

Color in Computer Graphics

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Your Intensity/Color Sensors

Rods

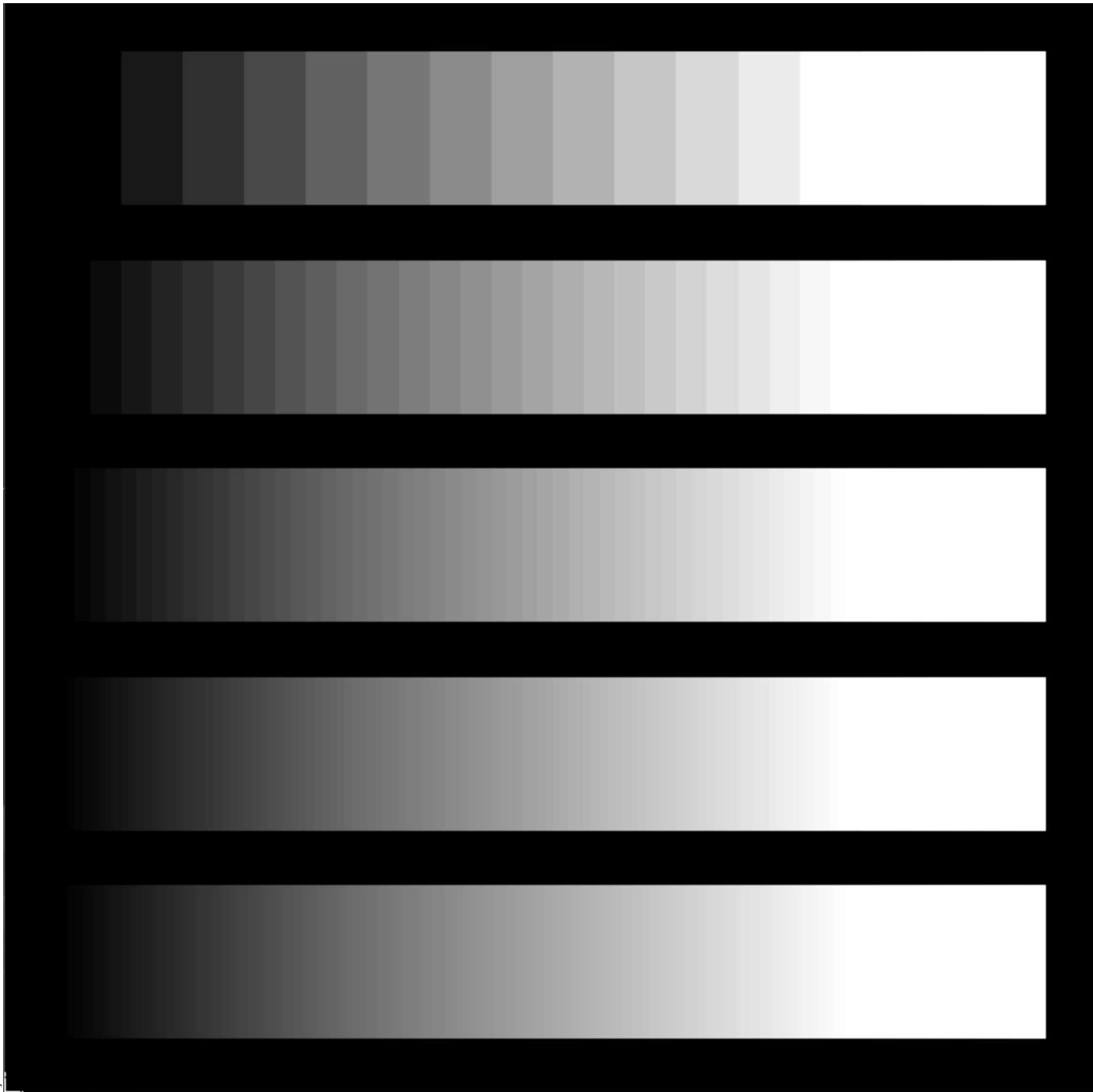
- ~115,000,000
- Concentrated on the *periphery* of the retina
- Sensitive to *intensity*
- Most sensitive at 500 nm (~green)

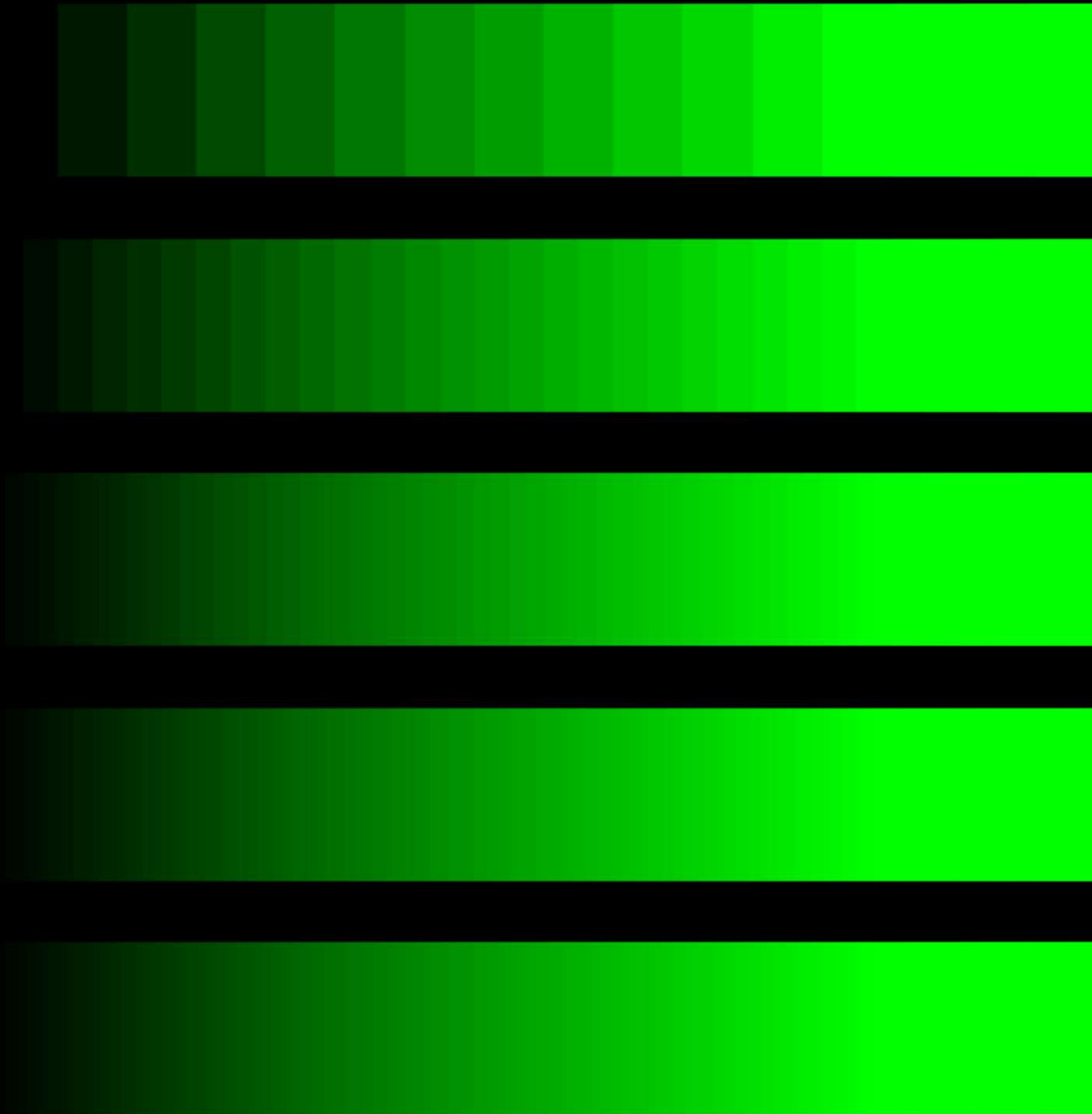
Cones

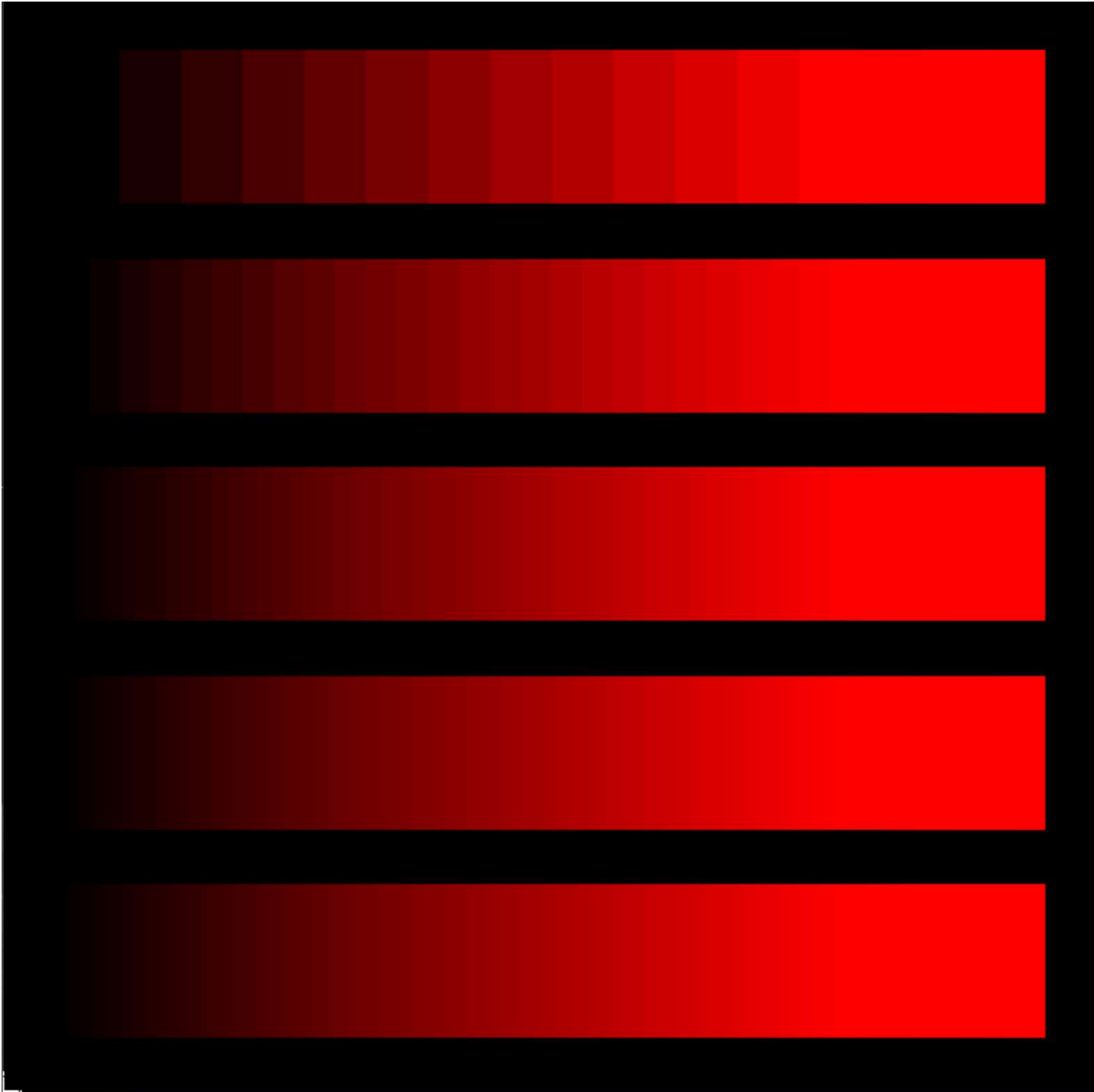
- ~7,000,000
- Concentrated near the *center* of the retina
- Sensitive to *color*
- Three types of cones: long(~red), medium (~green), and short (~blue) wavelengths

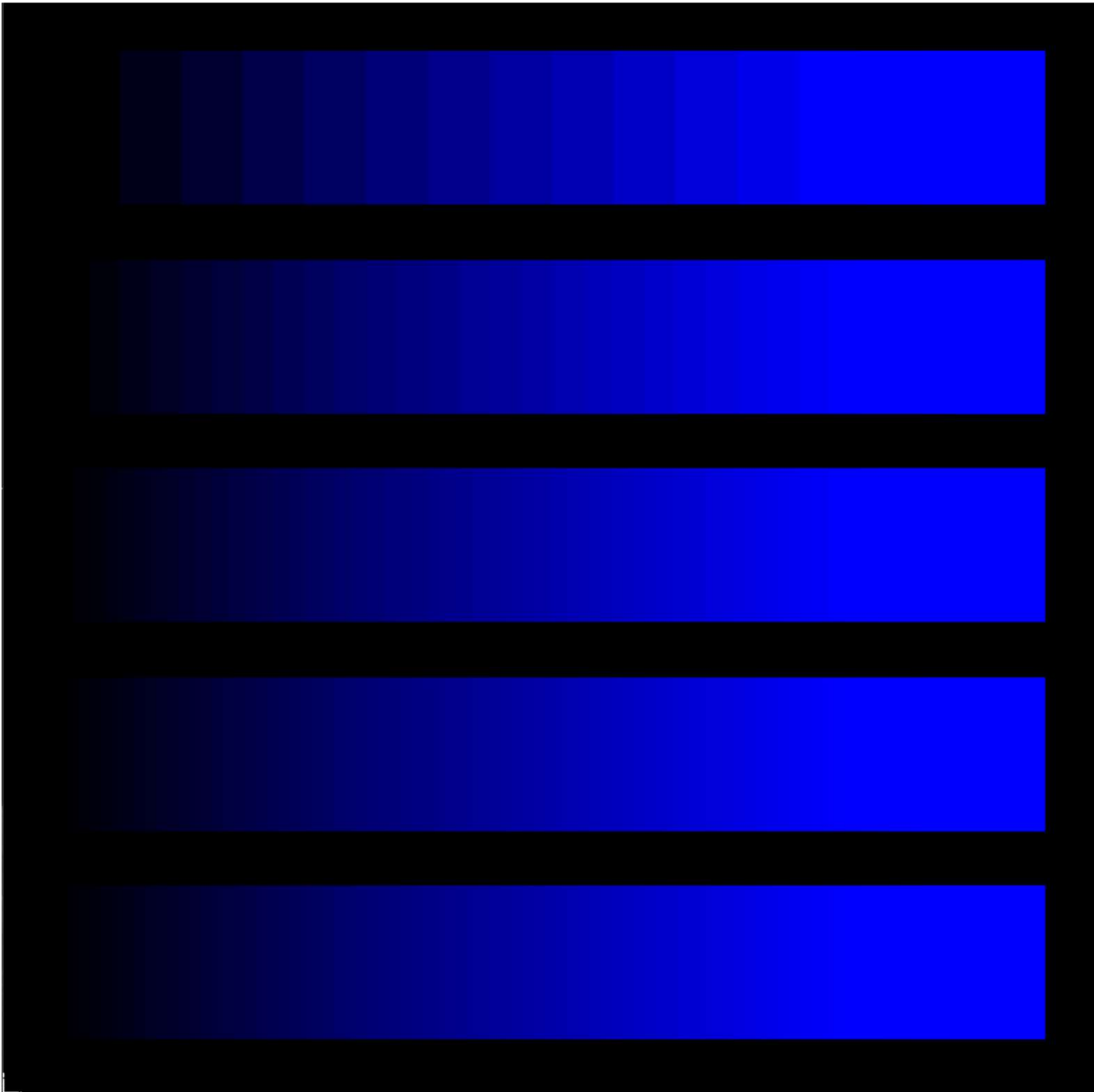


But, are you equally-sensitive to all wavelengths?









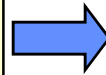
Sidebar: How Many Pixels Do You Need?

7

A person with 20/20 vision has a visual acuity of:
1 arc-minute = $1/60^\circ$

$$\Theta = 1/60^\circ = .00029^R$$

$$\text{Density} = \frac{1}{D\Theta}$$



Viewing Distance (inches)	Required Pixel Density (ppi)
36	95
31	111
24	143
12	286
9	400
6	600

If the monitor's
resolution is 1600
x 1200, then its
diagonal size
would need to be:

21"

18"

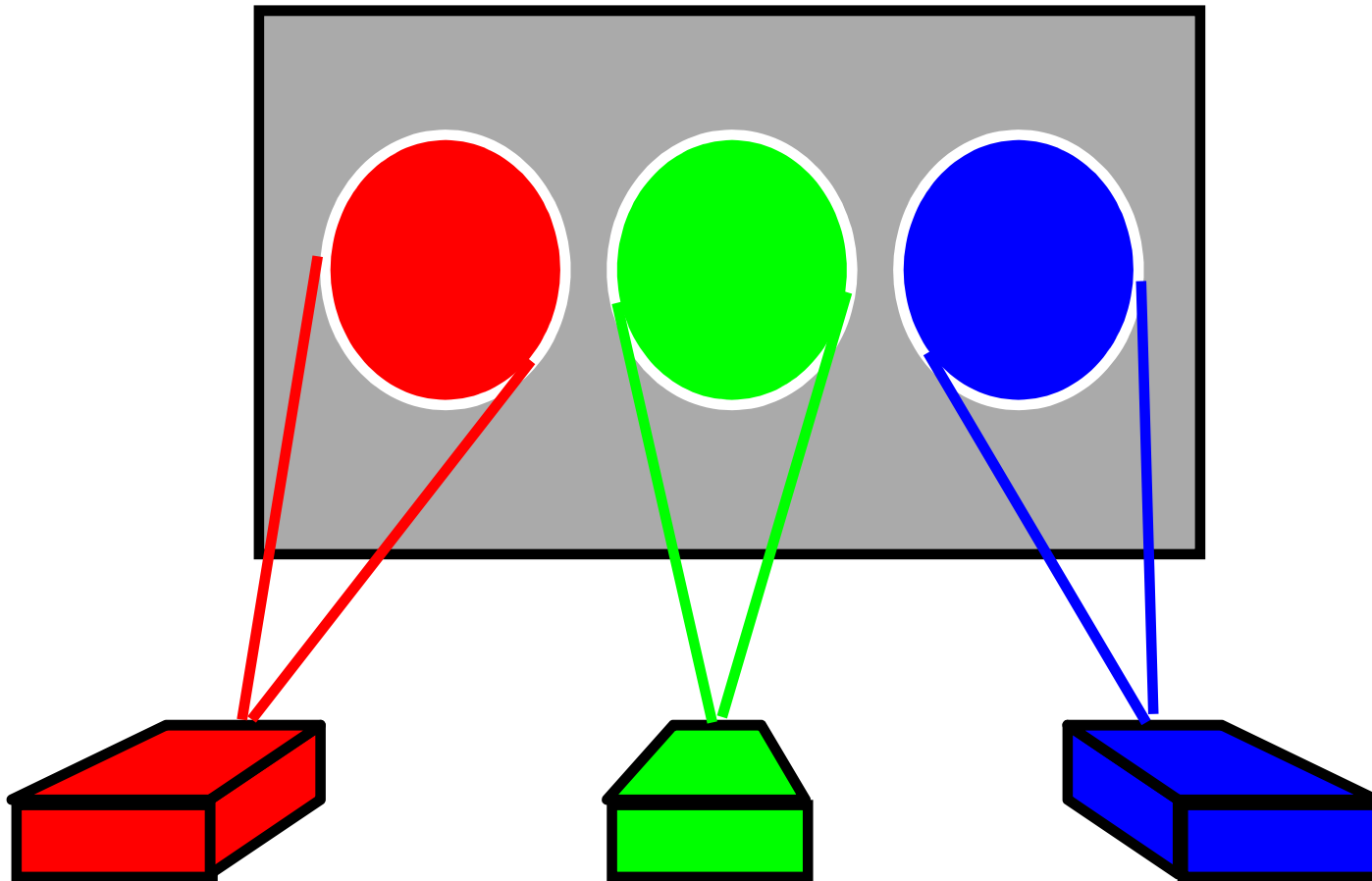
14"

7"

