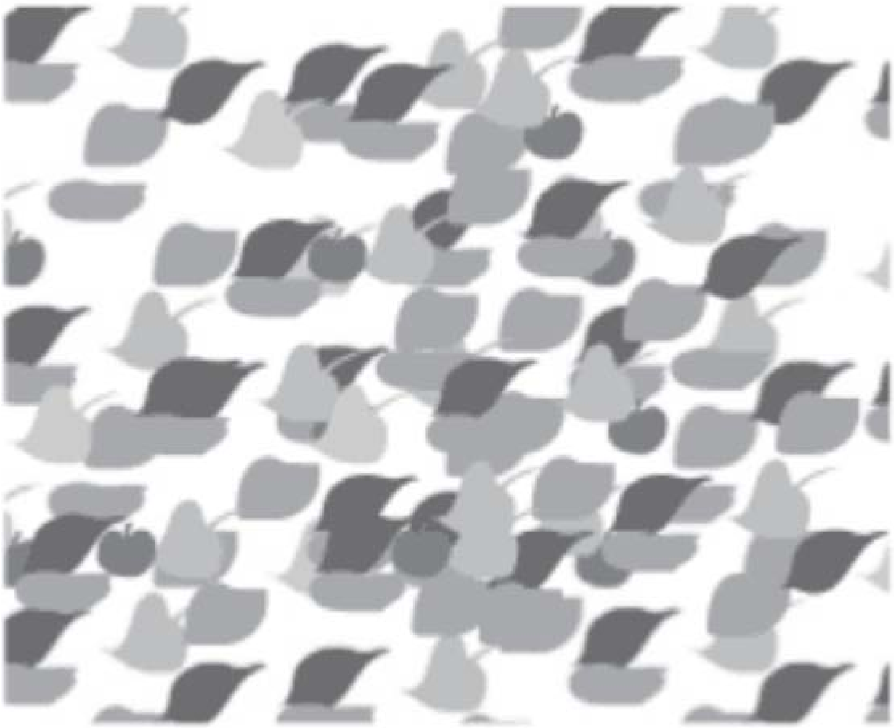
Colors in Visualization

Adapted from the Slides by Dr. Mike Bailey at Oregon State University

Goal: to know how we perceive colors; common color models and spaces; what to pay attention to when using colors;

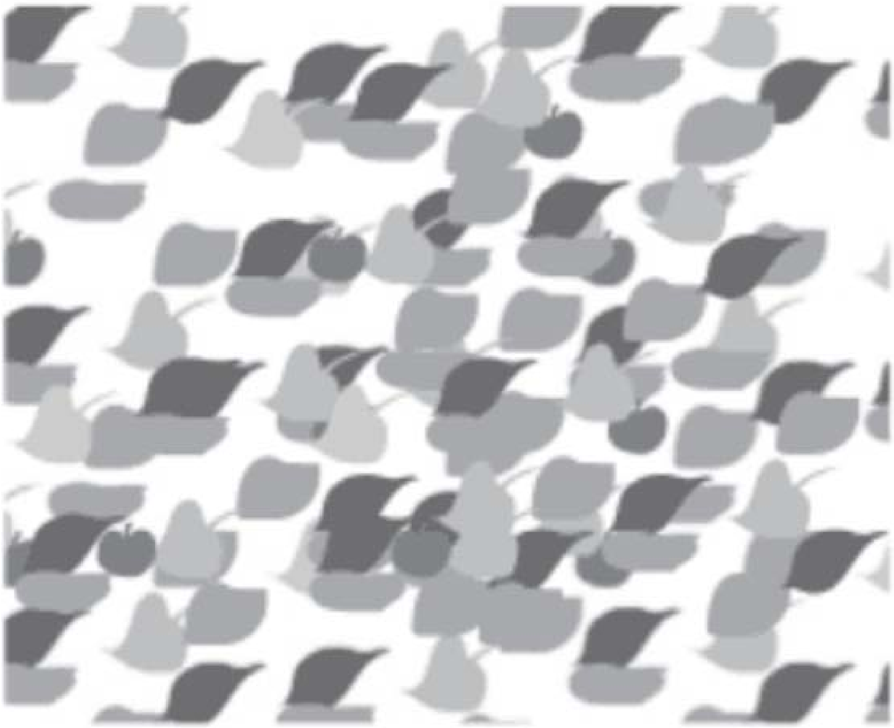
Find the cherries!

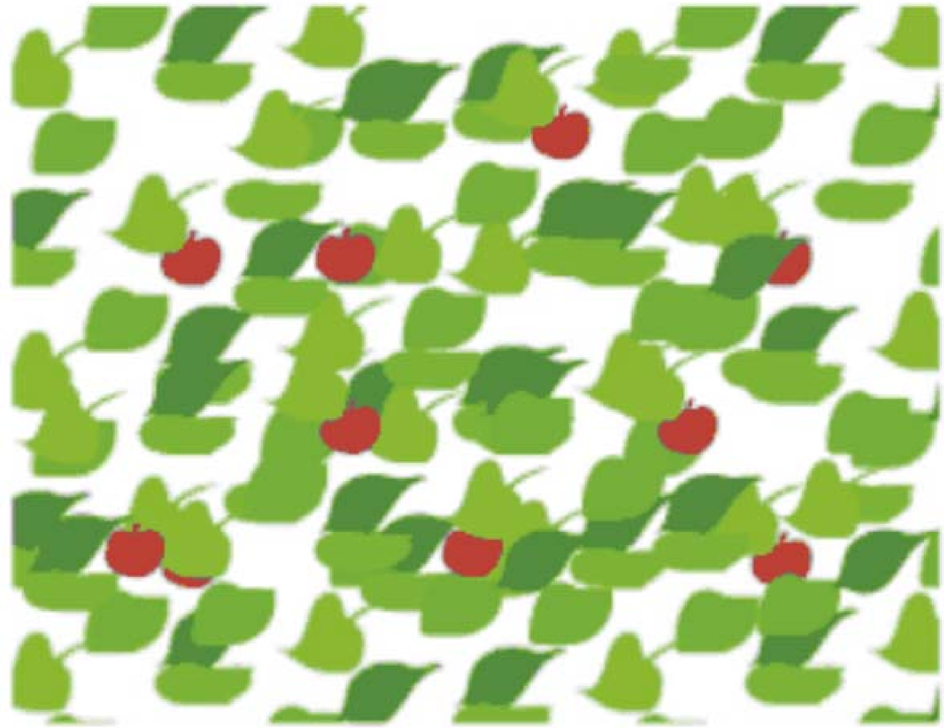


Colors help us break camouflage.

Find the cherries!

Pre-attentive!!!

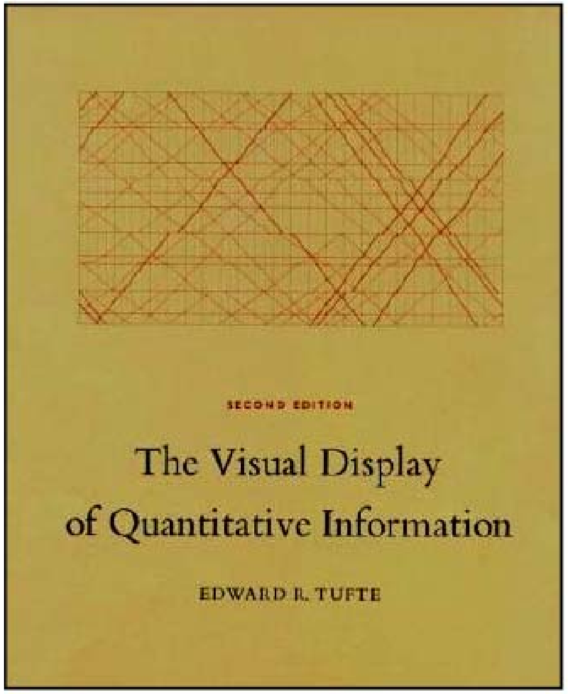




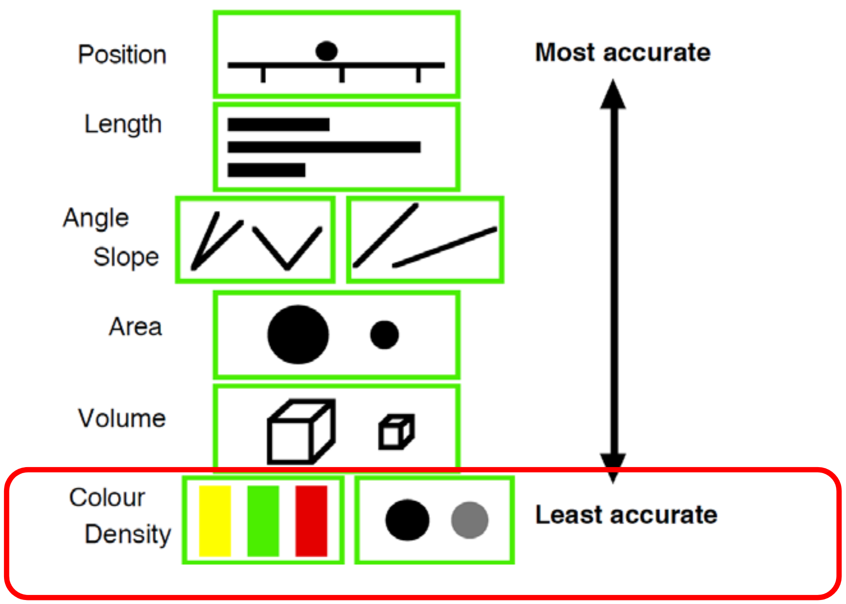
Colors help us break camouflage.

- “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



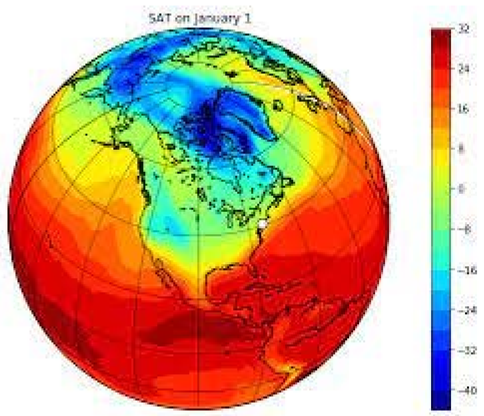
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey **quantitative** information.



Conflict???

Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey **quantitative** information.

Color is one of the most effective ways to **encode quantitative data defined in two-dimensional space to reveal patterns**.



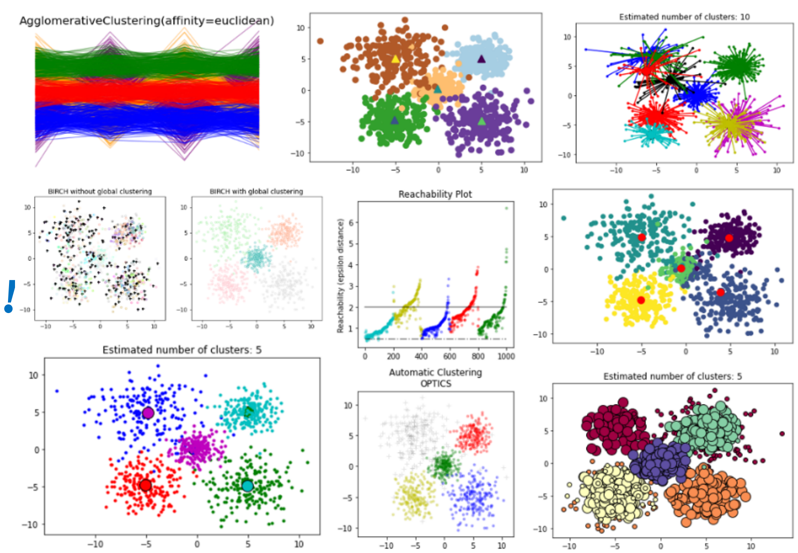
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey **quantitative** information.

Color is one of the most effective ways to **encode quantitative data defined in two-dimensional space to reveal patterns**.

