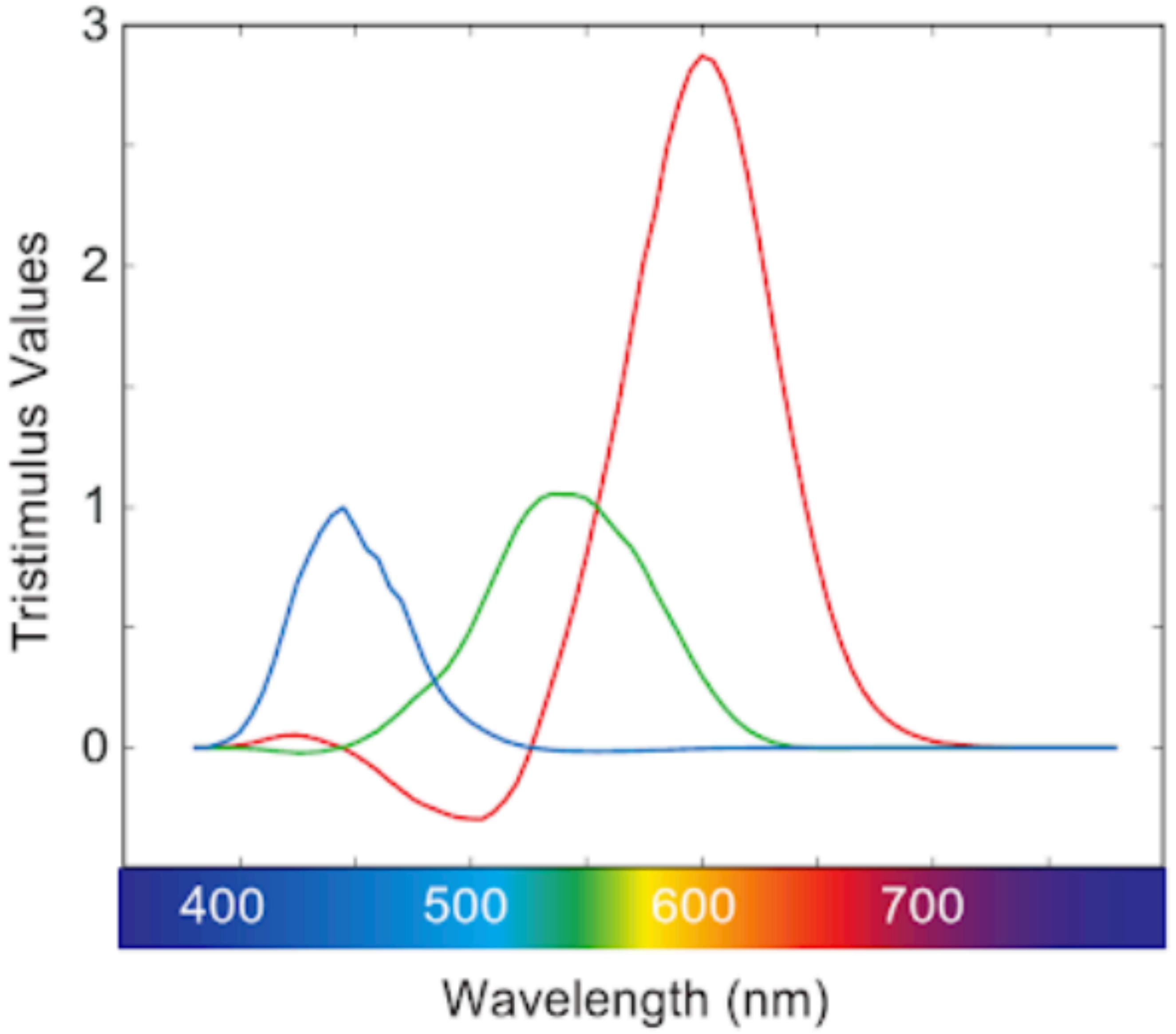

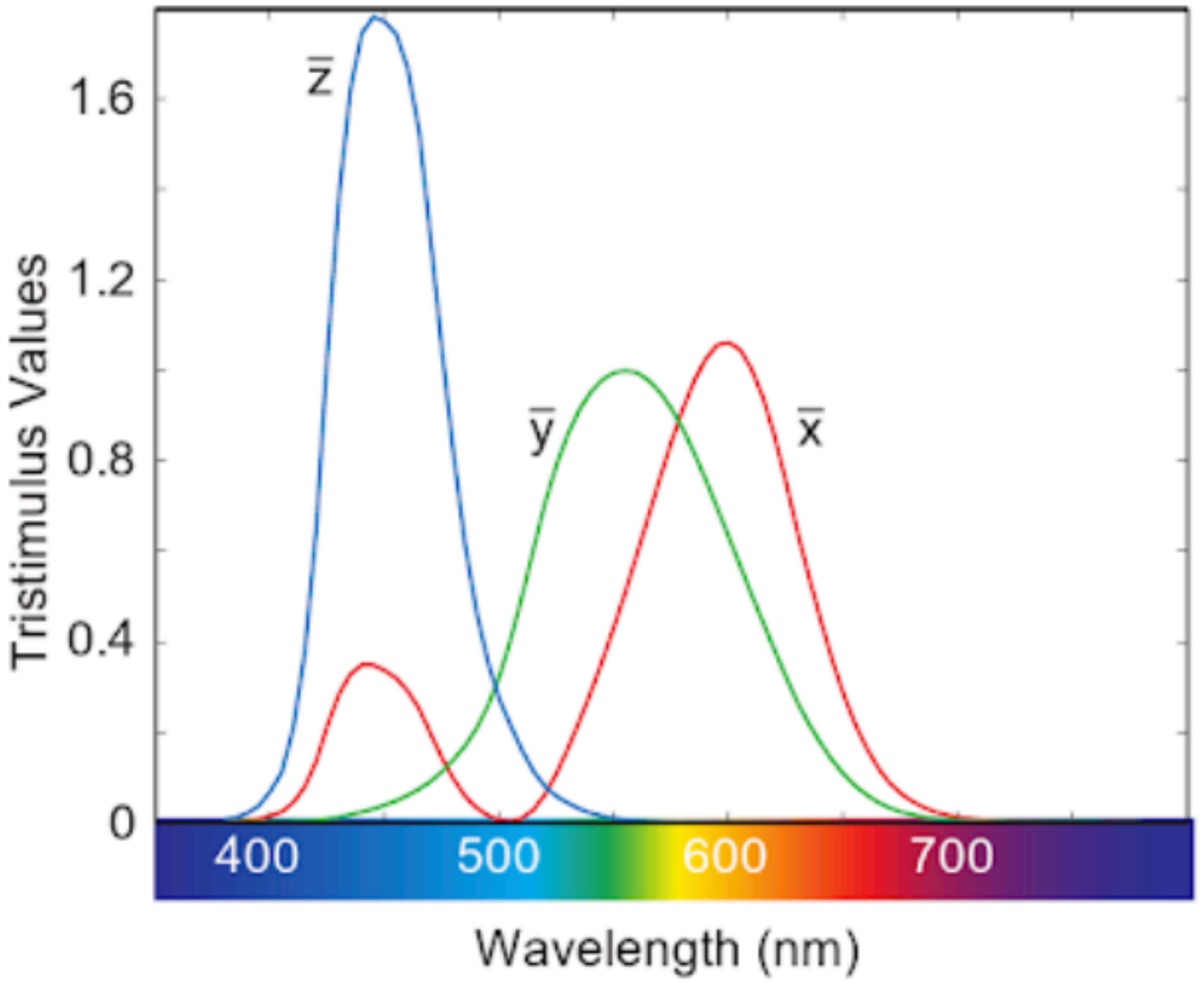

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mathematic transformation
No real lights can produce the x, y, z response curves.

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

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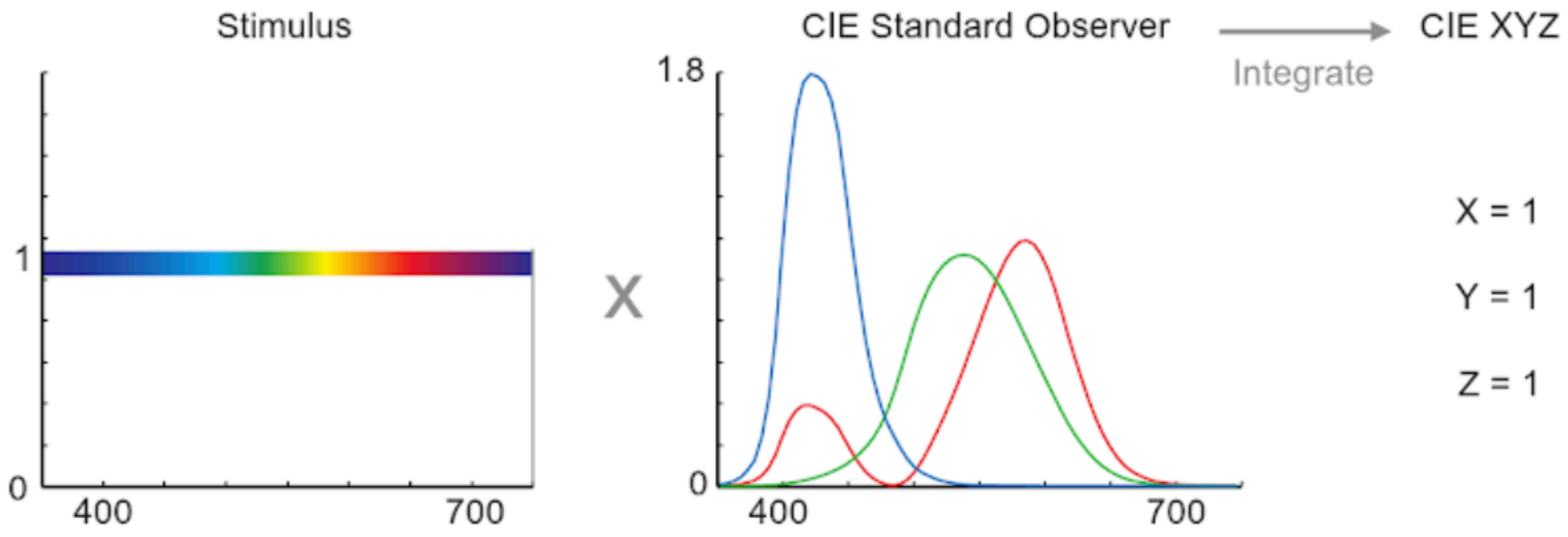


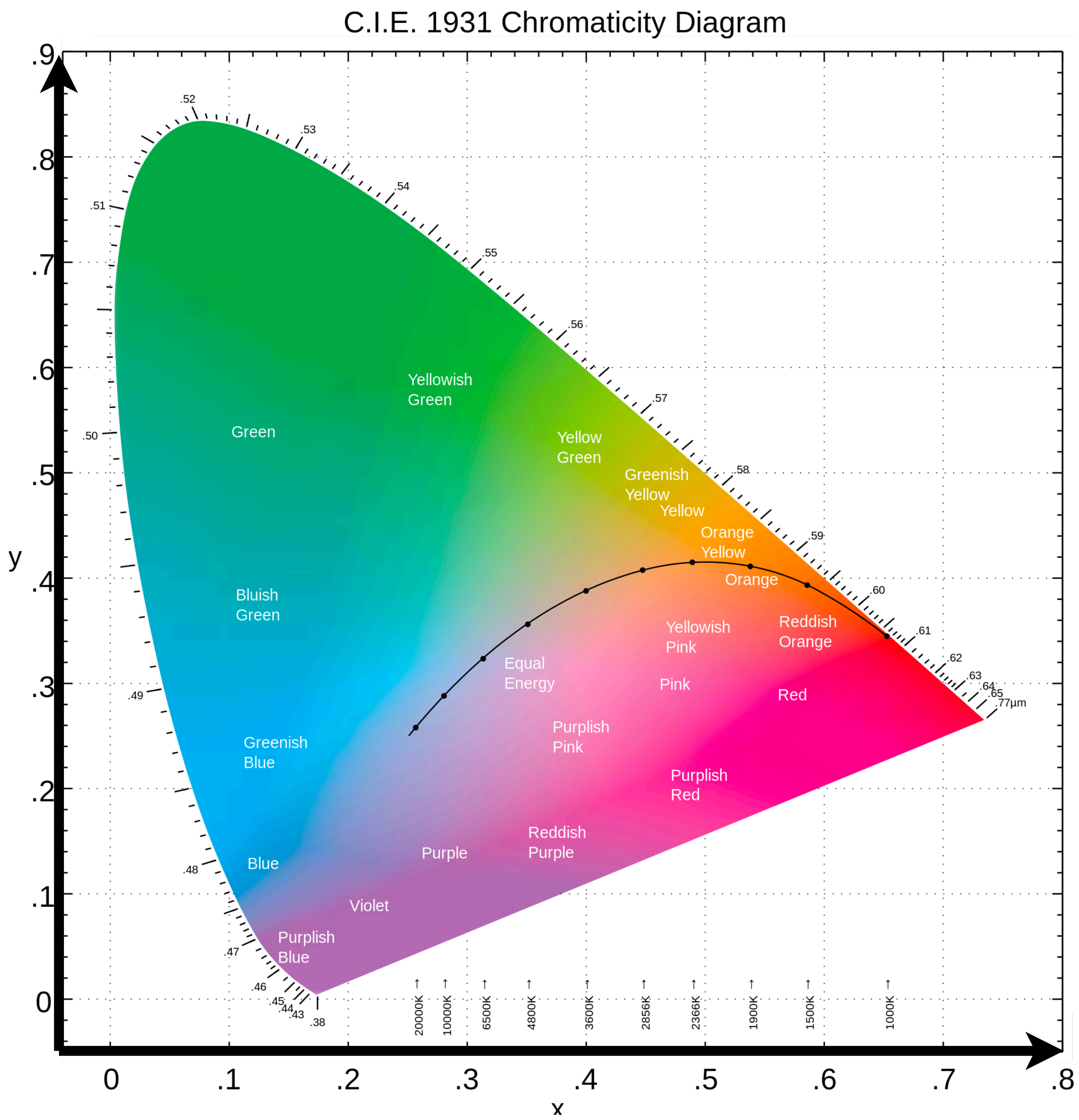
CIE XYZ Color Space

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

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

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

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$



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

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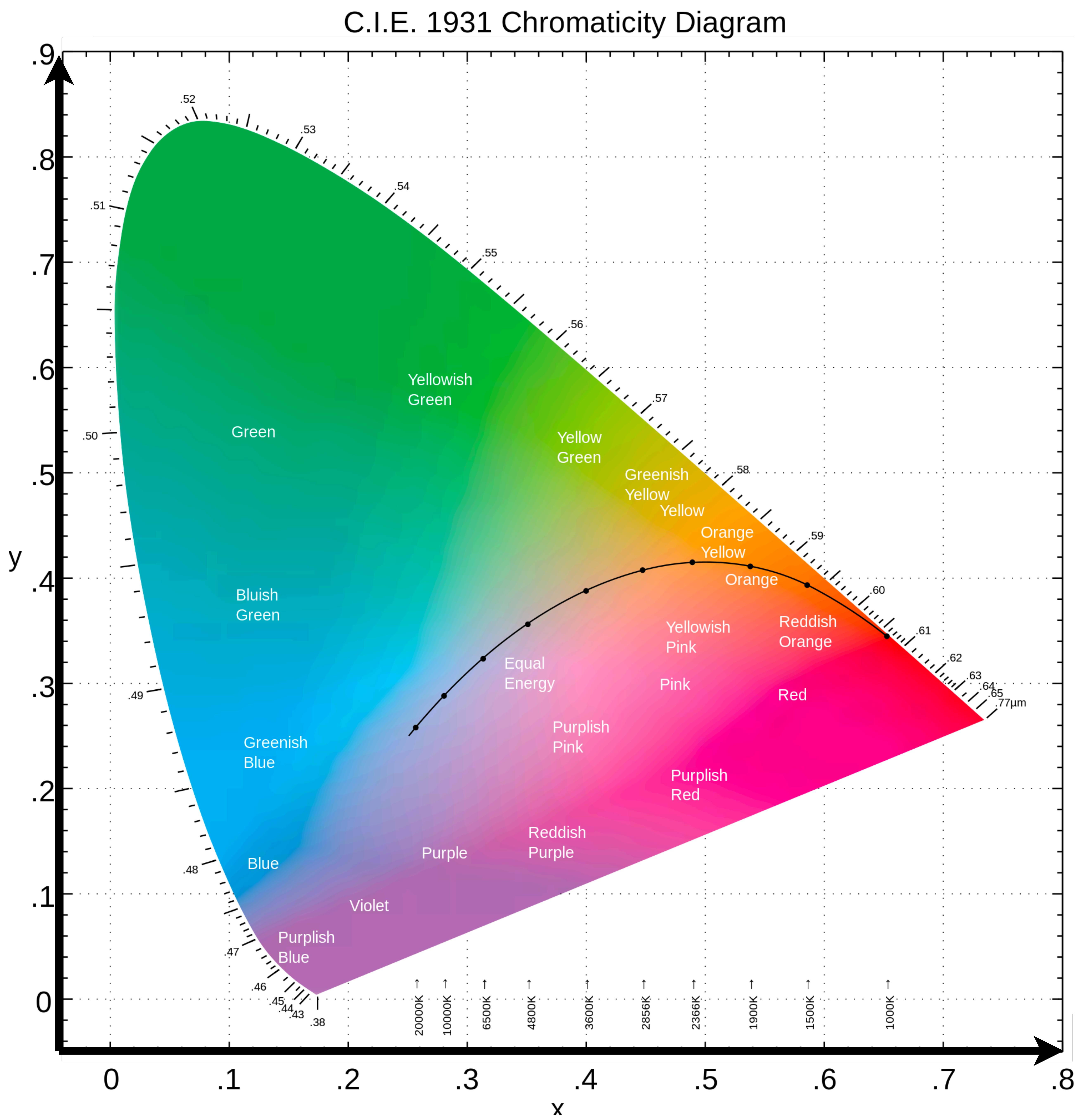
Straight line = mixture of two light sources.



CIE XYZ Color Space

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

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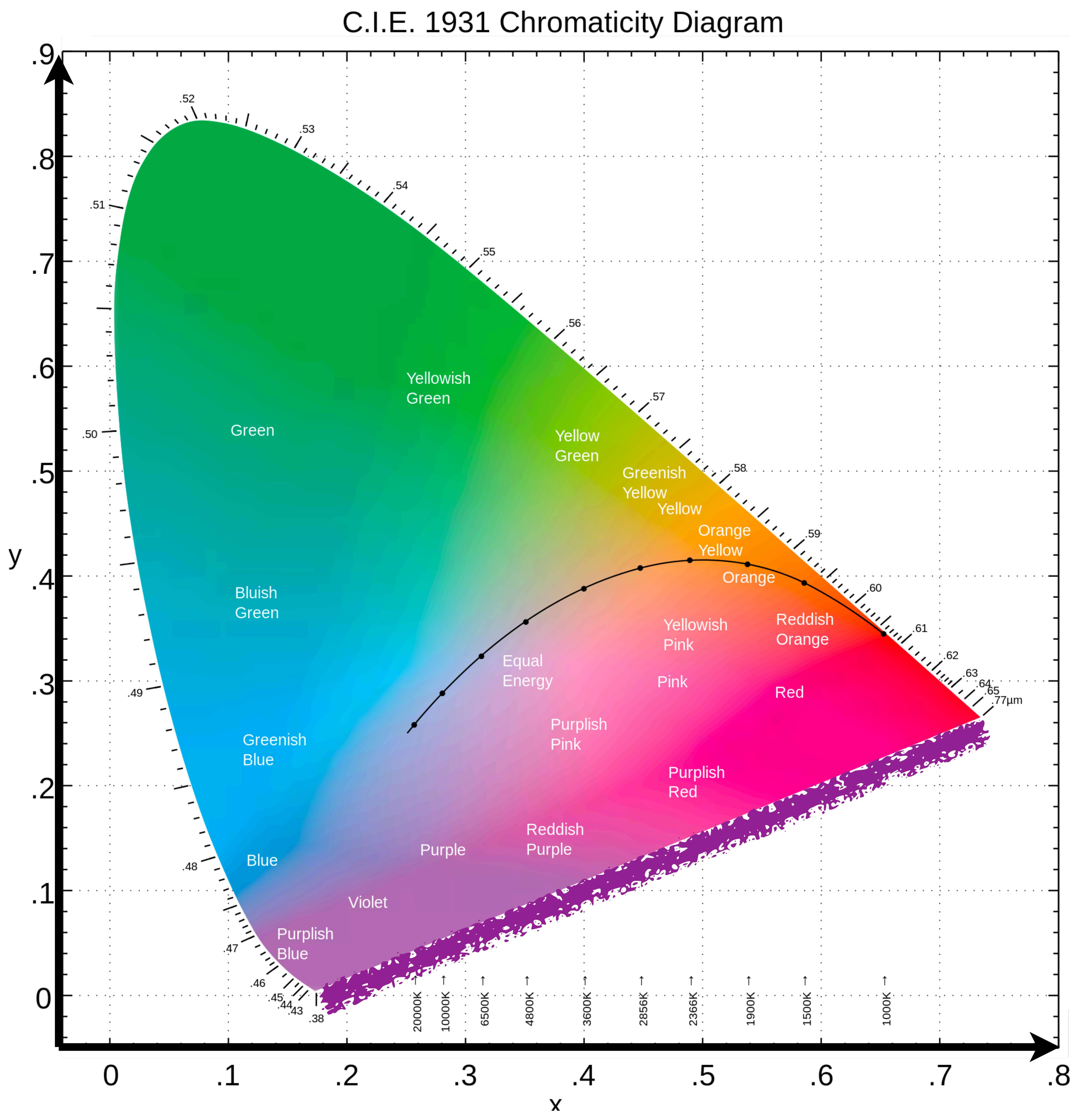
Purple line – not possible to recreate with a monochromatic light source.

