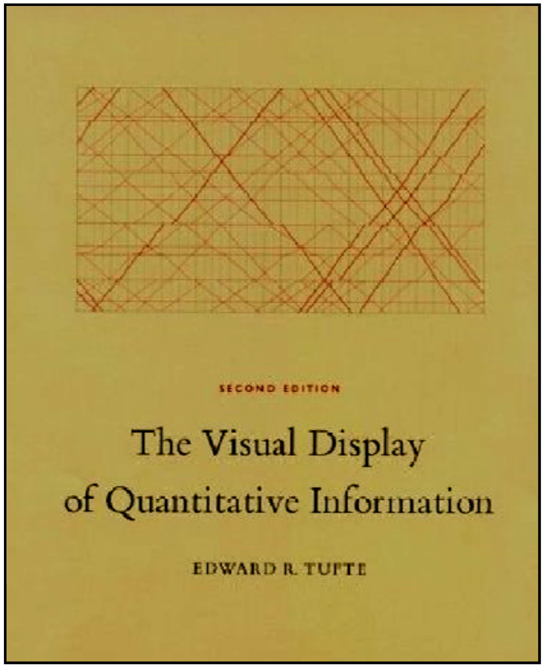
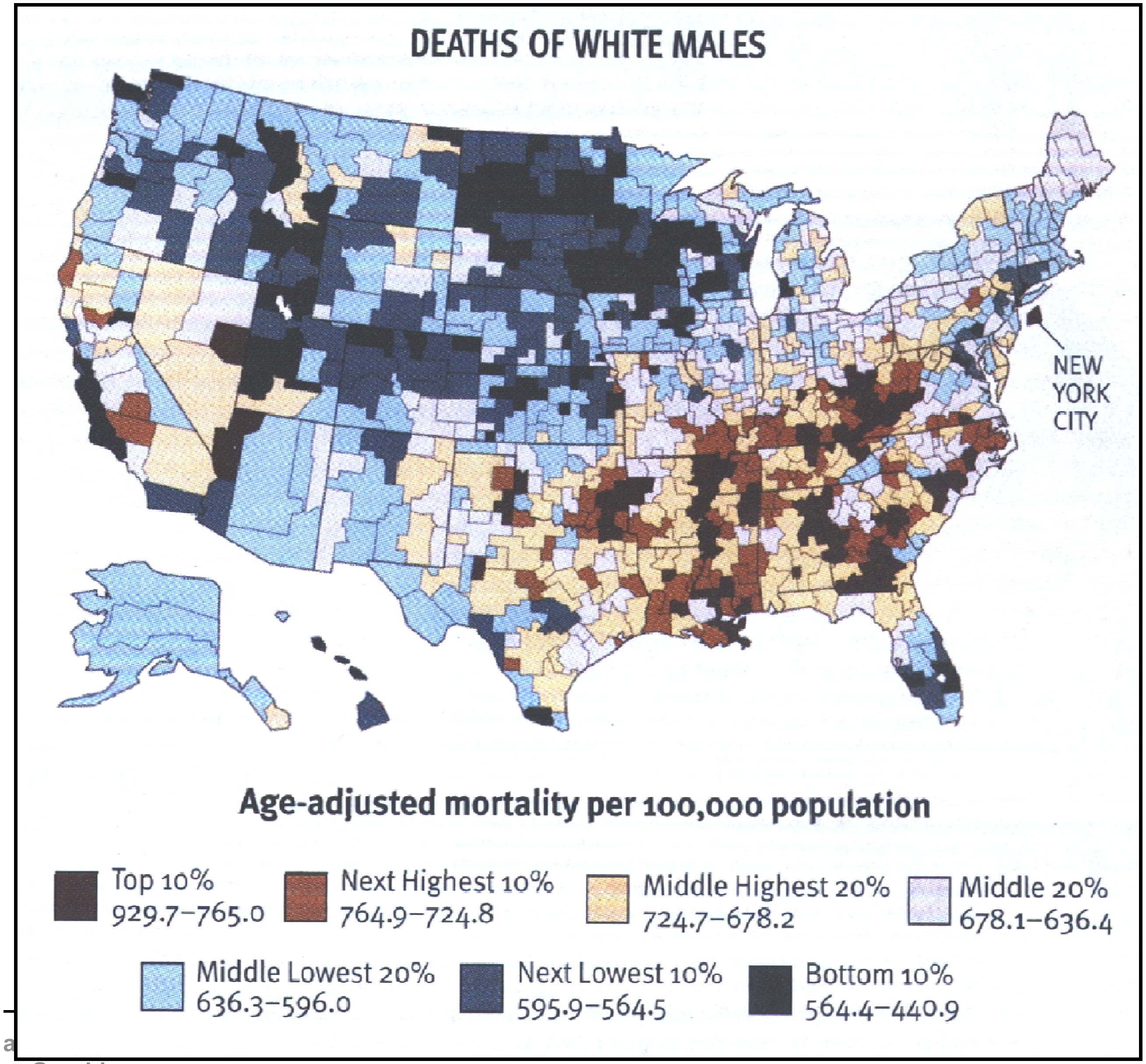
Color in Scientific Visualization

"The often scant benefits derived from coloring data indicate that even putting a good color in a good place is a complex matter. Indeed, so difficult and subtle that avoiding catastrophe becomes the first principle in bringing color to information. *Above all, do no harm*."

-- Edward Tufte

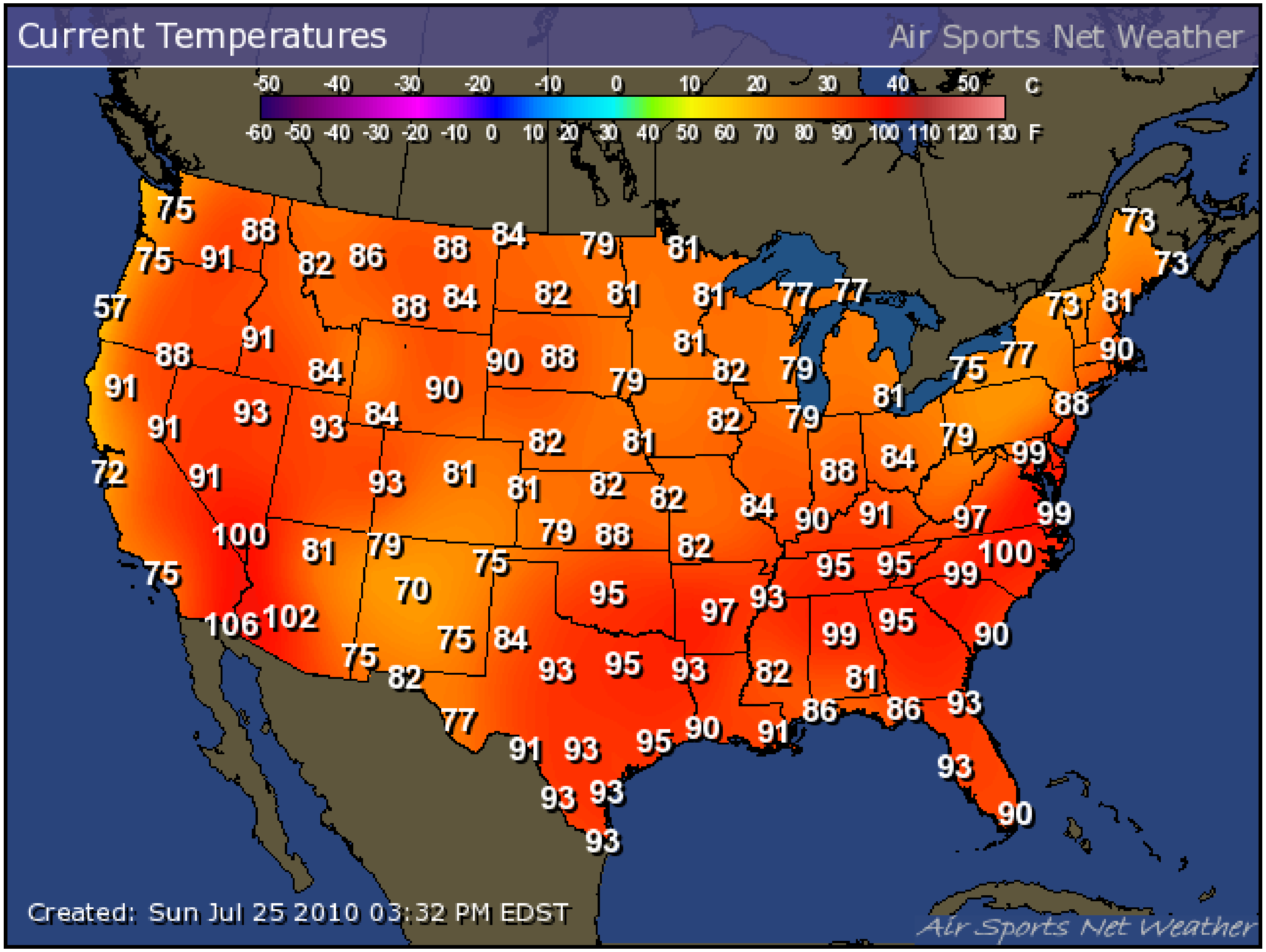


What's Wrong with this Color Scale?



Source:
Scientific American,
June 2000

Not a bad choice of color scale, but the Dynamic Range needs some work



Let's start with the most important component in a visualization system – You!

How Many Shades of Different Colors Are We Able to Detect?

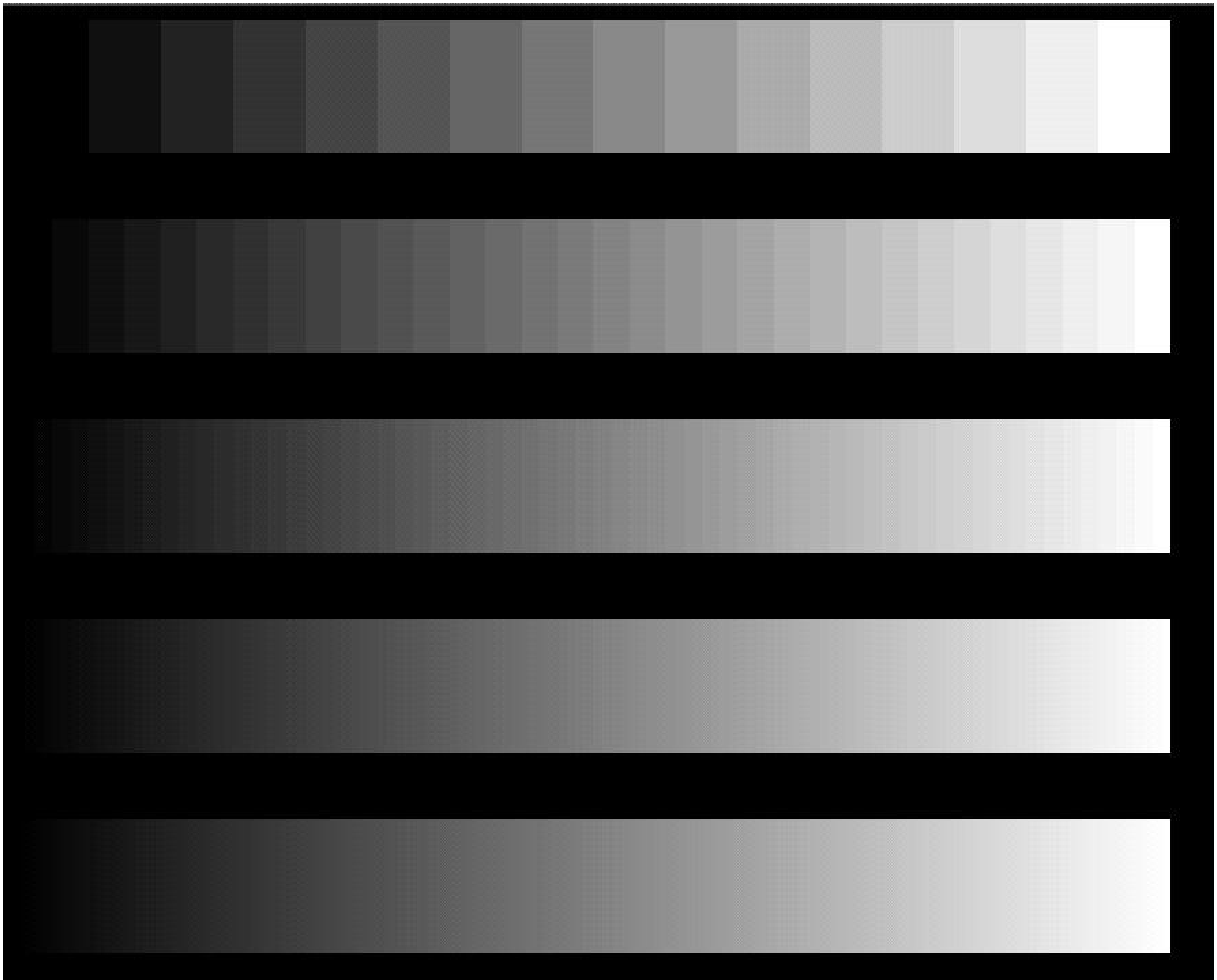
Sensors in Your Retina

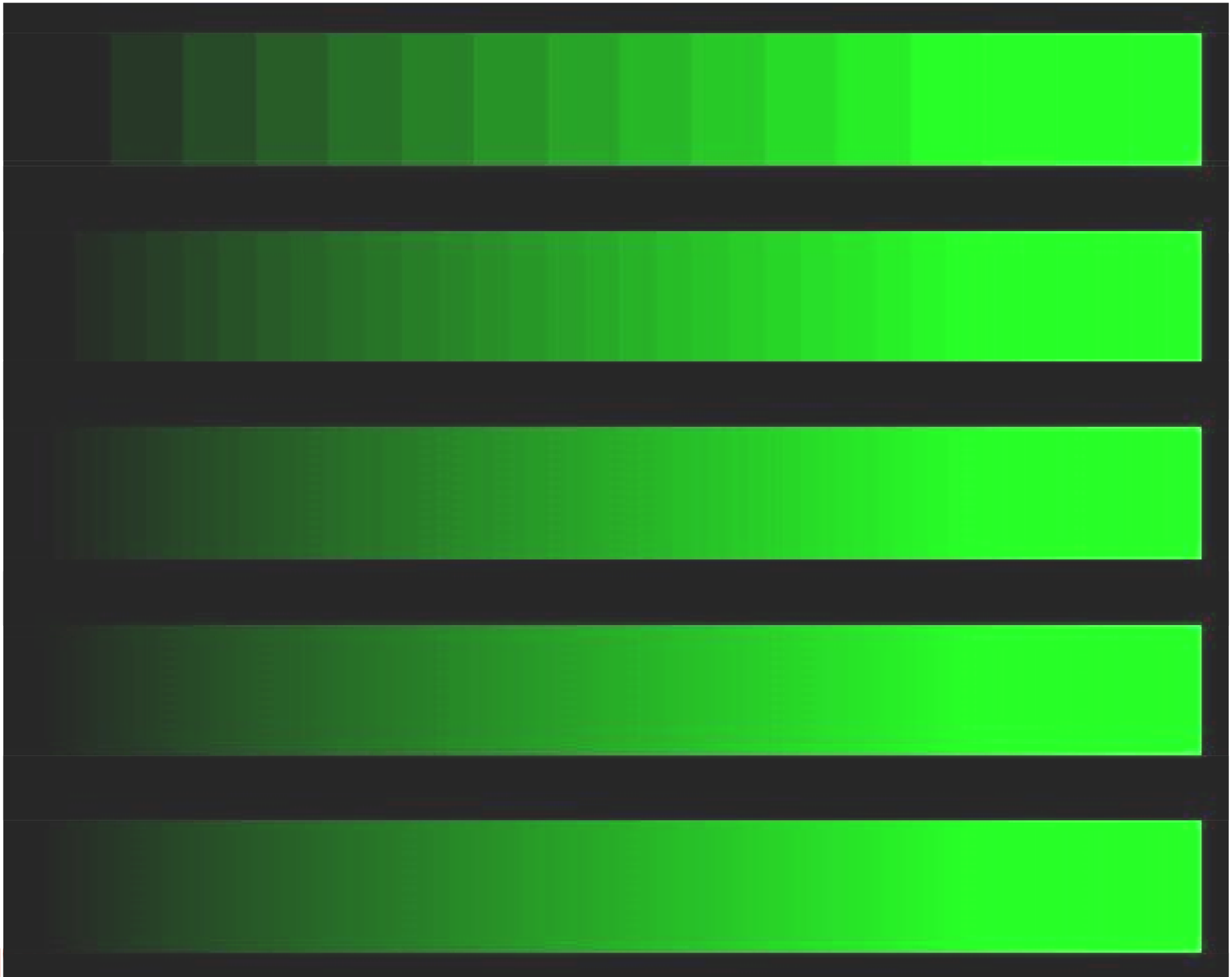
Rods

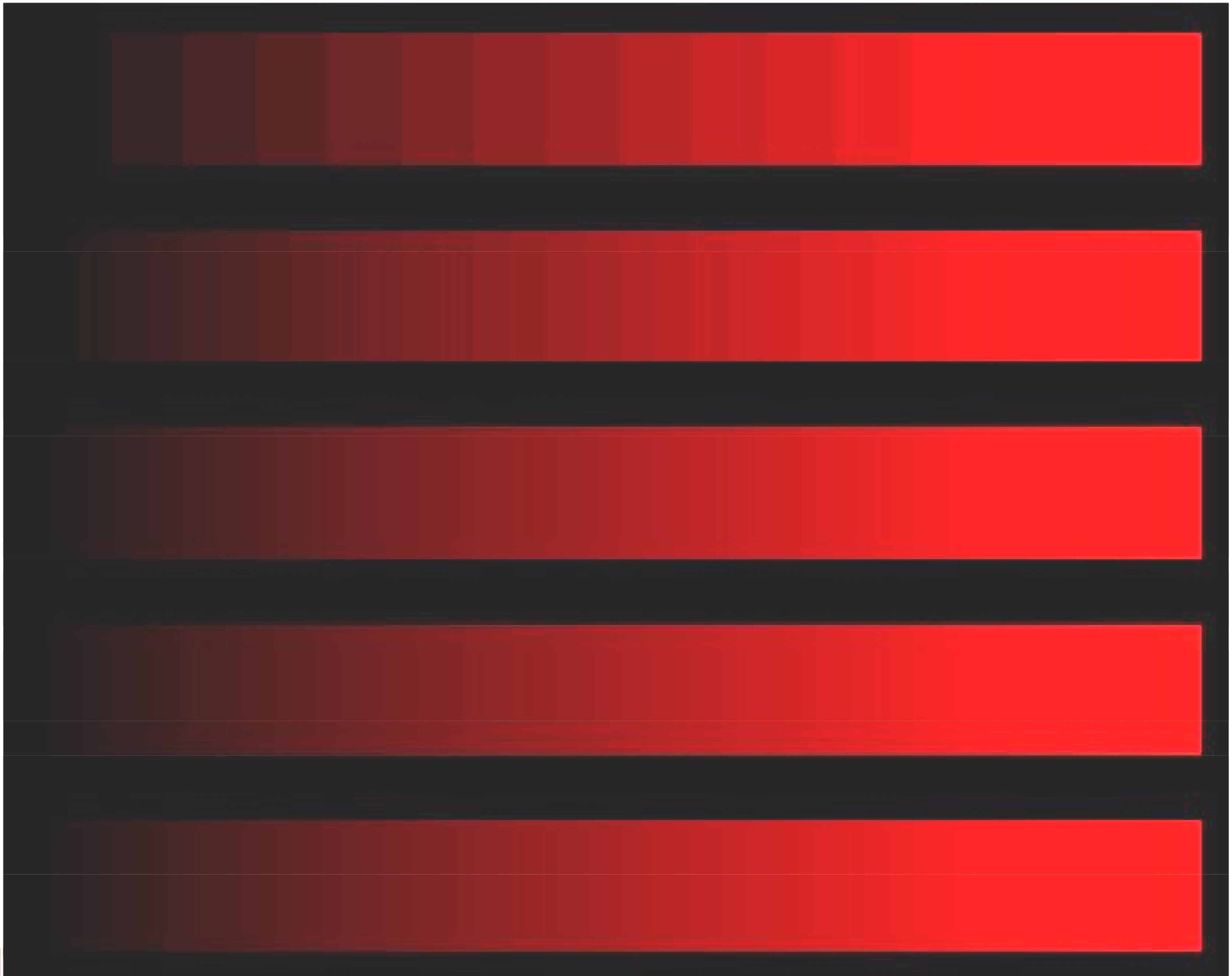
- ~115,000,000
- Concentrated on the periphery of the retina
- Sensitive to *intensity*
- Most sensitive at 500 nm (~green)

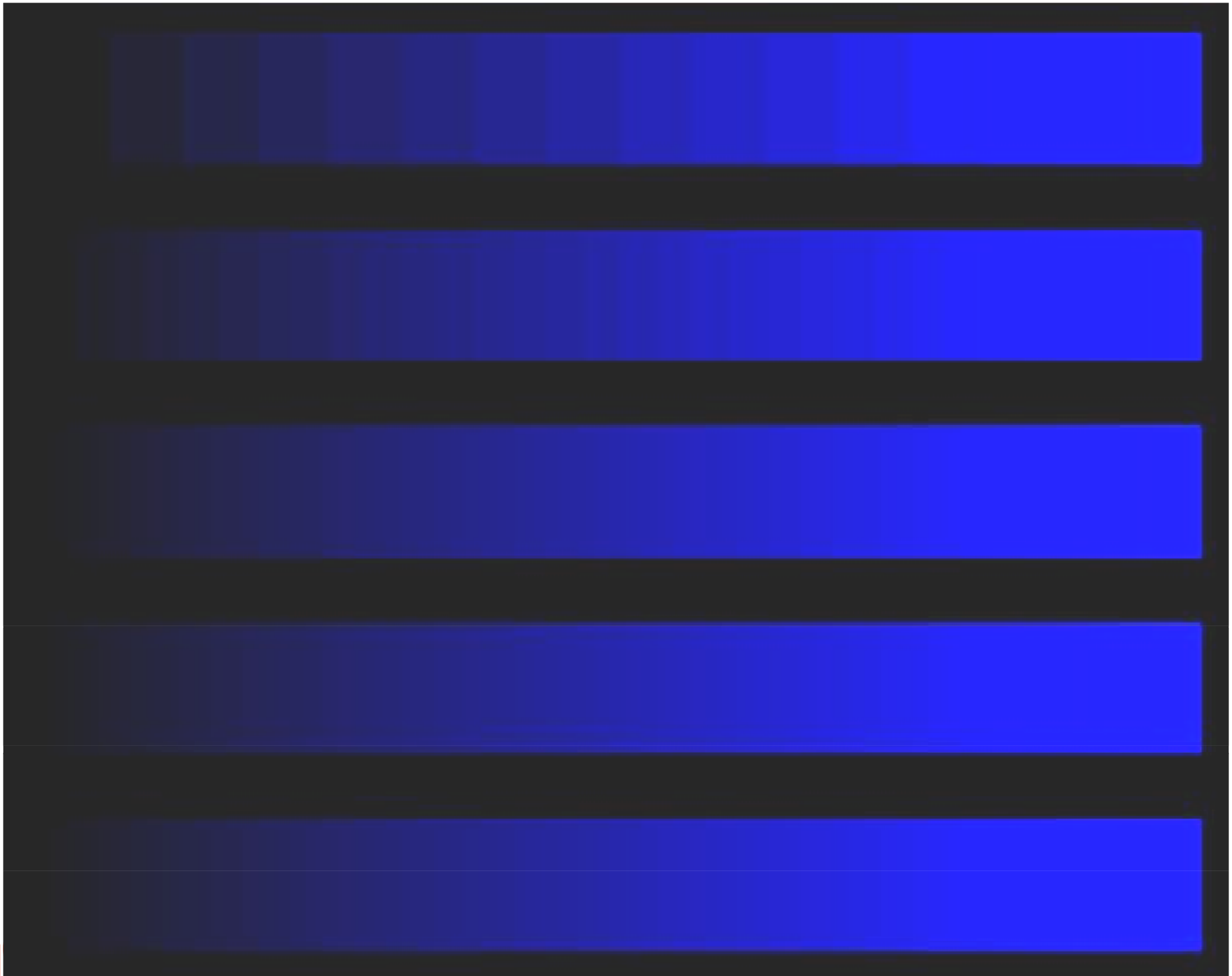
Cones

- ~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









Sidebar: How Many Pixels Do You Need?

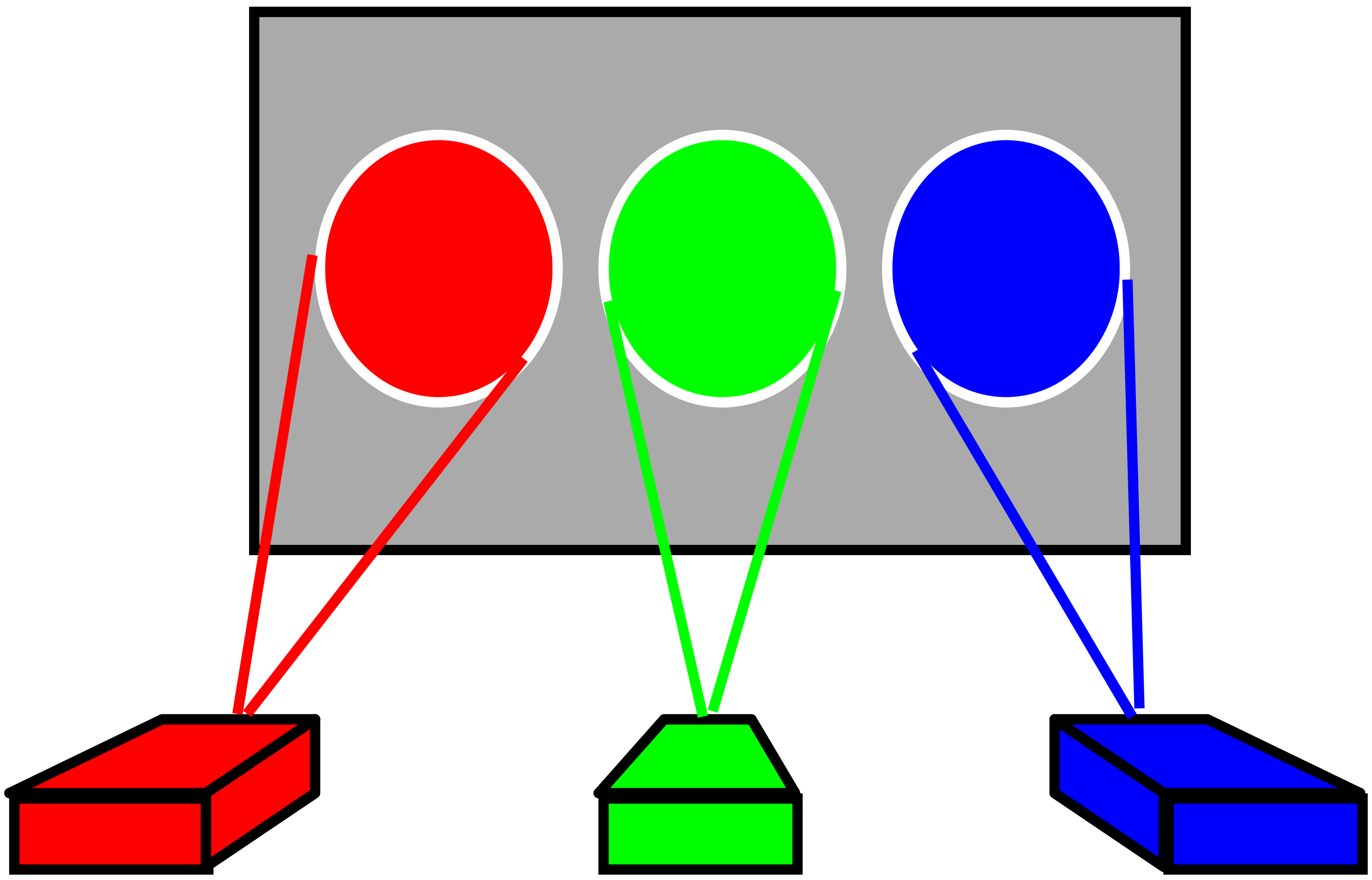
A person with 20/20 vision has a visual acuity of:
1 arc-minute = 1/60°

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

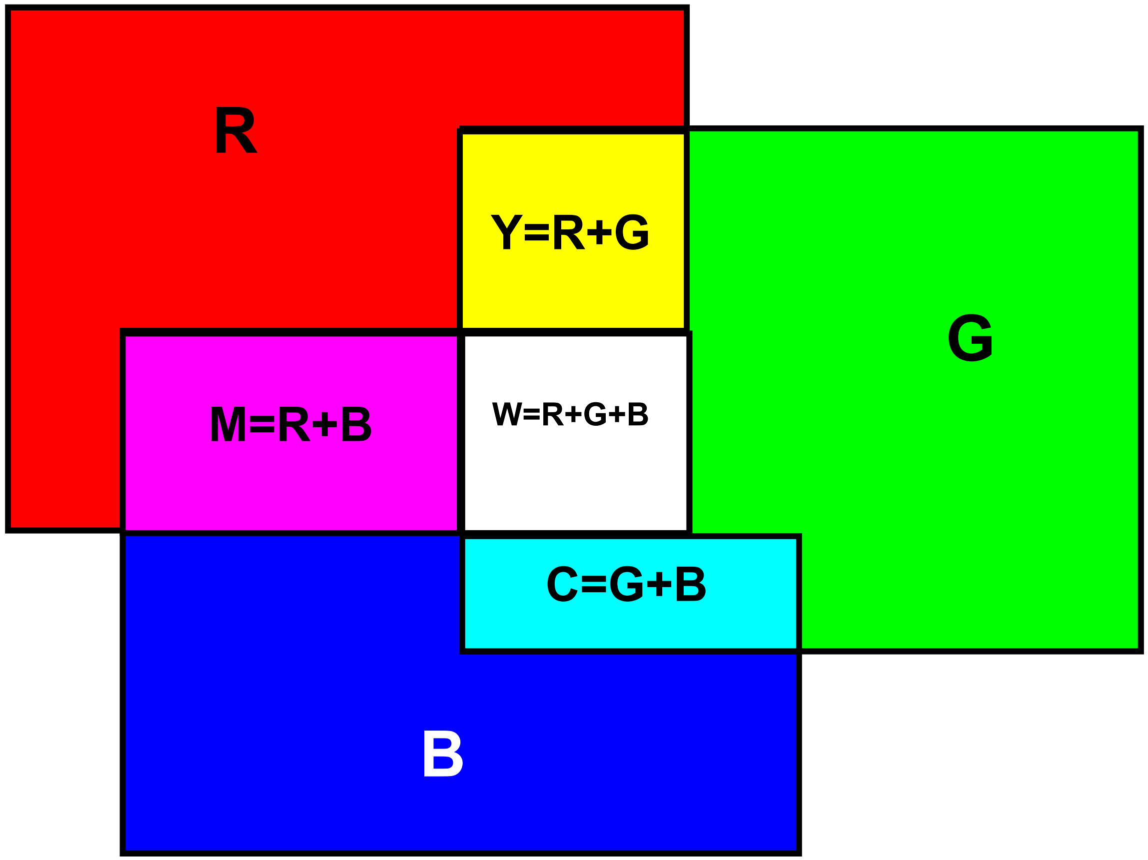
$$\text{Density} = \frac{1}{D\Theta}$$

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)