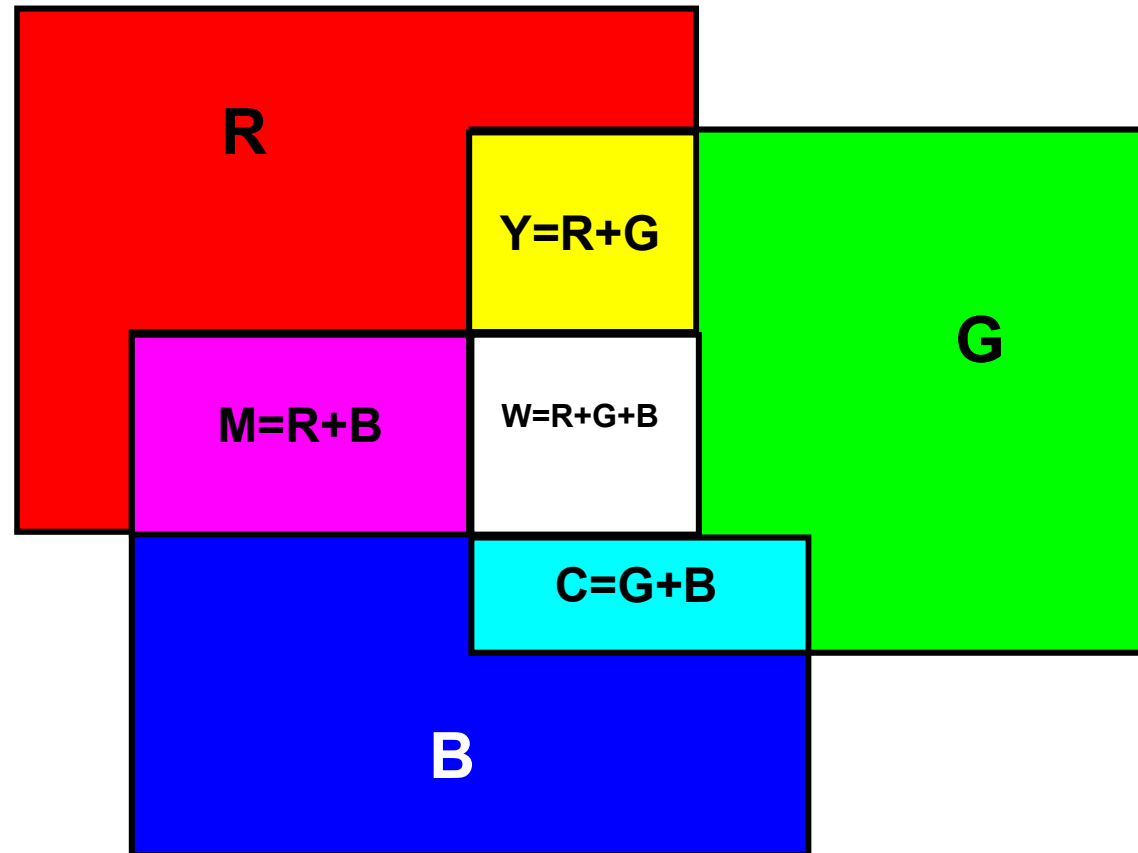
5"

3"

Monitors: Additive Colors



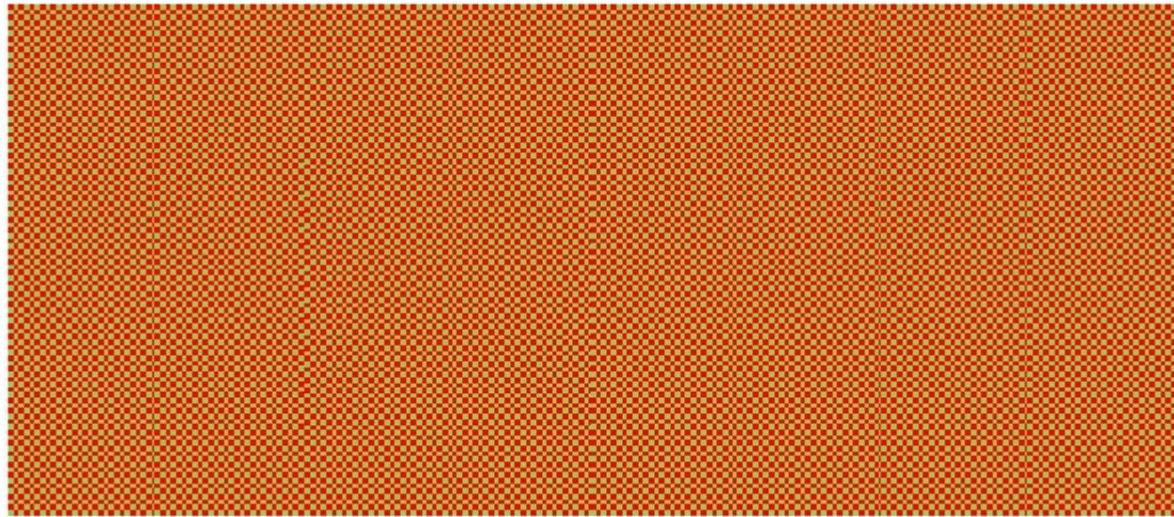
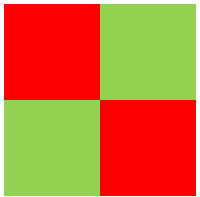
Additive Color (RGB)



OpenGL: \longrightarrow `glColor3f(r, g, b);`

$$0. \leq r, g, b \leq 1.$$

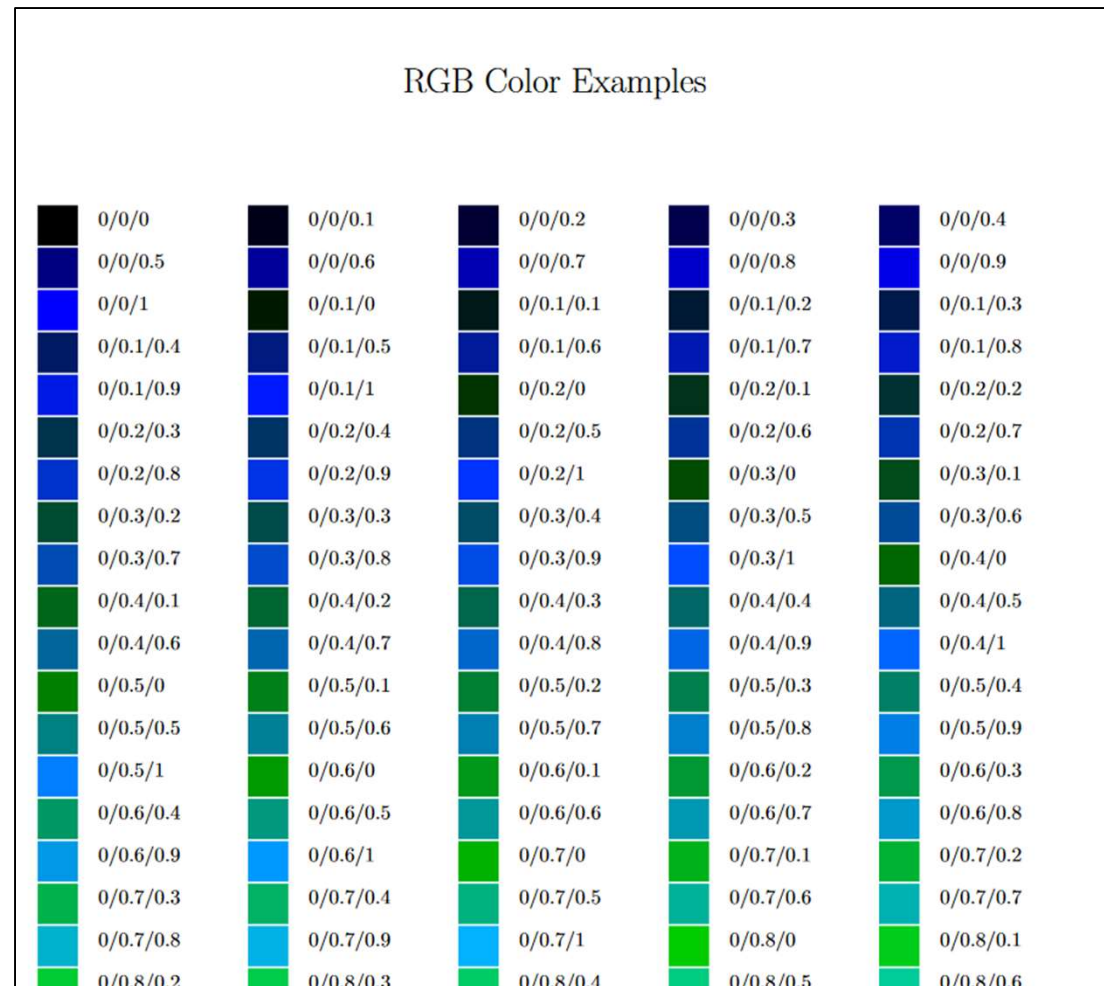
Yes, Our Vision System Really Does Mush Red and Green Together to Make Yellow!



Color Combinations

Here's a cool website that shows a lot of different color combinations:

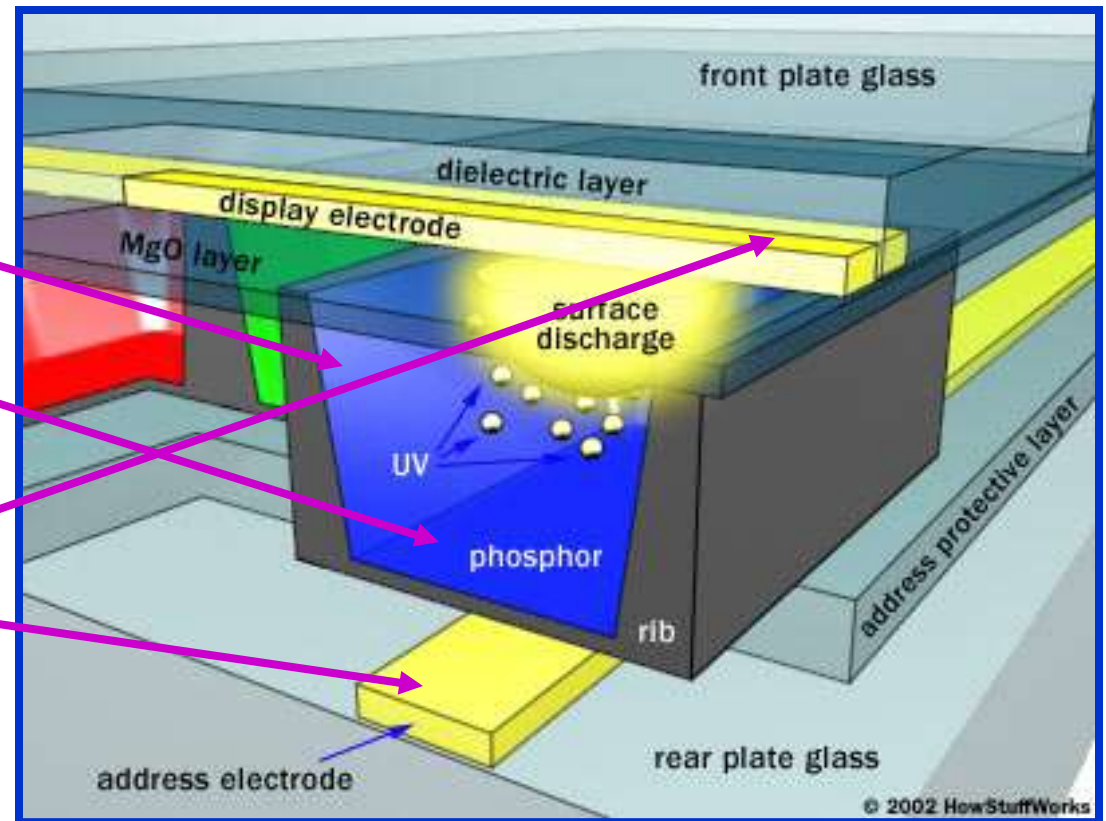
<https://www.tug.org/pracjourn/2007-4/walden/color.pdf>



Plasma Displays and LED Displays Emit Color

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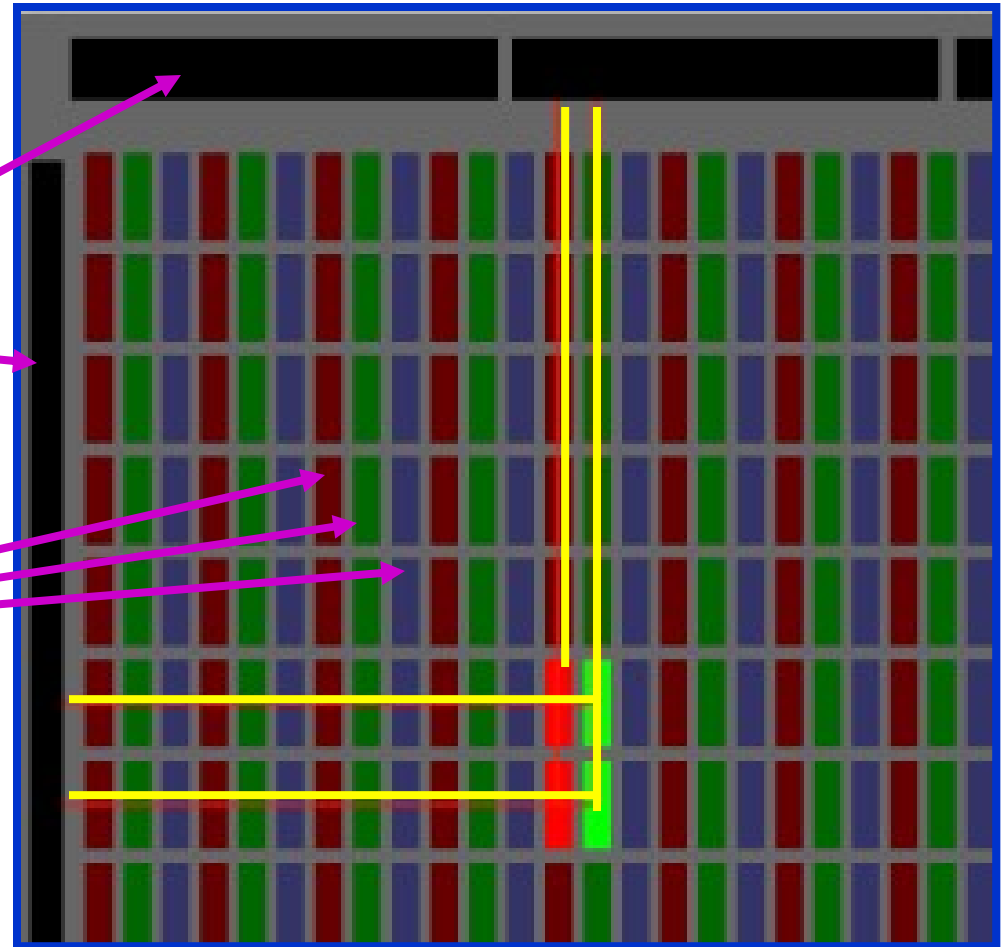
- Gas cell
- Phosphor
- Grid of electrodes



LCD Displays “Gate” Color

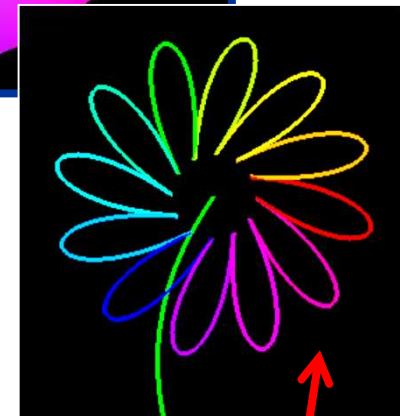
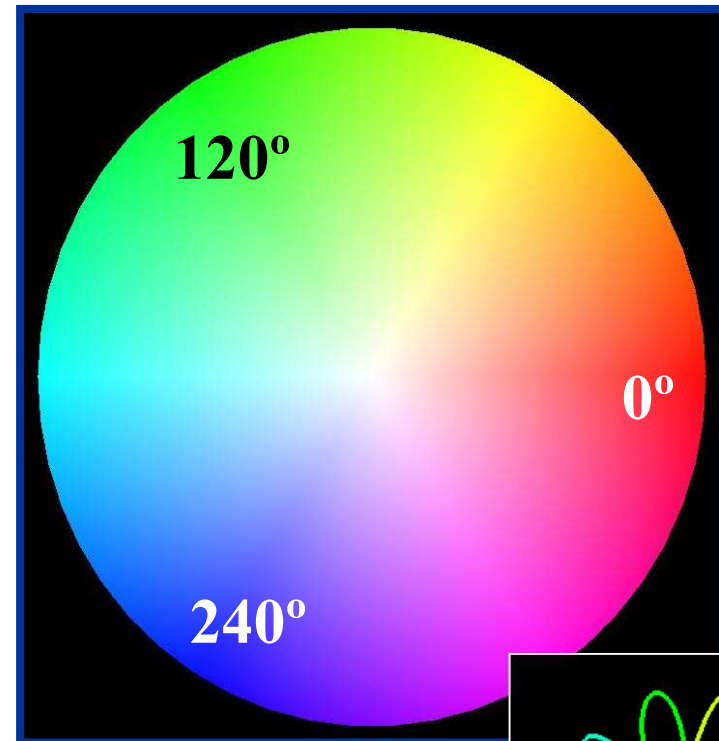
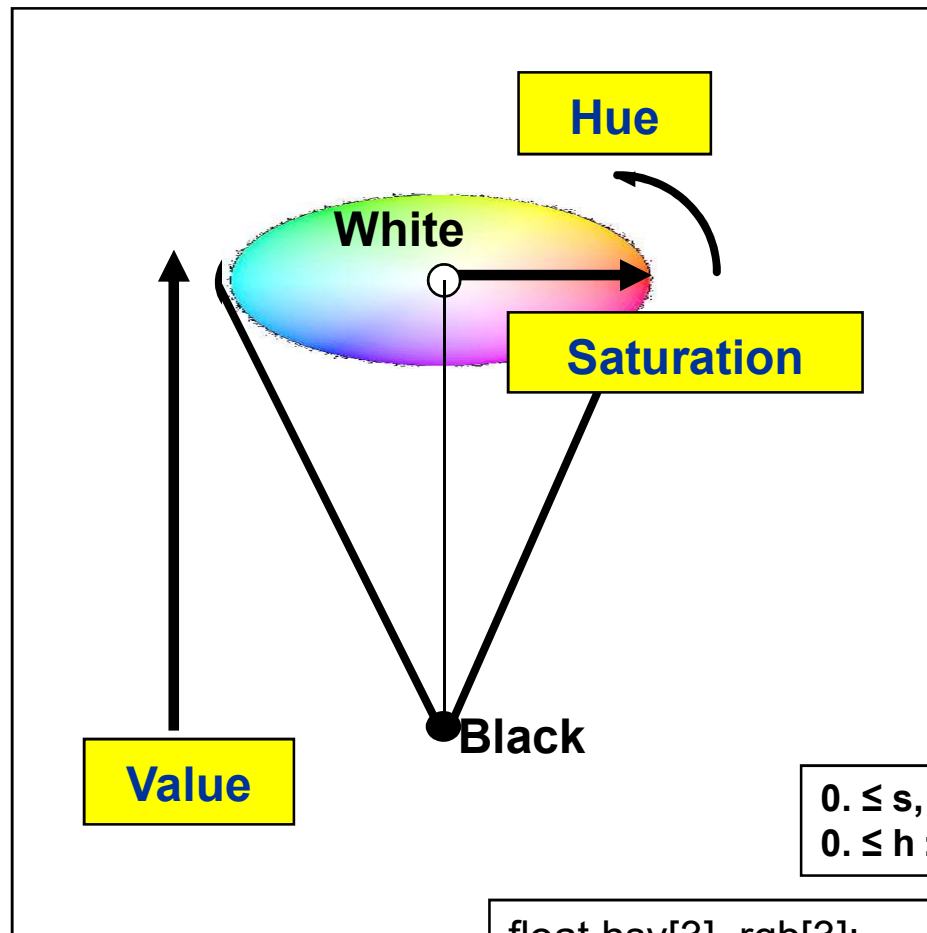
- Grid of electrodes

- Color filters



Hue-Saturation-Value (HSV):

For many applications, a more intuitive way to specify additive color



$0. \leq s, v, r, g, b \leq 1.$
 $0. \leq h \leq 360.$

```
float hsv[3], rgb[3];
hsv[0] = something between 0. and 360.
hsv[1] = hsv[2] = 1.;
HsvRgb( hsv, rgb );
glColor3fv( rgb );
```



The HsvRgb() function
is in your sample code

Marching around the Hue color wheel is
a nice way to get a range of colors

Home Depot uses a form of HSV :-)