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



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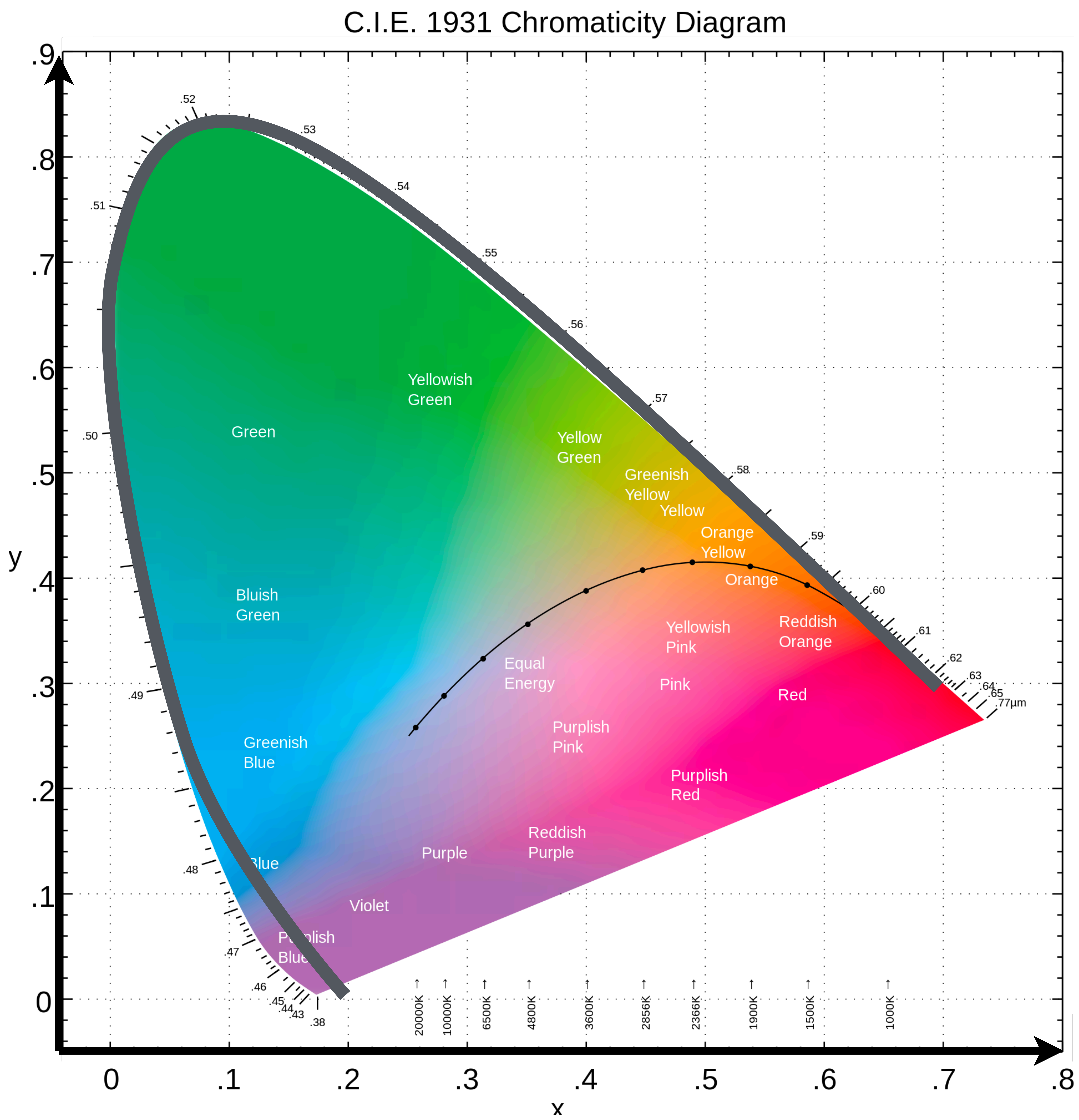
$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z} = 1 - x - y$$

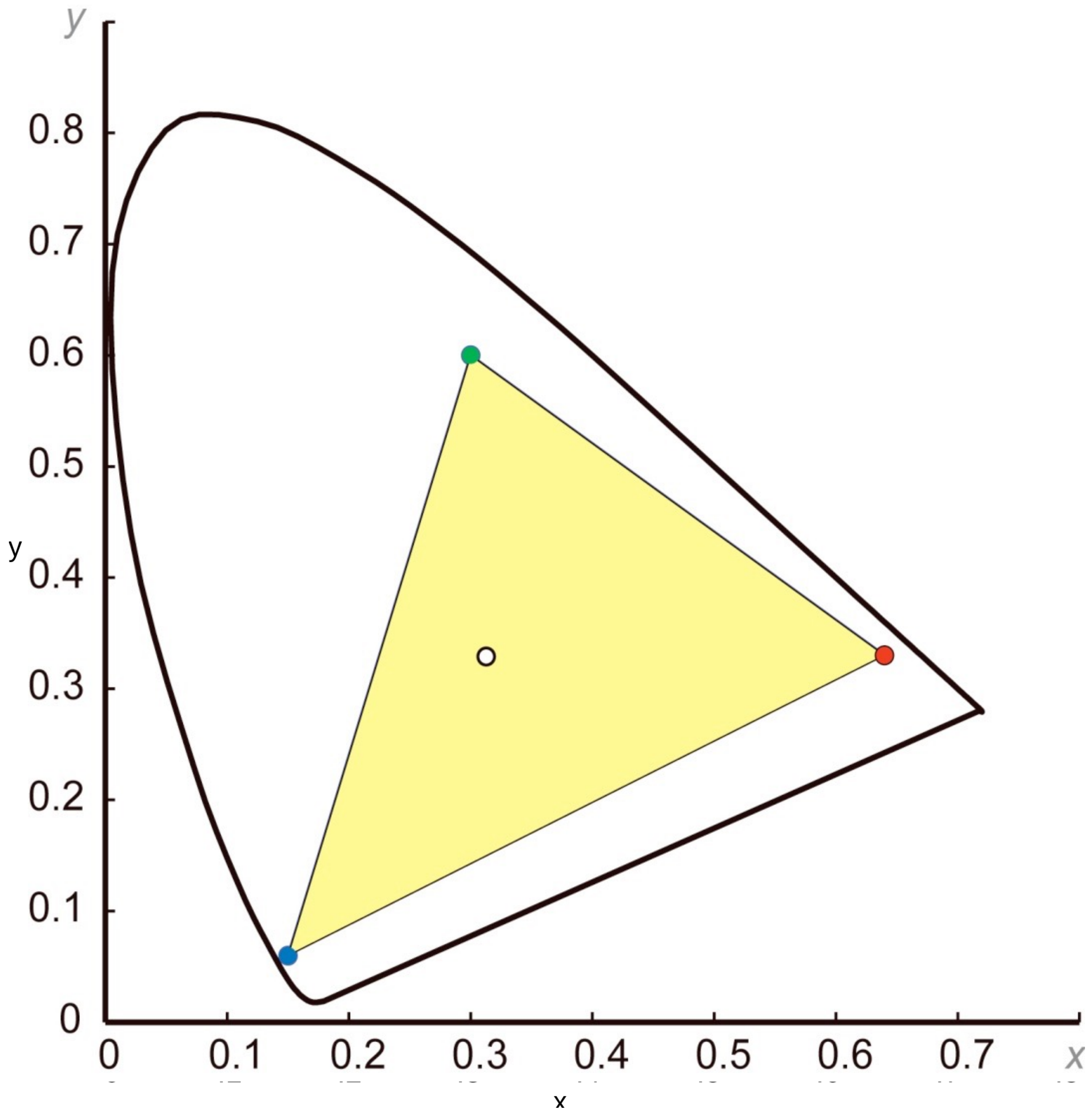
Spectral locus – set of pure colors (i.e., lasers of a single wavelength).

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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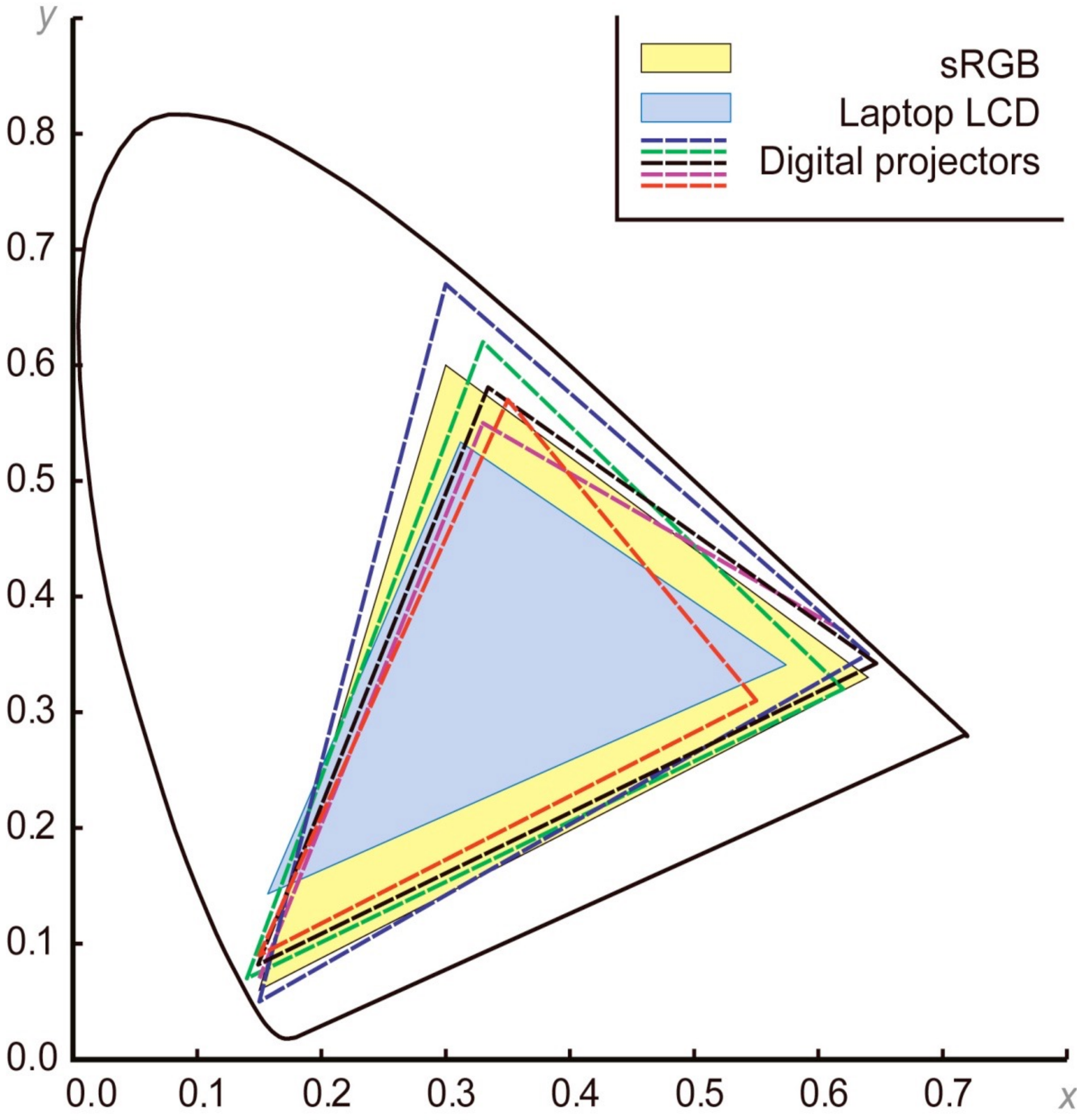


CIE XYZ Color Space

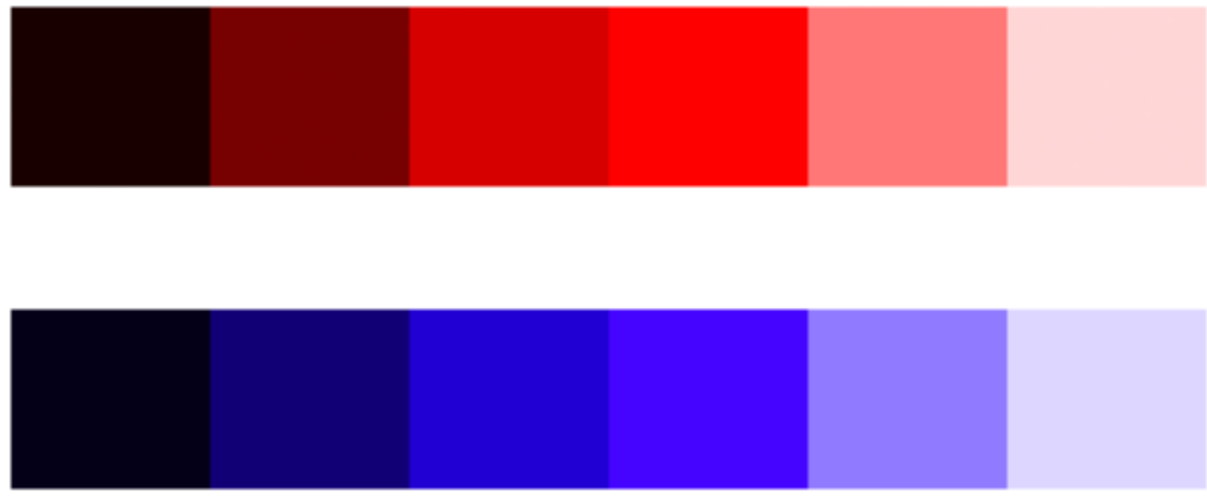
Display gamut = portion of the color space that can be reproduced by a display.

The angry rainbow in sRGB.

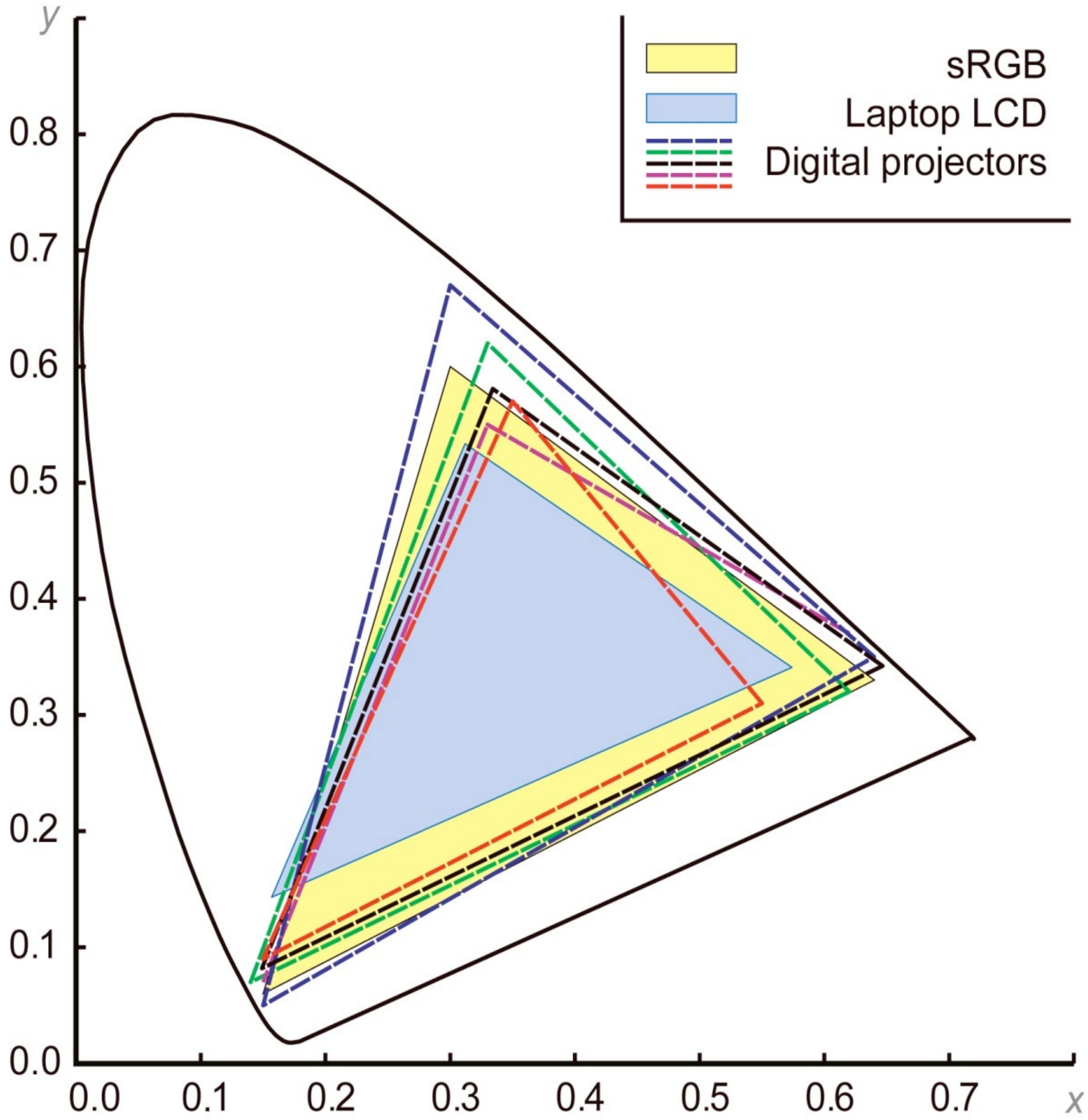
Corners of sRGB

Photoshop grayscale

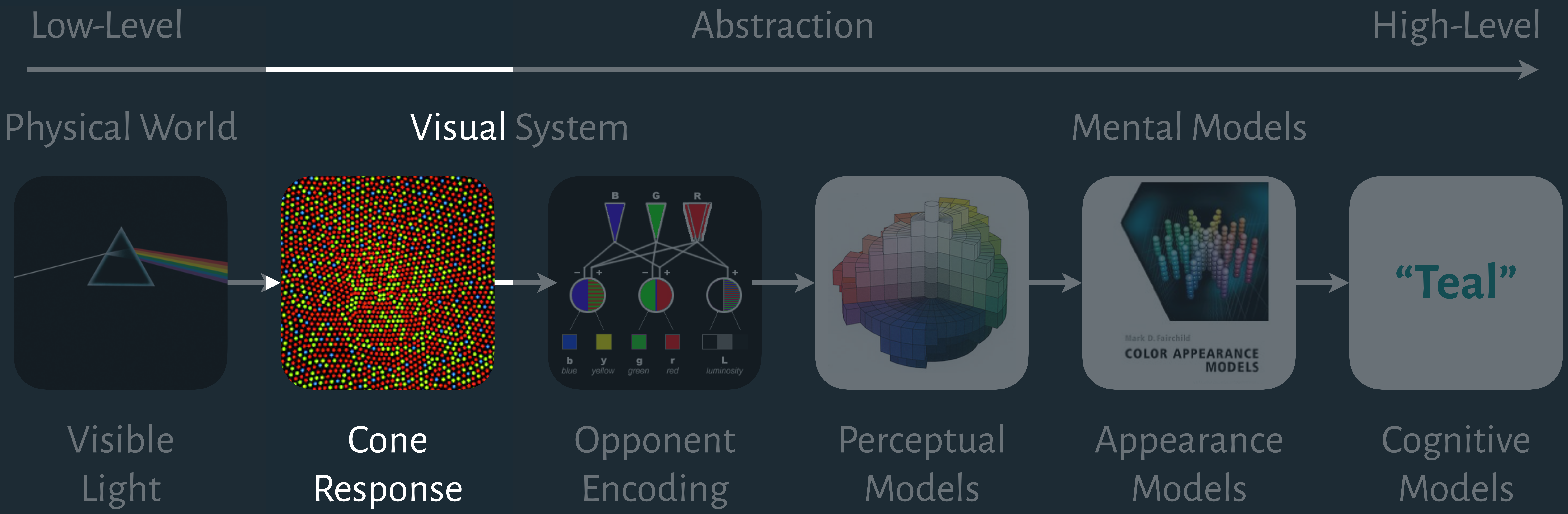
No linear brightness gradient within a single hue.