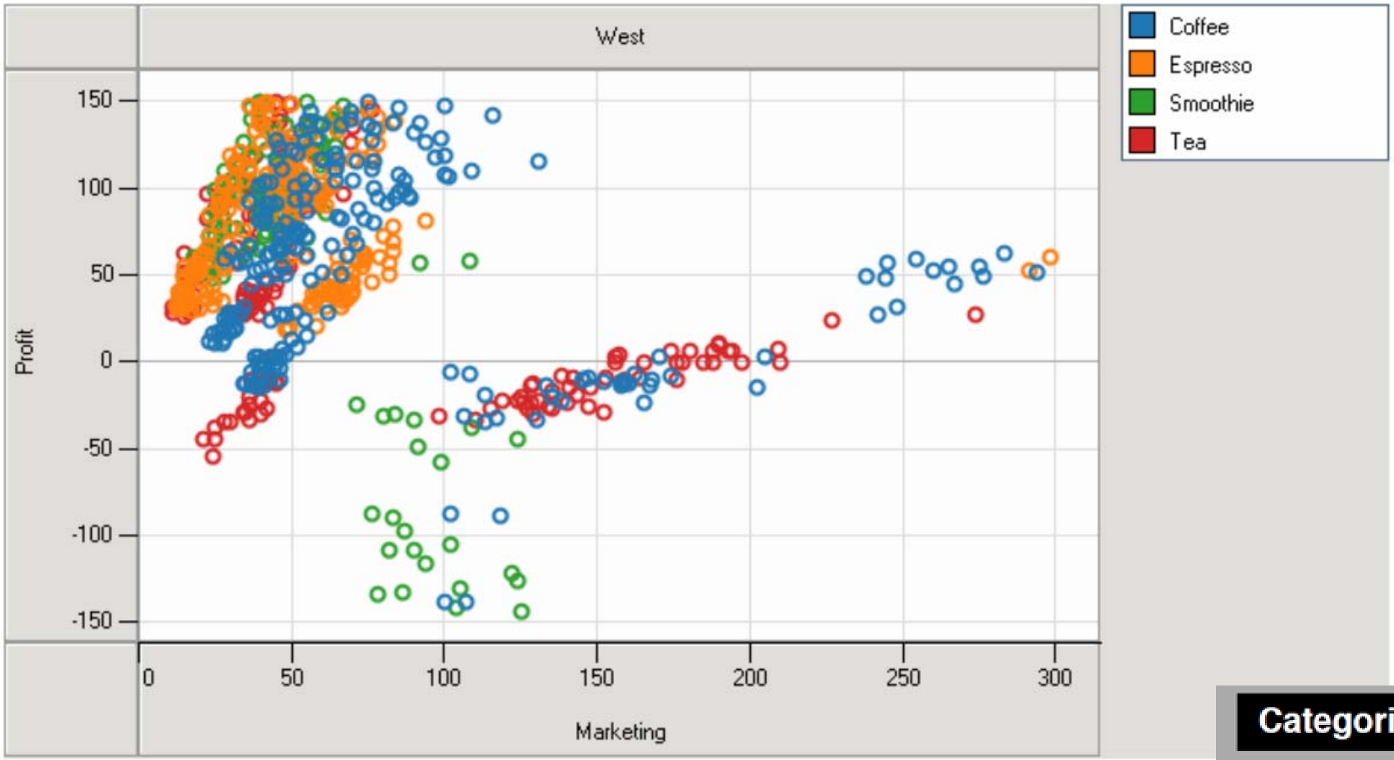
Differences in color can distinguish different categories (for example, cropland, forest, or urban areas in a land cover map) or indicate quantity (percent forest cover or population).

We are good at telling relative difference!

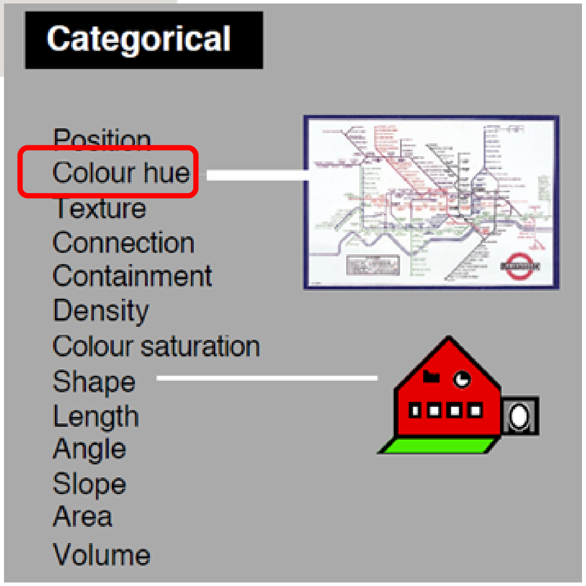
Also, similarity in **Gestalt Principles**



Is this a good place to use color? Why?



Conflict???



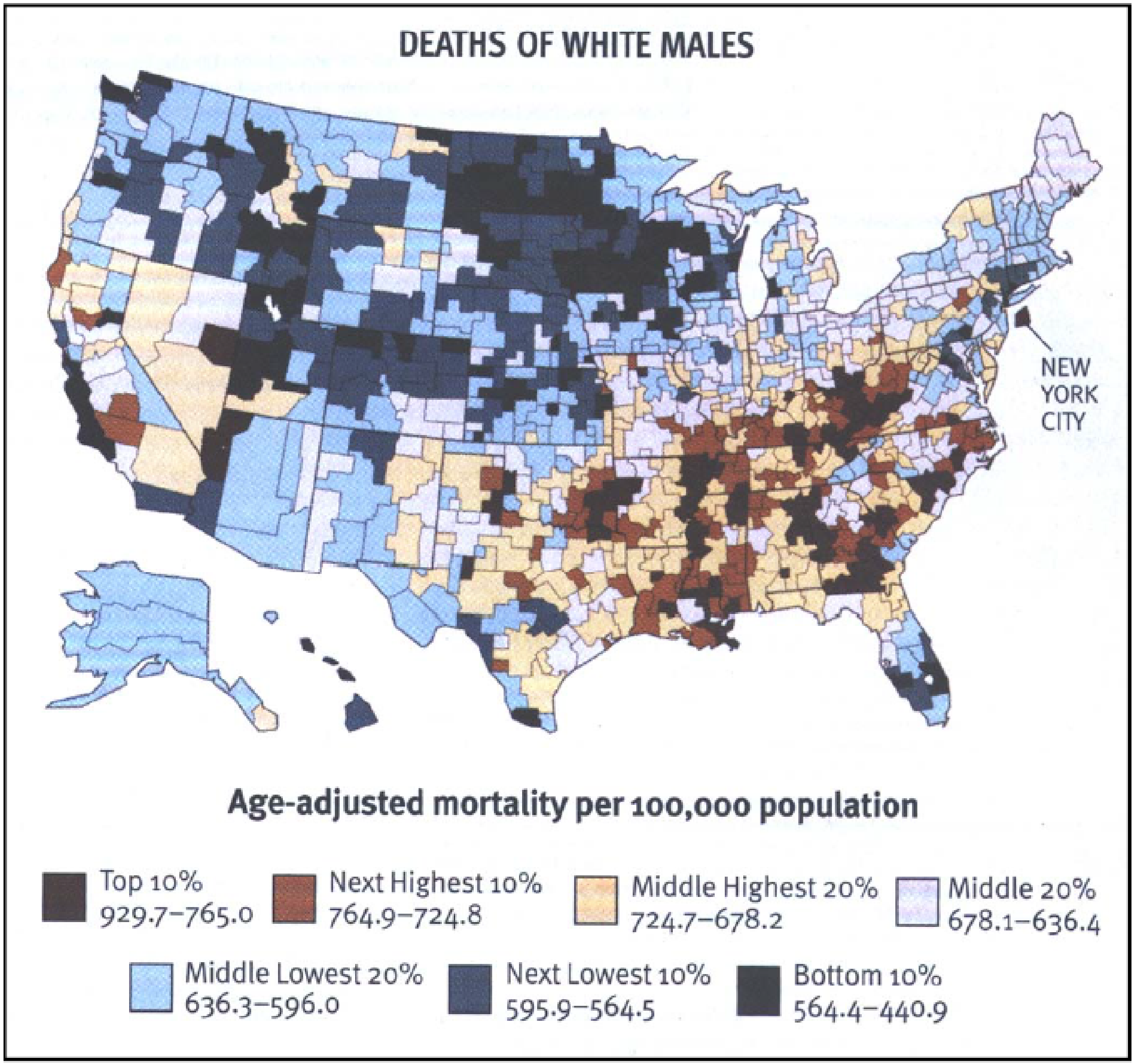
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey **quantitative** information.

Color is one of the most effective ways to **encode quantitative data defined in two-dimensional space to reveal patterns**.

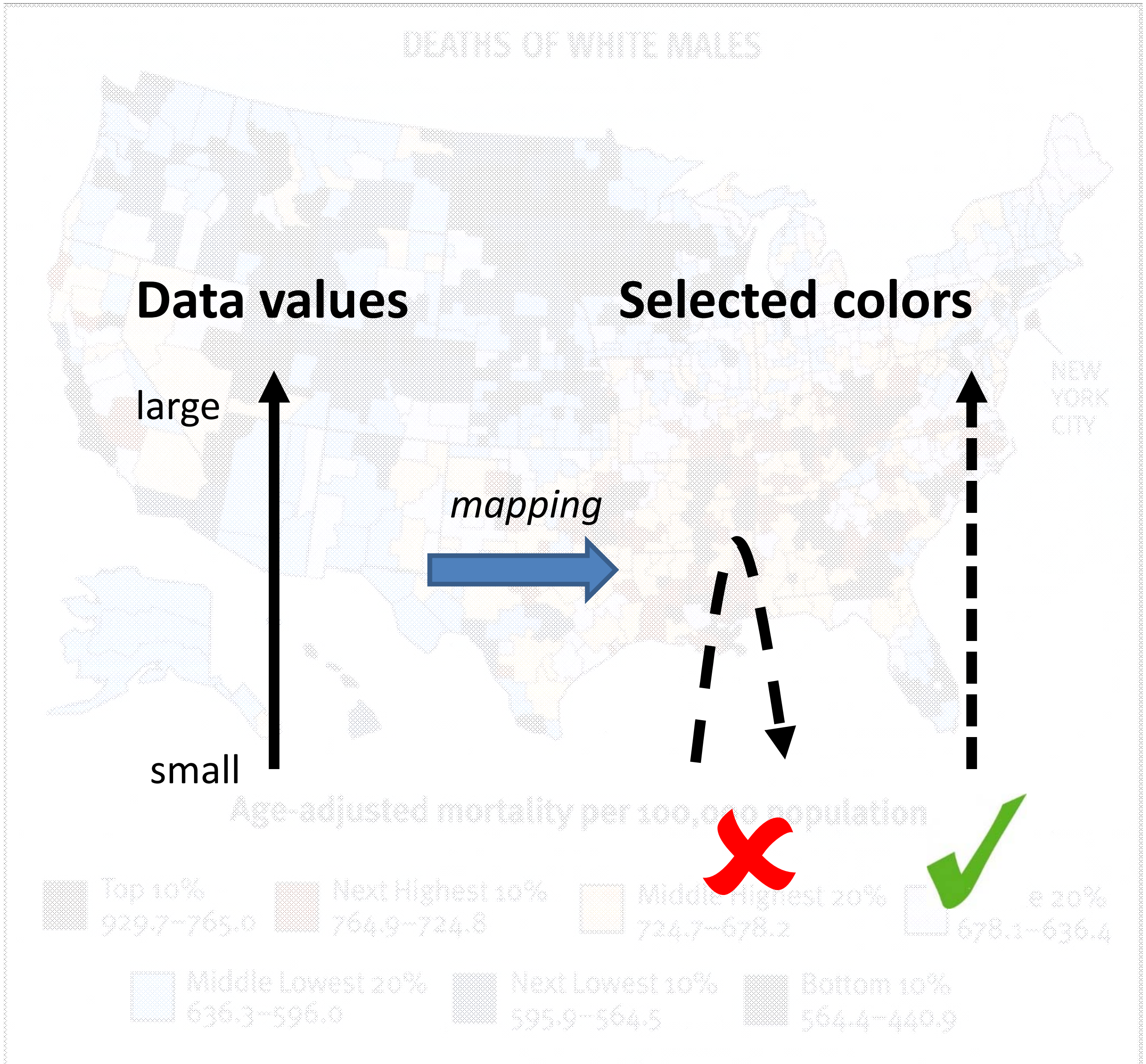
Differences in color can distinguish different categories (for example cropland, forest, or urban areas in a land cover map) or indicate quantity (percent forest cover or population).

Properly selected colors convey the underlying data accurately, in contrast to many color schemes commonly used in visualization that **distort relationships** between data values.