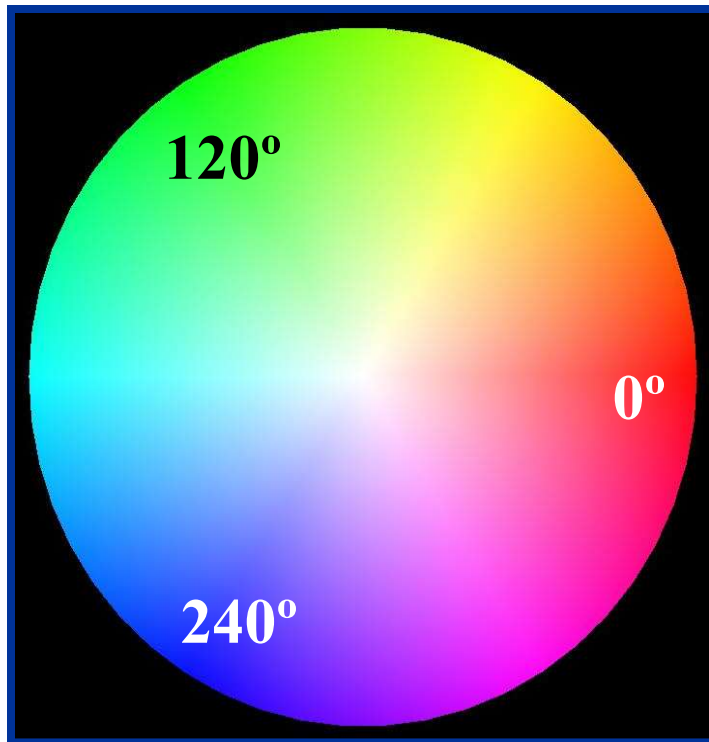
15



Hue-Saturation-Value (HSV):

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For many vis applications, a simpler way to specify additive color

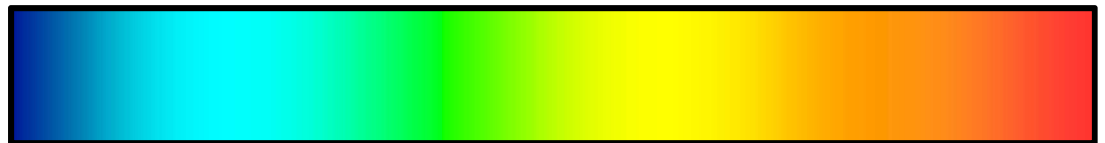


Notice that blue-green-red in HSV space corresponds to the visible portion of the electromagnetic spectrum

Blue: 380 nm

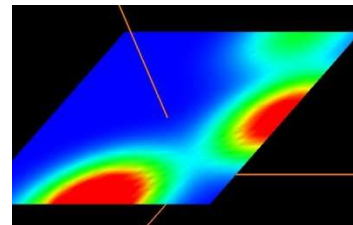
Green: 520 nm

Red: 780 nm

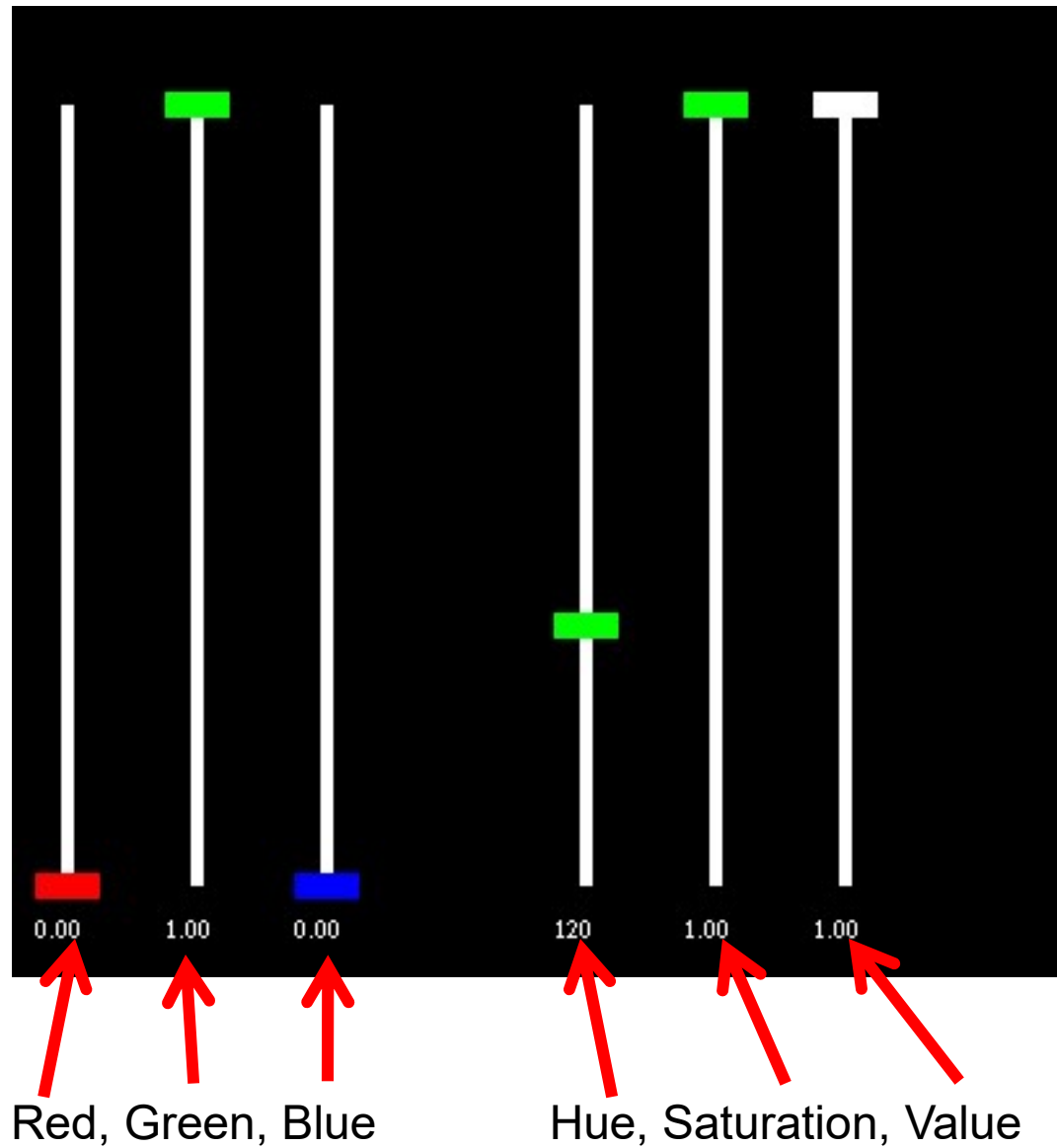


Turning a scalar value into a hue when using the Rainbow Color Scale

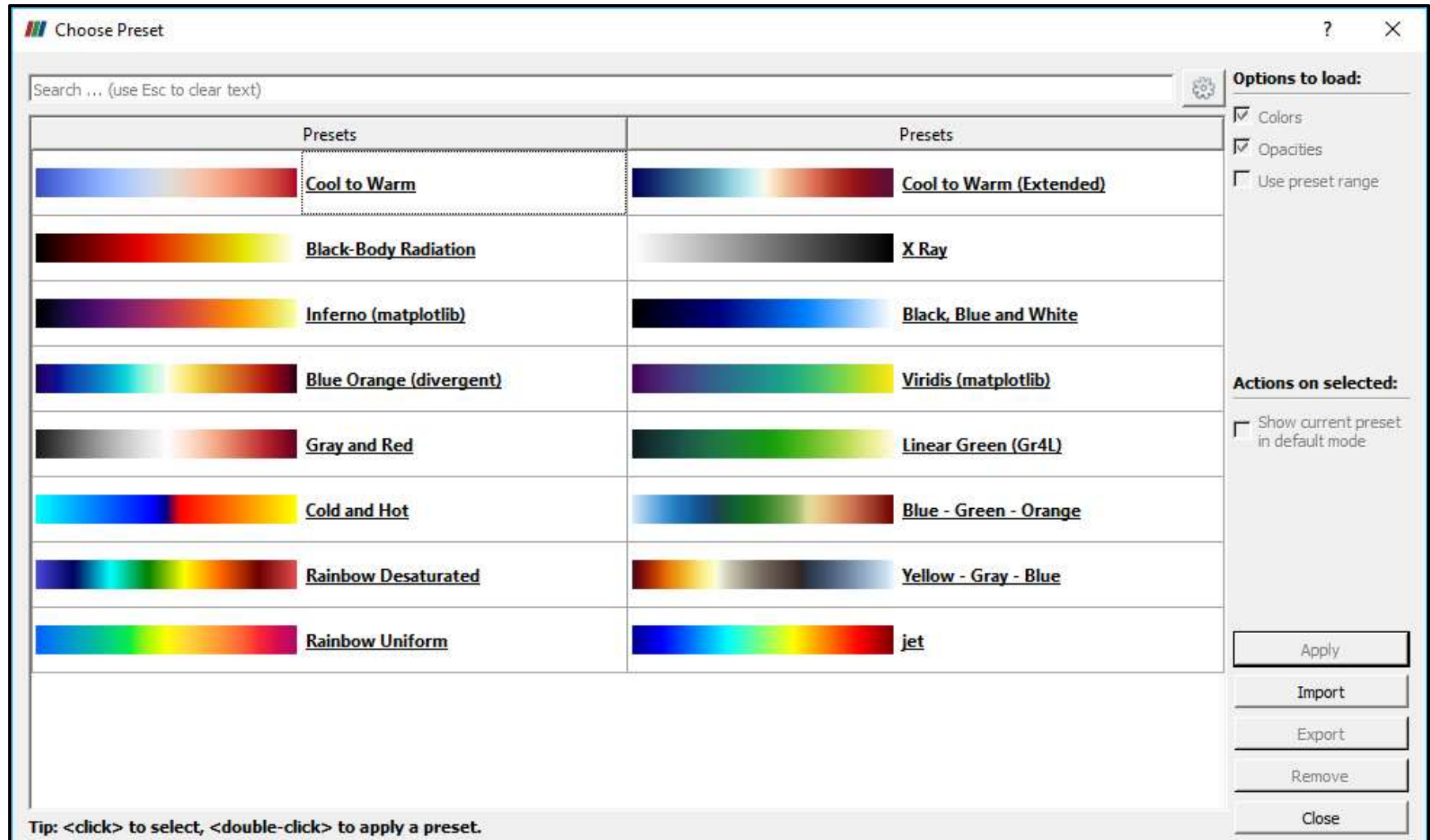
$$Hue = 240. - 240. \frac{S - S_{\min}}{S_{\max} - S_{\min}}$$



Hue-Saturation-Value: The *OSU ColorPicker* Program

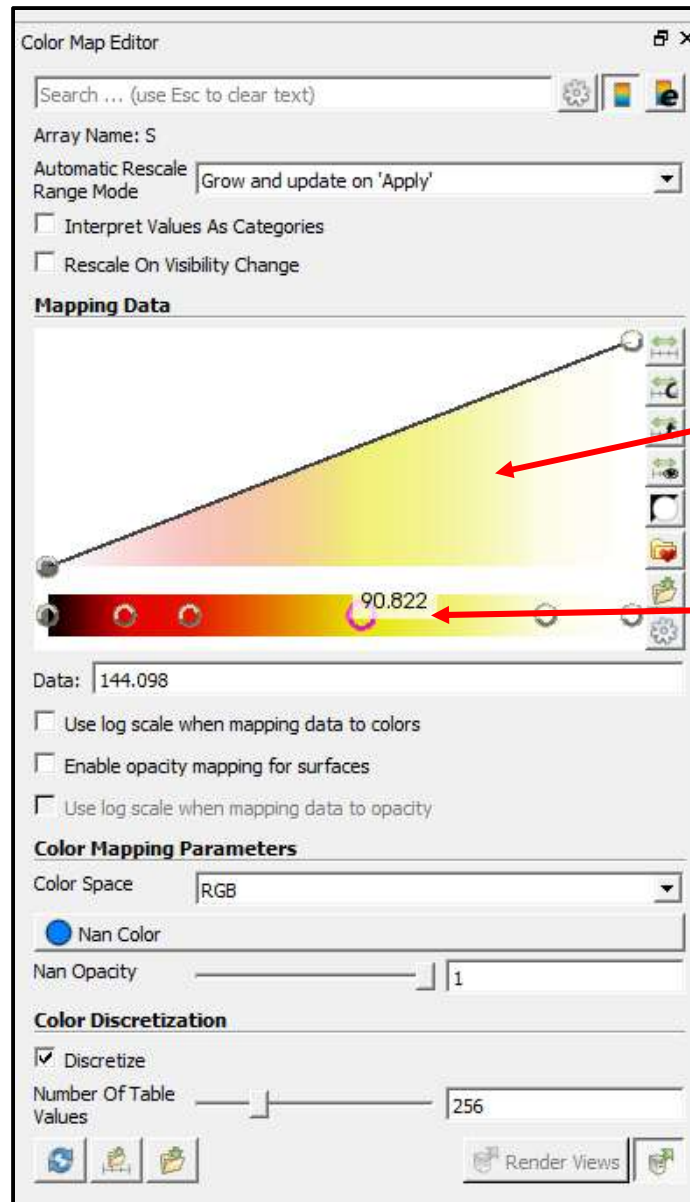


ParaView Allows You to Pick Among Several Preset Color Ranges¹⁸



ParaView Allows You to Sculpt Your Own Color Range

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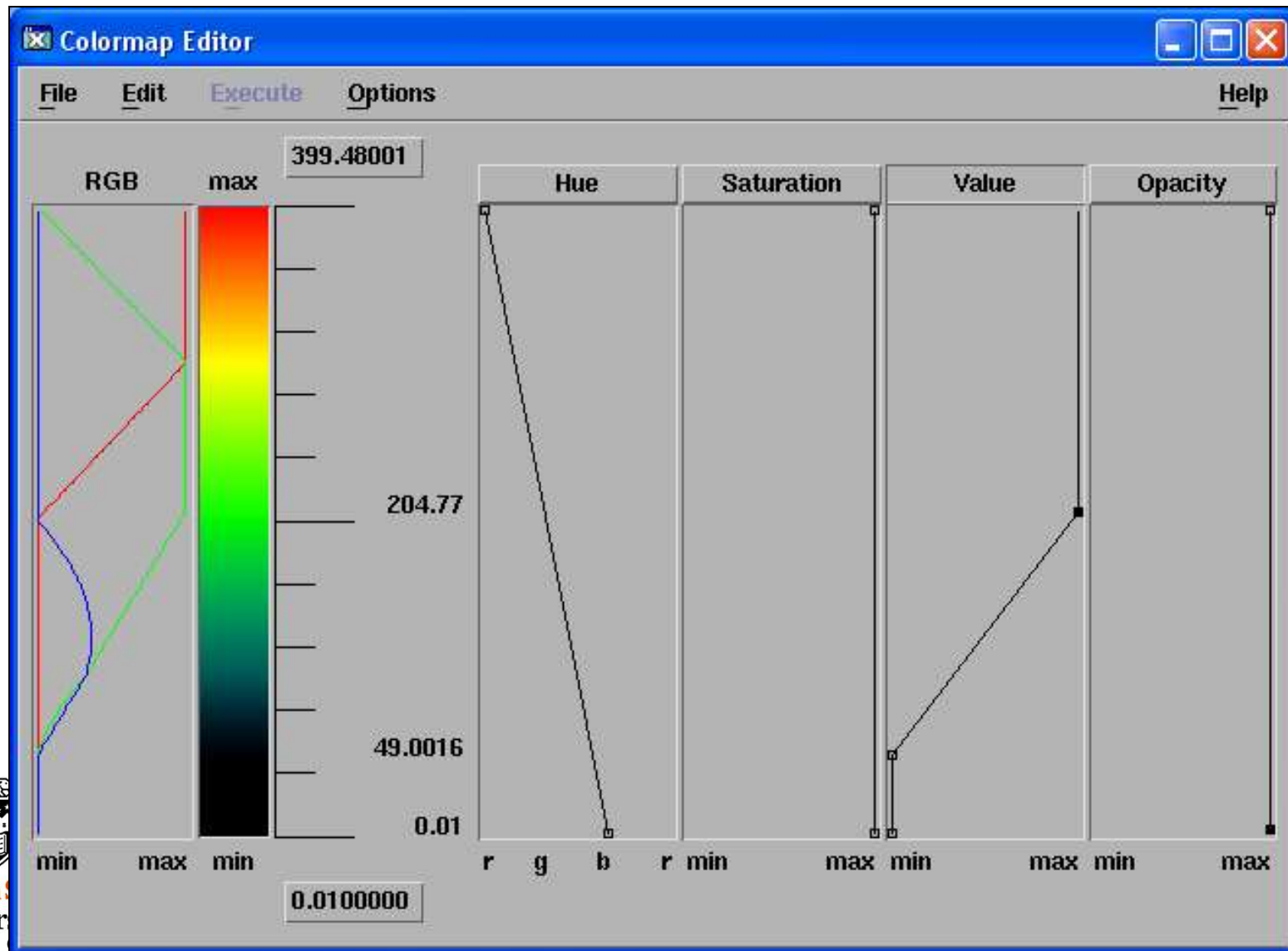


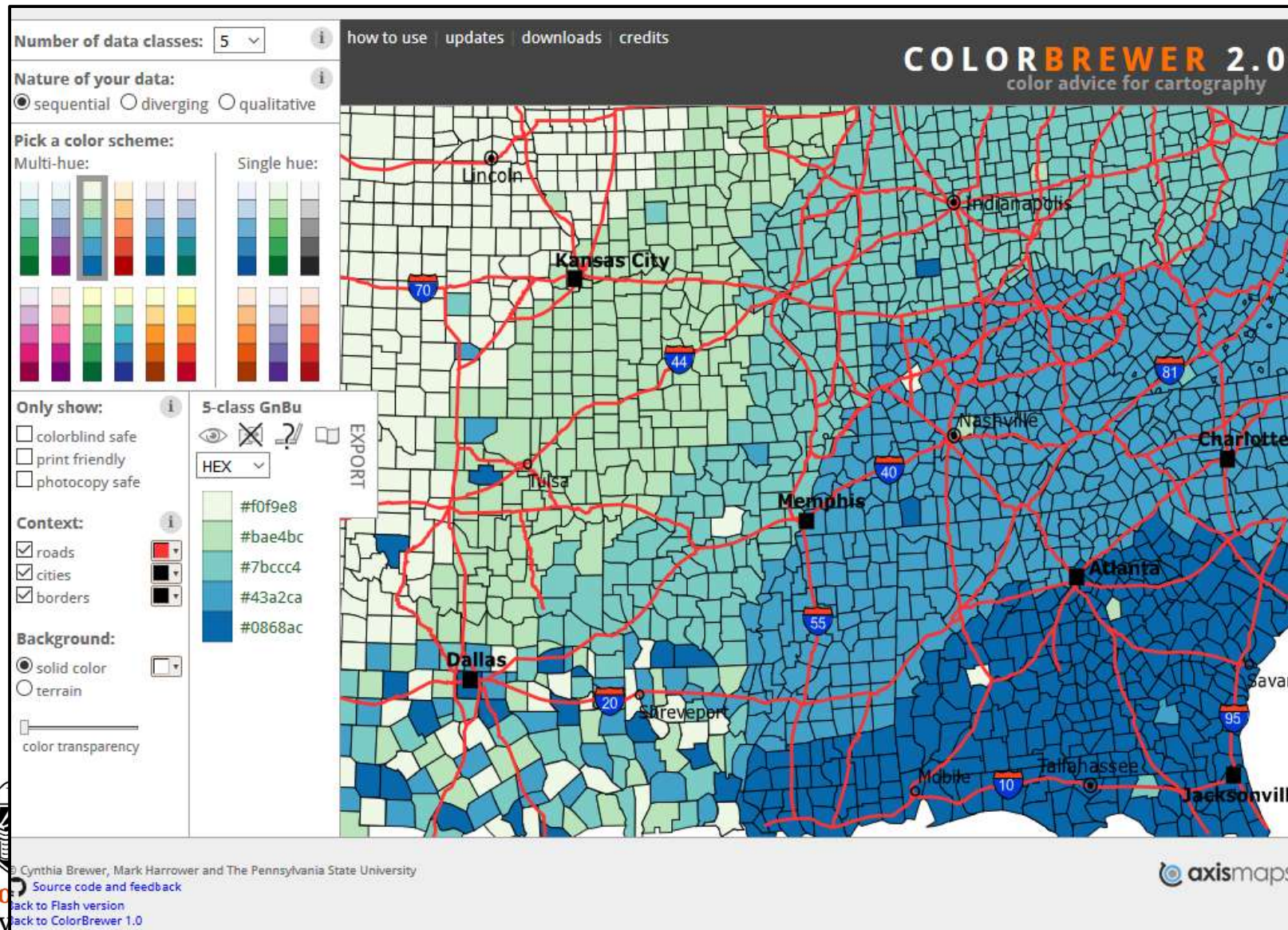
Opacity

Color

OpenDX Allows you to Sculpt the Transfer Function in HSV

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The screenshot shows the ColorBrewer 2.0 web interface. Red circles and arrows highlight specific features: the 'Number of data classes' dropdown is set to 5; the 'Nature of your data' section has 'sequential' selected; the 'Pick a color scheme' section shows various color schemes with one highlighted; the 'Only show' section has checkboxes for 'colorblind safe', 'print friendly', and 'photocopy safe'; and the 'Context' section has checkboxes for 'roads', 'cities', and 'borders'. The 'Background' section has 'solid color' selected. The '5-class GnBu' color scheme is shown with its corresponding hex codes: #f0f9e8, #bae4bc, #7bccc4, #43a2ca, and #0868ac.

