Color

DSC 106: Data Visualization

Sam Lau

UC San Diego

Slides adapted with permission from Arvind Satyanarayan

Announcements

Lab 3 due today

Project 2 checkpoint due on Tuesday

FAQs:

1. When will Project 1 be graded? Aiming for Tuesday!

Modeling Color Perception

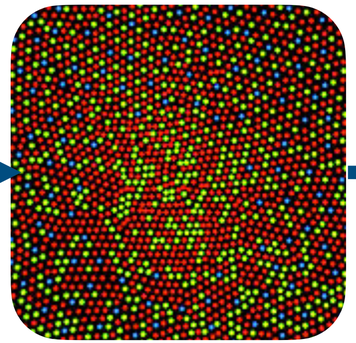
Low-Level

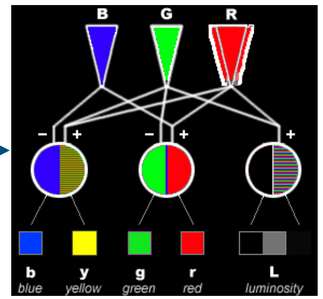
High-Level

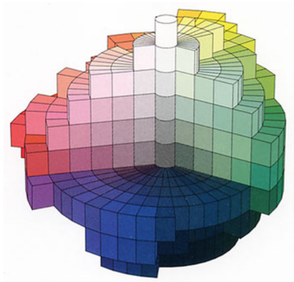
Physical World

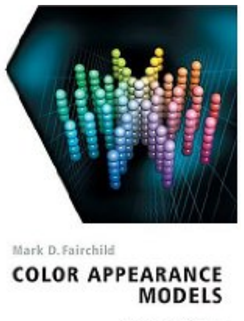
Visual System

Mental Models









“Teal”

Visible Light

Cone Response

Opponent Encoding

Perceptual Models

Appearance Models

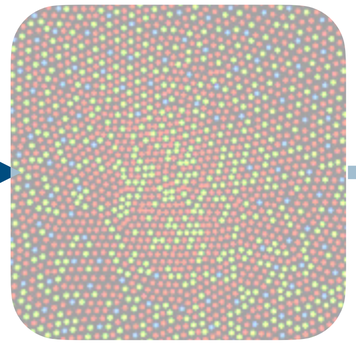
Cognitive Models

Modeling Color Perception

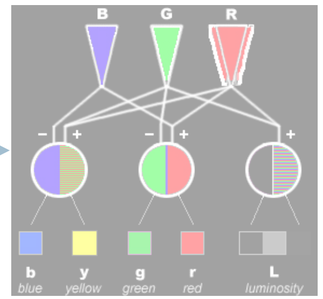
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

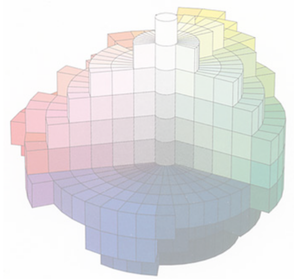
Visible Light



Cone Response



Opponent Encoding



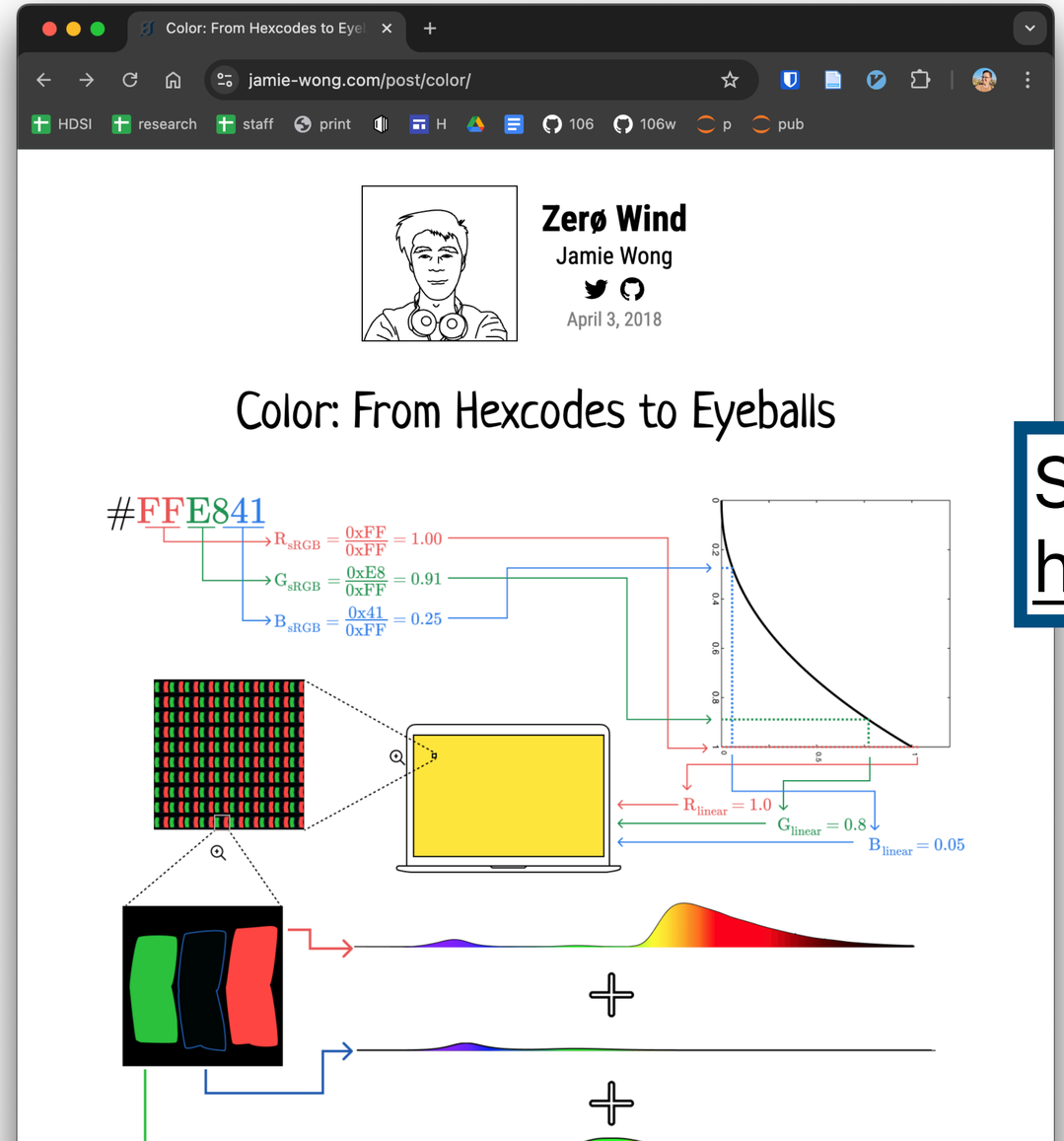
Perceptual Models

Appearance Models

“Teal”

Cognitive Models

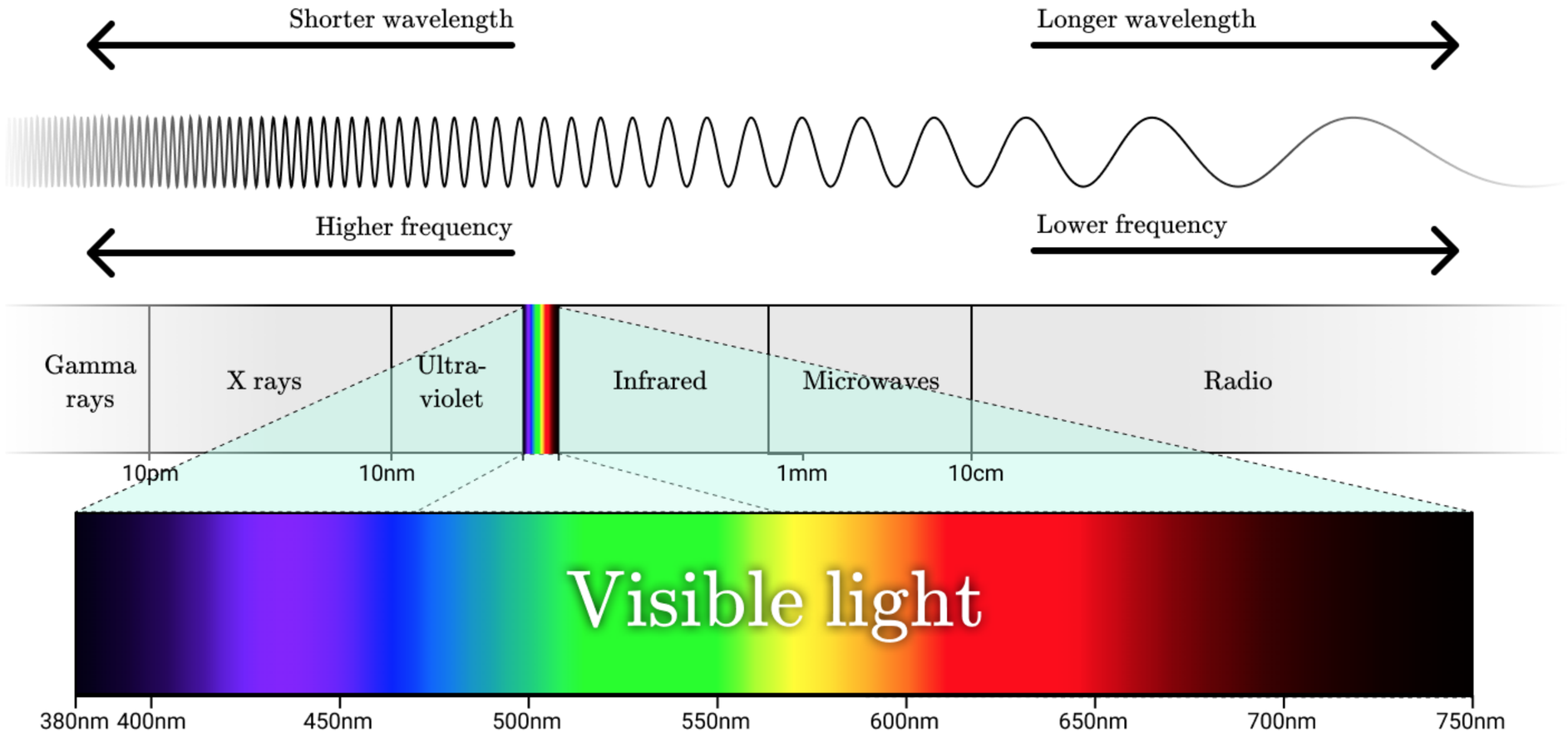
Credit to Jamie Wong for many of the images



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

Visible Light

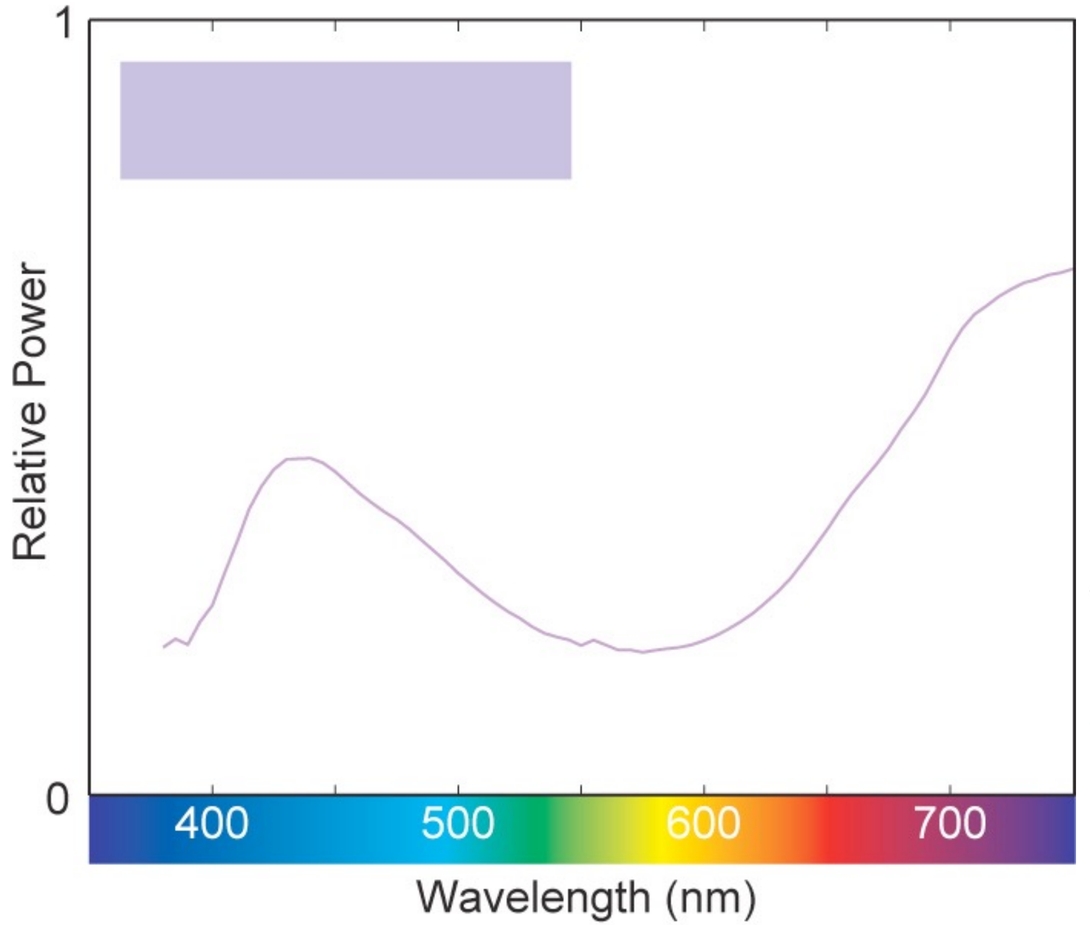
Electromagnetic wave: longer wavelength (λ) = less energy



Visible light is λ between 370nm – 730nm.

Visible Light

Most colors are combinations of spectral (pure) colors



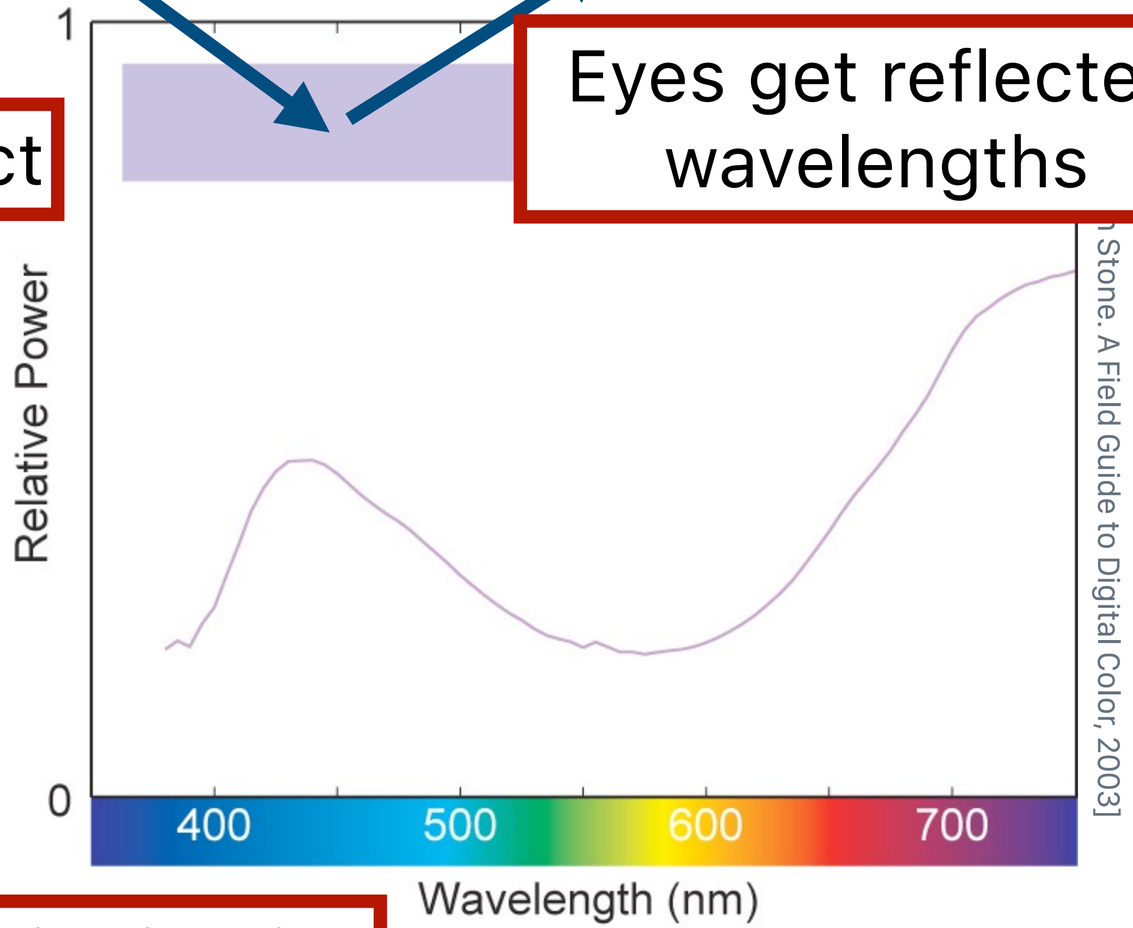
[Maureen Stone. A Field Guide to Digital Color, 2003]