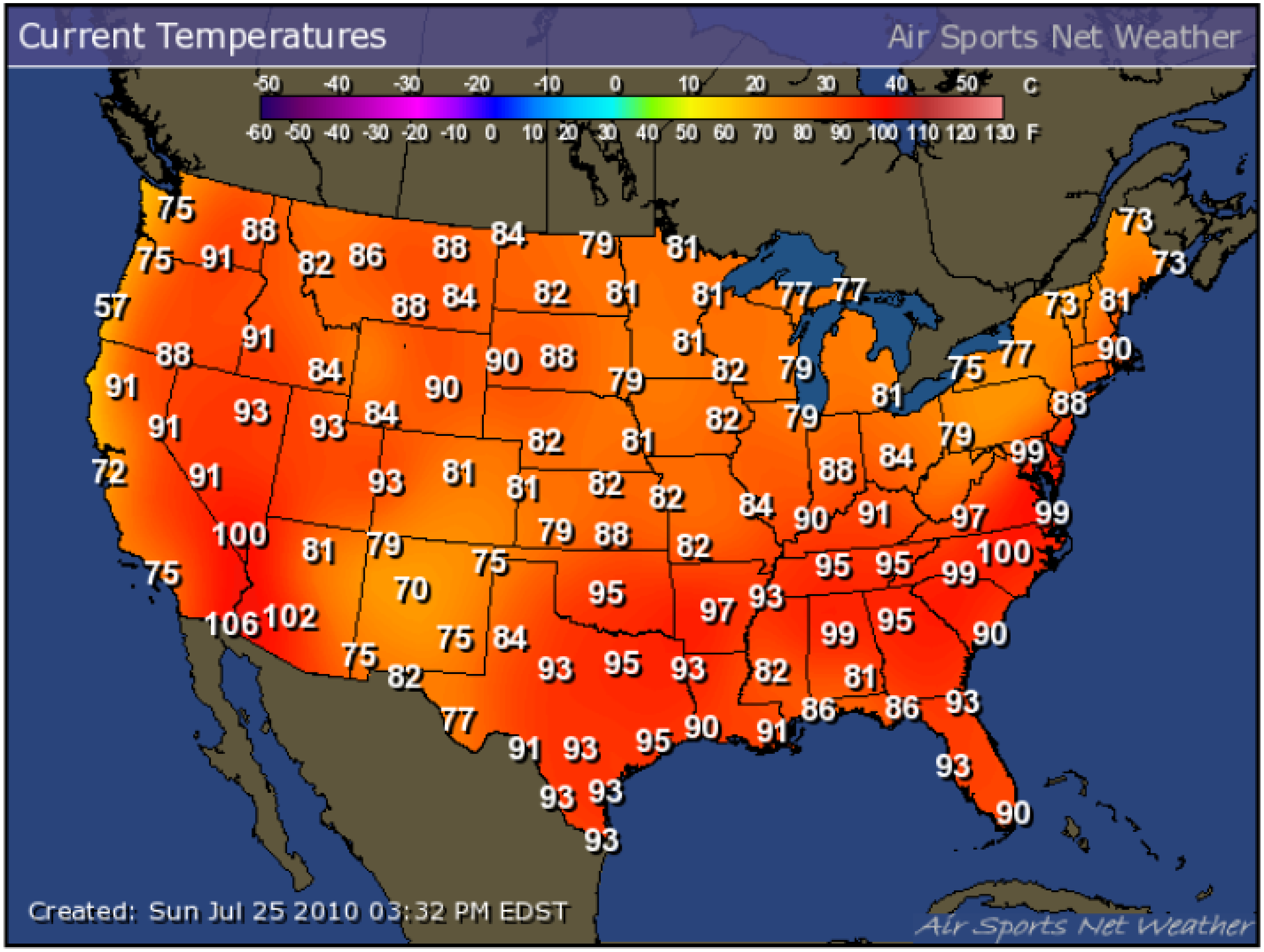
What is Wrong with this Color Scale



What is Wrong with this Color Scale



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



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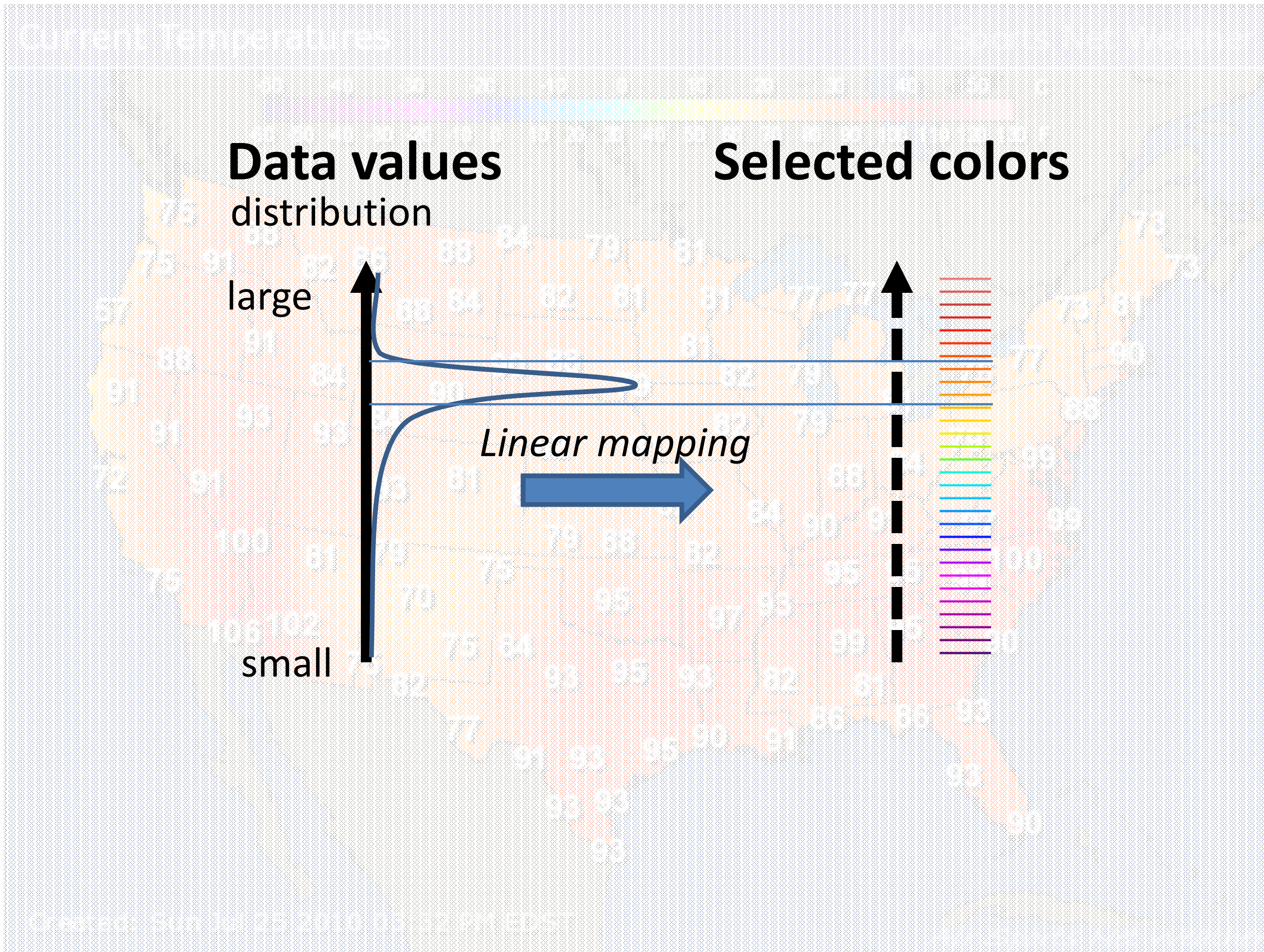
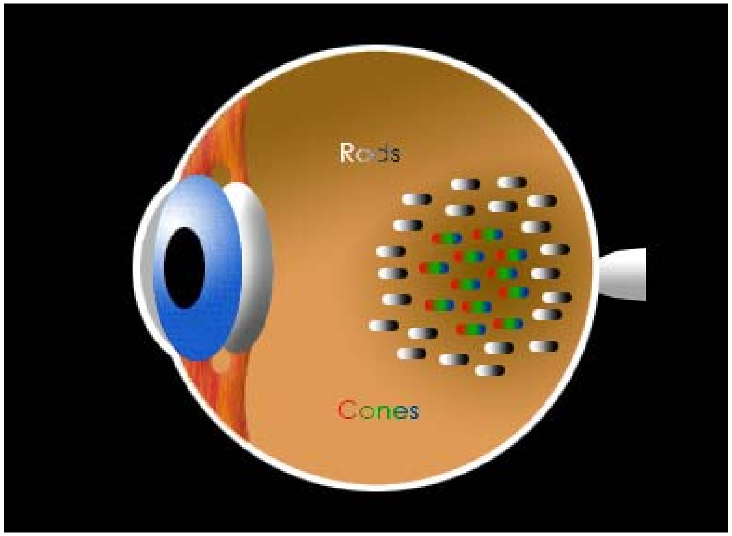


Let’s start with the most important component in a visualization system – You!

How do we see colors?

Rods

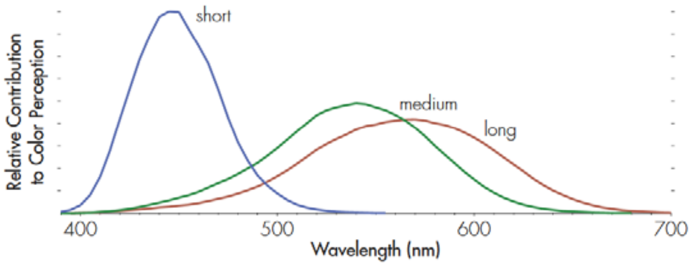
- ~115,000,000
- Concentrated on the periphery of the retina
- Sensitive to intensity
- <u>Most sensitive at 500 nm (~green)</u>



