Color in Computer Graphics

Your Intensity/Color Sensors

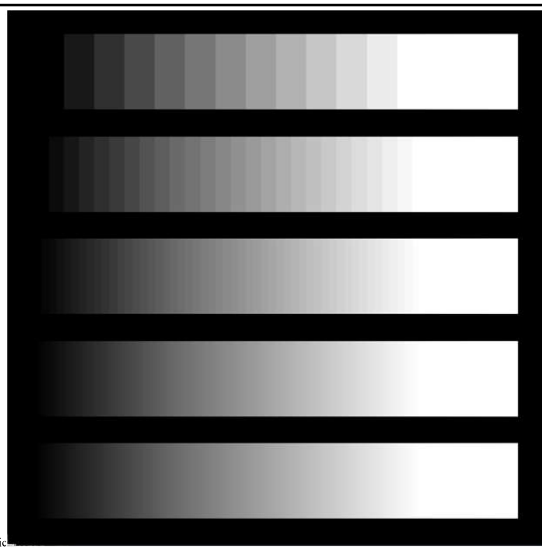
Rods

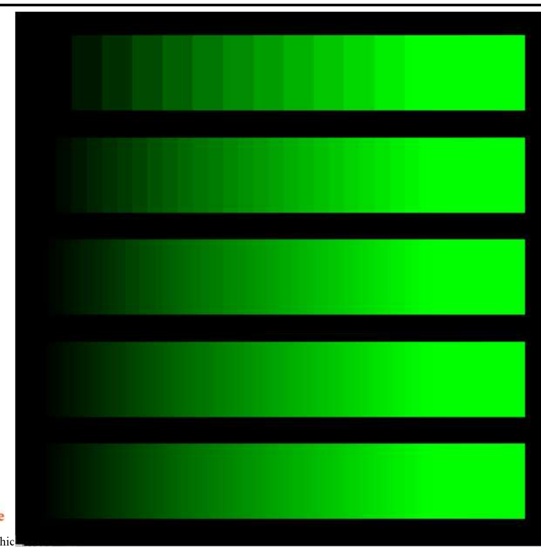
- ~115,000,000
- Concentrated on the *periphery* of the retina
- Sensitive to *intensity*
- Most sensitive at 500 nm (~green)

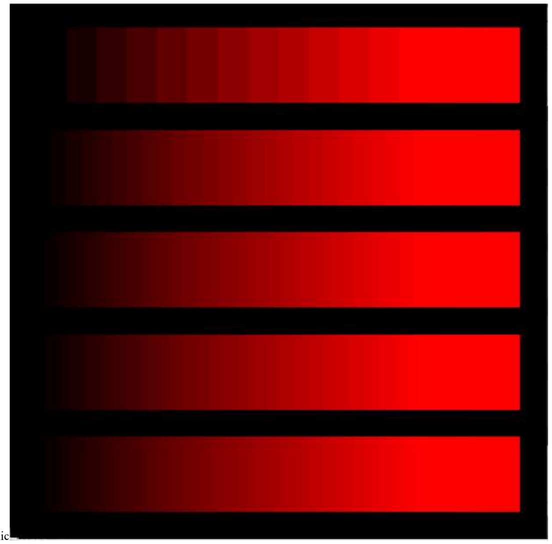
Cones

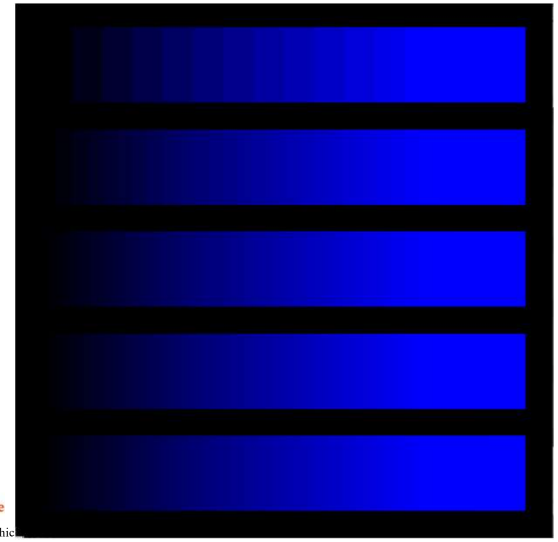
- ~7,000,000
- Concentrated near the *center* of the retina
- Sensitive to *color*
- Three types of cones: long(~red), medium (~green), and short (~blue) wavelengths

But are you equally-sensitive to all wavelengths?









Sidebar: How Many Pixels Do You Need?

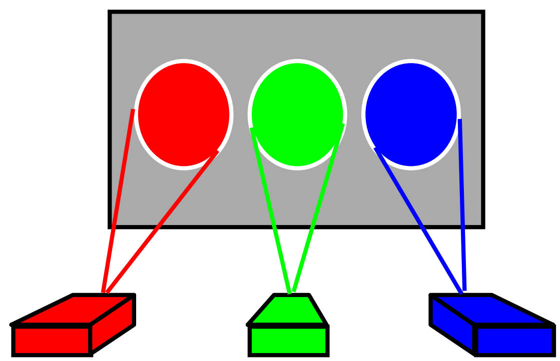
A person with 20/20 vision has a visual acuity of:
1 arc-minute = 1/60°