Visible Light

Most colors are combinations of spectral (pure) colors

Light hits object

Eyes get reflected wavelengths

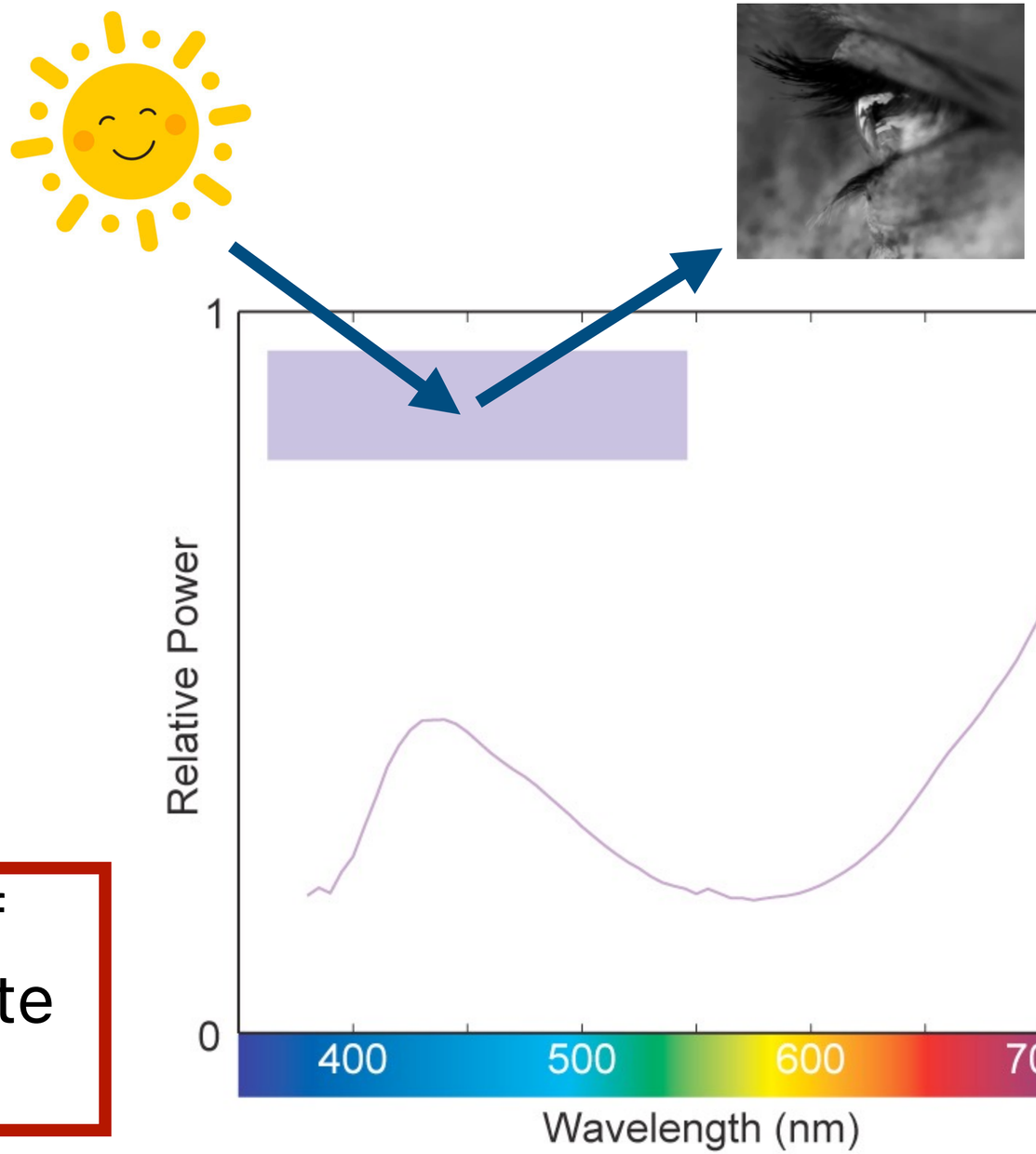


Some wavelengths are reflected, others absorbed

Called a *spectral distribution*

Visible Light

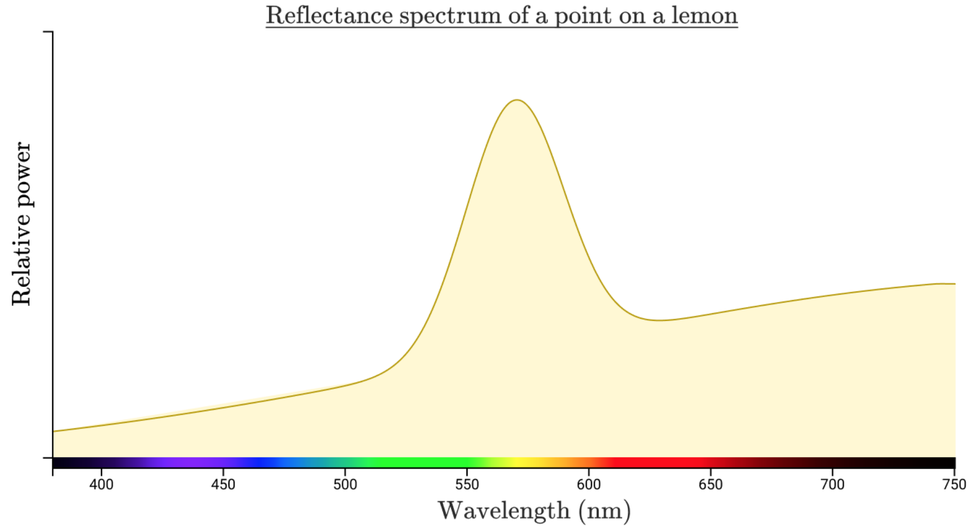
Most colors are combinations of spectral (pure) colors

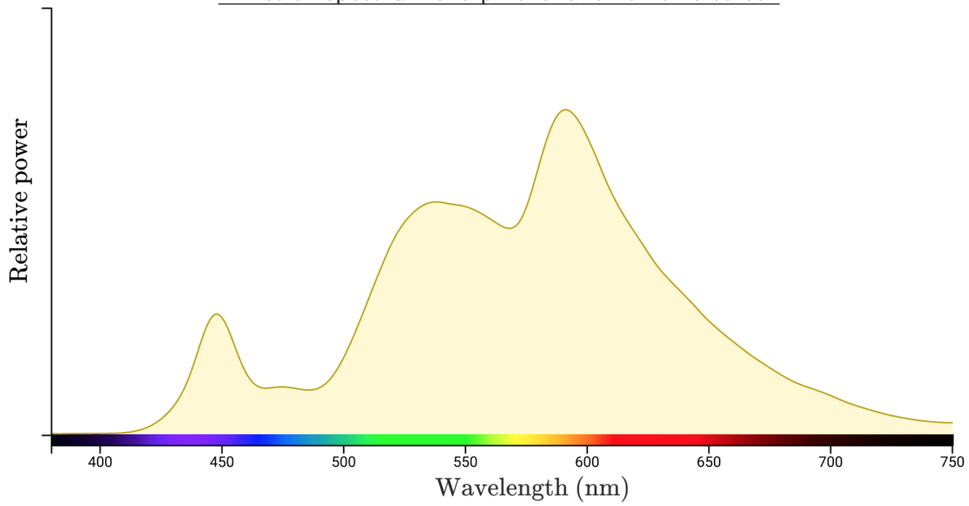


[Maureen Stone. A Field Guide to Digital Color, 2003]

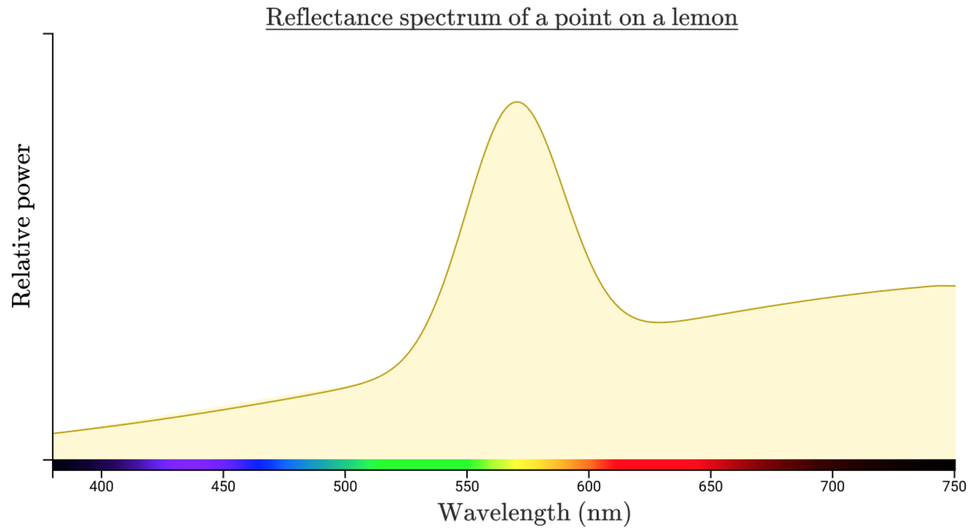
Implication: shine a bunch of lightblubs for each λ = recreate this color

Metamers


Reflectance spectrum of a point on a lemon
Relative power
400
450
500
550
600
650
700
750
Wavelength (nm)

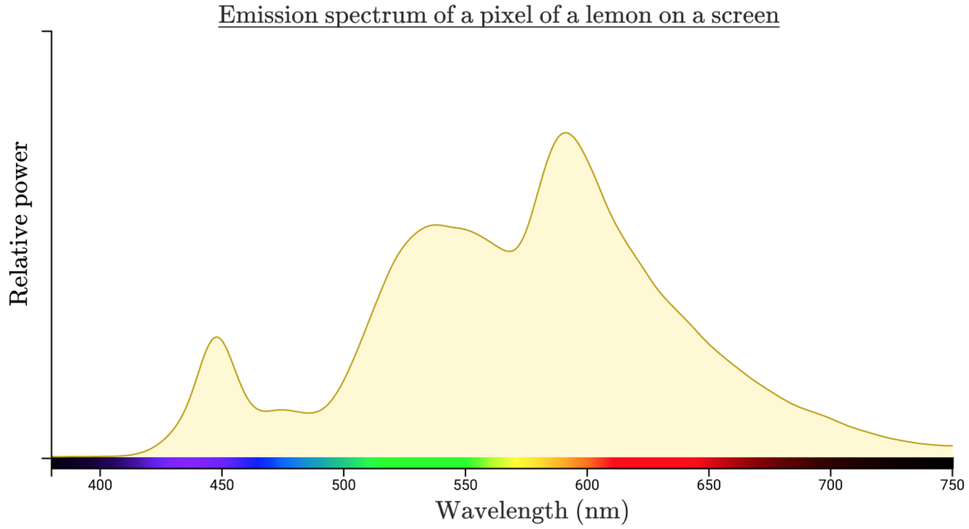

Emission spectrum of a pixel of a lemon on a screen
Relative power
400
450
500
550
600
650
700
750
Wavelength (nm)

Metamers



Different spectra, but looks the same to our eyes!

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

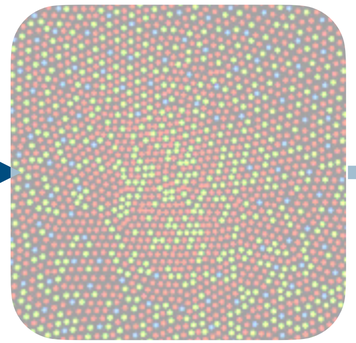


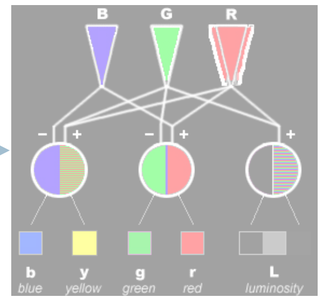
Why does this work?

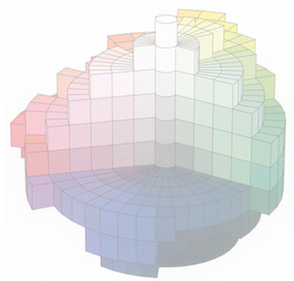
Modeling Color Perception

Low-Level Abstraction High-Level

Physical World Visual System Mental Models







“Teal”

Visible Light

Cone Response

Opponent Encoding

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Appearance Models

Cognitive Models

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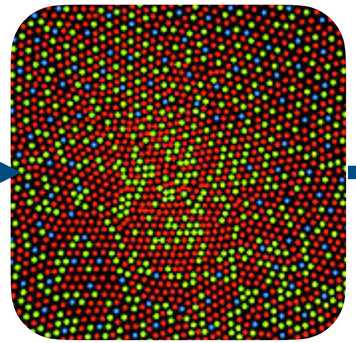

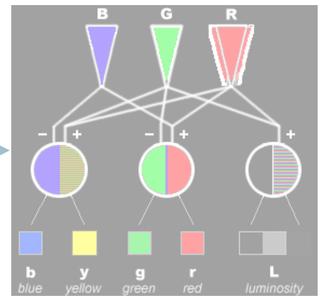

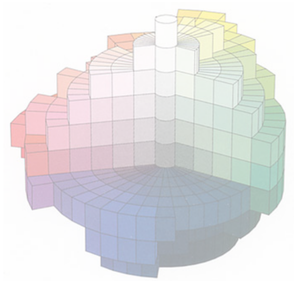

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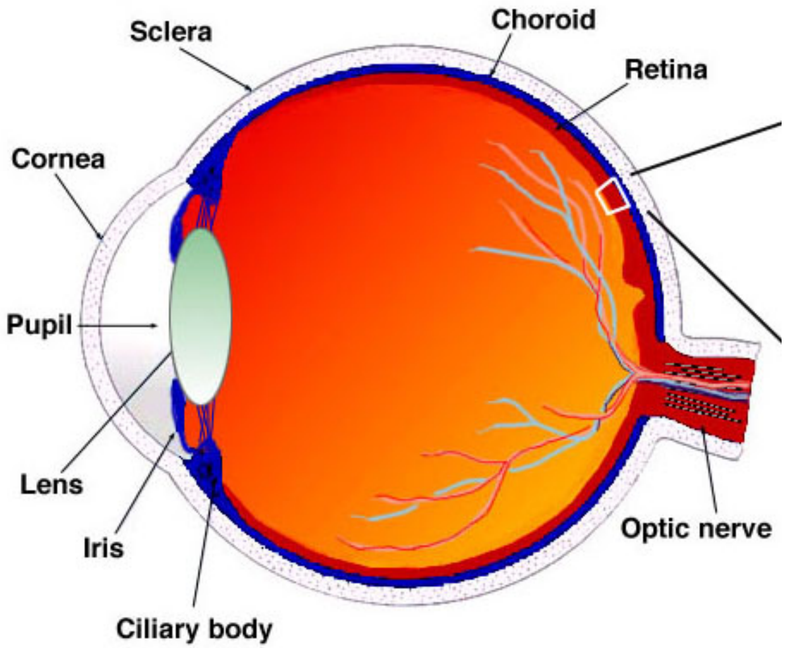
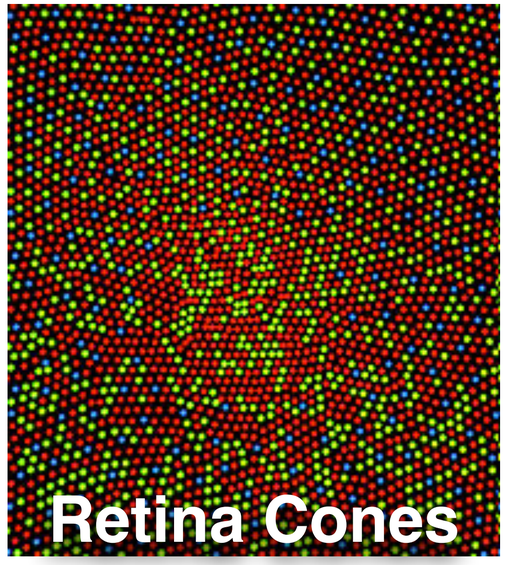
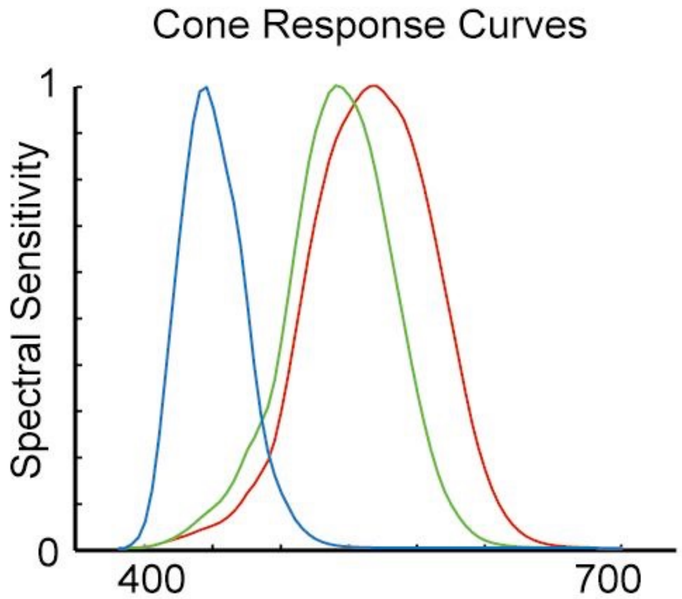
The Retina

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



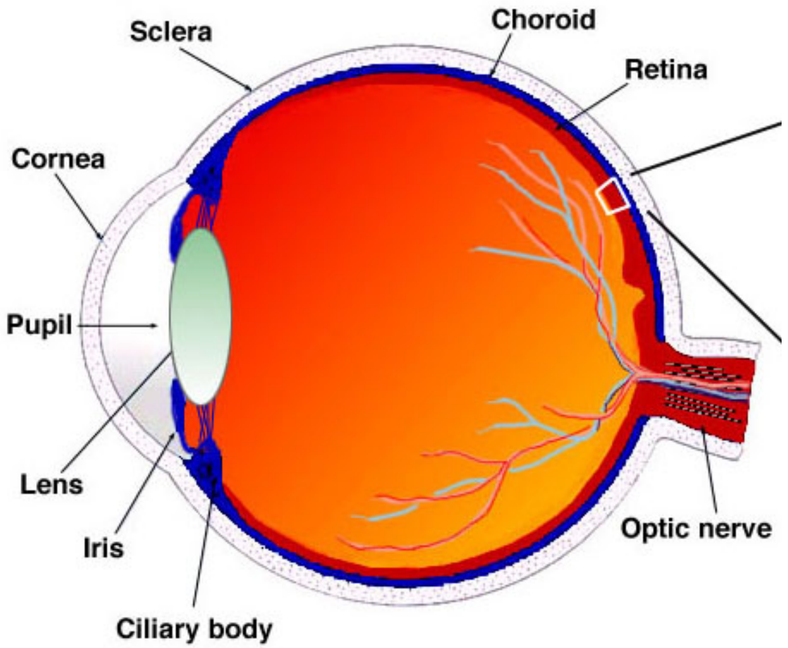
[Helga Kolb Simple Anatomy of the





The Retina

Firefox and Chrome have built in simulators



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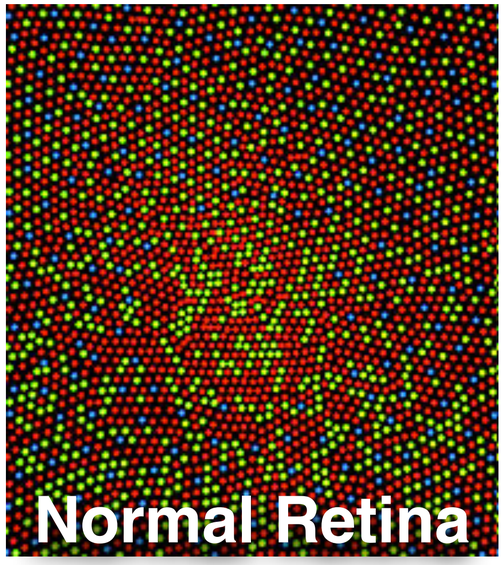
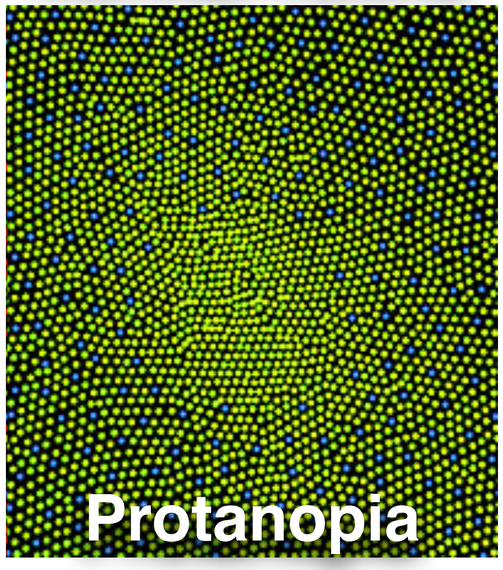