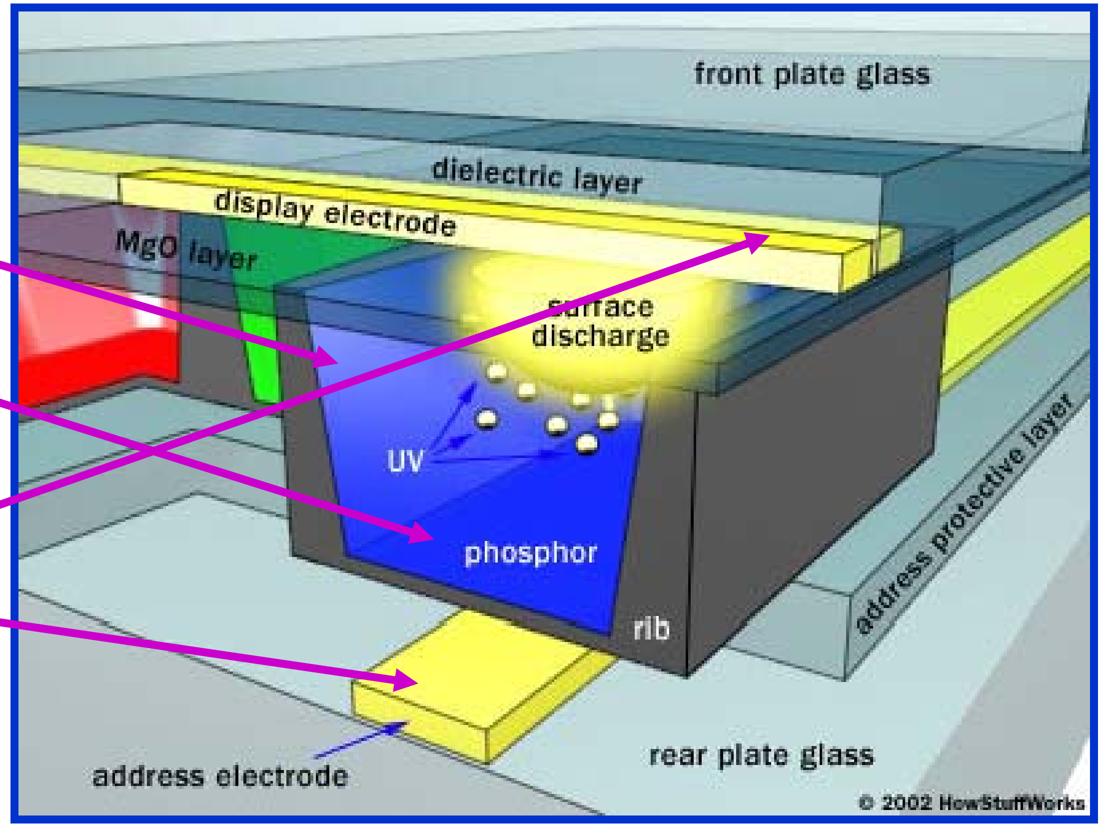


OpenGL: → **glColor3f(r, g, b);**

0. ≤ r, g, b ≤ 1.

Plasma Displays use Additive Color

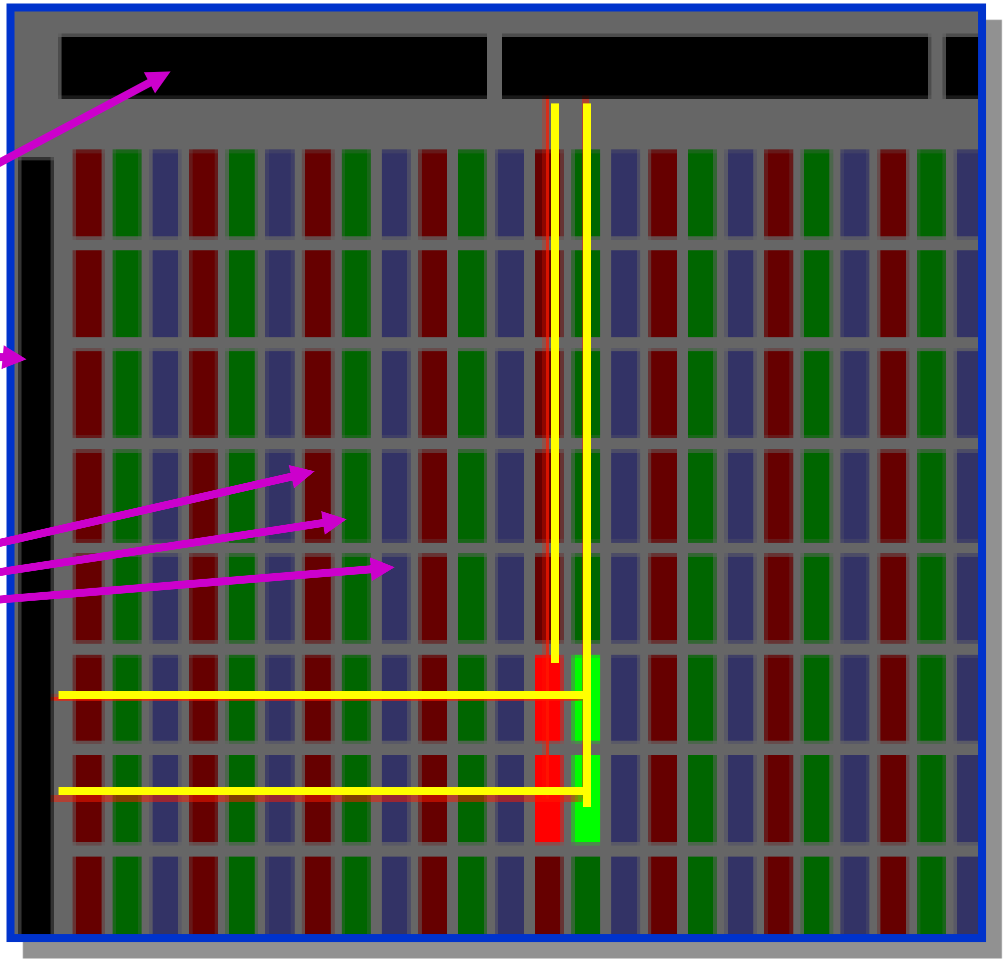
- **Gas cell**
- **Phosphor**
- **Grid of electrodes**



http://electronics.howstuffworks.com

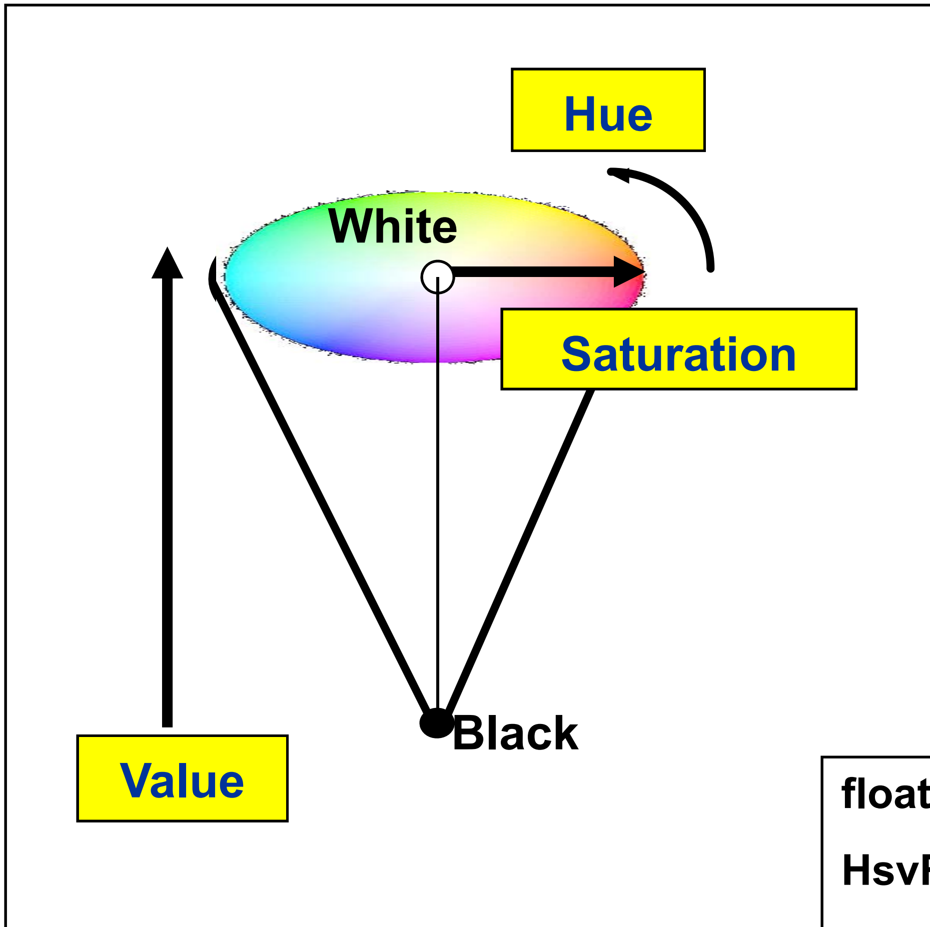
LCD Displays use Additive Color

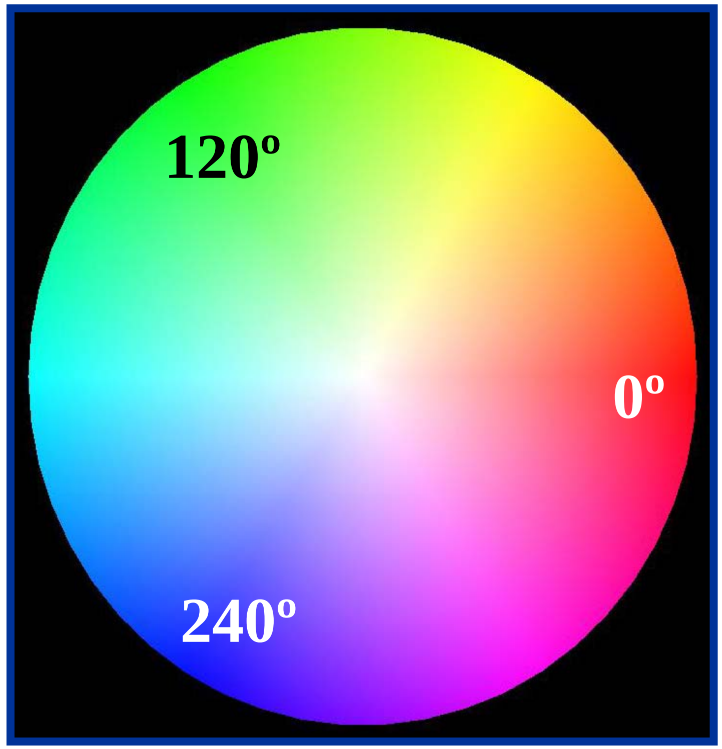
- **Grid of electrodes**
- **Color filters**



http://electronics.howstuffworks.com

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





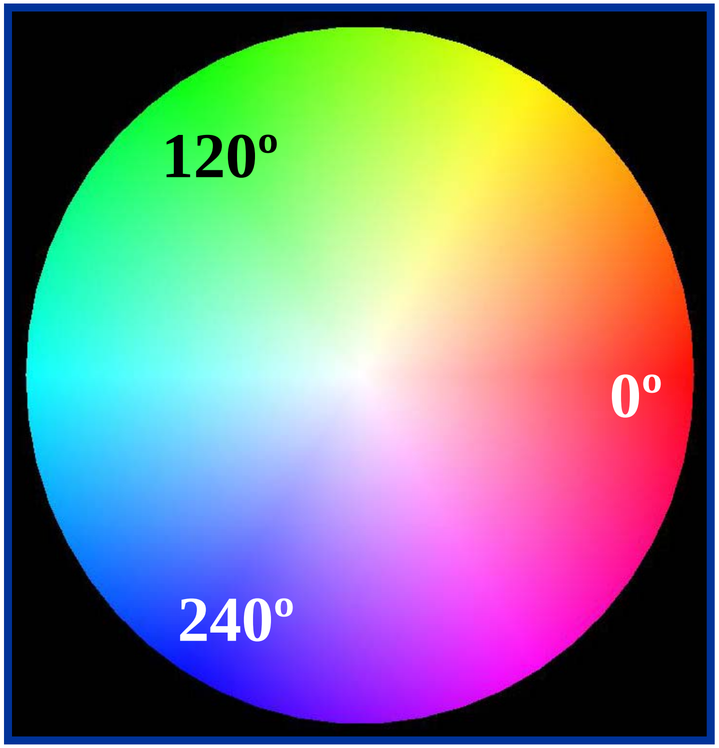
The HsvRgb function is in your sample code

```
float hsv[3], rgb[3];
HsvRgb( hsv, rgb );
glColor3fv( rgb );
```

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

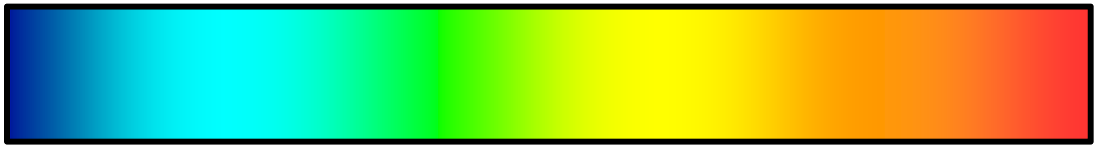
Home Depot uses a form of HSV :-)

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



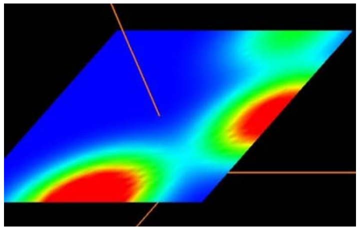
Notice that blue-green-red in HSV space corresponds to the visible portion of the electromagnetic spectrum

Blue: 380 nm Green: 520 nm Red: 780 nm

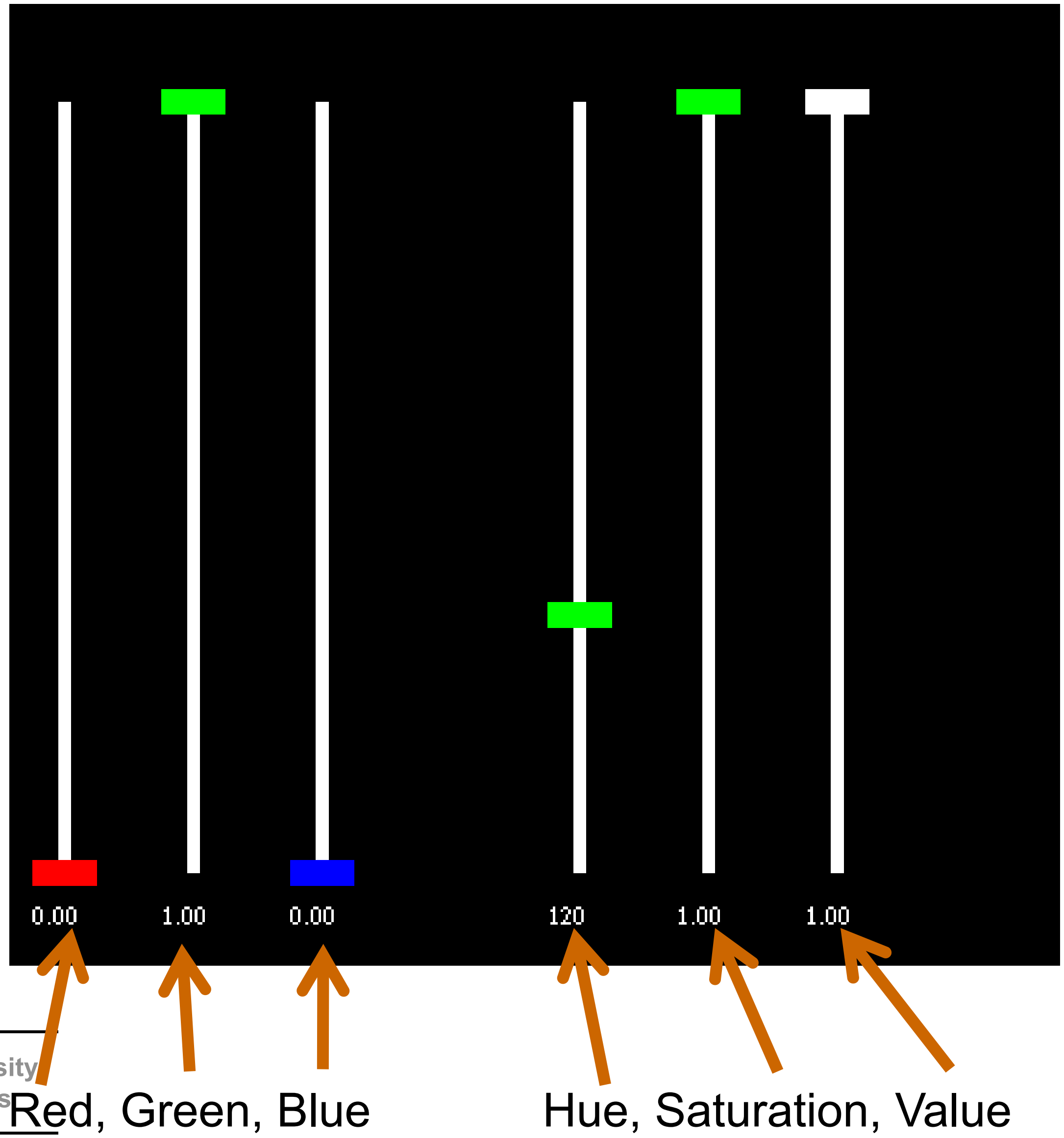


$$Hue = 240. - 240.\frac{S - S_{min}}{S_{max} - S_{min}}$$

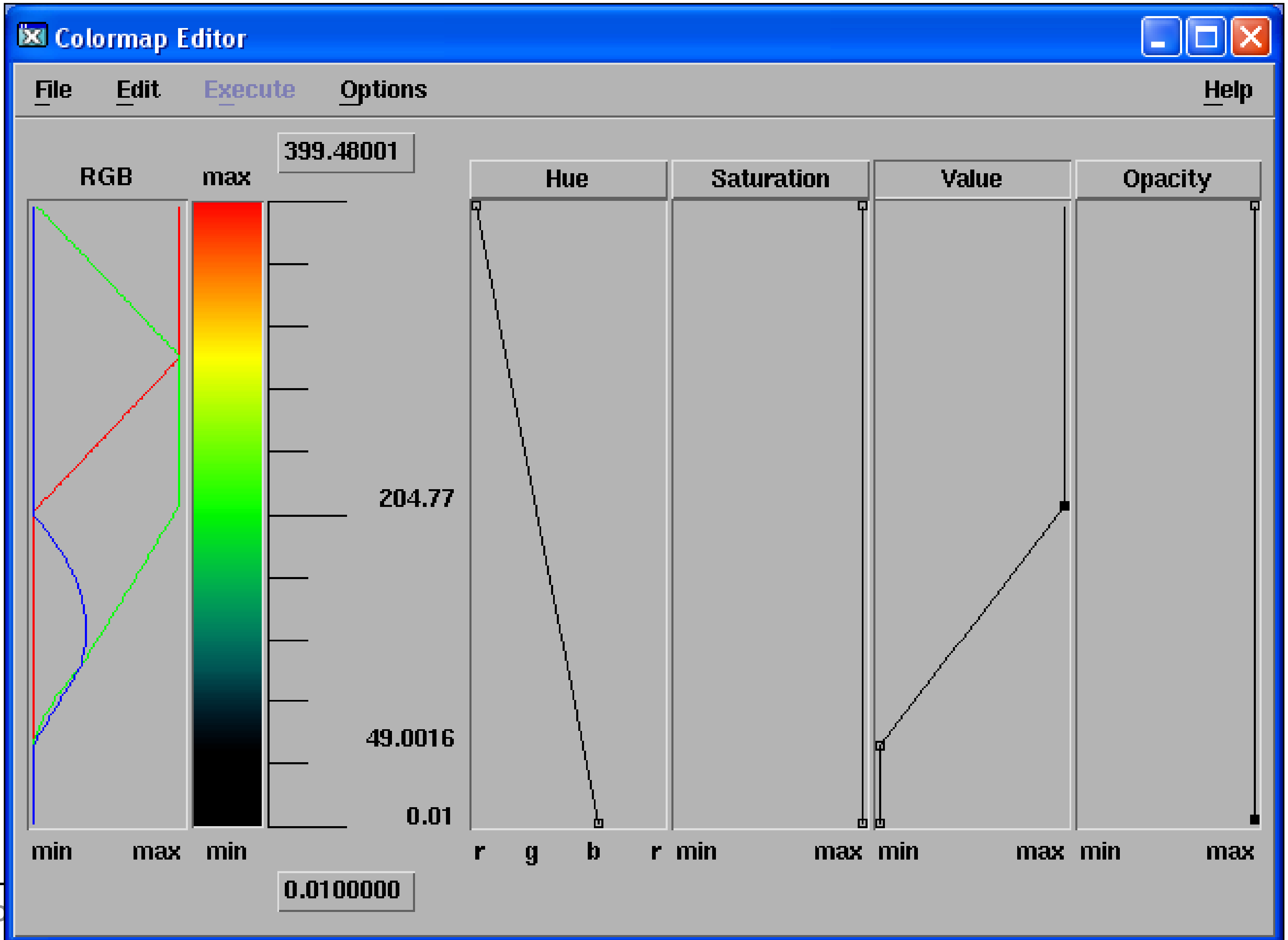
Turning a scalar value into a hue when using the Rainbow Color Scale



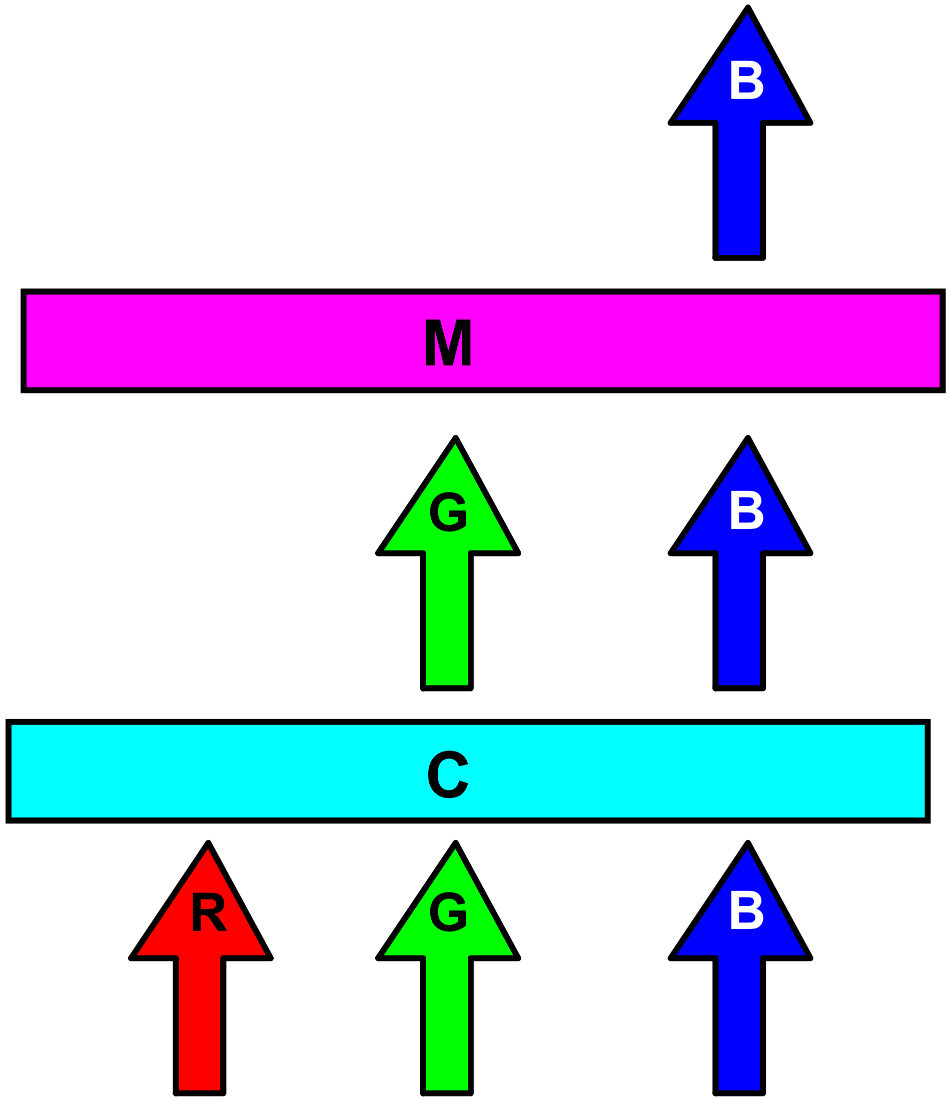
Hue-Saturation-Value:
The *OSU ColorPicker* Program

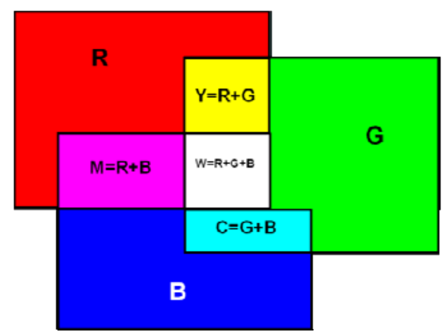


The OpenDX Visualization Software Allows you to Sculpt the Transfer Function in HSV

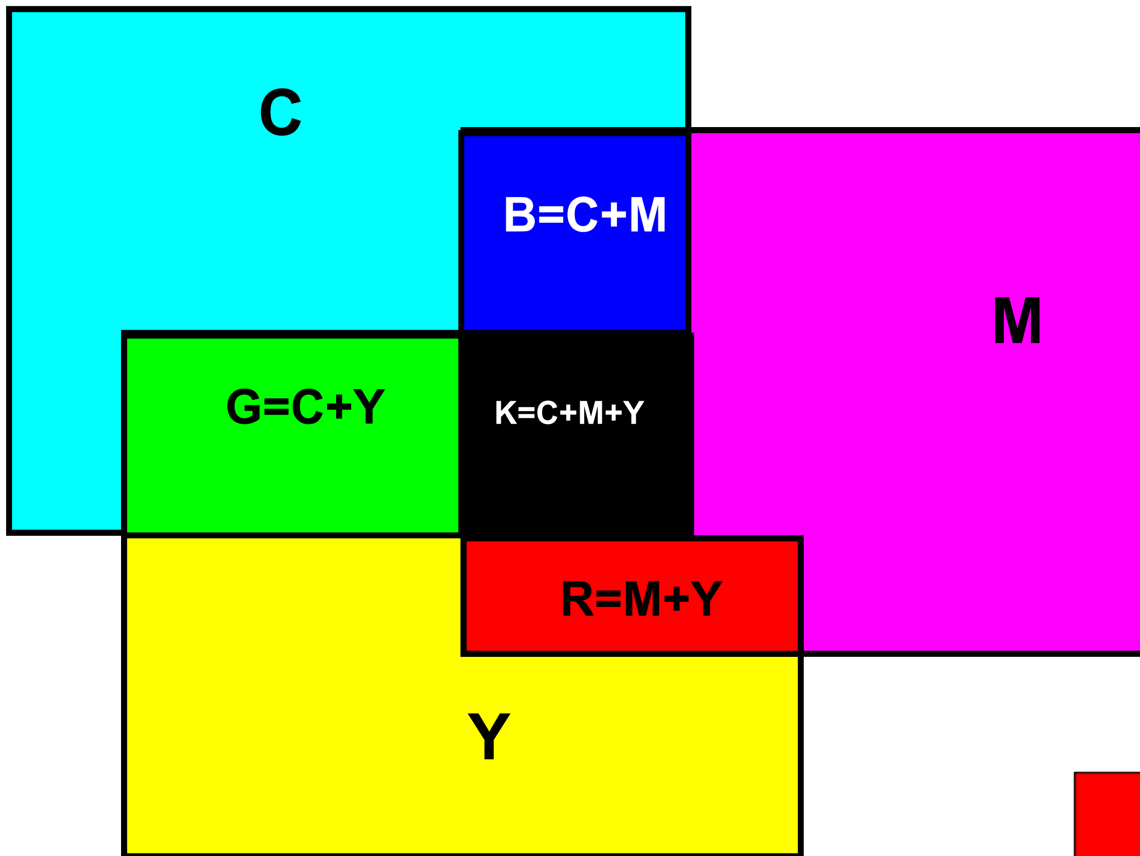


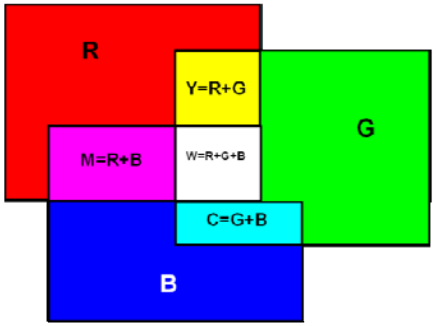
Subtractive Colors (CMYK)