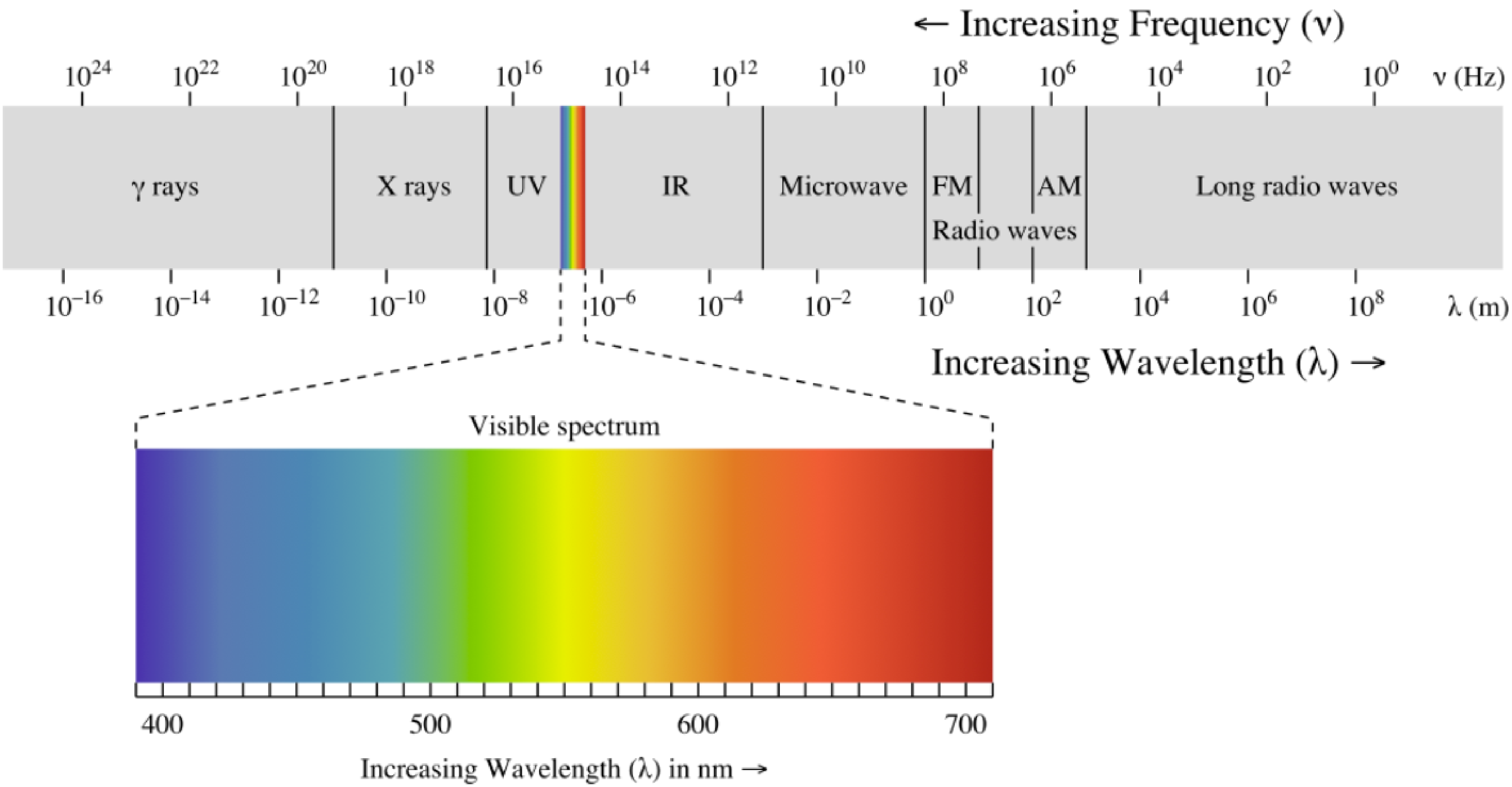
Source: starizona.com

Cones

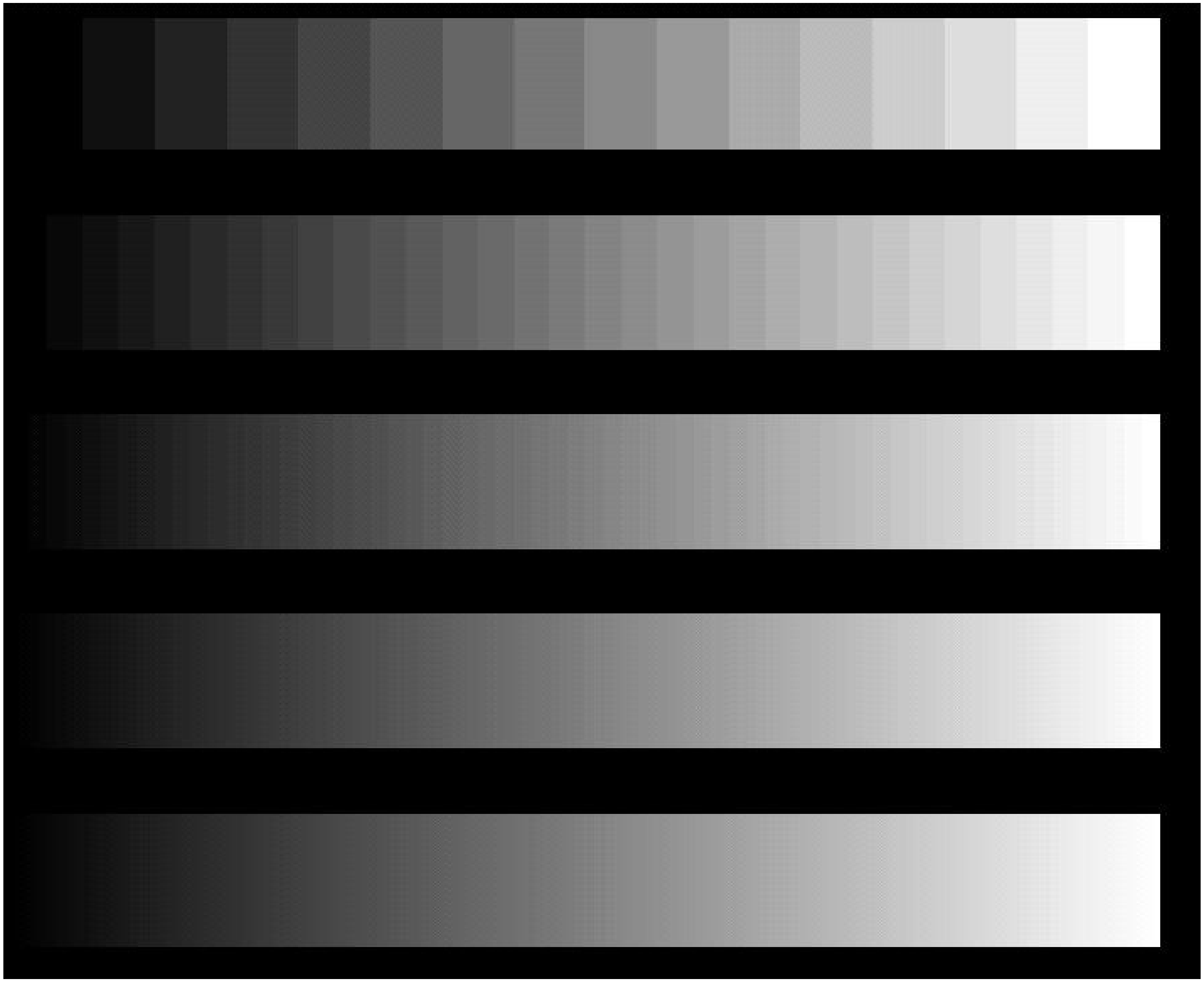
- ~7,000,000
- Concentrated near the center of the retina
- Sensitive to color
- Three lengths of cones: long(~red), medium (~green), and short (~blue) wavelengths



Visible colors to human eyes



We sense different brightness for different color hues



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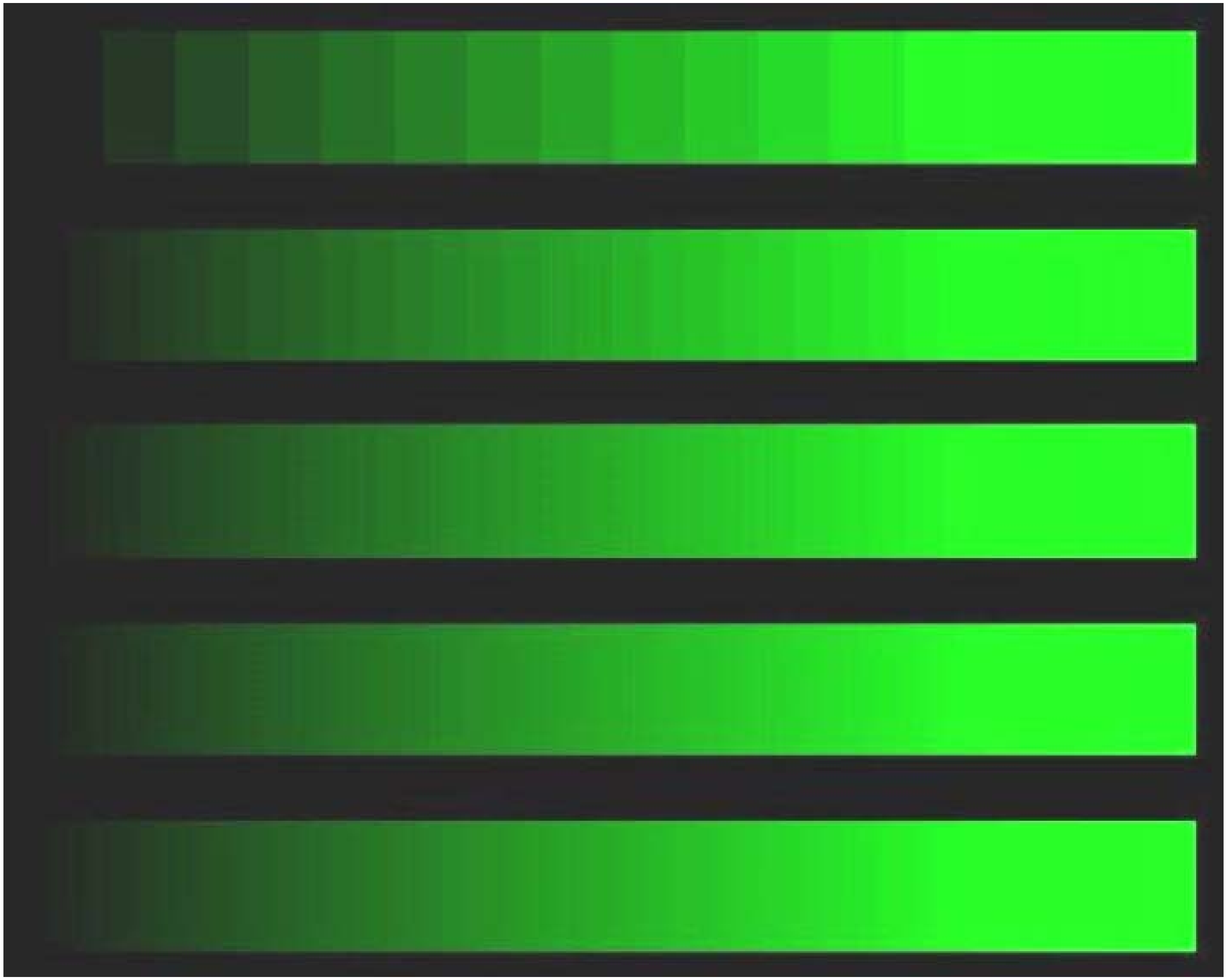

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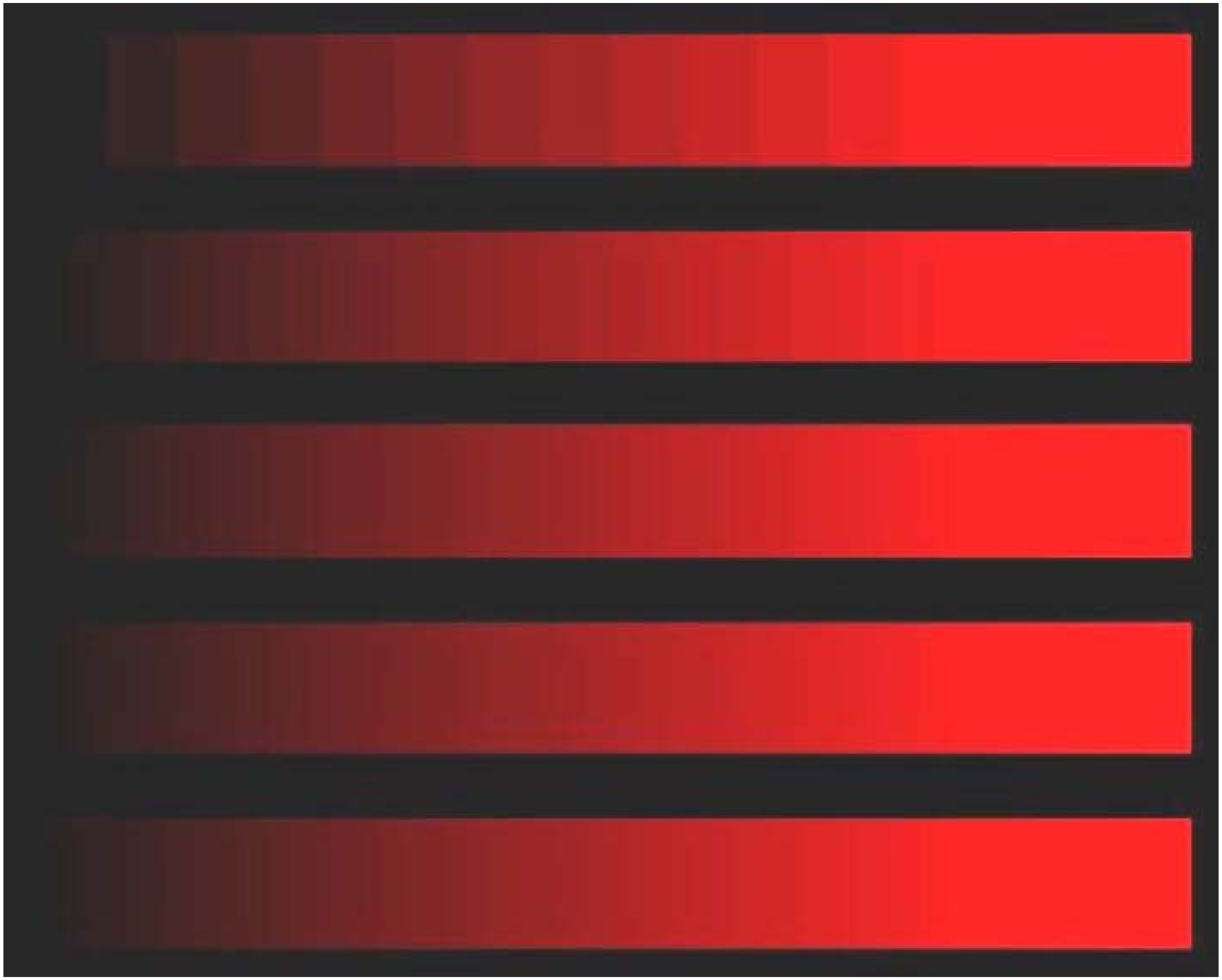