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

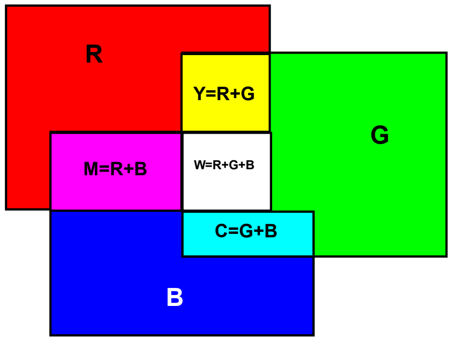
$$\text{Density} = \frac{1}{D\Theta}$$

Viewing Distance (inches)	Required Pixel Density (ppi)	If the monitor's resolution is 1600 x 1200, then its diagonal size would need to be:
36	95	21"
31	111	18"
24	143	14"
12	286	7"
9	400	5"
6	600	3"

Monitors: Additive Colors



Additive Color (RGB)



OpenGL: → **glColor3f(r, g, b);**

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

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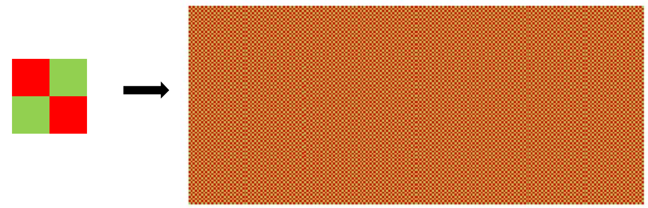
Yes, Our Vision System Really Does Mush Red and Green Together to Make Yellow!



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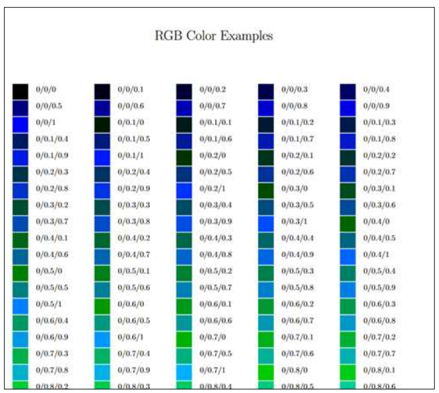
Color Combinations

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

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



RGB Color Examples

0/0/0	0/0/0.1	0/0/0.2	0/0/0.3	0/0/0.4
0/0/0.5	0/0/0.6	0/0/0.7	0/0/0.8	0/0/0.9
0/0/1	0/0.1/0	0/0.1/0.1	0/0.1/0.2	0/0.1/0.3
0/0.1/0.4	0/0.1/0.5	0/0.1/0.6	0/0.1/0.7	0/0.1/0.8
0/0.1/0.9	0/0.1/1	0/0.2/0	0/0.2/0.1	0/0.2/0.2
0/0.2/0.3	0/0.2/0.4	0/0.2/0.5	0/0.2/0.6	0/0.2/0.7
0/0.2/0.8	0/0.2/0.9	0/0.2/1	0/0.3/0	0/0.3/0.1
0/0.3/0.2	0/0.3/0.3	0/0.3/0.4	0/0.3/0.5	0/0.3/0.6
0/0.3/0.7	0/0.3/0.8	0/0.3/0.9	0/0.3/1	0/0.4/0
0/0.4/0.1	0/0.4/0.2	0/0.4/0.3	0/0.4/0.4	0/0.4/0.5
0/0.4/0.6	0/0.4/0.7	0/0.4/0.8	0/0.4/0.9	0/0.4/1
0/0.5/0	0/0.5/0.1	0/0.5/0.2	0/0.5/0.3	0/0.5/0.4
0/0.5/0.5	0/0.5/0.6	0/0.5/0.7	0/0.5/0.8	0/0.5/0.9
0/0.5/1	0/0.6/0	0/0.6/0.1	0/0.6/0.2	0/0.6/0.3
0/0.6/0.4	0/0.6/0.5	0/0.6/0.6	0/0.6/0.7	0/0.6/0.8
0/0.6/0.9	0/0.6/1	0/0.7/0	0/0.7/0.1	0/0.7/0.2
0/0.7/0.3	0/0.7/0.4	0/0.7/0.5	0/0.7/0.6	0/0.7/0.7
0/0.7/0.8	0/0.7/0.9	0/0.7/1	0/0.8/0	0/0.8/0.1
0/0.8/0.2	0/0.8/0.3	0/0.8/0.4	0/0.8/0.5	0/0.8/0.6

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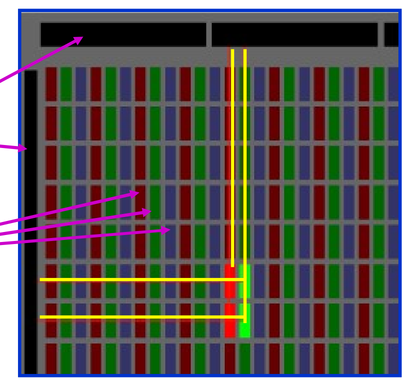
LCD Displays "Gate" Color

Most desktop monitors are LCD displays that use white LEDs for backlighting

- **Grid of electrodes**
- **Color filters**



http://electronics.howstuffworks.com

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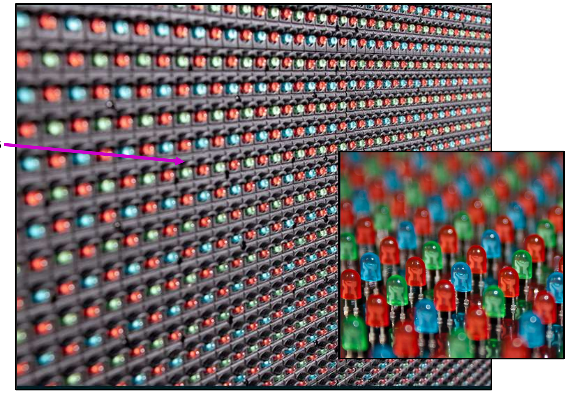
LED Displays *Emit* Color