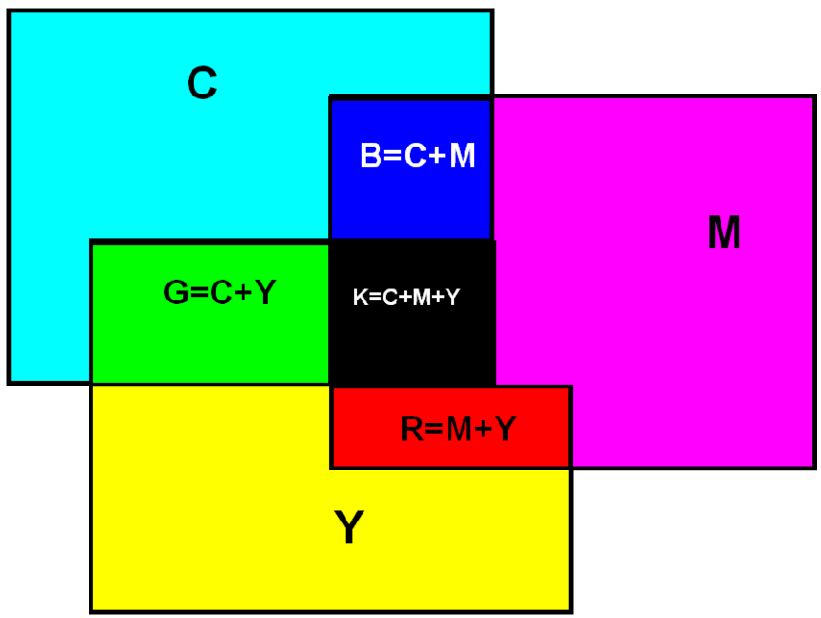
Subtractive Color (CMYK)



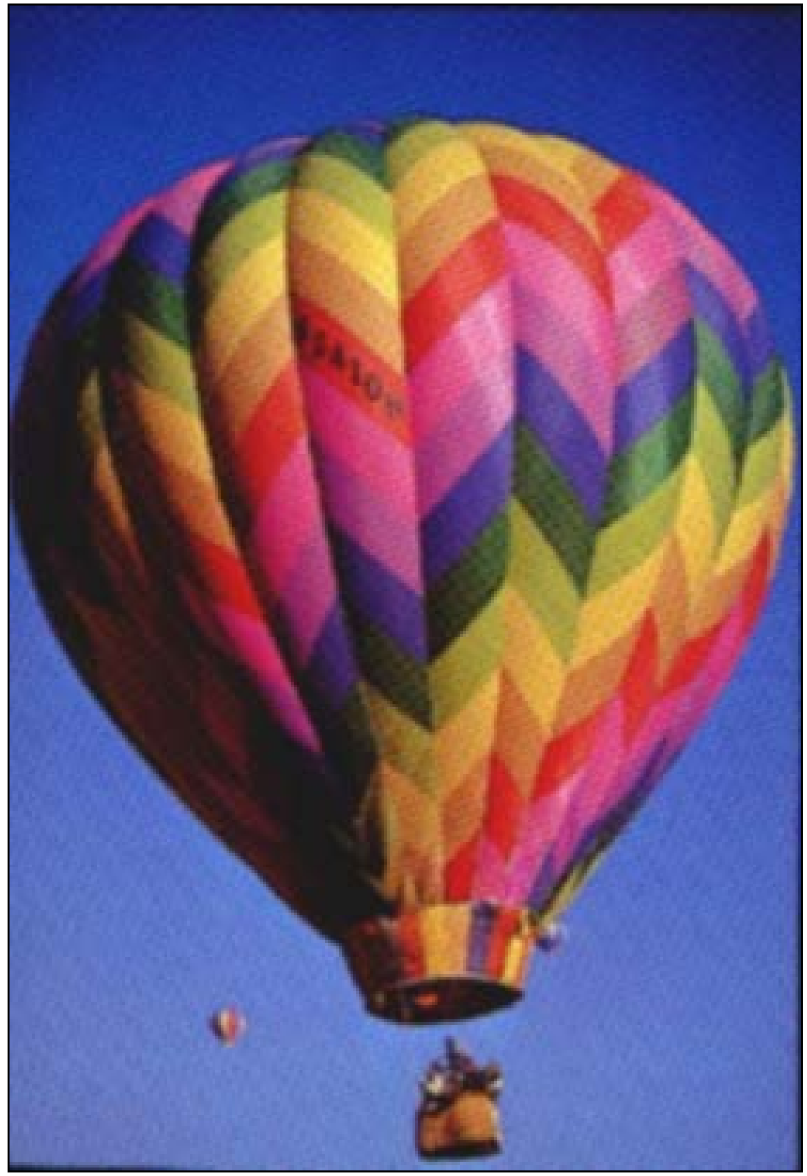


Color Printing

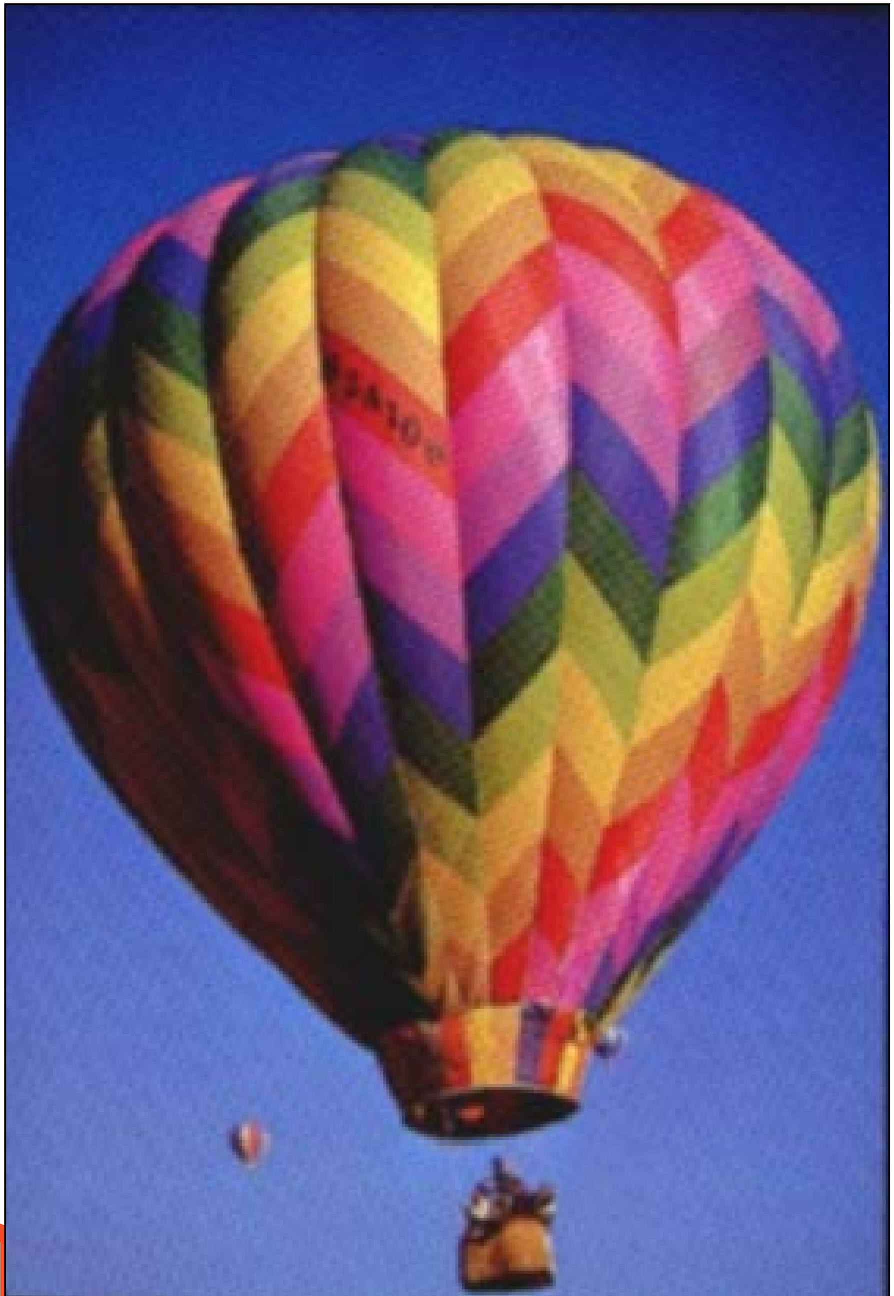
- Uses subtractive colors
- Uses 3 (CMY) or 4 (CMYK) passes
- CMYK printers have a better-looking black
- There is a considerable variation in color *gamut* between products

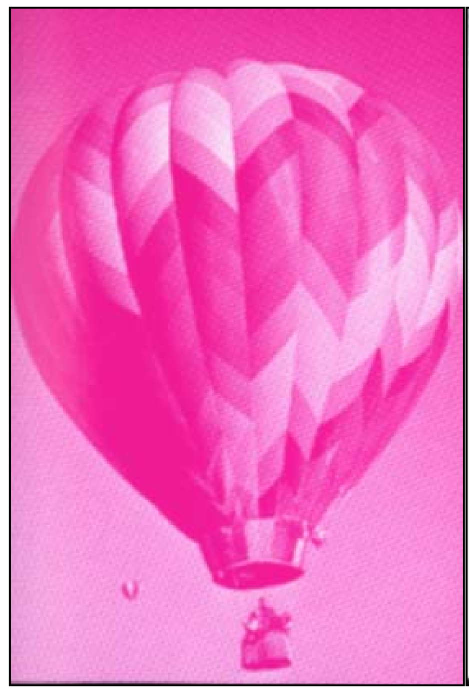


How Do Color Separations Work in Color Printing?

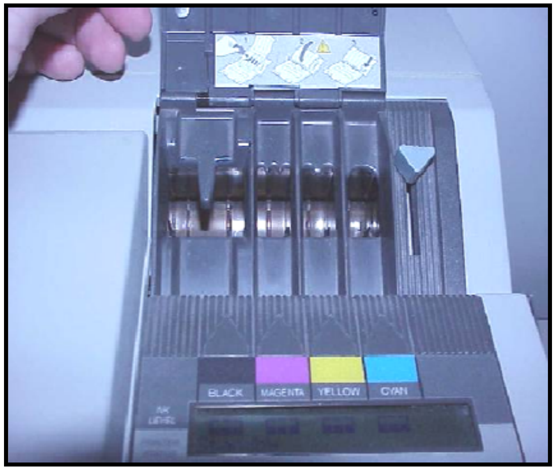


Source: R. Daniel Overheim and David Wagner, *Light and Color*, John Wiley & Sons, 1982.