Number of discrete colors needed

Type of data

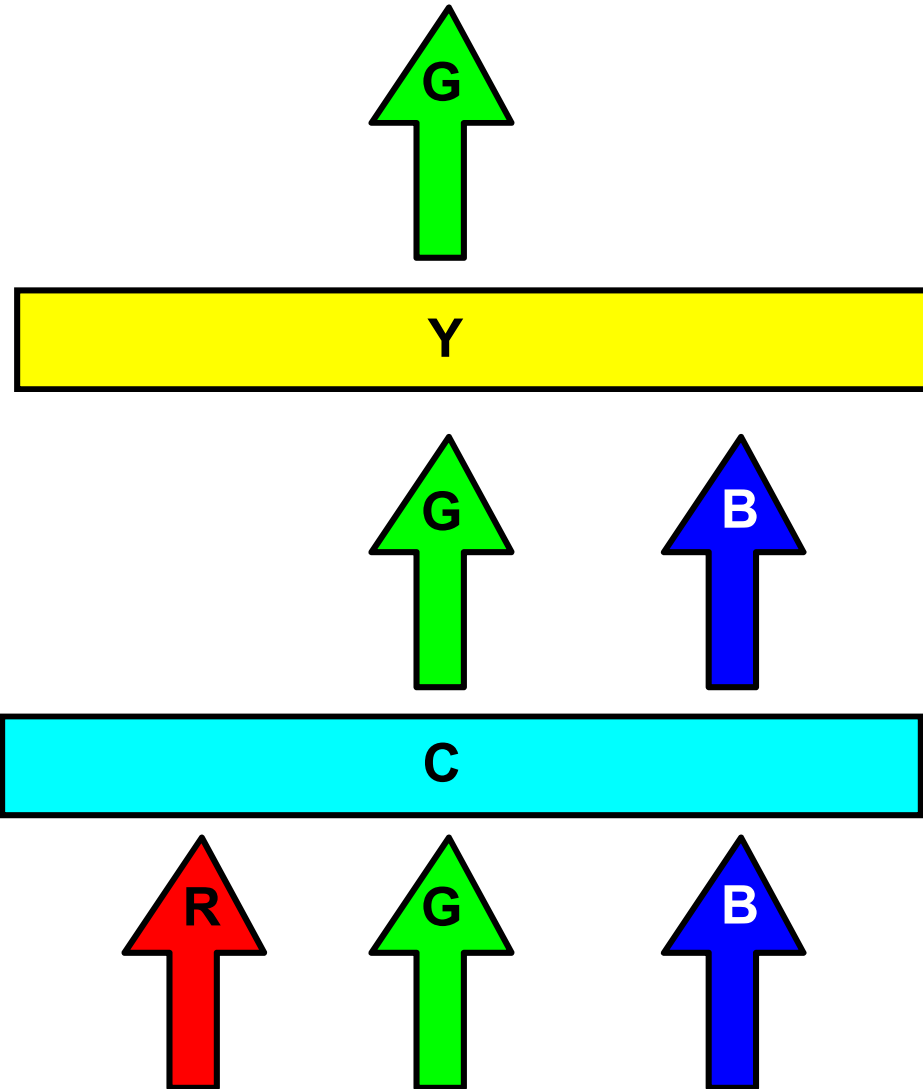
Color schemes

Ways of restricting the color schemes
(the *colorblind safe* option is especially important!)

A good way to explore discrete color spaces

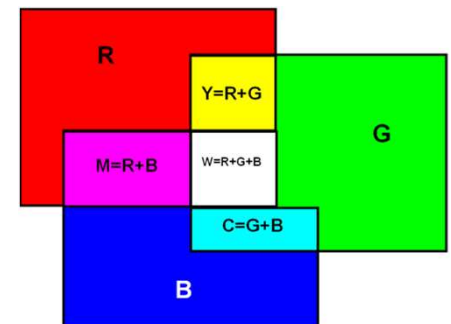
Subtractive Colors (CMYK)

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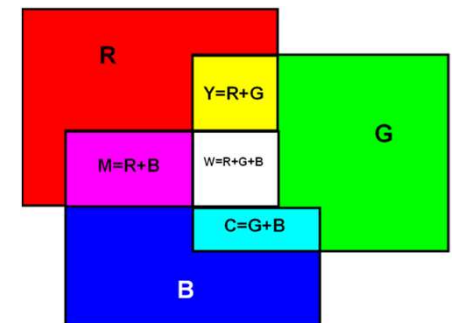
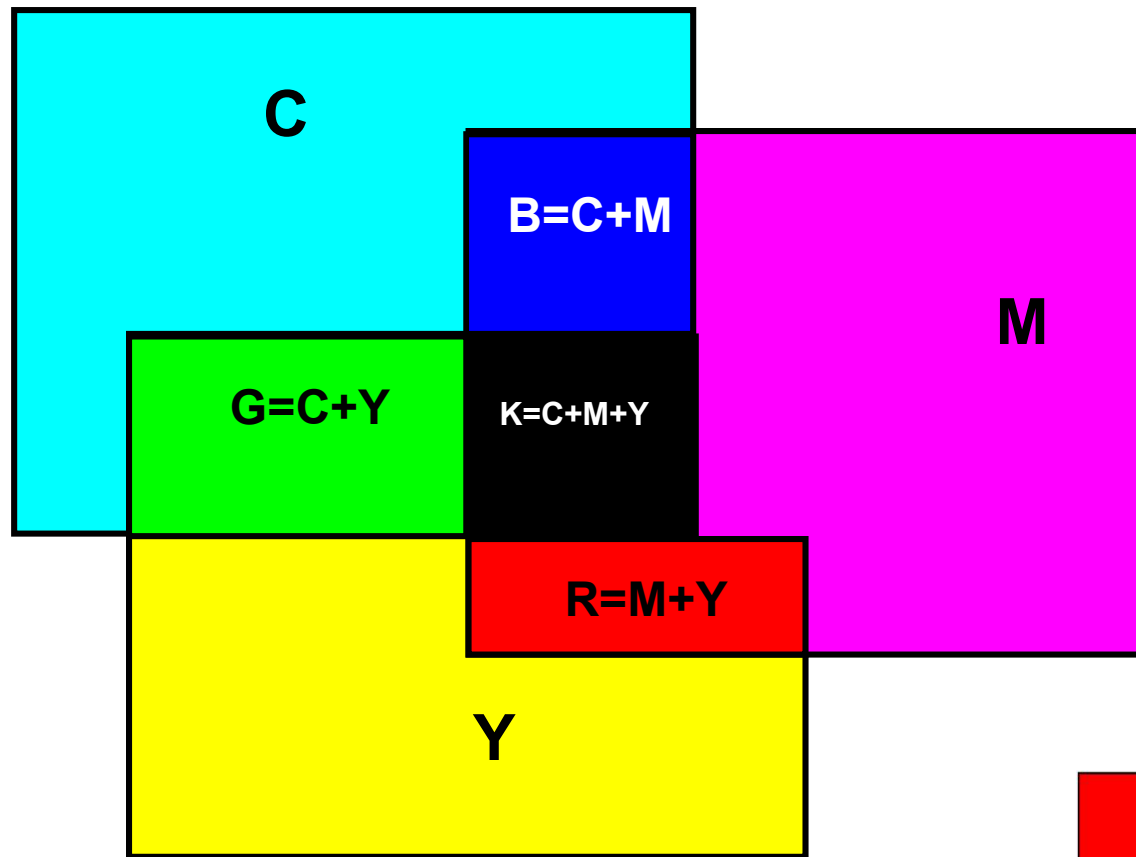
R = Red
G = Green
B = Blue
W = White

C = Cyan
M = Magenta
Y = Yellow
K = Black

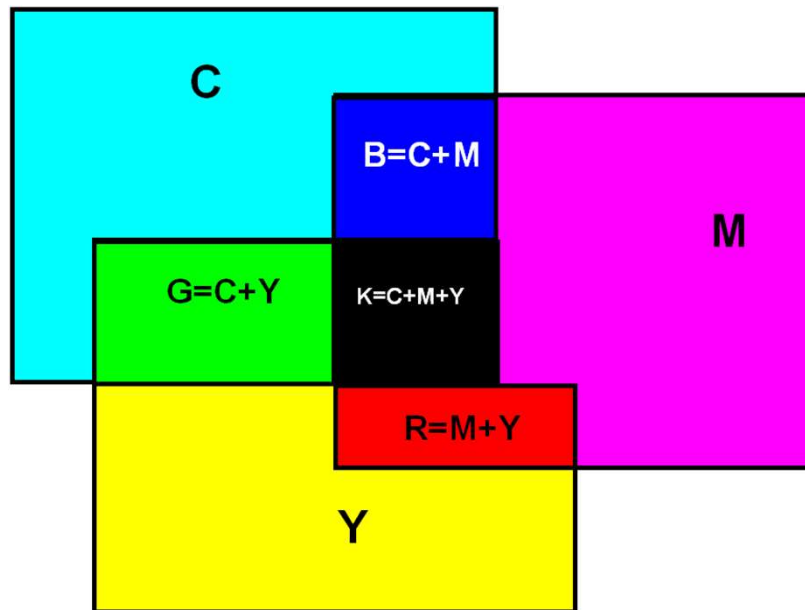


Subtractive Colors (CMYK)

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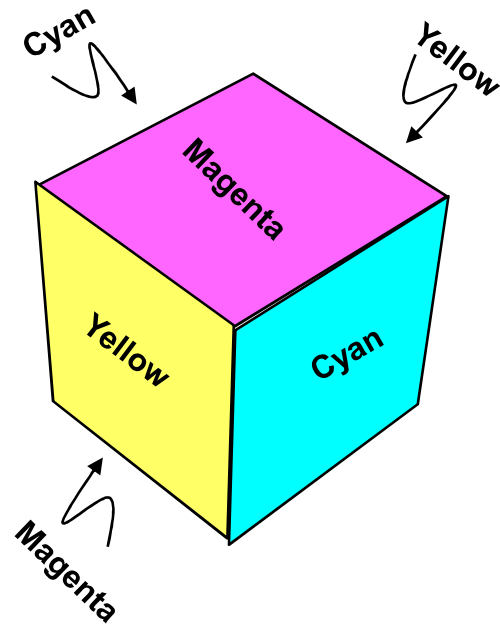
- Uses subtractive colors
- Uses 3 (CMY) or 4 (CMYK) passes
- CMYK printers have a better-looking black
- There is a considerable variation in color *gamut* between products



The CYM Cube

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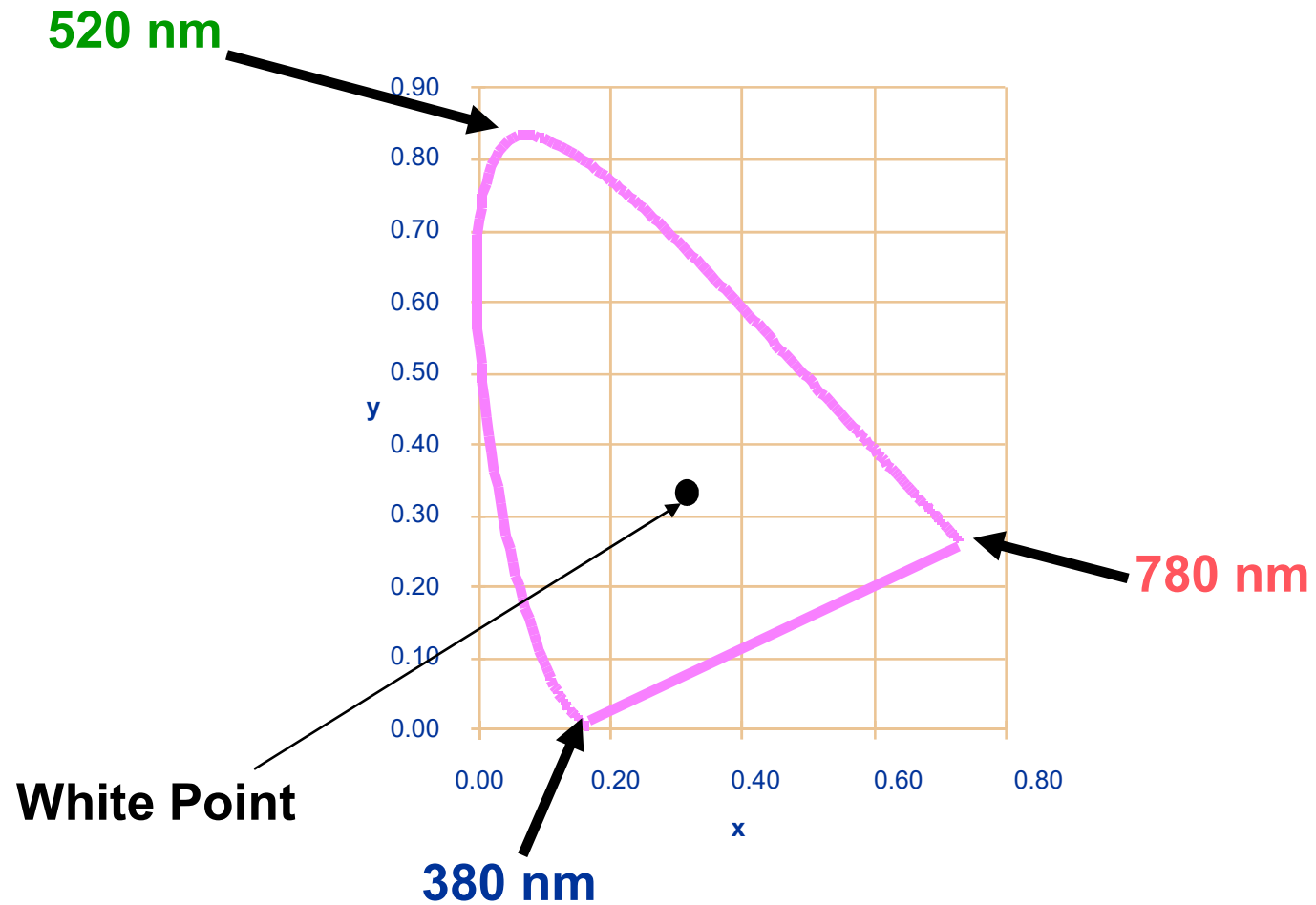
How the Cube is setup:



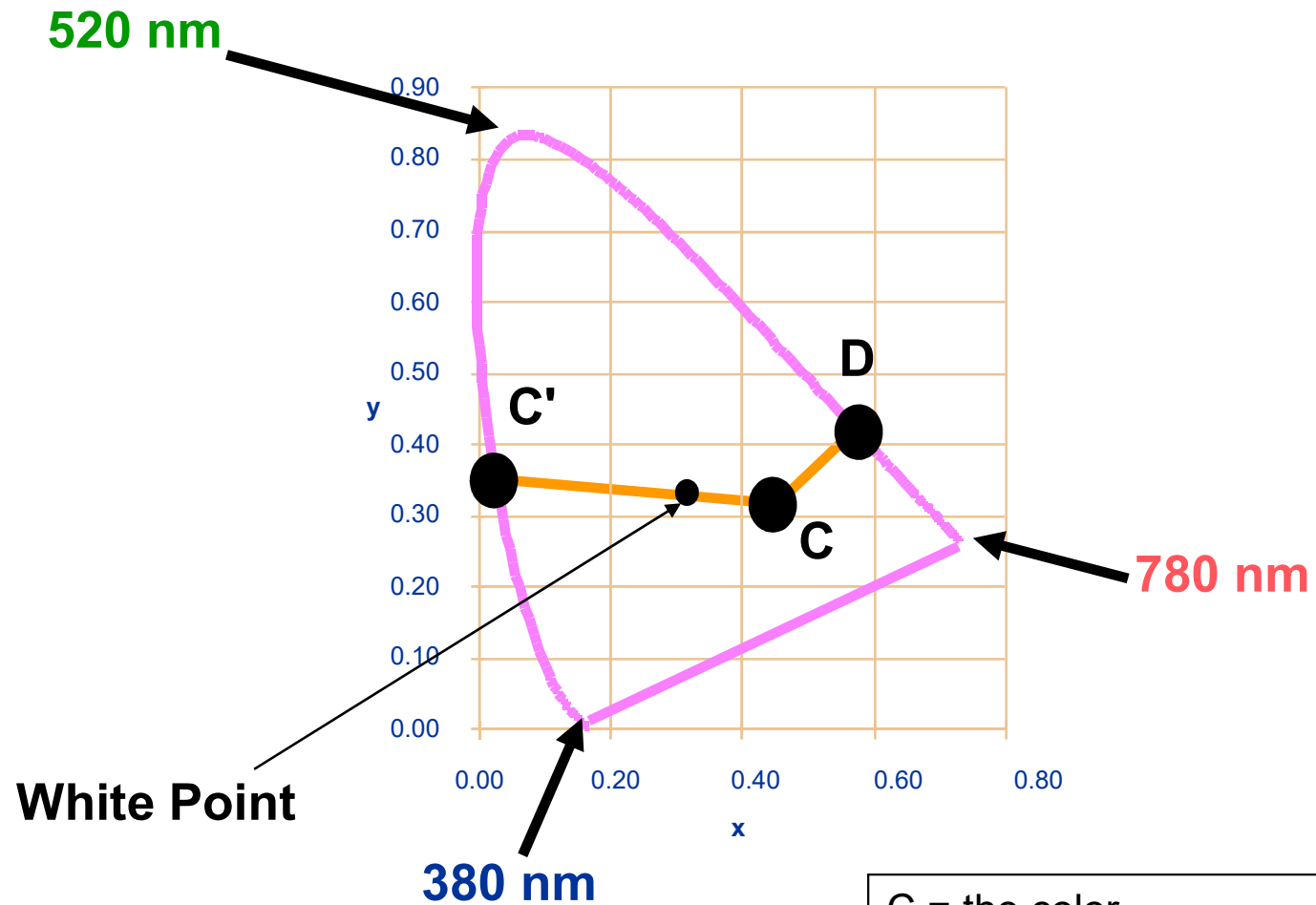
How it looks when you sight through two faces:



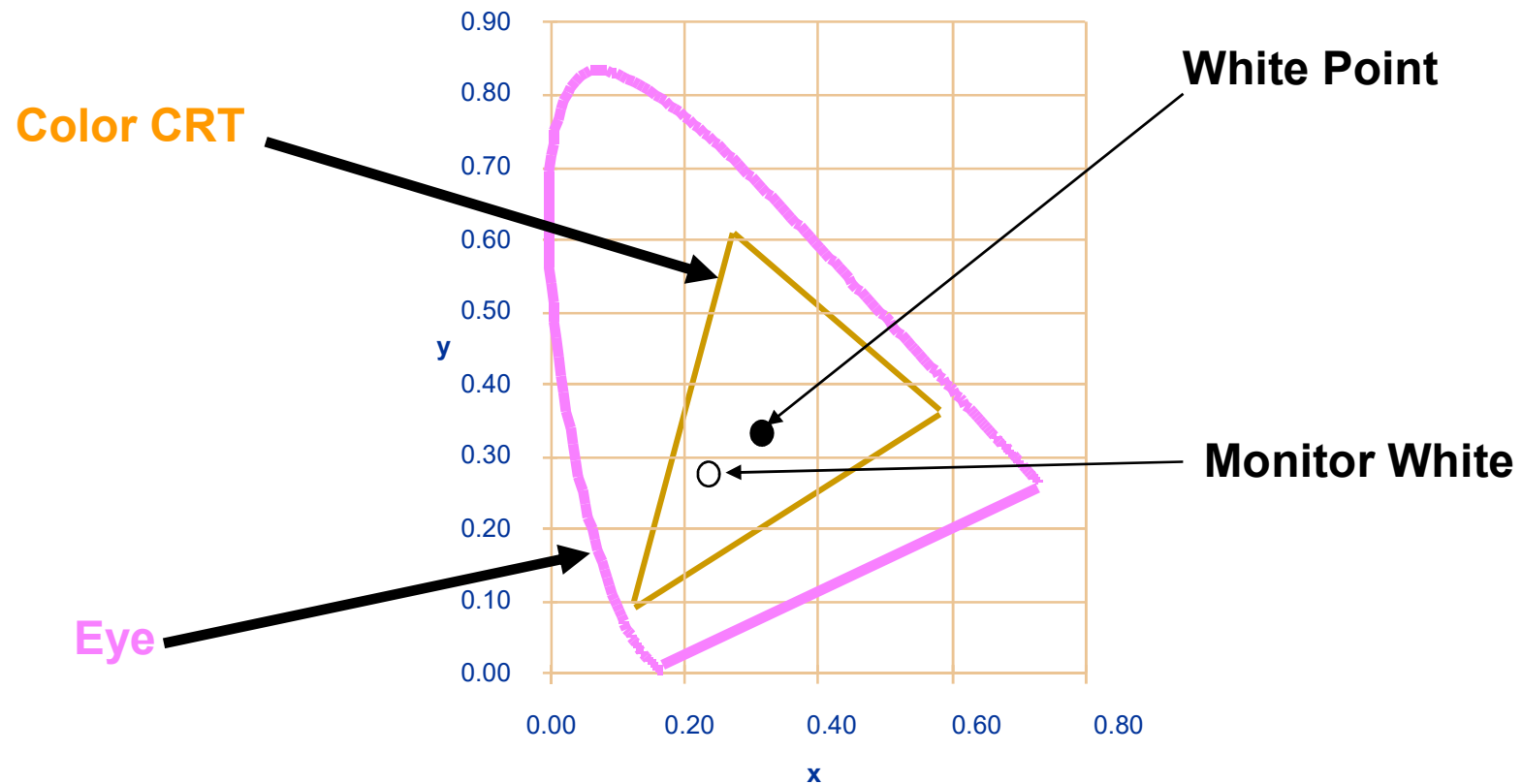
CIE Chromaticity Diagram



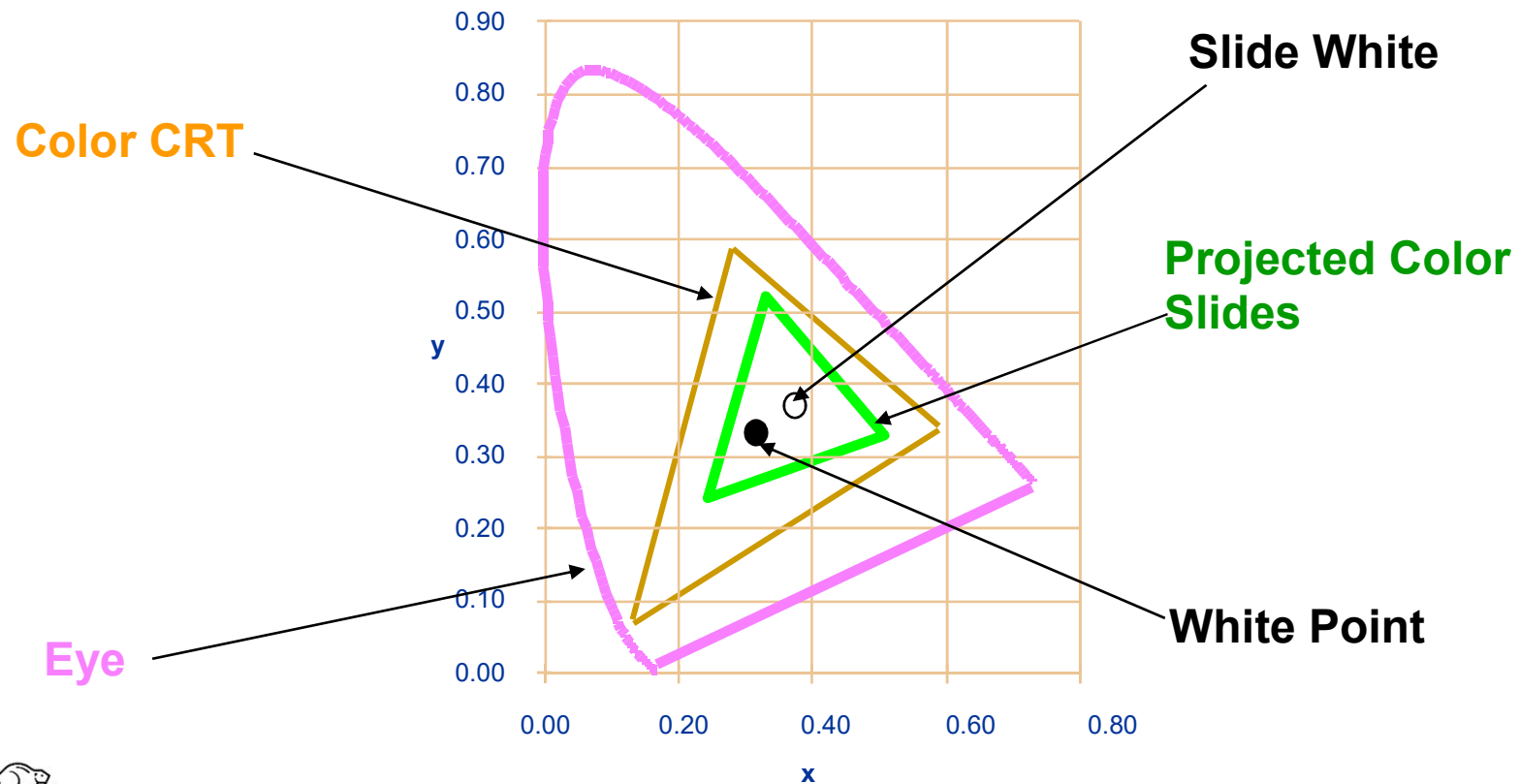
CIE Chromaticity Diagram



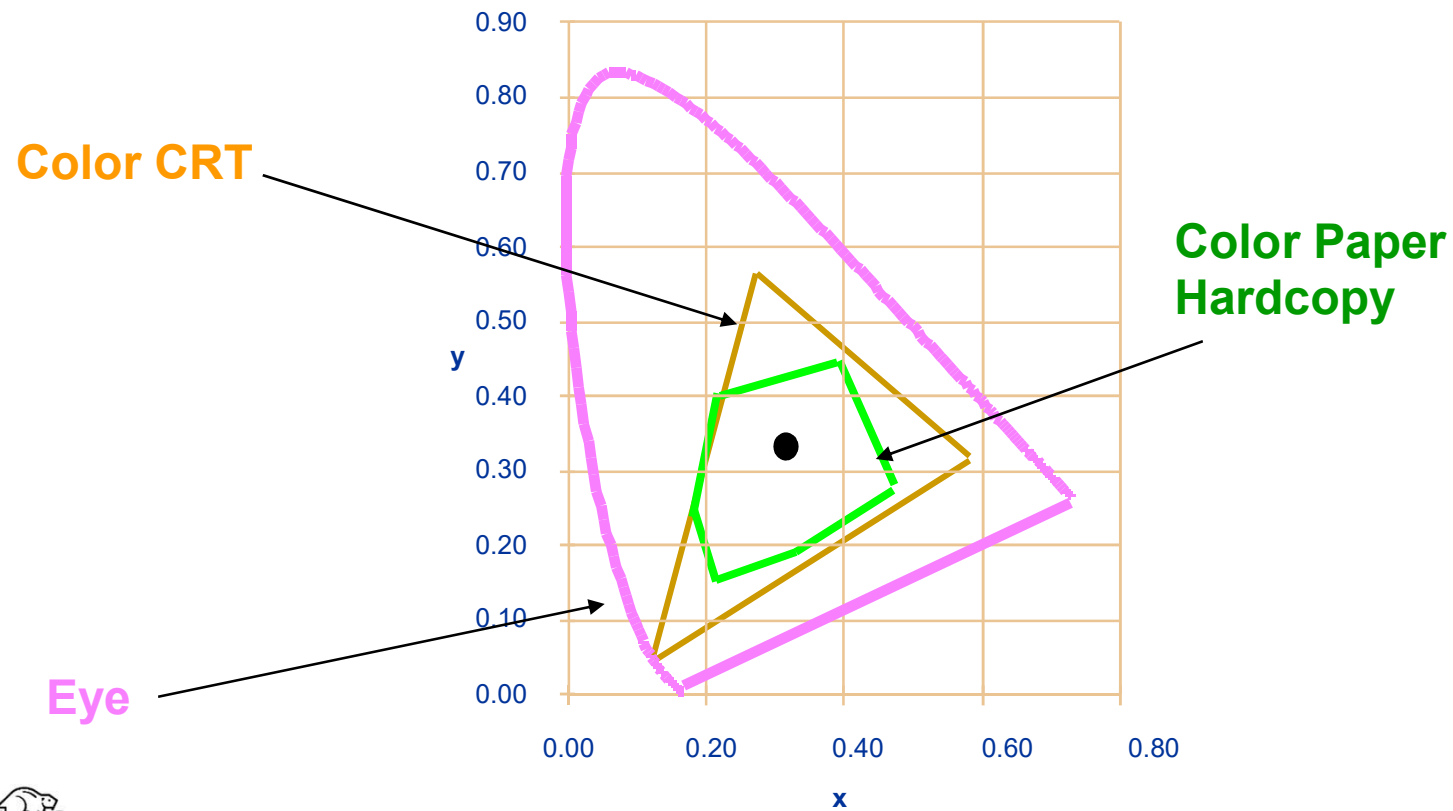
Color Gamut for a Workstation Monitor



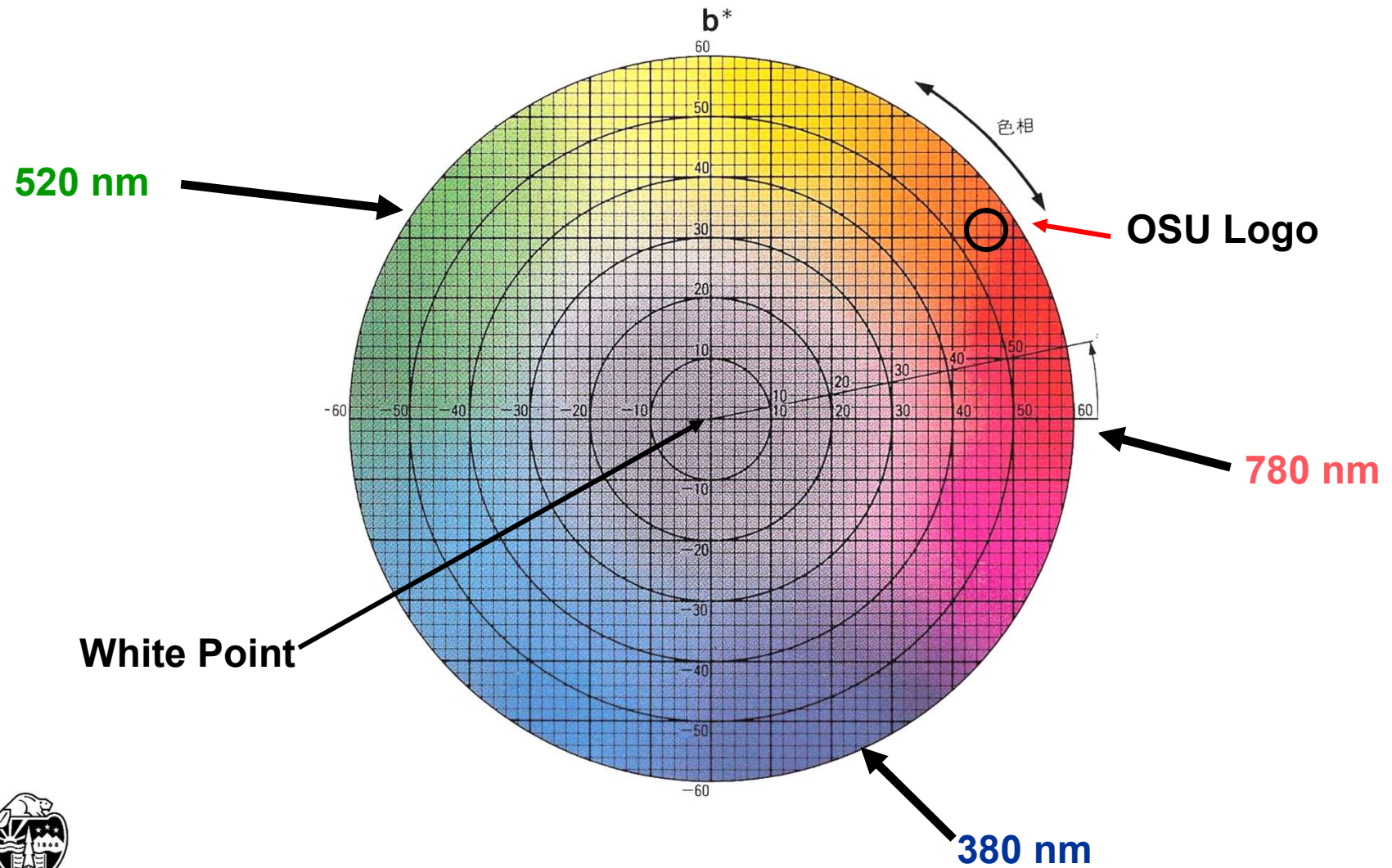
Color Gamut for a Monitor and Color Slides



Color Gamut for a Monitor and Color Printer



The *Perceptually Uniform* L-a-b Color Space



Color Meters Are Able to Measure L-a-b Coordinates



What Makes a Good Contrast?

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- Many people think simply adding color onto another color makes a good contrast
- In fact, a better measure is the **Δ Luminance**
- Using this also helps if someone makes a grayscale photocopy of your color hardcopy

Color Alone Doesn't Cut It !

**I sure hope that my
life does not depend
on being able to read
this quickly and
accurately!**



Luminance Contrast is Crucial !

I would prefer that
my life depend on
being able to read *this*
quickly and
accurately!



TUESDAY
MARCH 29
3-4 PM

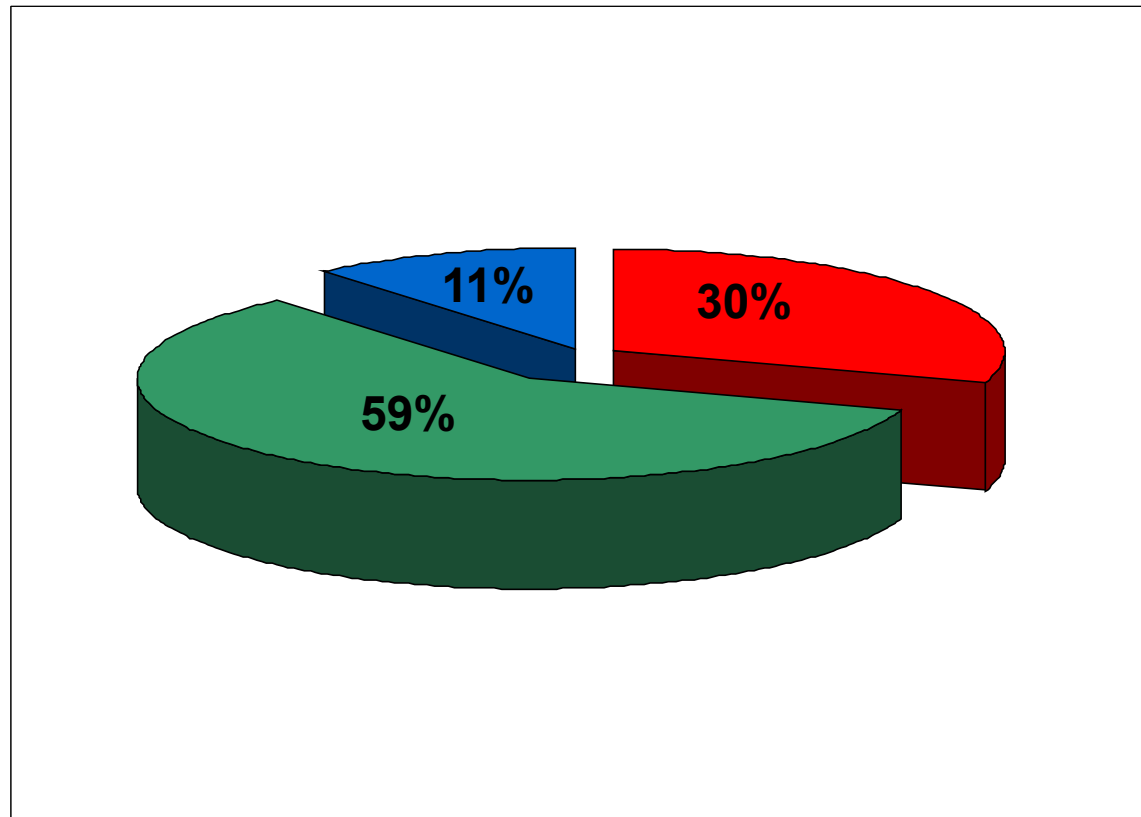
RSVP to:

[http://oregonstate.qualtrics.com/
jfe/form/SV_cGGdsS219DIFXIR](http://oregonstate.qualtrics.com/jfe/form/SV_cGGdsS219DIFXIR)

Or call: 541.737.0664

The Luminance Equation

$$Y = .30*Red + .59*Green + .11*Blue$$



Luminance Table

	R	G	B	Y
Black	0.0	0.0	0.0	0.00
White	1.0	1.0	1.0	1.00
Red	1.0	0.0	0.0	0.30
Green	0.0	1.0	0.0	0.59
Blue	0.0	0.0	1.0	0.11
Cyan	0.0	1.0	1.0	0.70
Magenta	1.0	0.0	1.0	0.41
Orange	1.0	0.5	0.0	0.60
Yellow	1.0	1.0	0.0	0.89

≈ Contrast Table

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(I use a ΔL^* of about 0.40)

	Black	White	Red	Green	Blue	Cyan	Magenta	Orange	Yellow
Black	0.00	1.00	0.30	0.59	0.11	0.70	0.41	0.60	0.89
White	1.00	0.00	0.70	0.41	0.89	0.30	0.59	0.41	0.11
Red	0.30	0.70	0.00	0.29	0.19	0.40	0.11	0.30	0.59
Green	0.59	0.41	0.29	0.00	0.48	0.11	0.18	0.01	0.30
Blue	0.11	0.89	0.19	0.48	0.00	0.59	0.30	0.49	0.78
Cyan	0.70	0.30	0.40	0.11	0.59	0.00	0.29	0.11	0.19
Magenta	0.41	0.59	0.11	0.18	0.30	0.29	0.00	0.19	0.48
Orange	0.60	0.41	0.30	0.01	0.49	0.11	0.19	0.00	0.30
Yellow	0.89	0.11	0.59	0.30	0.78	0.19	0.48	0.30	0.00

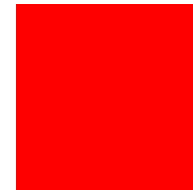
	Black	Black	Black	Black	Black	Black	Black	Black
White		White	White	White	White	White	White	White
Red	Red		Red	Red	Red	Red	Red	Red
Yellow	Yellow	Yellow		Yellow	Yellow	Yellow	Yellow	Yellow
Green	Green	Green	Green	Green		Green	Green	Green
Blue	Blue	Blue	Blue	Blue	Blue	Blue		Blue

Limit the Total Number of Colors if Viewers are to Discern Information Quickly

Instructions:

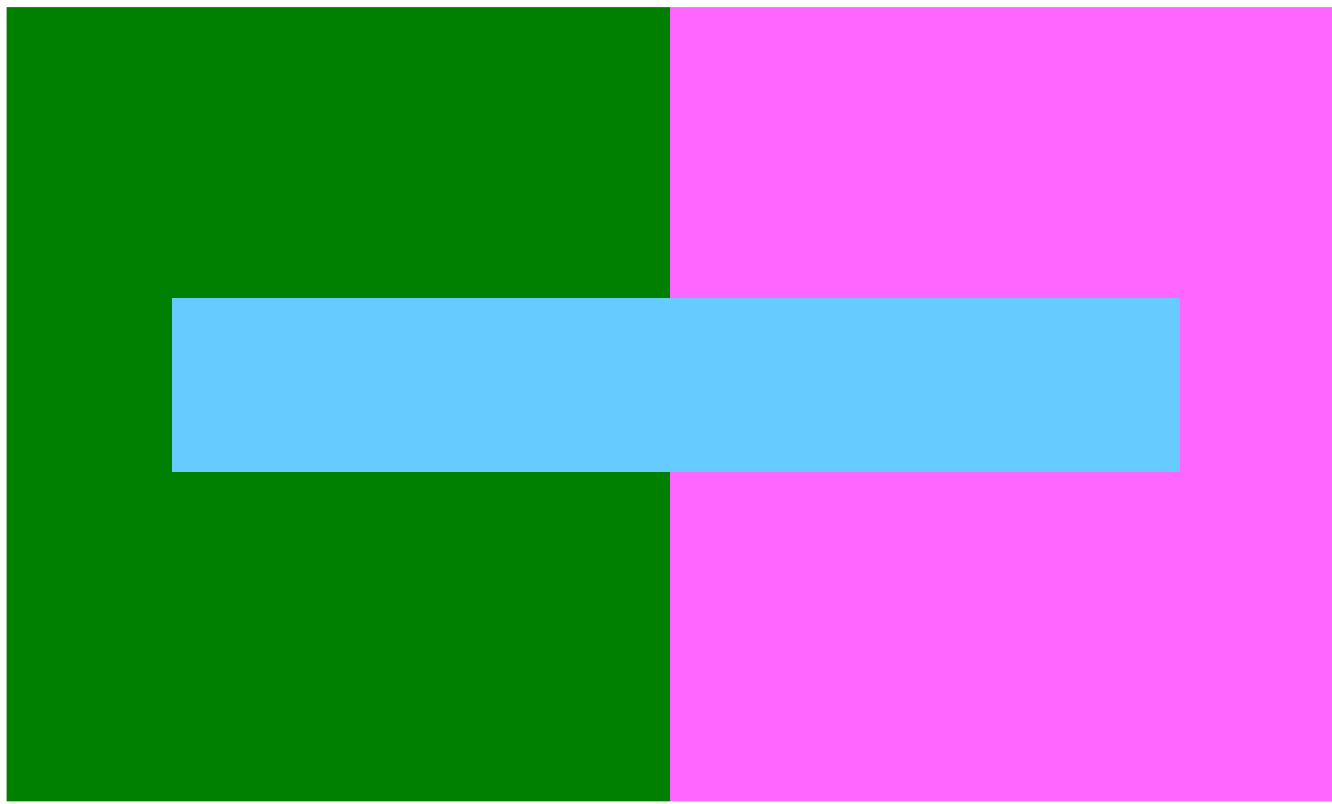
- 1. Press red to logoff normally**
- 2. Press light red to delete all your files, change your password to something random, and logoff**

You have 2 seconds . . .