[Gregor Aisch How to Avoid Equidistant HSV Colors.]



Modeling Color Perception



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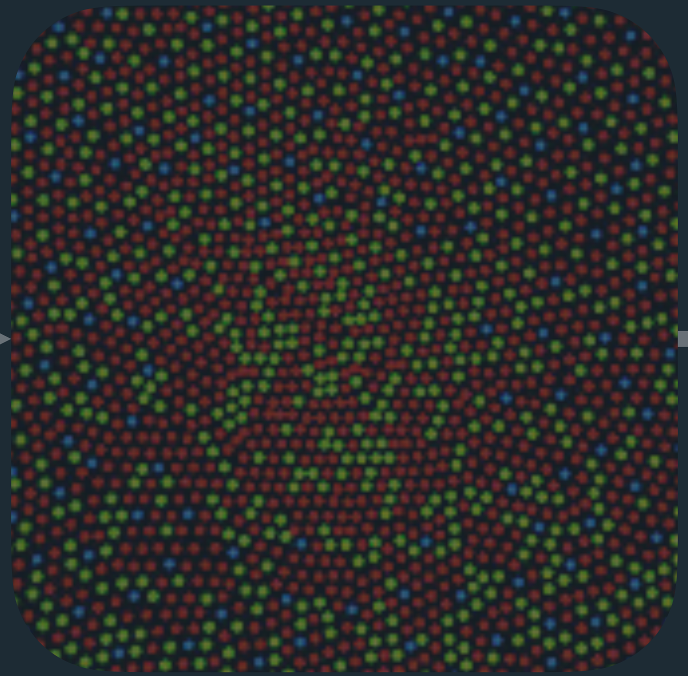

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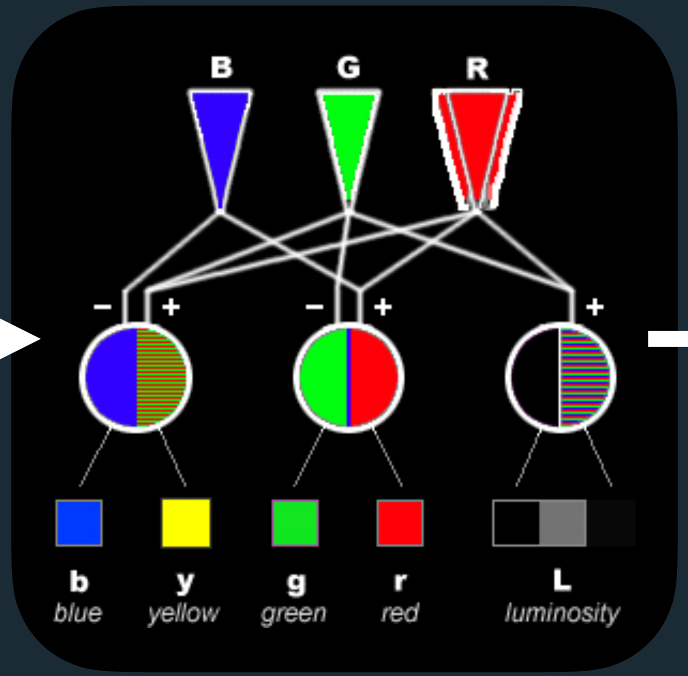

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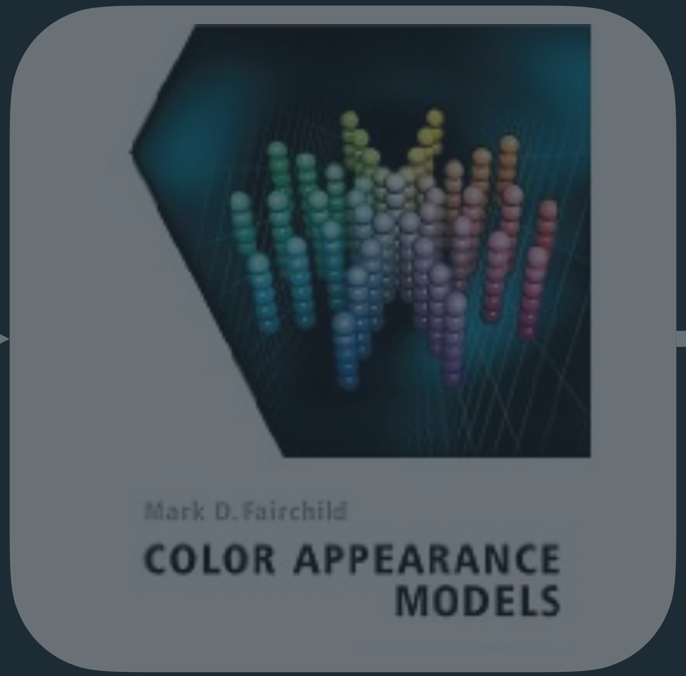
Perceptual Models



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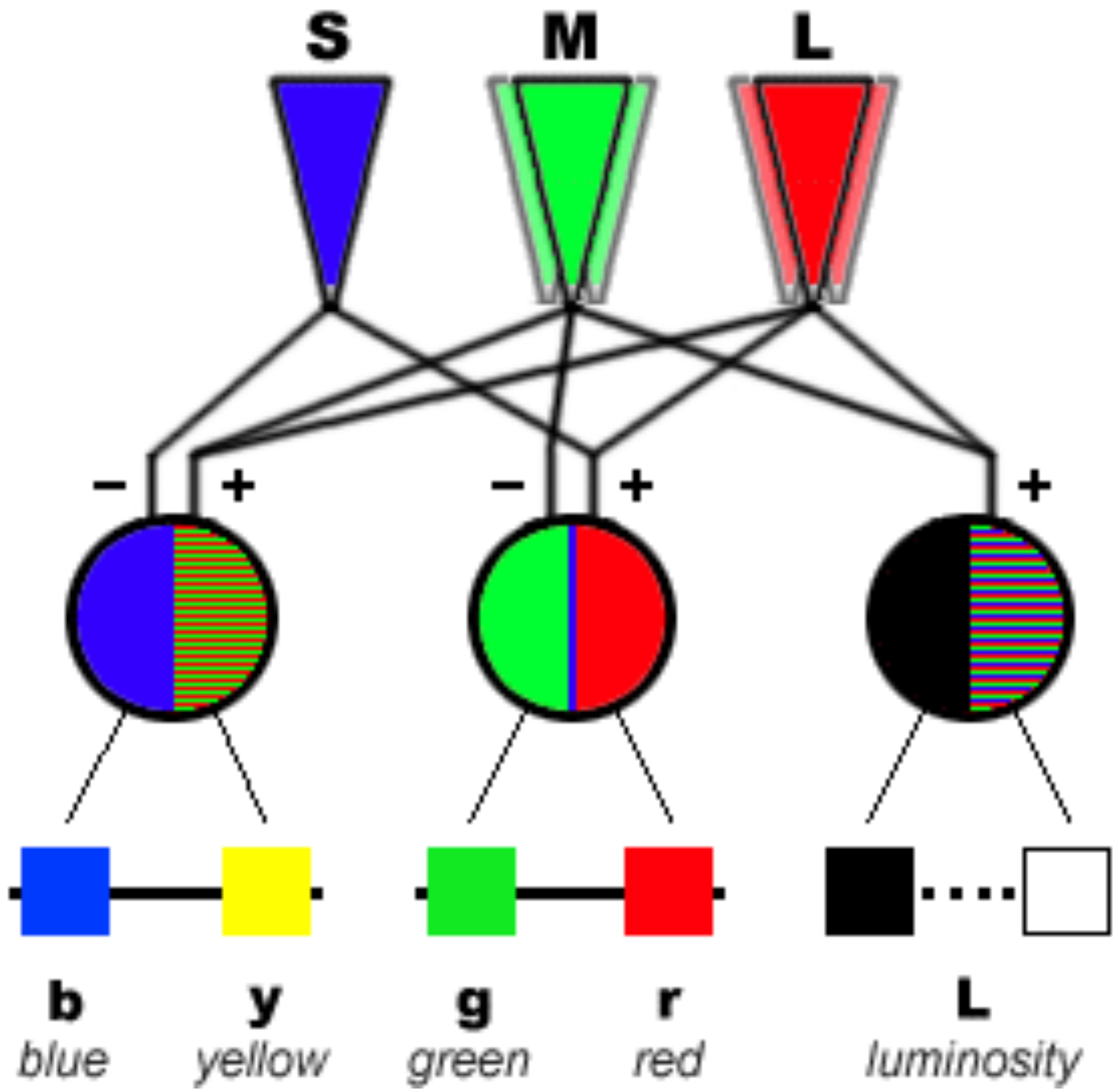
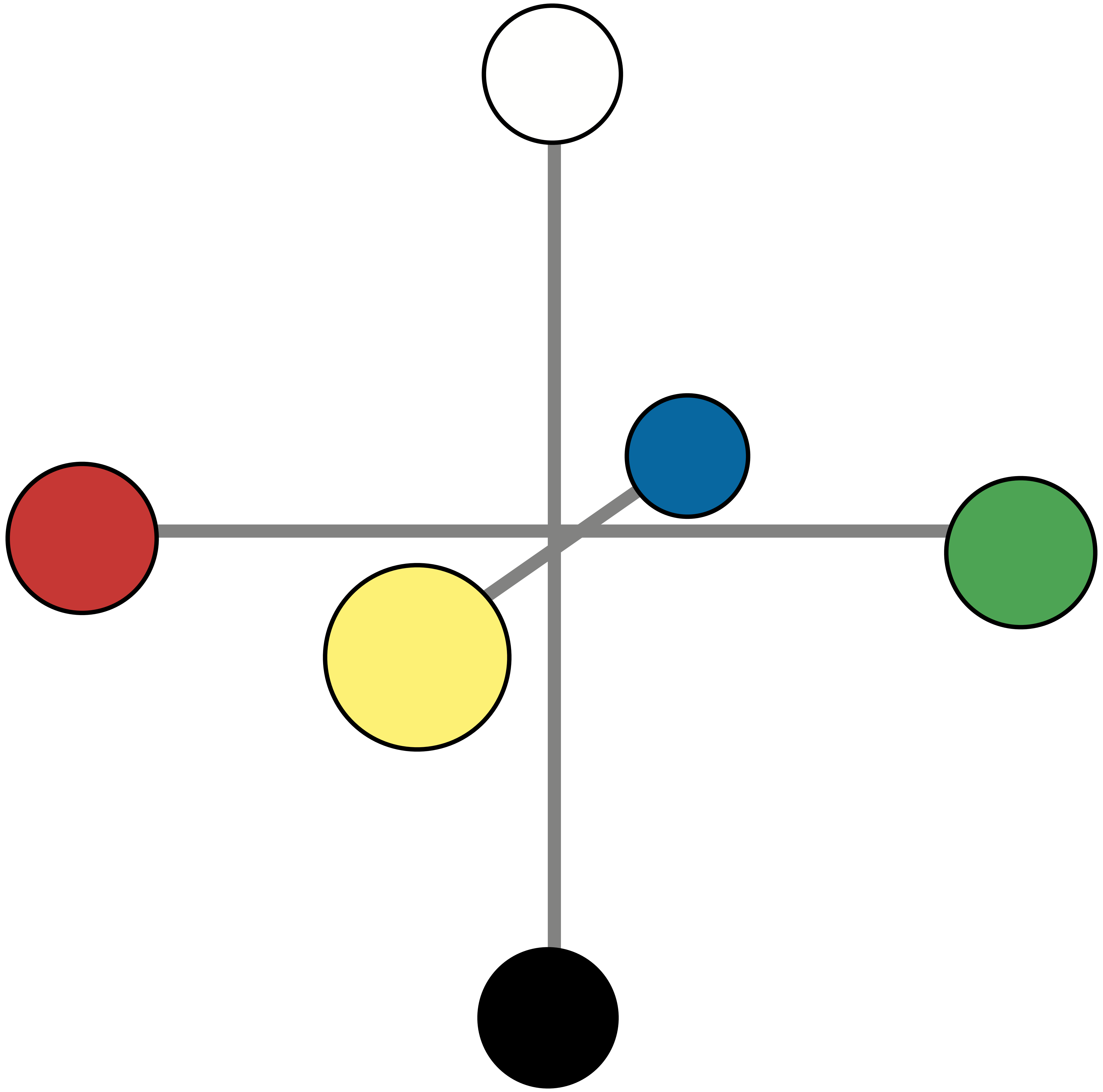
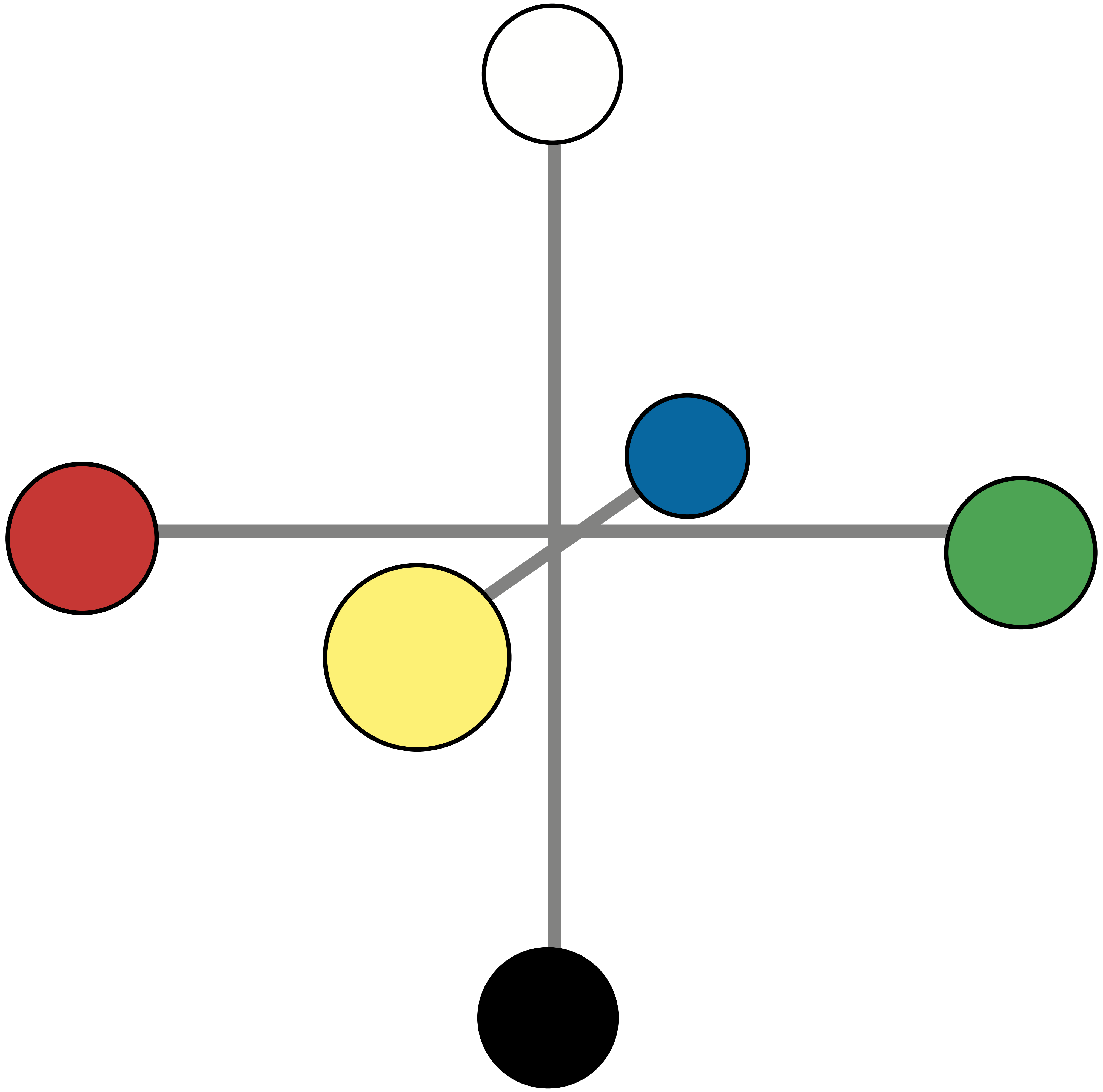




CIE LAB Color Space

Axes correspond to opponent signals:

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



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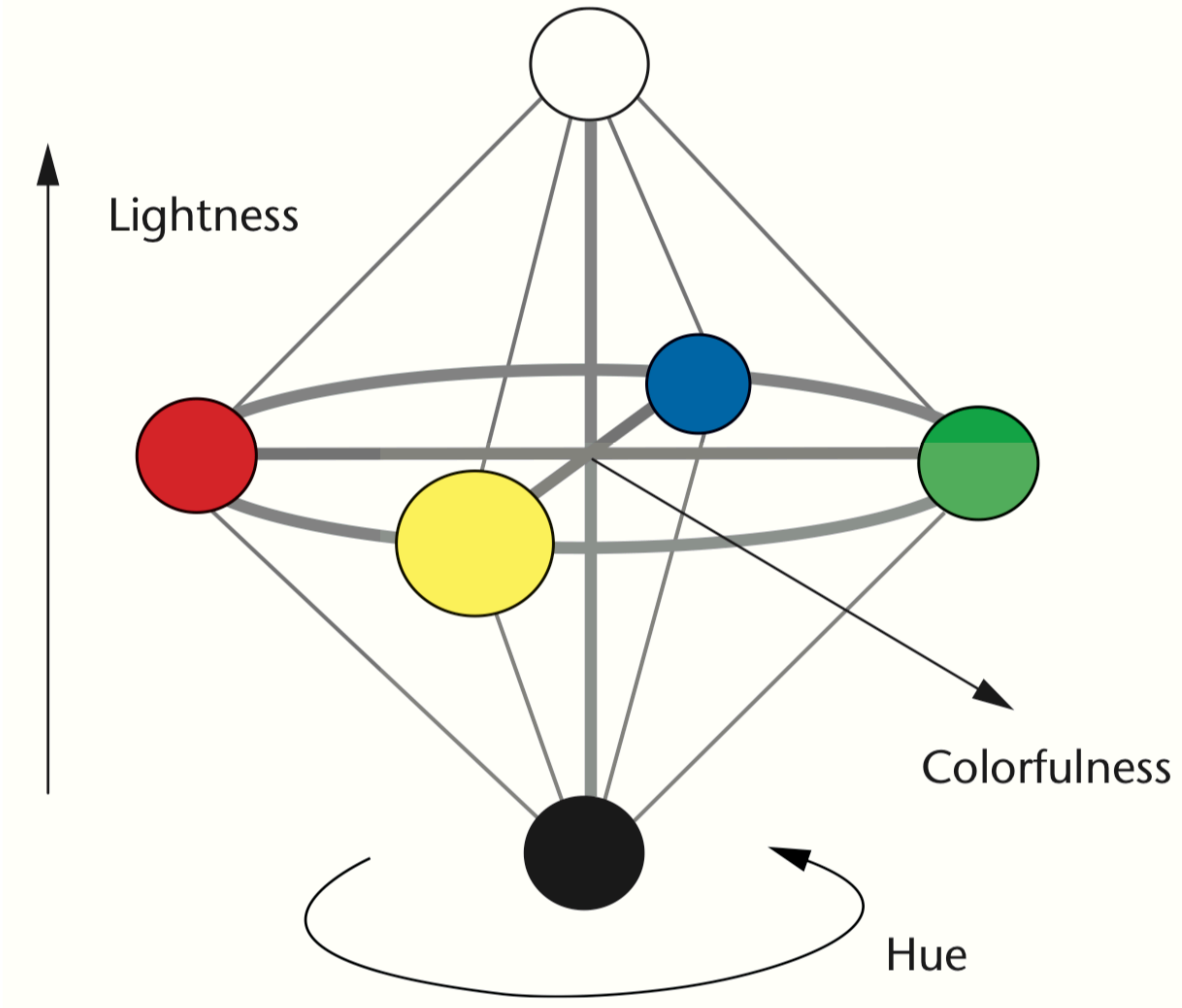