Getting the CMYK Colors

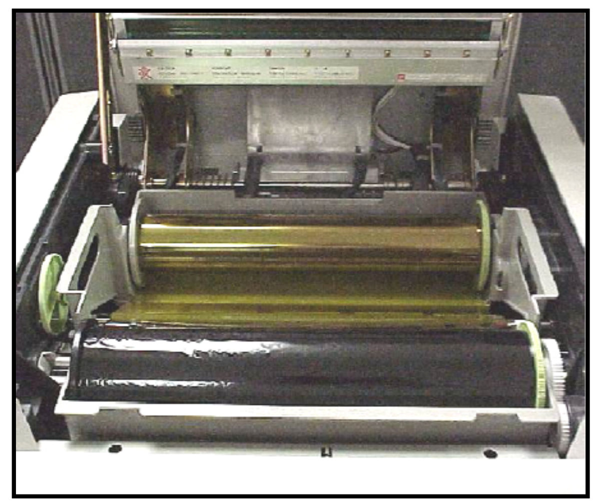


Wax

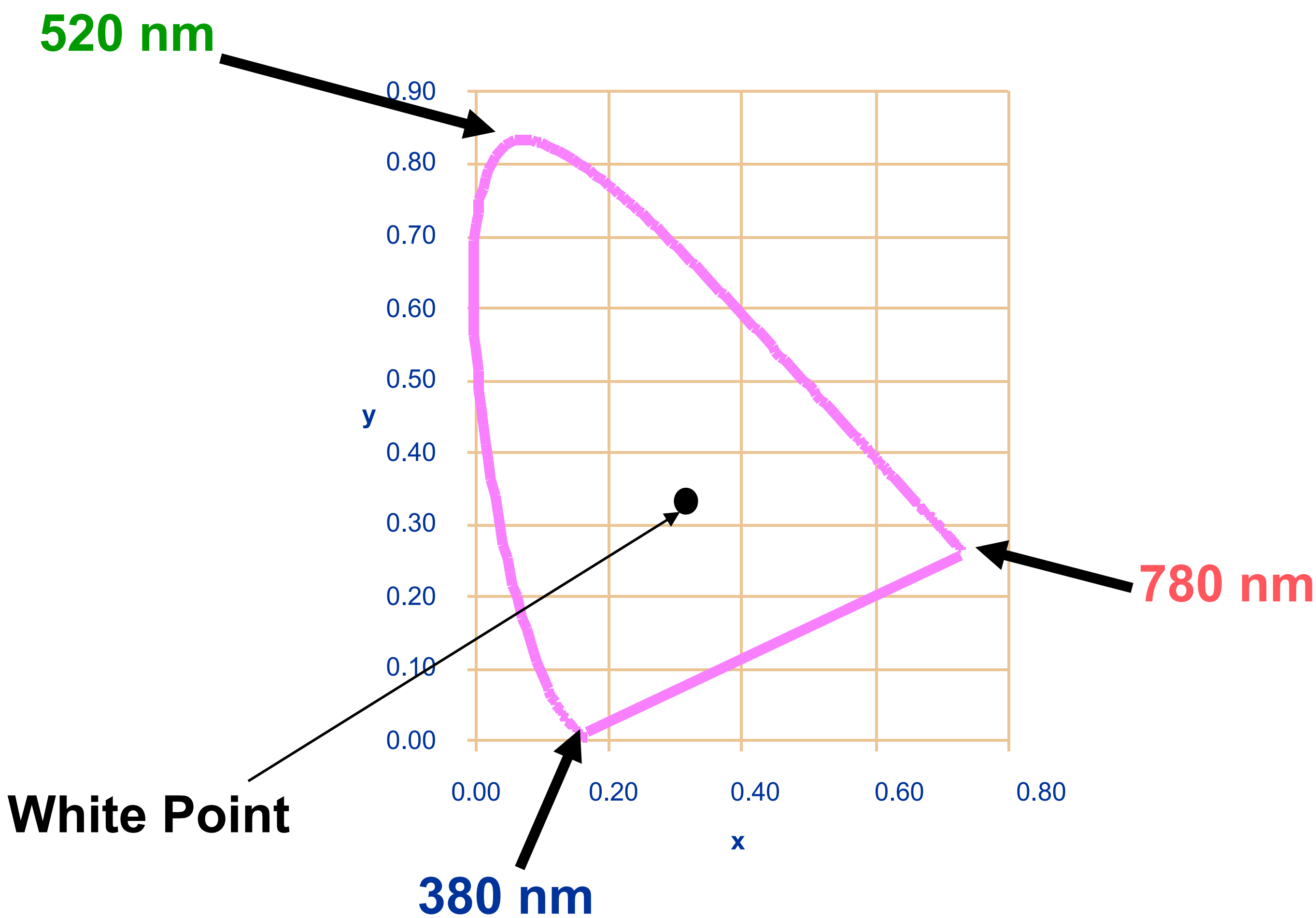
Toner

Toner

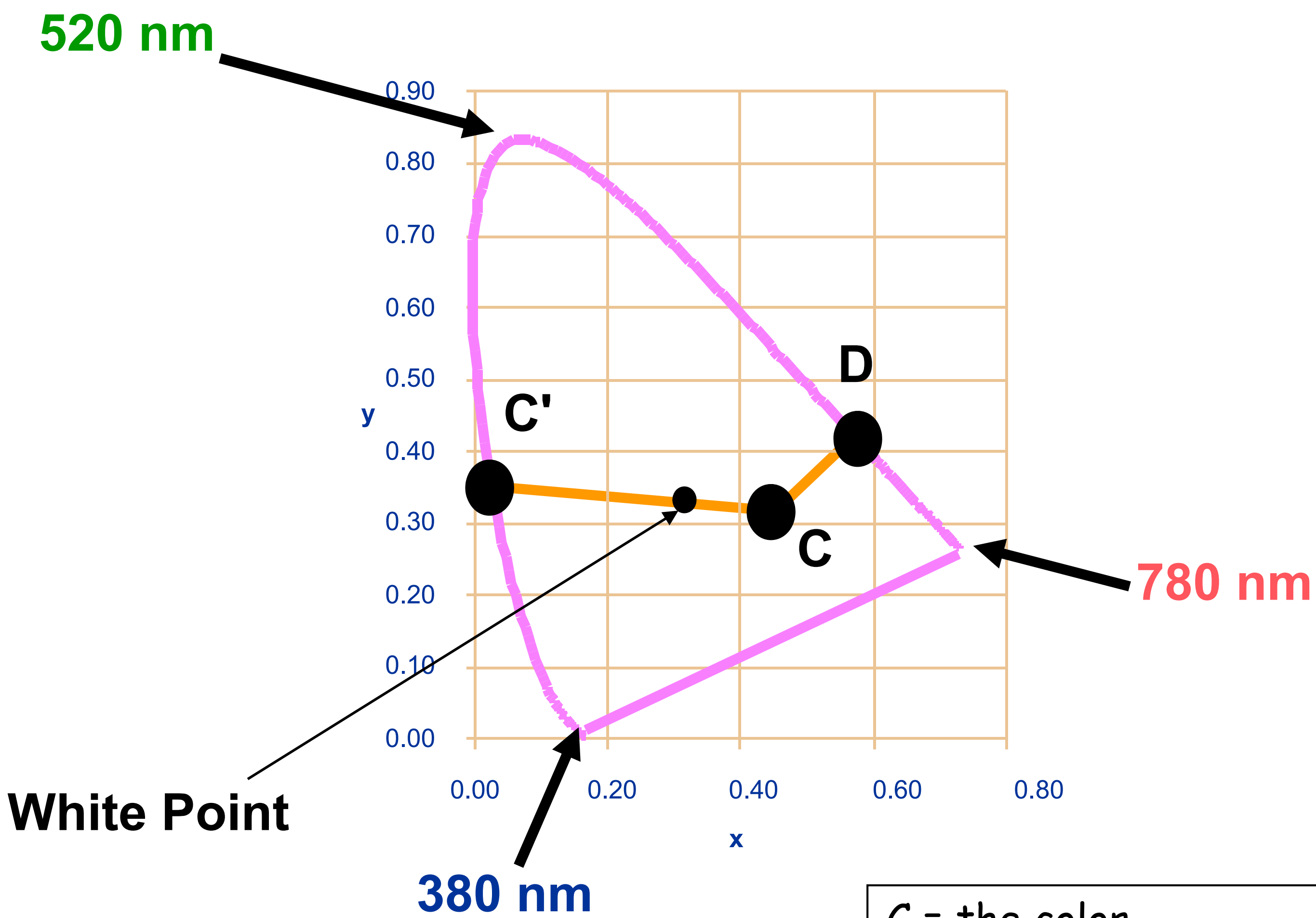
Sheets



CIE Chromaticity Diagram

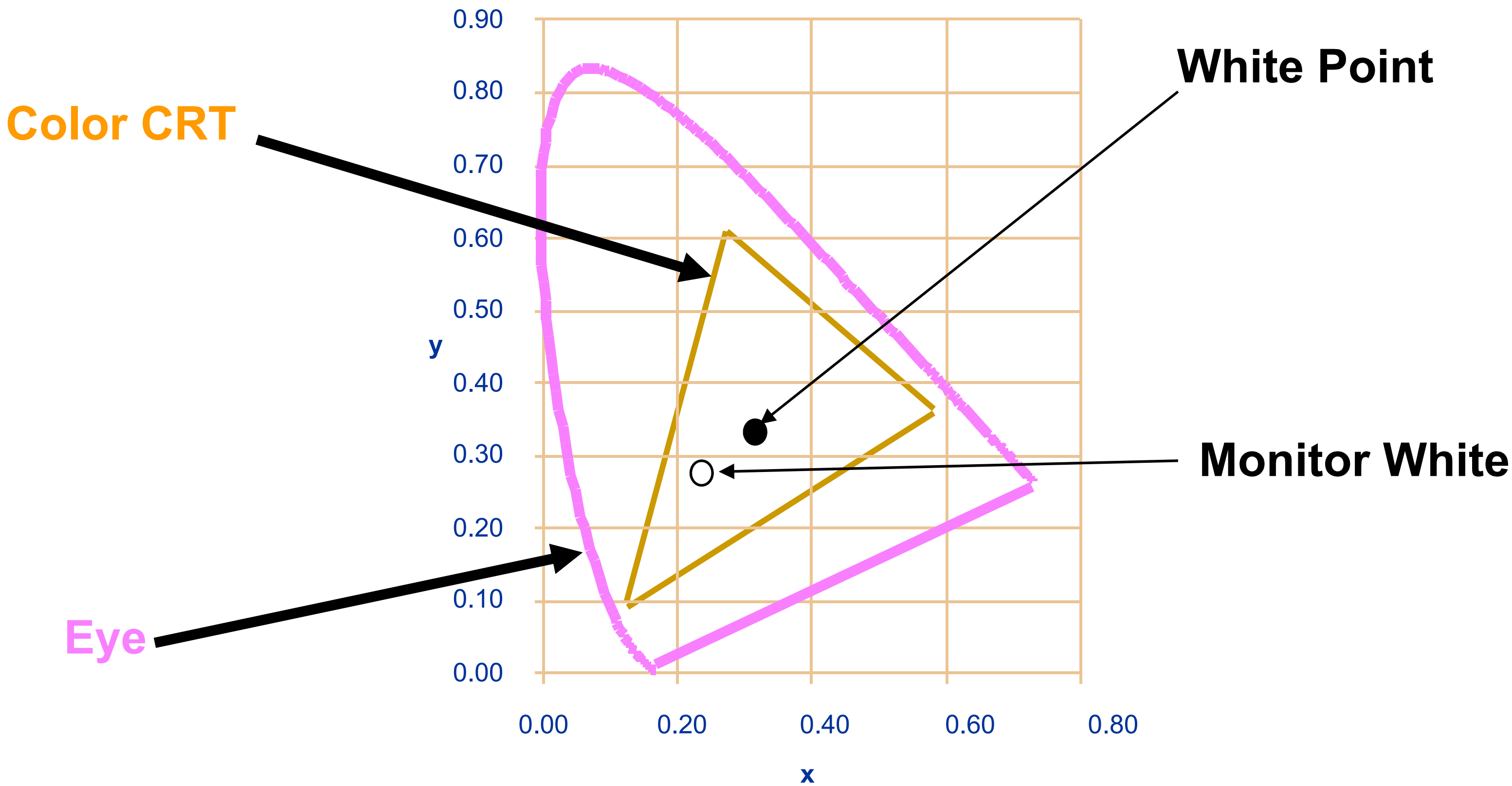


CIE Chromaticity Diagram

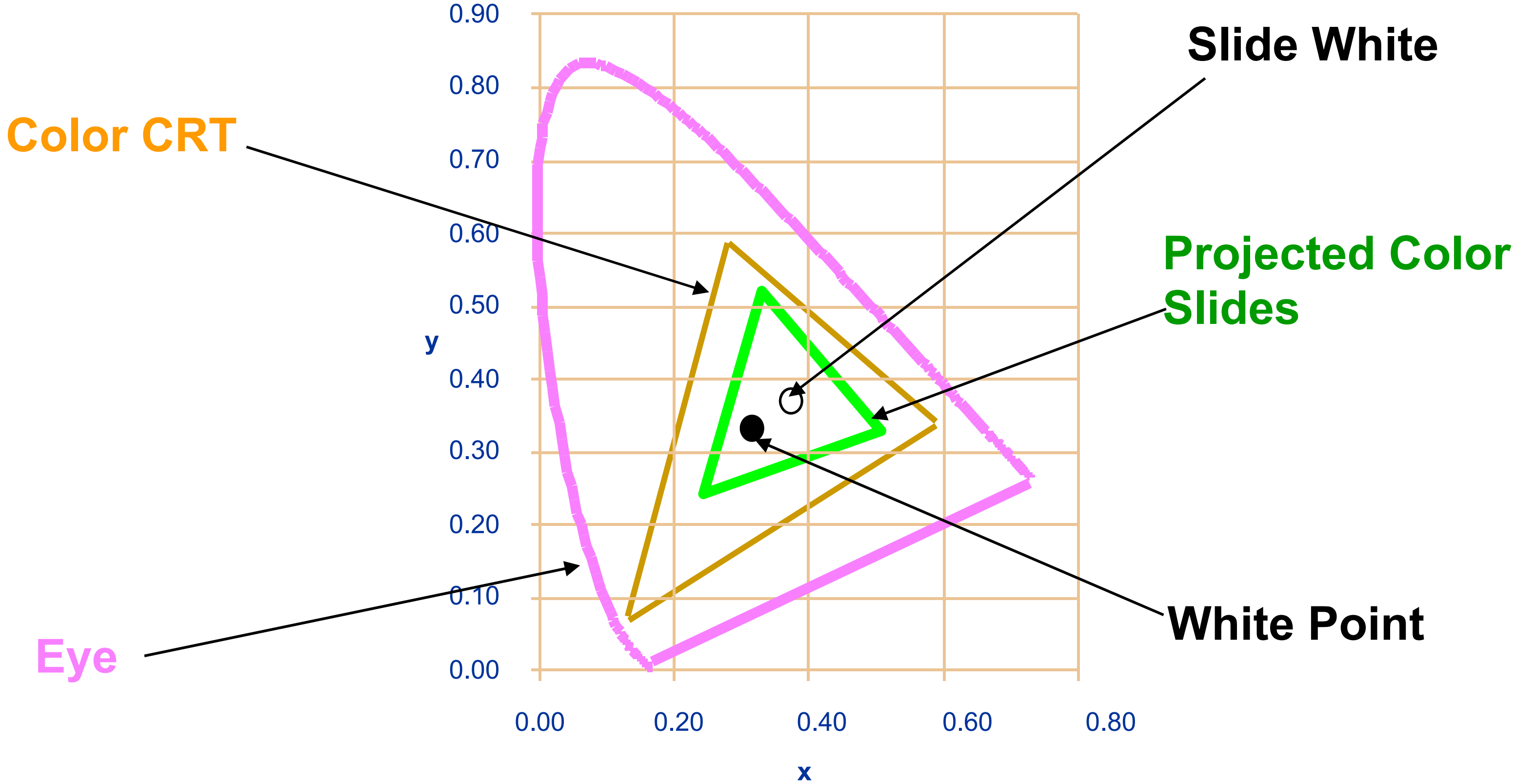


C = the color
D = the dominant wavelength
C ' = the complementary color

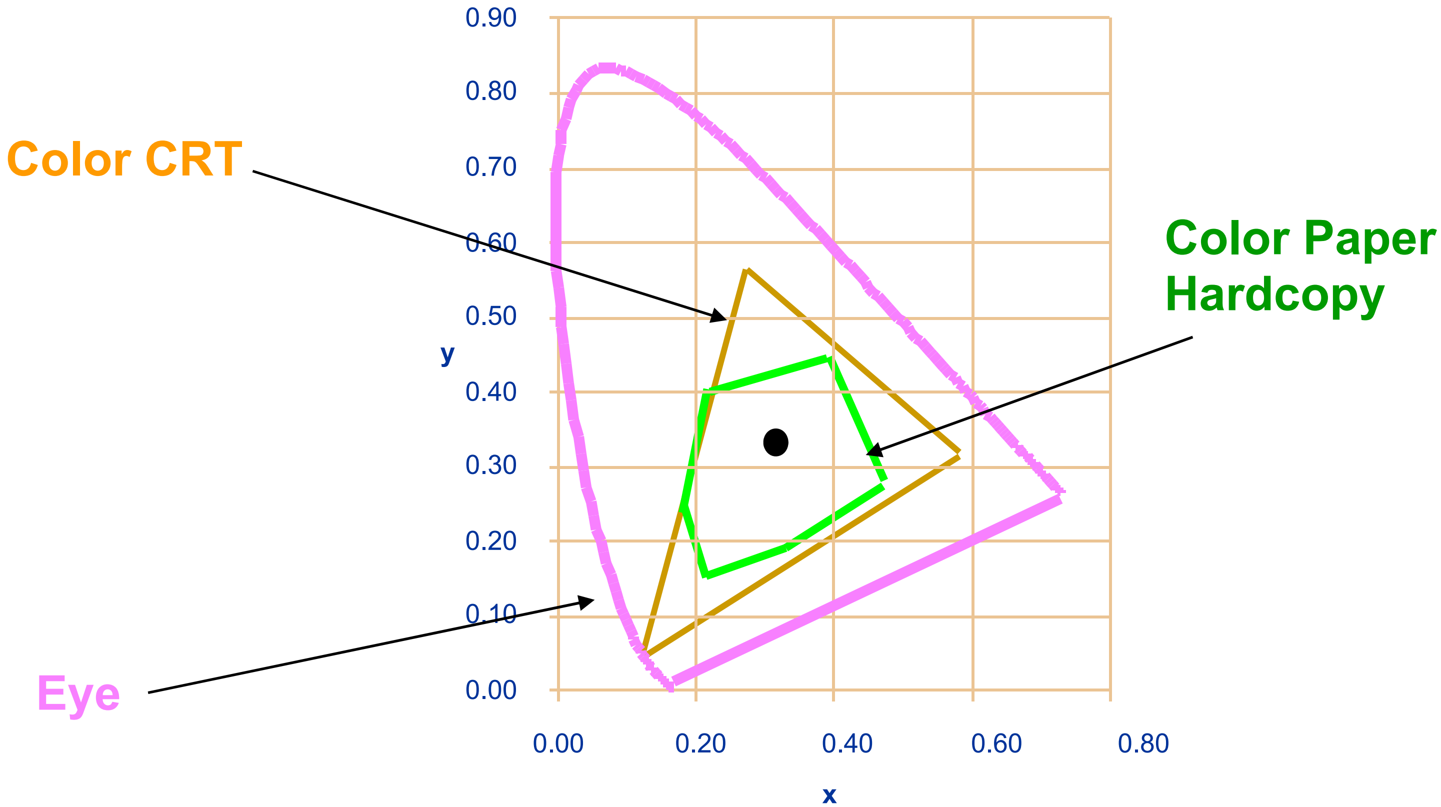
Color Gamut for a Workstation Monitor



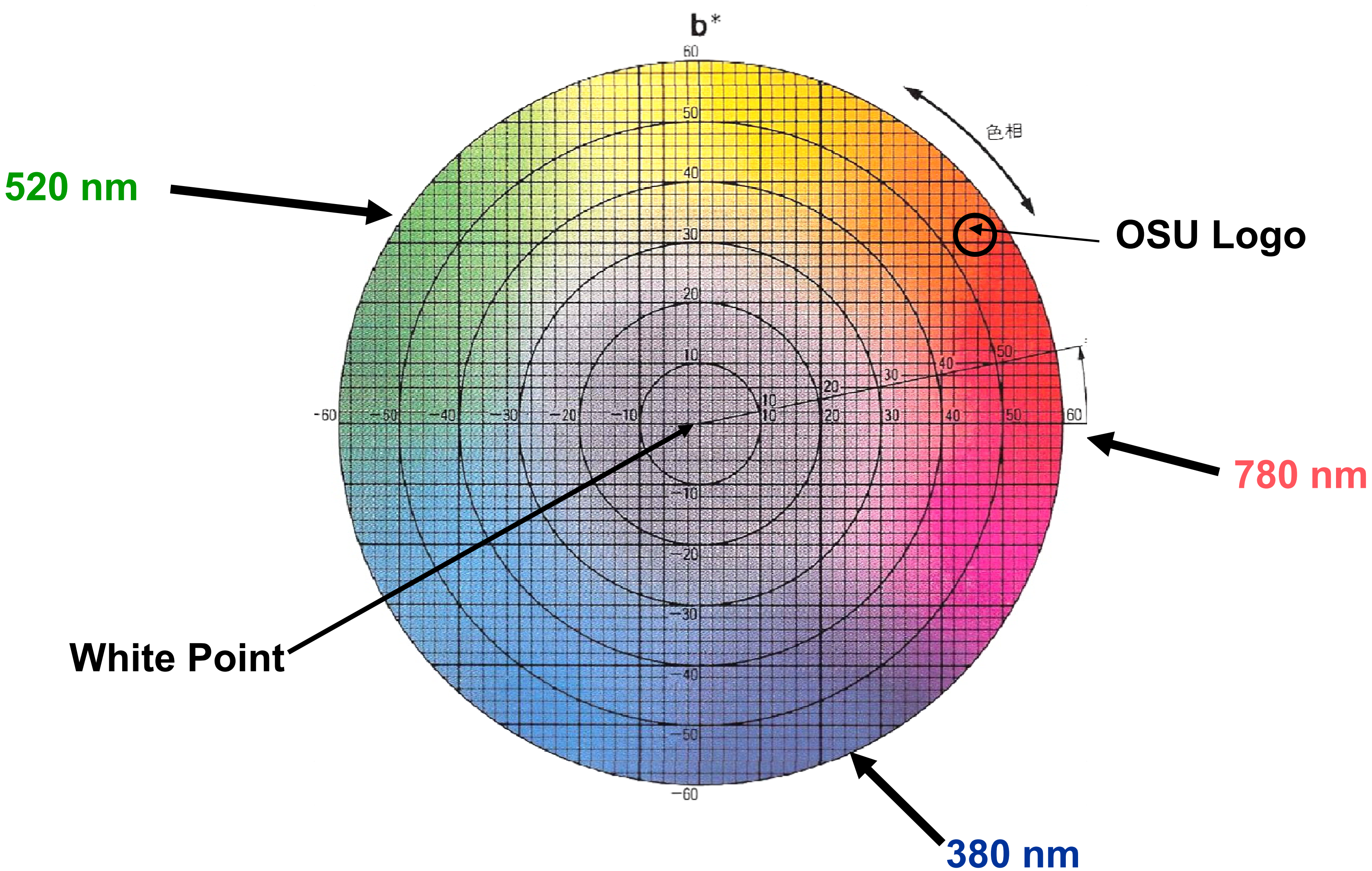
Color Gamut for a Monitor and Color Slides



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

Some Good Rules of Thumb When Using Color for Scientific Visualization

What Makes a Good Contrast?

- 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 !

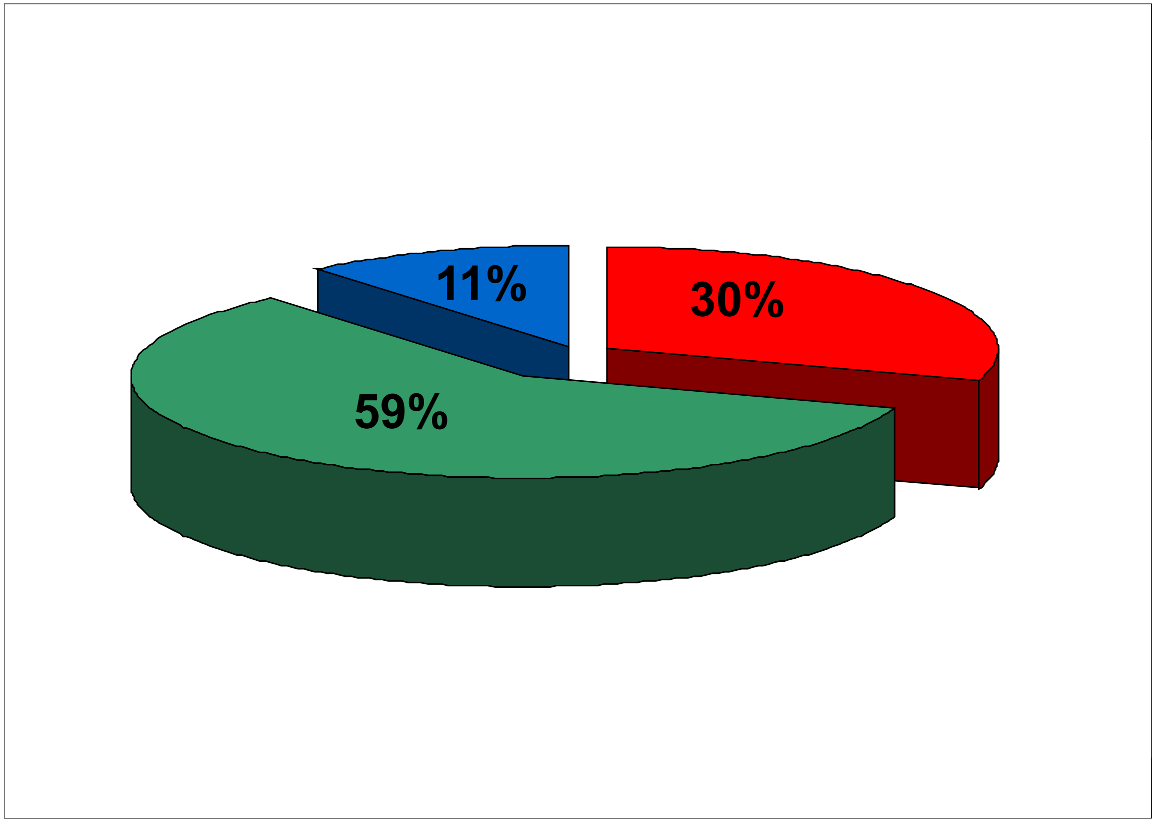
I sure hope that my life does not depend on being able to read this quickly and accurately!

Luminance Contrast is Crucial !

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

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

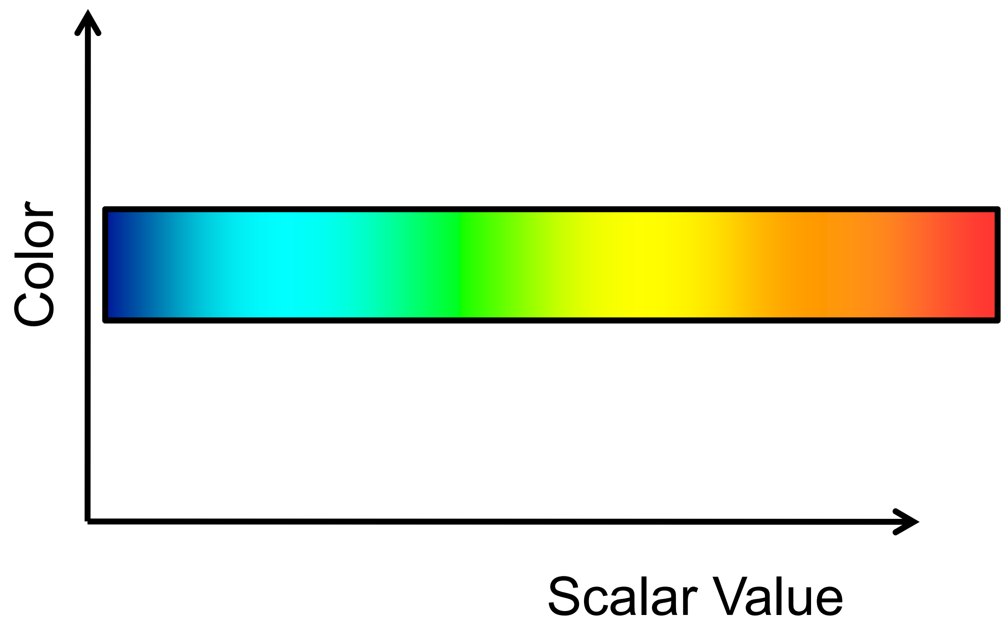
	Black	Black	Black	Black	Black	Black	Black	Black
White		White	White	White	White	White	White	White
Red	Red		Red	Red	Red	Red	Red	Red
Yellow	Yellow	Yellow		Yellow	Yellow	Yellow	Yellow	Yellow
Green	Green	Green	Green	Green		Green	Green	Green
Blue	Blue	Blue	Blue	Blue	Blue	Blue		Blue

Do Not Attempt to Fight Pre-Established Color Meanings

Pre-Established Color Meanings

Red:	Green:	Blue:	White:
Stop	On	Cool	Neutral
On	Plants	Safe	Hydrogen
Off	Carbon	Deep	
Dangerous	Moving	Nitrogen	
Hot	Money		
High stress			
Oxygen			
Shallow			
Money loss			

In Visualization, we Use the Concept of a *Transfer Function* to set Color and Opacity as a Function of Scalar Value

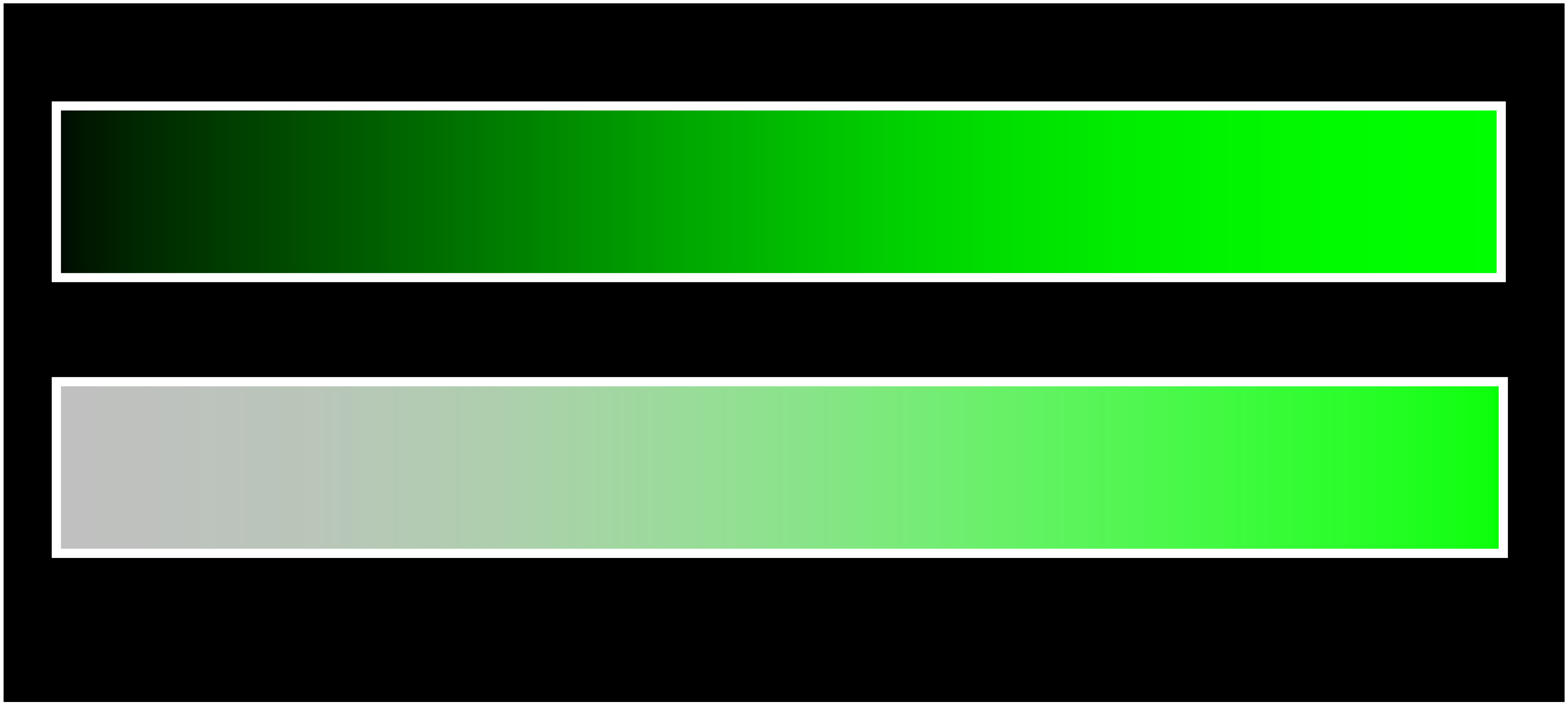


Use the Right Transfer Function Color Scale to Represent a Range of Scalar Values

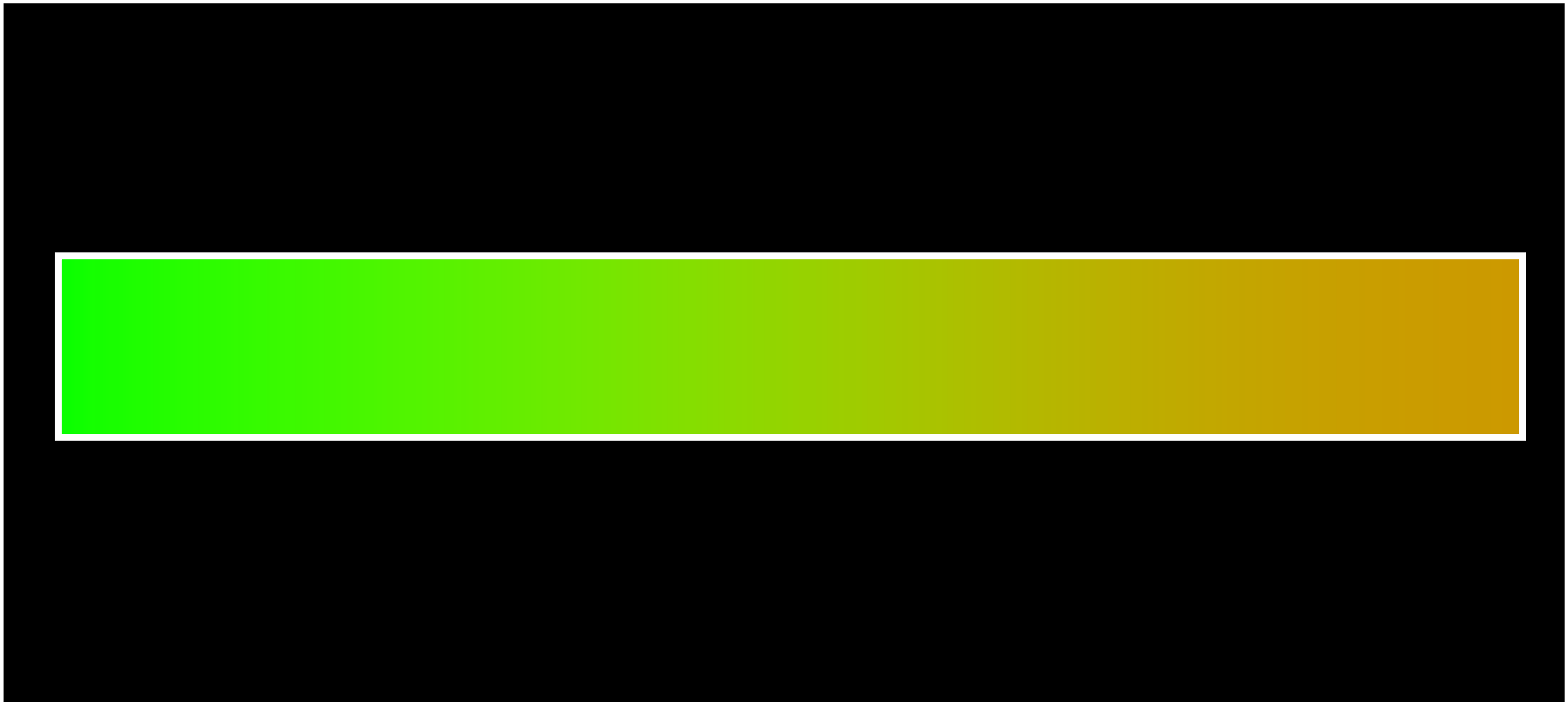
- Gray scale
- Intensity Interpolation
- Saturation interpolation
- Two-color interpolation
- Rainbow scale
- Heated object interpolation
- Blue-White-Red