- Grid of LEDs



https://www.expromo.eu/en/led-display-facts/

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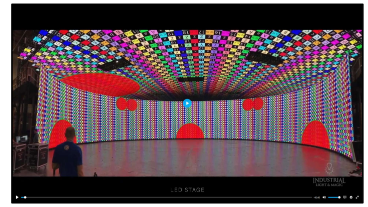
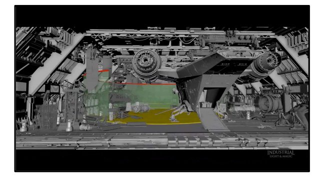
The New Sound Stages use LED Displays





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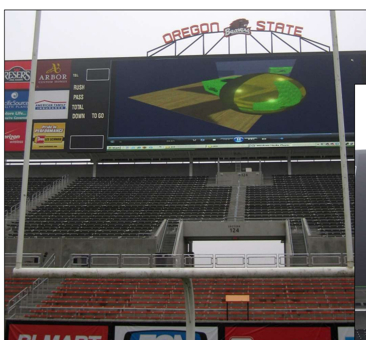
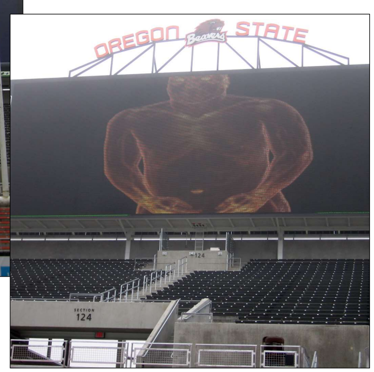
Stadium Jumbotrons use LED Displays





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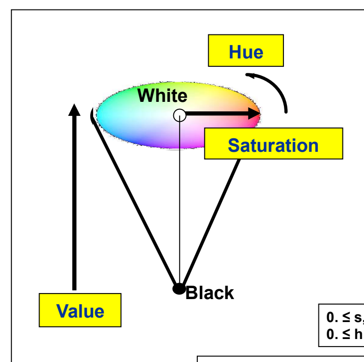
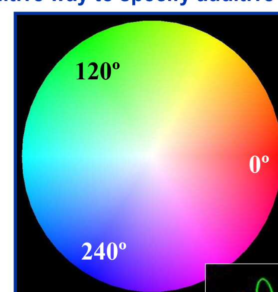
Hue-Saturation-Value (HSV): For many applications, a more intuitive way to specify additive color