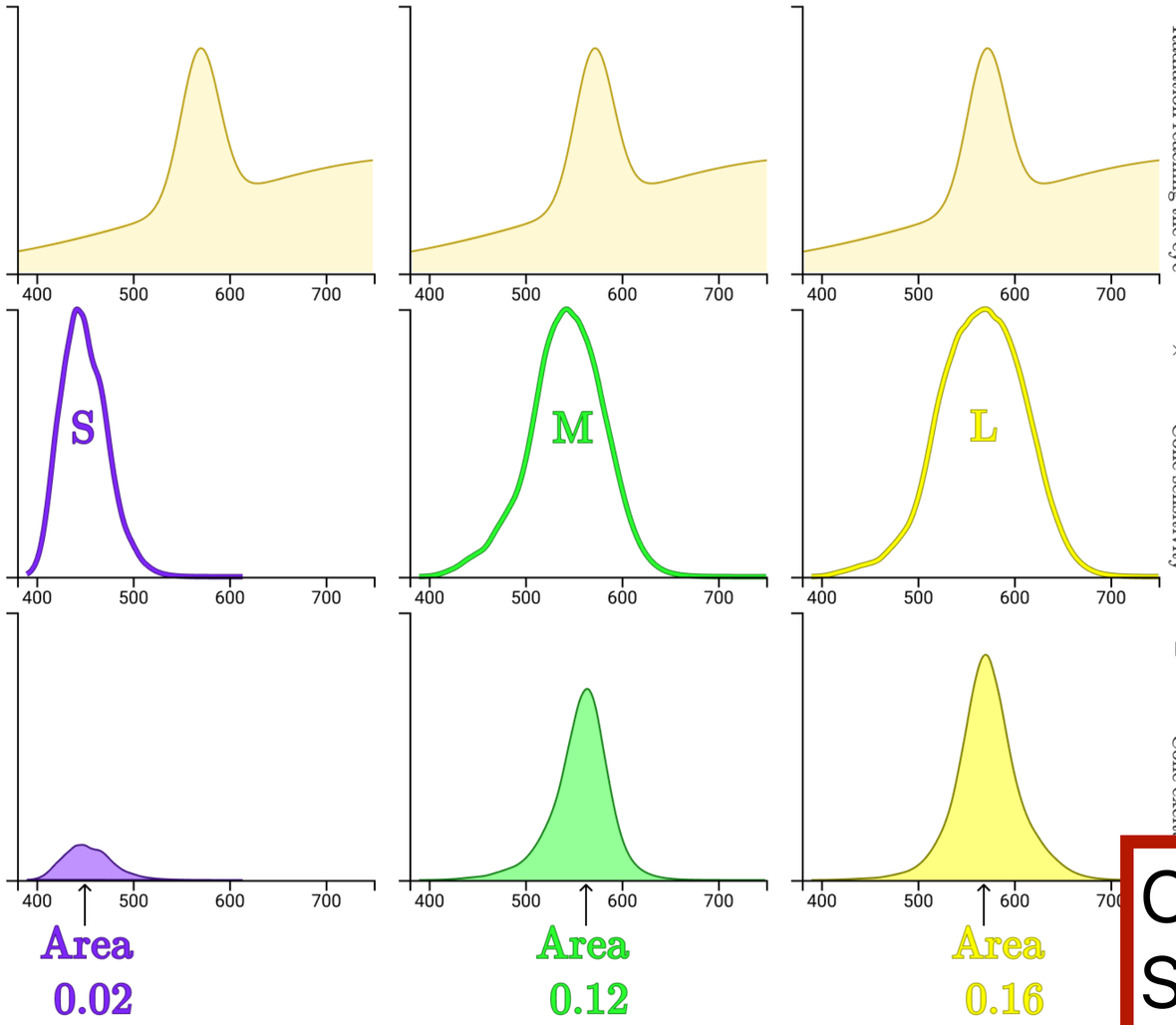


Protanope

Deuteranope

Tri-Stimulus Response

Sunlight hits lemon



Light spectrum

Cone sensitivity

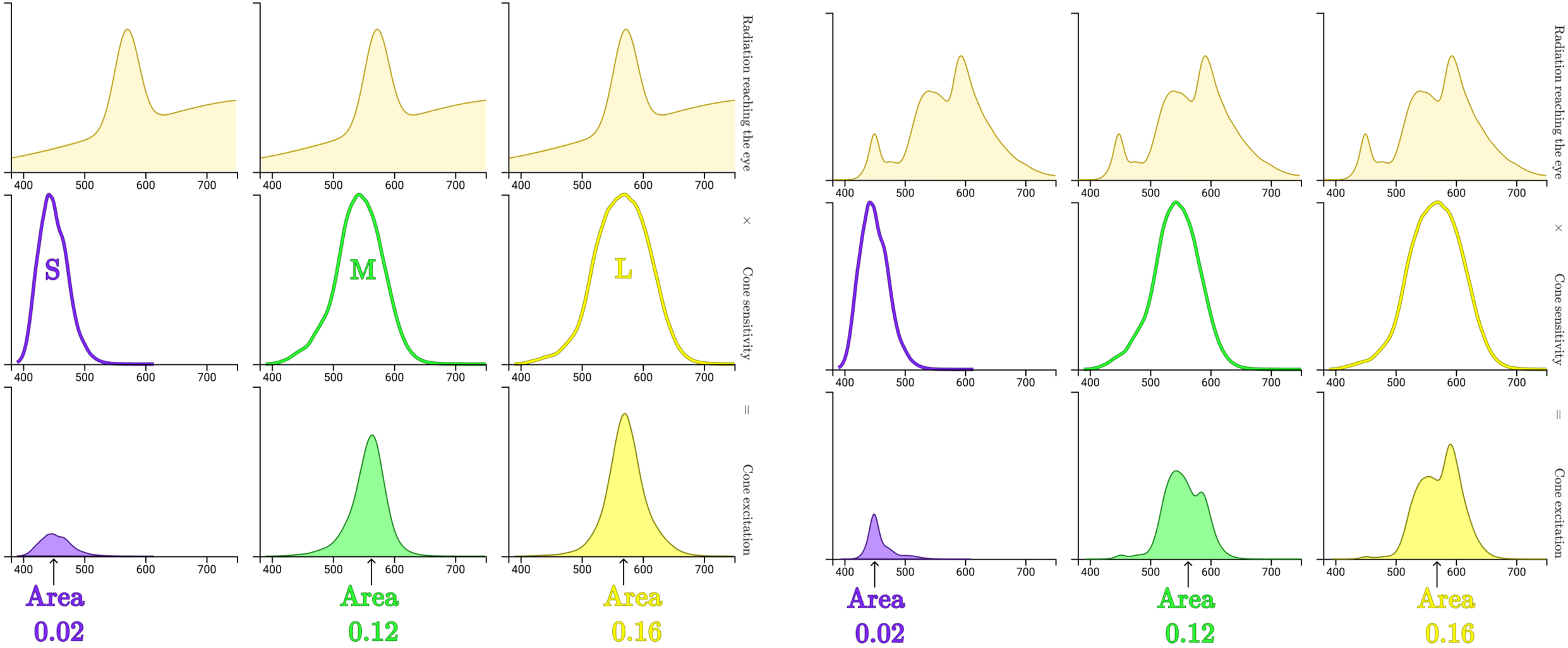
Cone response

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

Tri-Stimulus Response

Sunlight hits lemon

Image of lemon on screen



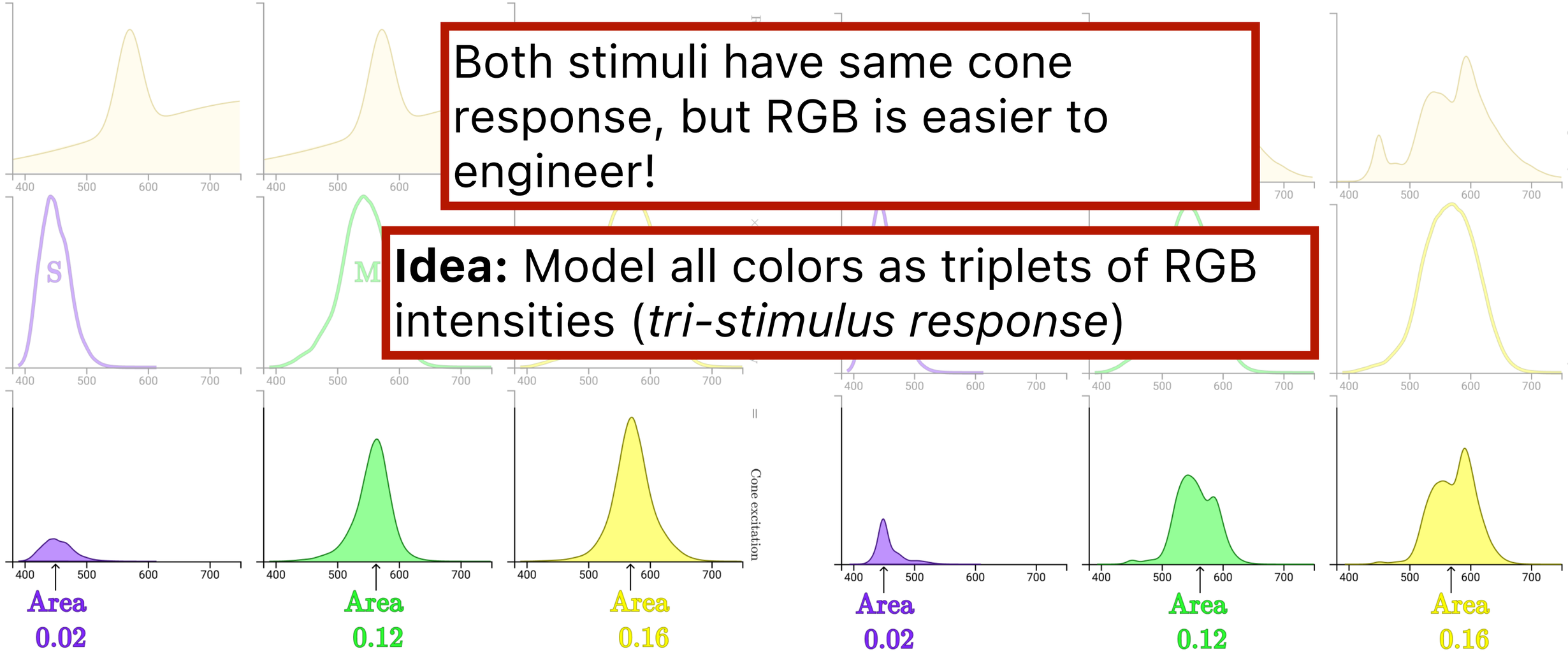
Tri-Stimulus Response

Sunlight hits lemon

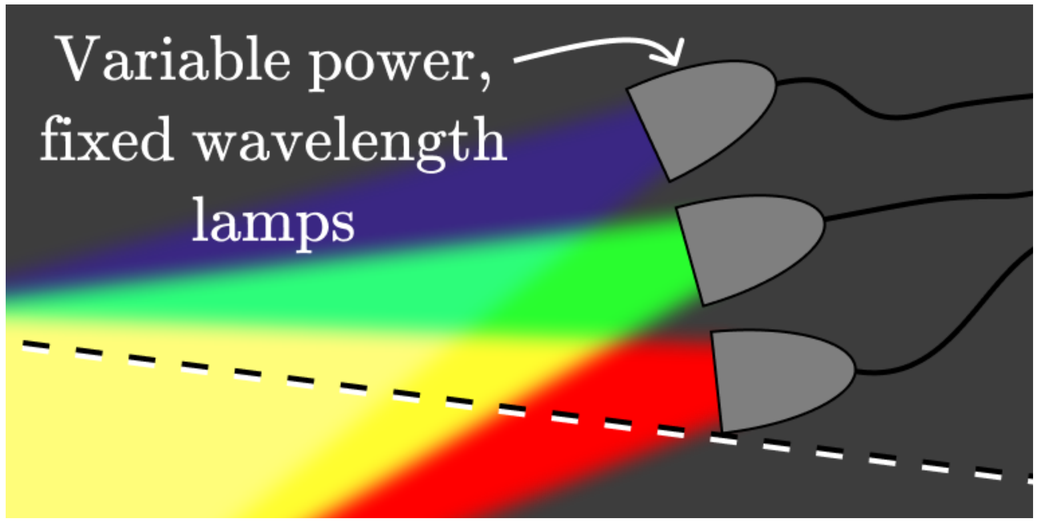
Image of lemon on screen

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

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



CIE XYZ (1931)



Take red, green, blue lamp, record RGB tuples (r, g, b).

Normalize values to be between 0 and 1.

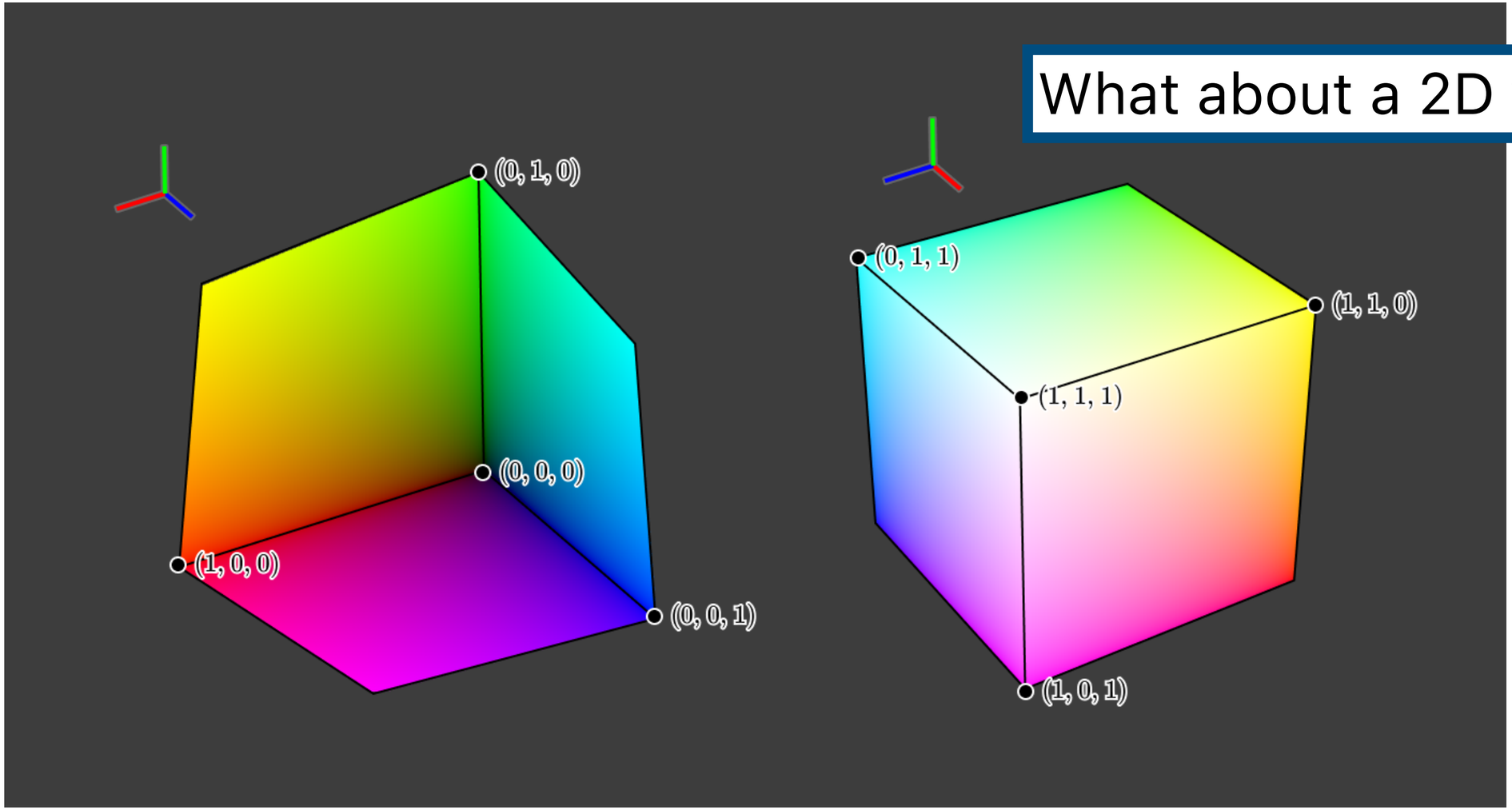
(1, 1, 1) = white light

(1, 0, 0) = pure red

...etc.

How to visualize all colors?

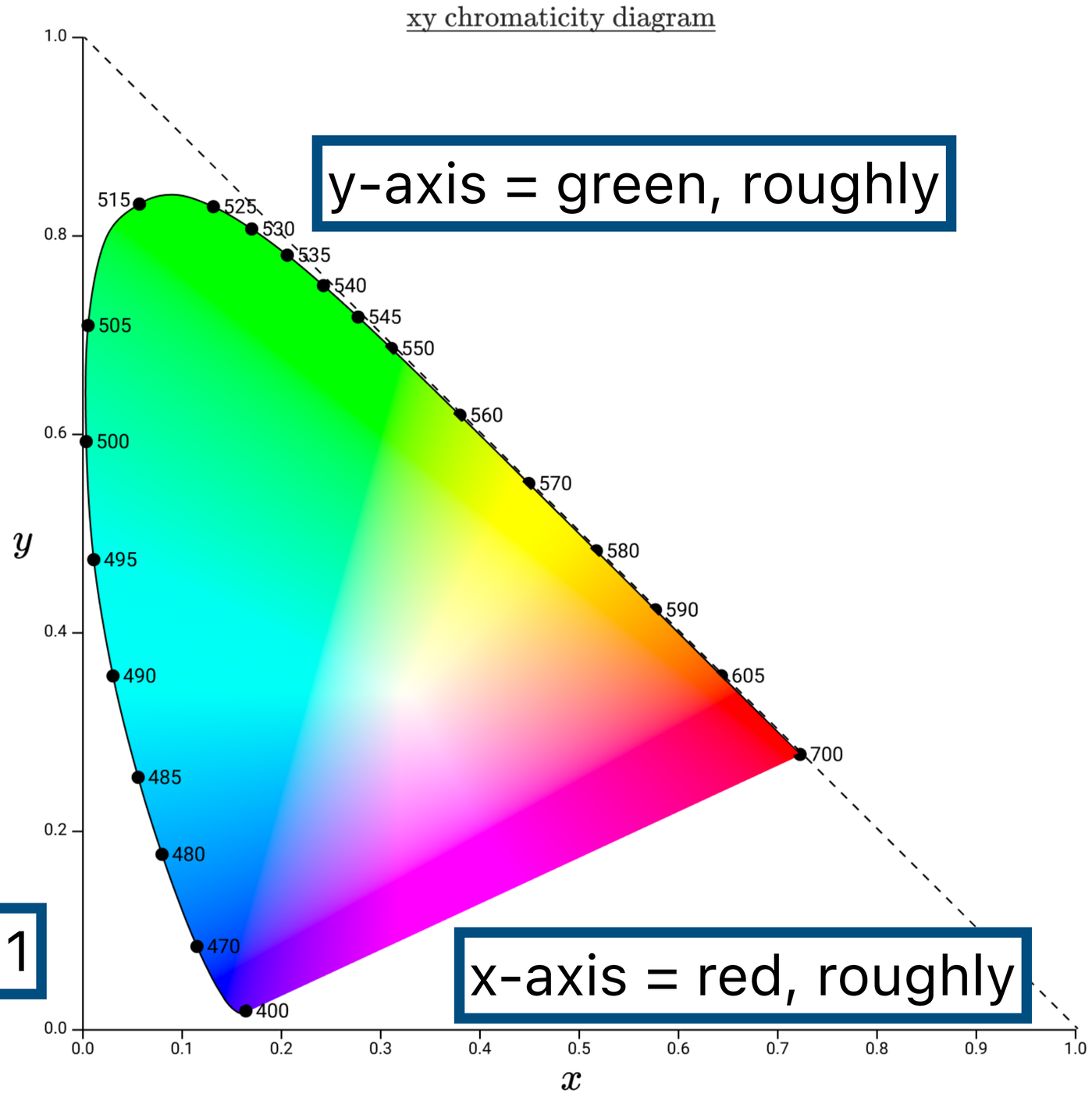
CIE XYZ (1931)



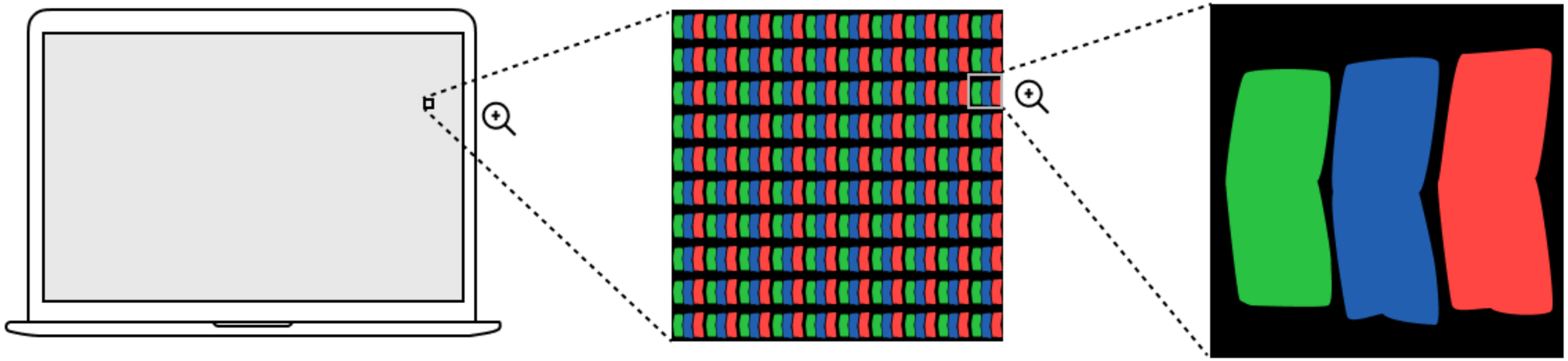
What about a 2D visualization?