Gray Scale

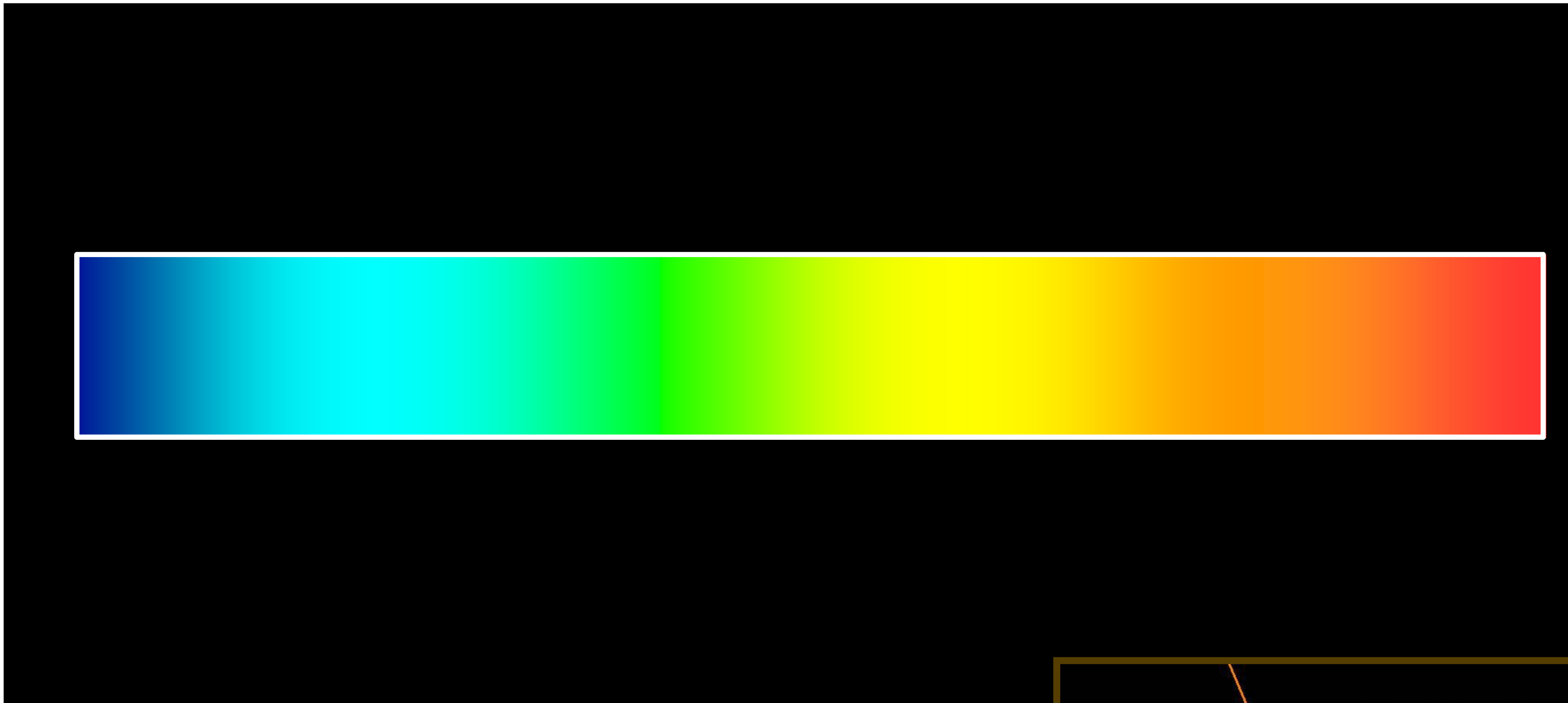
Intensity and Saturation Color Scales

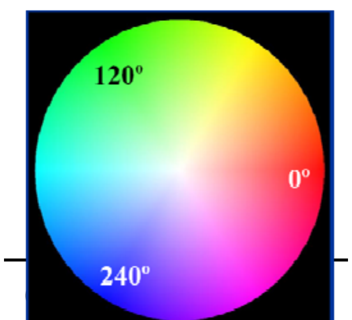


Two-Color Interpolation

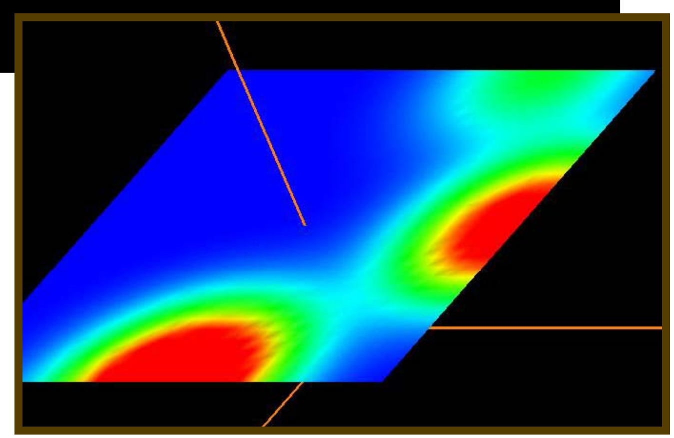


Rainbow Color Scale

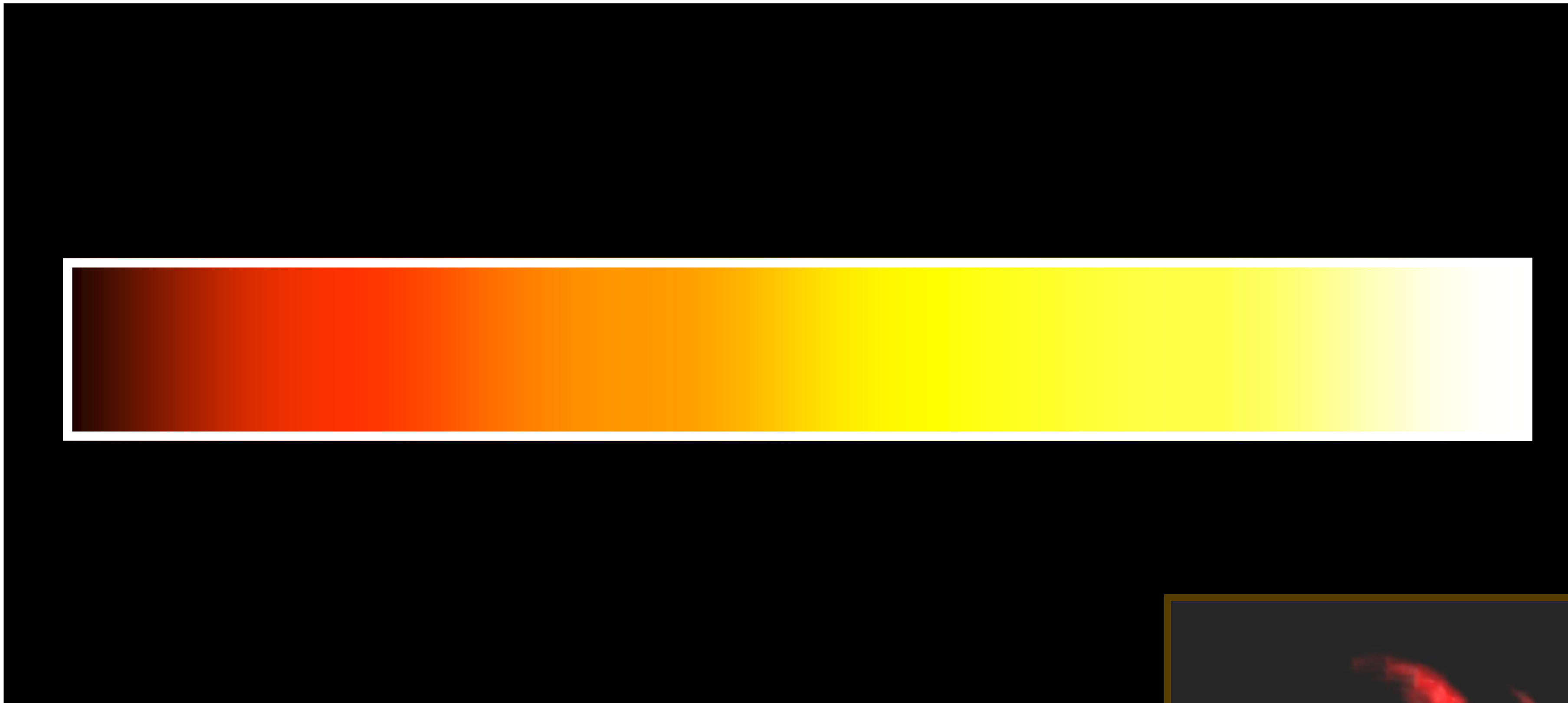




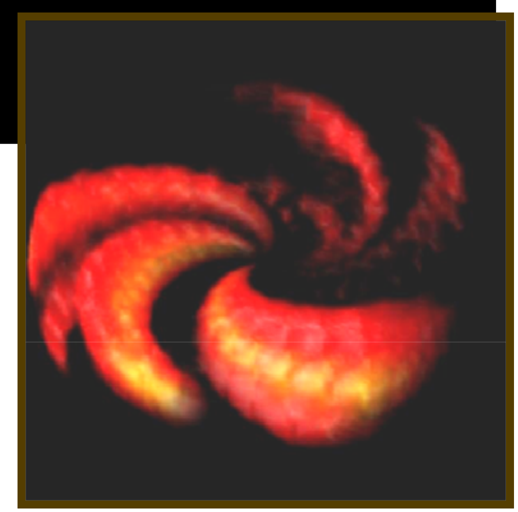
Implementation:
240° →120° → 0°



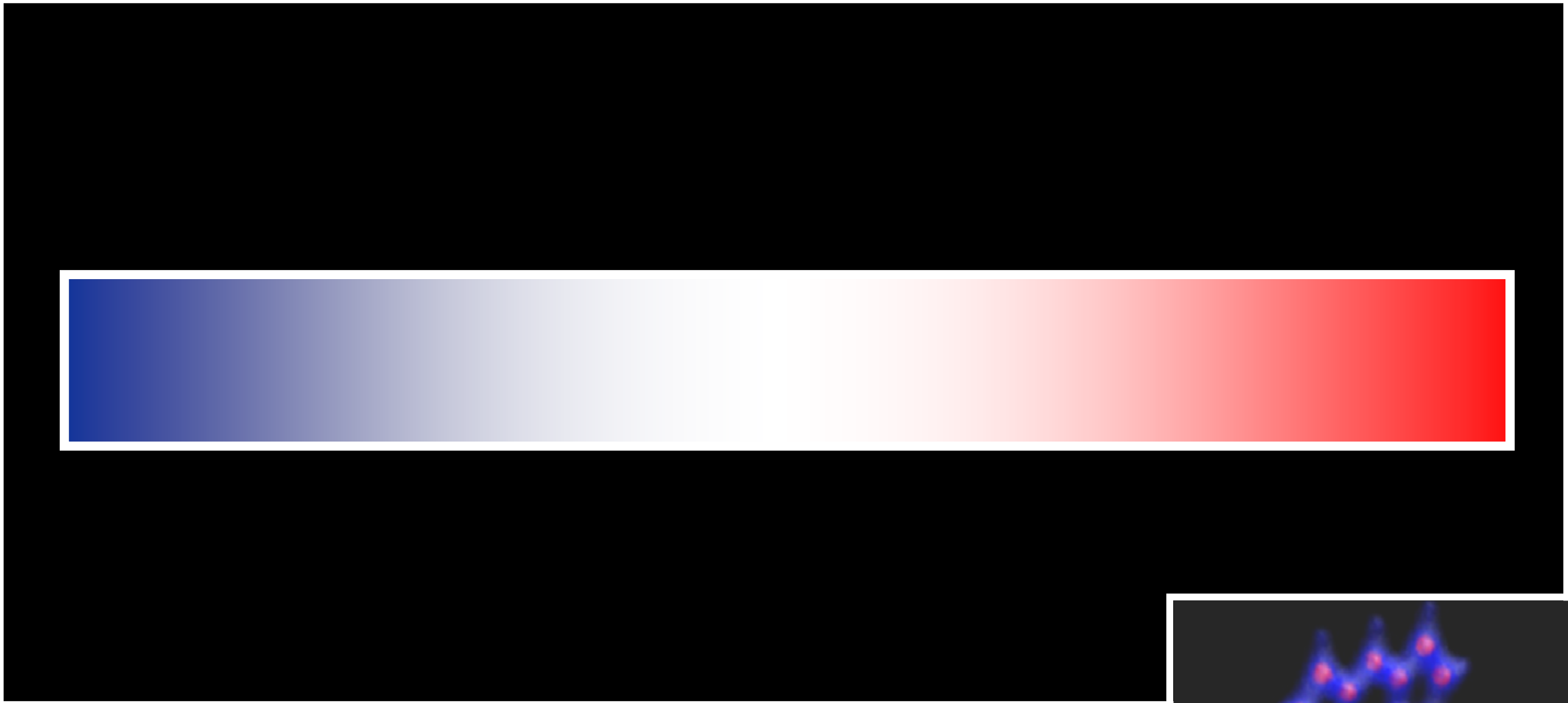
Heated Object Color Scale

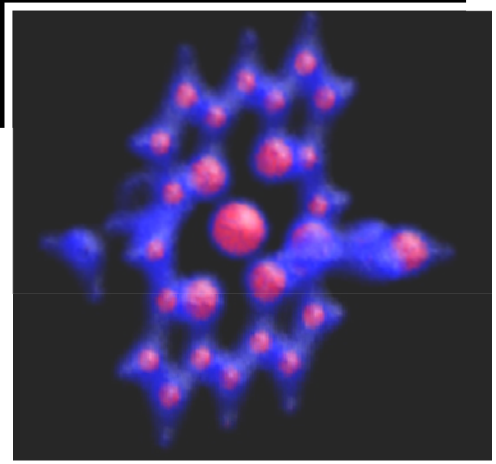


Implementation: add one color component at a time

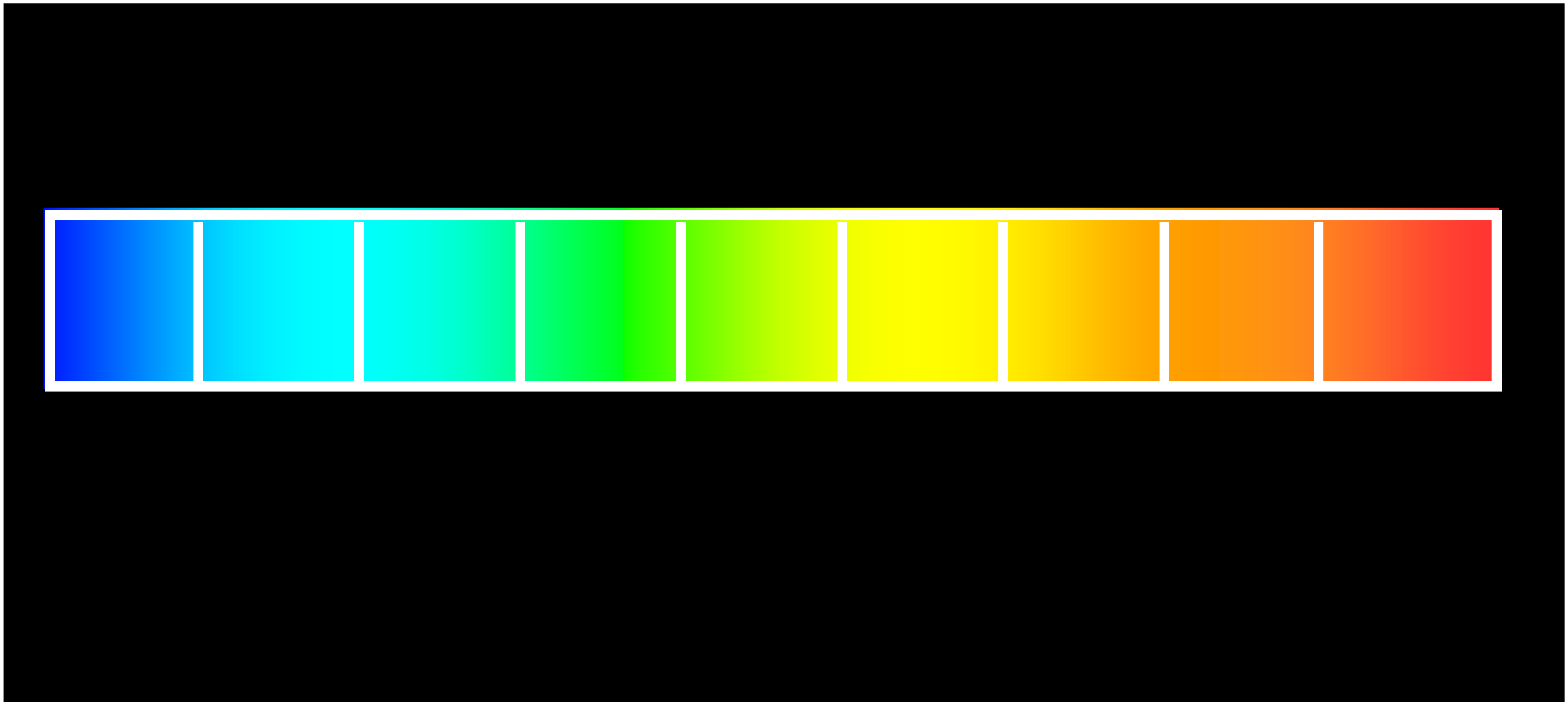


Blue-White-Red Color Scale

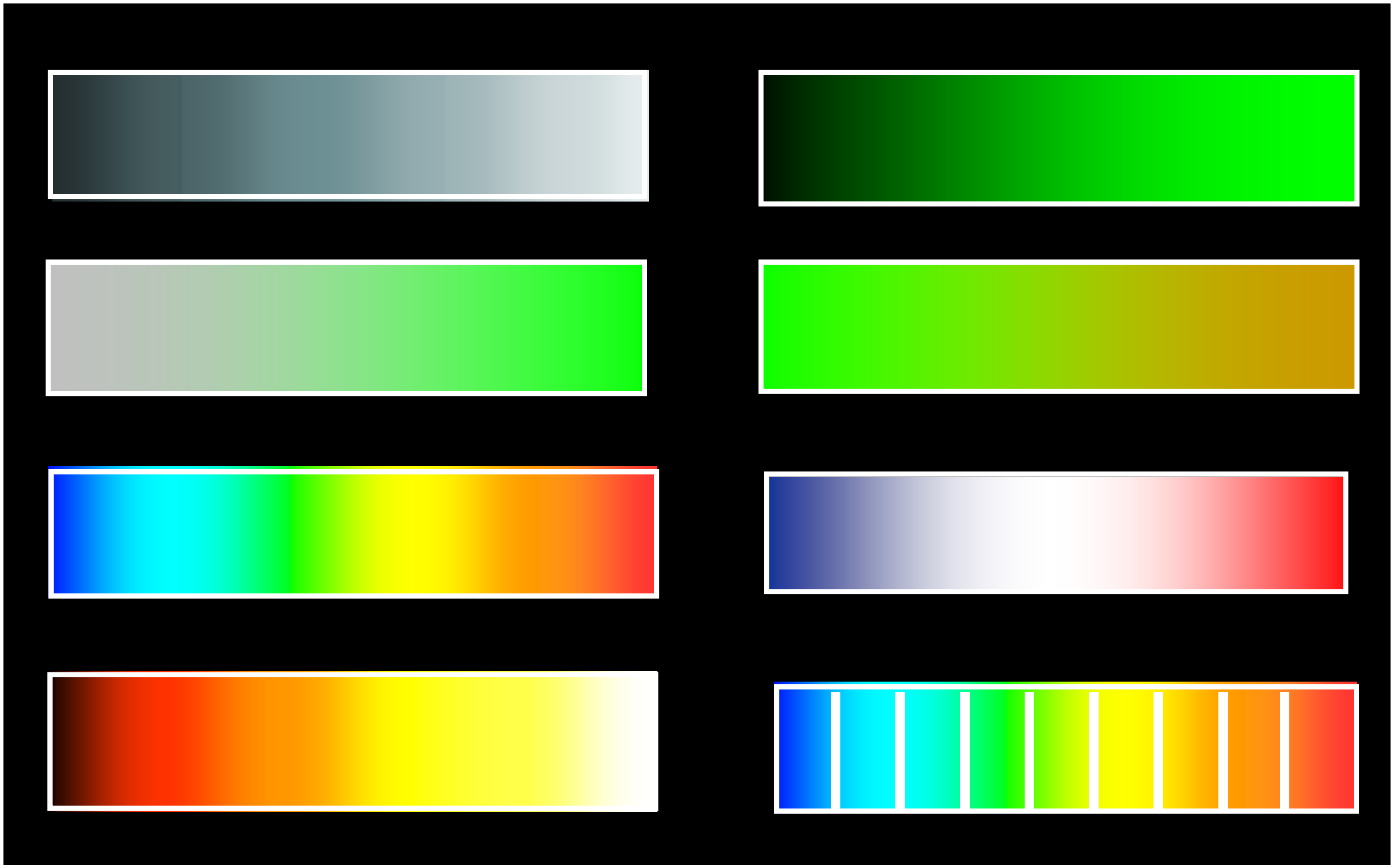




Color Scale Contours

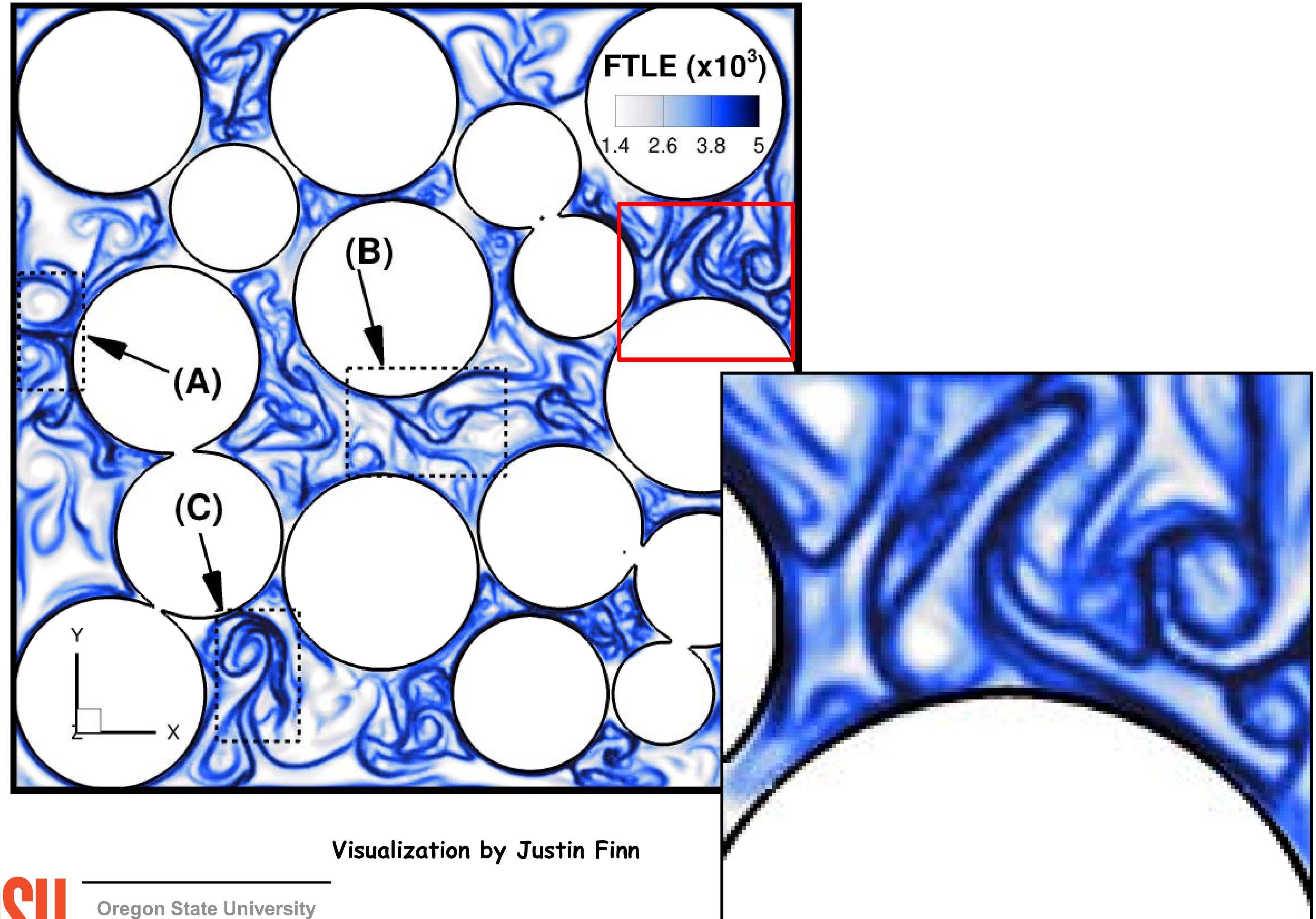


A Gallery of Color Scales



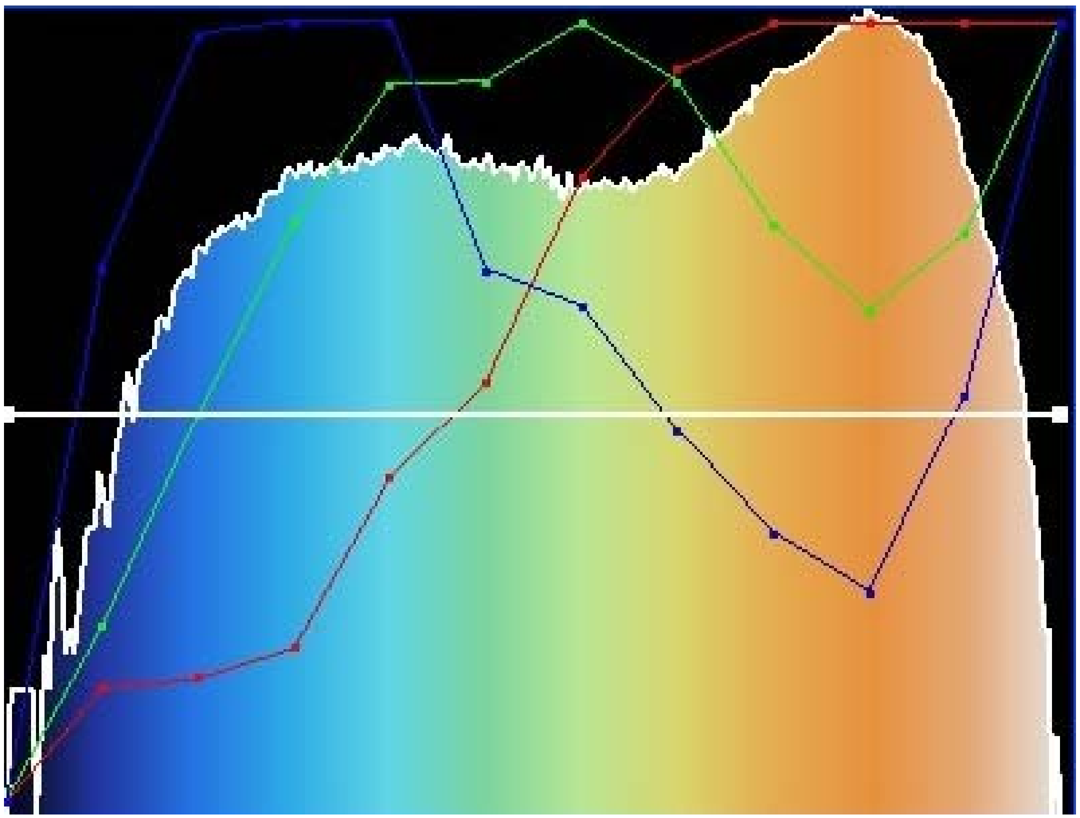
Something Different:
A Gallery of Add-One-Component-at-a-Time Color Scales

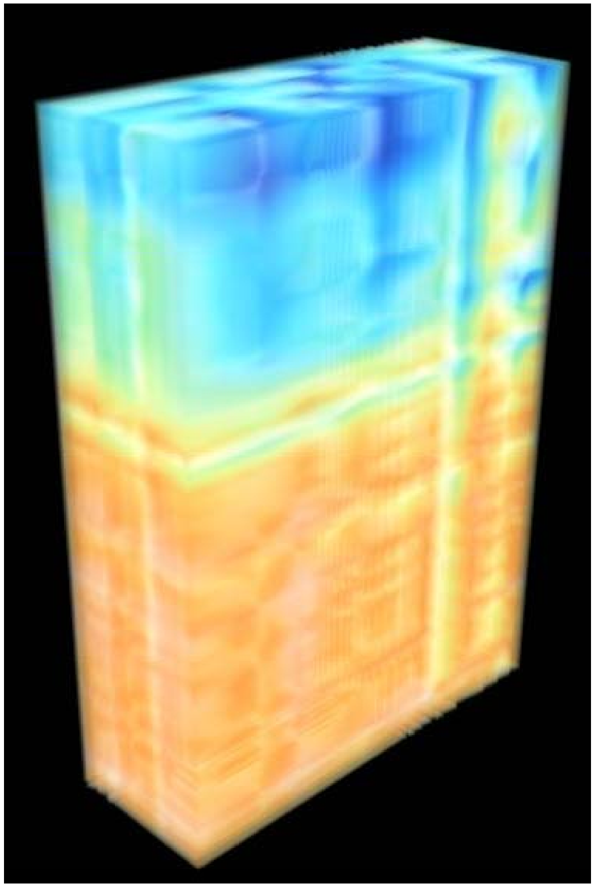
Something Different – Adding Black Beyond Blue



Visualization by Justin Finn

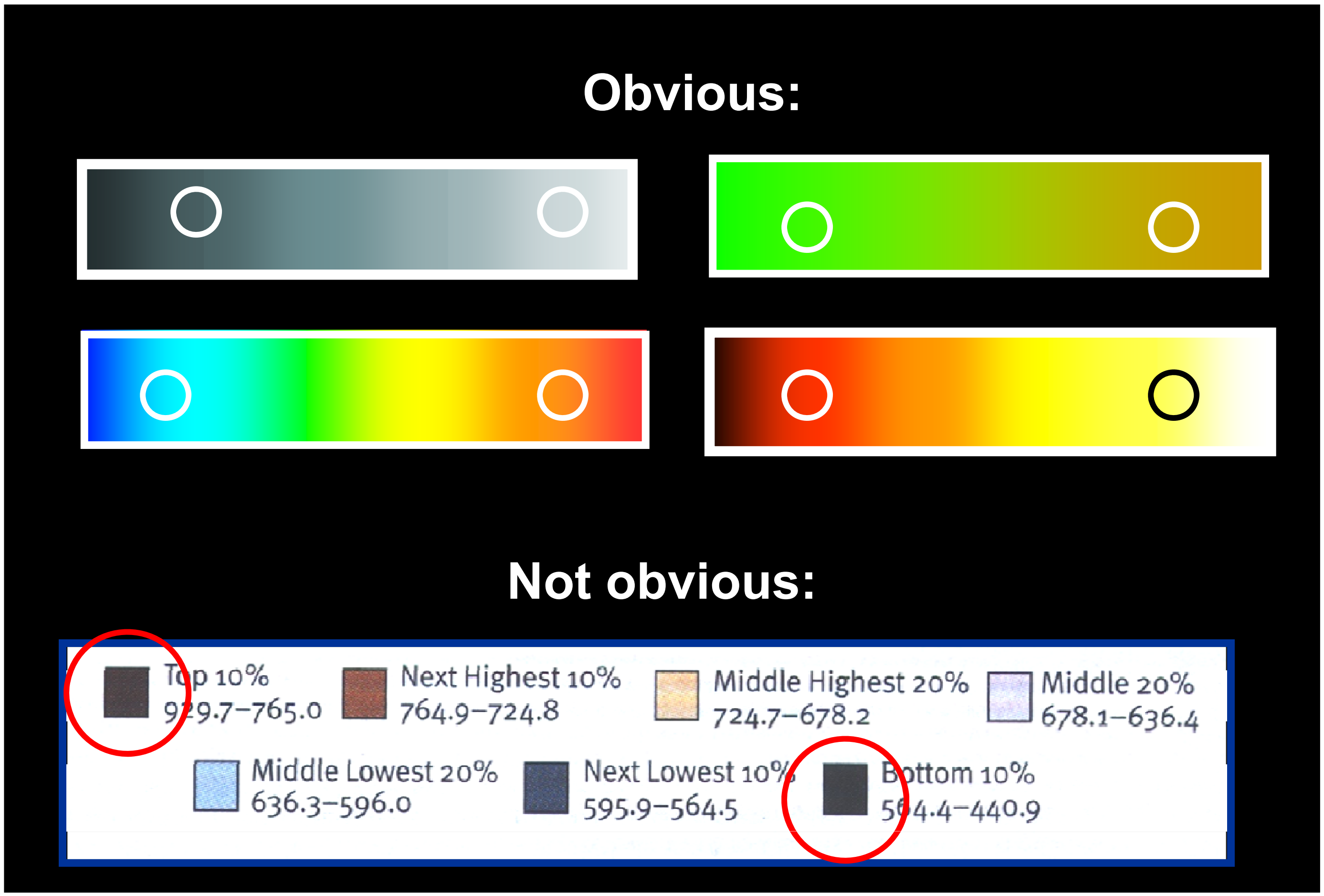
Something *Really* Different – The Haxby Color Scale



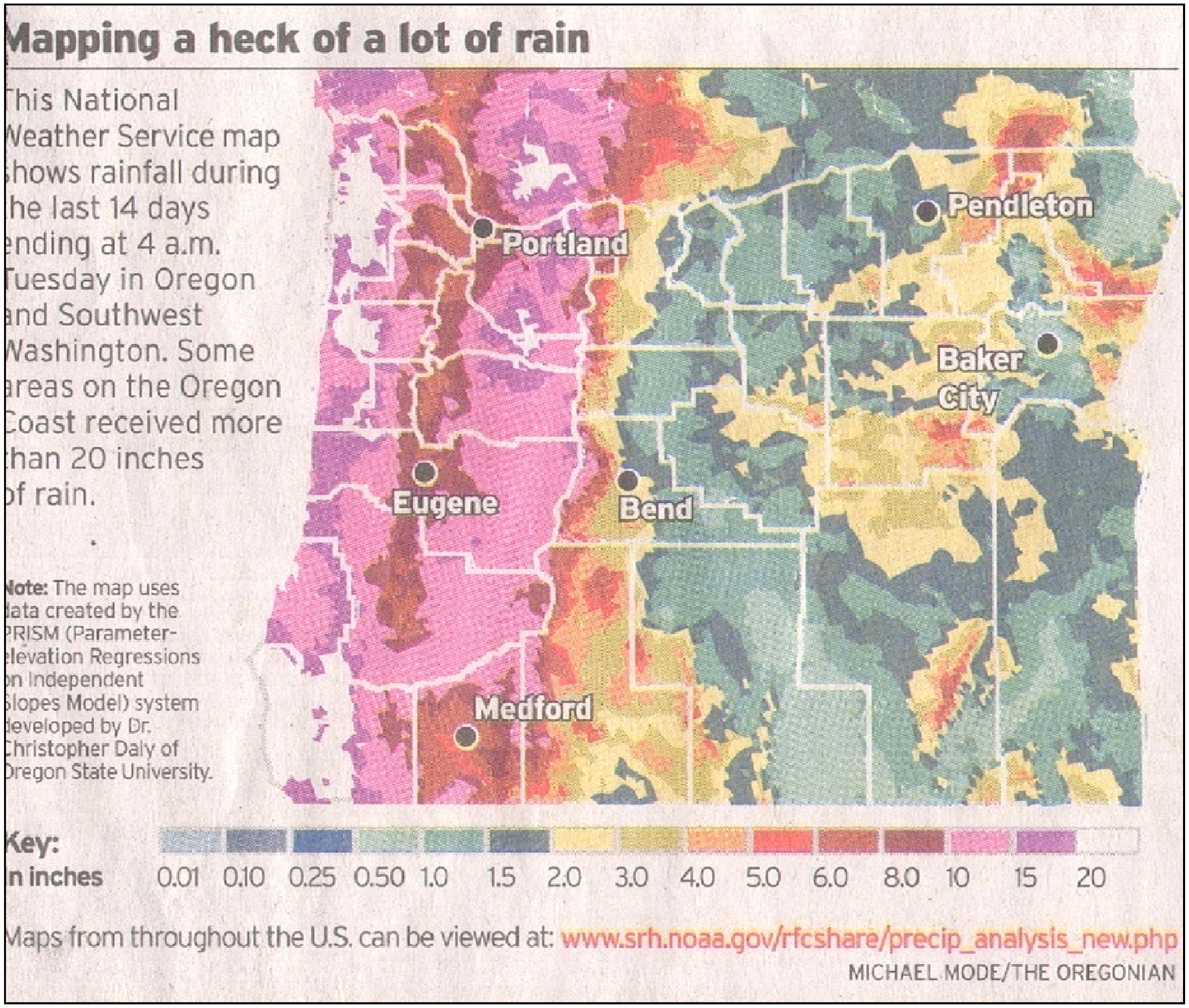


But, Here's What's Really Important:

Given any 2 colors, make it *intuitively obvious* which represents "higher" and which represents "lower"



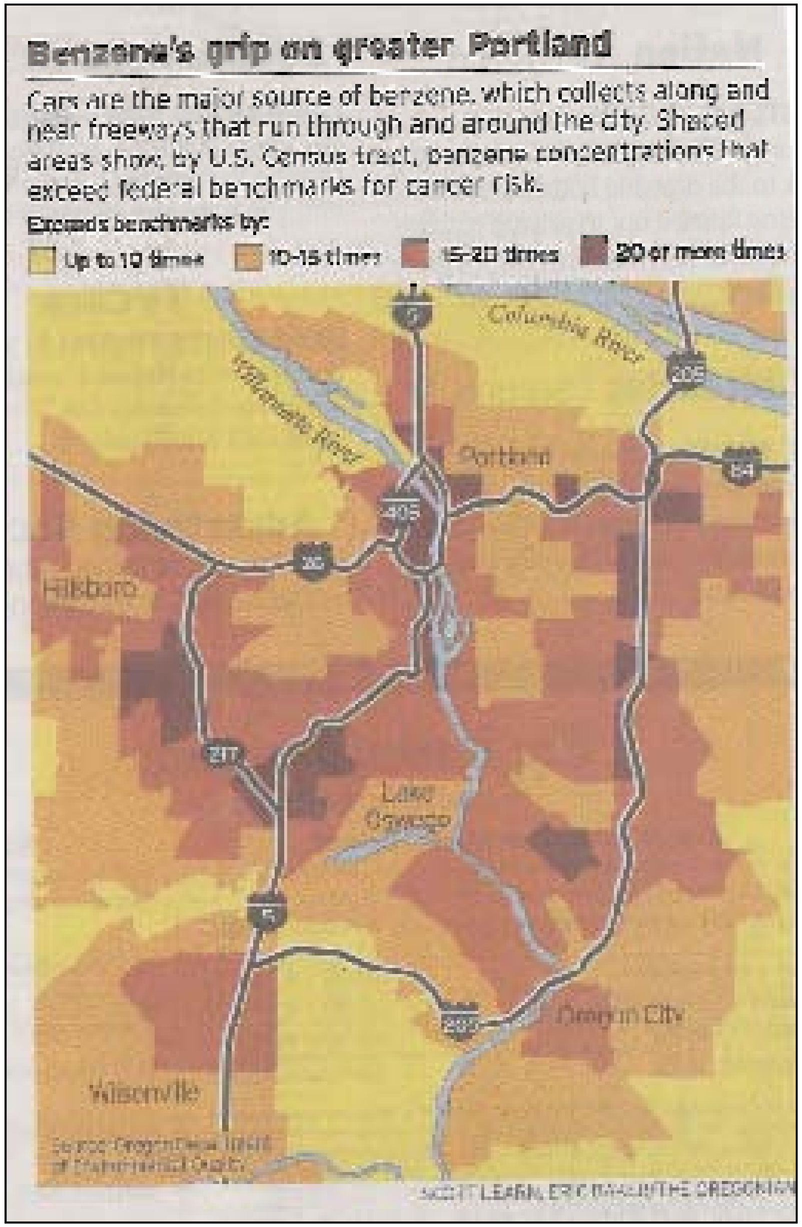
What in the World was *The Oregonian* Thinking When They Chose This Color Scale?