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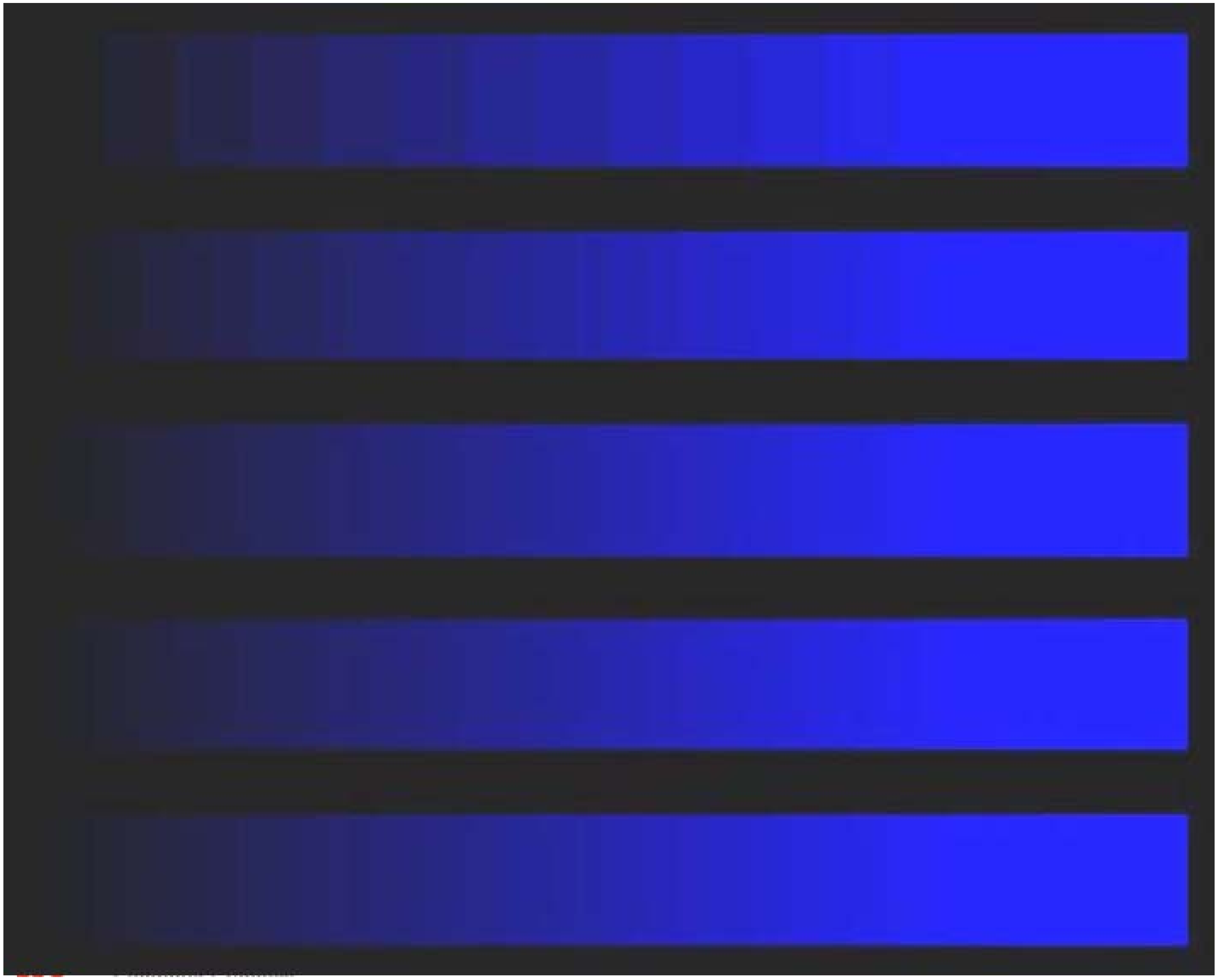
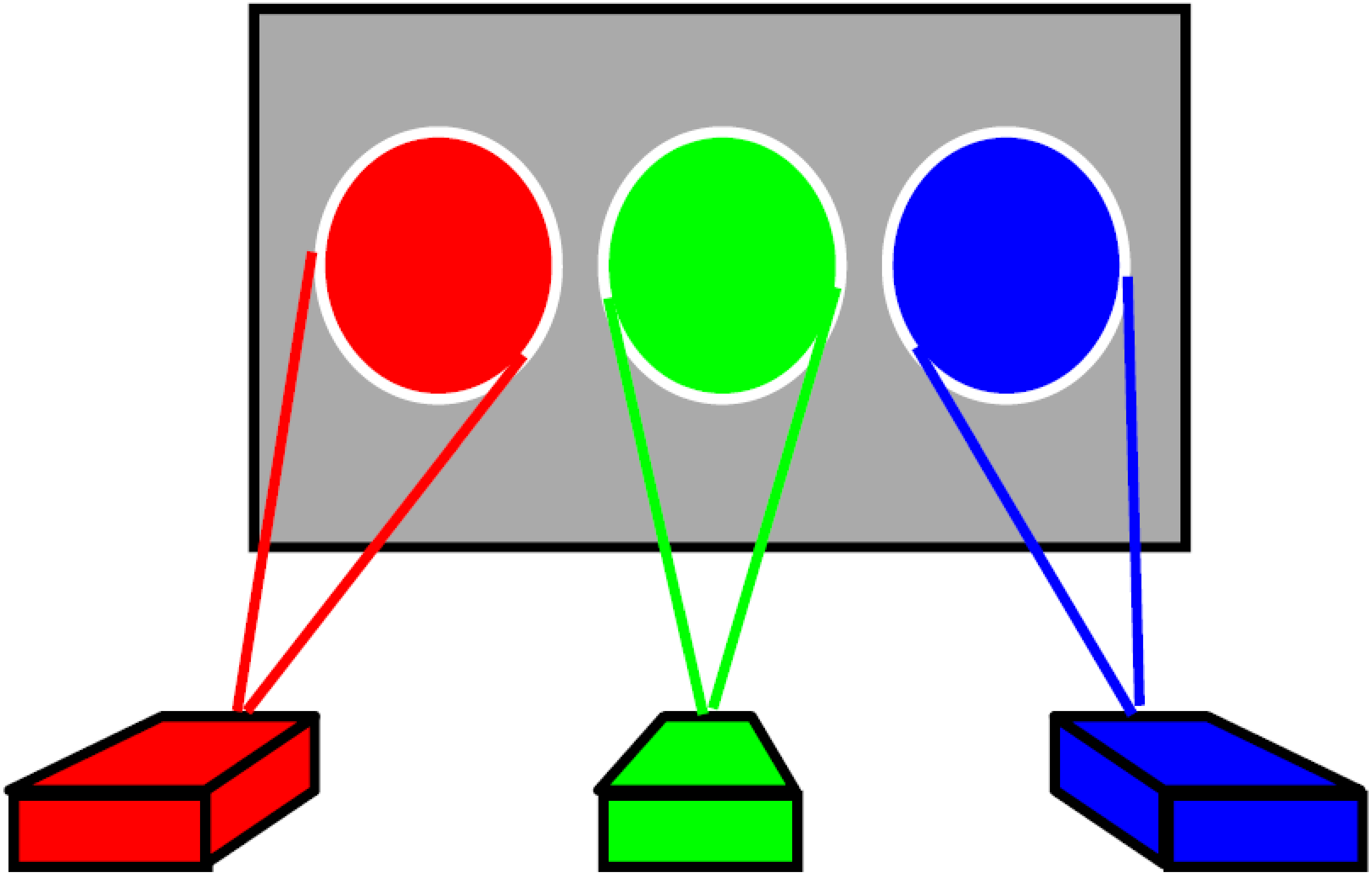


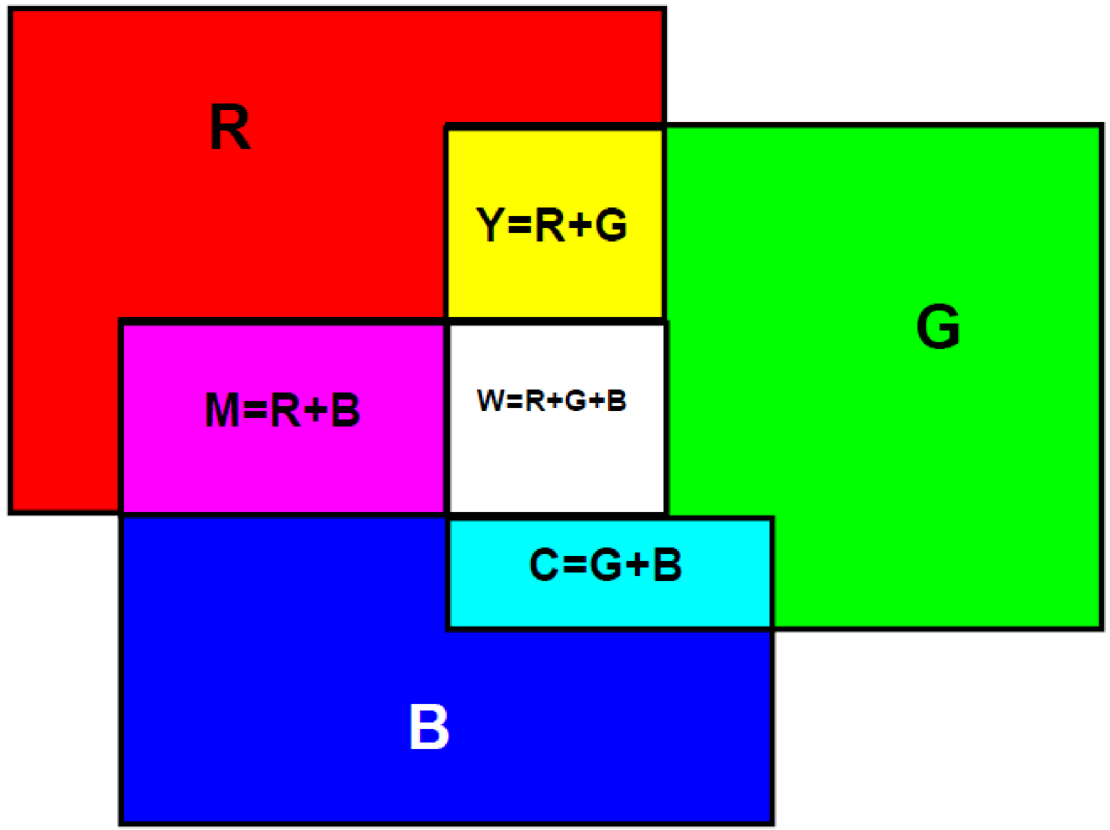
Color Models

There are only two color models!

Monitors: Additive Colors



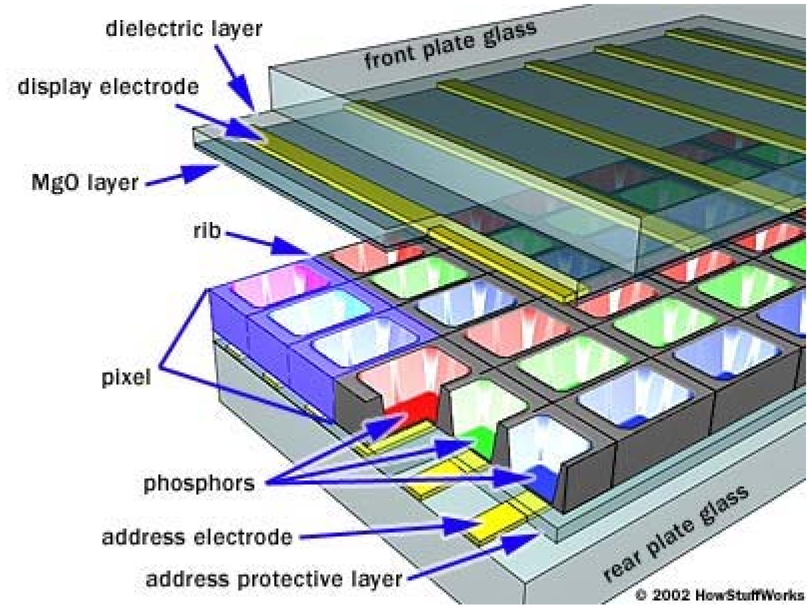
Additive Color (RGB)



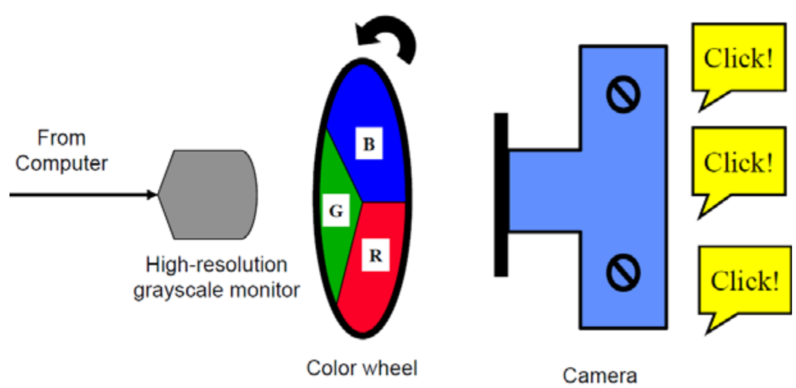
OpenGL: glColor3f (r, g, b) 0<=r, g, b <=1

What are Using Additive Color

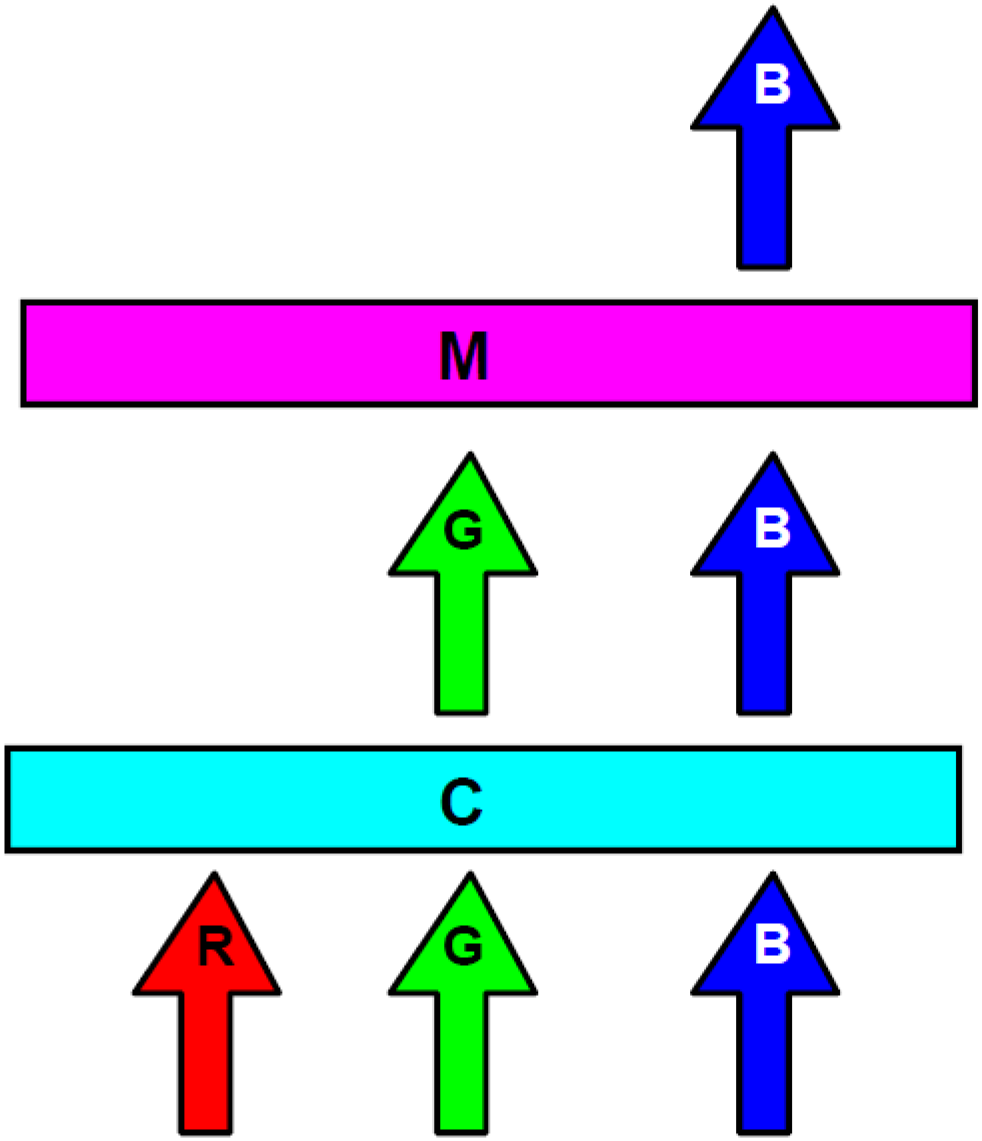
- Plasma
- LCD
- LED
- Digital film recorder