CIE XYZ (1931)

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



Our screens

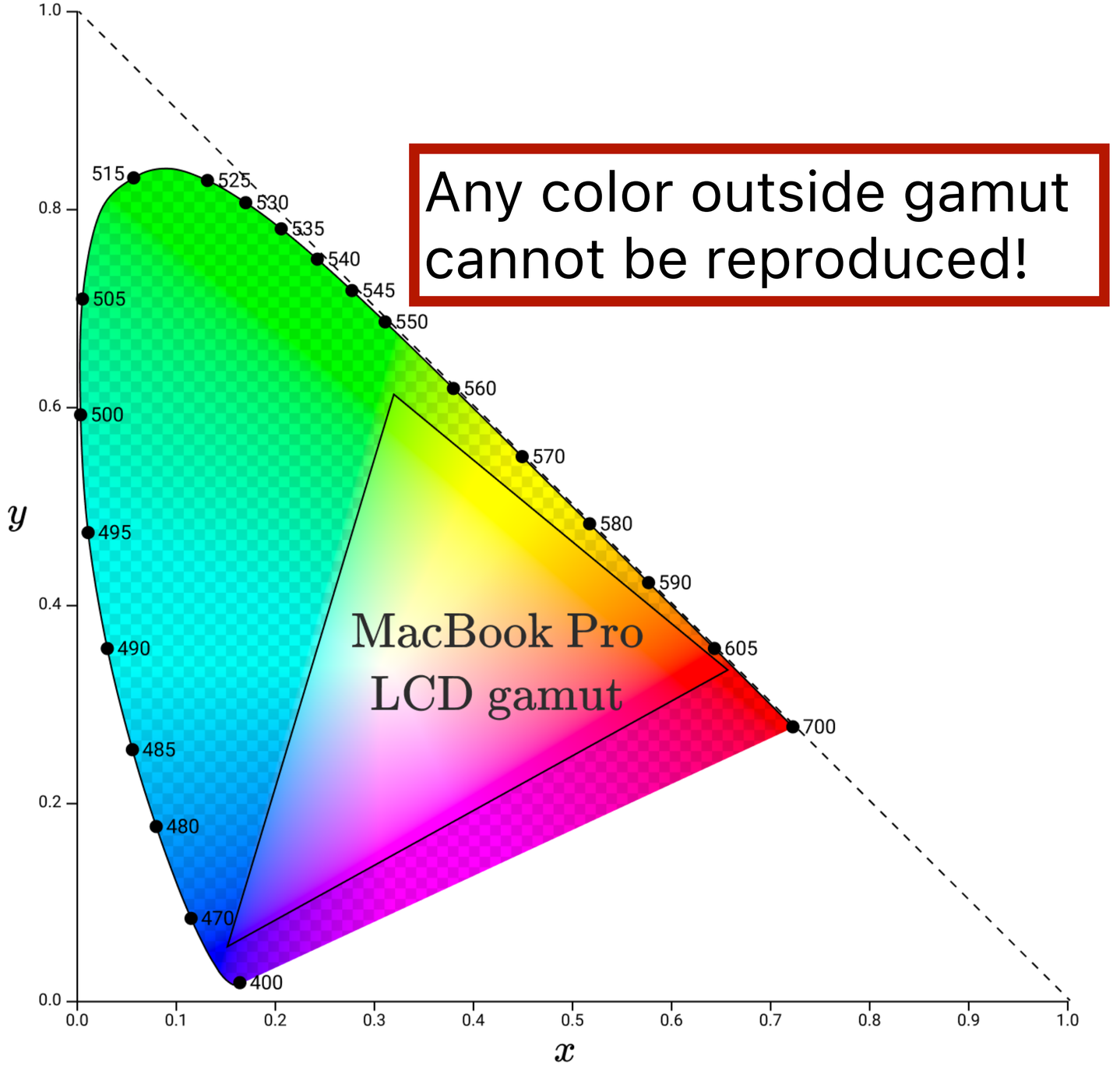


Not the same as the 1931 CIE light bulbs!

Color Gamuts

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

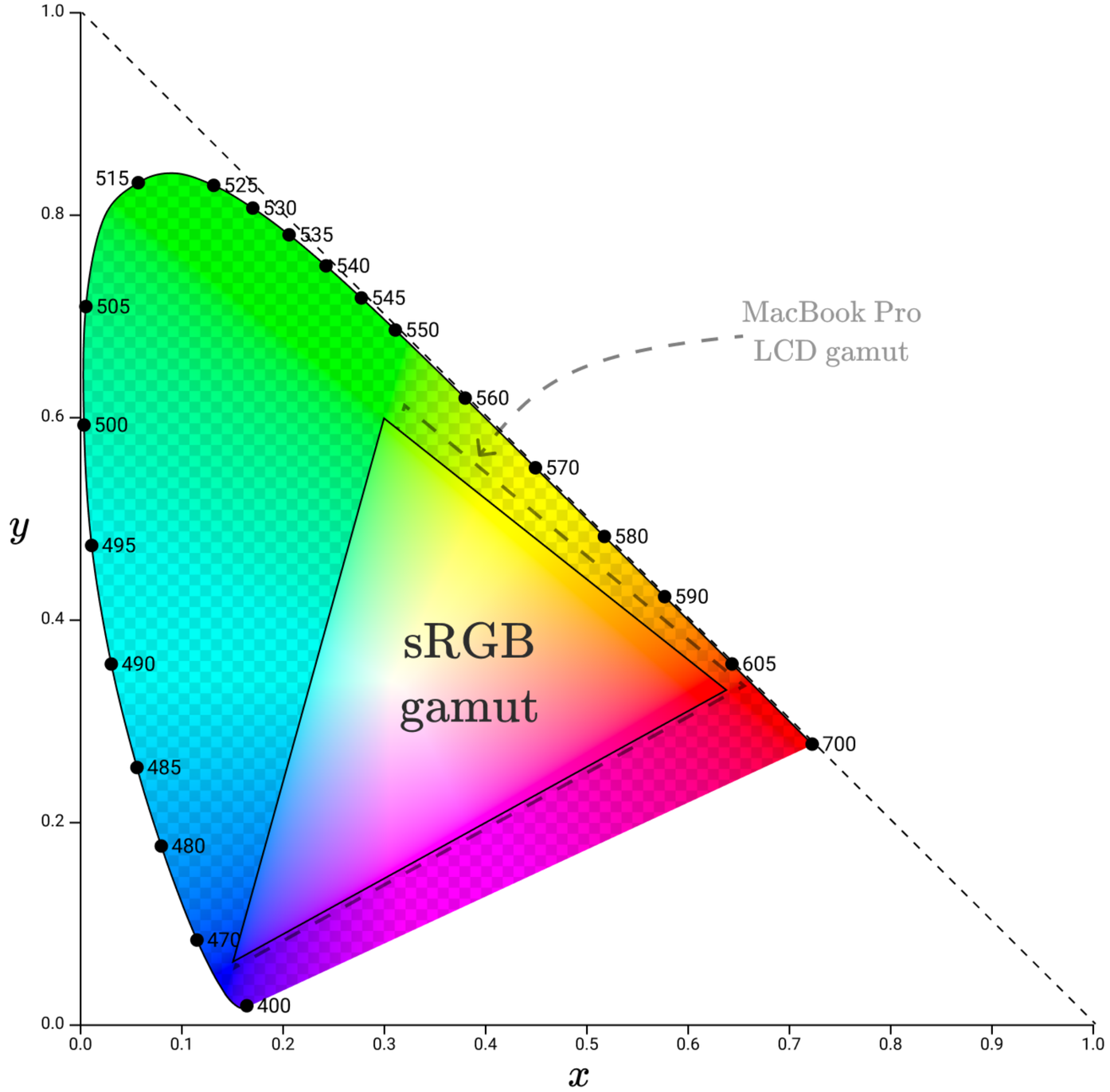
Any color outside gamut cannot be reproduced!



sRGB

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

CSS rgb() uses the sRGB gamut:

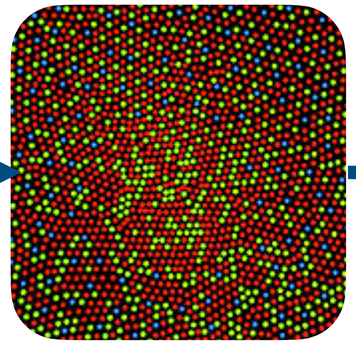


Modeling Color Perception

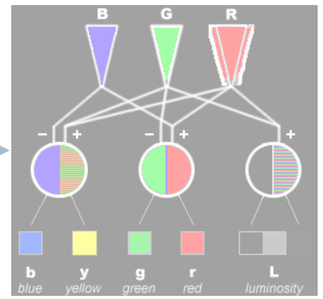
Low-Level — Abstraction — High-Level

Physical World | Visual System | Mental Models

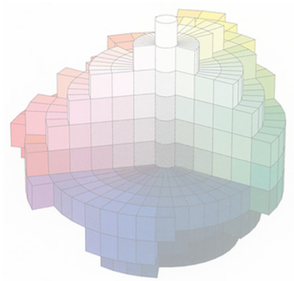
Visible Light



Cone Response



Opponent Encoding



Perceptual Models

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“Teal”

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Low-Level Abstraction High-Level

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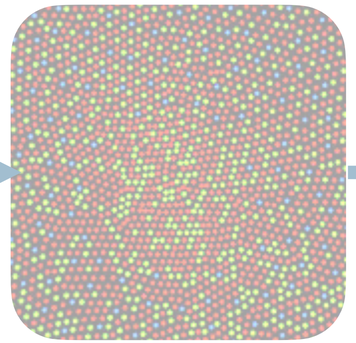

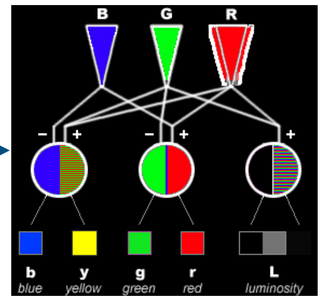

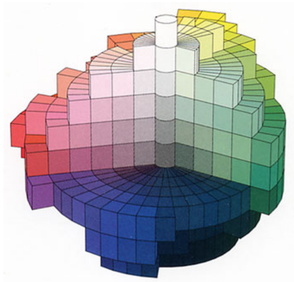

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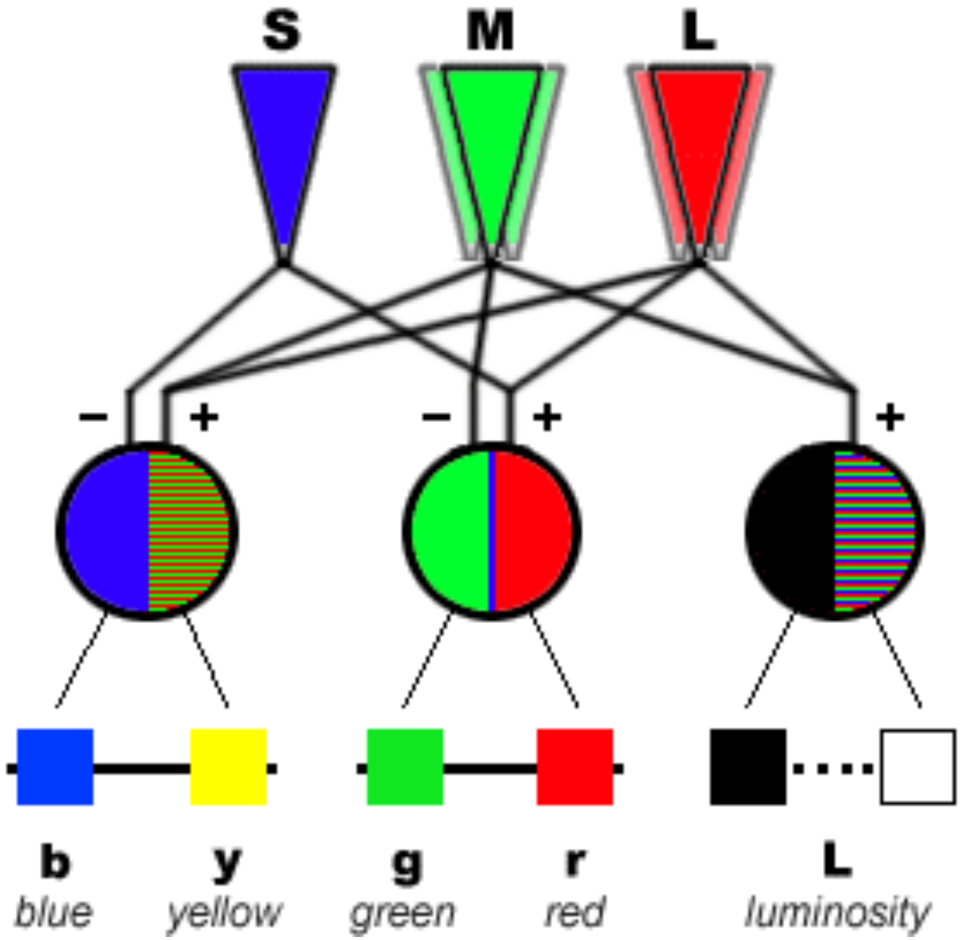
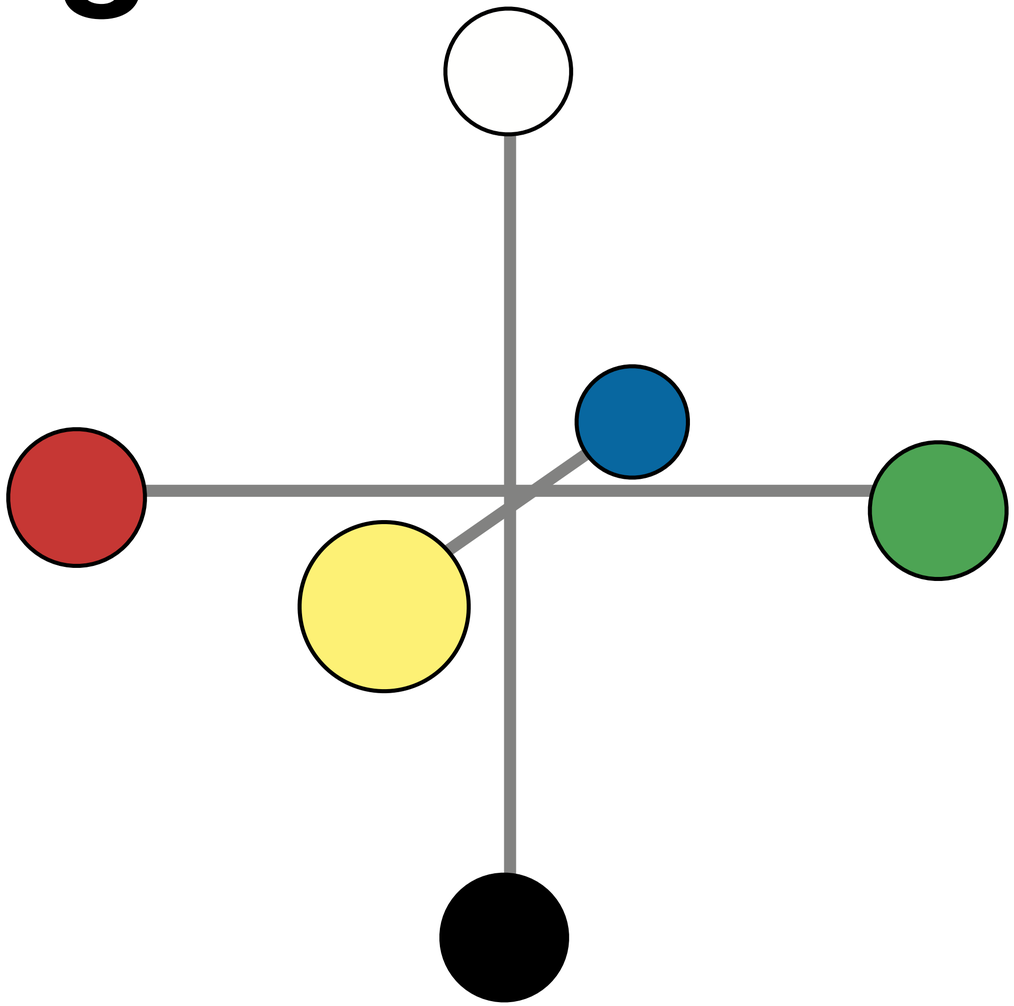




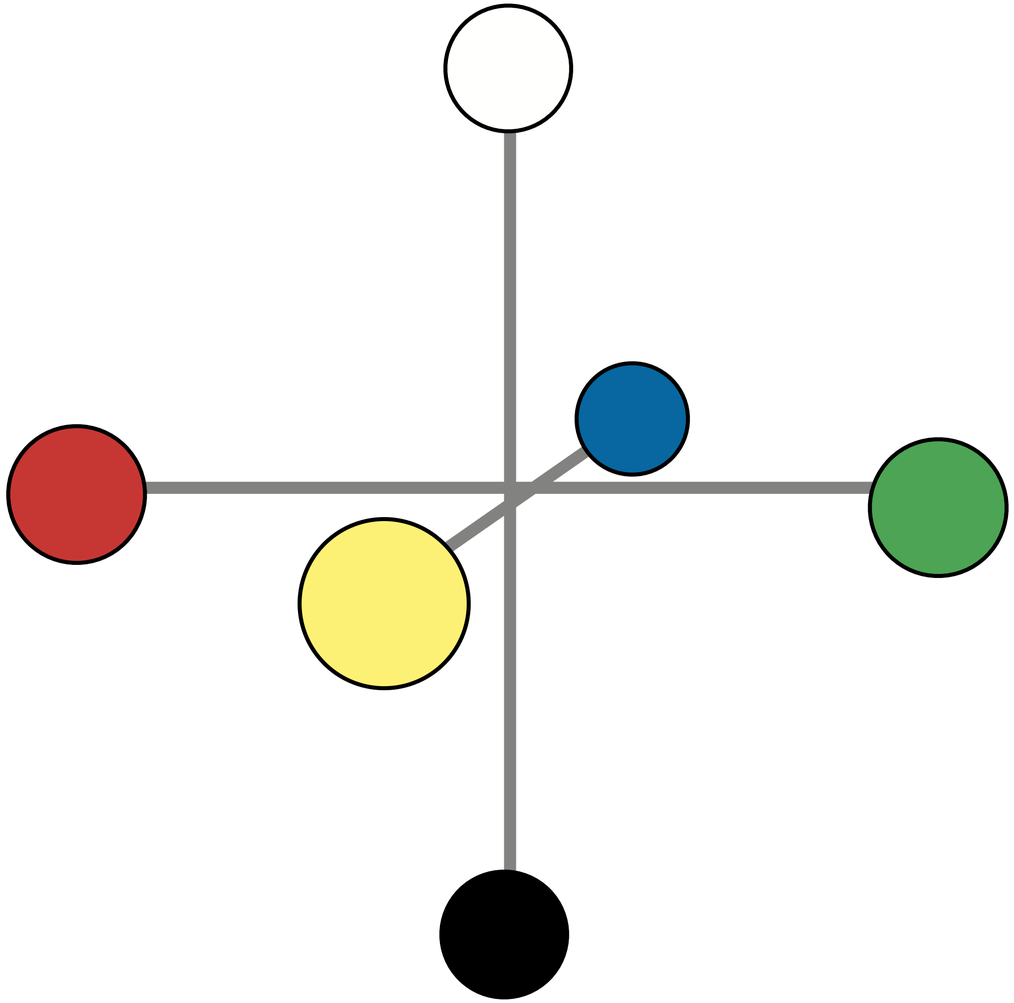
CIE LAB Color Space

Axes correspond to opponent signals:

L* = luminance

a* = red-green contrast

b* = yellow-blue contrast

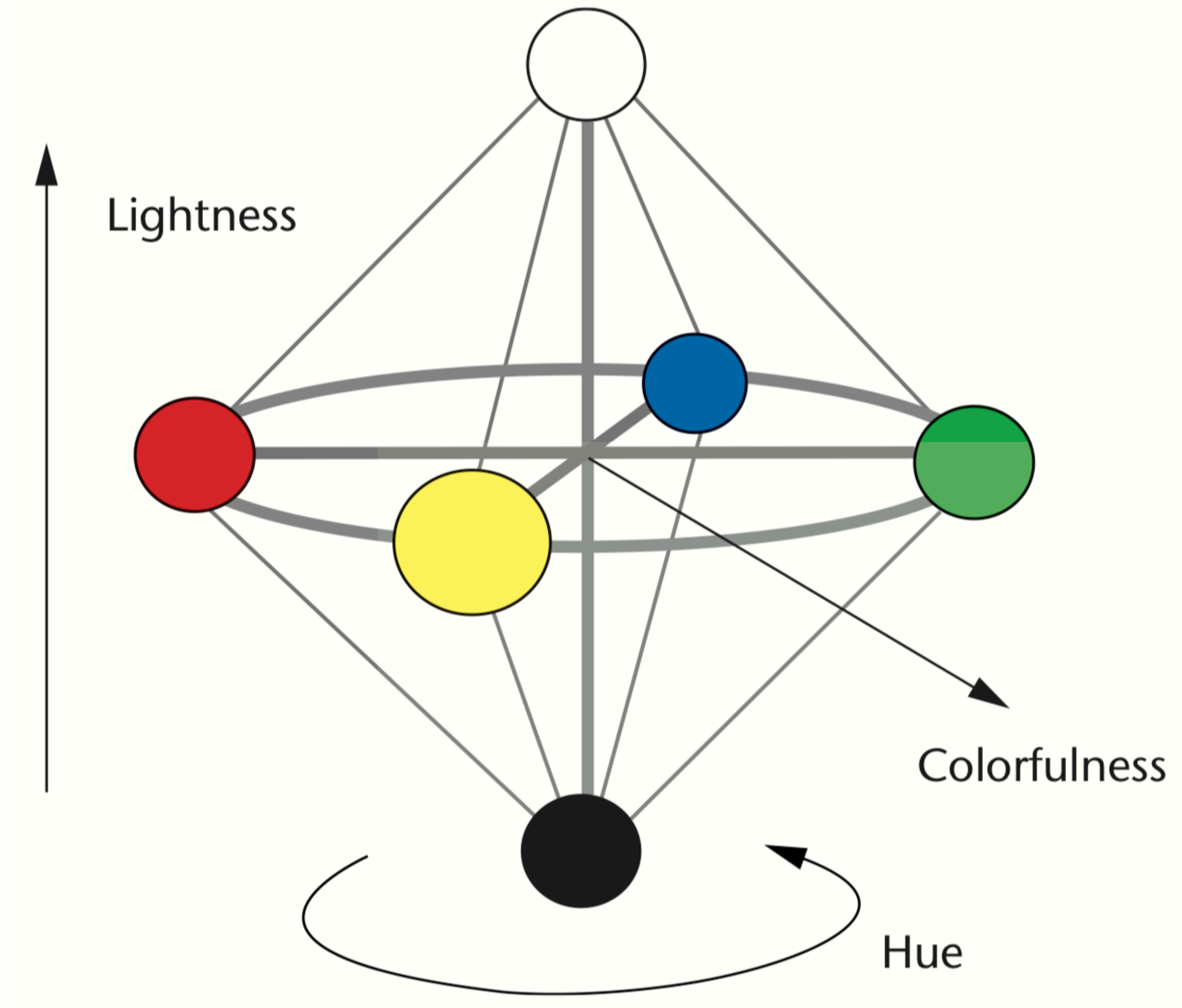


OKLAB Color Space

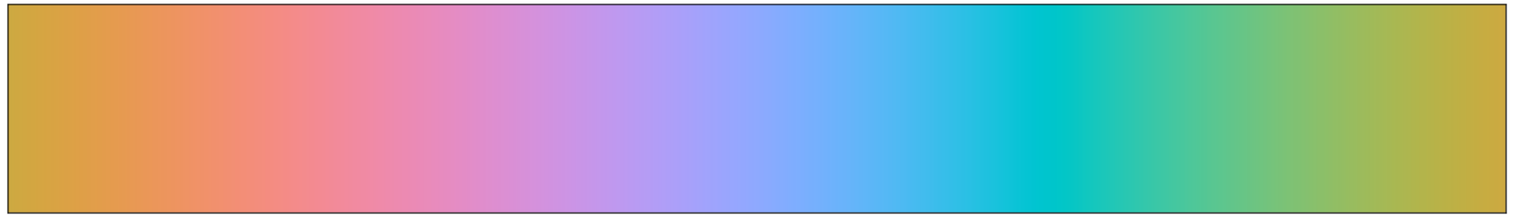
Oklab is modern version of CIELAB that we recommend

In CSS:

oklch(65% 50% 0)



OKLAB Color Space



Rainbow in Oklab

“Angry rainbow” in sRGB

Notice that there aren’t bright “bands”: **perceptually uniform**

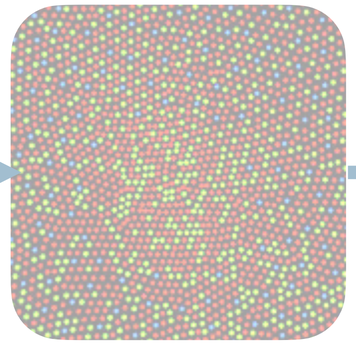
But still be wary!

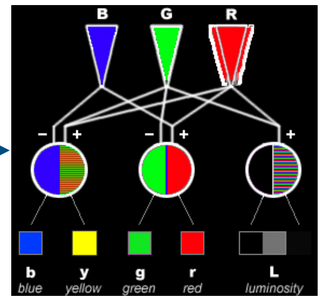
JND issues
Colorblind issues

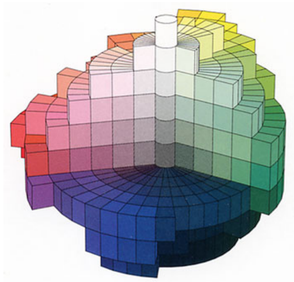
Modeling Color Perception

Low-Level Abstraction High-Level

Physical World Visual System Mental Models







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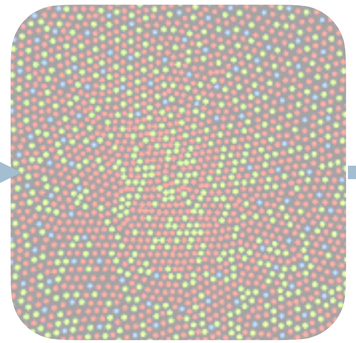
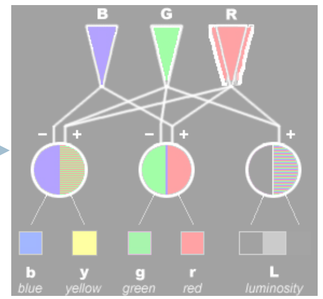
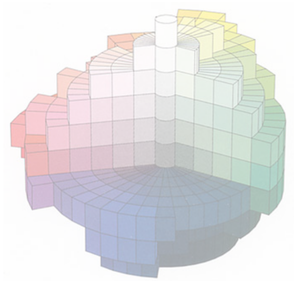
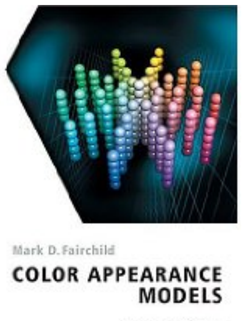
Physical World | Visual System | Mental Models







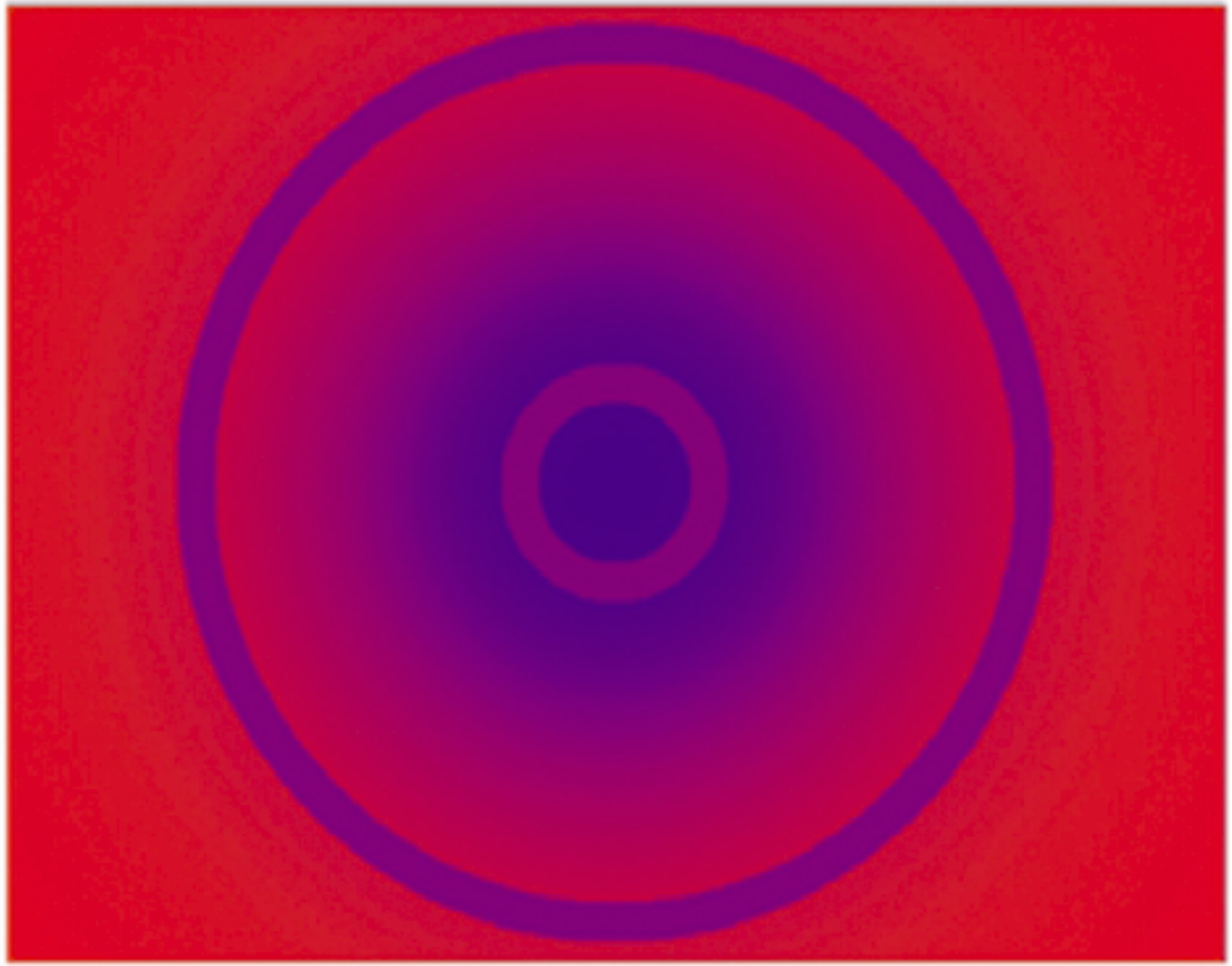


“Teal”

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

Simultaneous Contrast

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

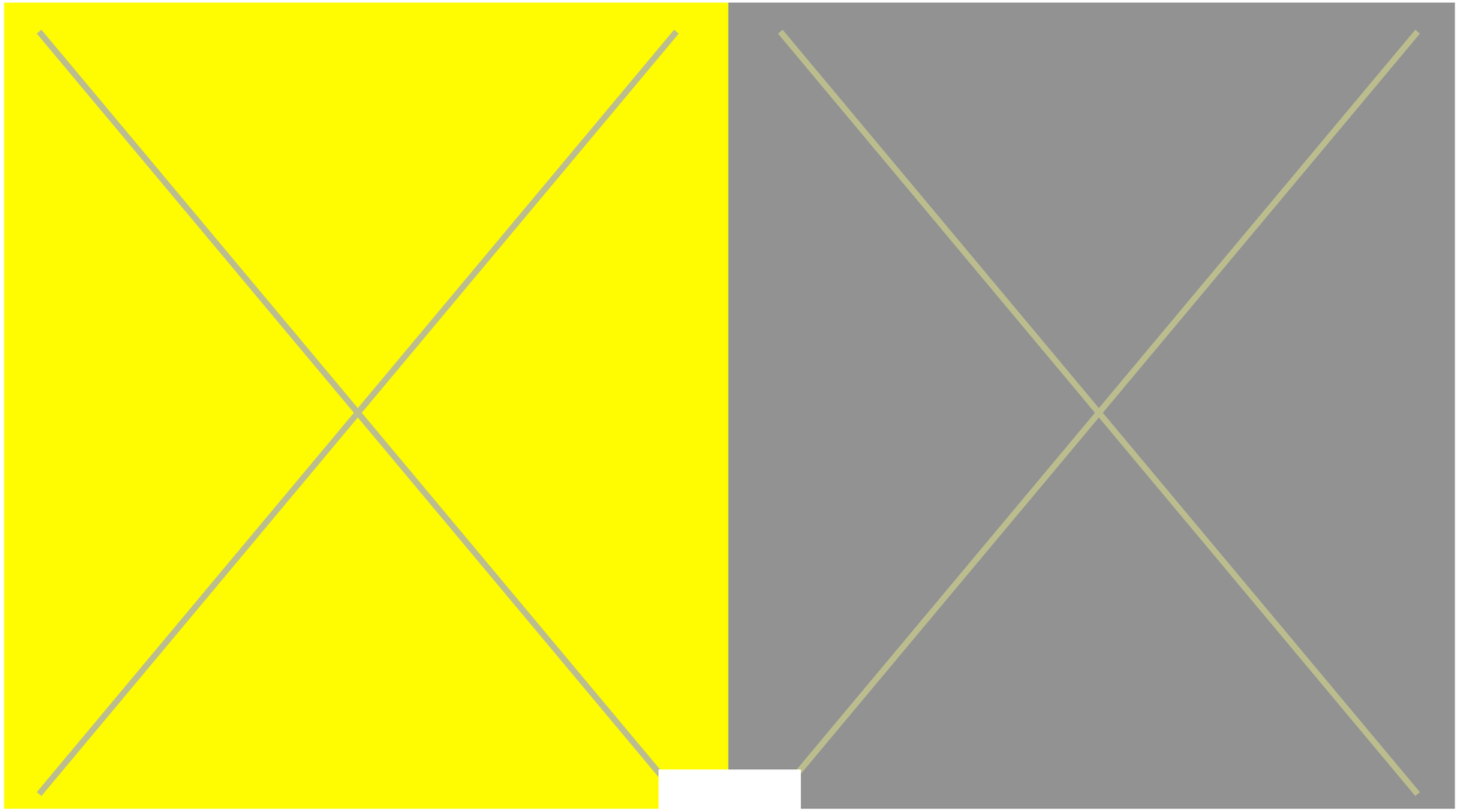


The inner and outer thin rings are, in fact, the same physical purple!

[Donald Macleod]

Simultaneous Contrast

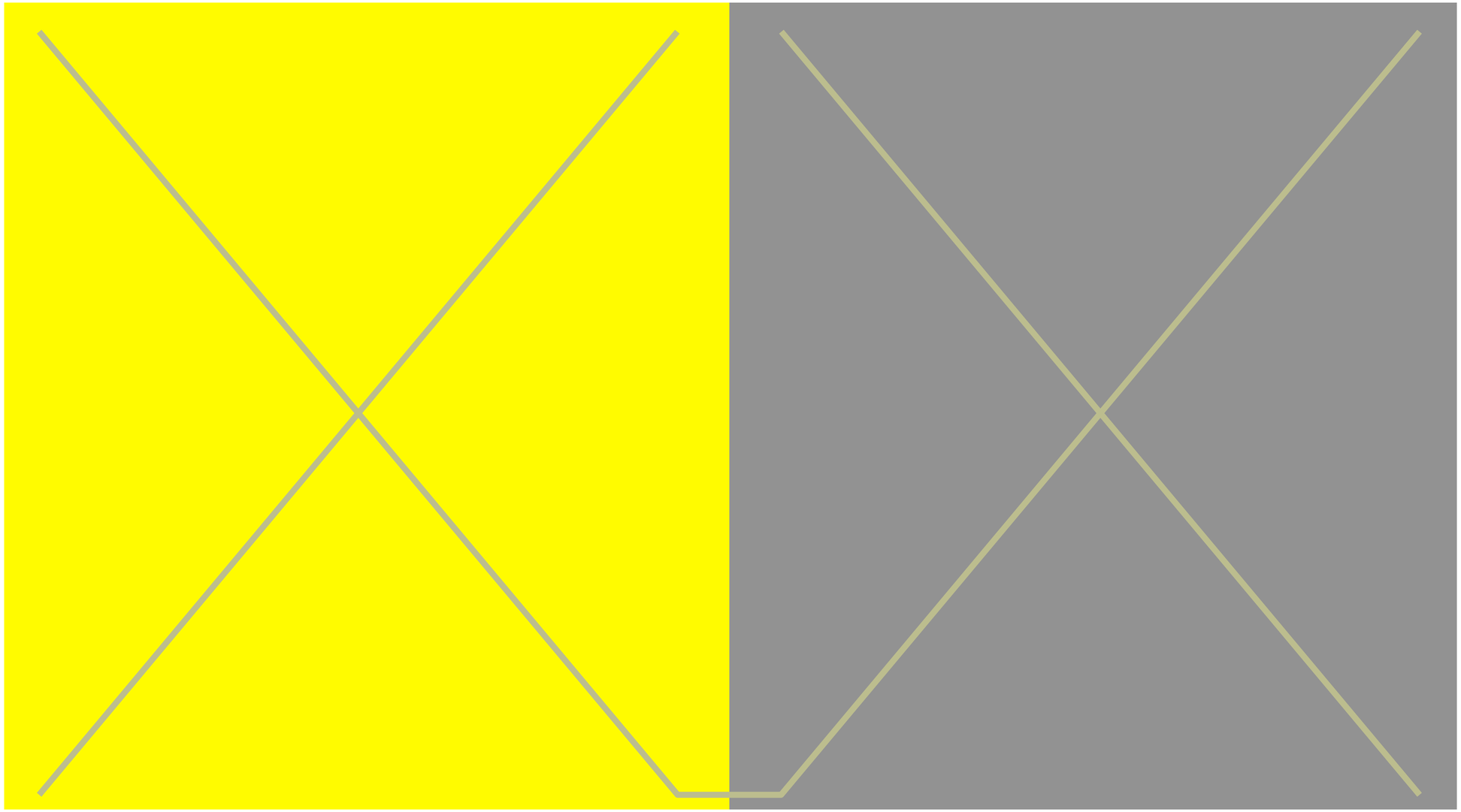
Two colors side-by-side interact and affect our perception