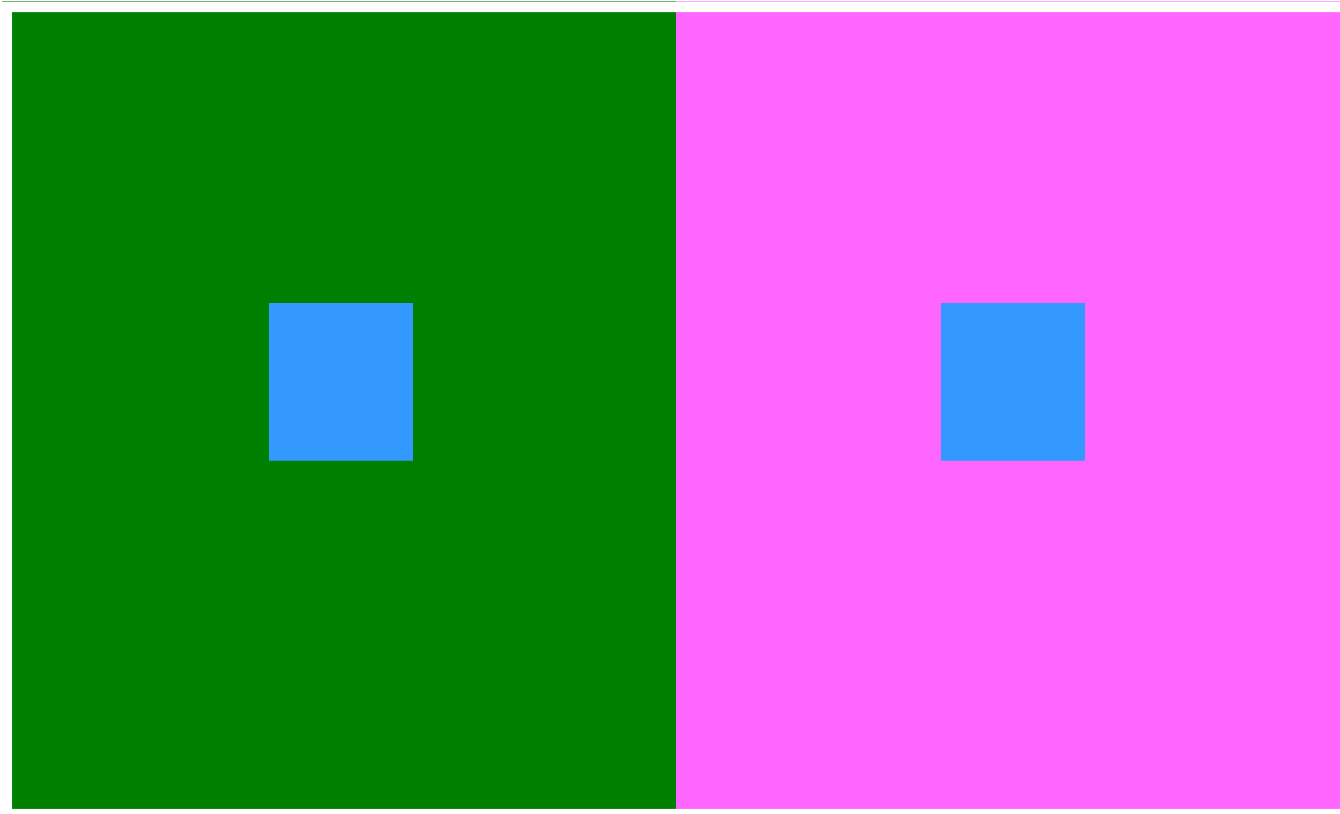


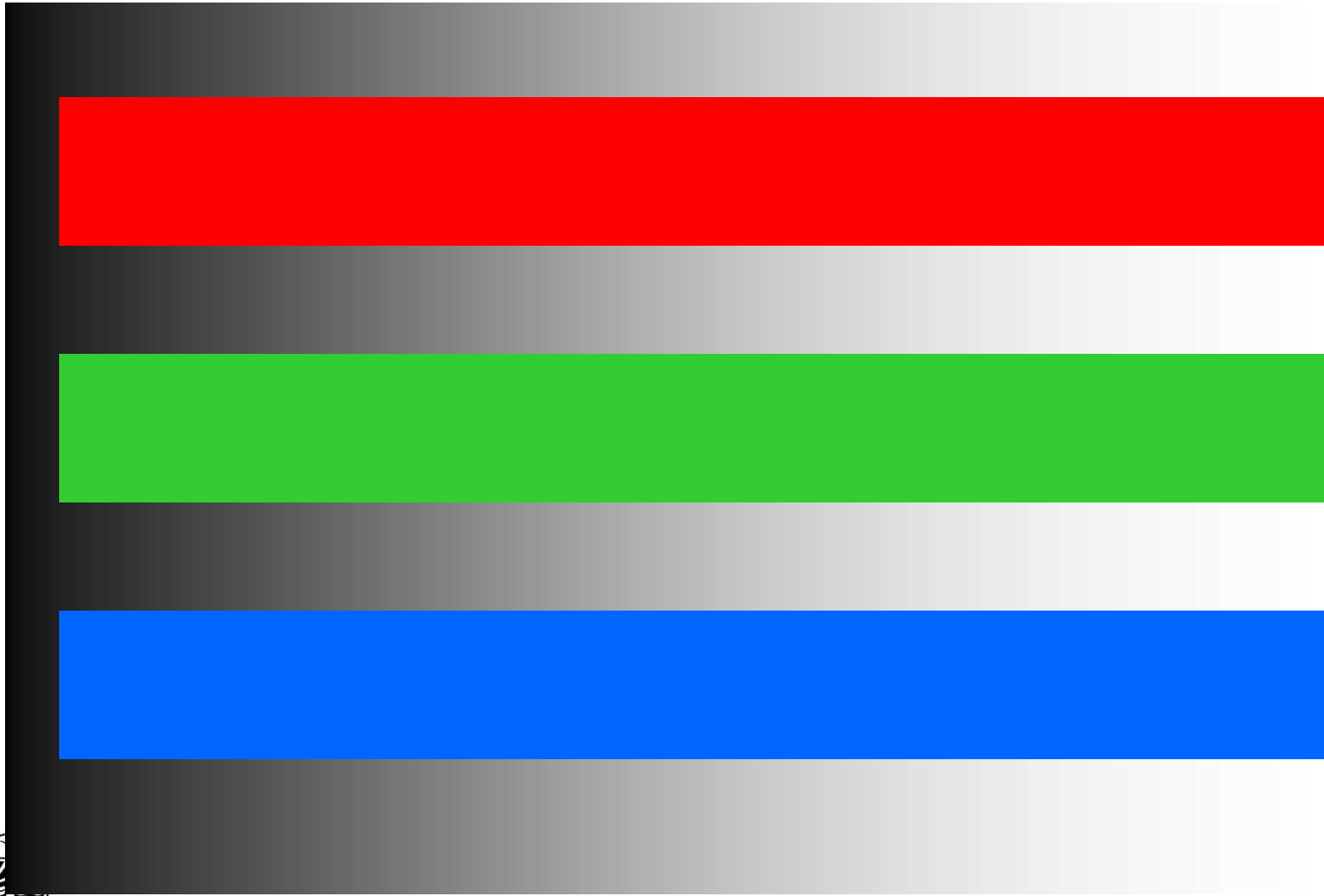
?

The Ability to Discriminate Colors Changes with Surrounding Color: “Simultaneous Contrast”

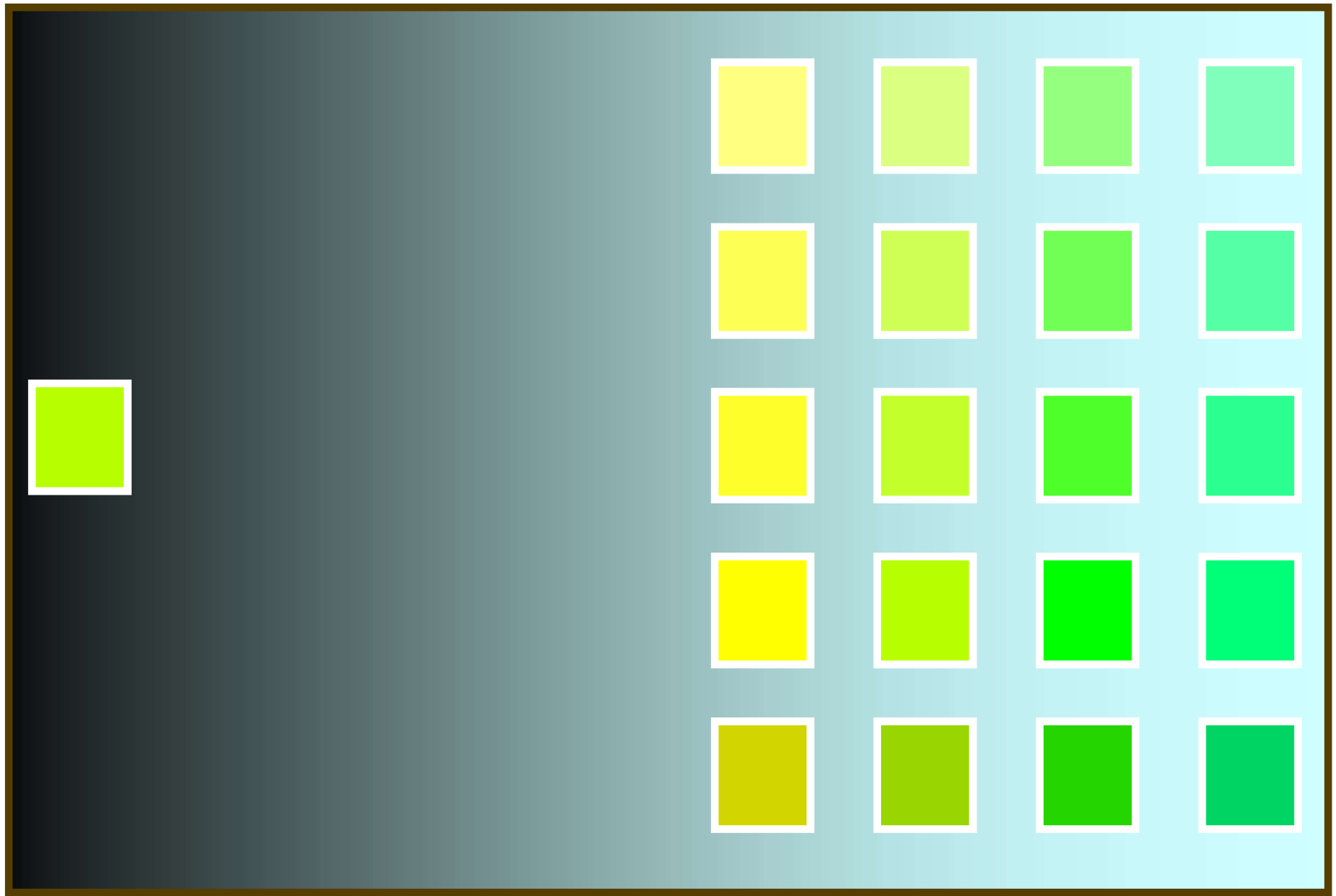


The Ability to Discriminate Colors Changes with Surrounding Color: “Simultaneous Contrast”









So, What's Up with the “Blue Dress” Debate?

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It's all part of the **Color Constancy** effect



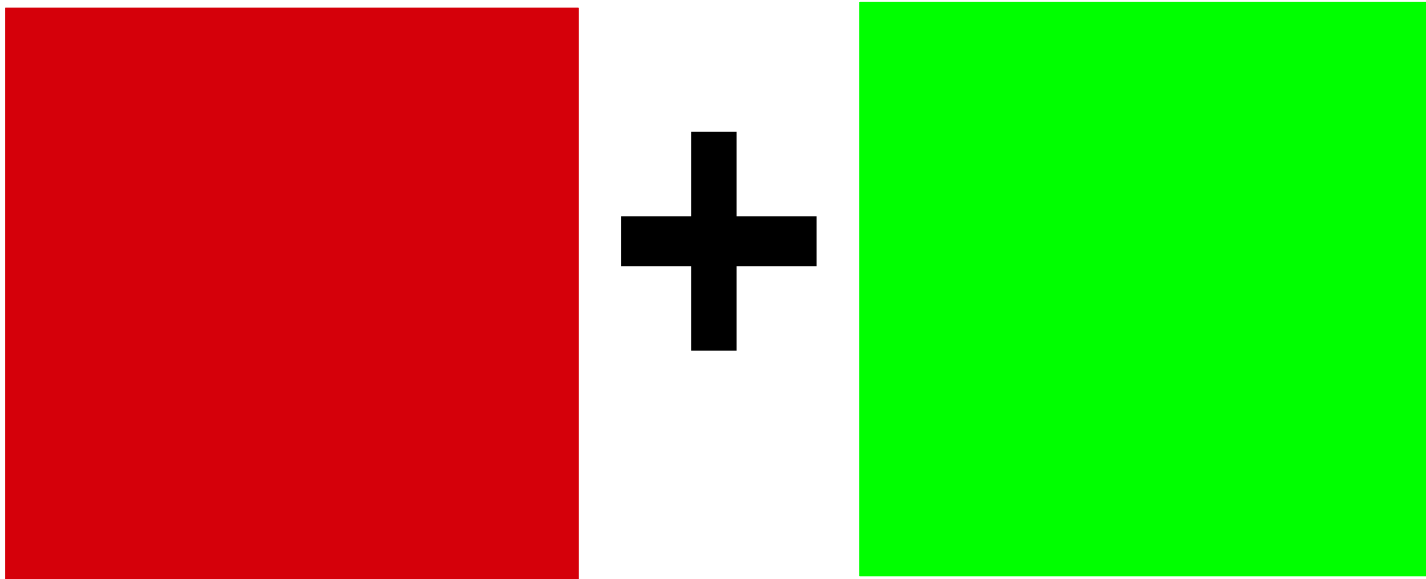
New York Times

If you see this color, but you think that the dress is currently in a shadow, you “know” that it must *really* be this color.

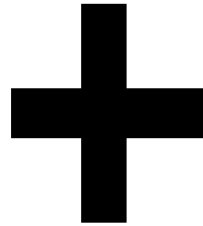


If you see this color, but you think that the dress is currently in bright light, you “know” that it must *really* be this color.