[Maureen Stone. *A Field Guide to Digital Color*, 2003]

CIE LAB Color Space

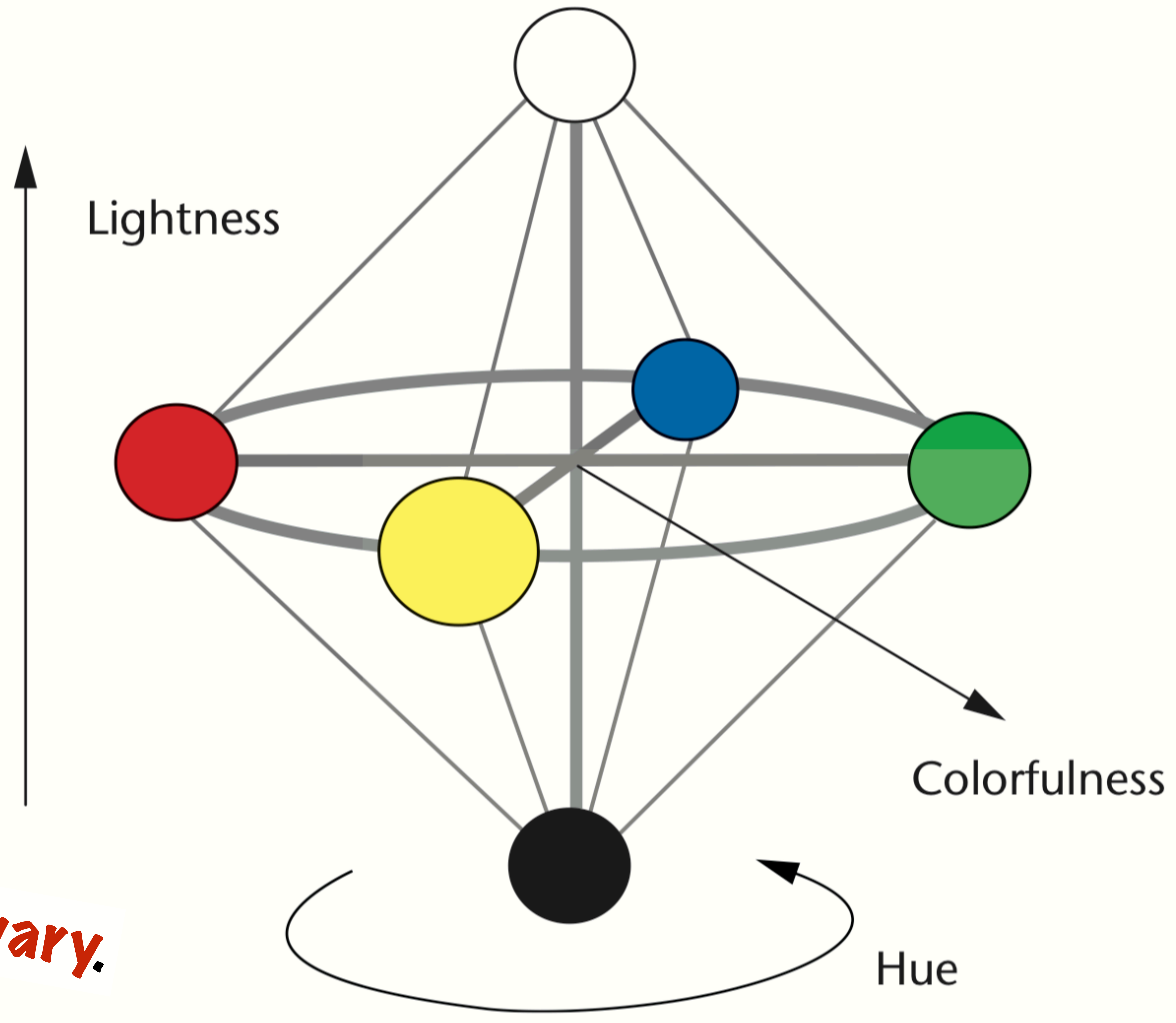
More perceptually uniform than sRGB.

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

The angry rainbow in sRGB.

Better. But still be wary.

A happier rainbow in LAB.



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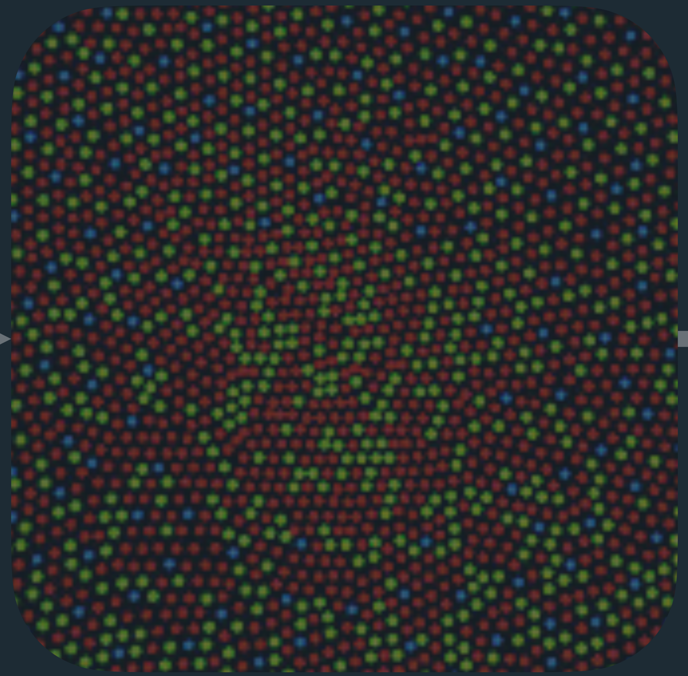

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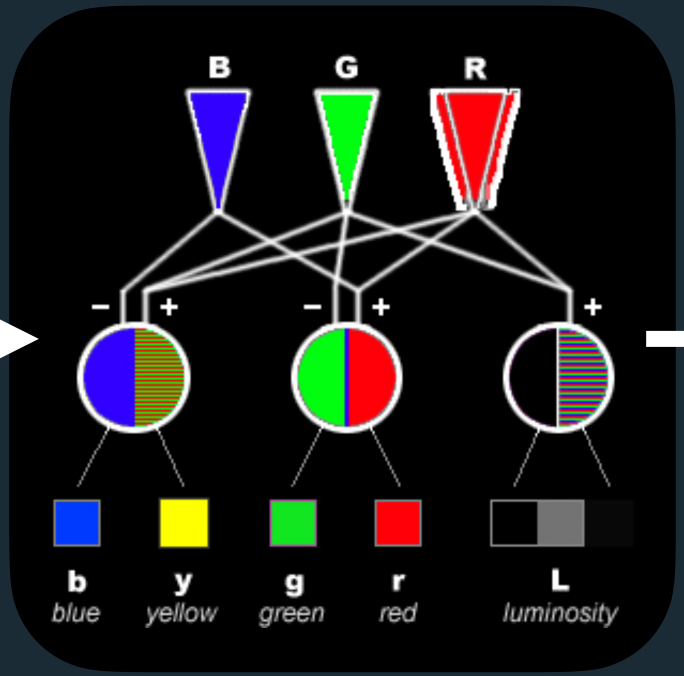

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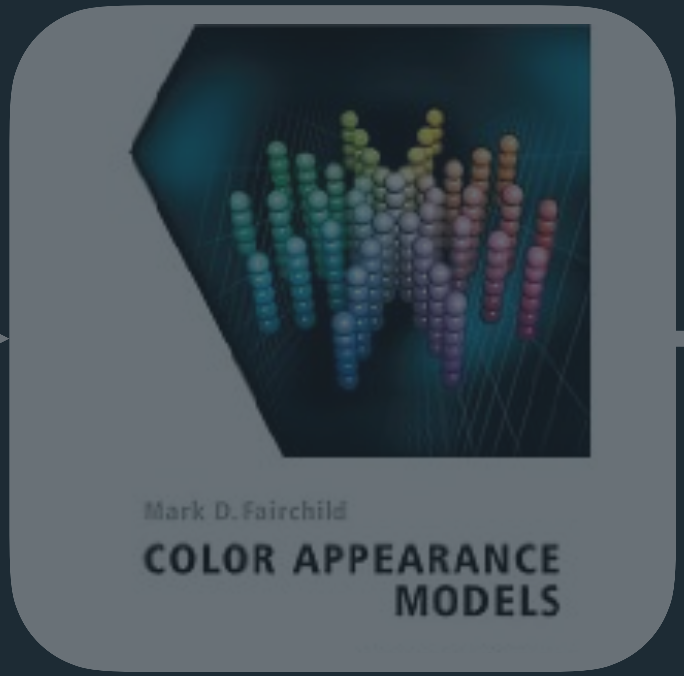

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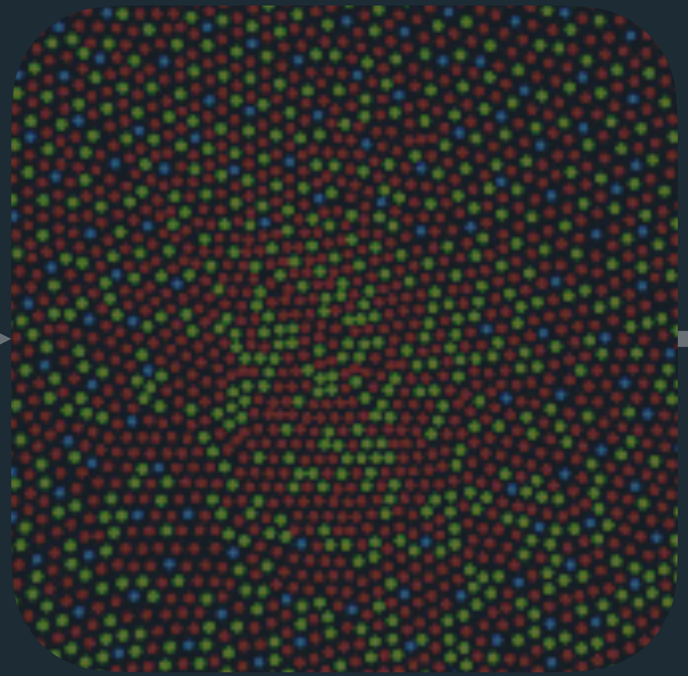

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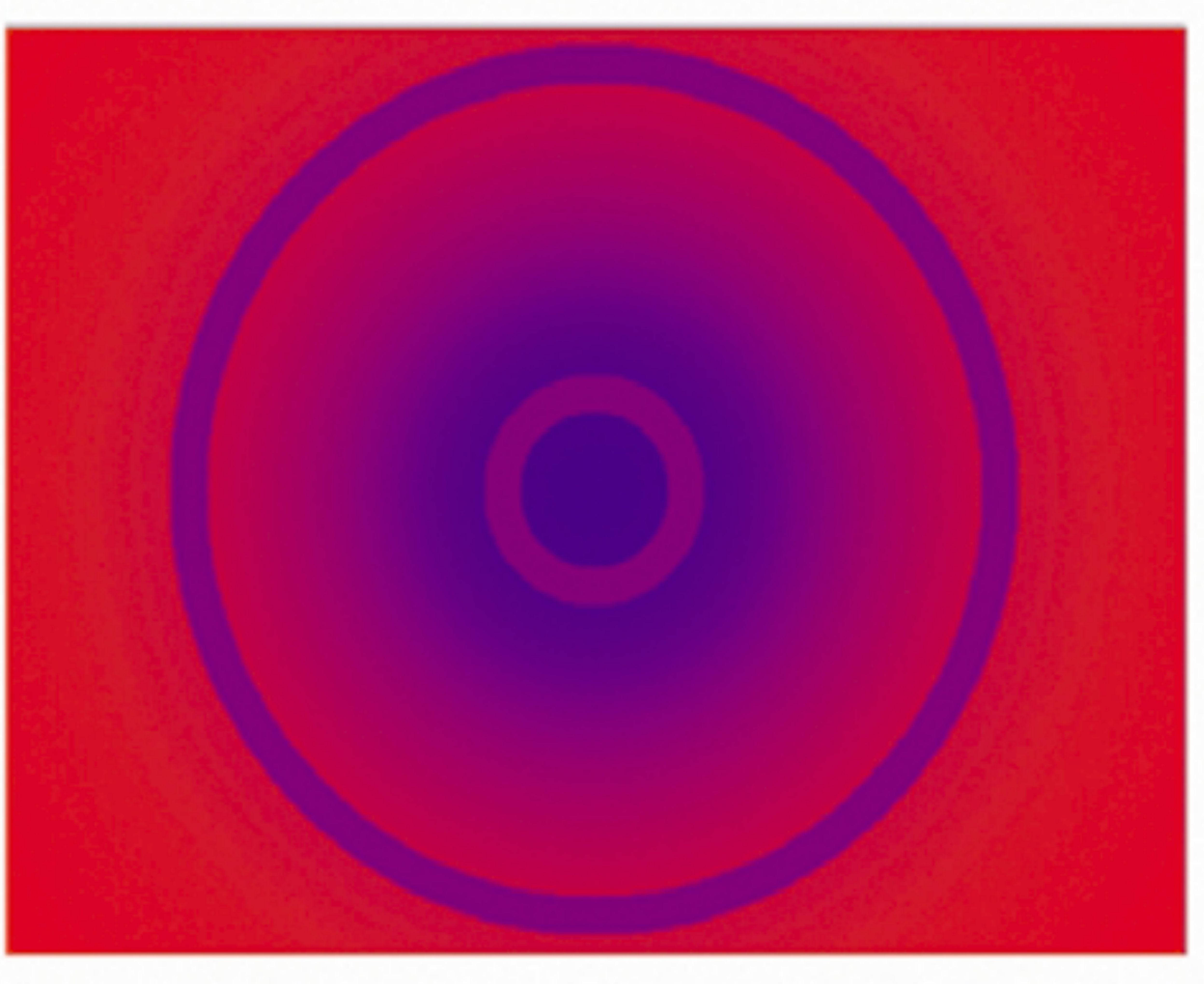
Simultaneous Contrast

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

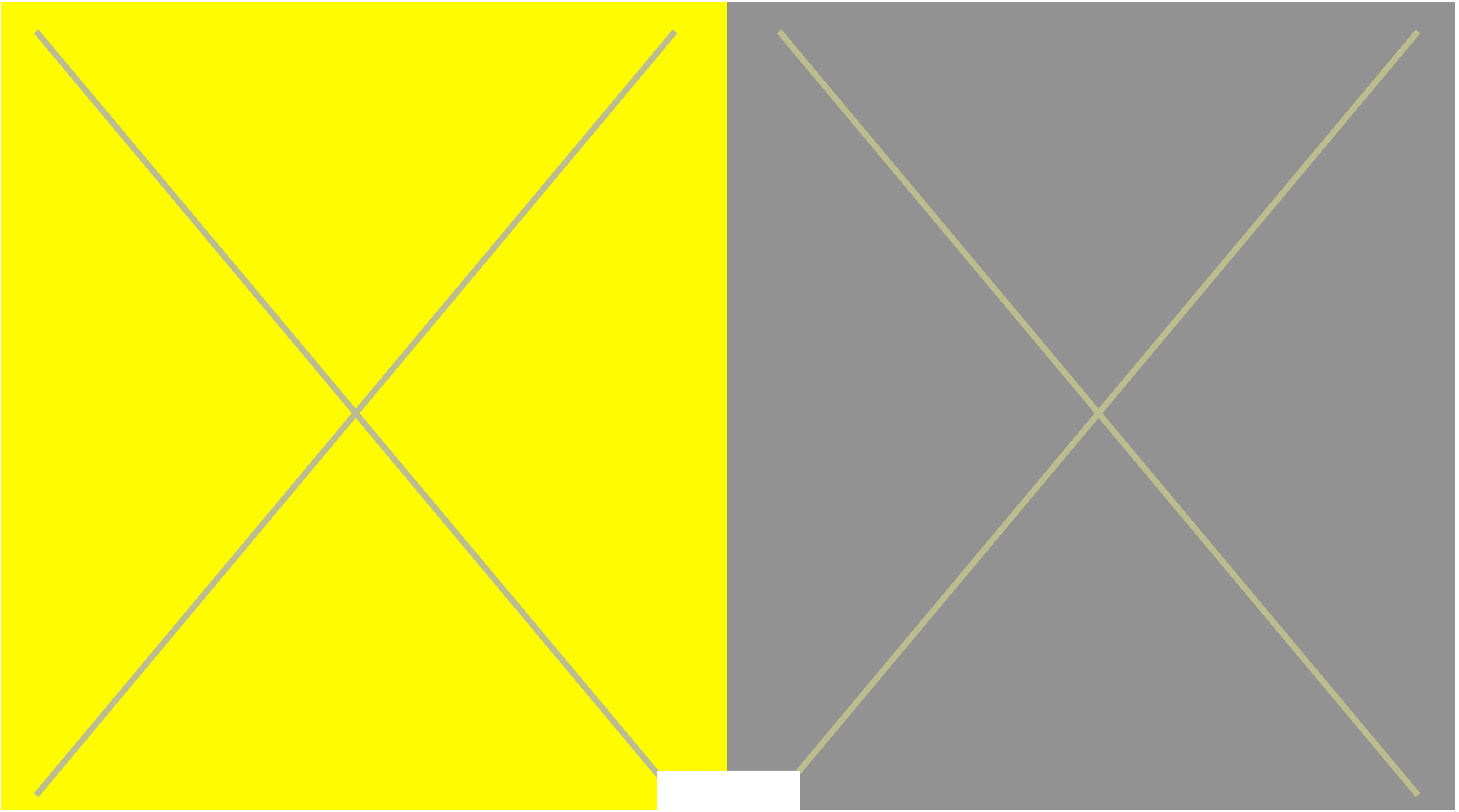
The inner and outer thin rings are,
in fact, the same physical purple!