Josef Albers

Simultaneous Contrast

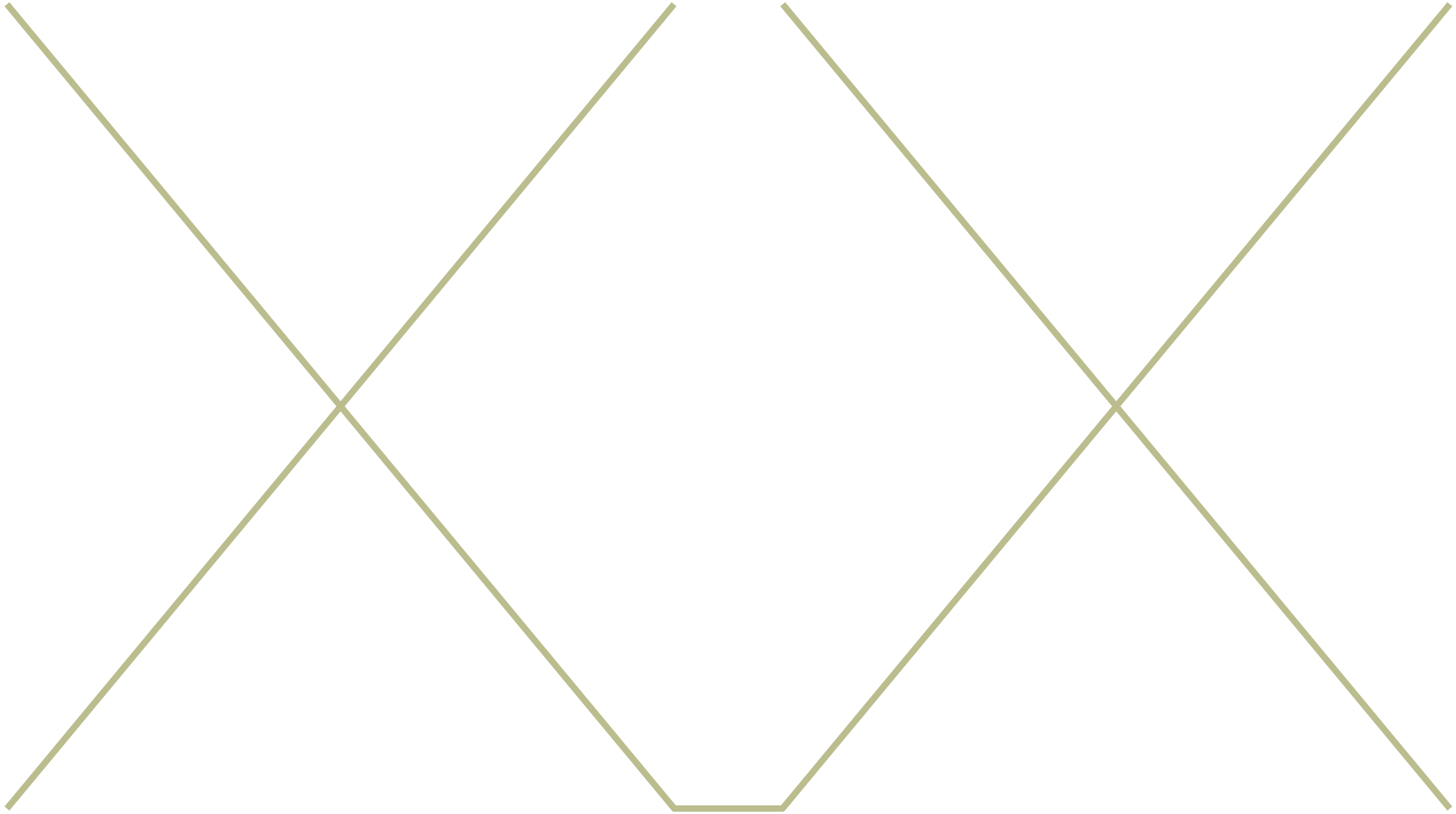
Two colors side-by-side interact and affect our perception



Josef Albers

Simultaneous Contrast

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

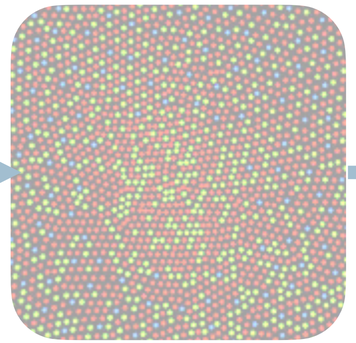


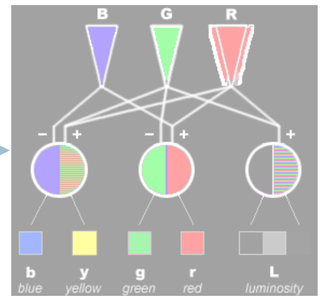
Josef Albers

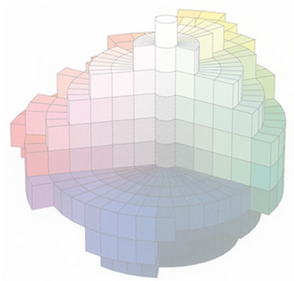
Modeling Color Perception

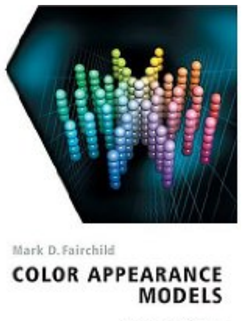
Low-Level → Abstraction → High-Level

Physical World | Visual System | Mental Models









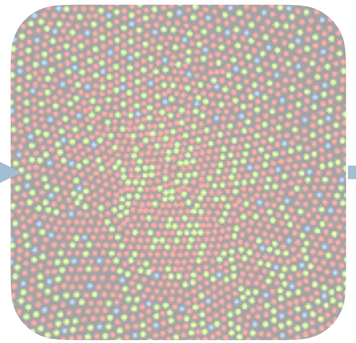
“Teal”

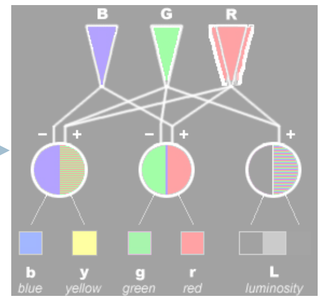
Visible Light | Cone Response | Opponent Encoding | Perceptual Models | **Appearance Models** | Cognitive Models

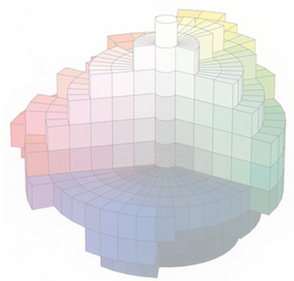
Modeling Color Perception

Low-Level Abstraction High-Level

Physical World Visual System Mental Models







“Teal”

Visible Light

Cone Response

Opponent Encoding

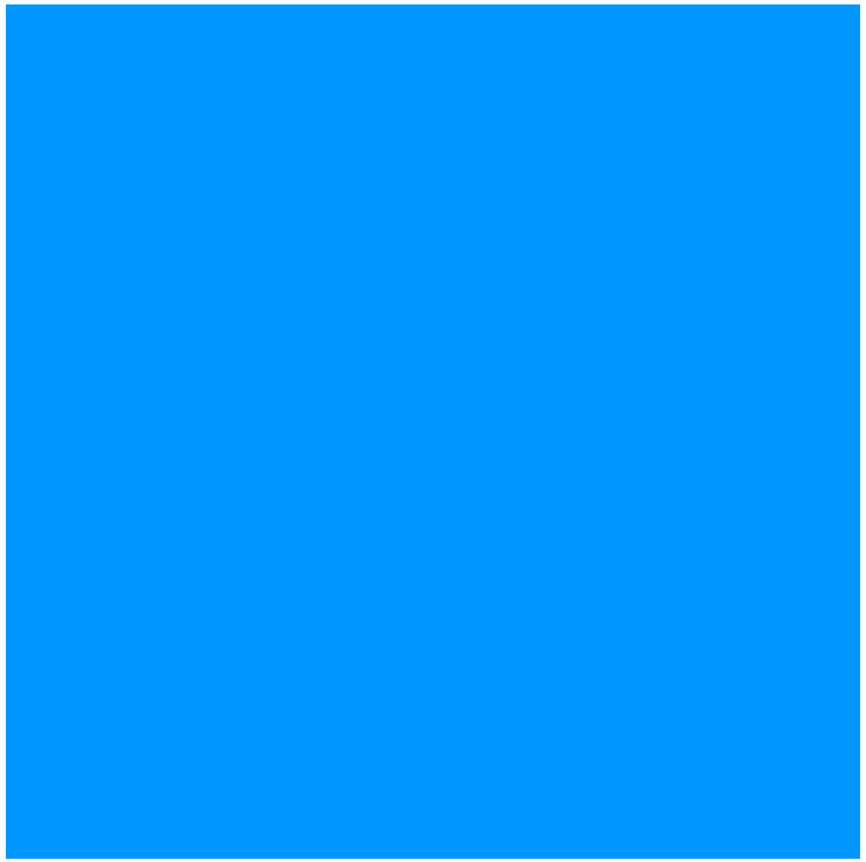
Perceptual Models

Appearance Models

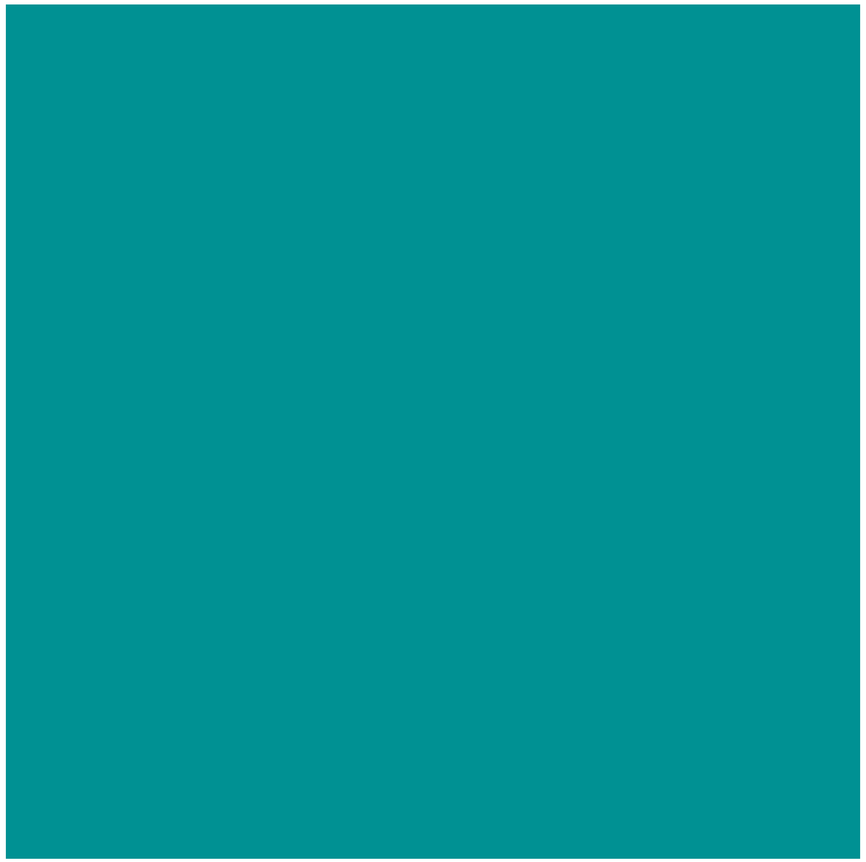
Cognitive Models

What color is this?

What color is this?

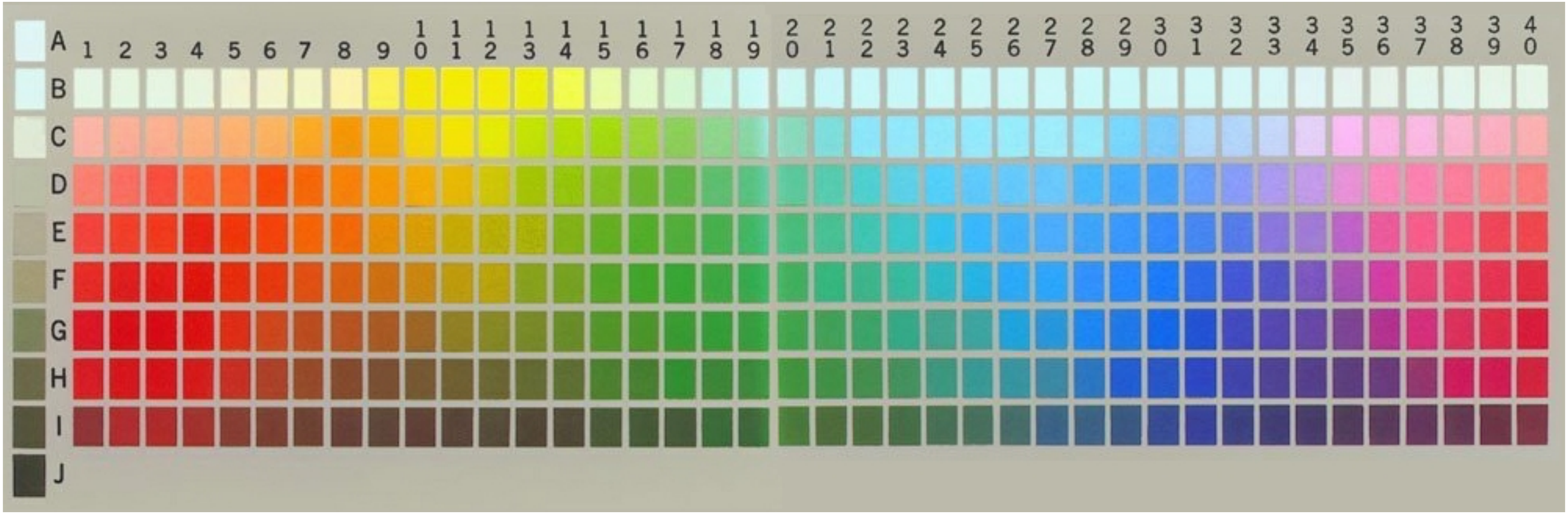


What color is this?



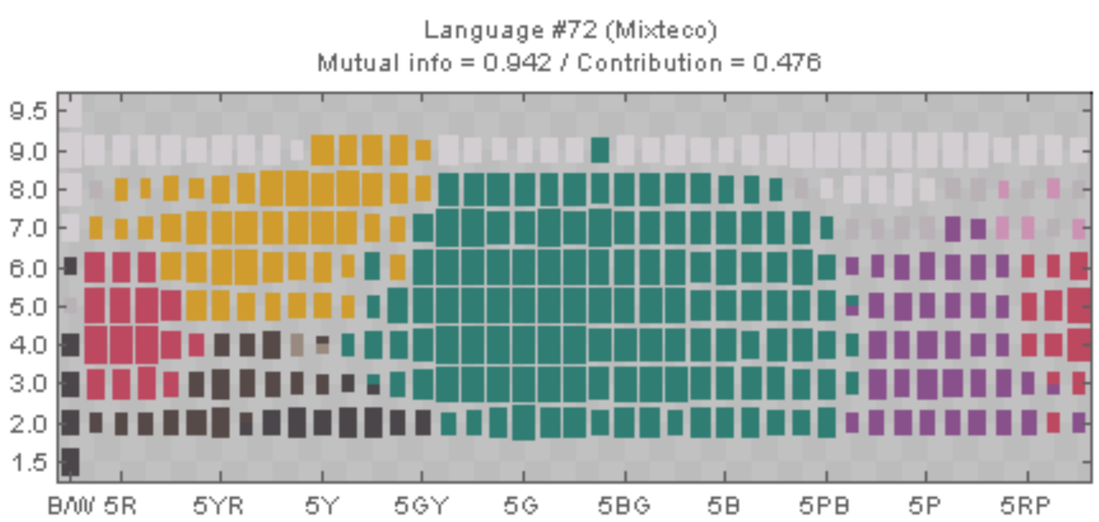
tryclassbuzz.com:
color

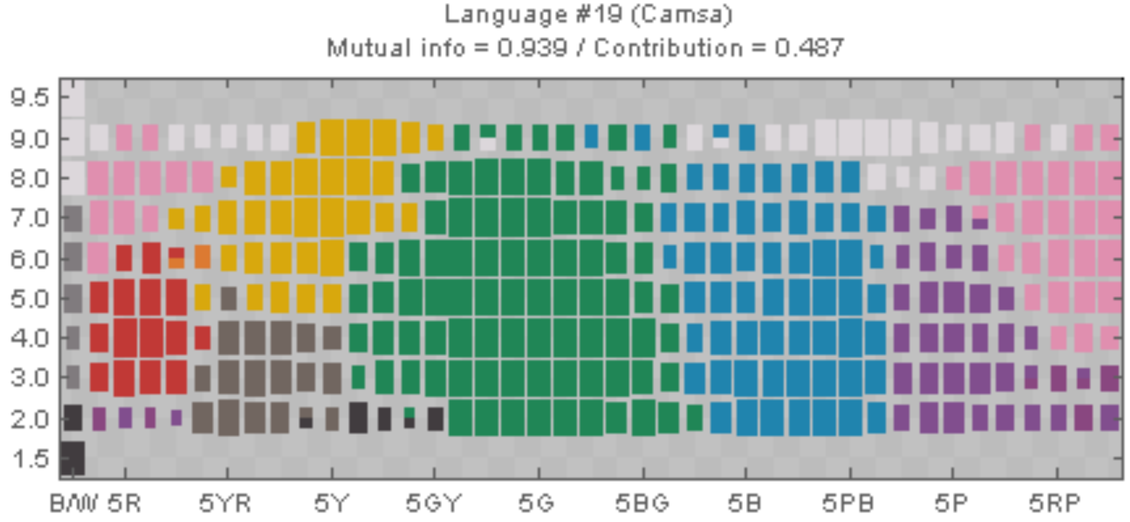
Color Naming

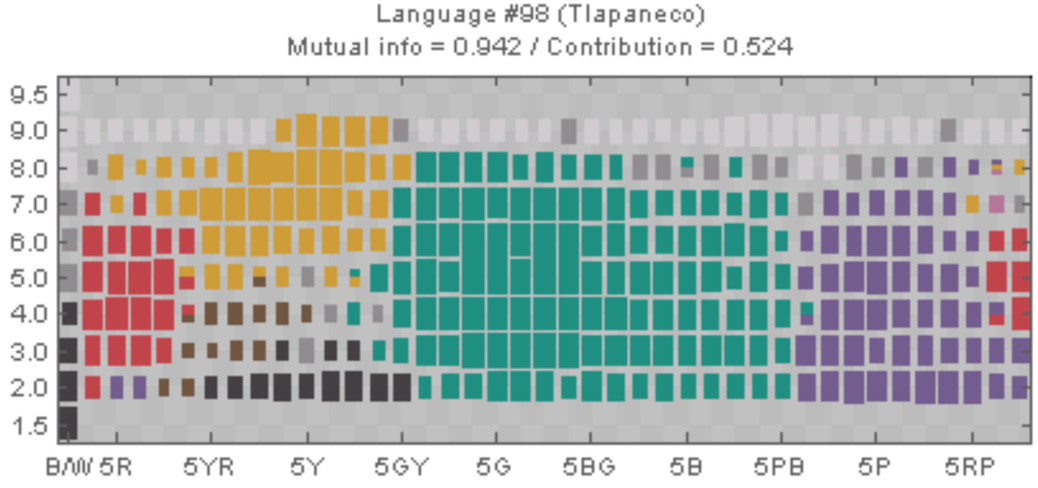


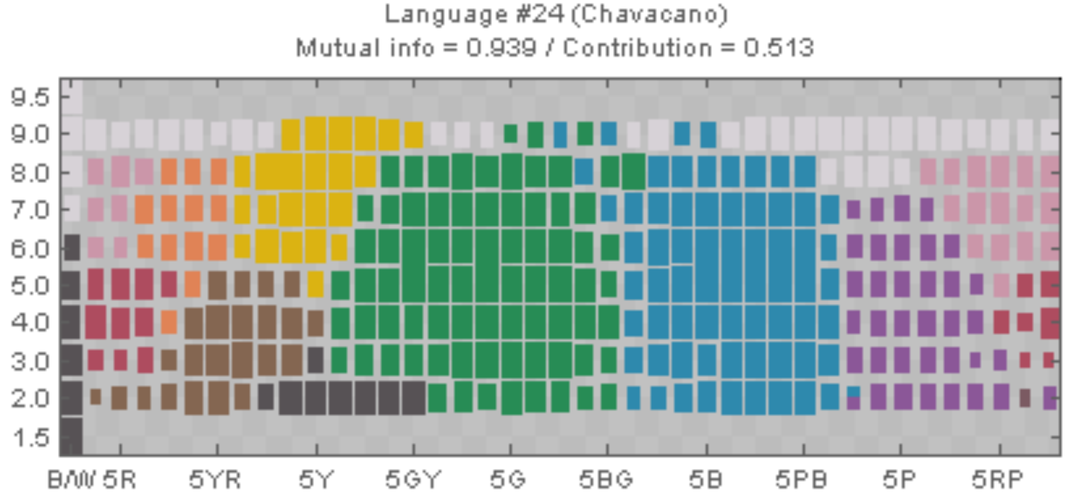
Task: Mark all the chips you would label as “red”, “green”, etc.