Source:
The Oregonian,
January 11, 2006

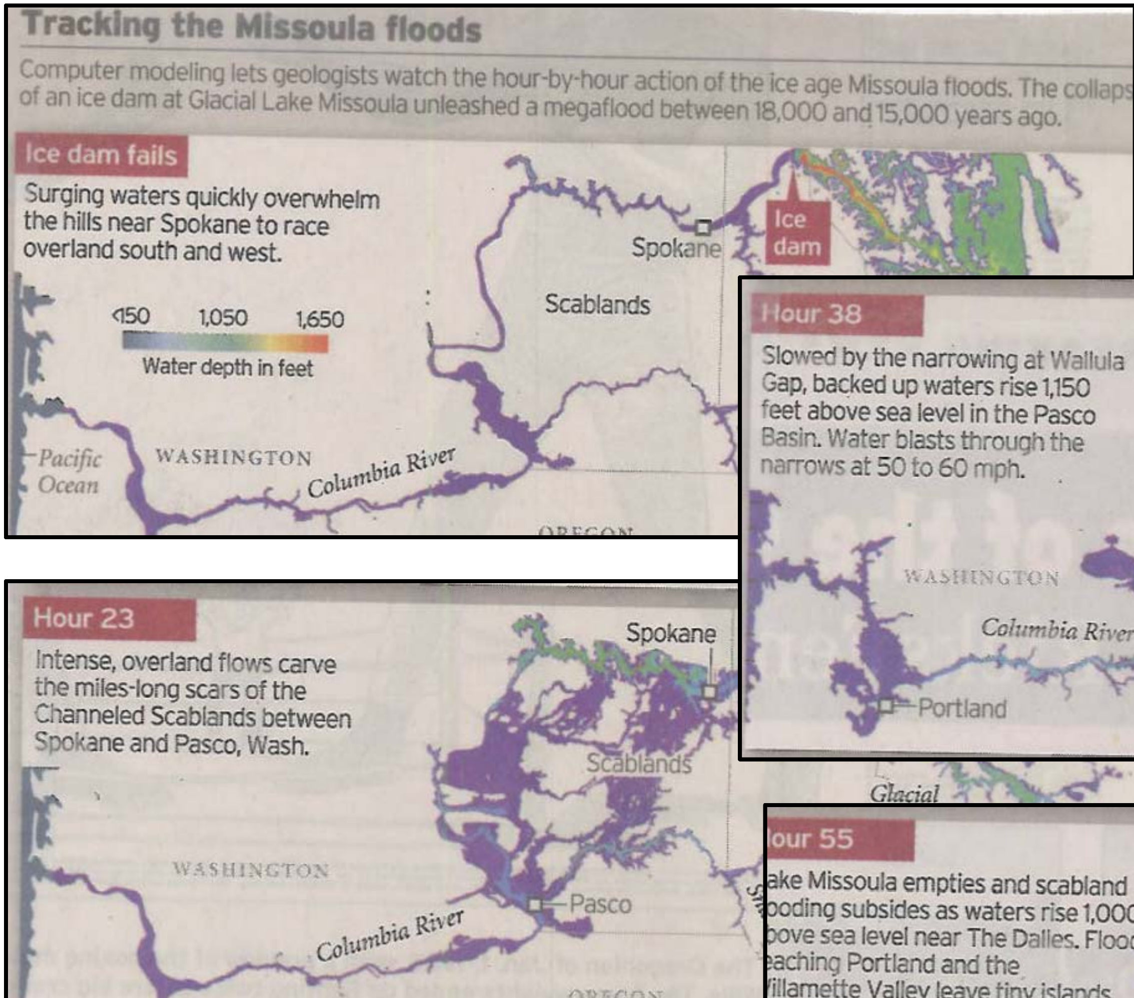
Shouldn't lush-green colors represent wet and sand-colors represent dry?

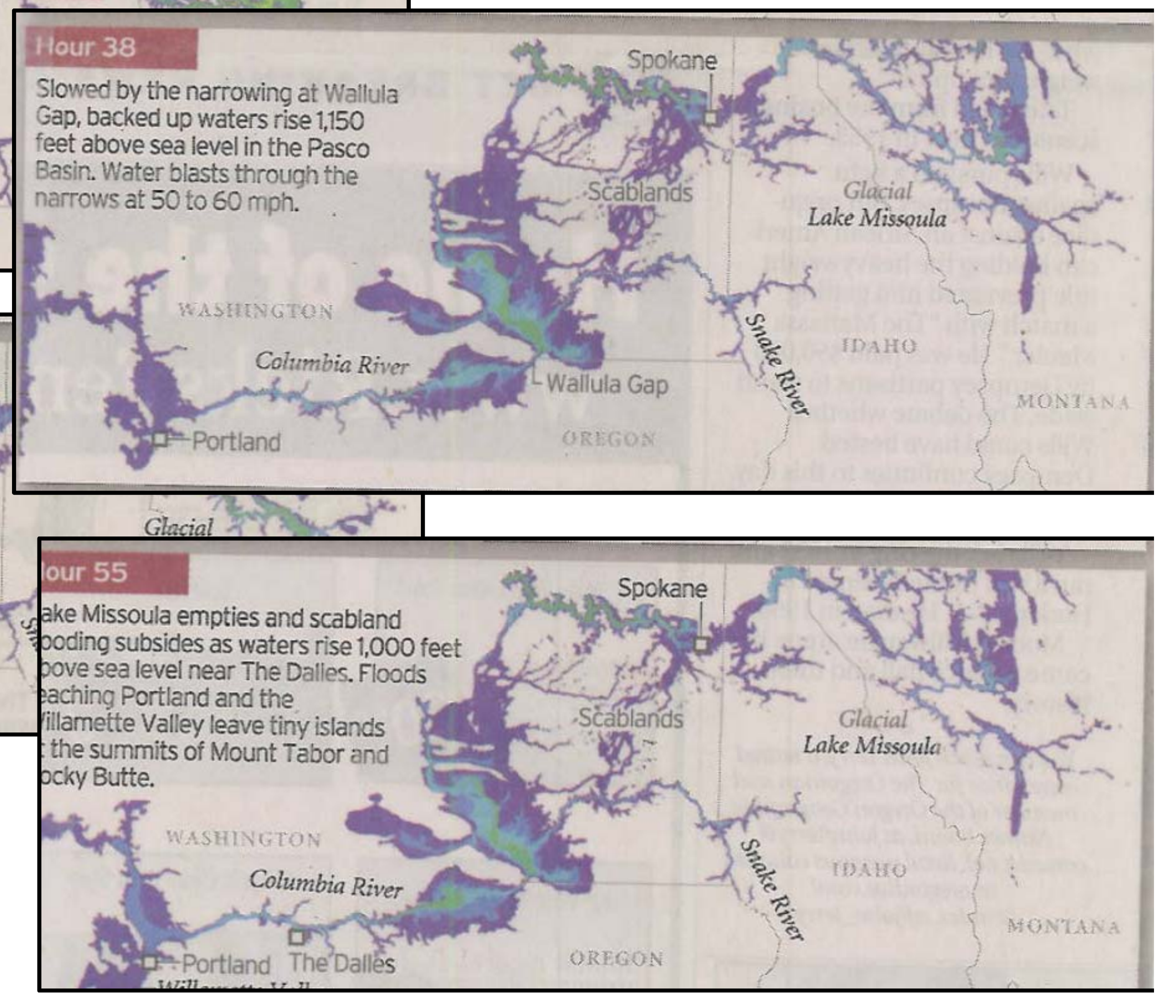
This is Better …



Source:
The Oregonian, October 31, 2006

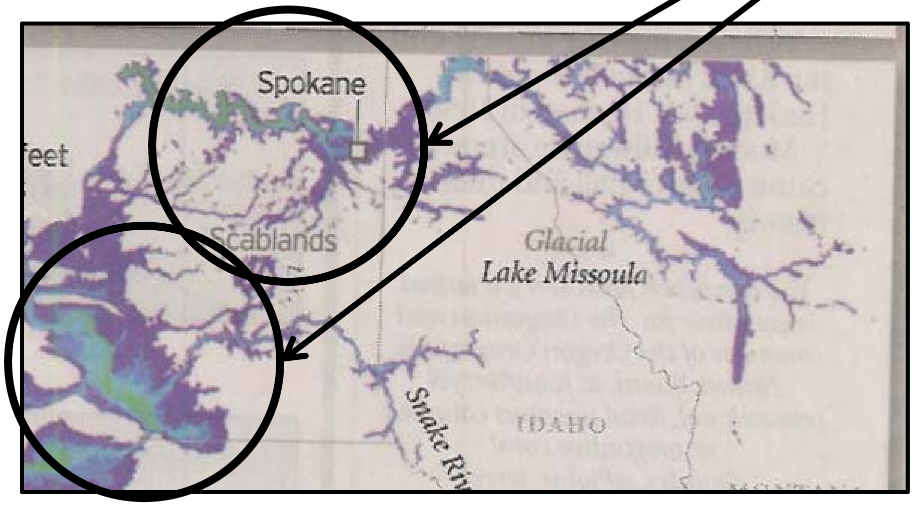
And, one more



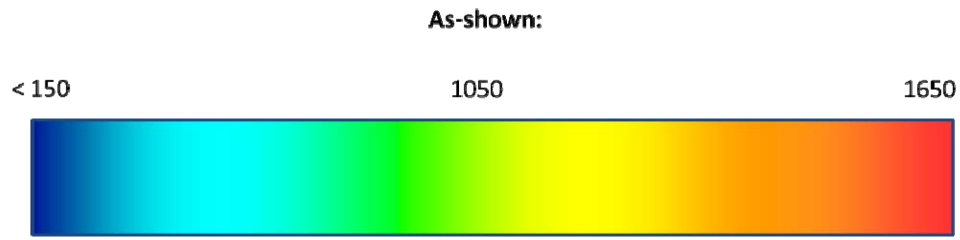


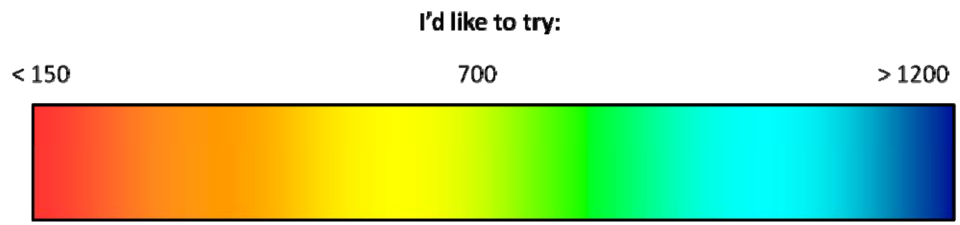
Source:
The Oregonian, February 21, 2010

And, one more



Much of the total dynamic range of the color scale is used up in the first small percent of the animation, leaving little for the rest of the animation





Source:
The Oregonian, February 21, 2010

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 • • •

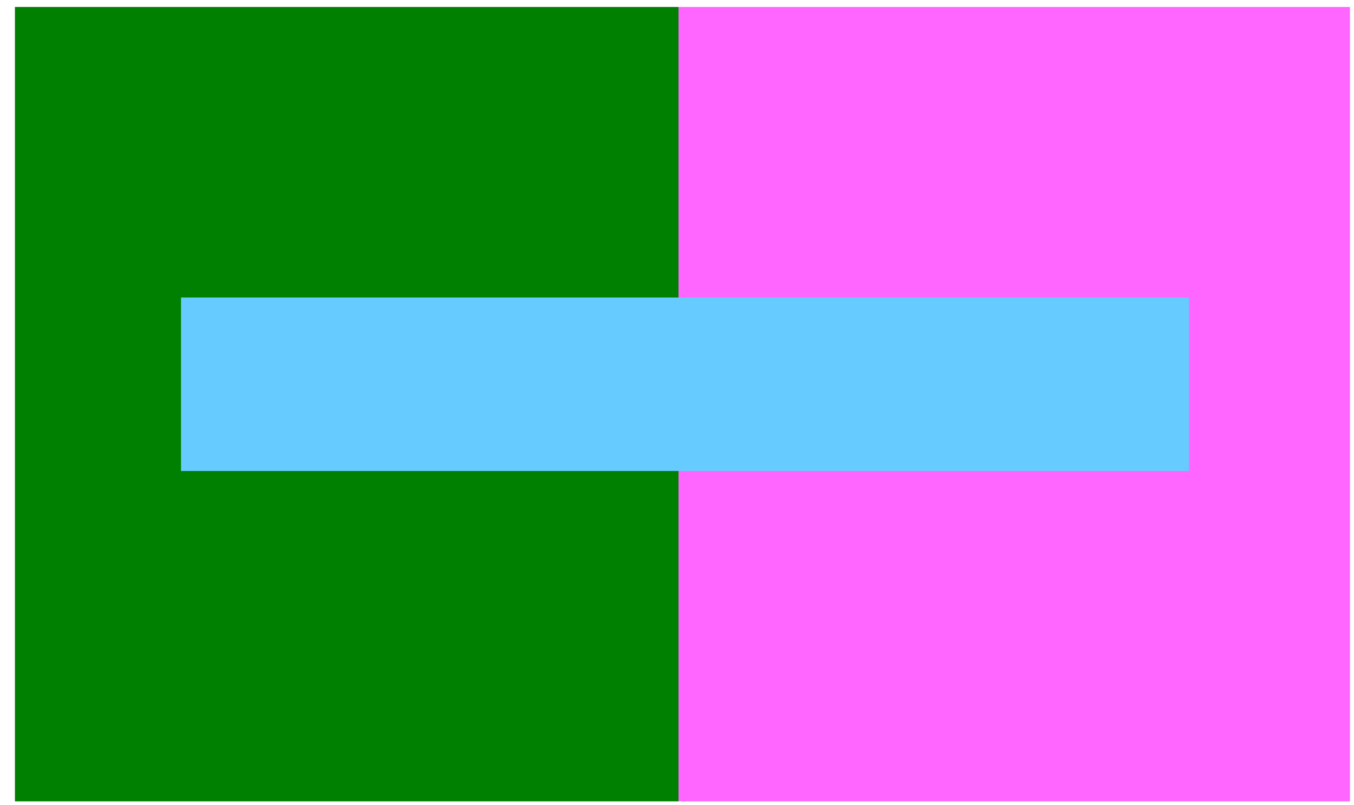
?

Color Rules

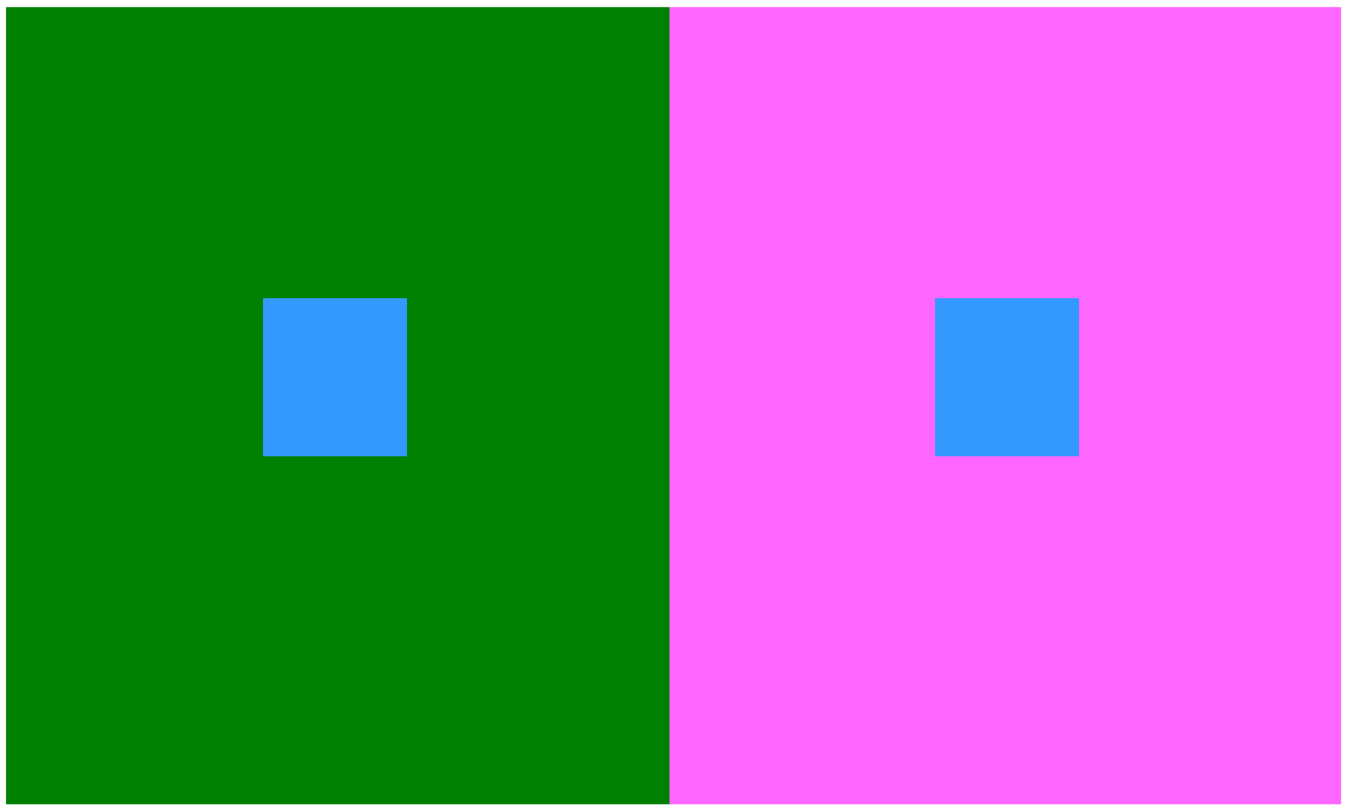
In visualization applications, we must be aware that our perception of color changes with:

- **The surrounding color**
- **How close two objects are**
- **How long you have been staring at the color**
- **Sudden changes in the color intensity**

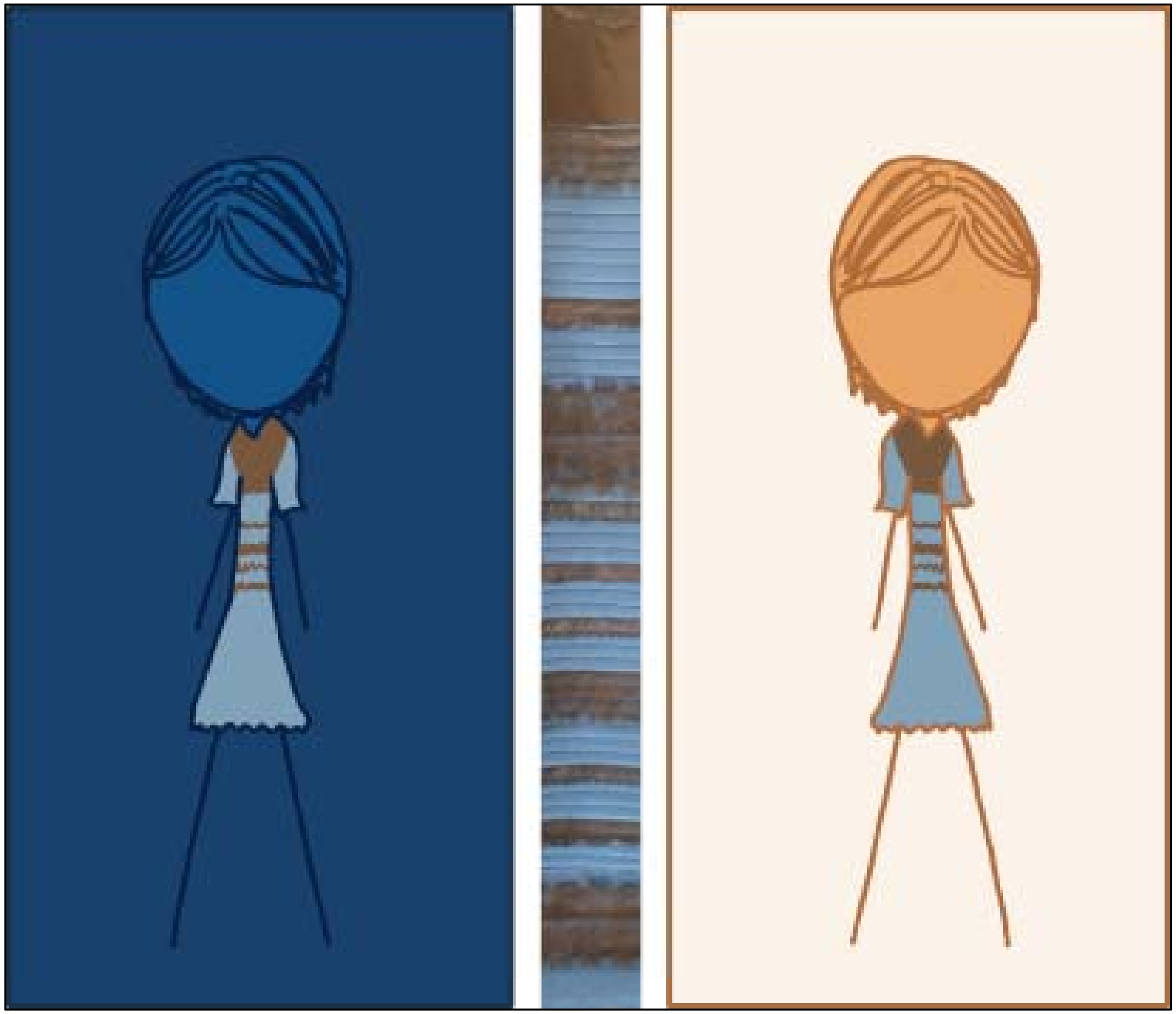
The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"



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

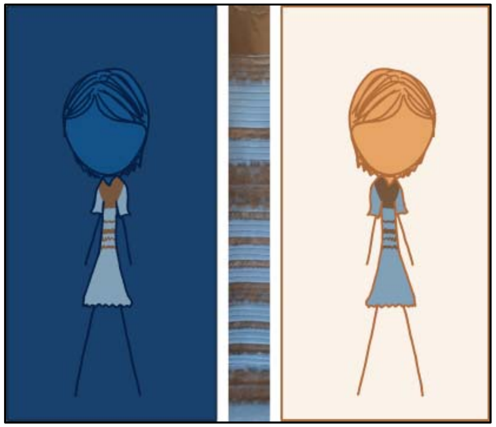


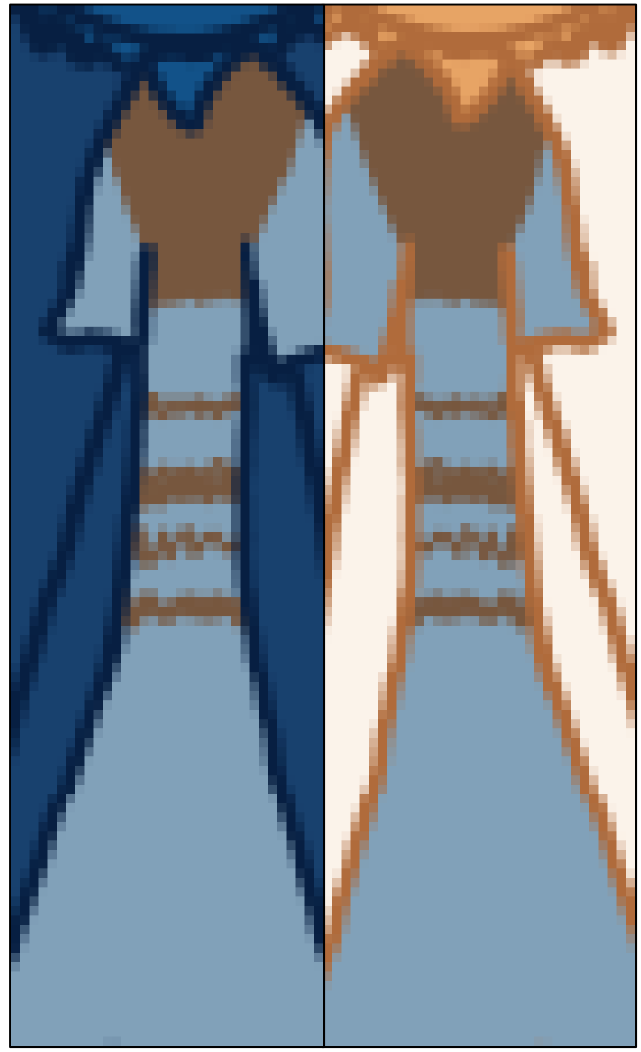
The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"



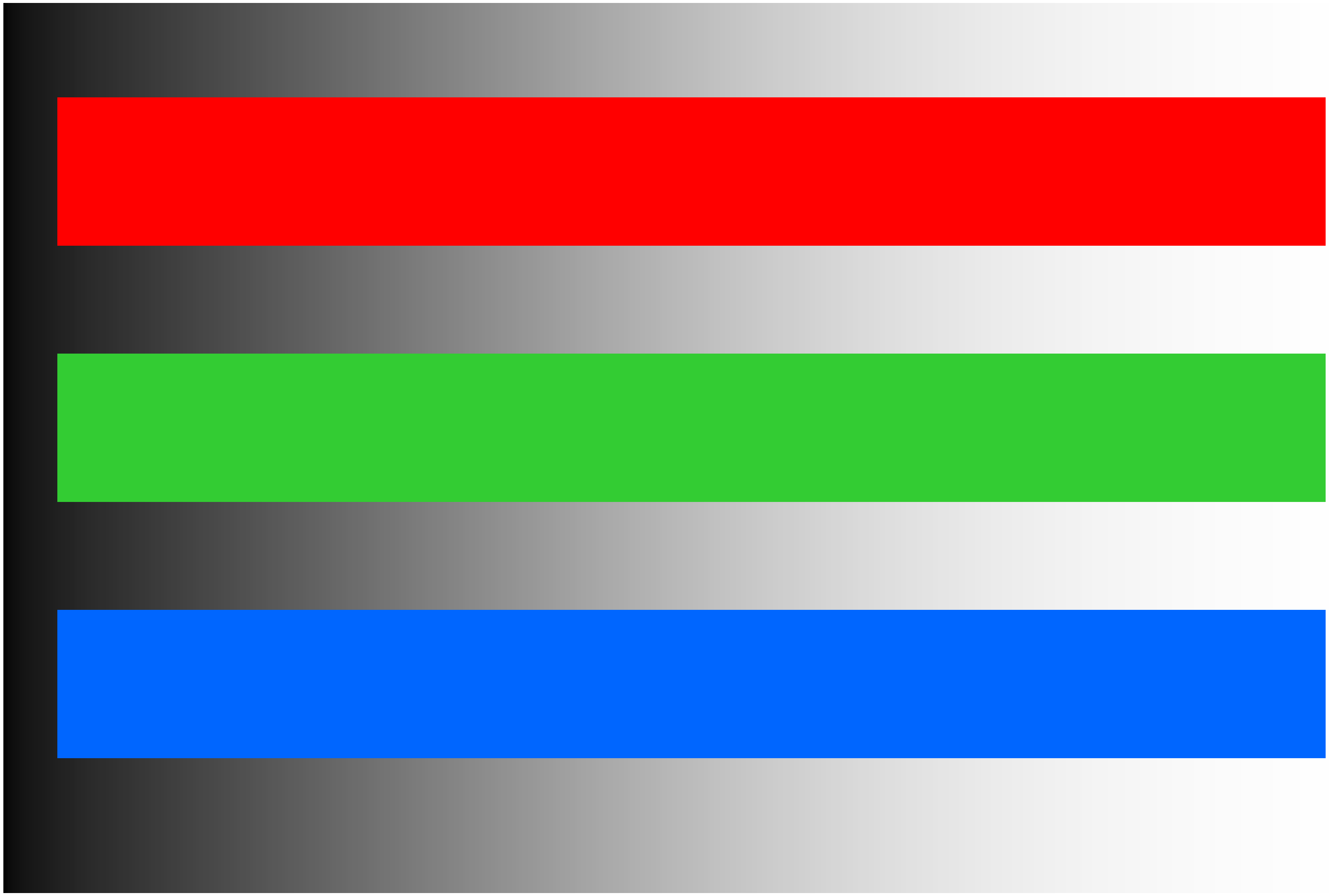
http://xkcd.com

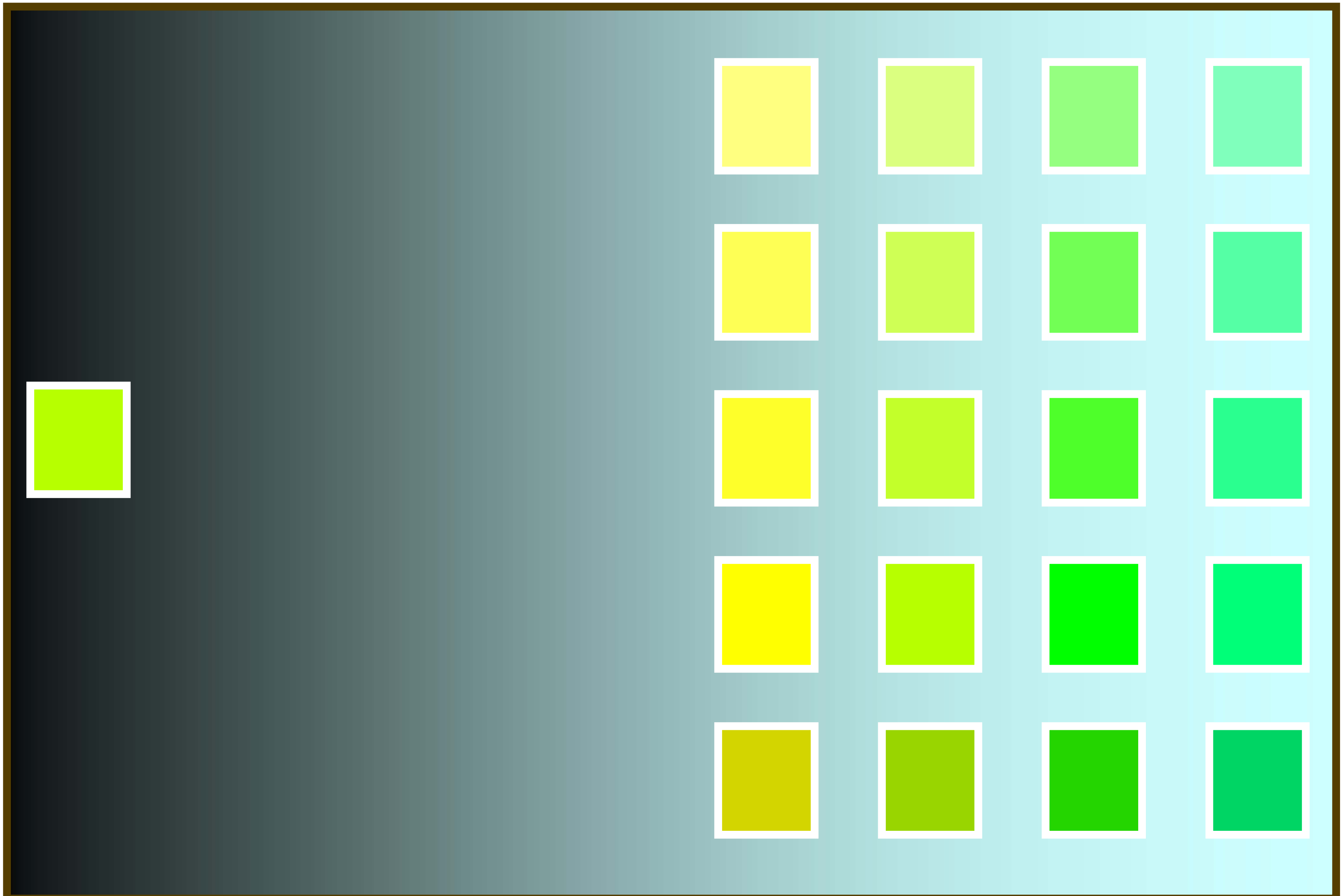
The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"





http://xkcd.com



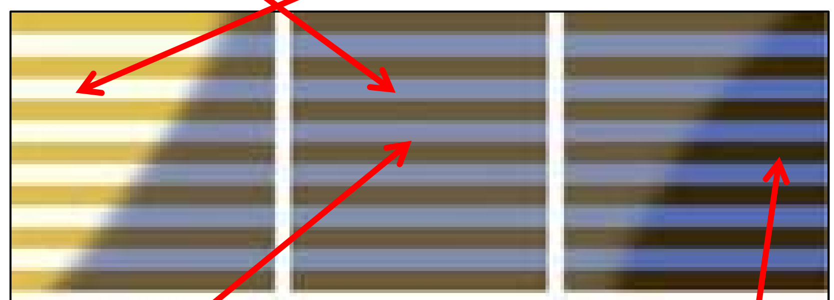


So, What's Up with the "Blue Dress" Debate?