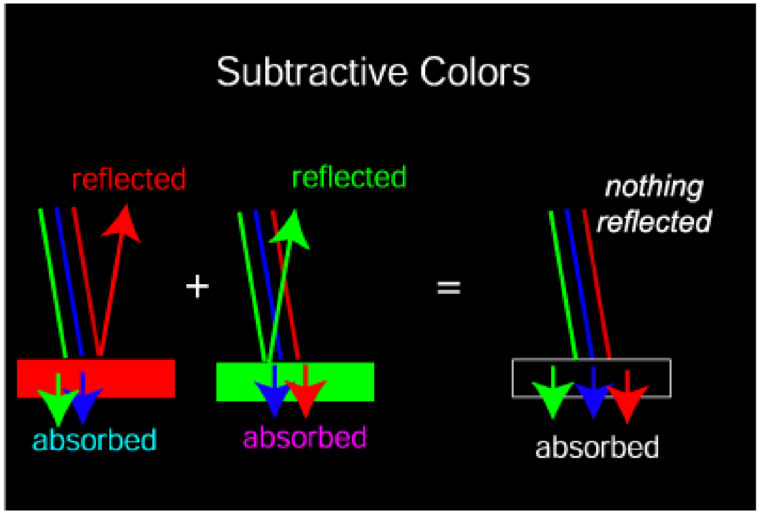


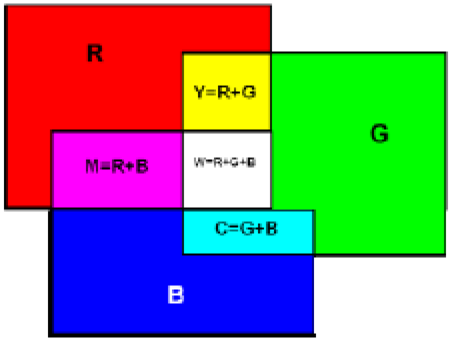
How plasma displays work



Subtractive Color (CMYK)







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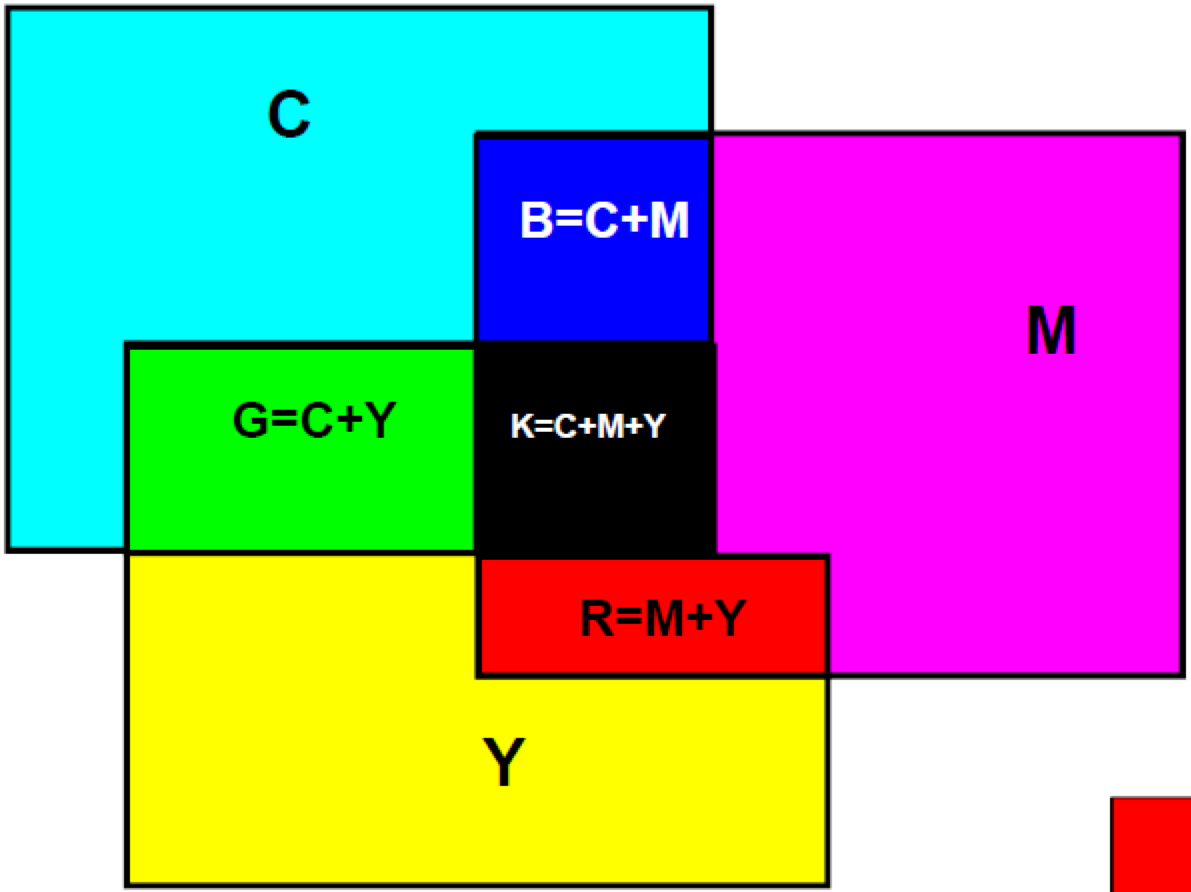
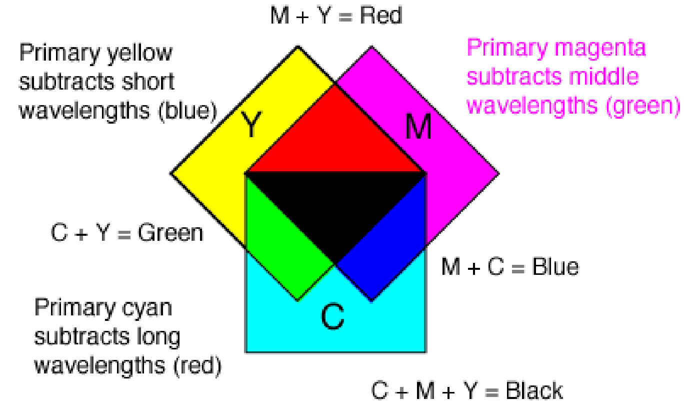
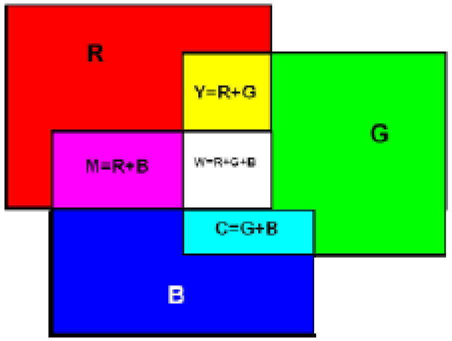




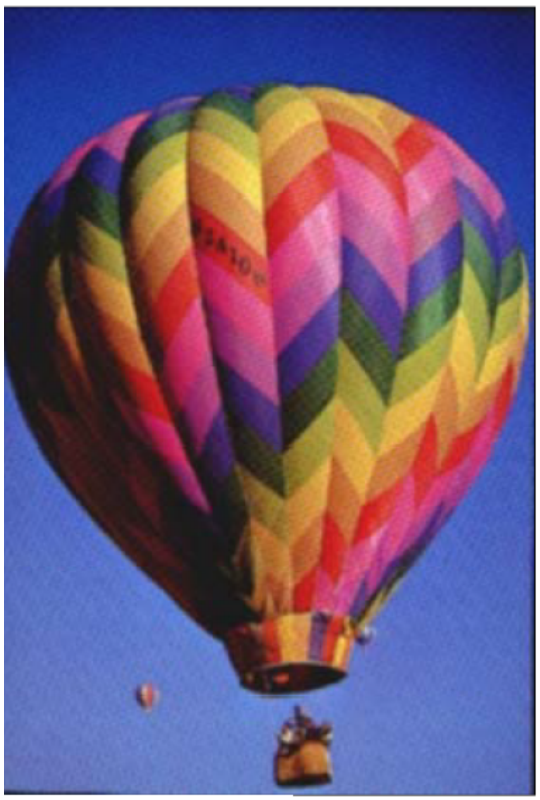
Color subtraction with idealized primary filters

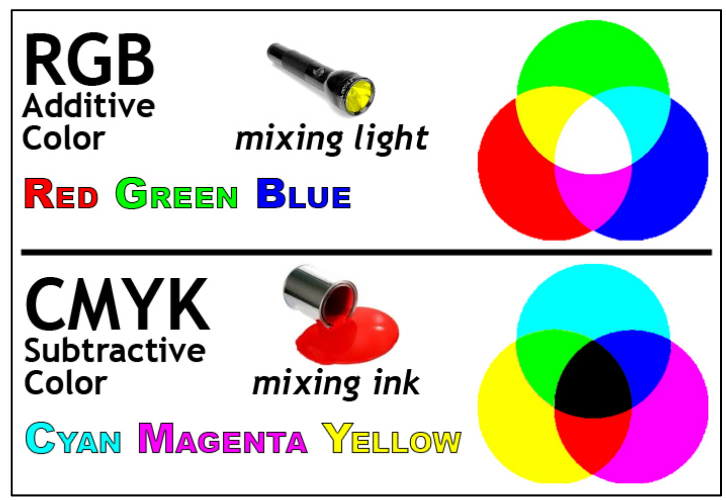
In contrast to the additive model!!



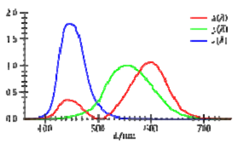
Color Printing

- Uses subtractive colors
- Uses 3 (CMY) or 4 (CMY**K**) passes (K stands for **K**ey (Blac**k**))
- CMYK printers usually have a better-looking black (with details)
- There is a considerable variation in **color *gamut*** between products