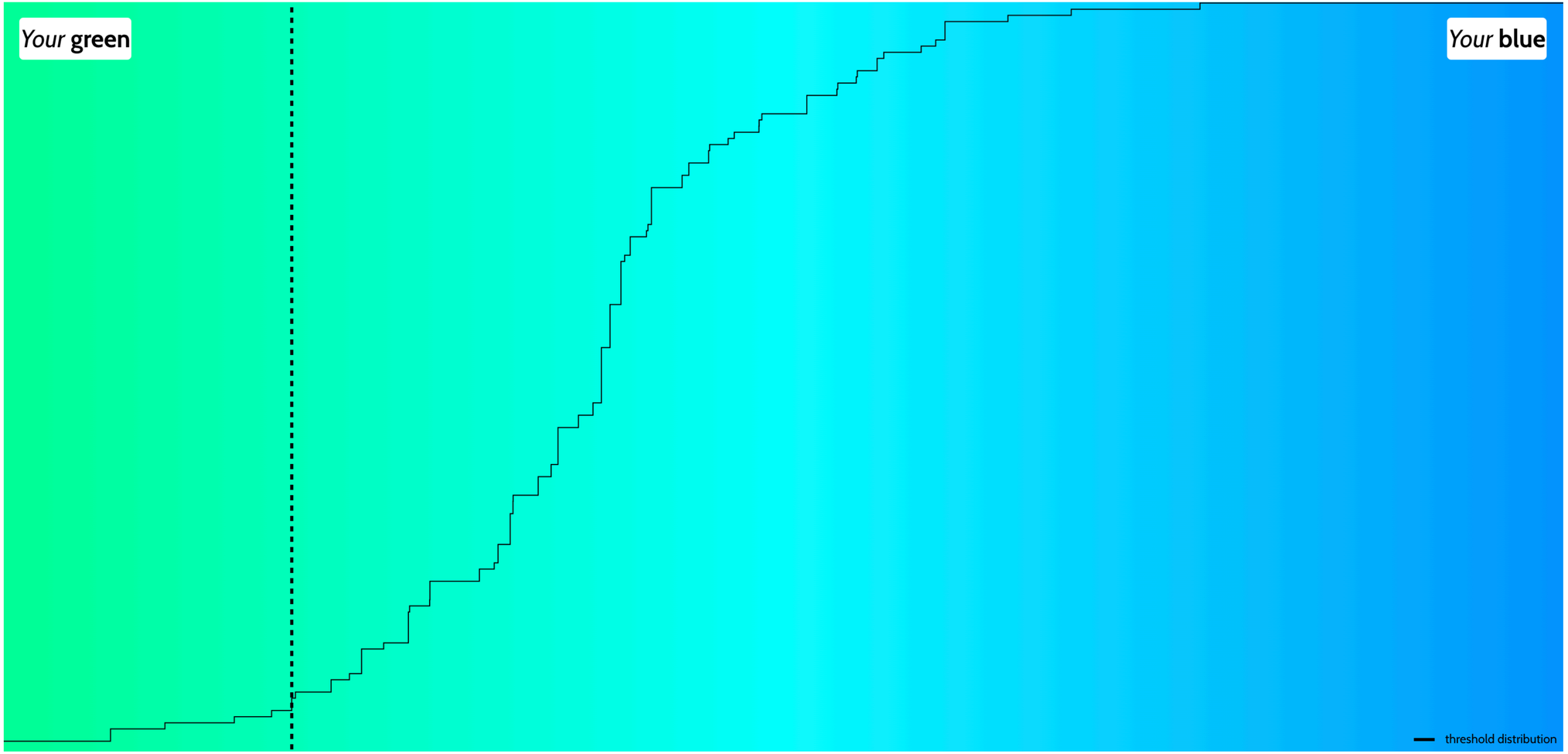
Color Naming







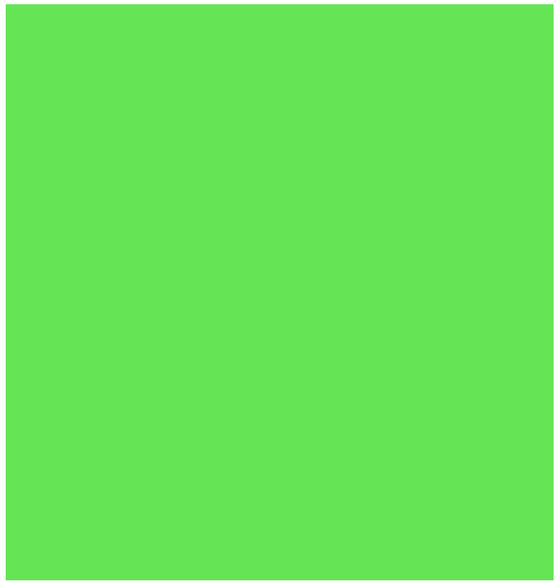


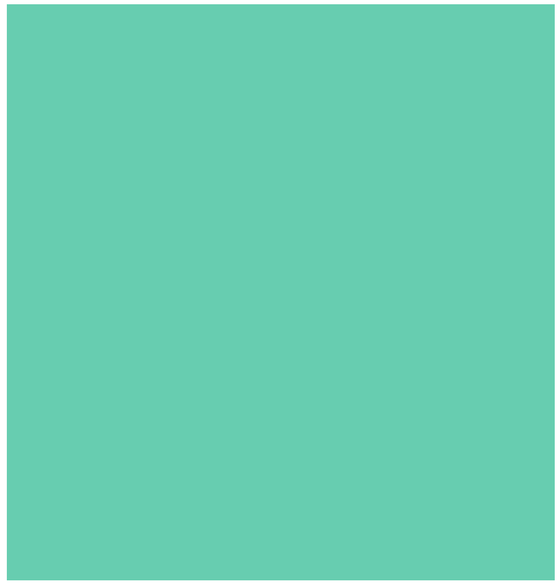


https://ismy.blue/

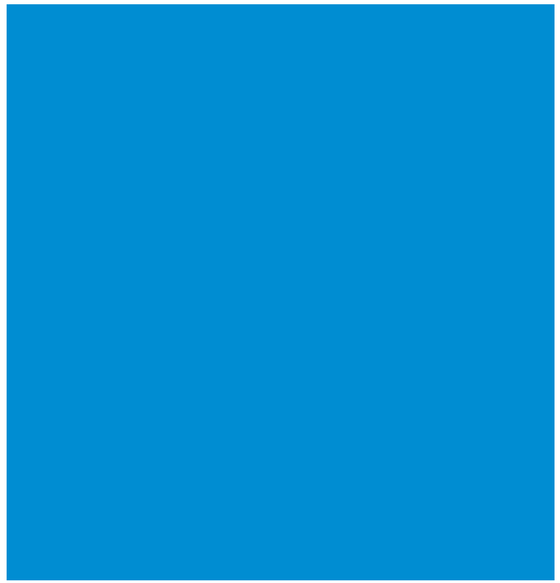
Color Naming Affects Perception

Green



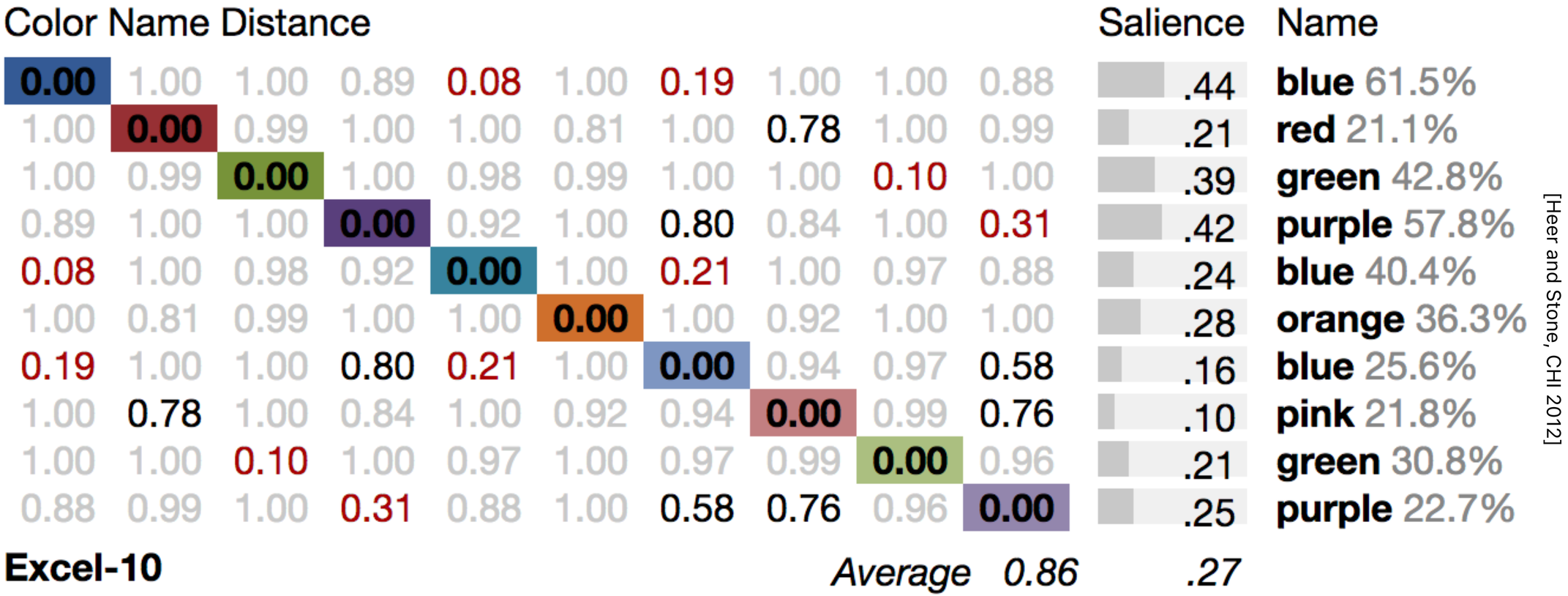


Blue



Color Naming Affects Perception

Minimize overlap and ambiguity of colors

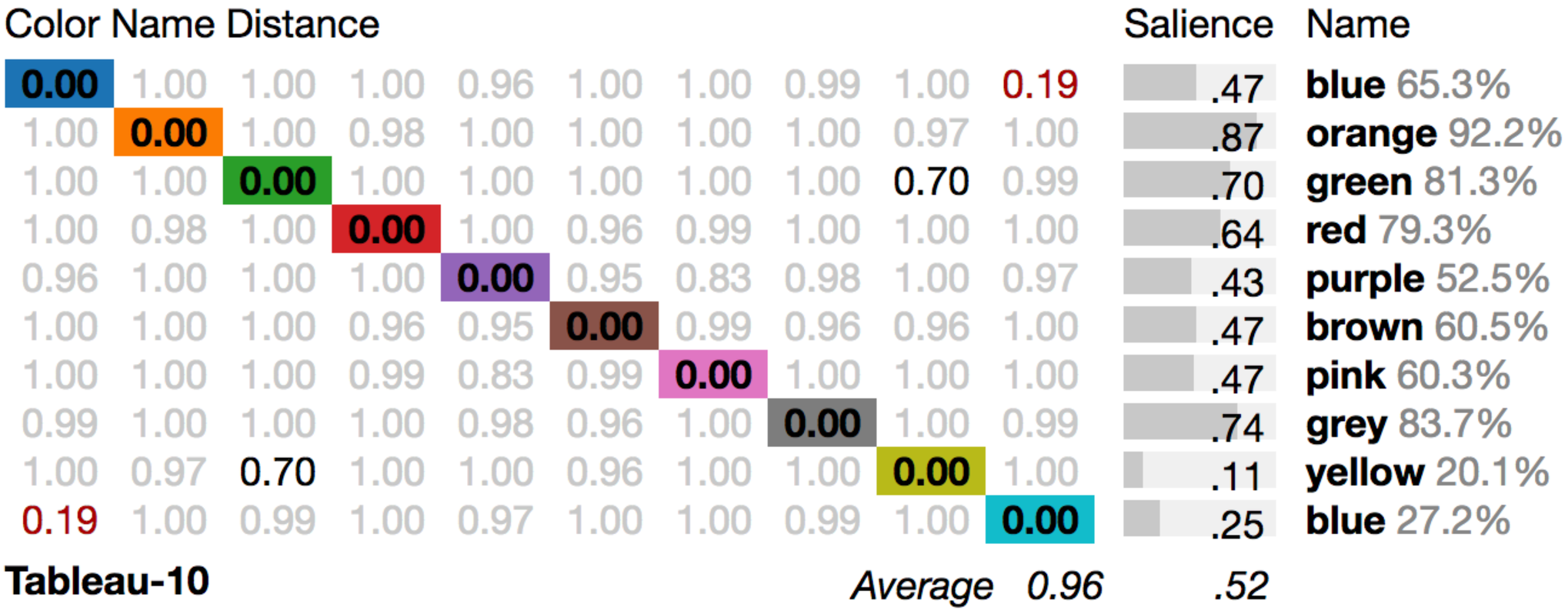


[Heer and Stone, CHI 2012]

Default color palette for Excel: confusion!

Color Naming Affects Perception

Minimize overlap and ambiguity of colors



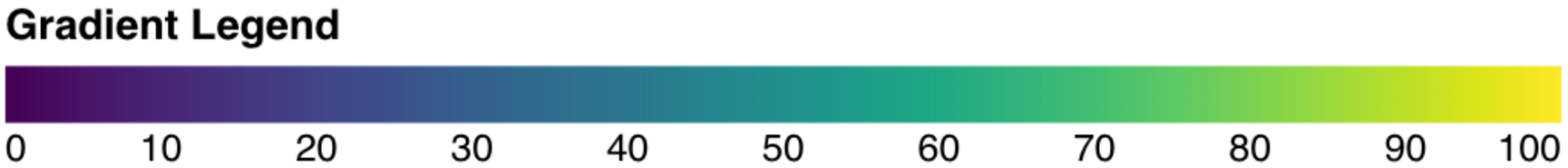
[Heer and Stone, CHI 2012]

Default color palette for Tableau: better!

Putting it together: Designing colormaps

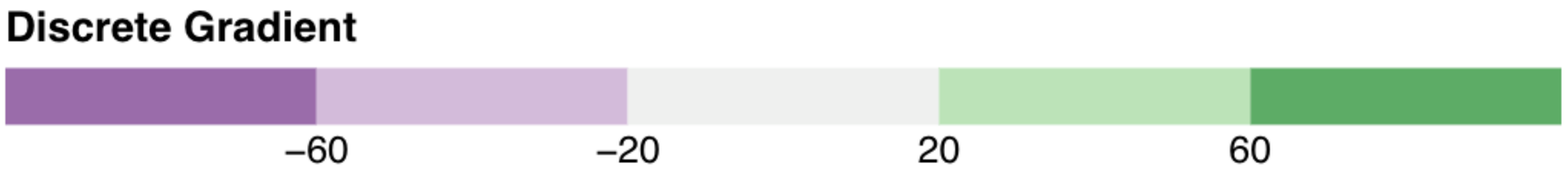
Discrete (binary, categorical)

Continuous (sequential, diverging, cyclic)

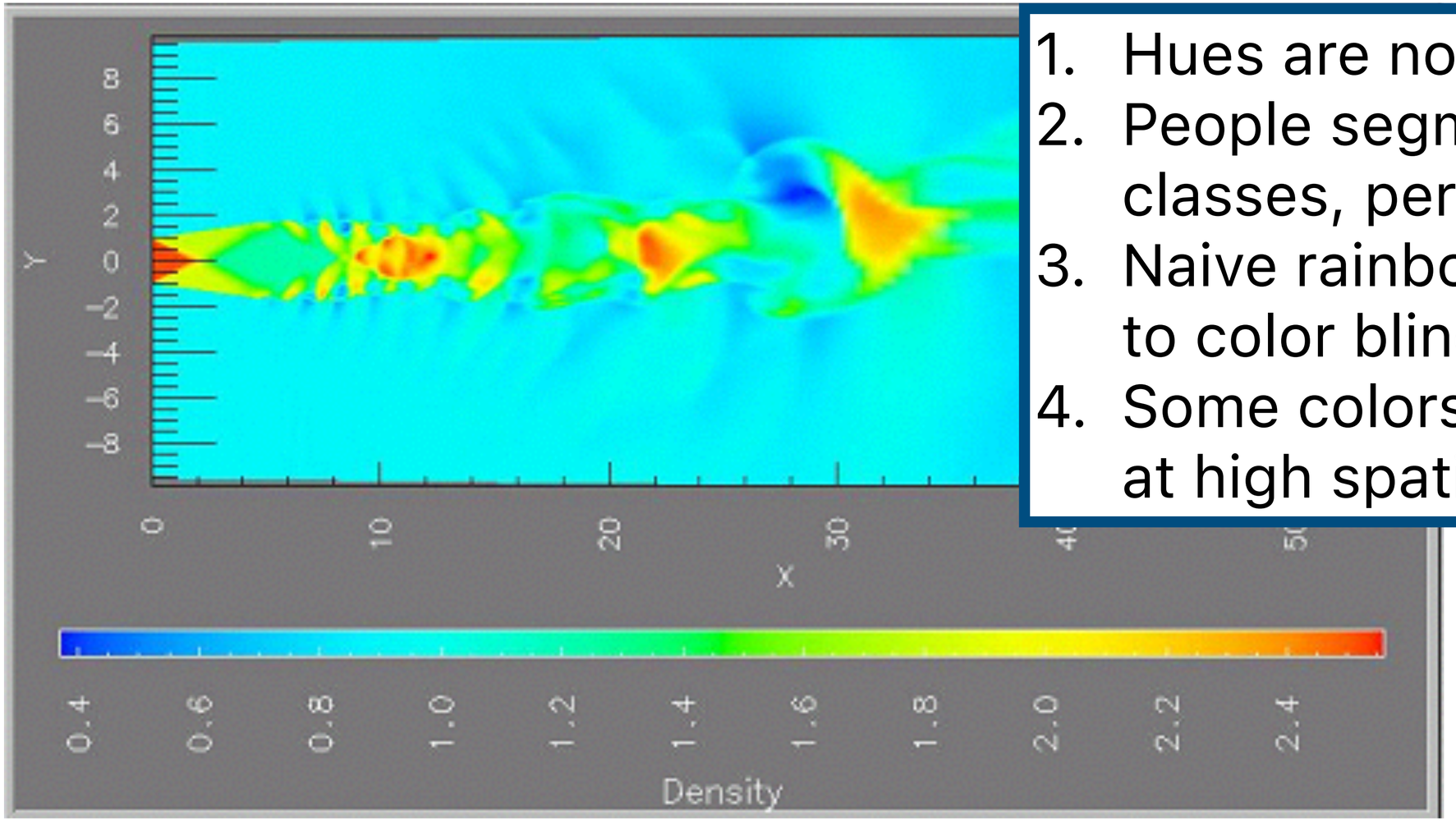


Discretized Continuous

In general, prefer this over continuous!