Donald Macleod

Simultaneous Contrast

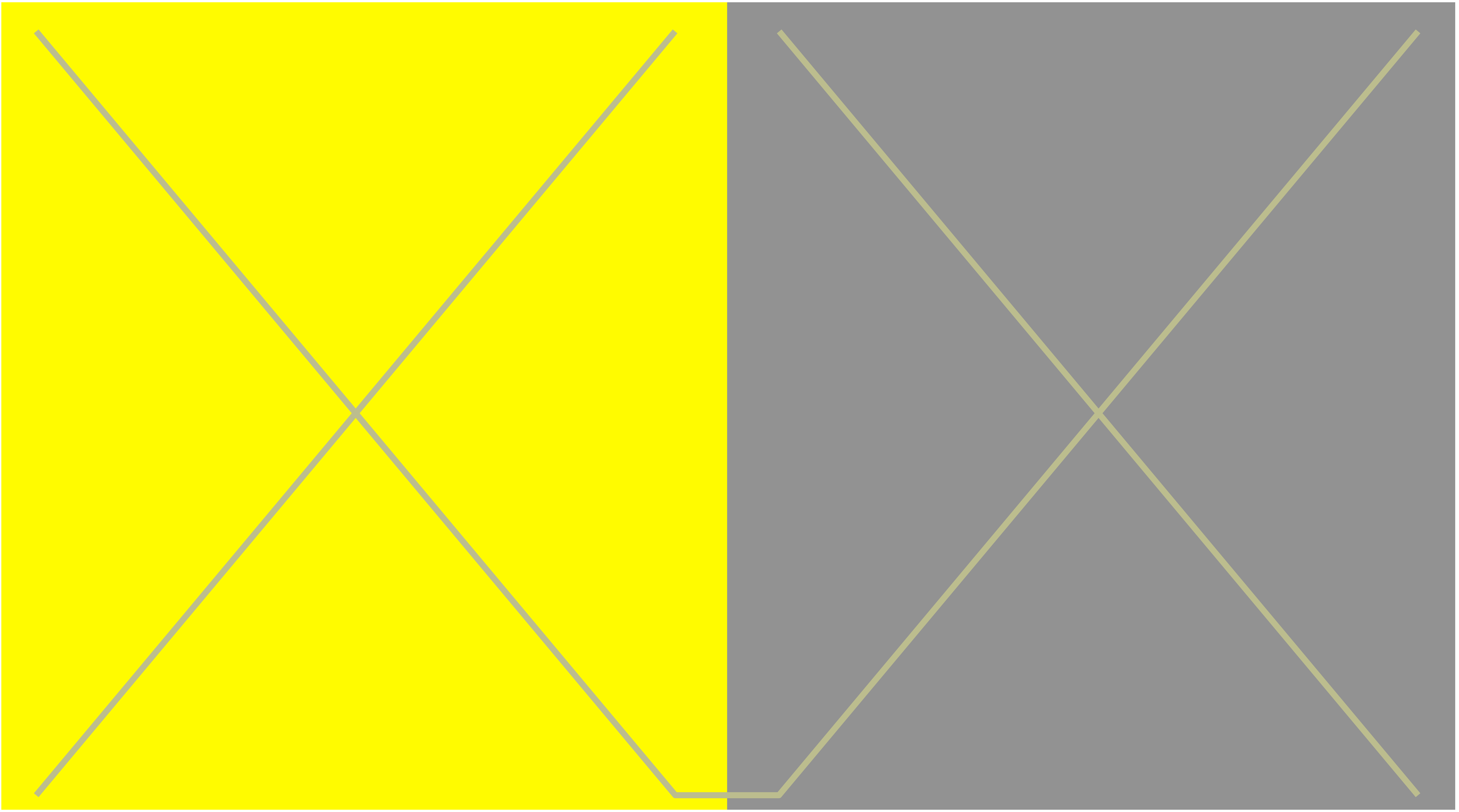
When two colors are side-by-side,
they interact and affect our perception



Josef Albers

Simultaneous Contrast

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



Josef Albers

Simultaneous Contrast

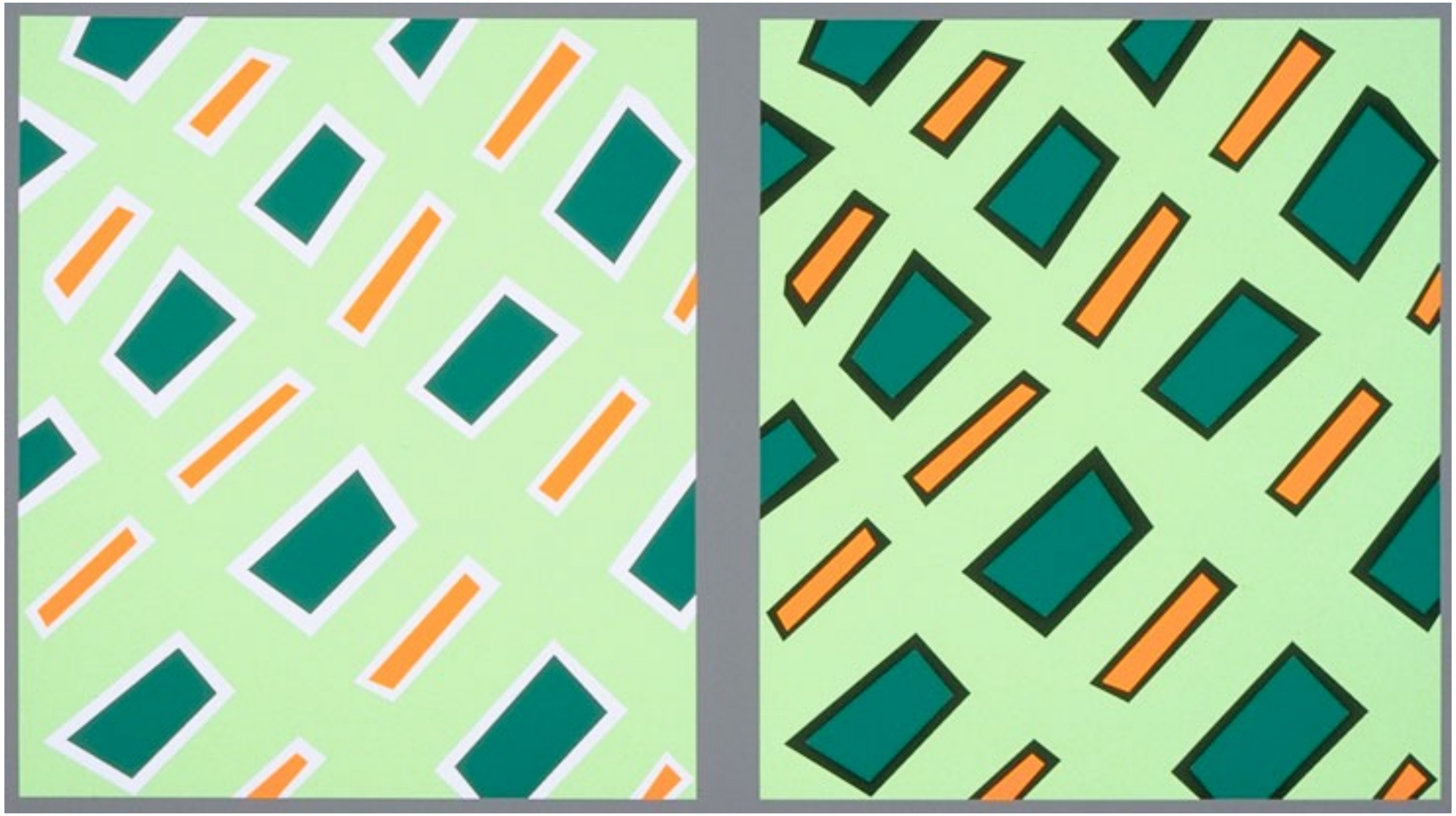
When two colors are side-by-side, they interact and affect our perception

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

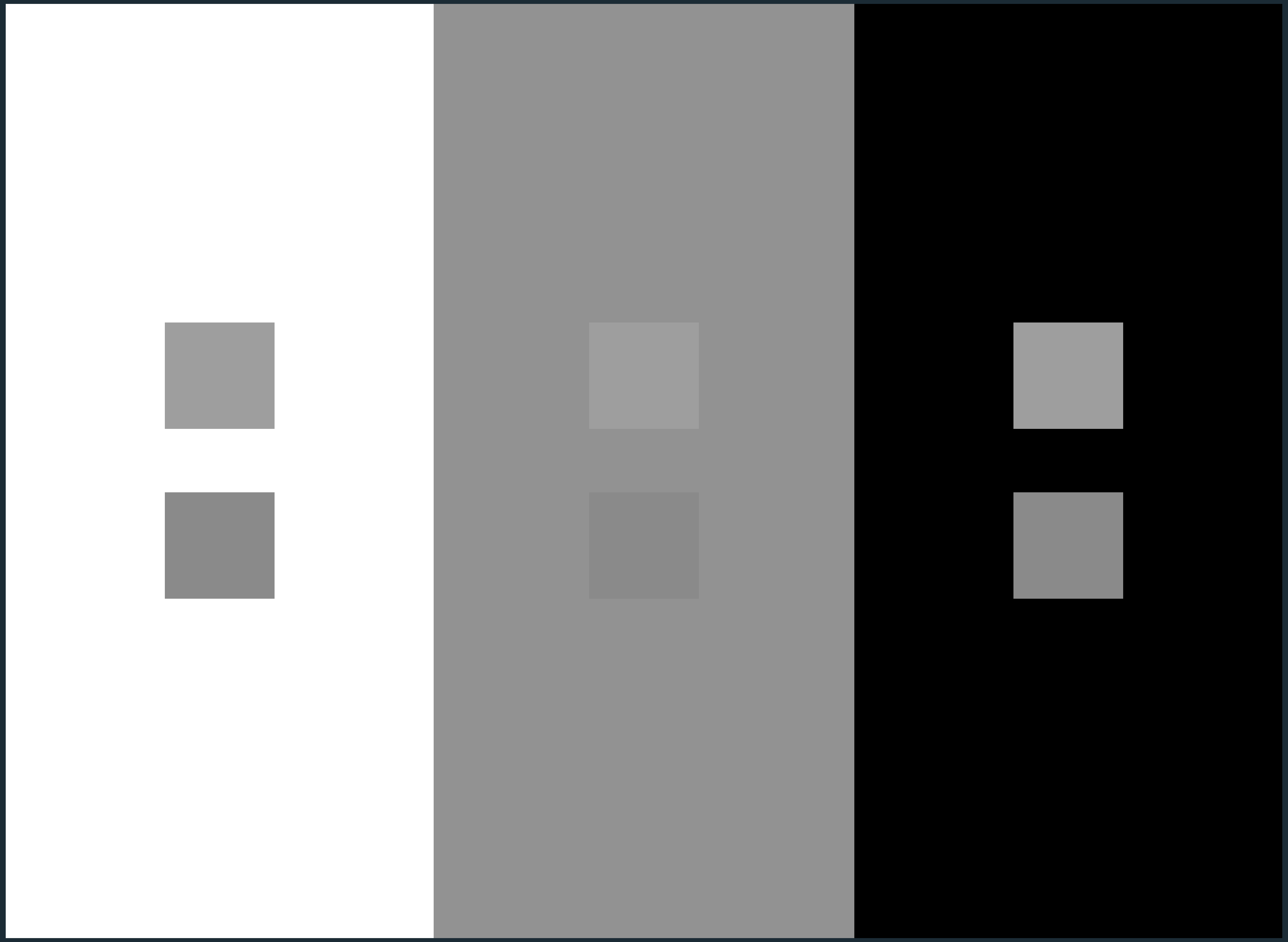
Our ability to adjust to color perception based on illumination

Chromatic Adaptation

Our ability to adjust to color perception based on illumination

Chromatic Adaptation

Perceived difference depends on background.



Quantitative Color Encoding

Sequential Color Scale

Ramp in luminance, possibly also hue.

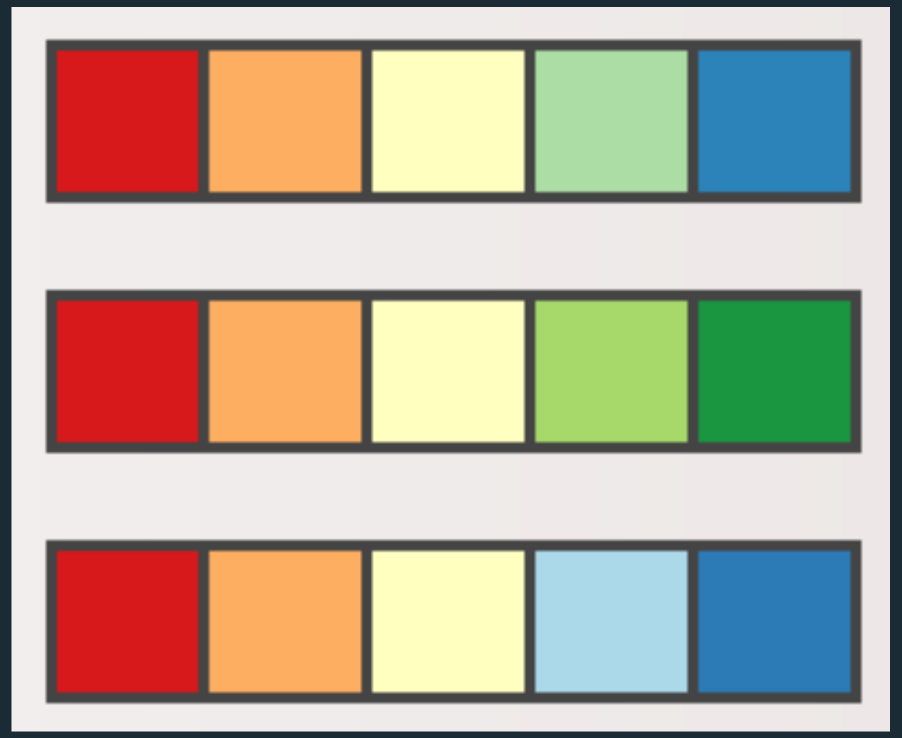
Typically higher values map to darker colors.

Diverging Color Scale

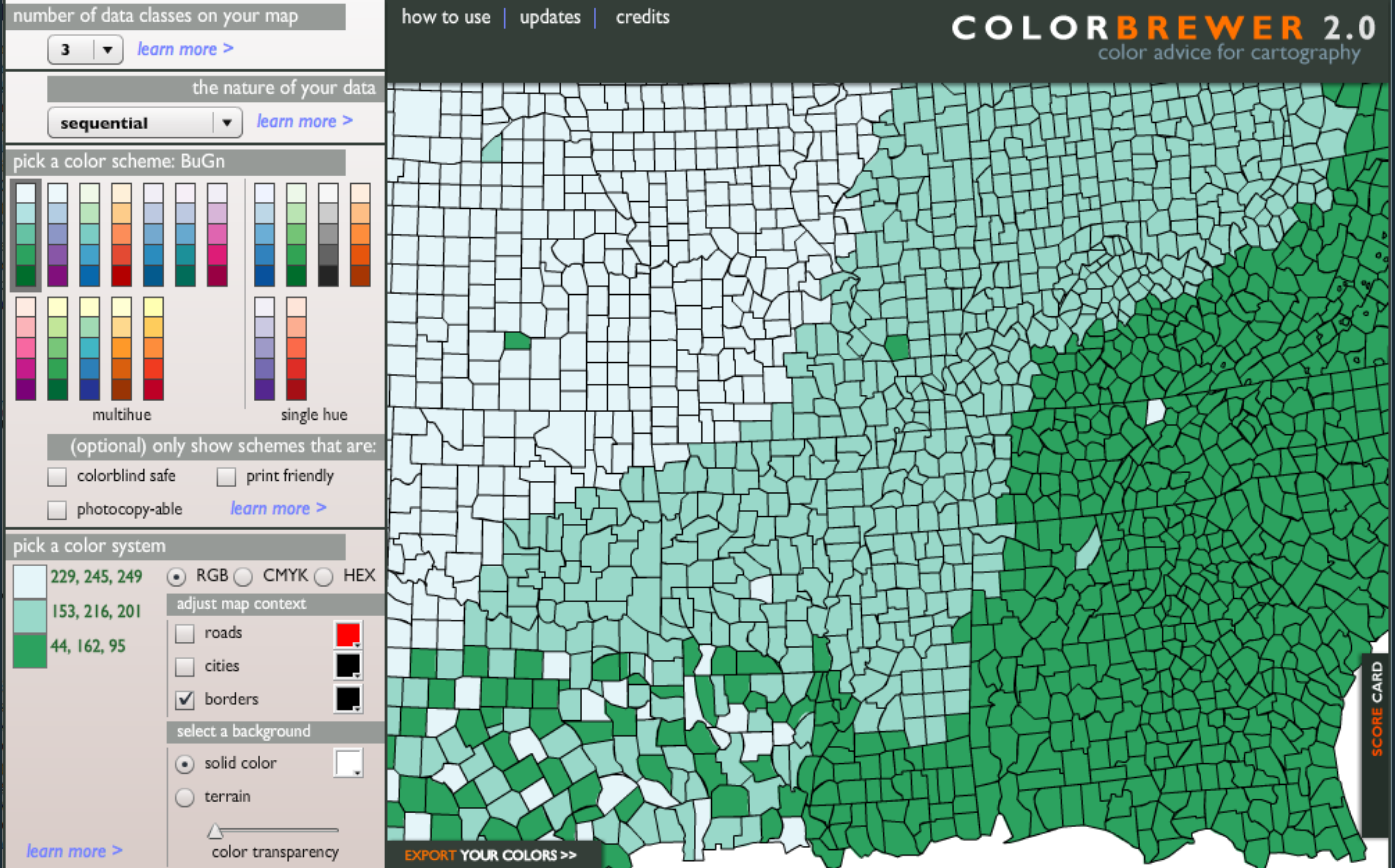
Useful when data has a meaningful "midpoint."

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

Use saturated colors for endpoints.



Limit number of steps in color to 3–9

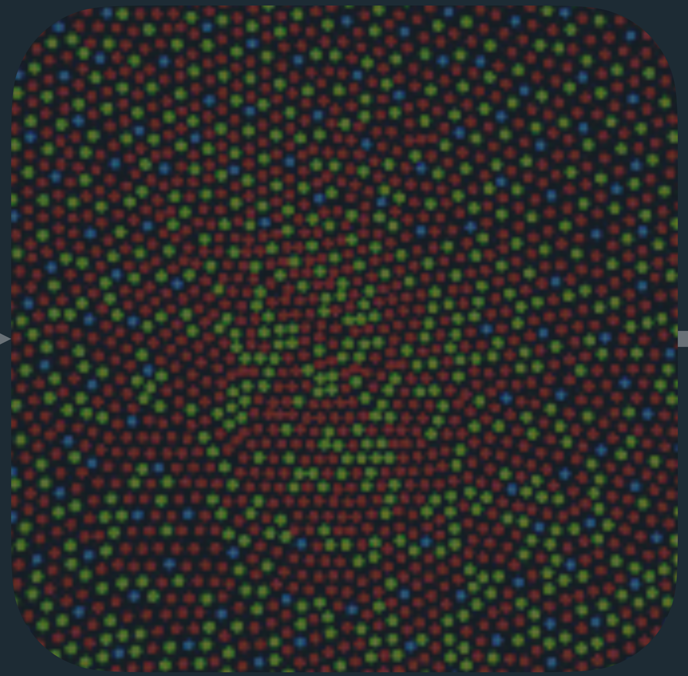

number of data classes on your map
3
learn more >
the nature of your data
sequential
learn more >
pick a color scheme: BuGn
multihue
single hue
(optional) only show schemes that are:
colorblind safe
print friendly
photocopy-able
learn more >
pick a color system
229, 245, 249
153, 216, 201
44, 162, 95
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
EXPORT YOUR COLORS >>
SCORE CARD

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"

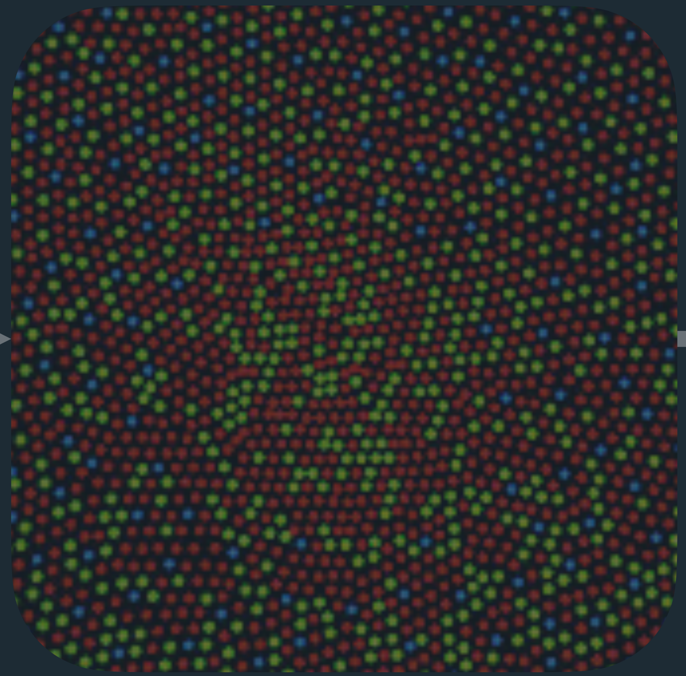
Cognitive Models

Modeling Color Perception

Low-Level | Abstraction | High-Level

Physical World | Visual System | Mental Models

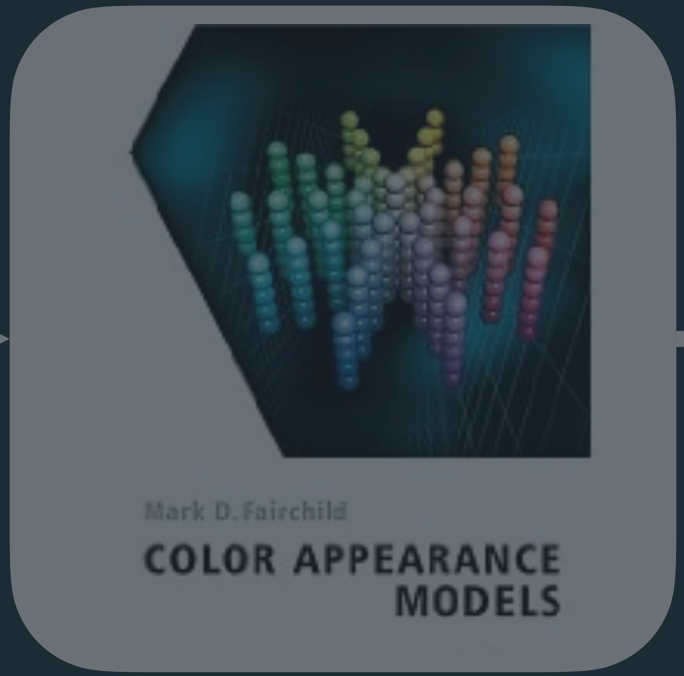
Visible Light



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.