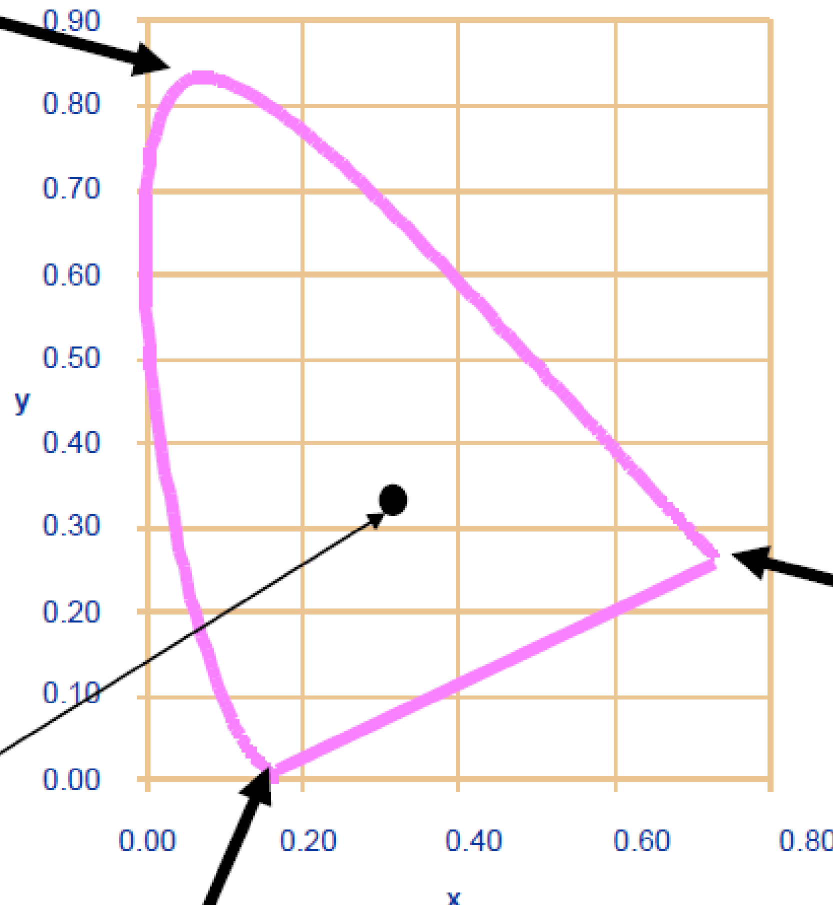


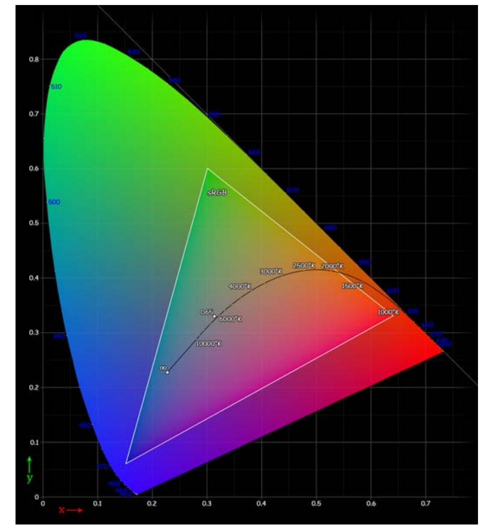
CIE Chromaticity Diagram



CIE xyY color space

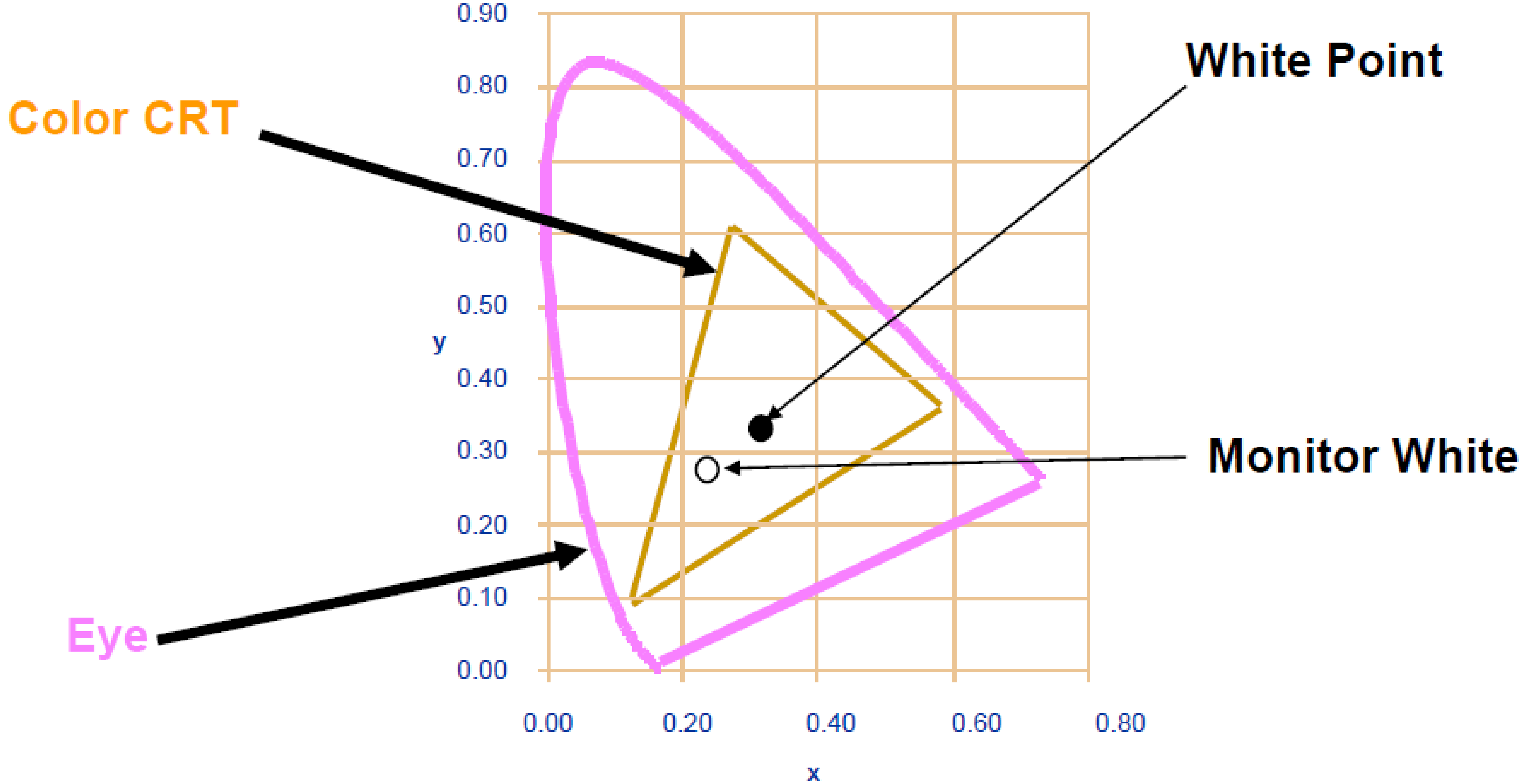
$$X = \int_{380}^{780} I(\lambda)\,\overline{x}(\lambda)\,d\lambda$$
$$Y = \int_{380}^{780} I(\lambda)\,\overline{y}(\lambda)\,d\lambda$$
$$Z = \int_{380}^{780} I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$
$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$



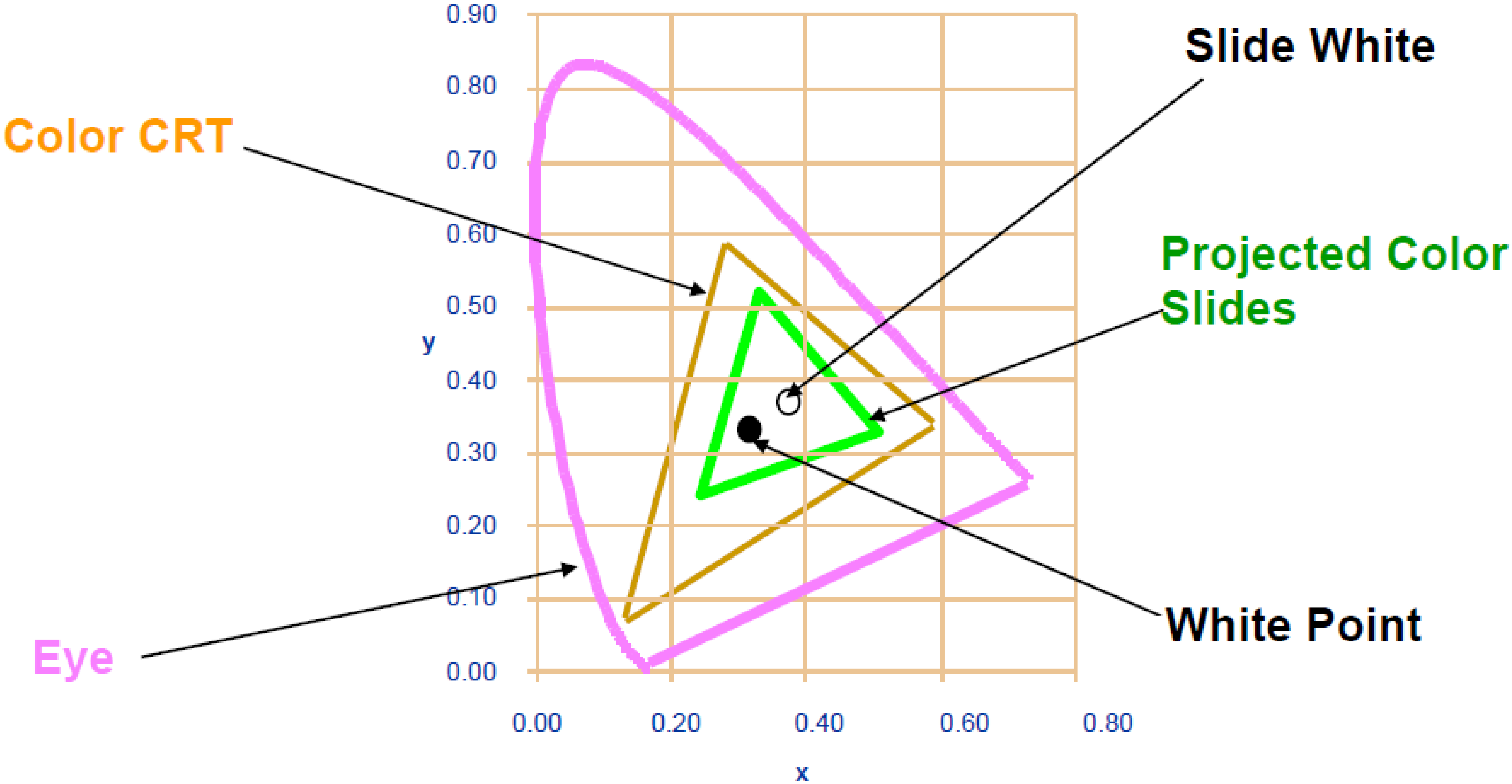


More details please see
http://en.wikipedia.org/wiki/CIE_1931_color_space
https://www.viewsonic.com/library/photography/what-is-color-gamut/

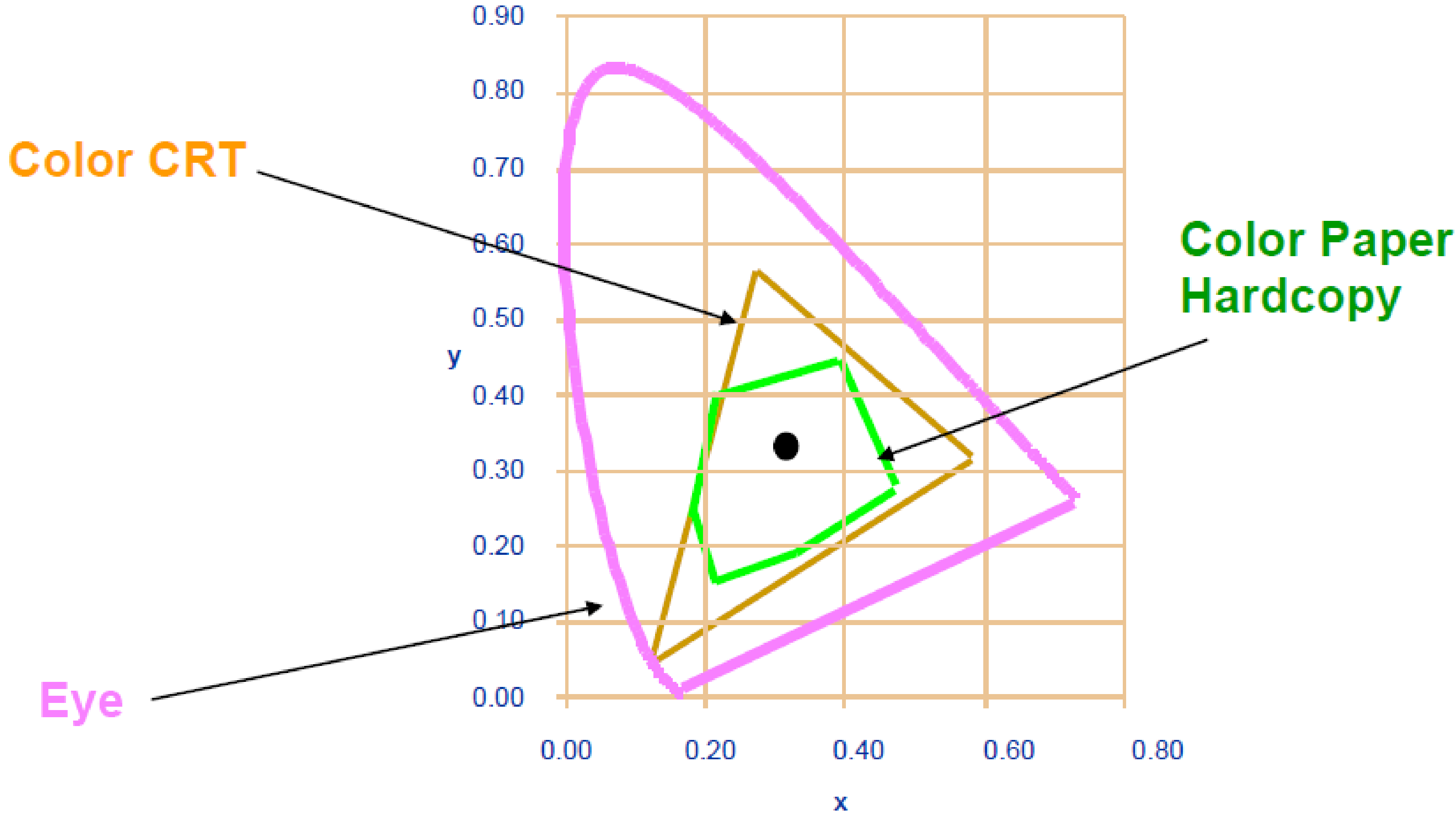
Color Gamut for a Workstation Monitor



Color Gamut for a Monitor and Color Slides



Color Gamut for a Monitor and Color Printer

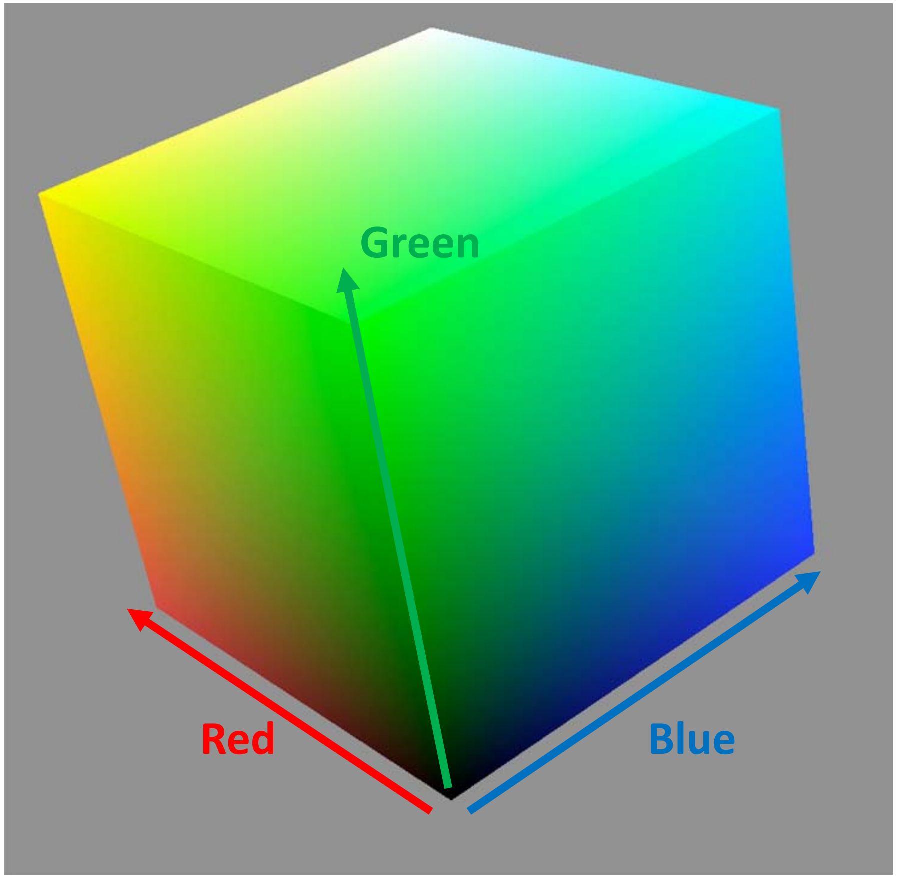


Color Spaces

Knowing different color spaces is important for choosing the right color mapping strategy!