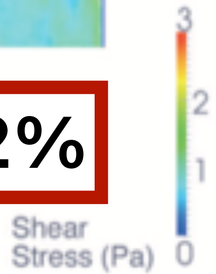
Beware of naive rainbows!



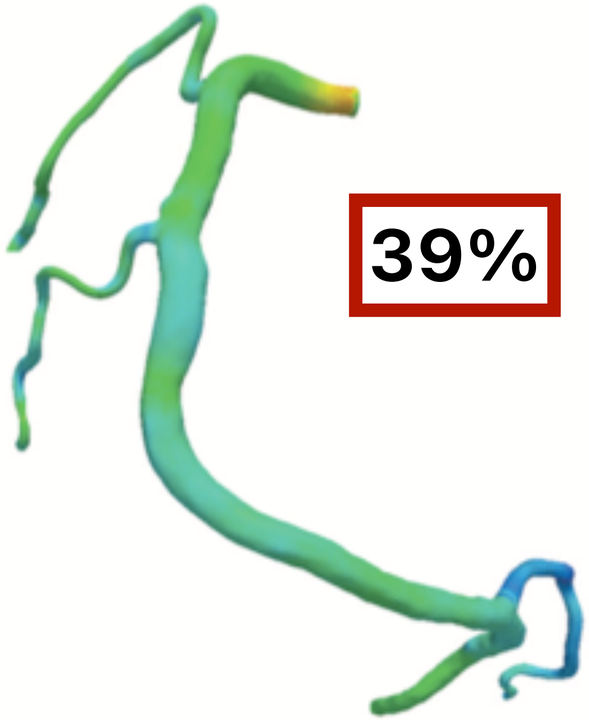
1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naive rainbows are unfriendly to color blind viewers
4. Some colors are less effective at high spatial frequencies

Beware of naive rainbows!

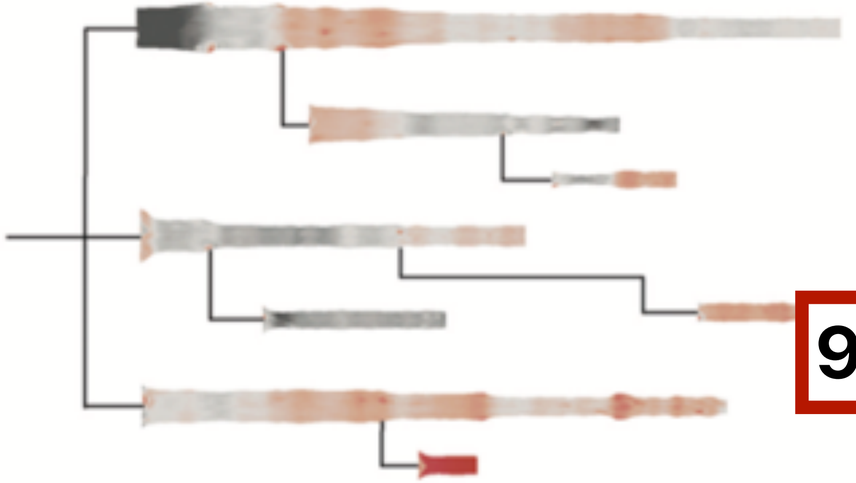
62%



Rainbow Palette

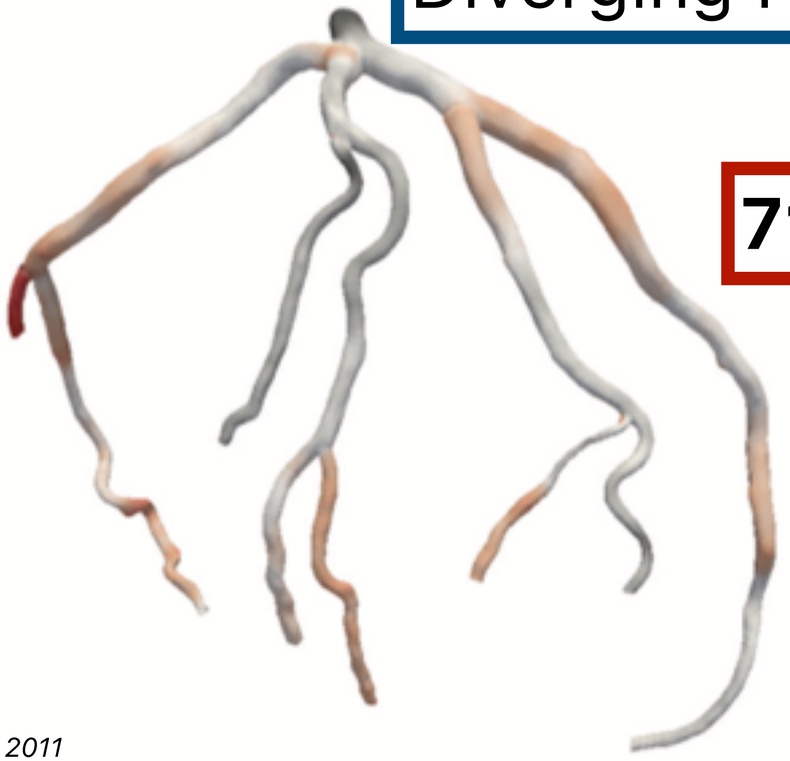


39%



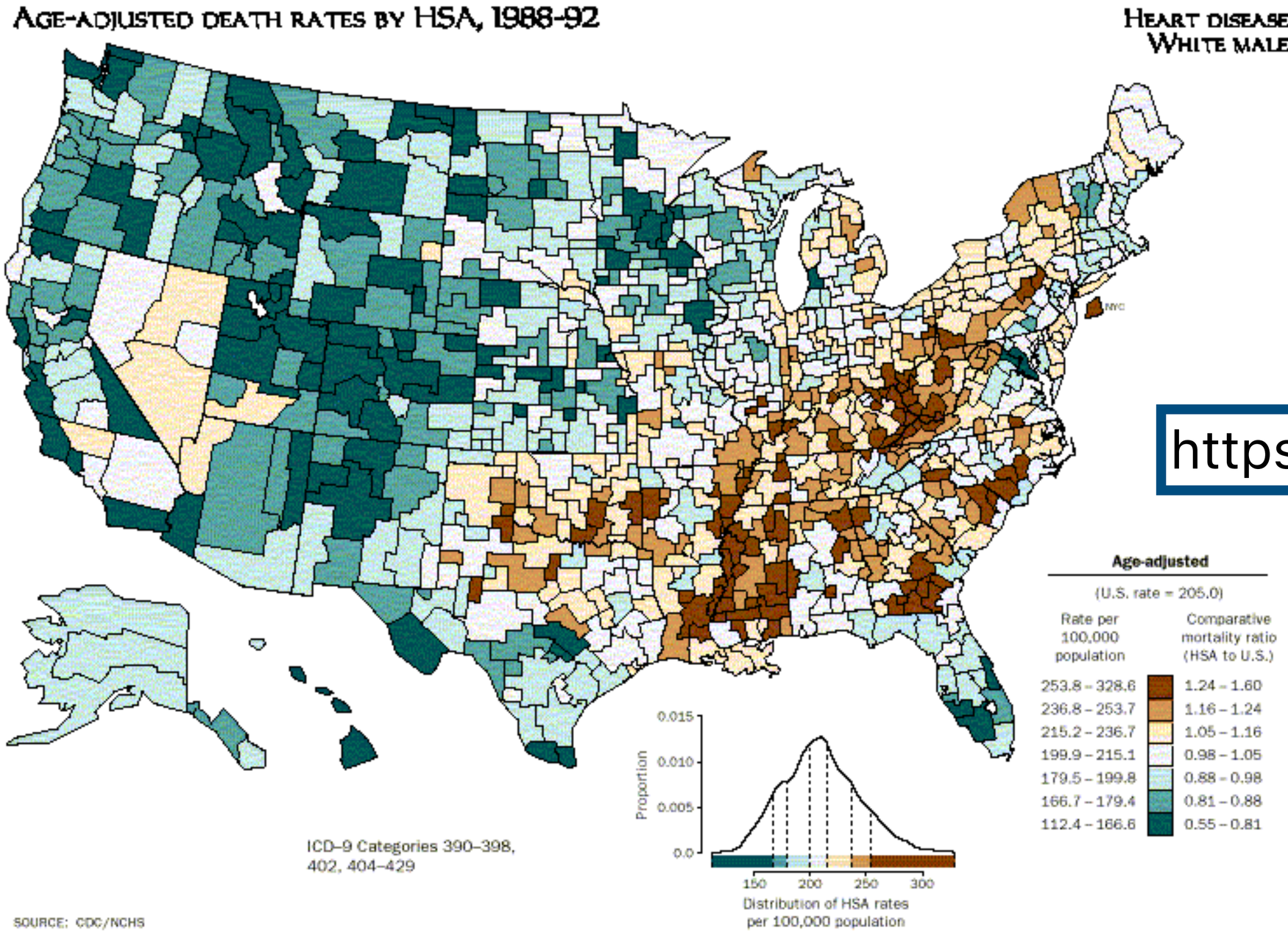
92%

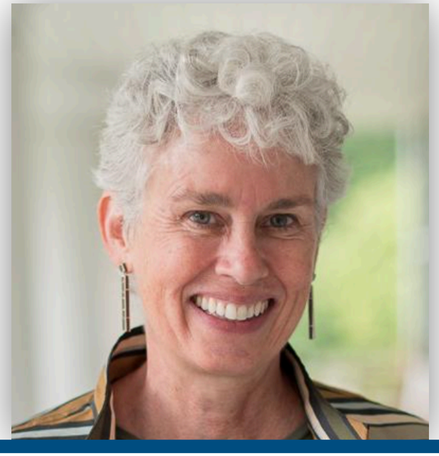
Diverging Palette



71%

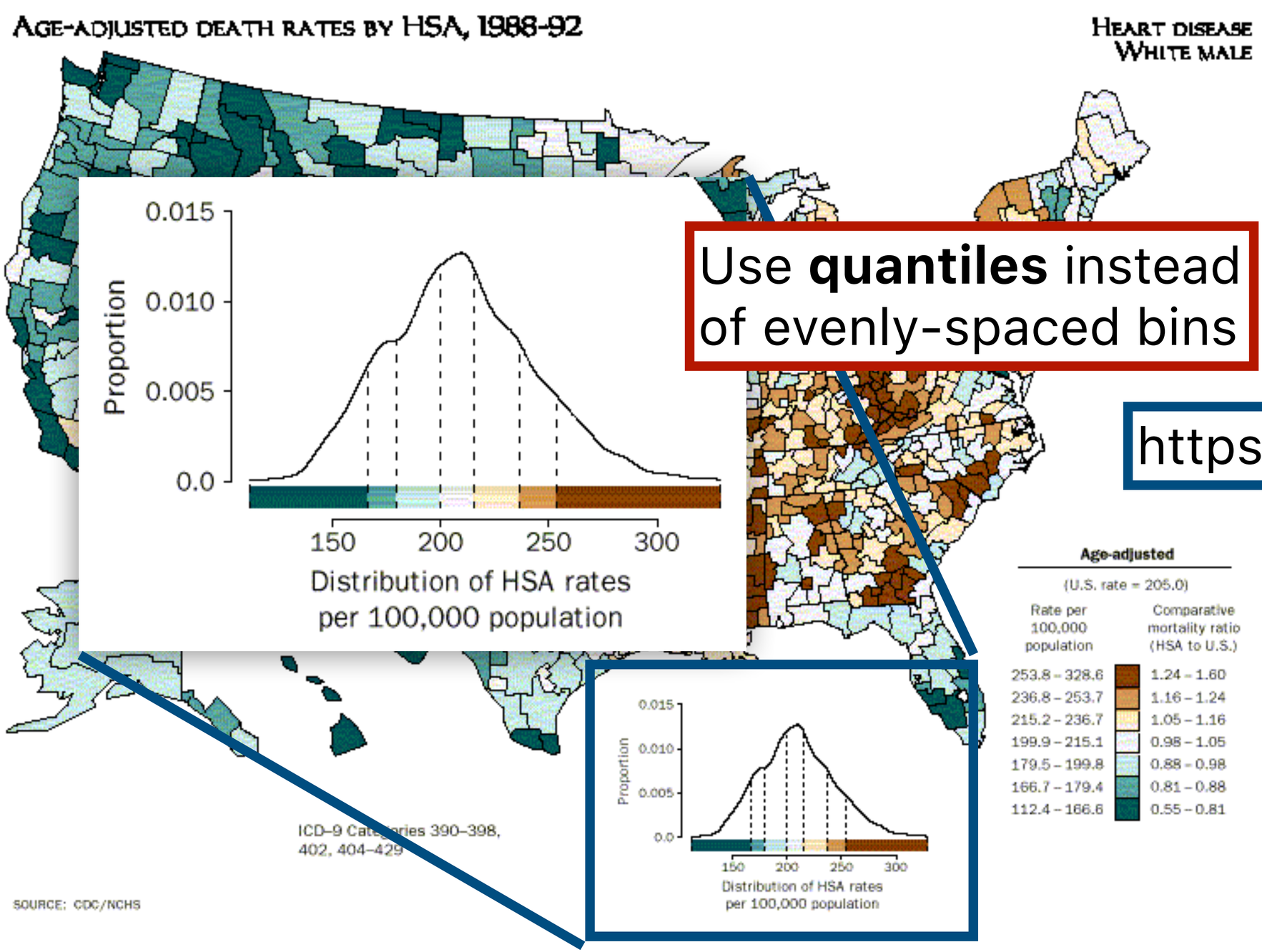
Borkin, Michelle, et al. "Evaluation of artery visualizations for heart disease diagnosis." *2011*



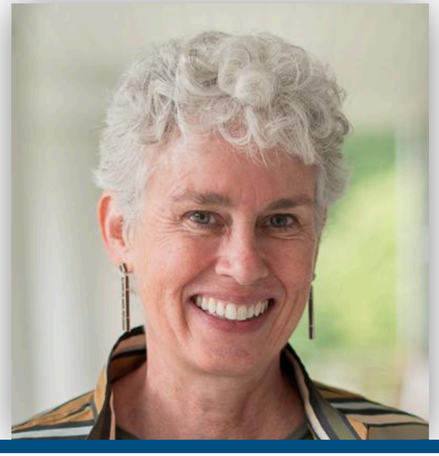


Cynthia Brewer

https://colorbrewer2.org/



Use **quantiles** instead of evenly-spaced bins

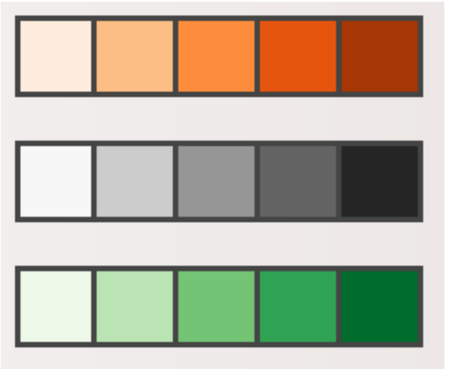


Cynthia Brewer

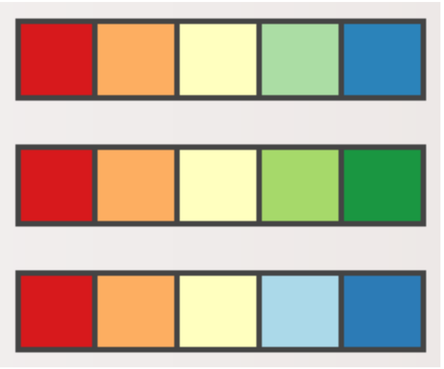
https://colorbrewer2.org/

Quantitative Color Encoding

Sequential Color Scale
Ramp in luminance, possibly also hue.
Typically higher values map to darker colors.

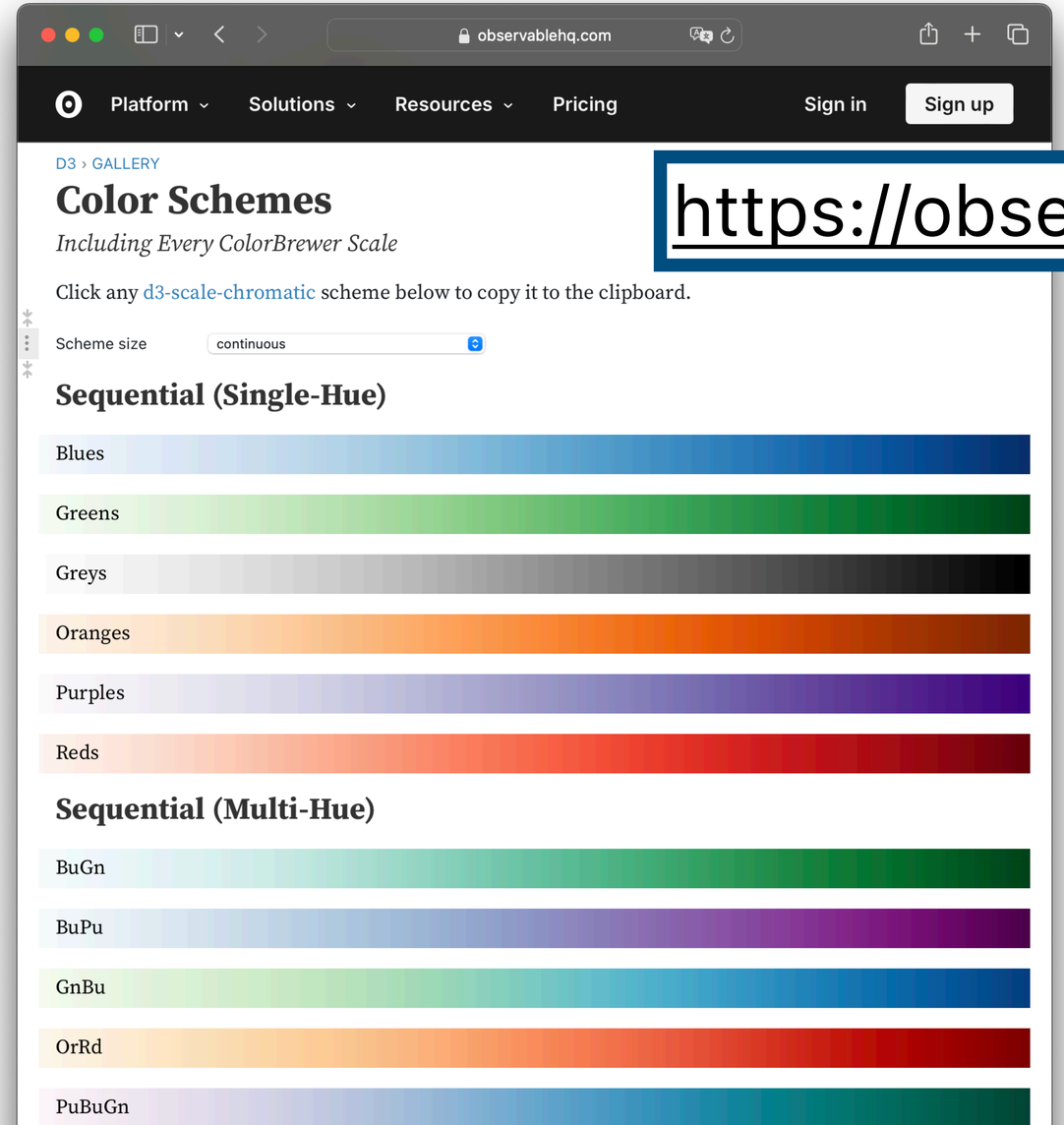


Diverging Color Scale
Useful when data has a meaningful “midpoint.”
Use neutral color (e.g., gray) for midpoint.
Use saturated colors for endpoints.



Limit number of steps in color to 3–7!

Use Perceptually Uniform Color Schemes!



https://observablehq.com/@d3/color-schemes

Takeaways

Use only a few colors (~5 ideally)

Colors should be distinctive and named.

Use/respect cultural conventions; appreciate symbolism.

Get it right in black and white.

Respect the color blind.

Take advantage of perceptual color spaces.