New York Times

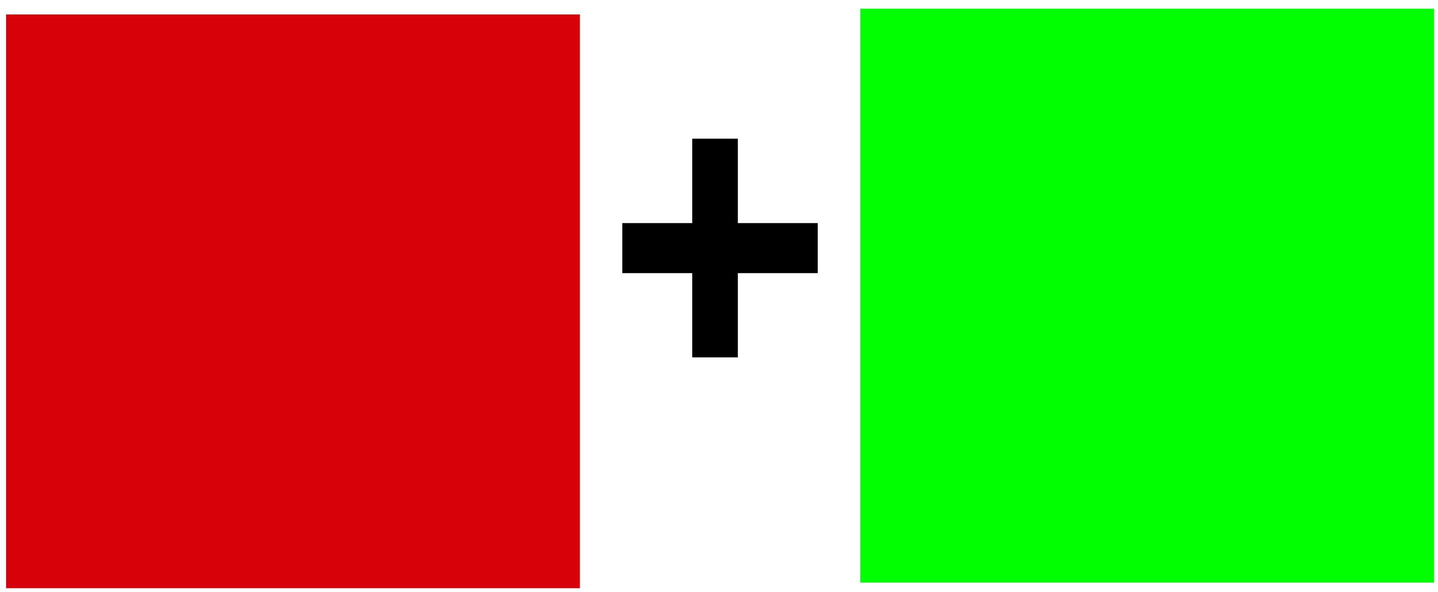
It's part of the ***Color Constancy*** effect

If you see this color, but you expect that the dress is currently in a shadow, you "know" that it must really be this color.

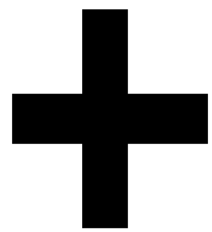


If you see this color, but you expect the dress is currently in bright light, you "know" that it must really be this color.

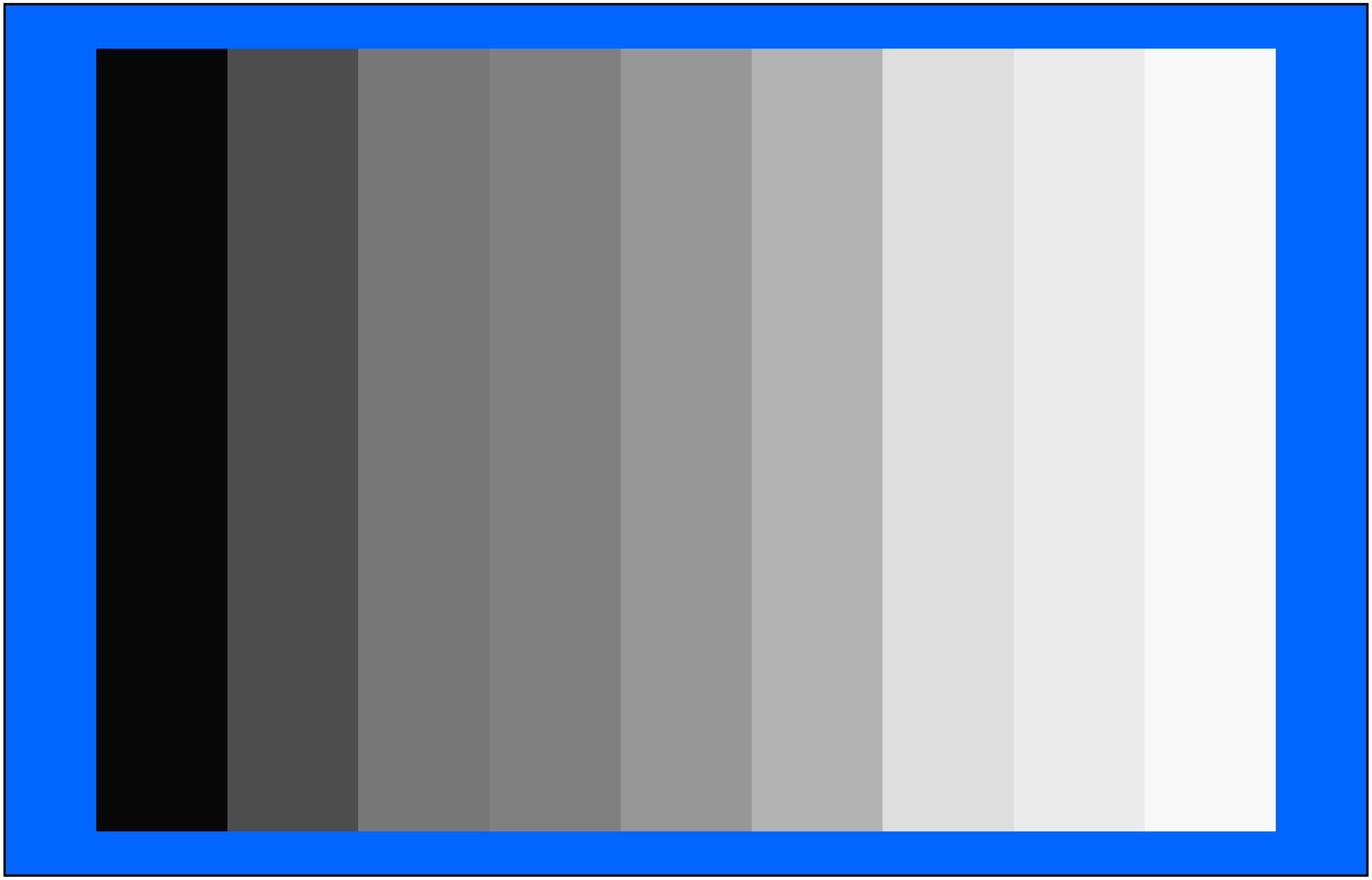
Afterimages



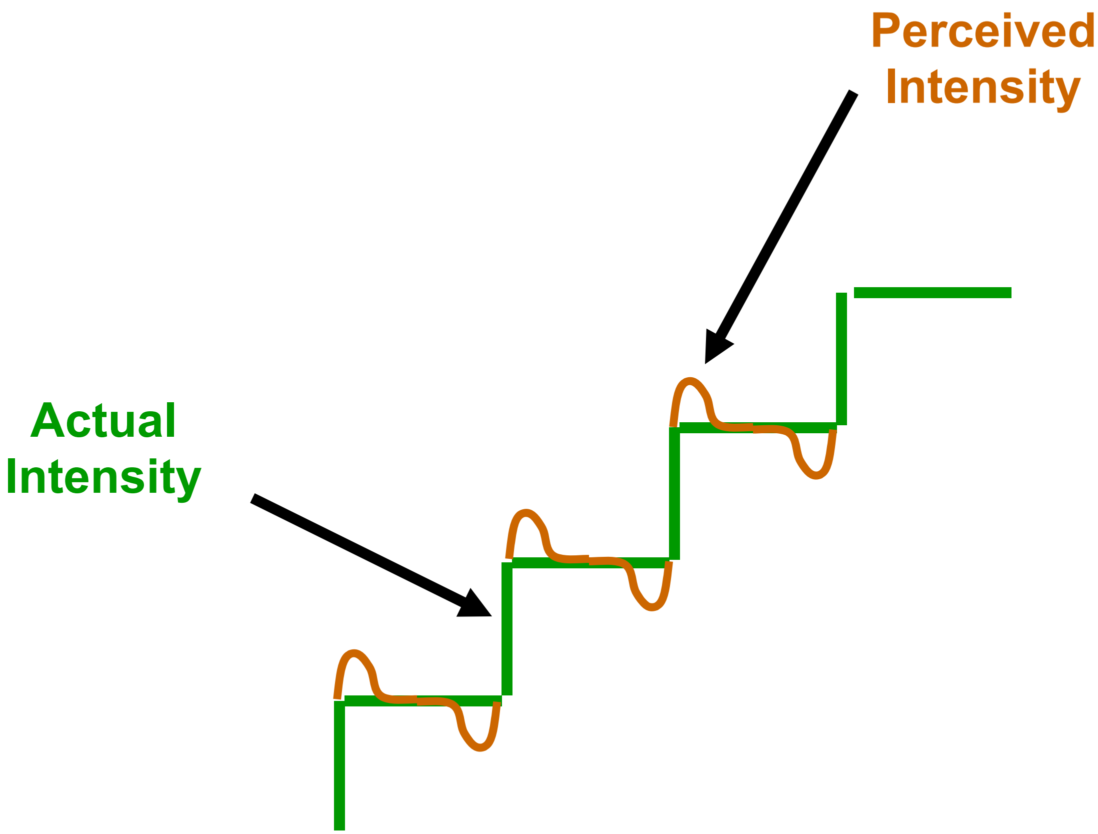
Afterimages



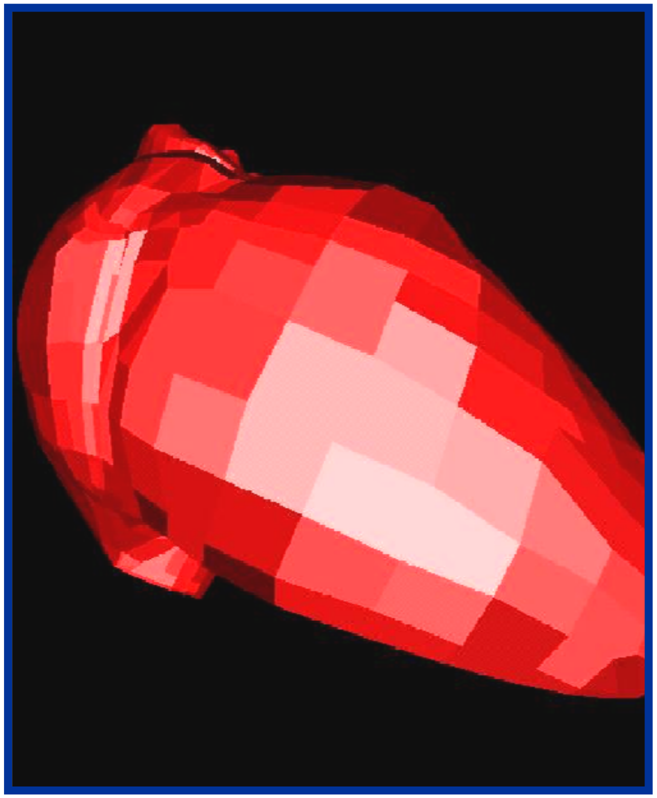
Beware of Mach Banding

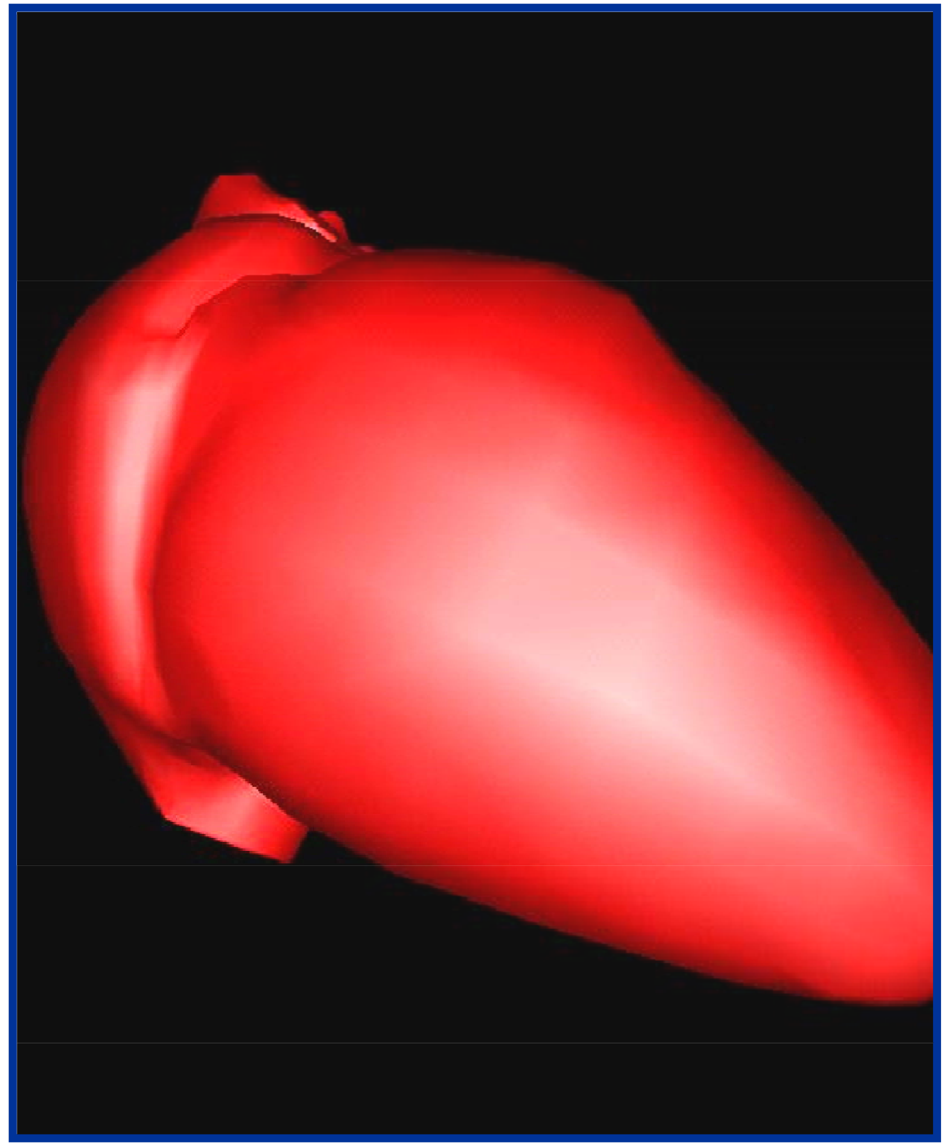


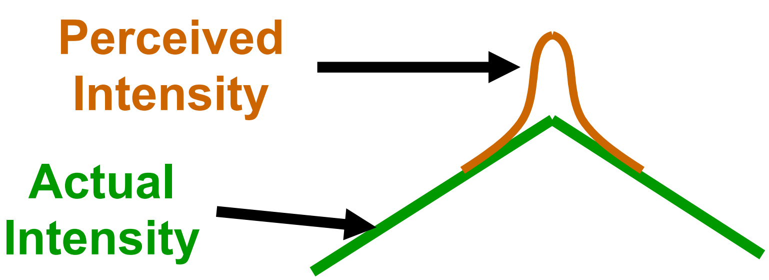
Beware of Mach Banding



Beware of Mach Banding

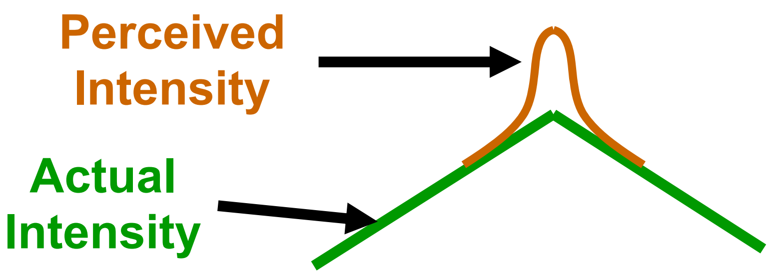






Beware of Mach Banding

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



The Ability to Discriminate Colors Changes with the Size of the Colored Area

The Ability to Discriminate Colors Changes with the Ambient Light

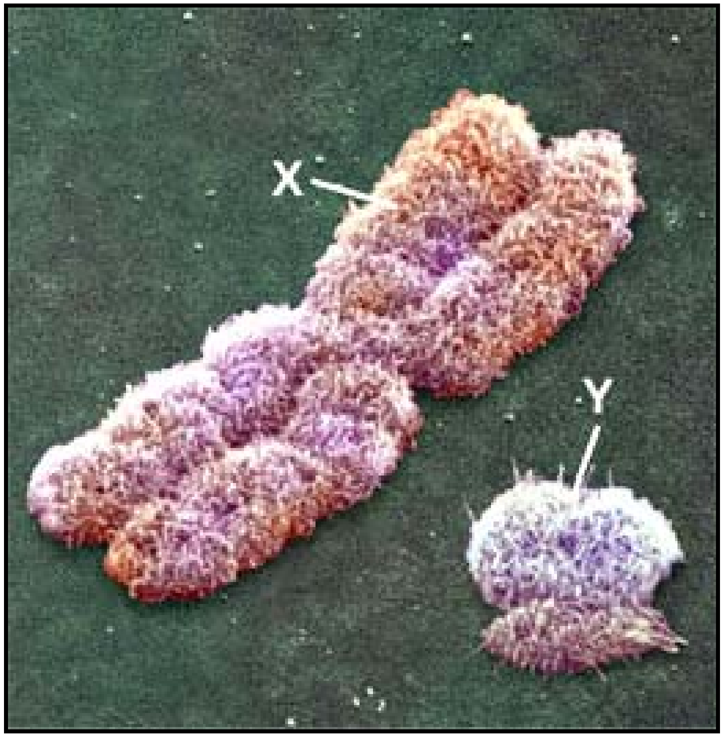
The Ability to Discriminate Colors Changes with the Age of the Viewer

Be Aware of Color Vision Deficiencies (CVD)

- There is actually no such thing as “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

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

A woman with the defective gene on one X chromosome probably has a dominant non-defective gene on the other. A man with a defect gene on his one X chromosome has no other gene to "fix" it.

Be Aware of CVD:
Code Information Redundantly

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

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

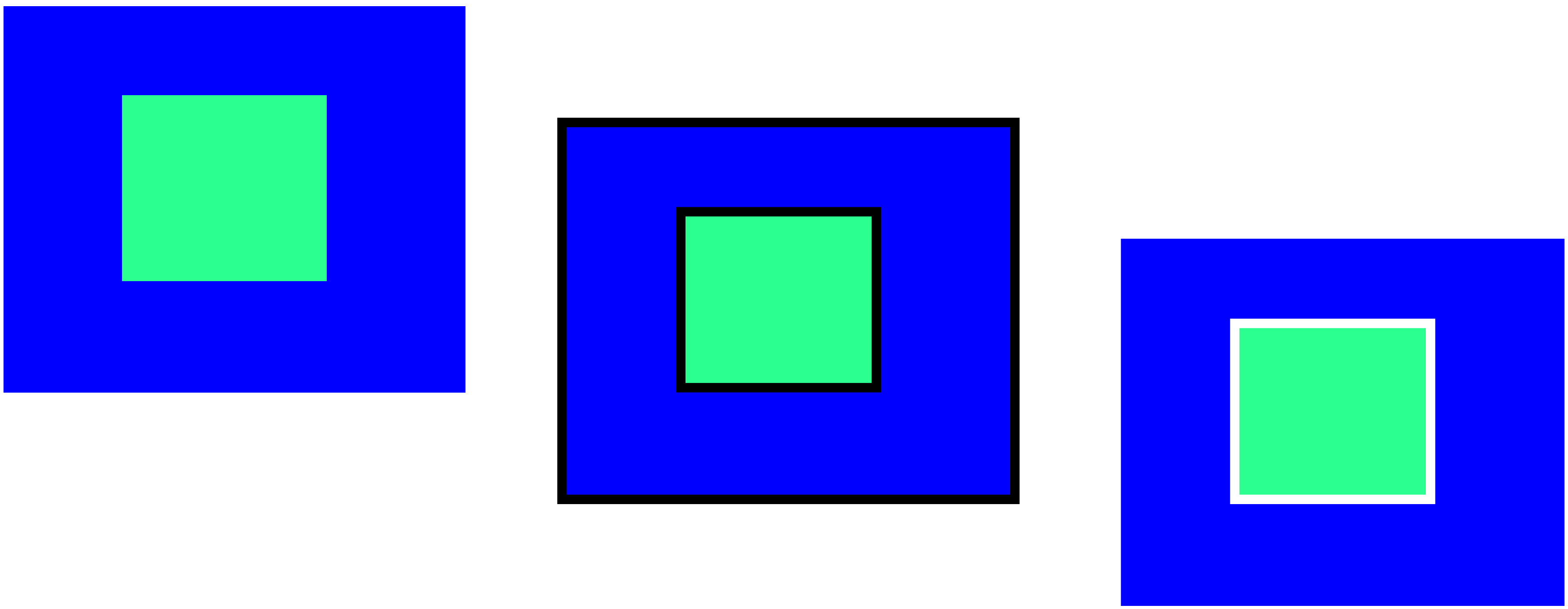
Four score and seven years ago, our forefathers brought forth upon this continent a new nation...

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

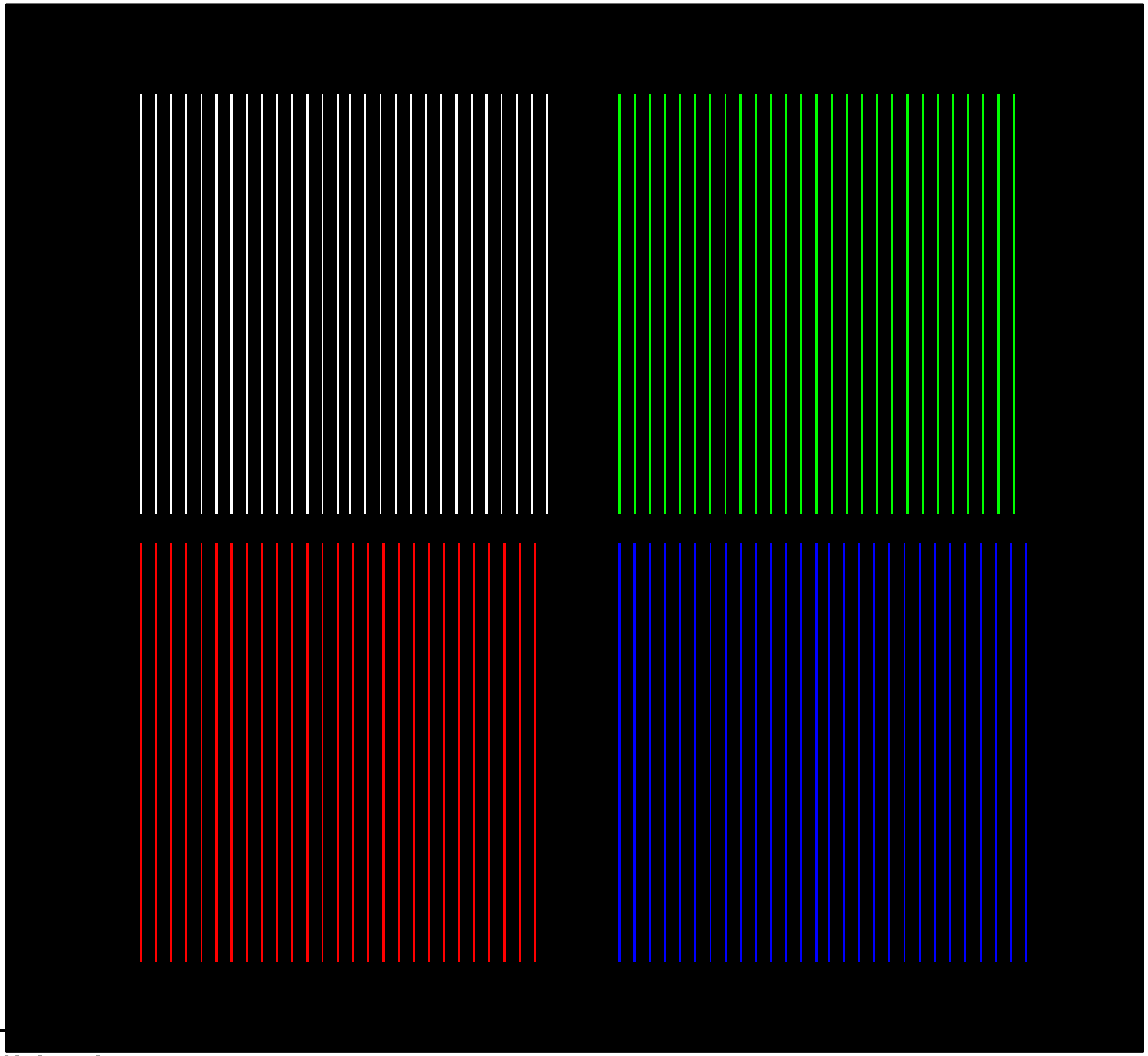
- **Different fonts**
- **Symbols**
- **Fill pattern**
- **Outline pattern**
- **Outline thickness**

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

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



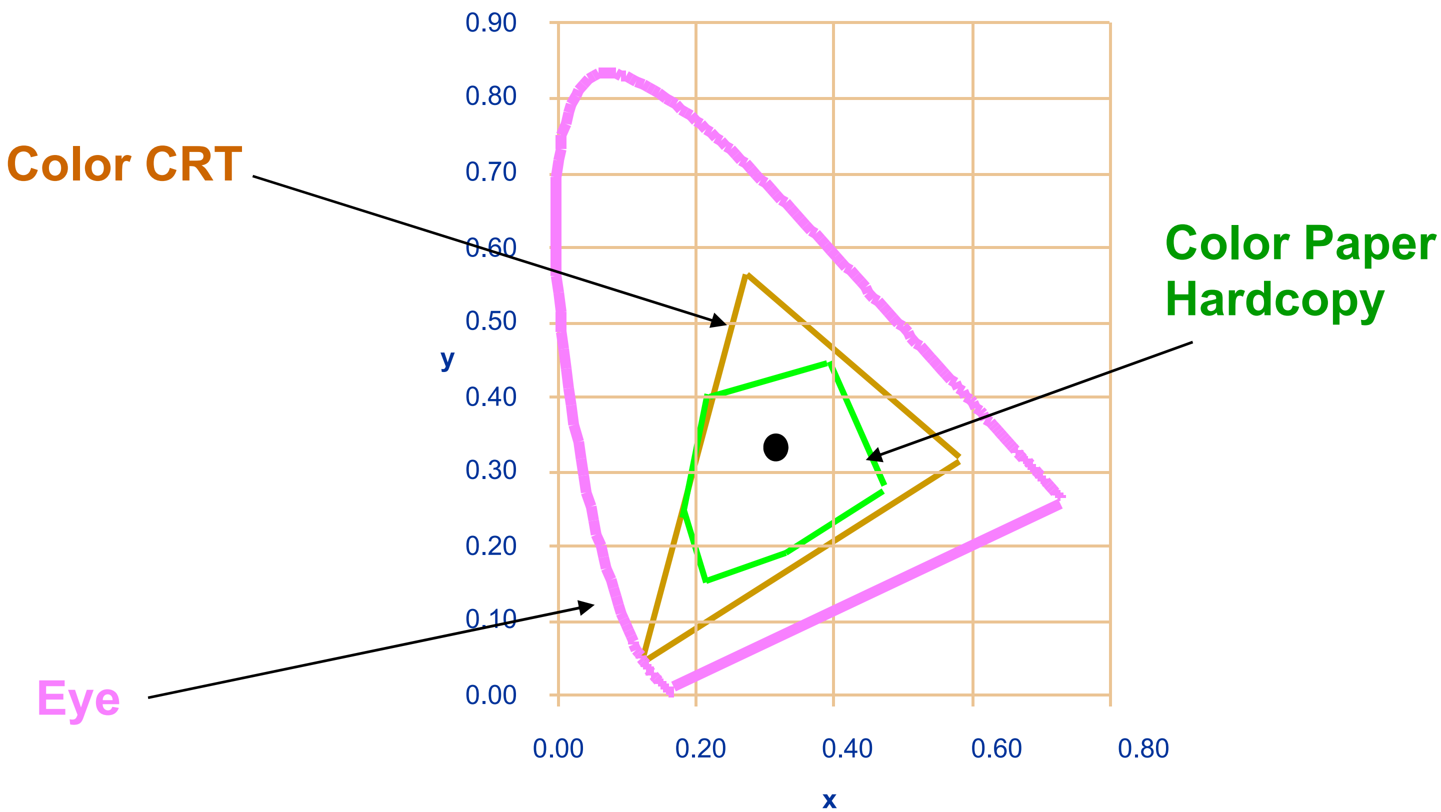
Watch the Use of Saturated Reds and Blues Together