Color Naming

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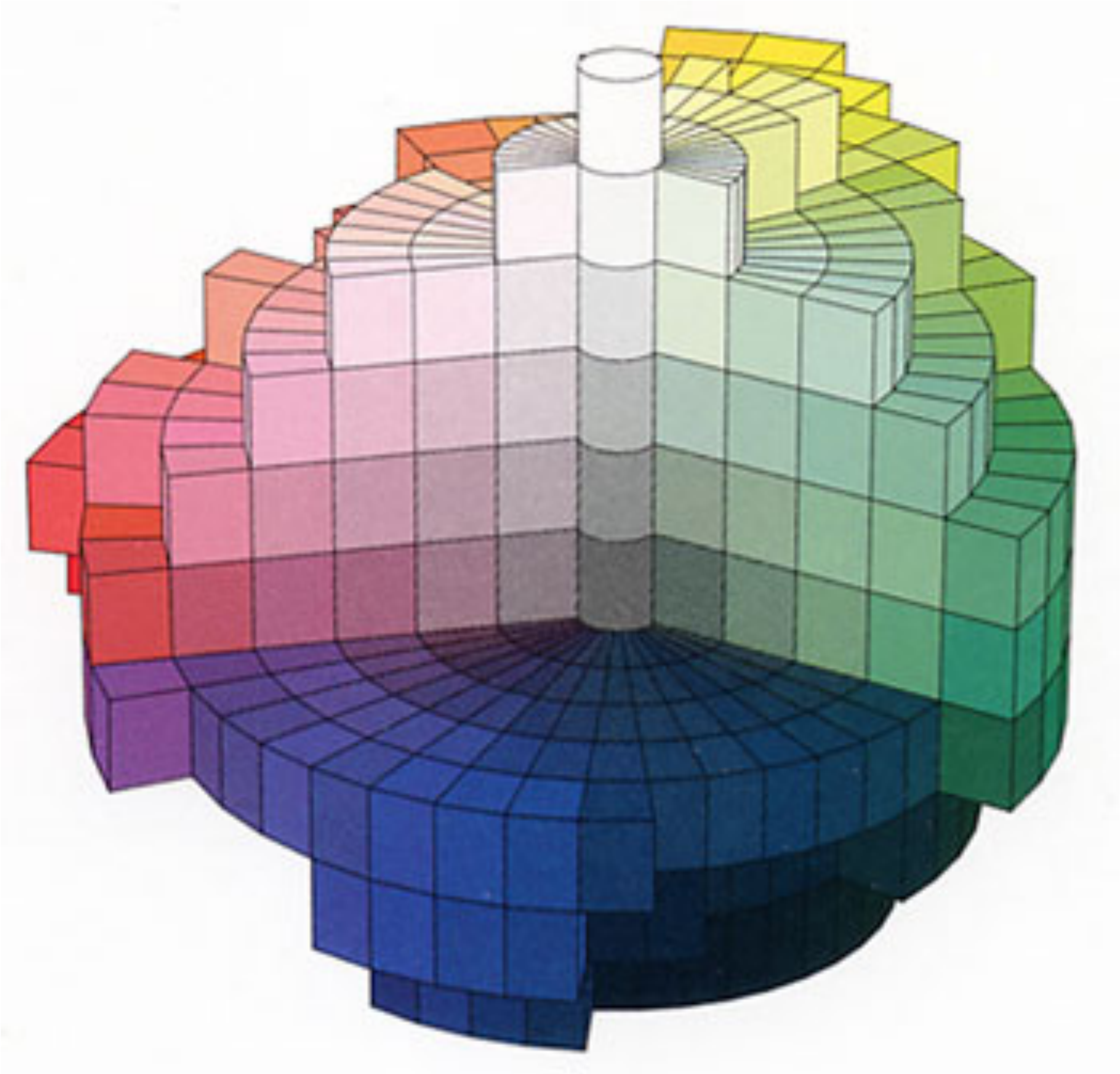

Name 320 Munsell color chips.
(Shares perceptual properties with CIE LAB, but predates it.)

Color Naming

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

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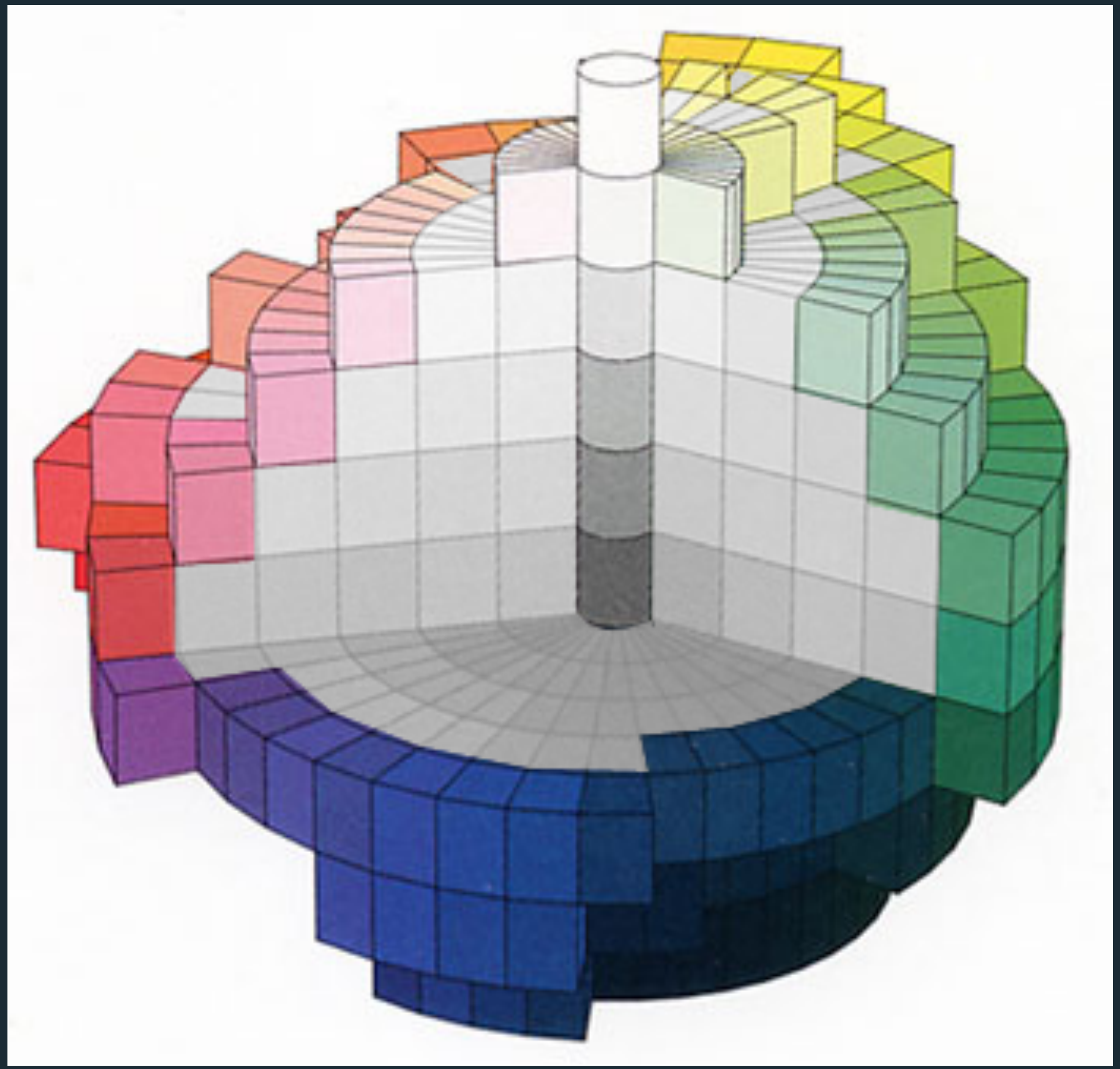


+10 achromatic chips

Color Naming

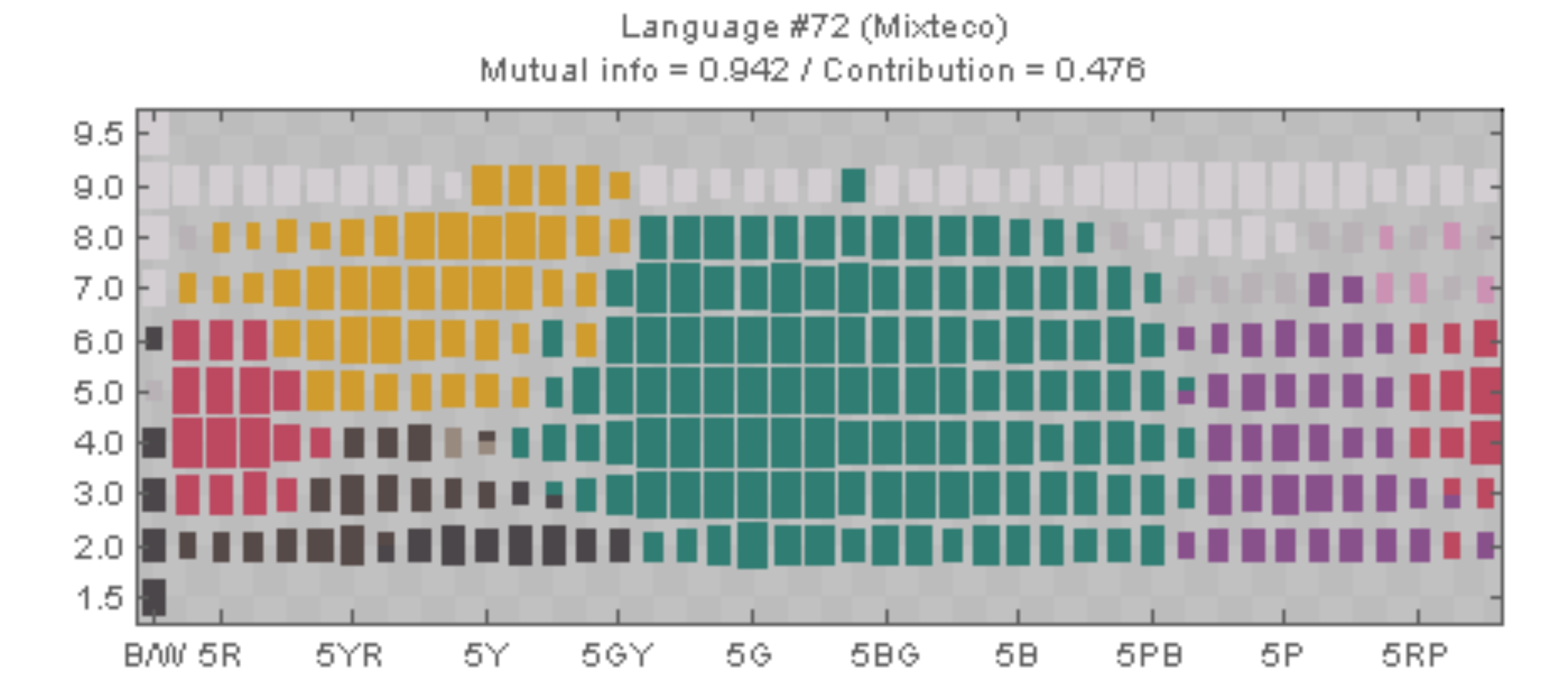
Is color naming universal? Do languages evolve color terms in similar ways?

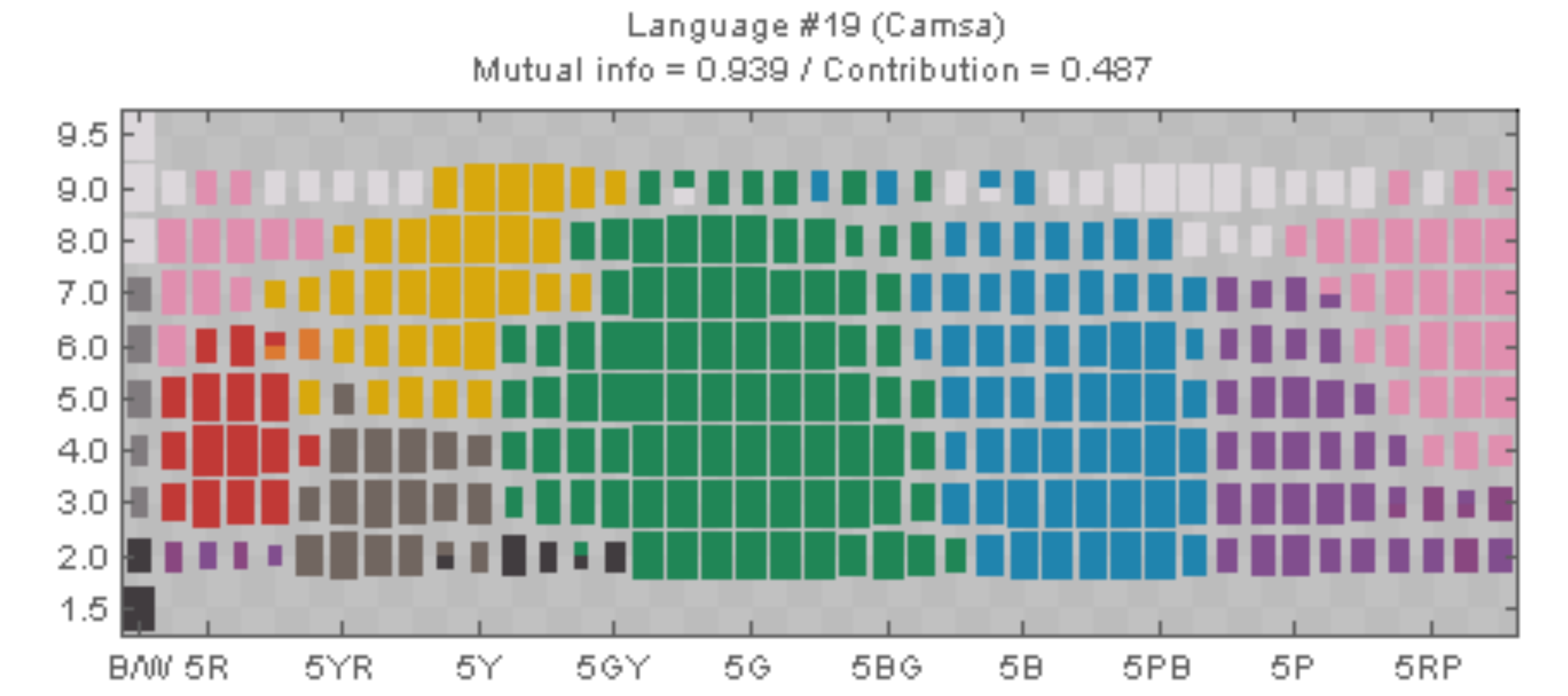
WCS stimulus array. For each basic color term (t) participants named, they were asked:

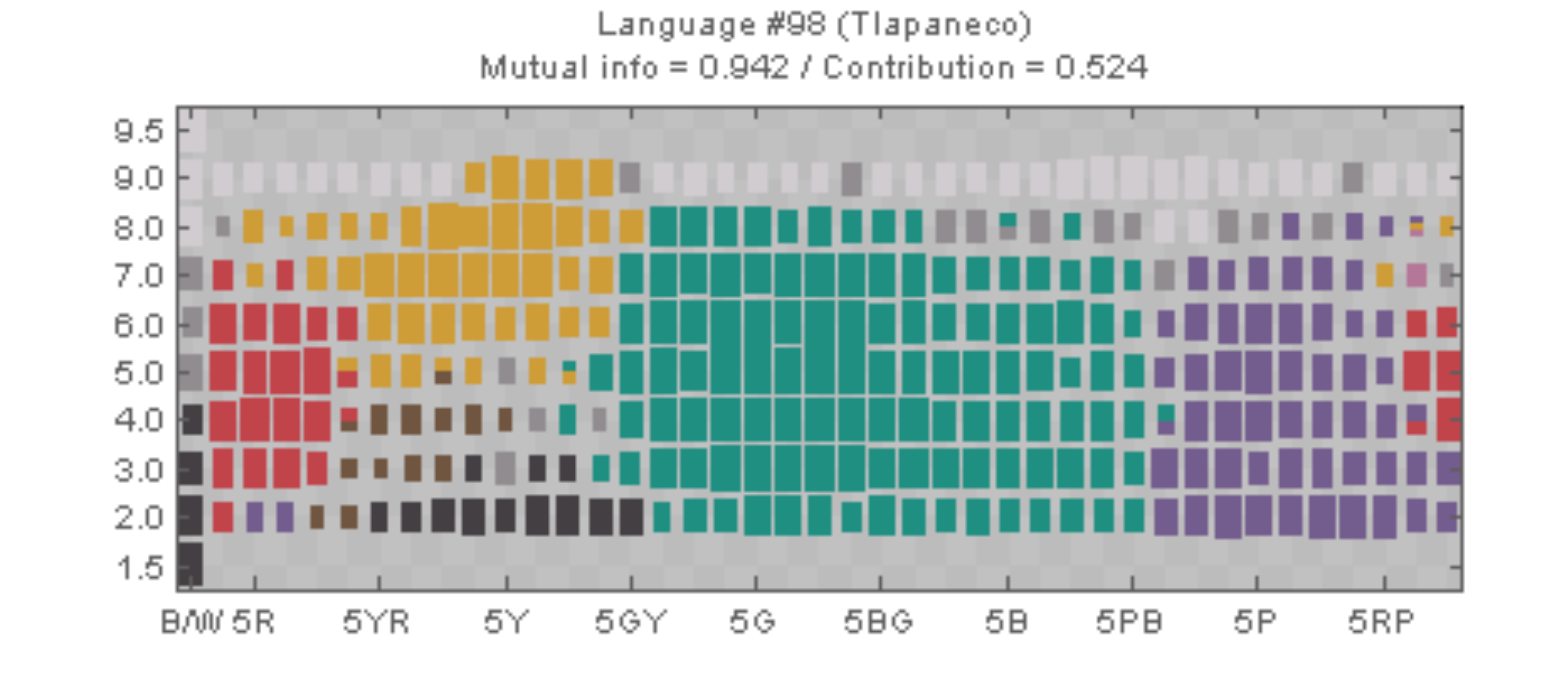
1. Mark all chips that you would call t.
2. Which chip is the best example(s) of t.