Afterimages

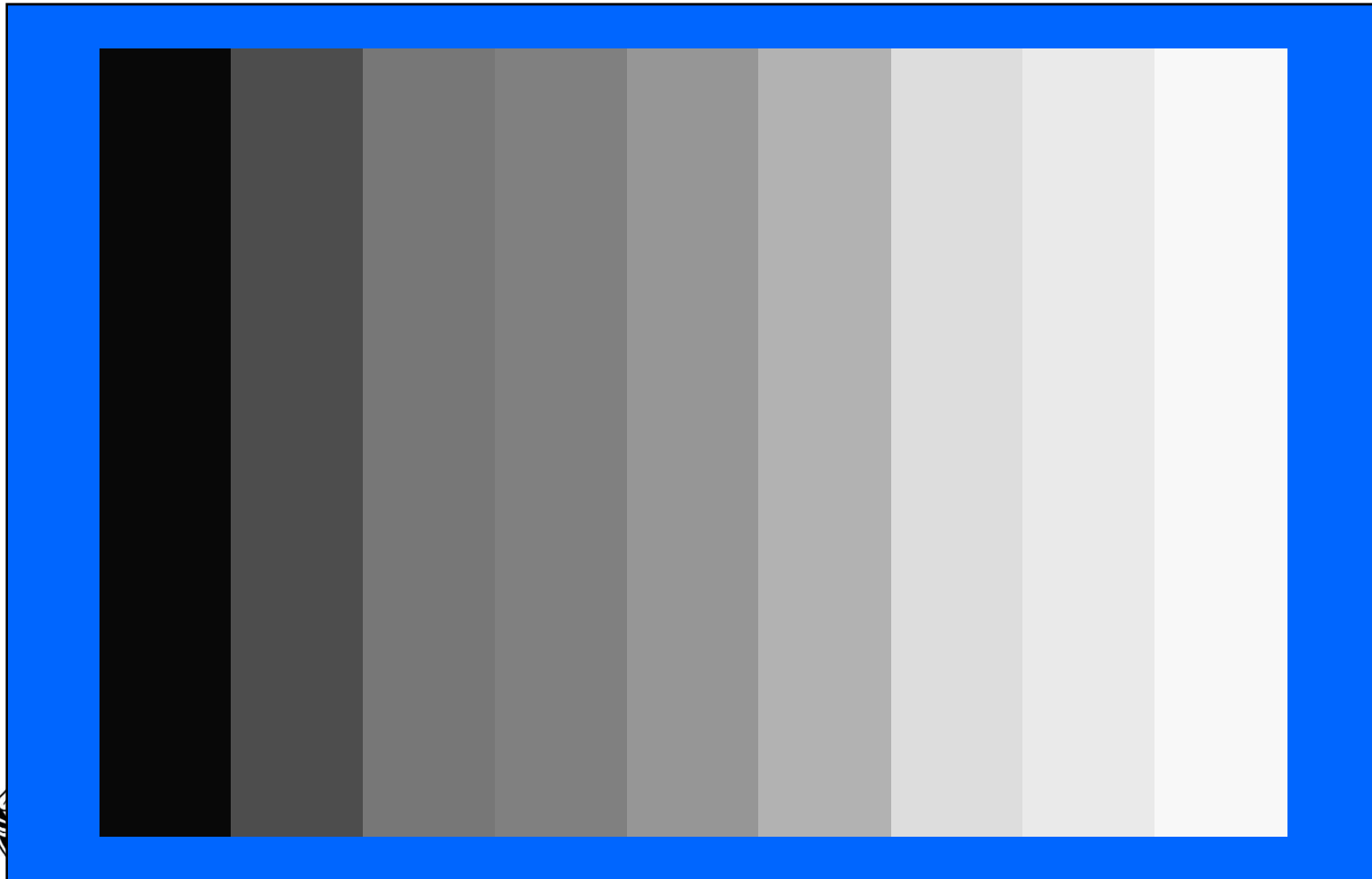


Afterimages



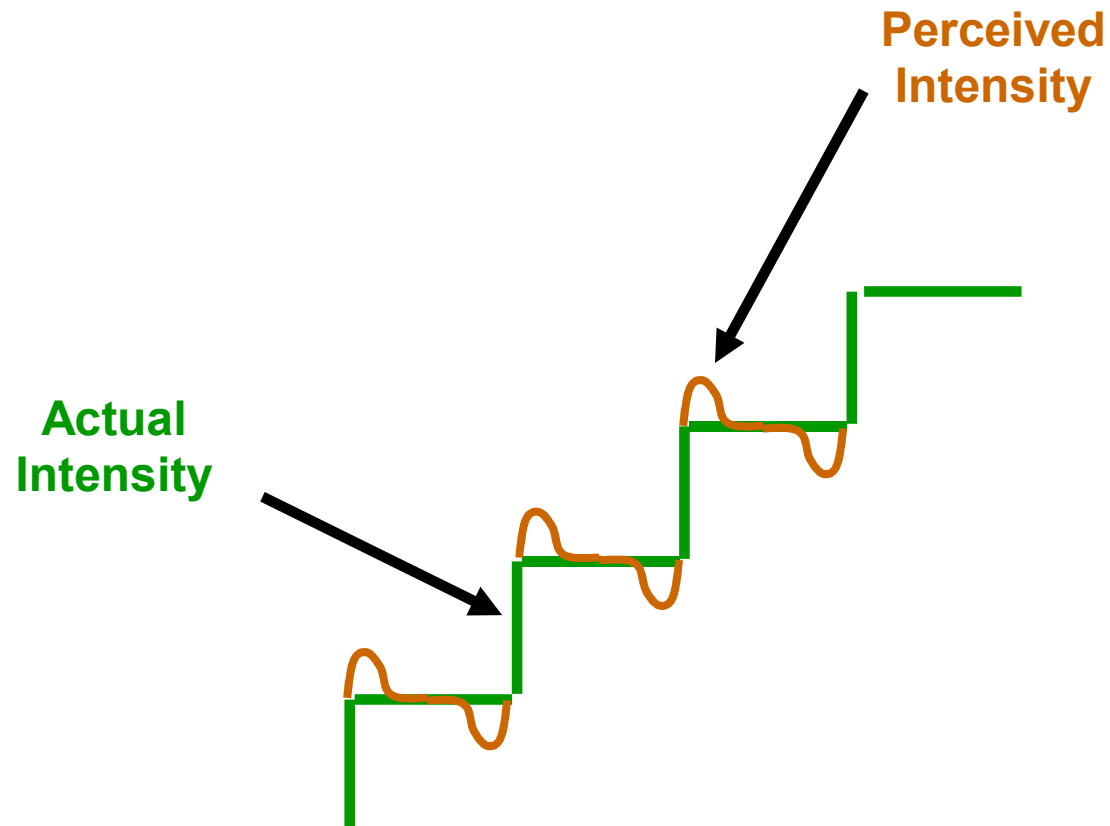
Beware of Mach Banding

52



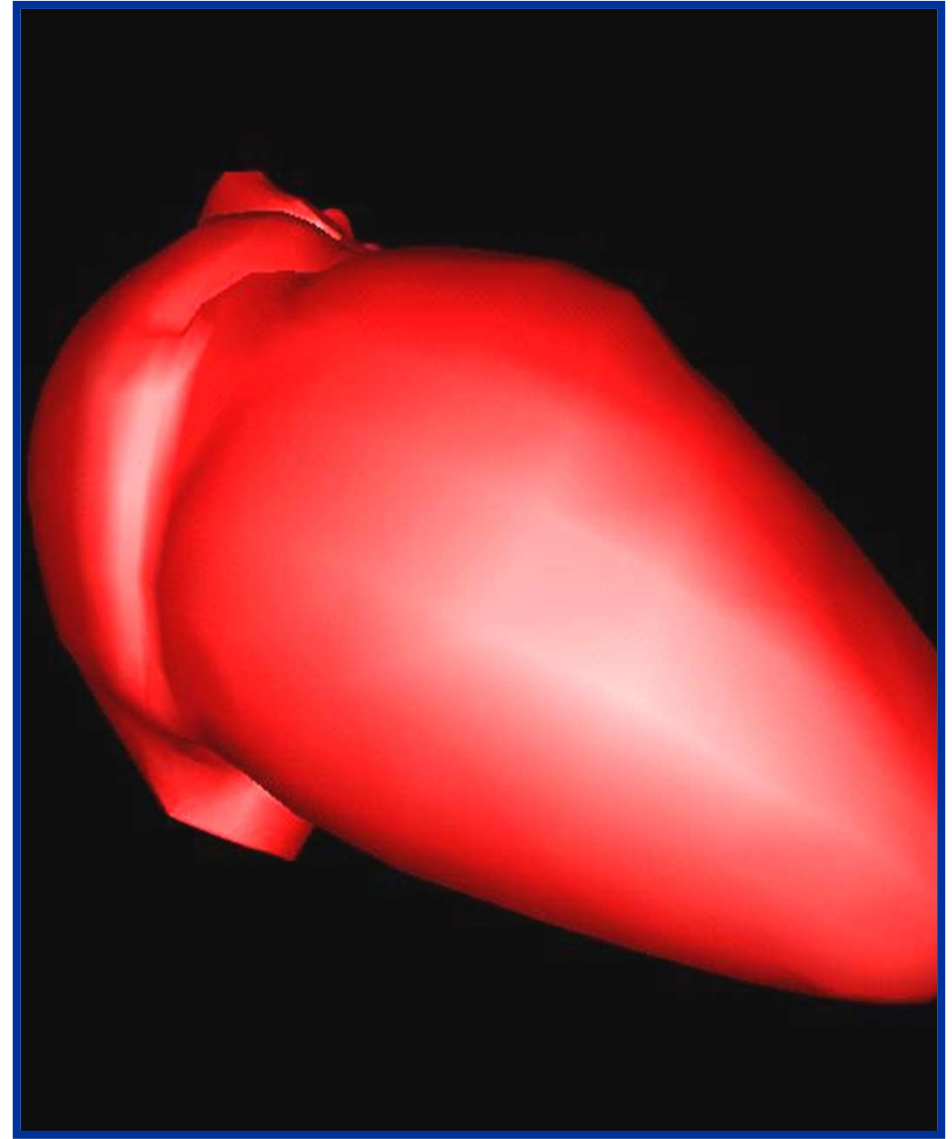
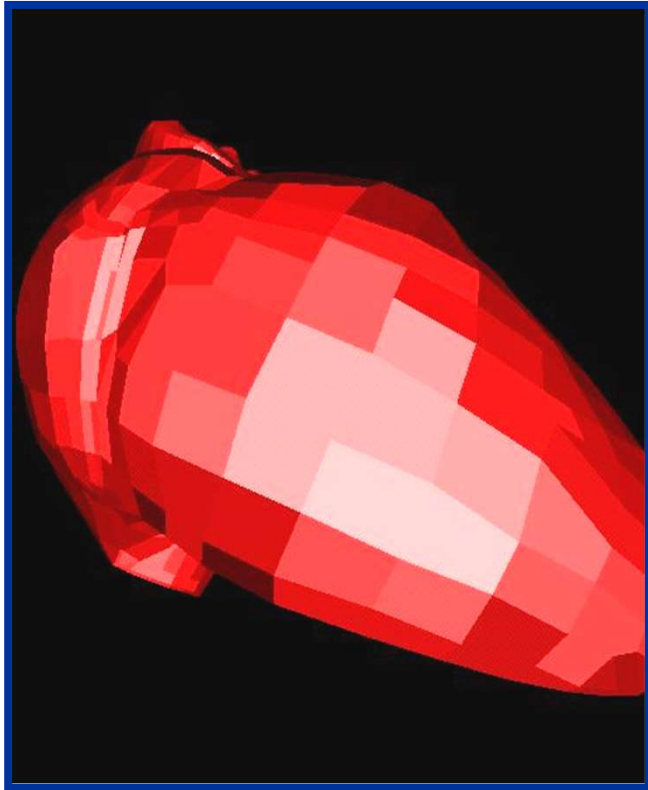
Beware of Mach Banding

53



Beware of Mach Banding

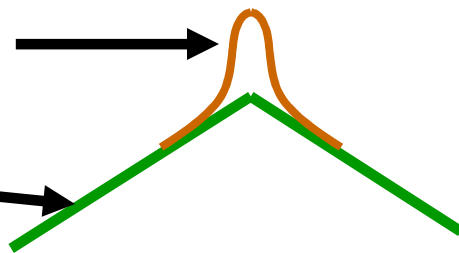
54



Perceived
Intensity



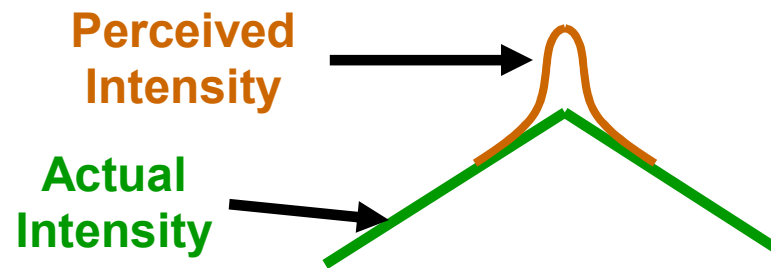
Actual
Intensity



Beware of Mach Banding

55

Think of the Mach Banding problem as being similar to trying to round second base at a 90° angle.



Be Aware of Color Vision Deficiencies (CVD)

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- In general, there is no such thing as total “color blindness”
- CVD affects ~10% of Caucasian men
- CVD affects ~4% of non-Caucasian men
- CVD affects ~0.5% of women
- The most common type of CVD is red-green
- Blue-yellow also exists

Resources for designing color schemes for people with color recognition deficiencies:

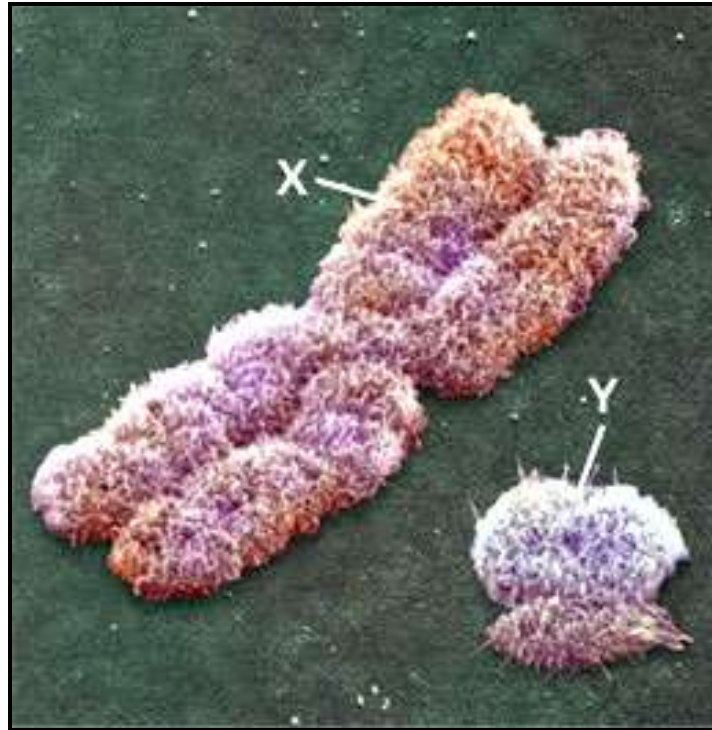
<http://colorbrewer2.org>

<http://colororacle.org/usage.html>

<http://mkweb.bcgsc.ca/colorblind/>



It's because the red-green CVD defect is carried on the X Chromosome



<http://www.bio.miami.edu/~cmallery/150/mendel/c7.15.X.Y.jpg>



An XX with the defective gene on one X chromosome probably has a dominant non-defective gene on the other. An XY with a defective gene on one X chromosome has no other gene to “fix” it.

Be Aware of CVD: Code Information Redundantly

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Four score and
seven years ago,
our fathers
brought forth
upon this
continent a new
nation...

Four score and
seven years ago,
our fathers
brought forth
upon this
continent a new
nation...

Four score and
seven years ago,
our fathers
brought forth
upon this
continent a new
nation...

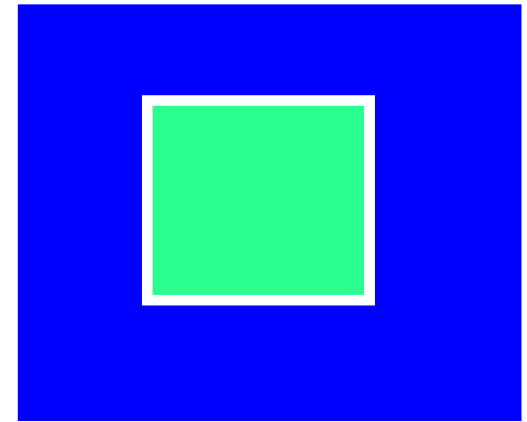
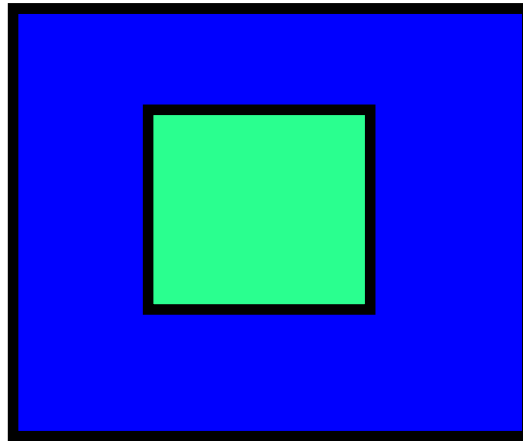
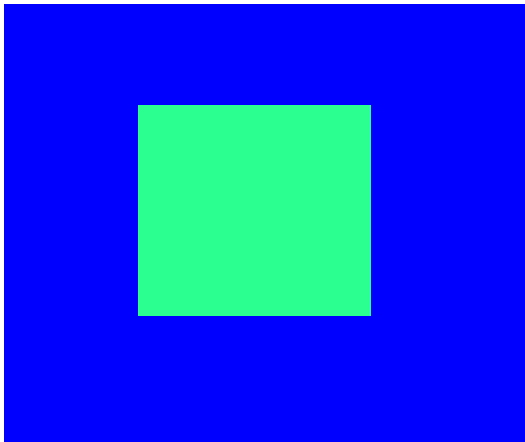
Be Aware of CVD: Code Information Redundantly: Color + ...

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- Different fonts
- Symbols
- Fill pattern
- Outline pattern
- Outline thickness

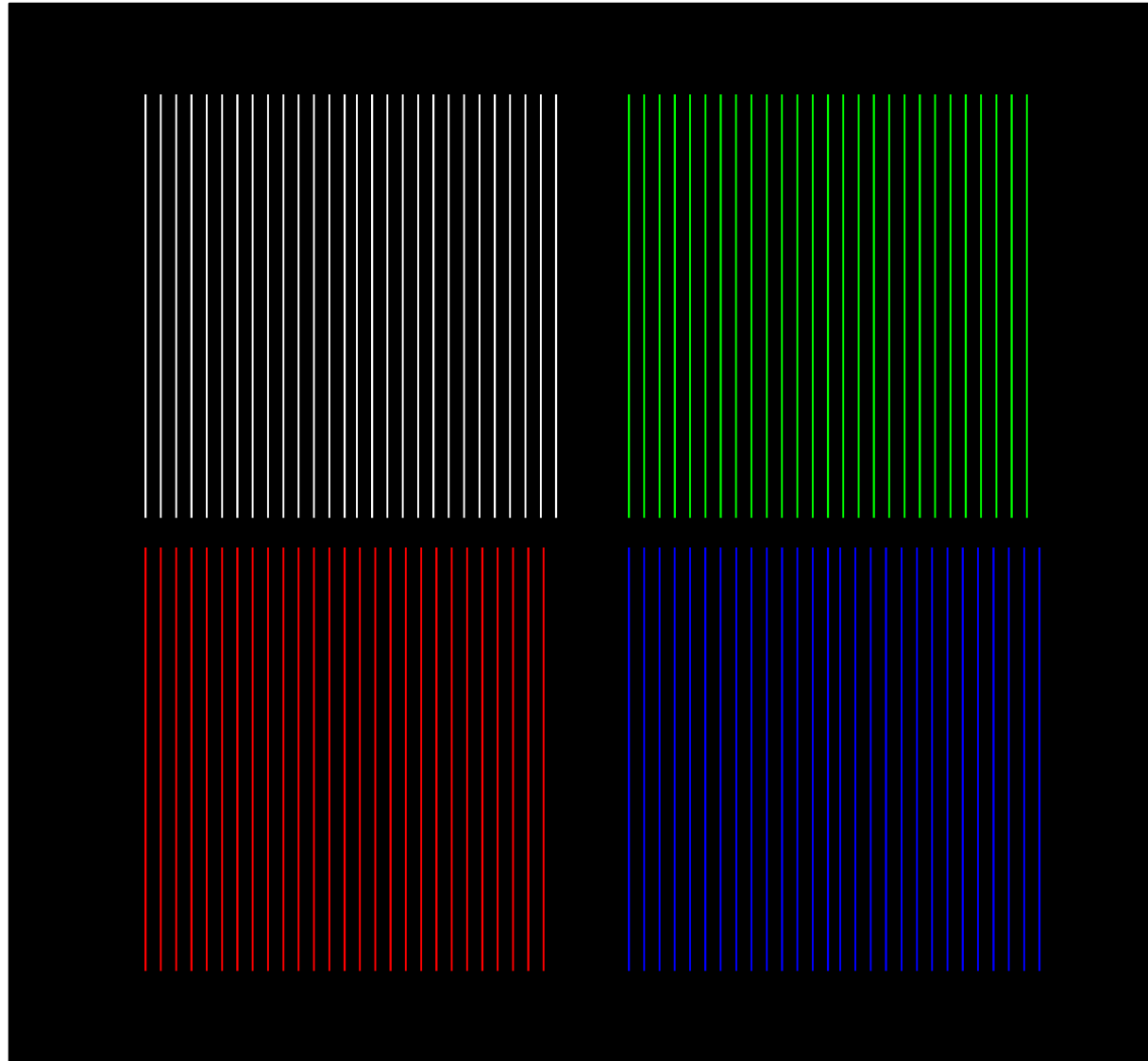
This also helps if someone makes a grayscale photocopy of your color hardcopy

Use a Black or White Line as the Boundary Between Colored Regions



Do Not Display Fast-moving or High-detail Items in Color, Especially Blue

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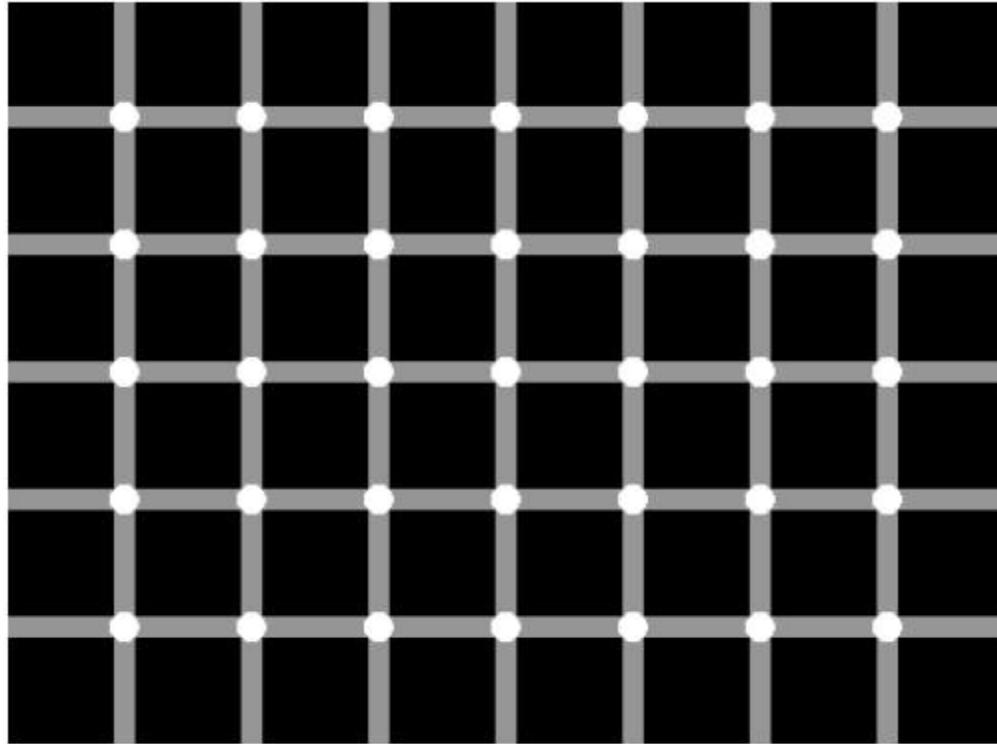