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

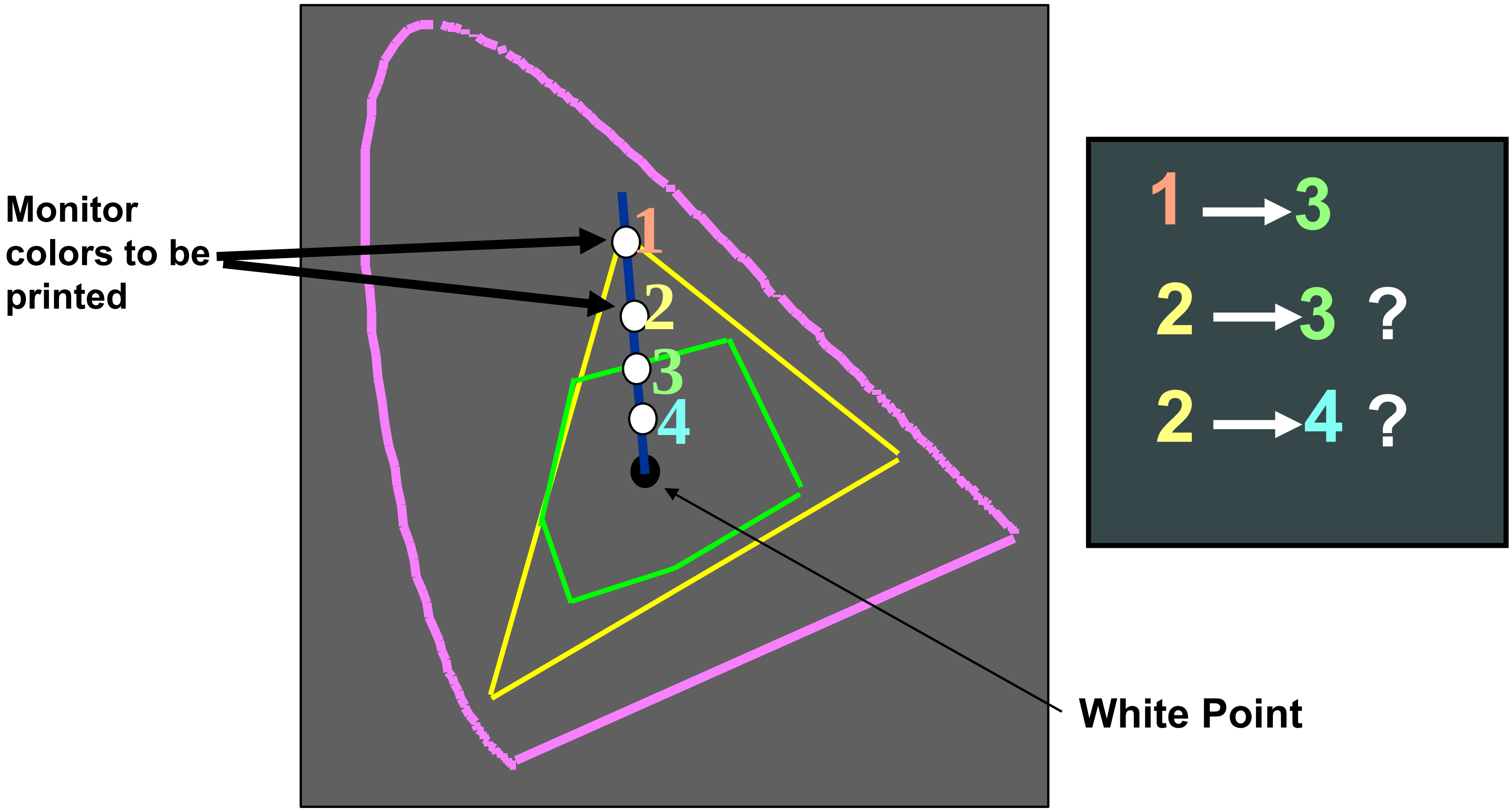
Be Aware of the Differences Between Color Gamuts –

Adapt by Deciding What is Most Important for Your Visualization

Color Gamut for a Monitor and a Color Printer



Color-Preserving vs. Contrast-Preserving Gamut Mappings



Some Basic Rules for Using NTSC (Analog) Video

or, Why I'm So Glad We Are in the Twilight of Analog TV…

Understand the Limitations of going from Monitors to NTSC Video

- Use less saturated colors due to color gamut considerations
- Expect an effective resolution of (at best) ~640x480
- Do not use single-pixel thick lines
- Stay away from the edges of the screen
- Some colors have better video resolution than others

NTSC Cycles-of-Encoding per Scanline

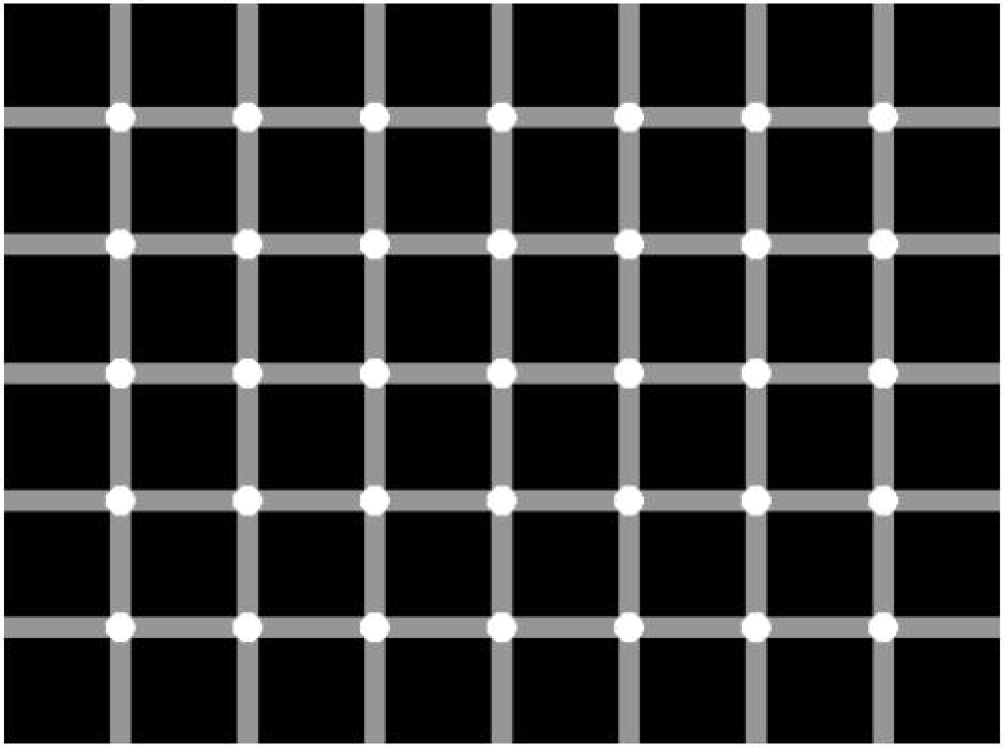
What:	Cycles/Scanline:
Intensity	267
Orange-Blue	96
Purple-Green	35

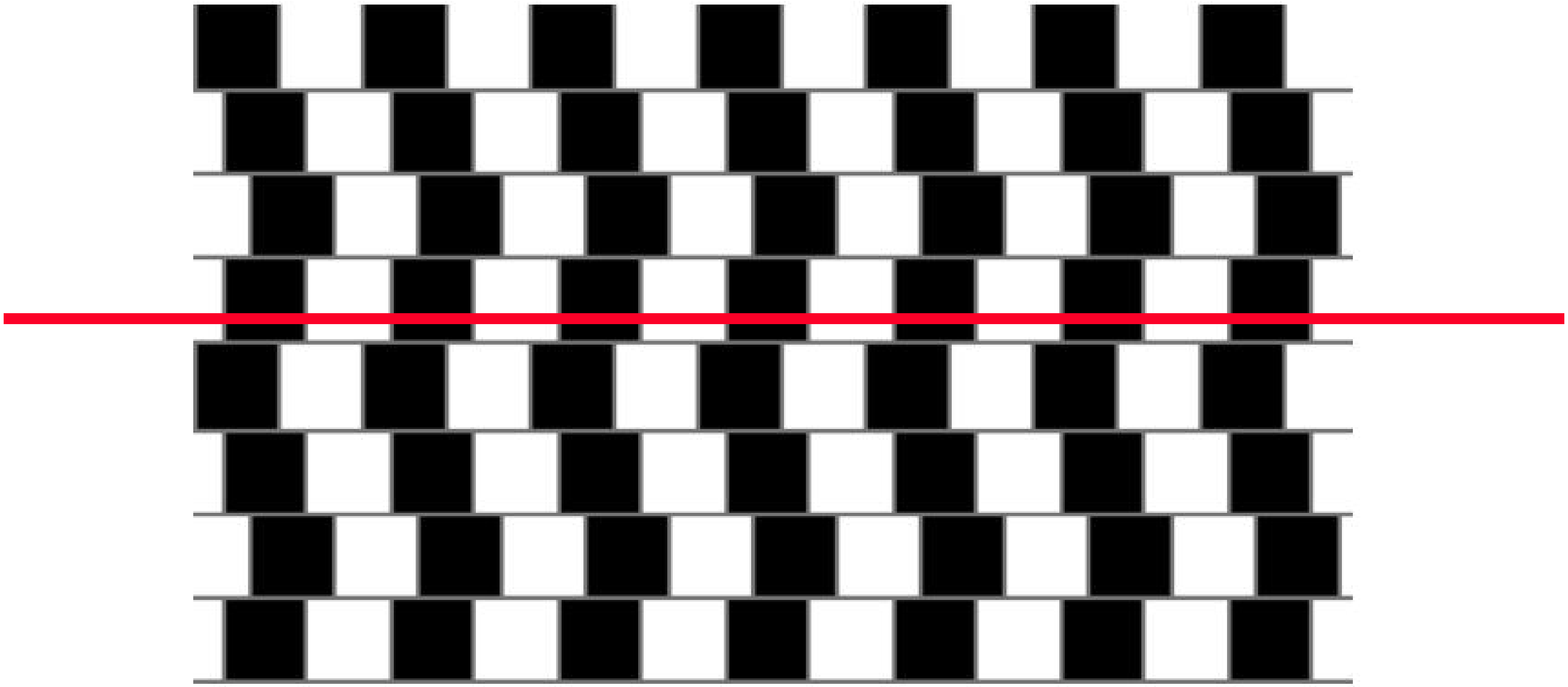
Beware of Gratuitous Color Pollution

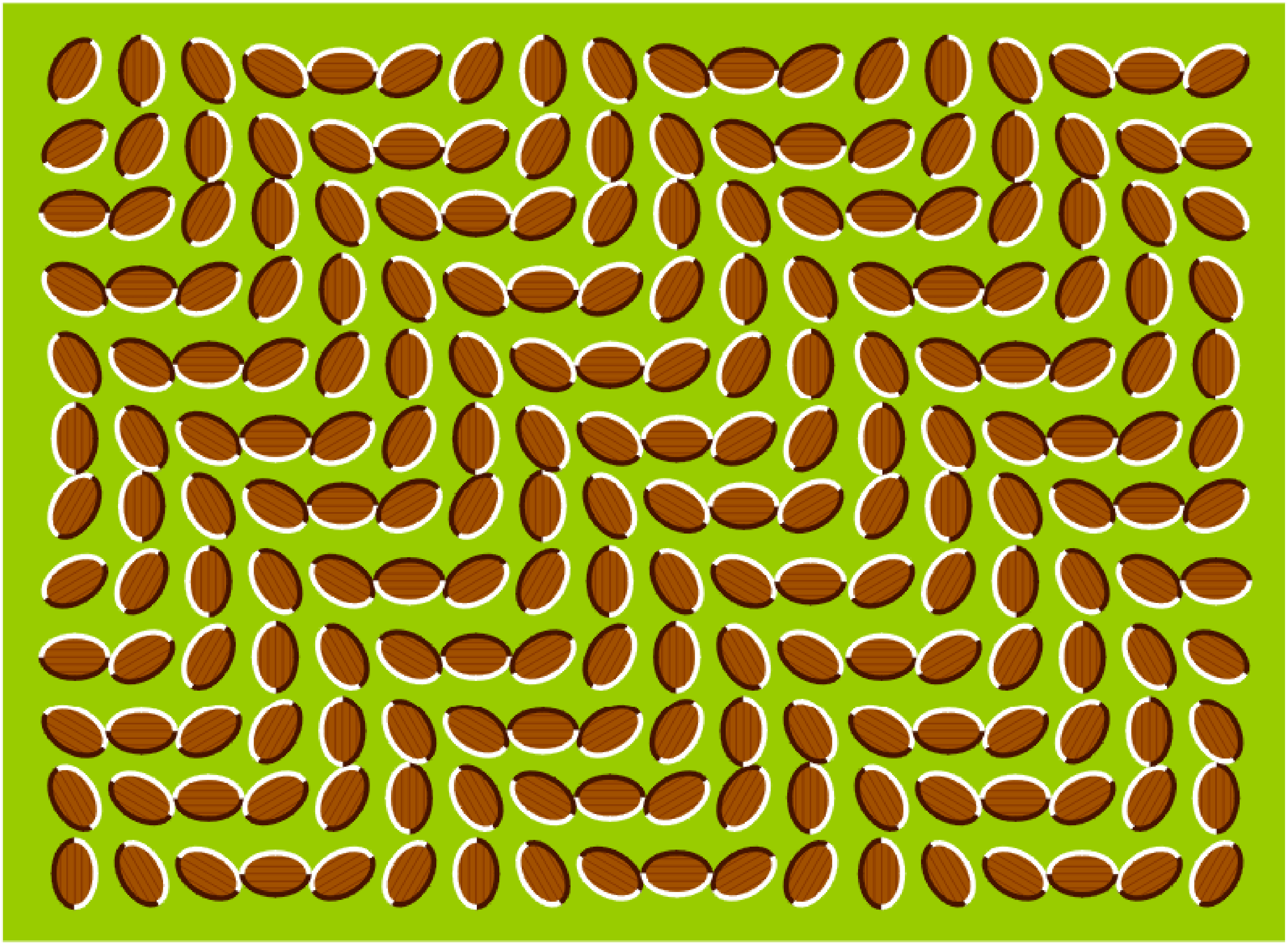
Just because you have millions of colors to choose from,

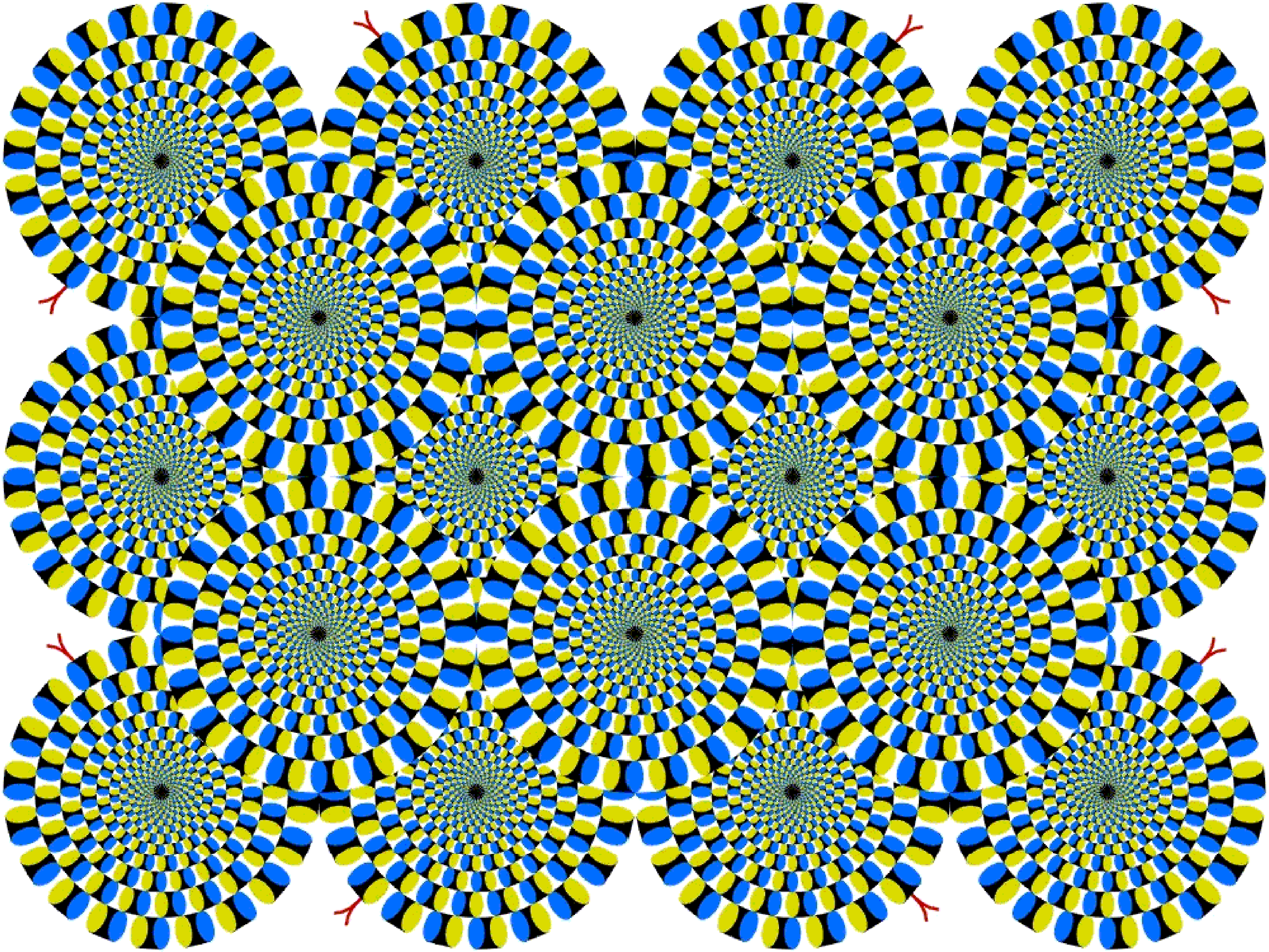
doesn't mean you must use them all •••

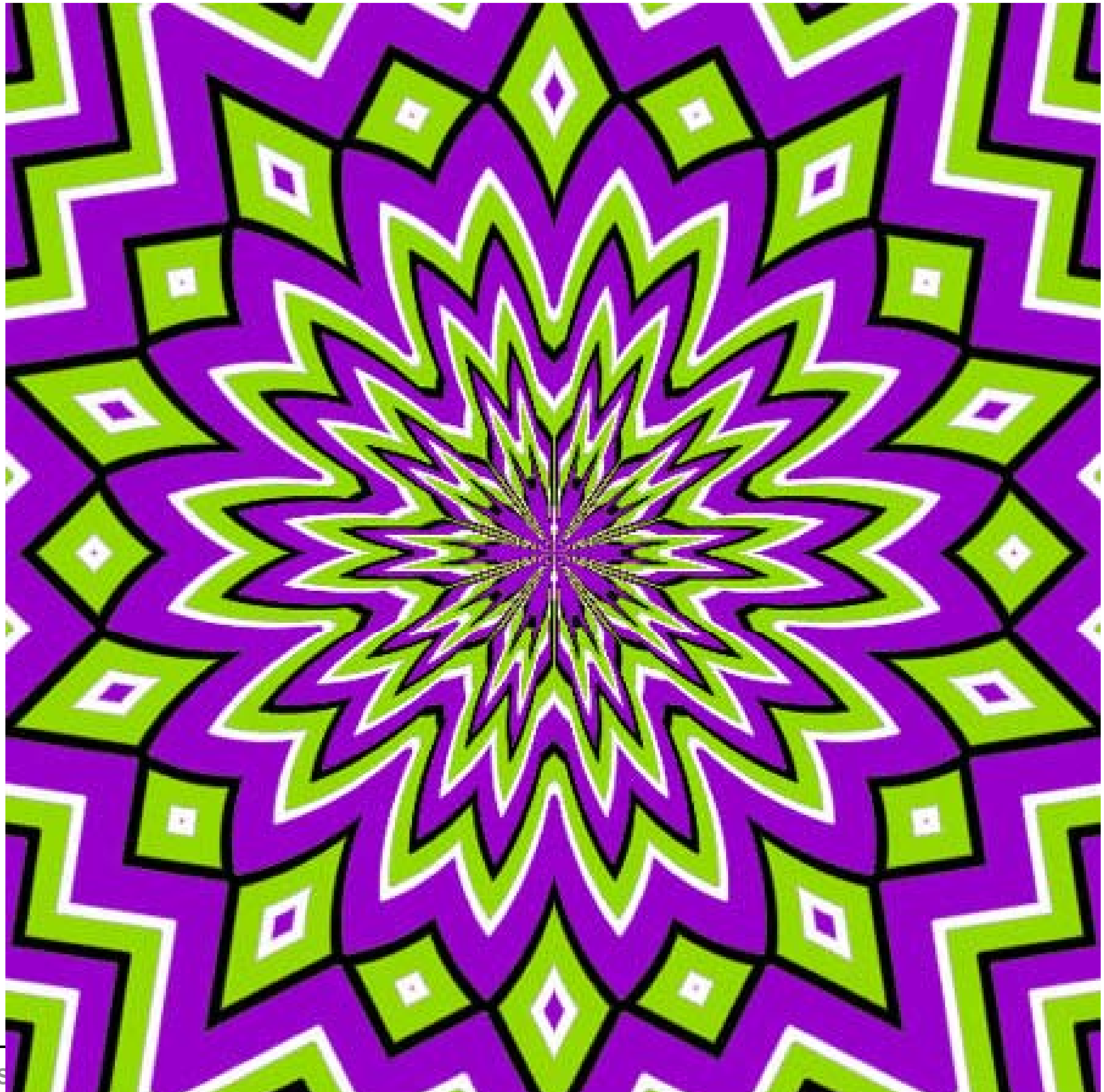
Beware of Lots of Other Stuff

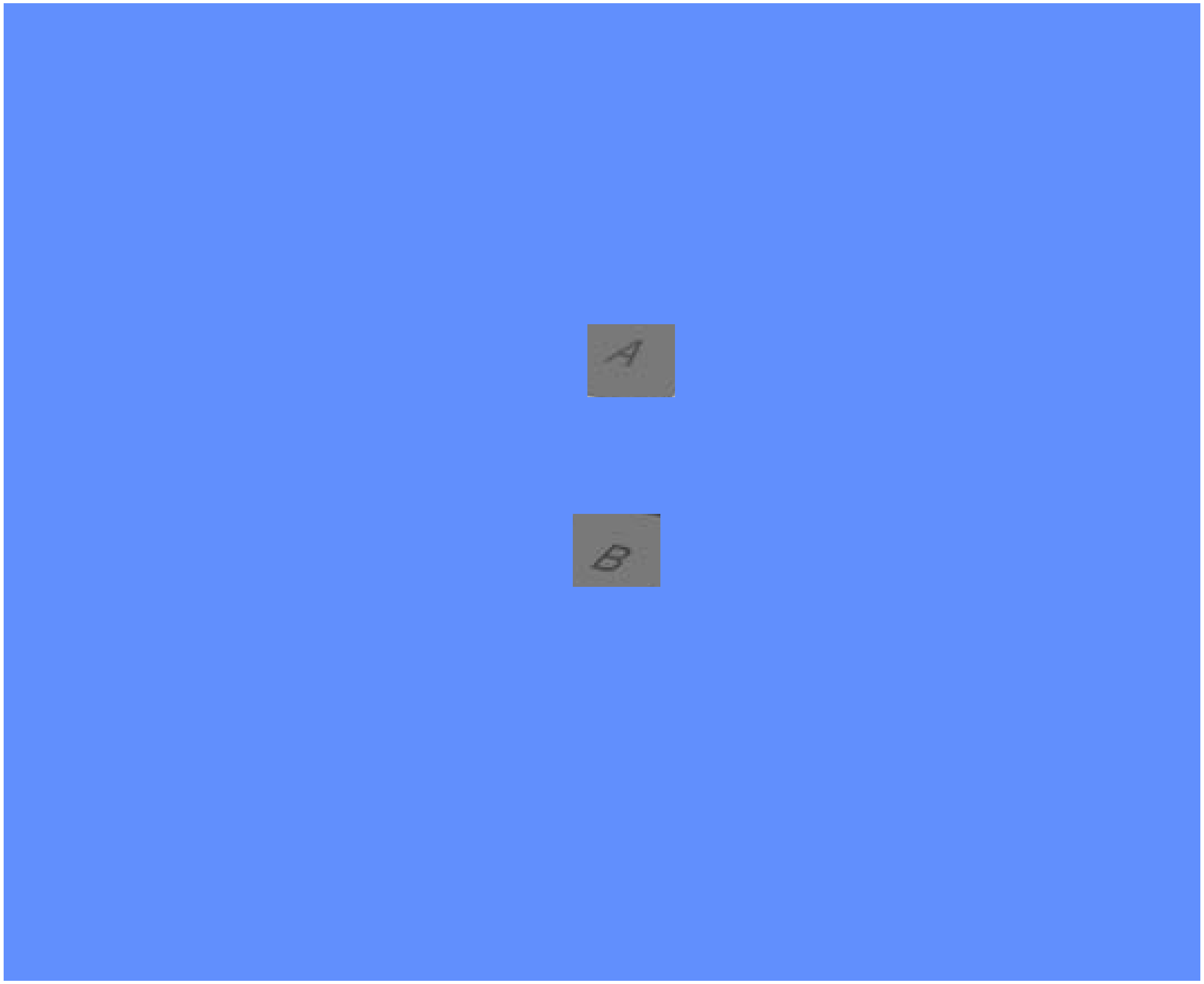


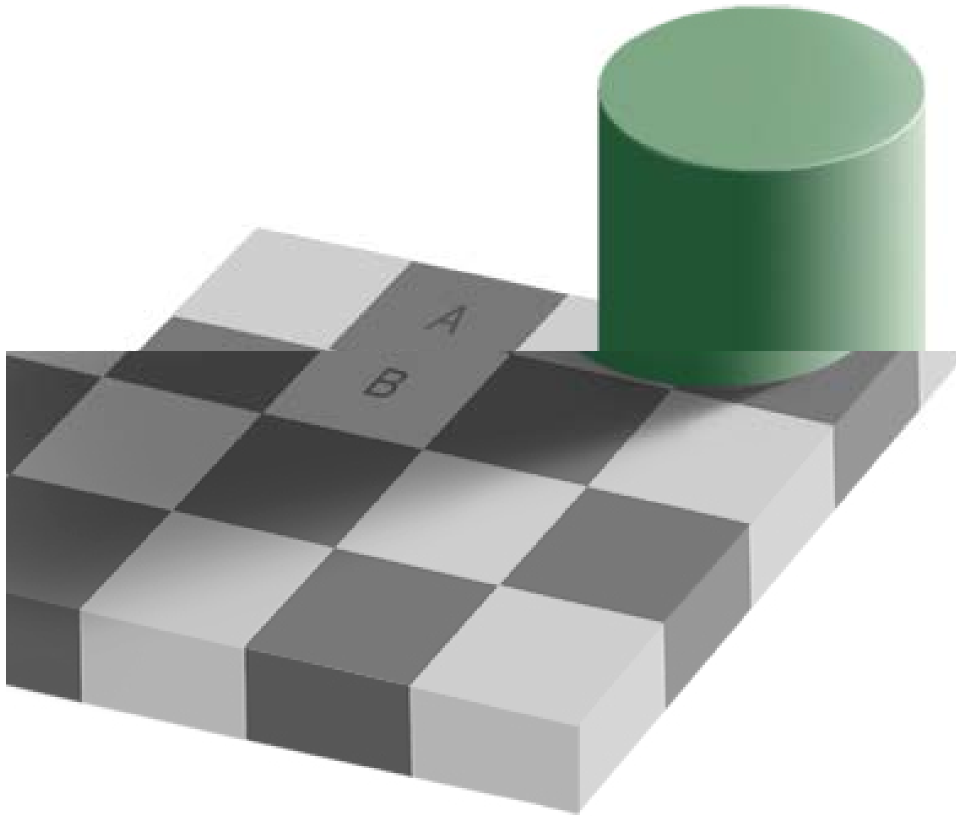









A
B


A
B

Good Color and Perception References

- Maureen Stone, *A Field Guide to Digital Color*, AK Peters, 2003.
- Roy Hall, *Illumination and Color in Computer Generated Imagery*, Springer-Verlag, 1989.
- R. Daniel Overheim and David Wagner, *Light and Color*, John Wiley & Sons, 1982.
- David Travis, *Effective Color Displays*, Academic Press, 1991.
- L.G. Thorell and W.J. Smith, *Using Computer Color Effectively*, Prentice Hall, 1990.
- Edward Tufte, *The Visual Display of Quantitative Information*, Graphics Press, 1983.
- Edward Tufte, *Envisioning Information*, Graphics Press, 1990.
- Edward Tufte, *Visual Explanations*, Graphics Press, 1997.
- Howard Resnikoff, *The Illusion of Reality*, Springer-Verlag, 1989.