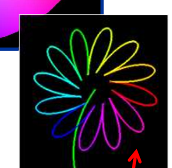




0. ≤ s, v, r, g, b ≤ 1.
0. ≤ h ≤ 360.

```
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 :-)

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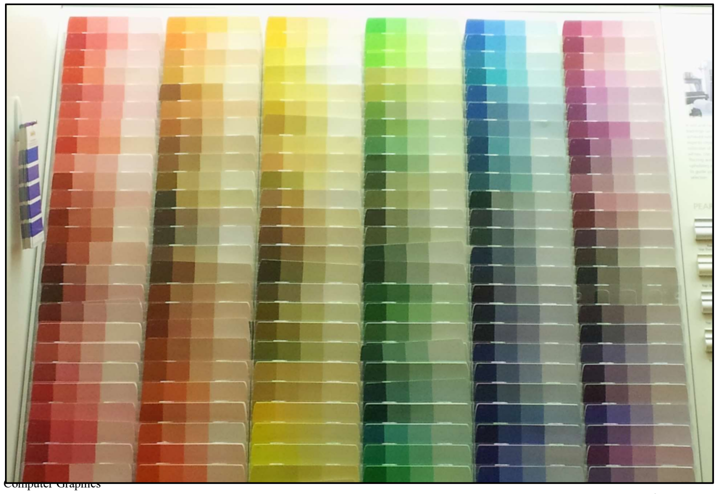

Computer Graphics

Hue-Saturation-Value (HSV): For many vis applications, a simpler way to specify additive color

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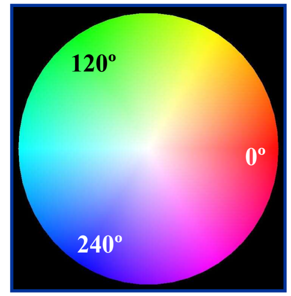
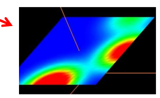


Notice that blue-green-red in HSV space corresponds to the visible portion of the electromagnetic spectrum

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

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



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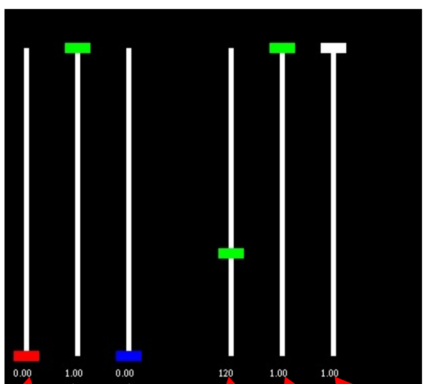
Hue-Saturation-Value: The *OSU ColorPicker* Program

19



Red, Green, Blue

Hue, Saturation, Value

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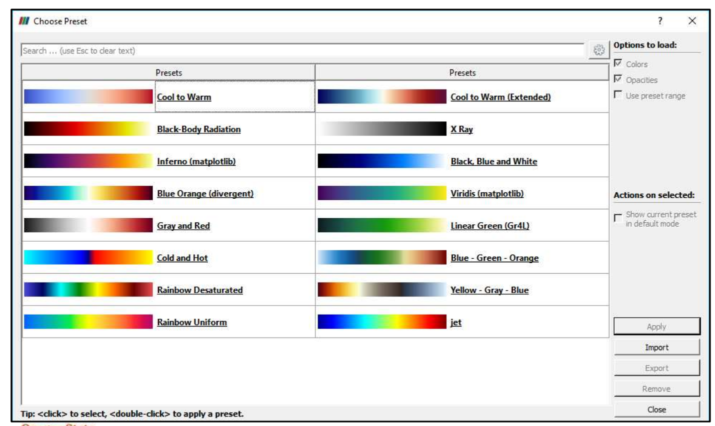
ParaView Allows You to Pick Among Several Preset Color Ranges

20



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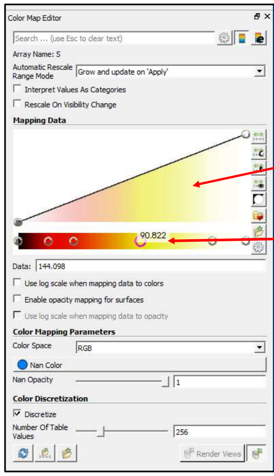
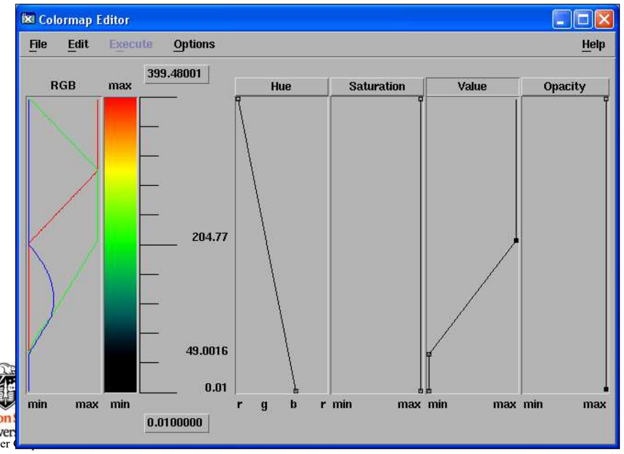
ParaView Allows You to Sculpt Your Own Color Range



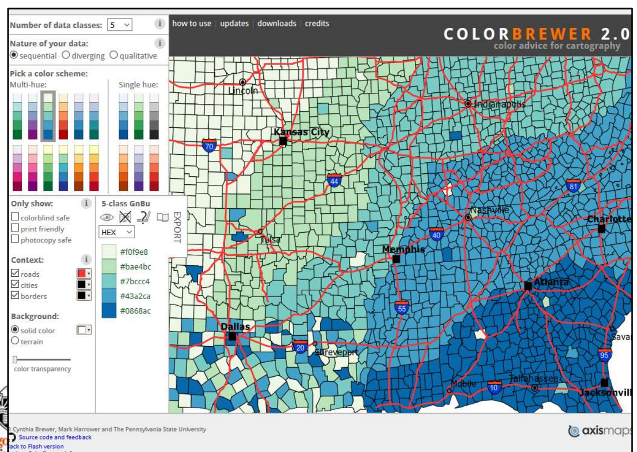
Opacity

Color

OpenDX Allows you to Sculpt the Transfer Function in HSV