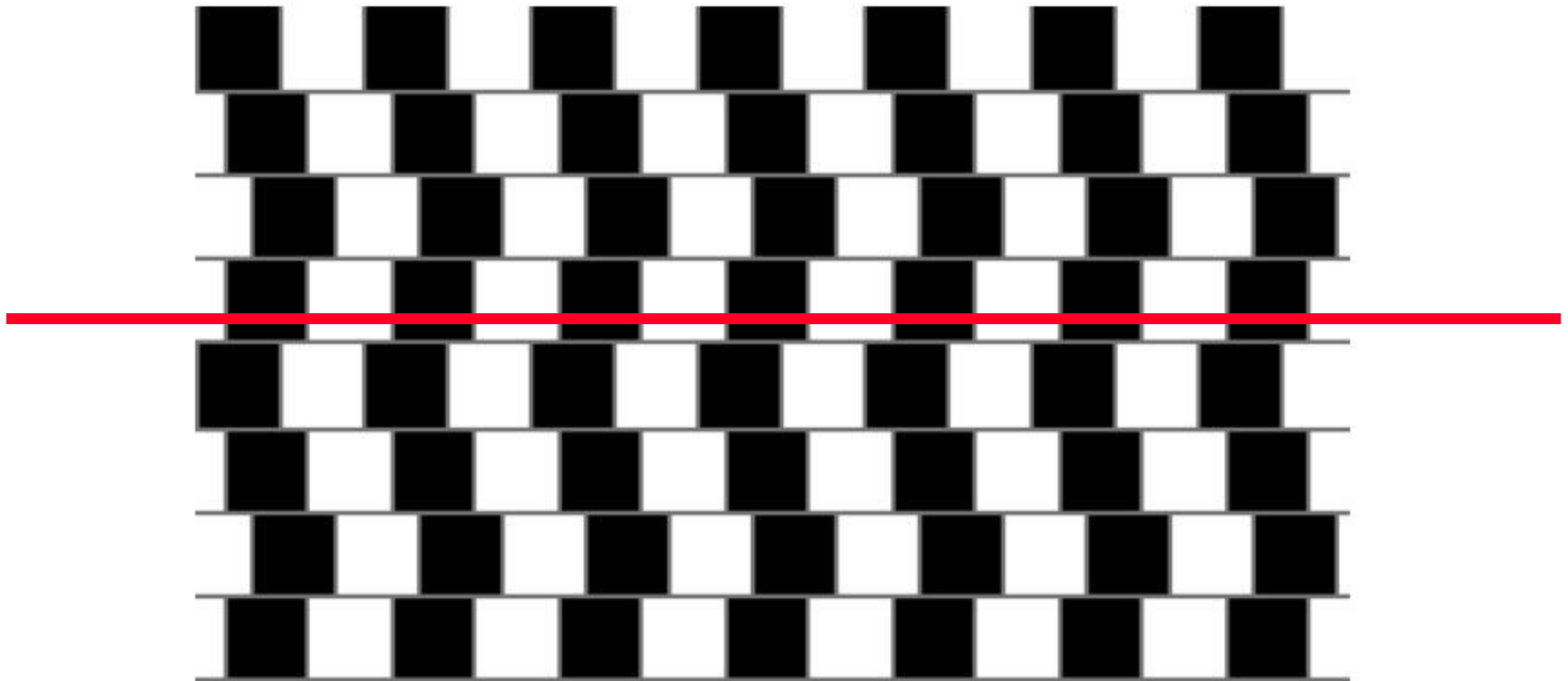
Watch the Use of Saturated Reds and Blues Together

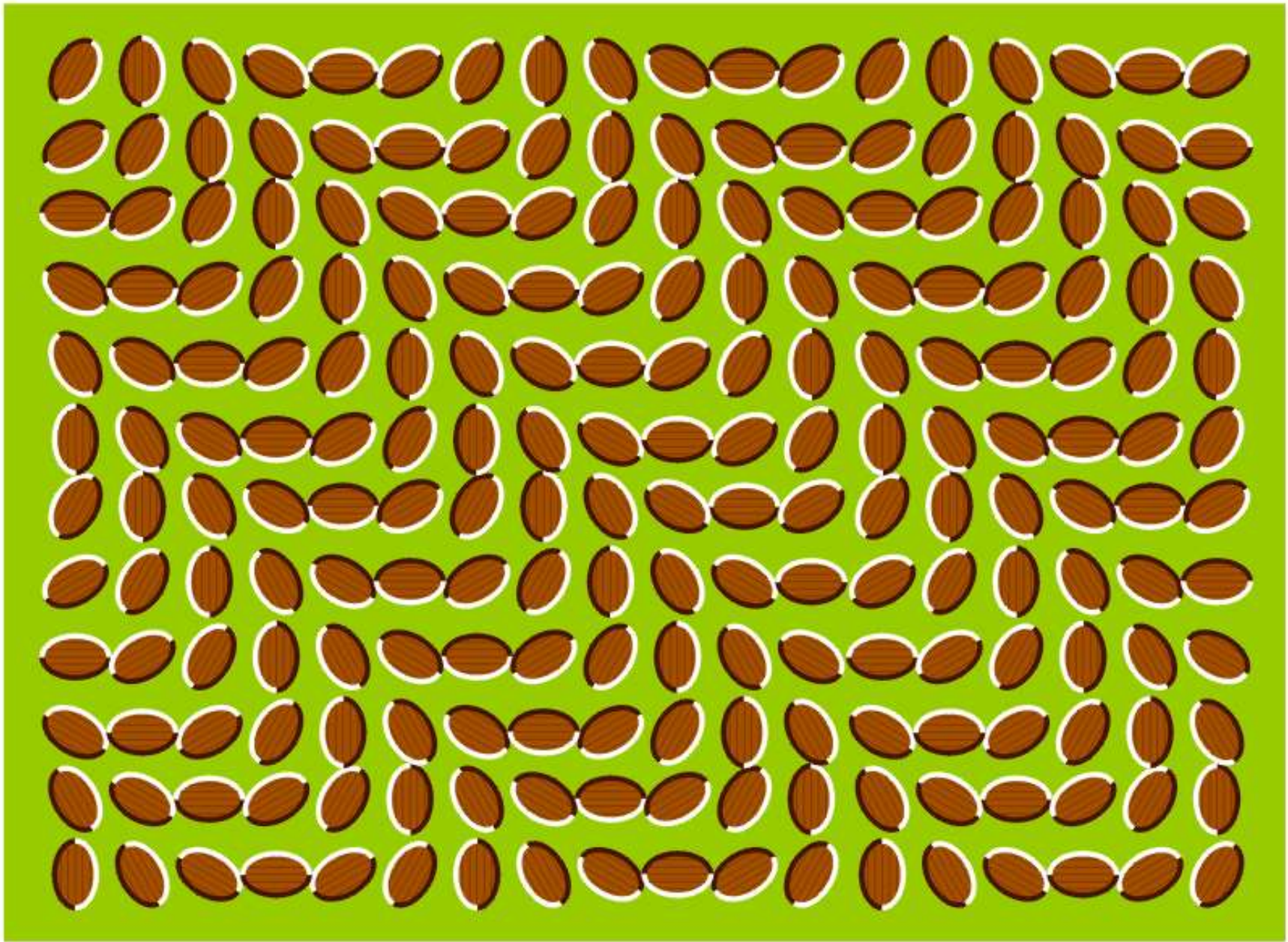
**Reds and Blues are
on opposite ends of
the color spectrum.
It is hard for your
eyes to focus on
both.**

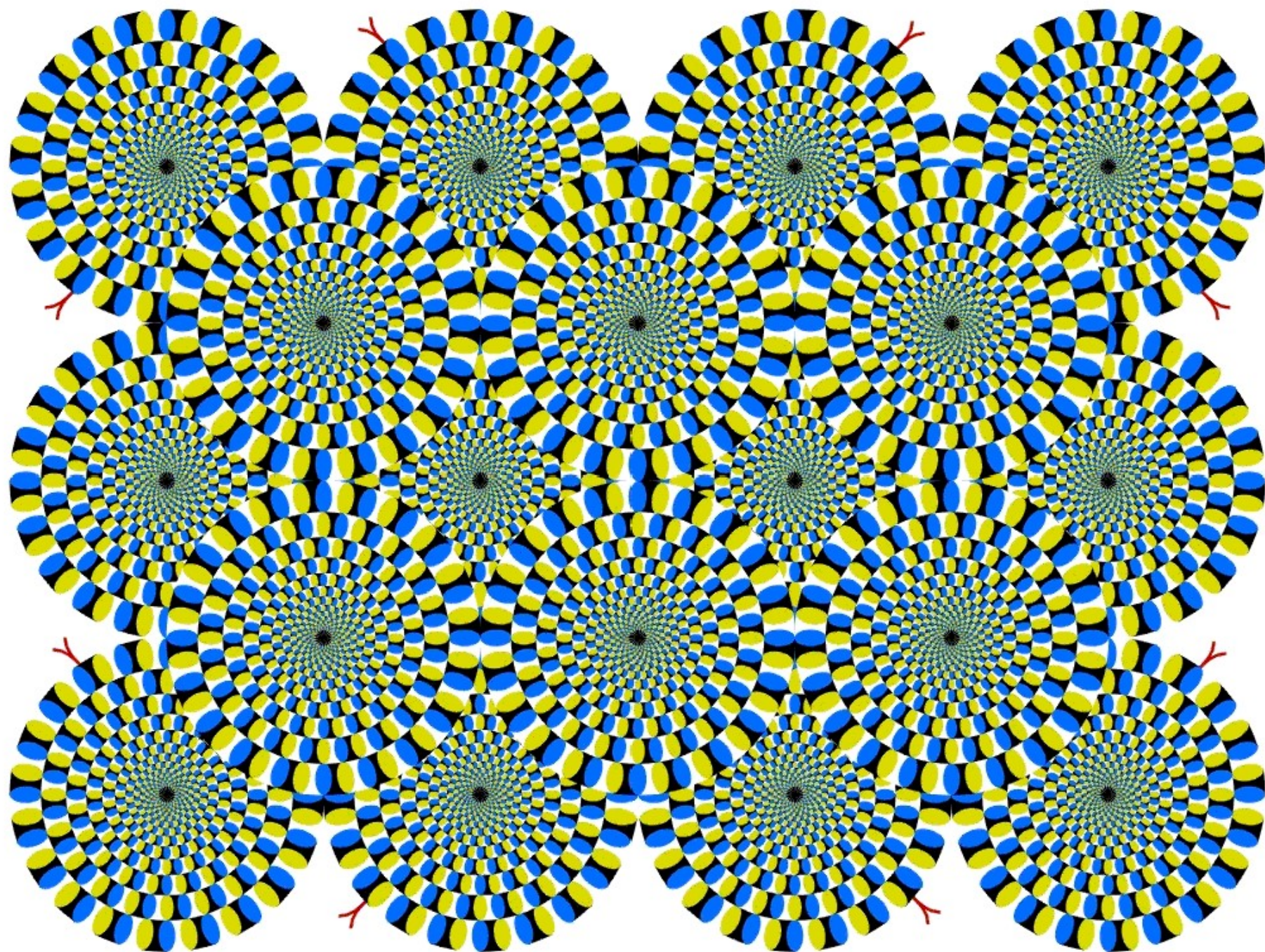


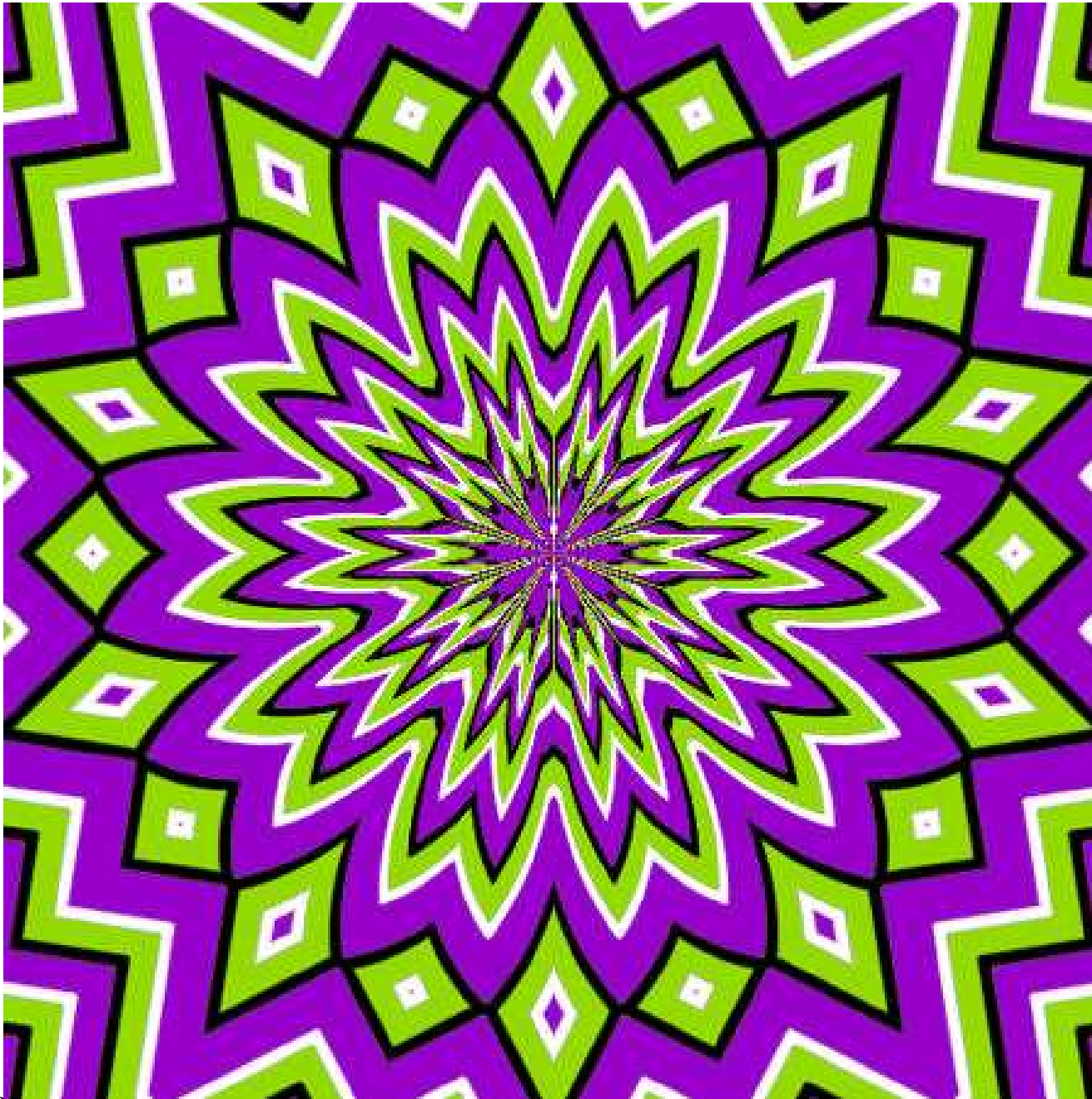
Beware of Lots of Other Stuff

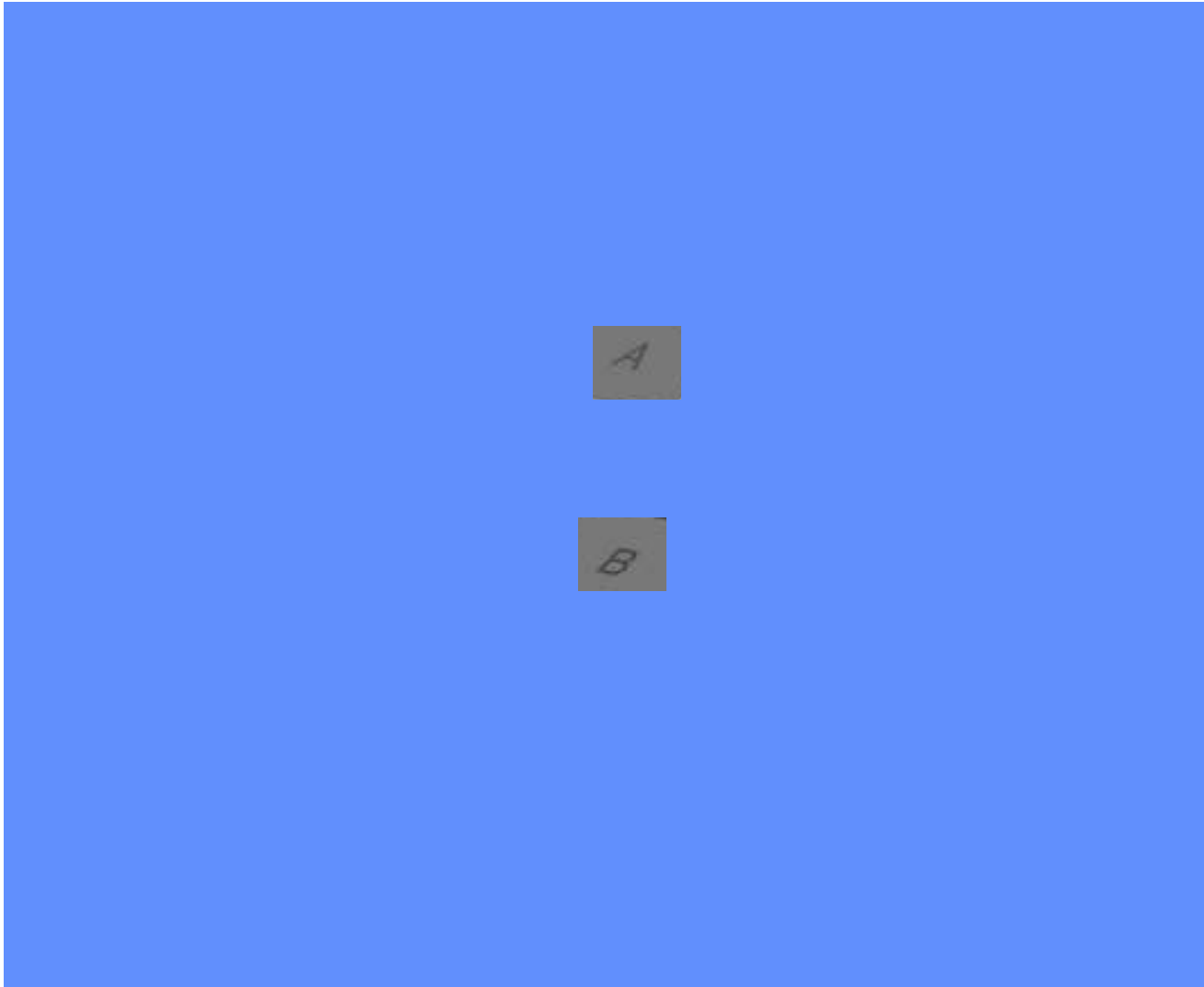


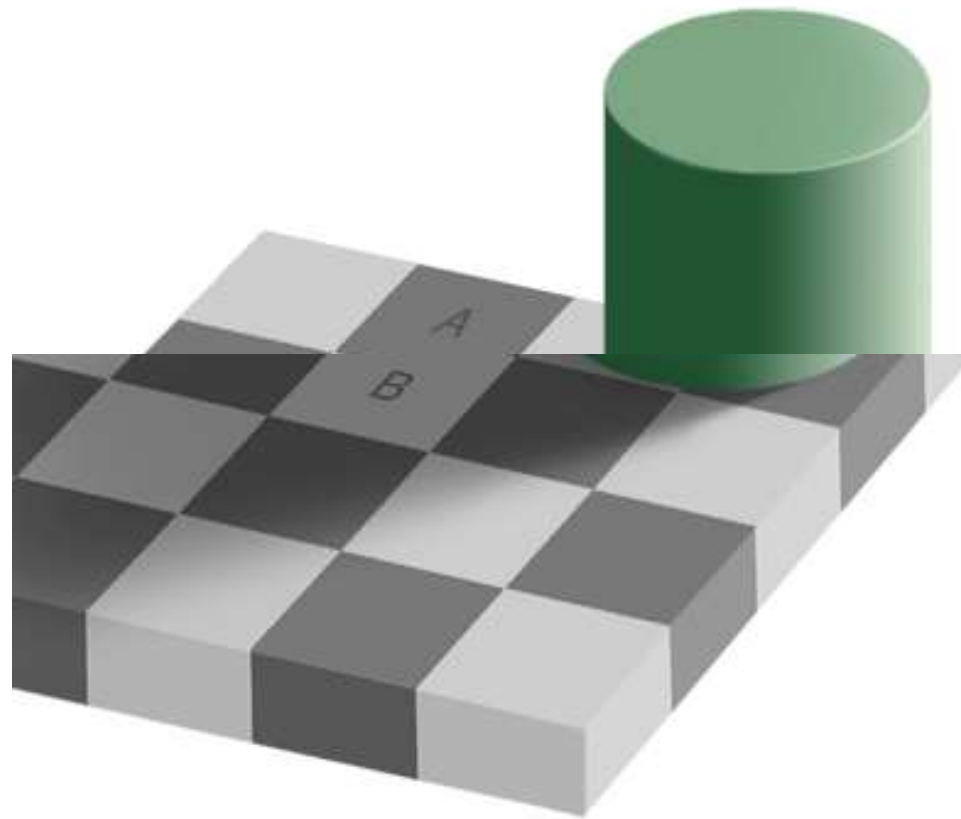












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