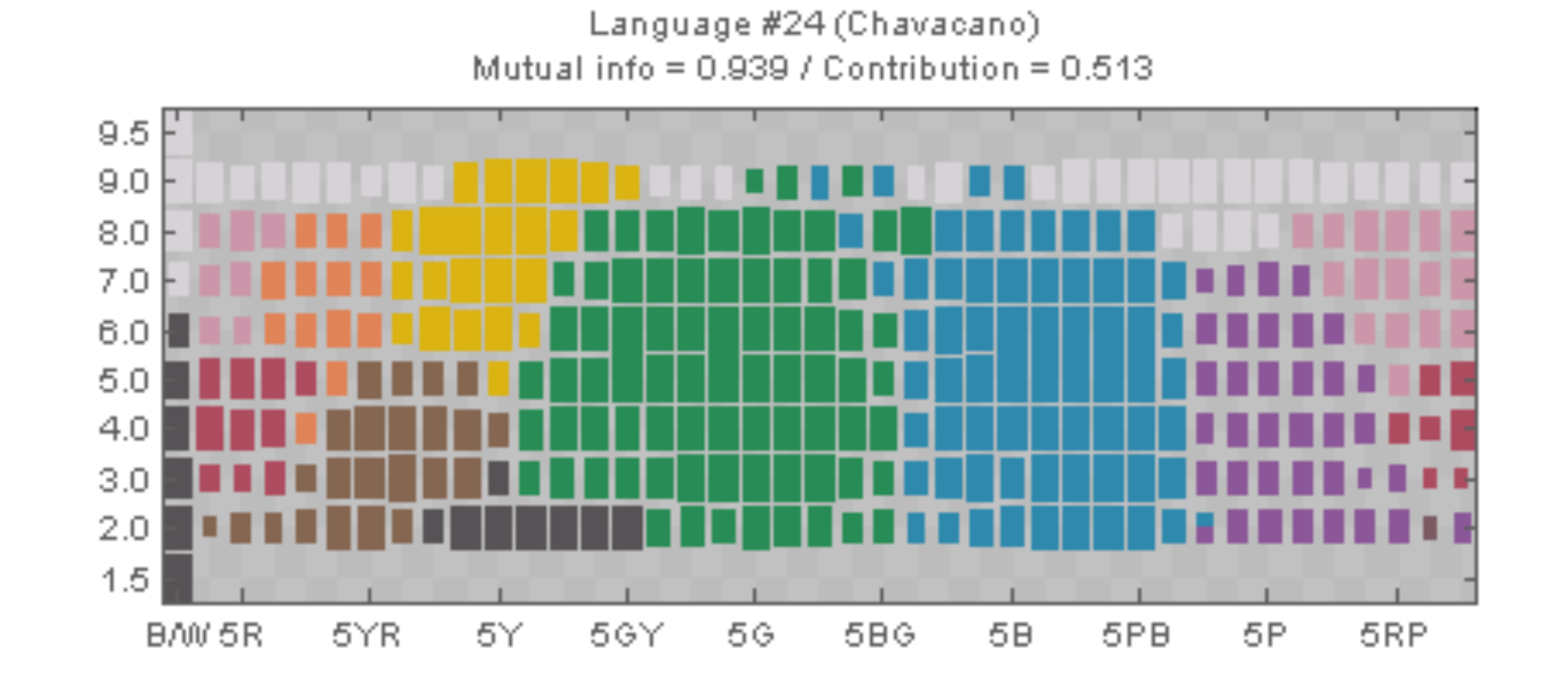
Color Naming

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:

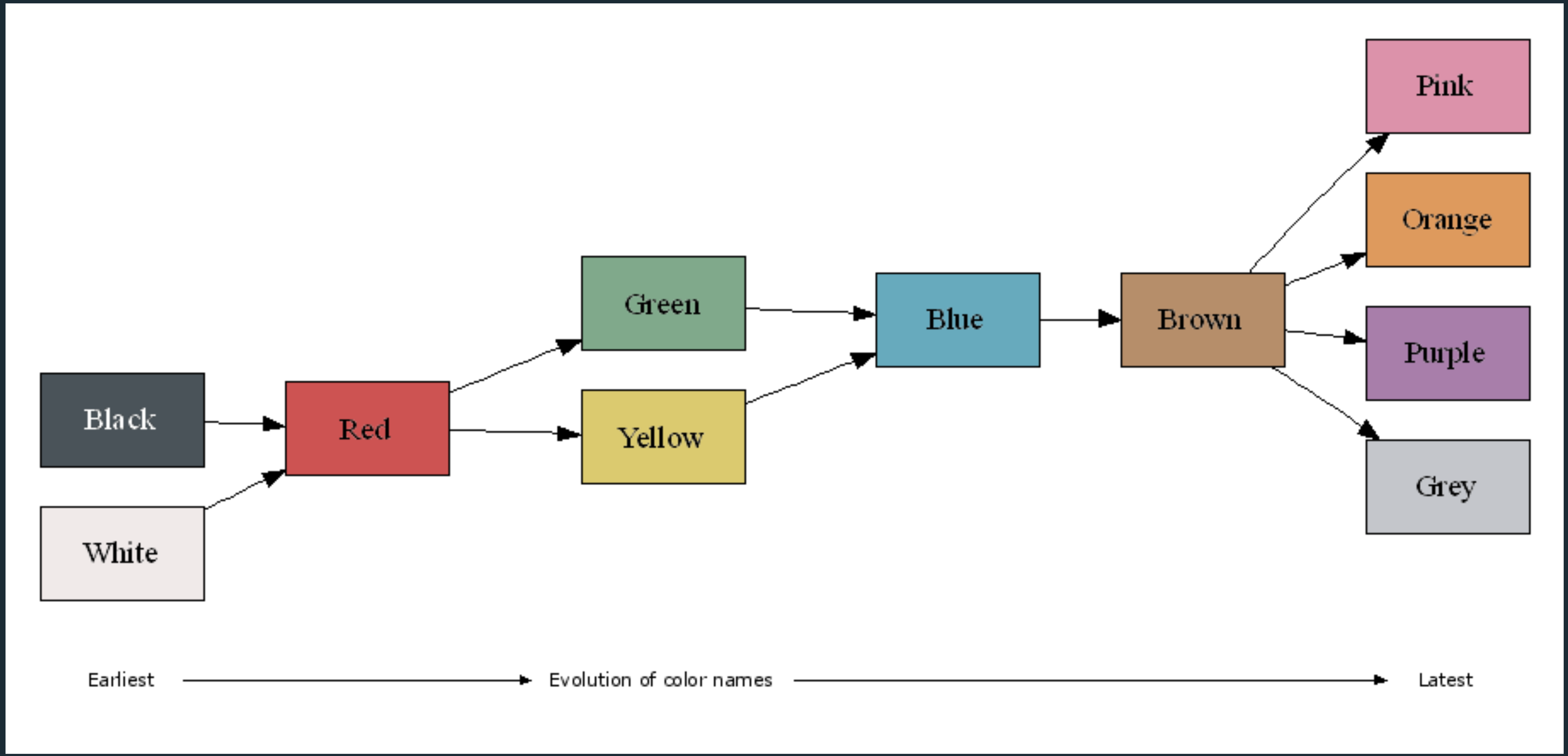
White Black Grey

Red Yellow

Green Blue

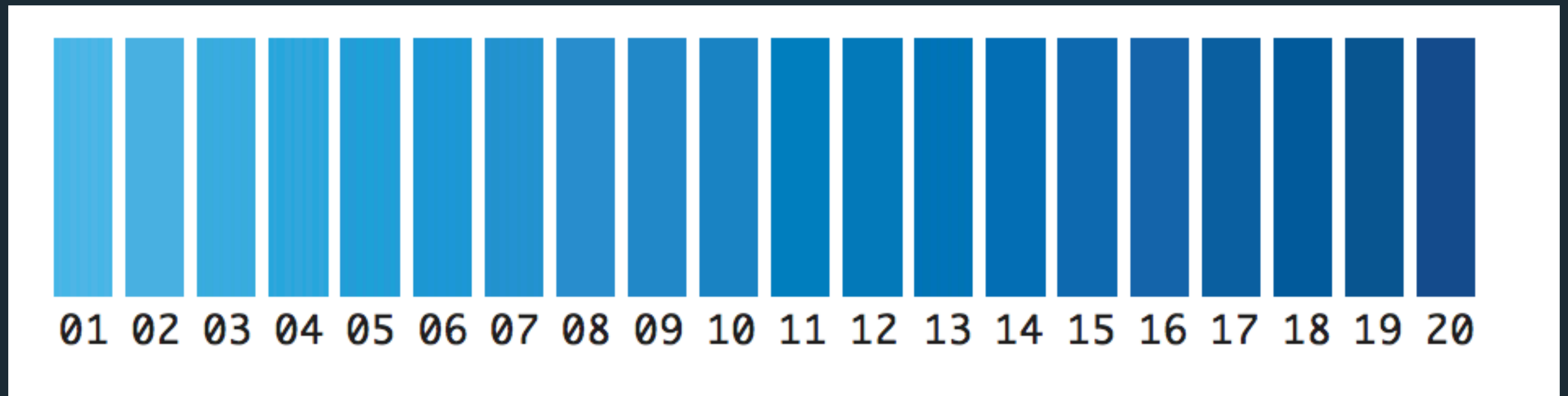
Pink Brown

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?

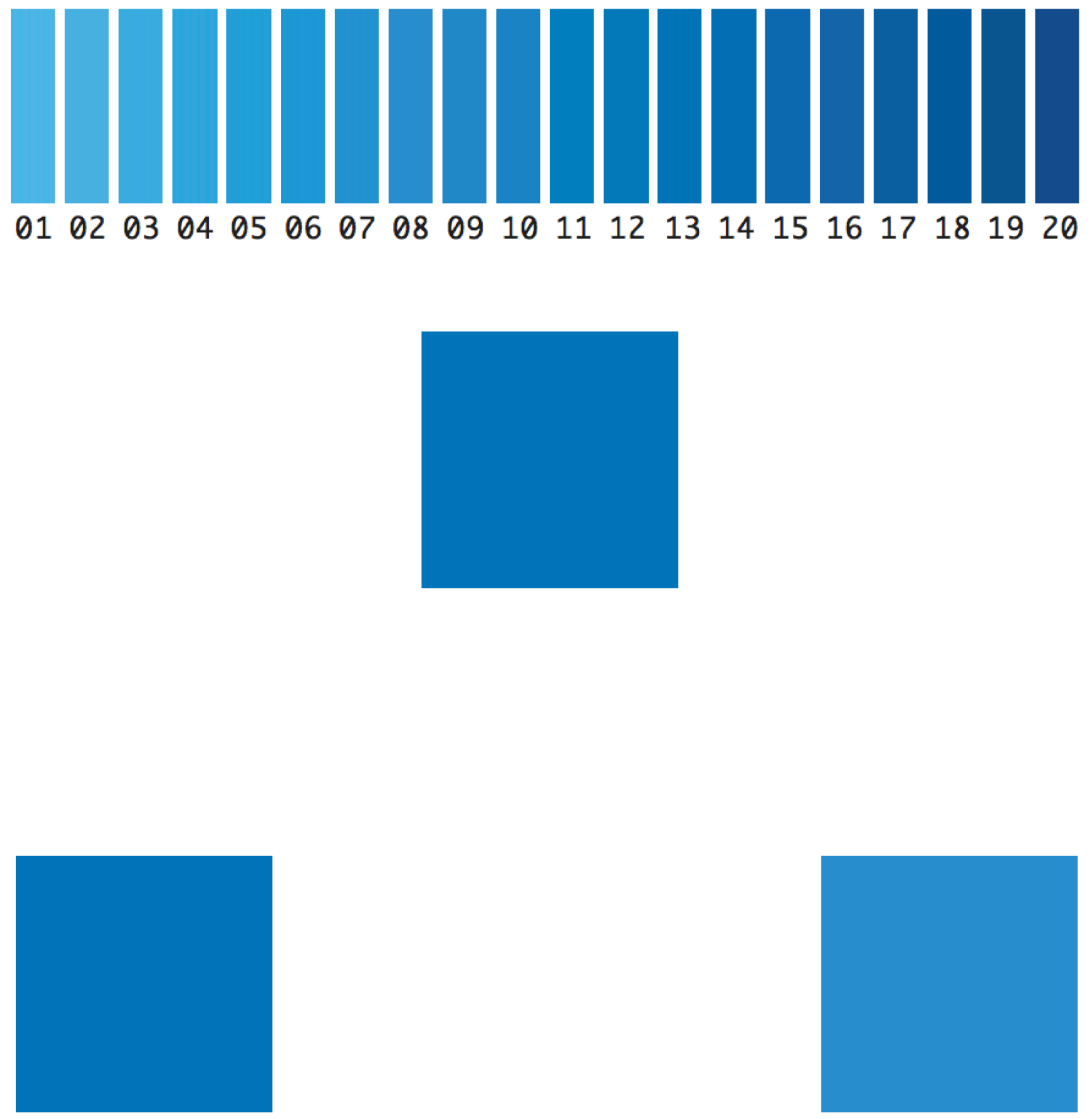


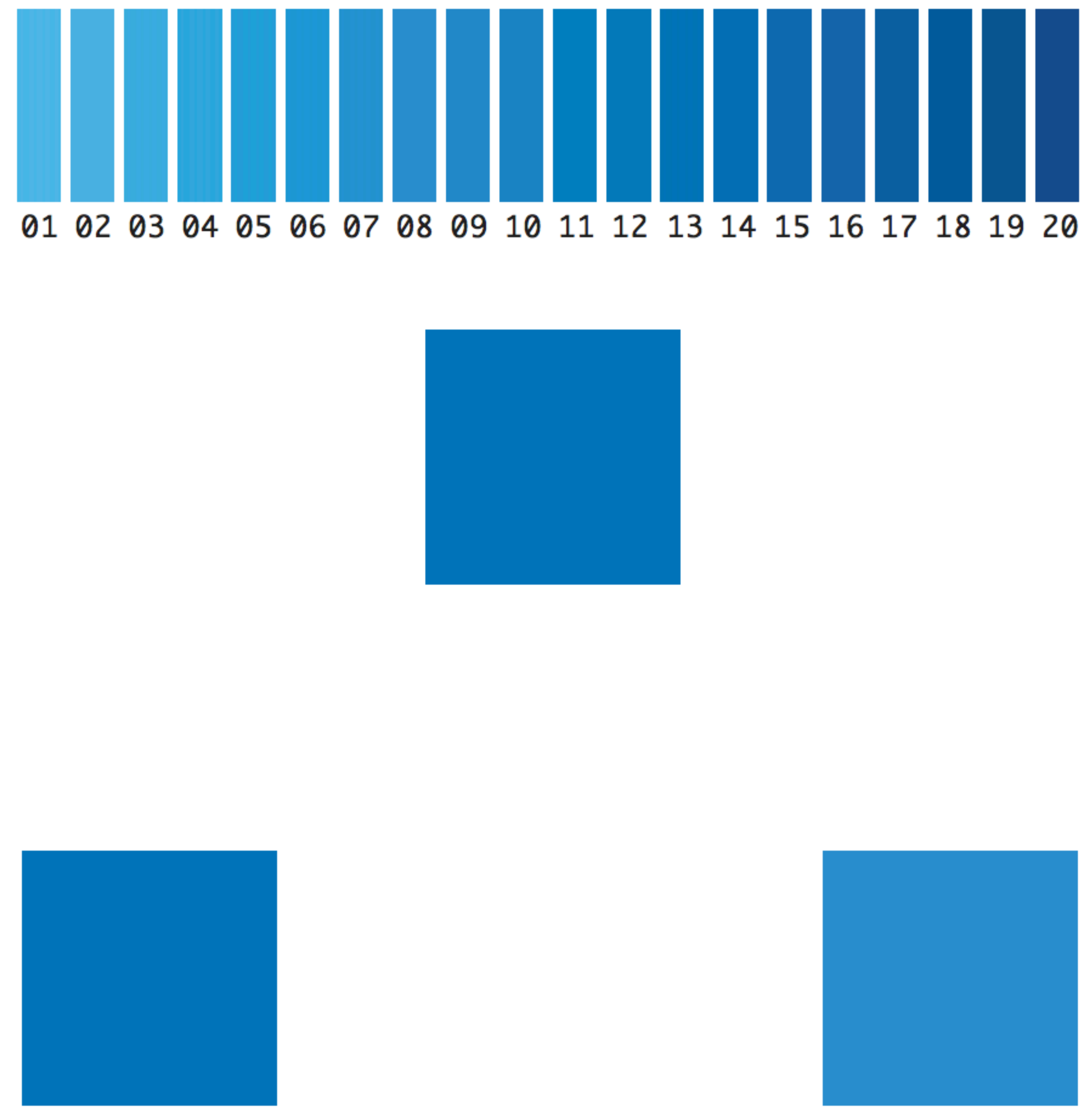
Fig. 1. The 20 blue colors used in this study are shown at the top of the figure. An example triad of color squares used in this study is shown at the bottom of the figure. Subjects were instructed to pick which one of the two bottom squares matched the color of the top square.

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).



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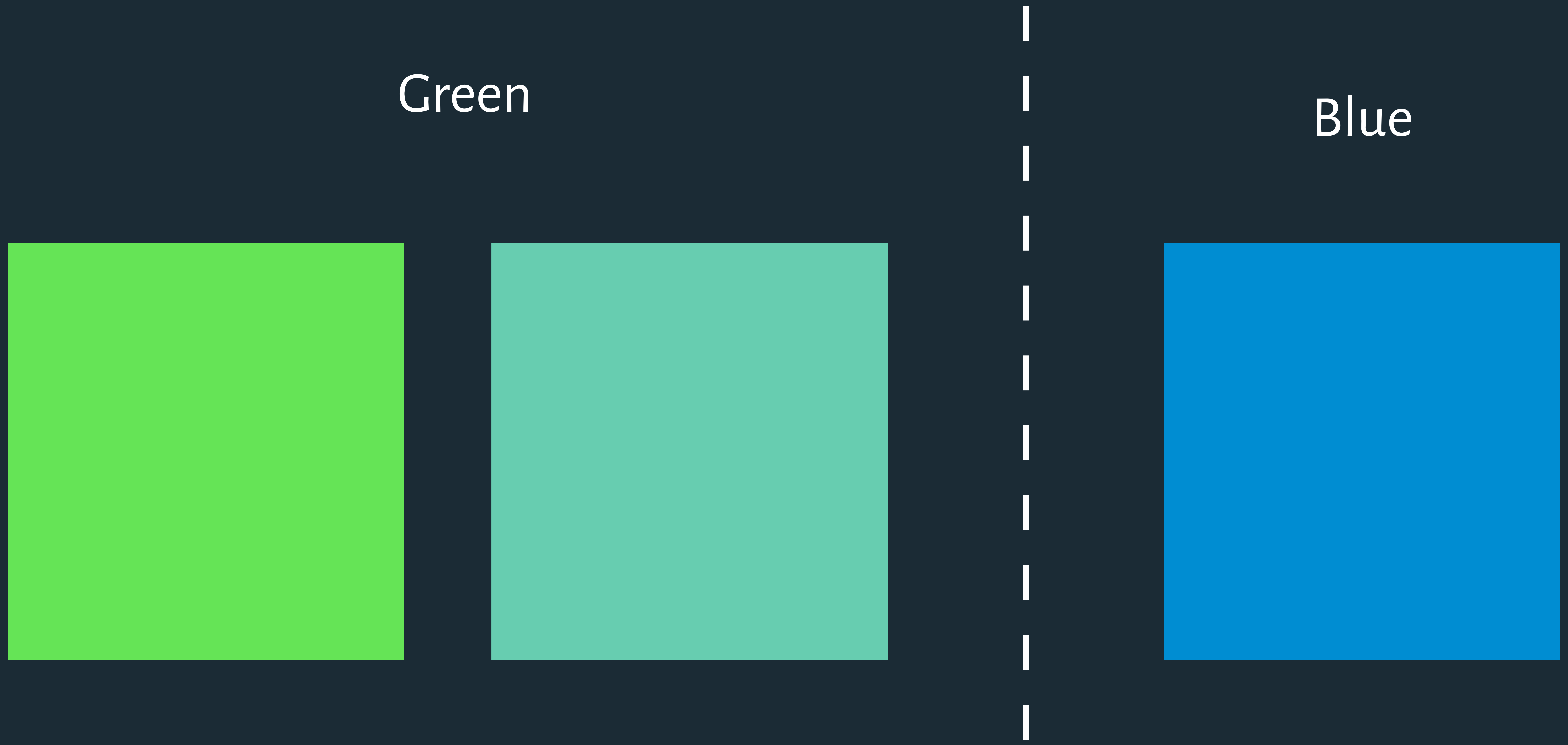
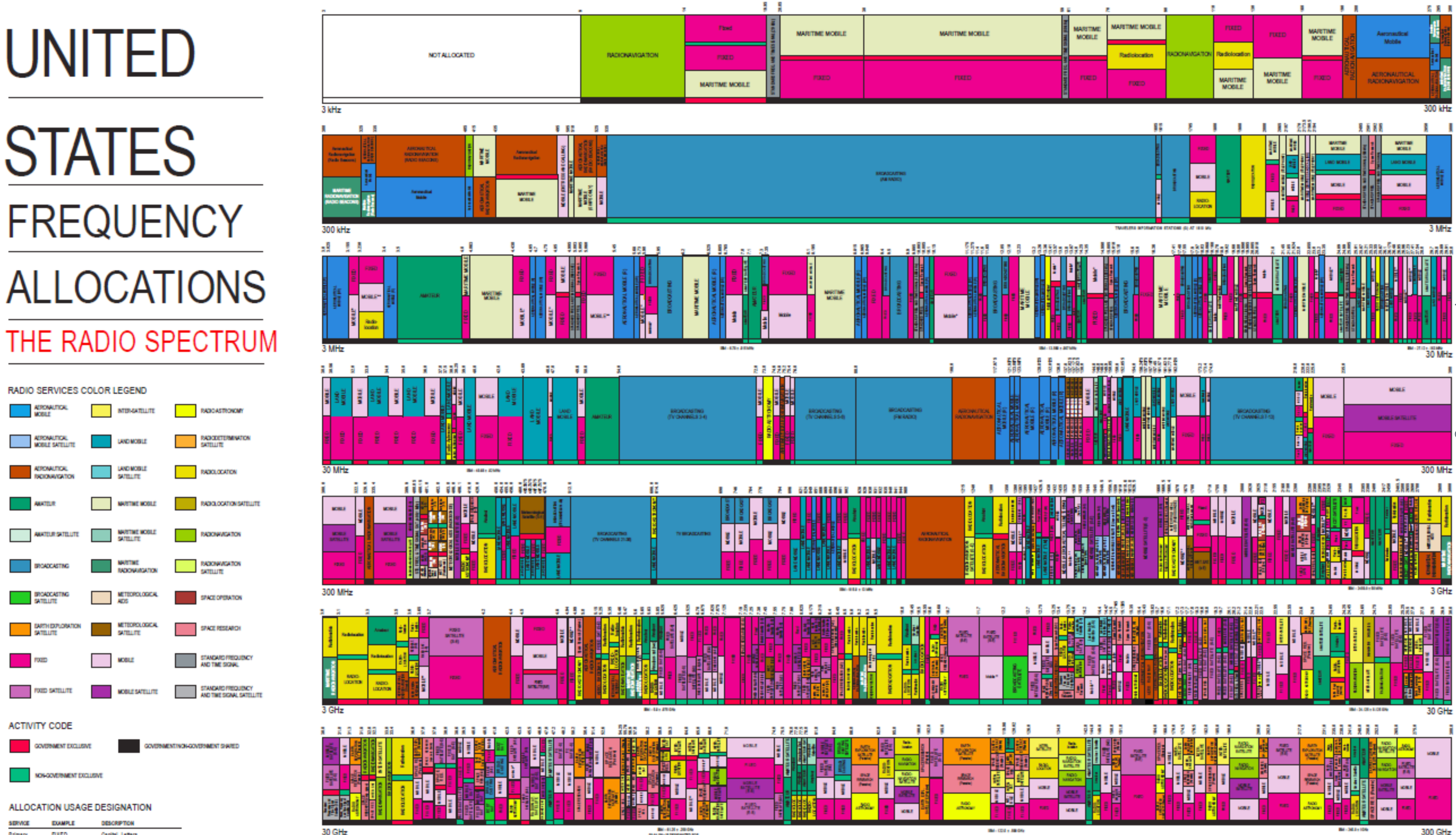
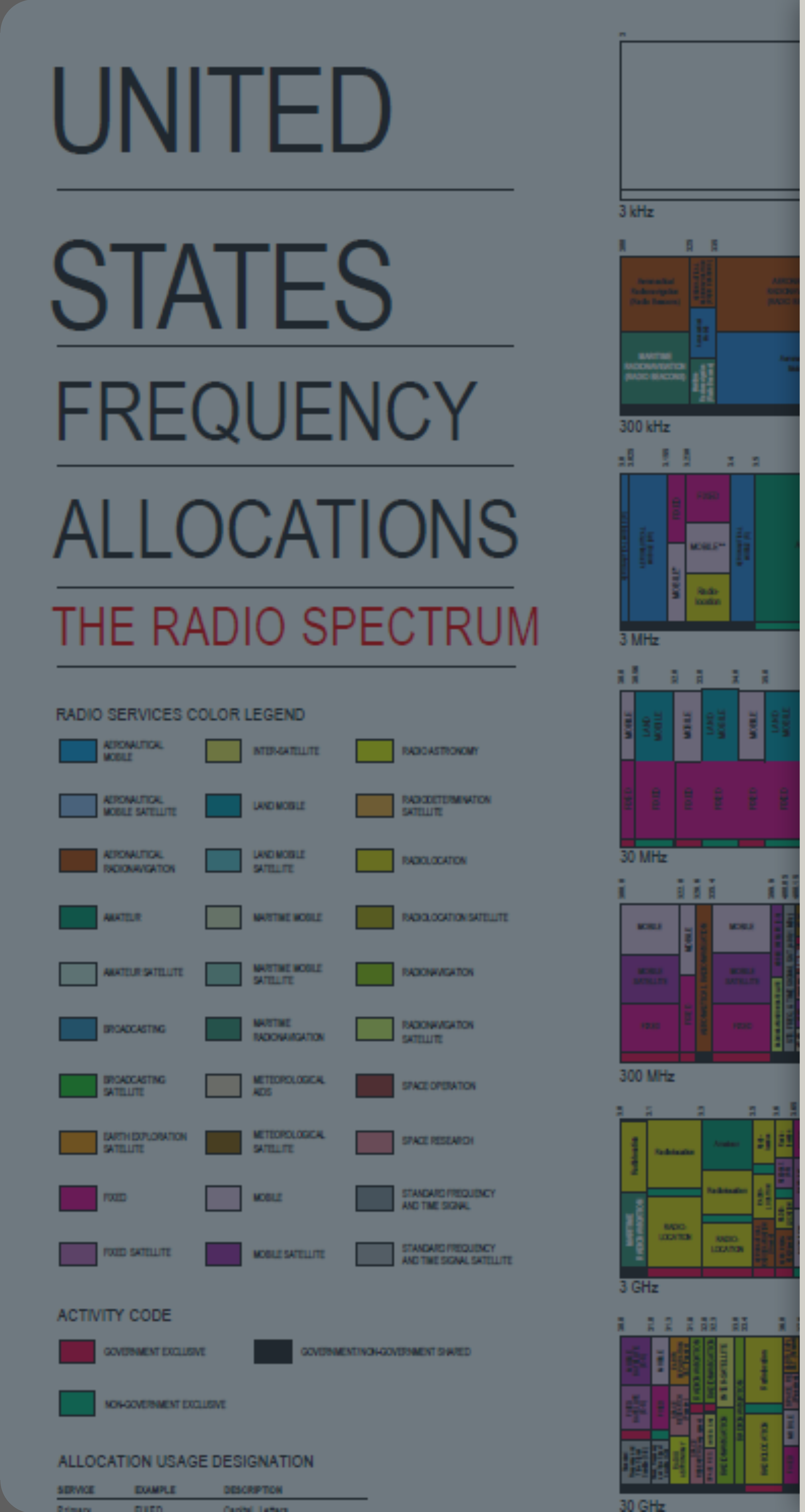
Color Naming Effects Perception