http://colorbrewer2.org



http://colorbrewer2.org

Number of discrete colors needed

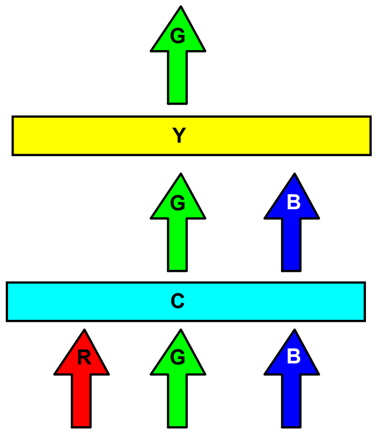
Type of data

Color schemes

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

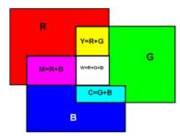
A good way to explore discrete color spaces

Subtractive Colors (CMYK)

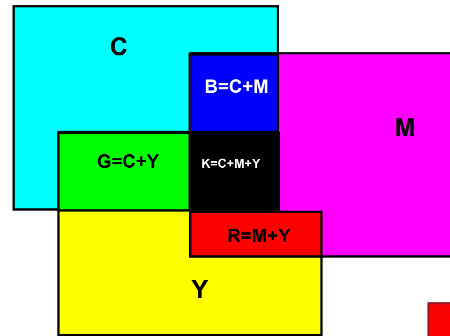


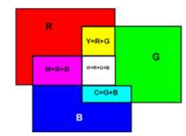
R = Red
G = Green
B = Blue
W = White

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



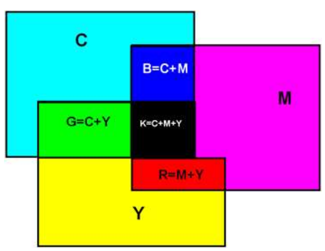
Subtractive Colors (CMYK)



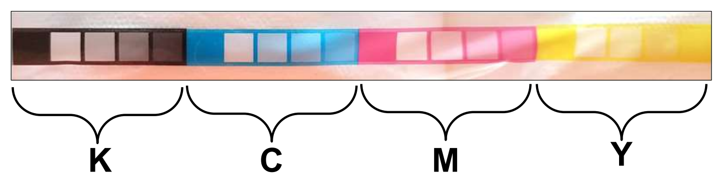


Color Printing

- 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

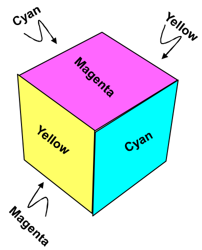


You Often See Color Printing QA Tests Like This

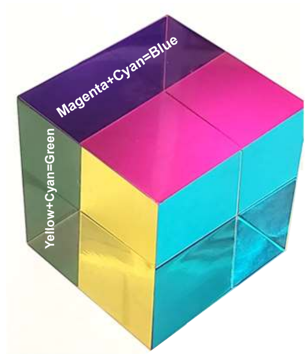


The CMY Cube

How the Cube is setup:

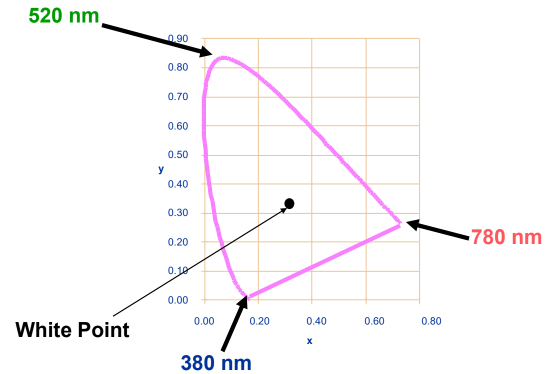


How it looks when you sight through two faces:

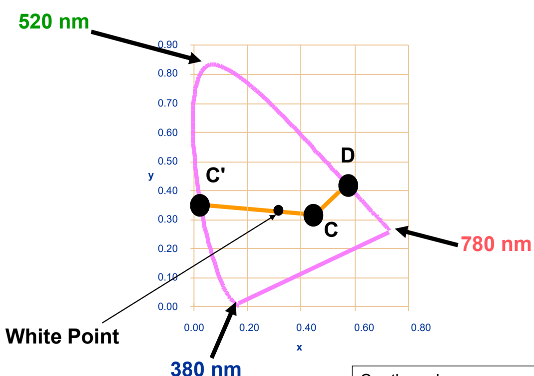


I have one of these in my office! ☺

CIE Chromaticity Diagram

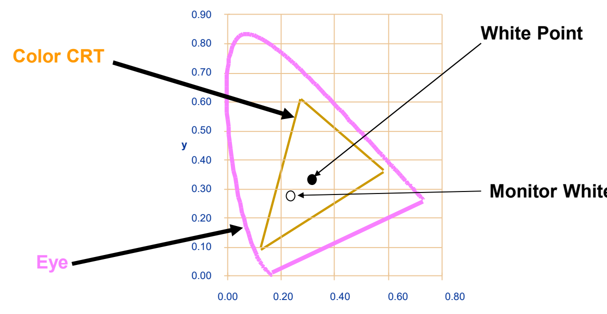


CIE Chromaticity Diagram

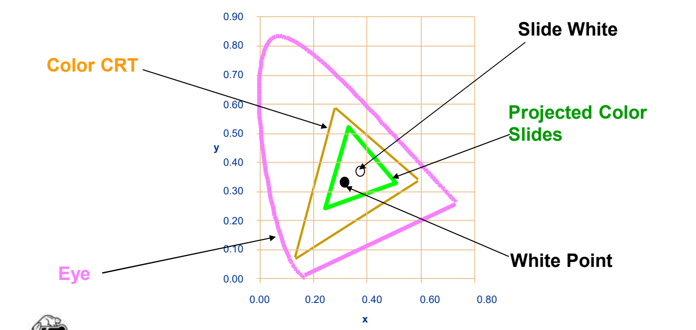


C = the color
D = the dominant wavelength
C ' = the complementary color

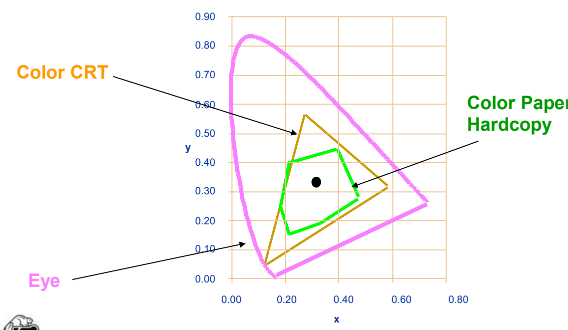
Color Gamut for a Workstation Monitor



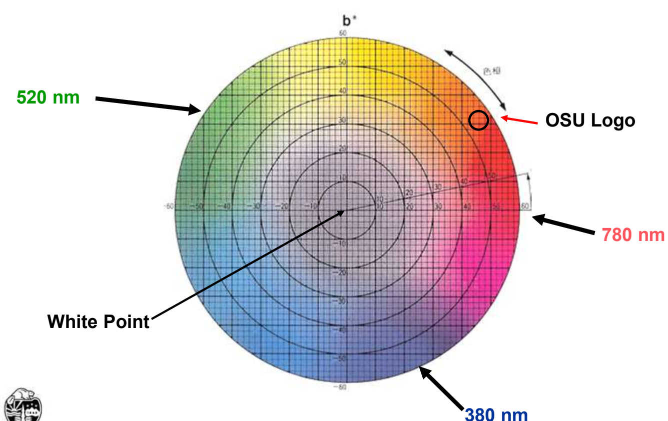
Color Gamut for a Monitor and Color Slides



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

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Color Alone Doesn't Cut It !

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

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Luminance Contrast is Crucial !

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

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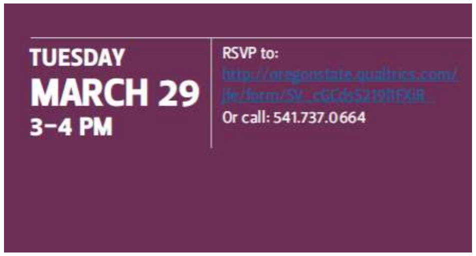

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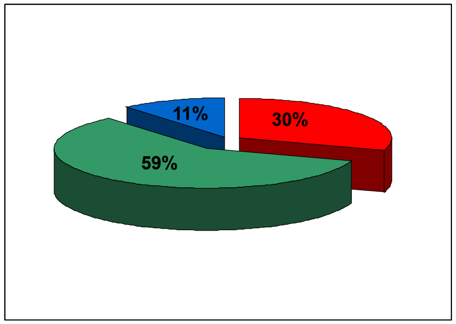
The Luminance Equation

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



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

(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

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

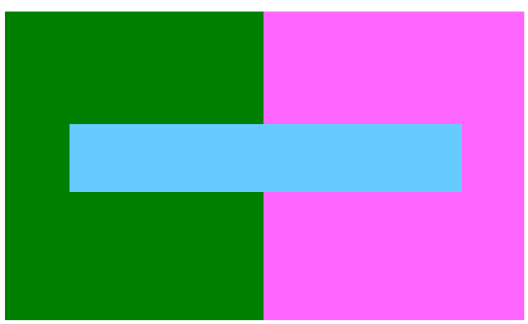
Instructions:

1. Press red to logoff normally

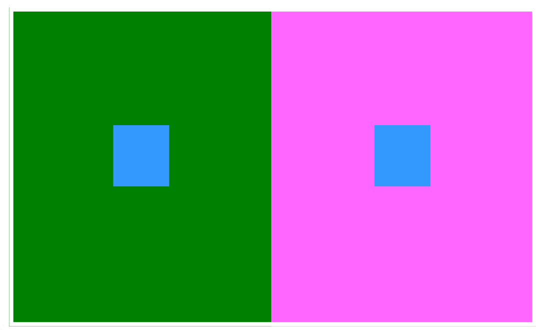
2. Press light red to delete all your files, change your password to something random, and logoff

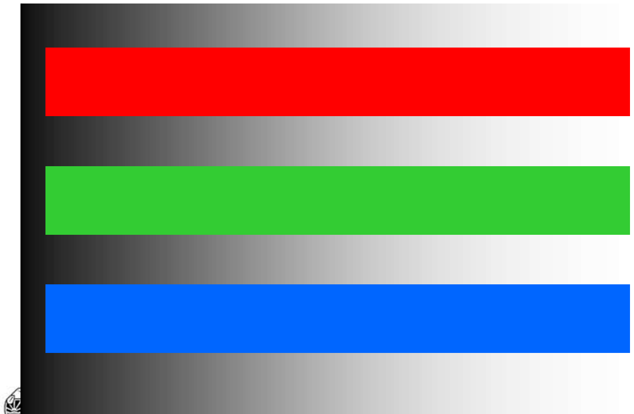
You have 2 seconds • • •

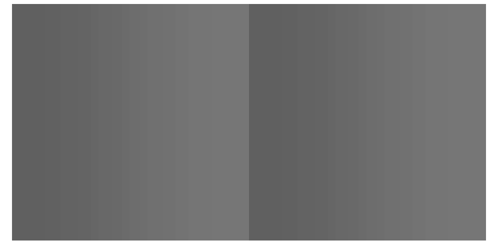
The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"

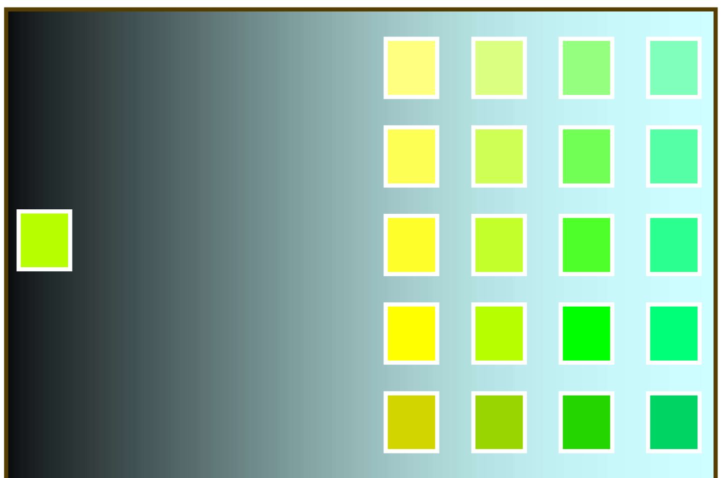


The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"