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

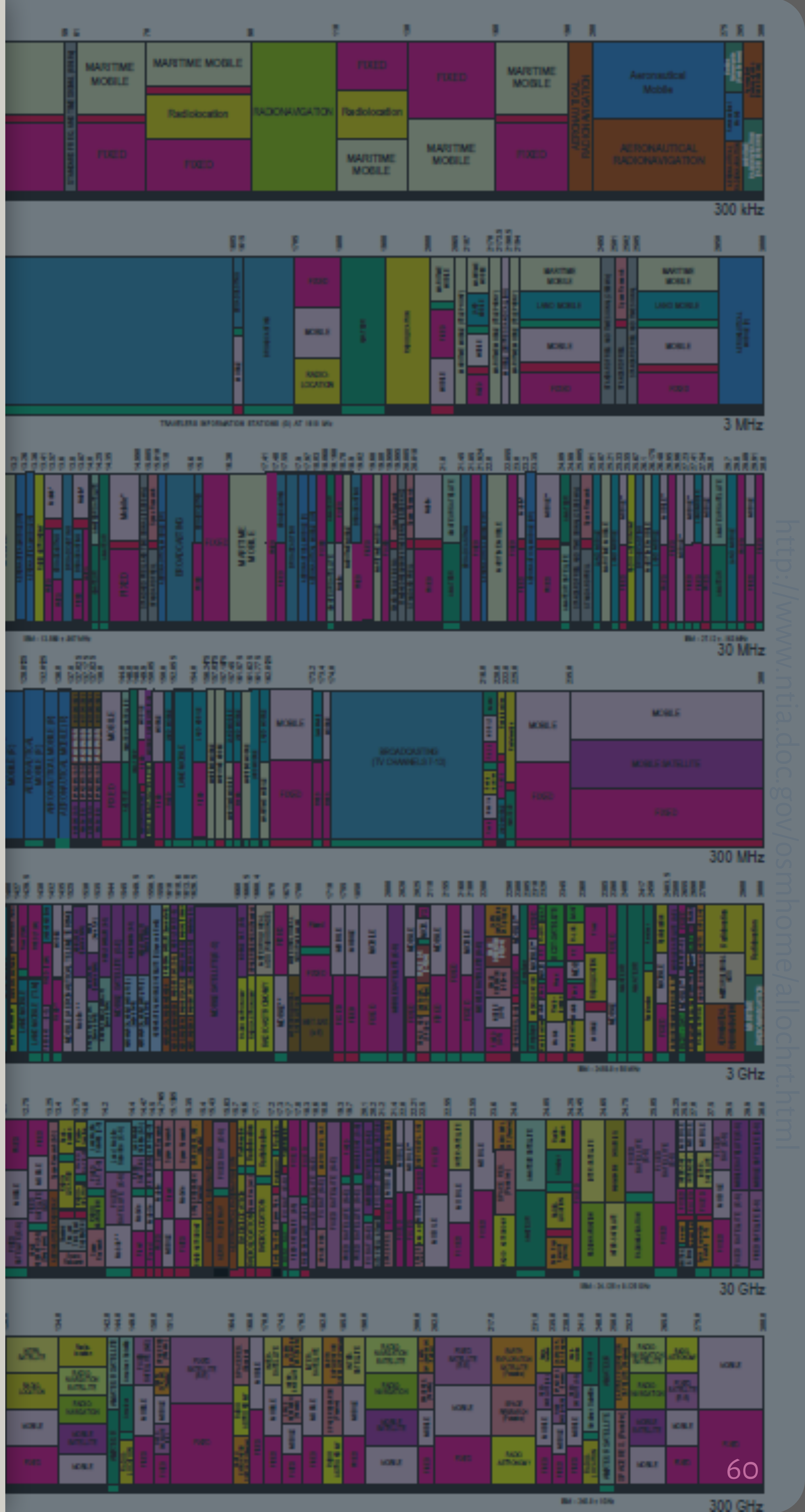


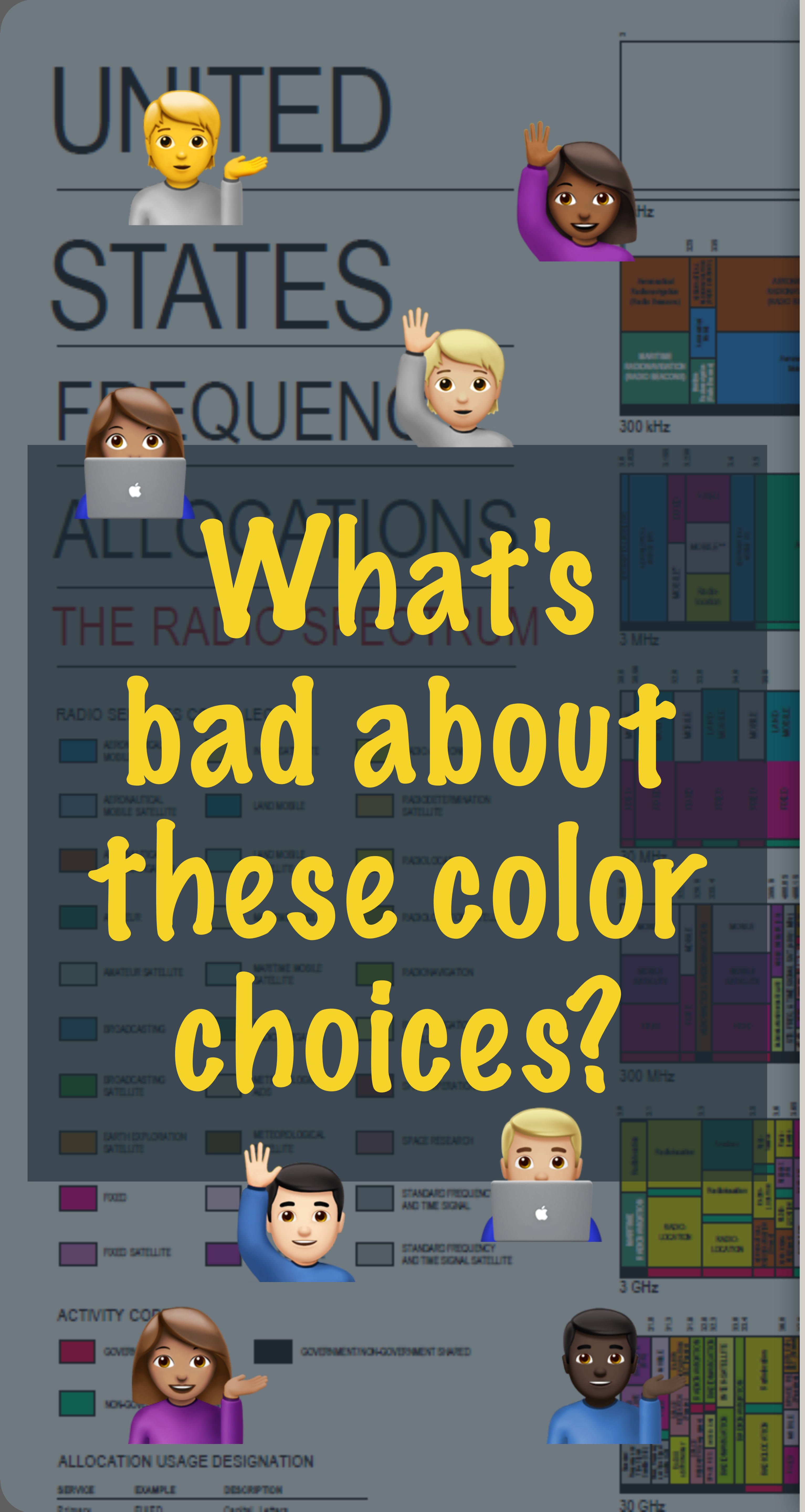
RADIO SERVICES COLOR LEGEND

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

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE





What's bad about these color choices?

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

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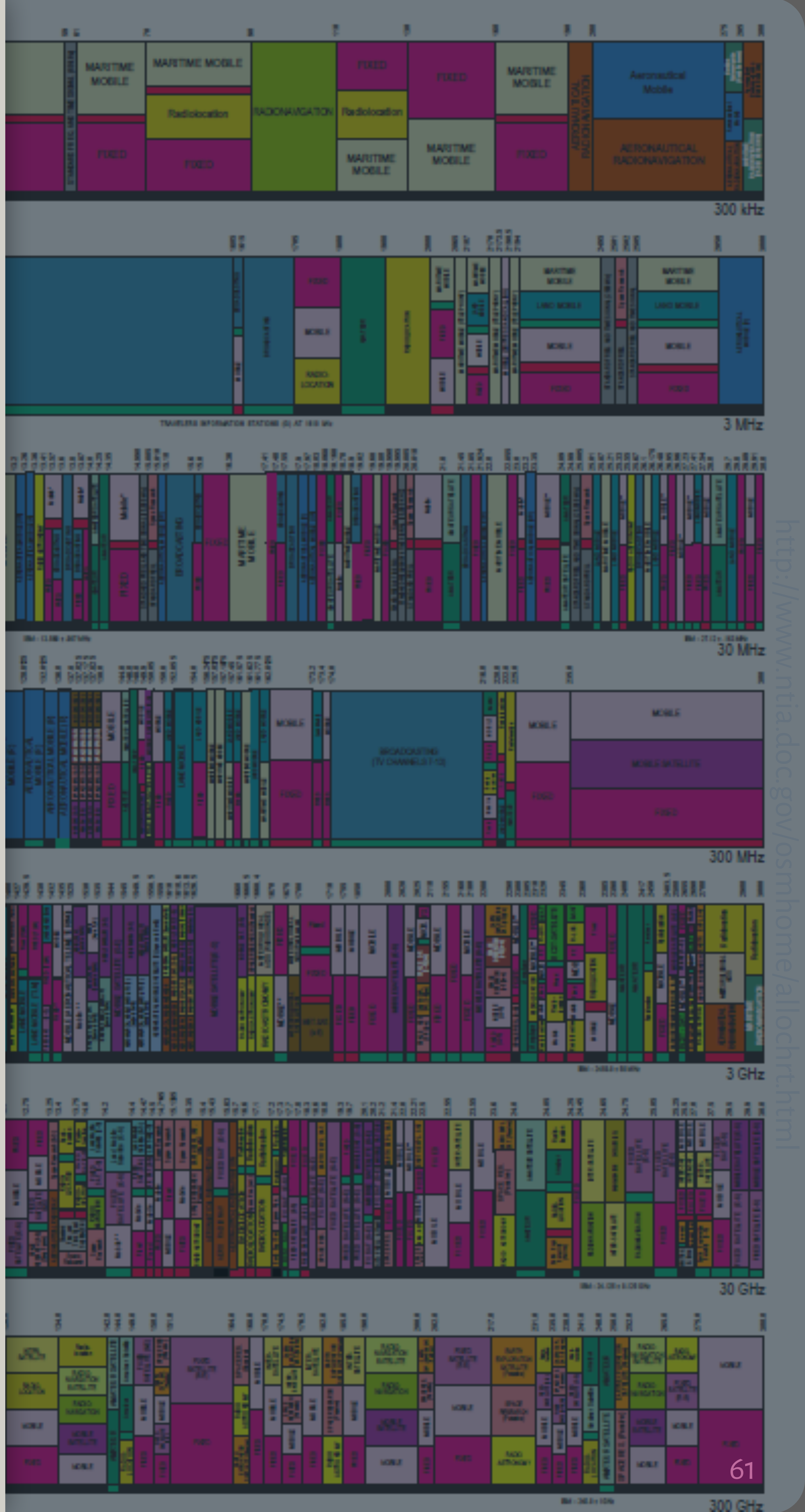

Color Naming Effects Perception

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]

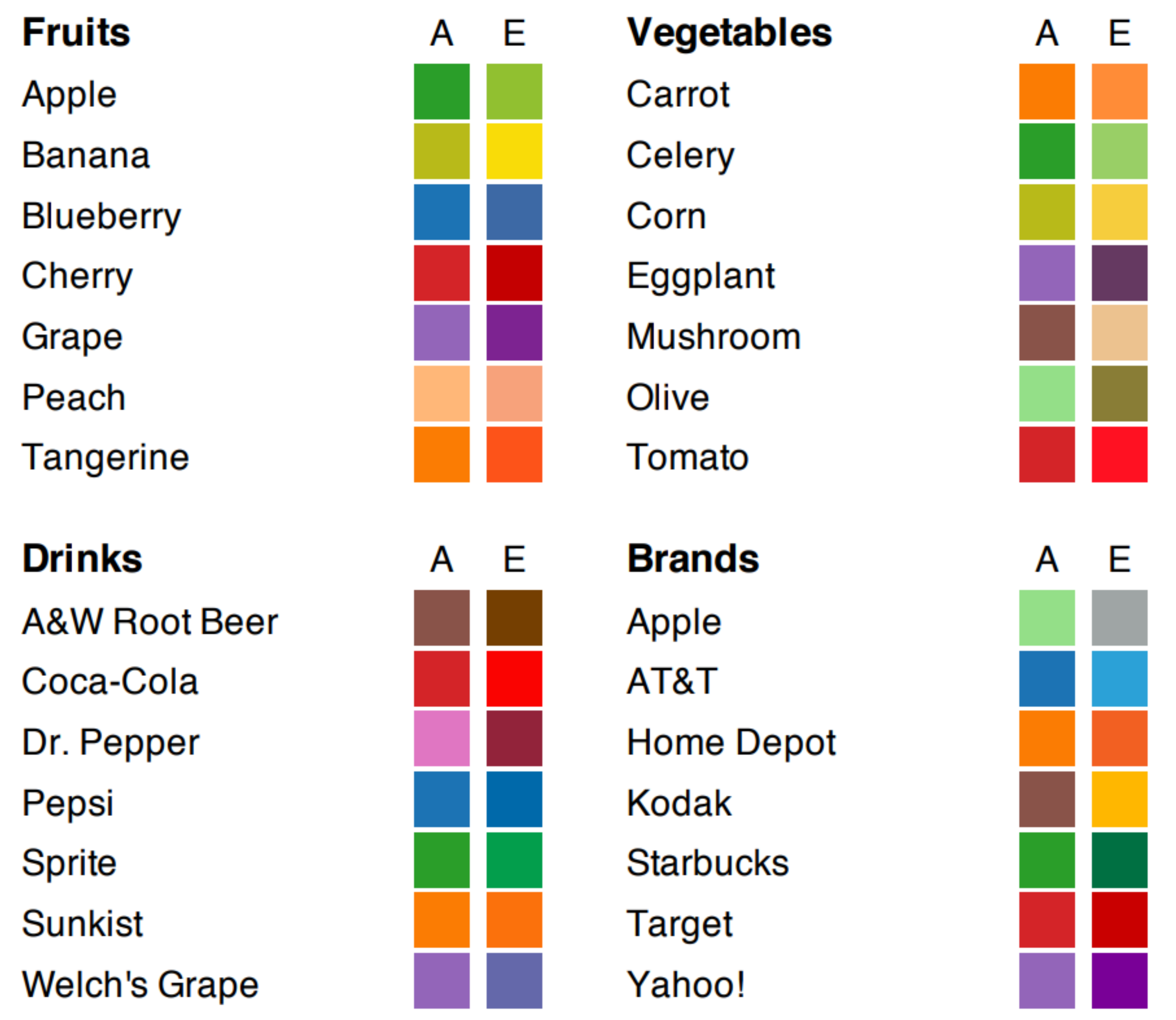

Figure 6: *Color assignments for categorical values in Experiment 1. (A = Algorithm, E = Expert)*

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

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**.