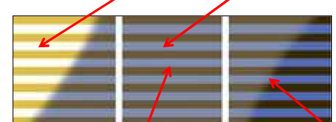


So, What's Up with the "Blue Dress" Debate?

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

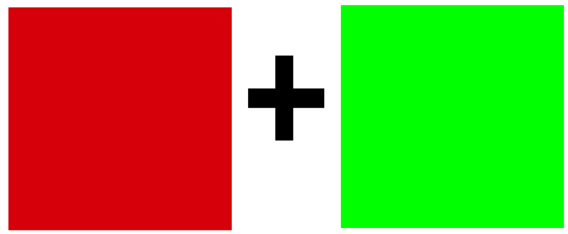
New York Times

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.

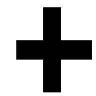


If you see this color, but you think that the dress is currently in bright light, you "know" that it must *really* be this color.

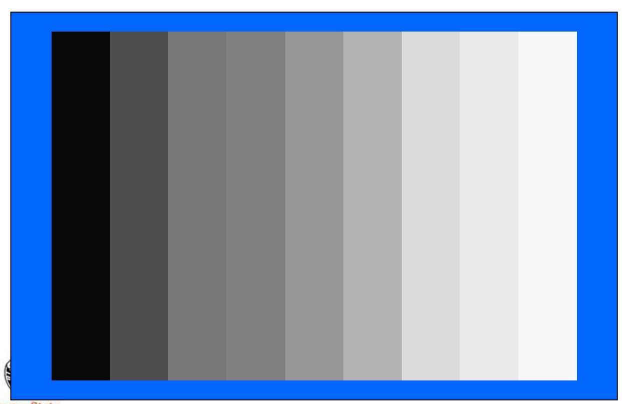
Afterimages



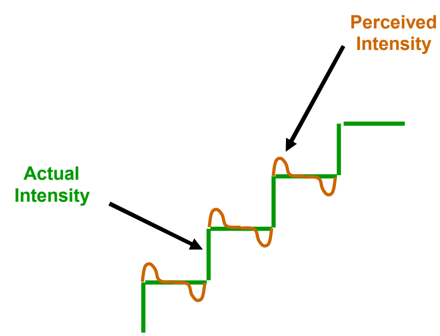
Afterimages



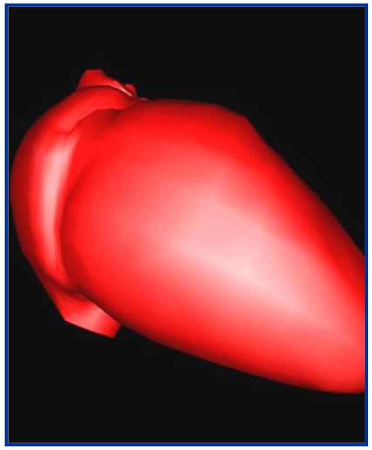
Beware of Mach Banding



Beware of Mach Banding

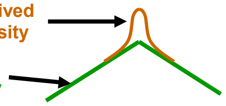


Beware of Mach Banding



Perceived Intensity

Actual Intensity

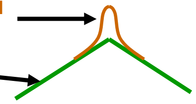


Beware of Mach Banding

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

Perceived Intensity

Actual Intensity



Be Aware of Color Vision Deficiencies (CVD)

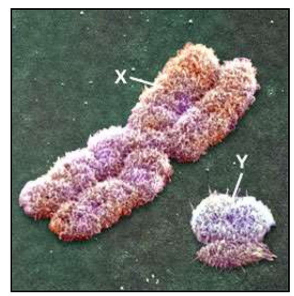
- In general, there is no such thing as total “color blindness”
- CVD affects ~10% of Caucasian men
- CVD affects ~4% of non-Caucasian men
- CVD affects ~0.5% of women
- The most common type of CVD is red-green
- Blue-yellow also exists

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

http://colorbrewer2.org
http://colororacle.org/usage.html
http://mkweb.bcgsc.ca/colorblind/

Why are more men affected by CVD than women?

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.

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Be Aware of CVD: Code Information Redundantly

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...

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

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

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

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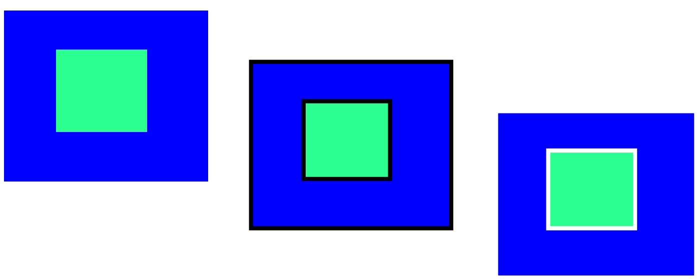
Use a Black or White Line as the Boundary Between Colored Regions



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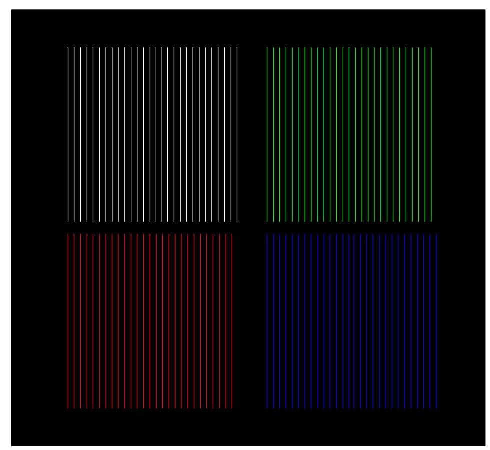
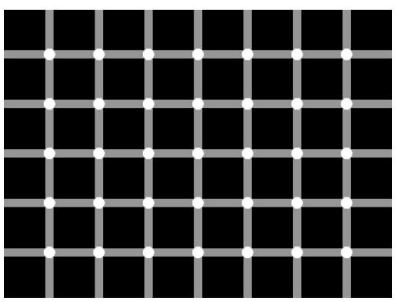
Do Not Display Fast-moving or High-detail Items in Color, Especially Blue

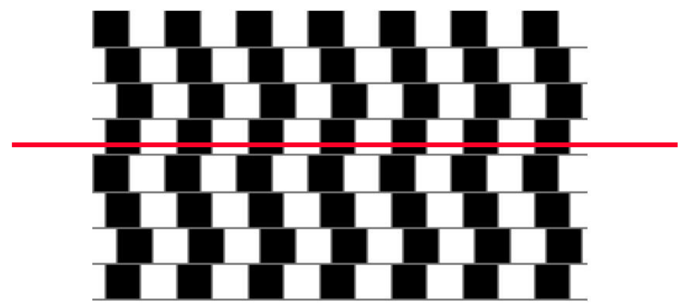


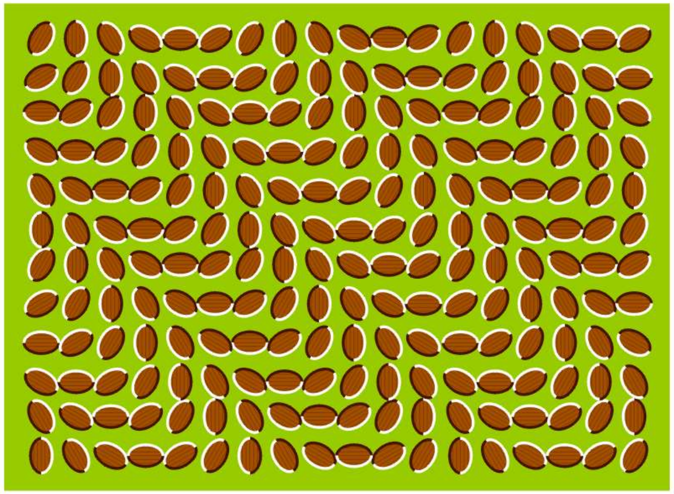
Watch the Use of Saturated Reds and Blues Together

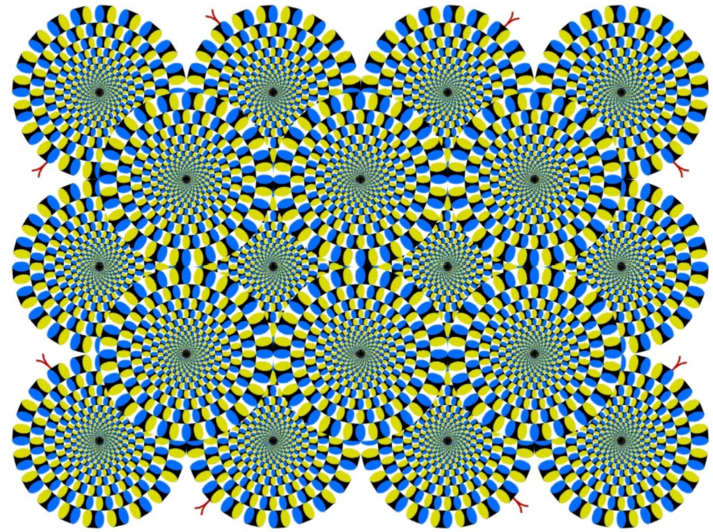
Reds and Blues are on opposite ends of the color spectrum. It is hard for your eyes to focus on both.

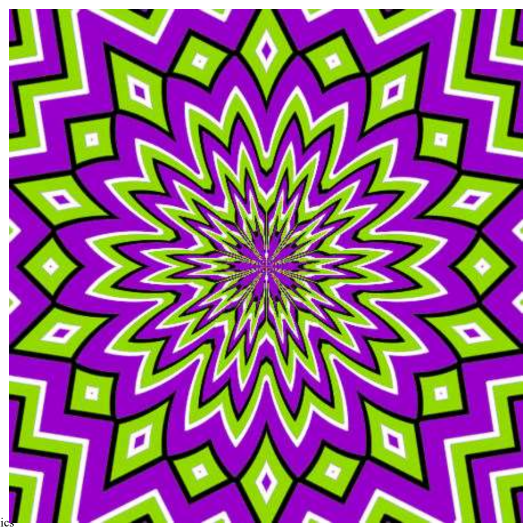
Beware of Lots of Other Stuff

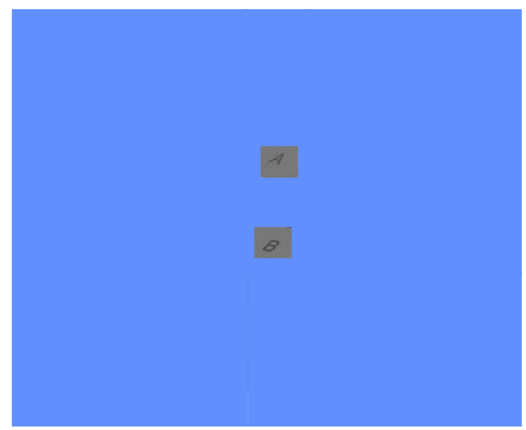


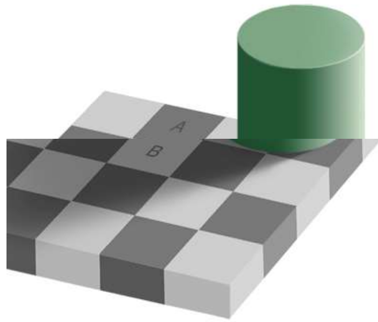









A
B



Good Color and Perception References

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