Red-Green-Blue:

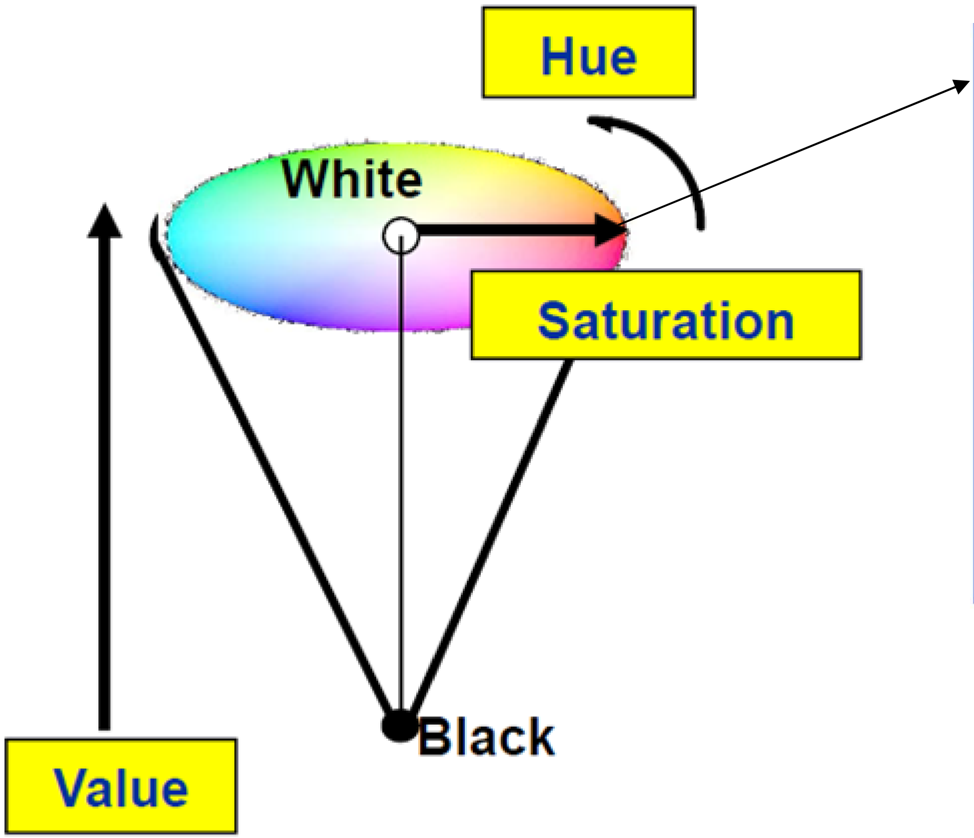
Can be easily represented by displays



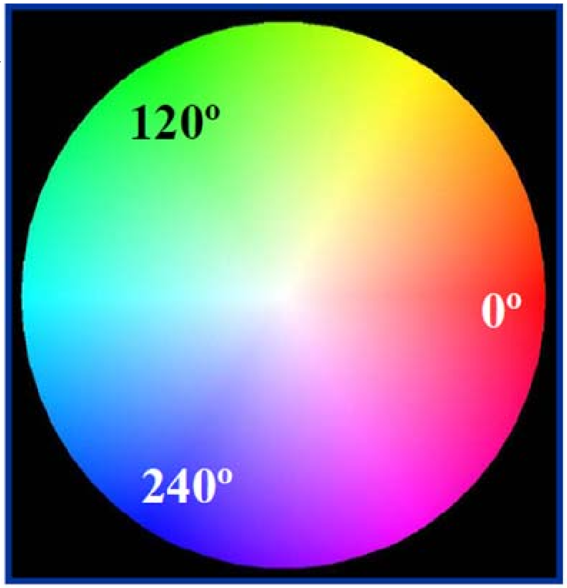
OpenGL coloring scheme

Hue-Saturation-Value:

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



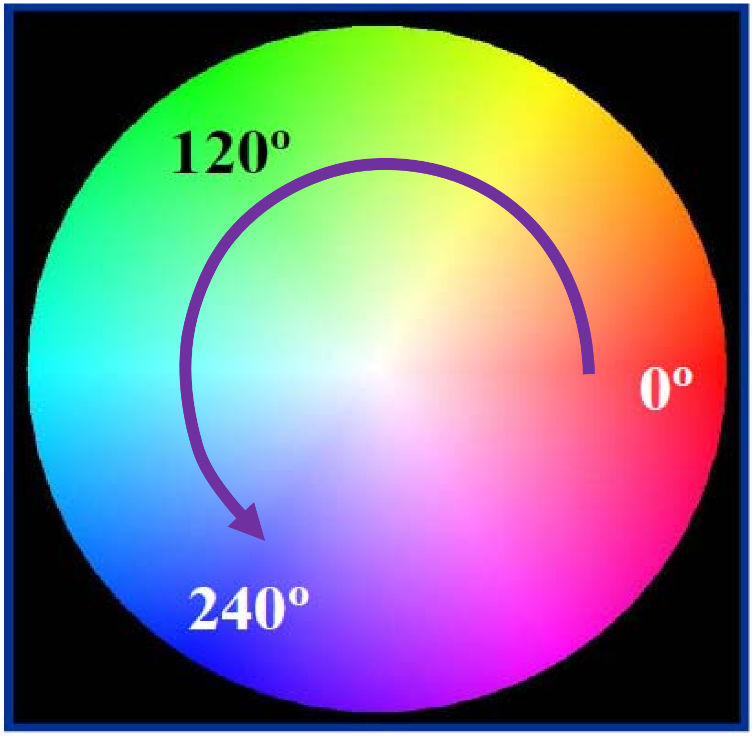
Hue disk



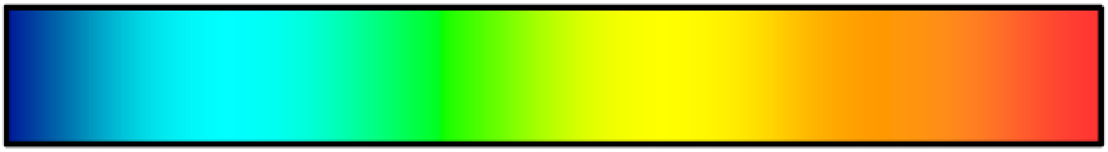
https://en.wikipedia.org/wiki/HSL_and_HSV

Hue-Saturation-Value:

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



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

Saturation=1

Value=1

HSV color → RGB color

An example of color transfer function

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

HSV to RGB

```
h = hue / 60.;
if ( h >= 6. )        h -= 6.;
if( h <  0. )         h += 6.;

s = saturation;
if( s < 0. ) s = 0.;
if( s > 1. ) s = 1.;

v = value;
if( v < 0. ) v = 0.;
if( v > 1. ) v = 1.;

if( s == 0.0 ) // if saturation=0 it is a gray color
{
     r = g = b = v;
     return;
}

i = floor( h );
f = h - i;
p = v * ( 1. - s );
q = v * ( 1. - s*f );
t = v * ( 1. - ( s * (1.-f) ) );

switch( (int) i ){
case 0:   r = v; g = t; b = p; break;
case 1:   r = q; g = v; b = p; break;
case 2:   r = p; g = v; b = t; break;
case 3:   r = p; g = q; b = v; break;
case 4:   r = t; g = p; b = v; break;
case 5:   r = v; g = p; b = q; break;
}
```

// validate input values

For your reference!

RGB to HSV

```
V = M = max(R, G, B);

m = min(R, G, B);

S = (M – m)/M;

if (R==M) h = (G-B)/(M-m);

if (G==M) h = 2 + (B-R)/(M-m);

if (B==M) h = 4 + (R-G)/(M-m);


if (h<0) H = h/6 + 1;

if (h>0) H = h/6;
```

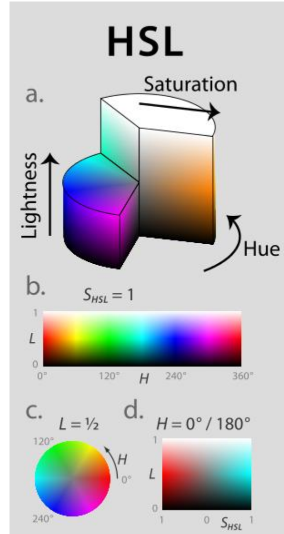
DO NOT MEMERIZE THIS!

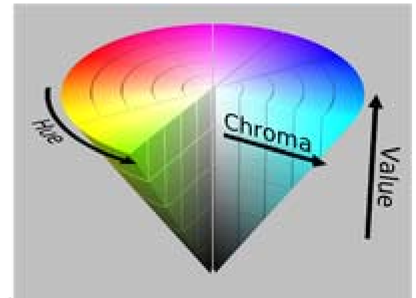
For your reference!

Hue-Saturation-Lightness:

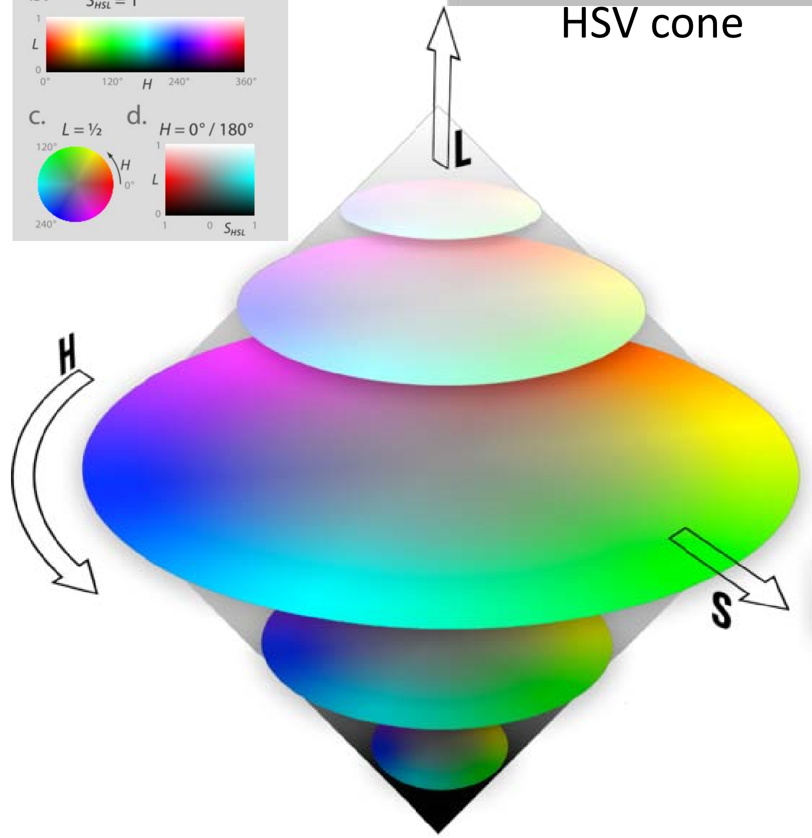
Similar to HSV but different

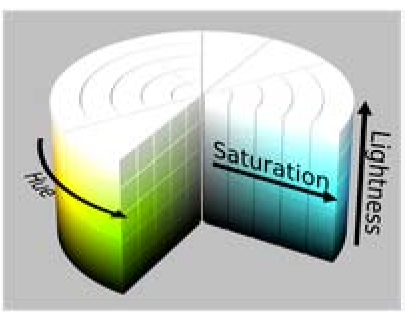
- Hue is a degree on the color wheel; 0 (or 360) is red, 120 is green, 240 is blue. Numbers in between reflect different shades.
- Saturation is a percentage value; 100% is the full color.
- Lightness is also a percentage; 0% is dark (black), 100% is light (white), and 50% is the average.

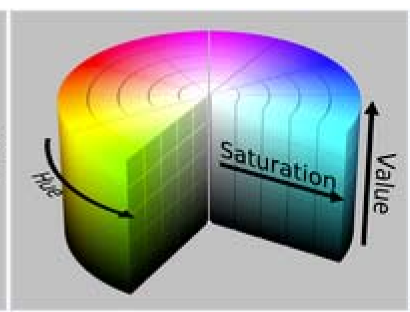




HSV cone







HSL HSV

https://en.wikipedia.org/wiki/HSL_and_HSV

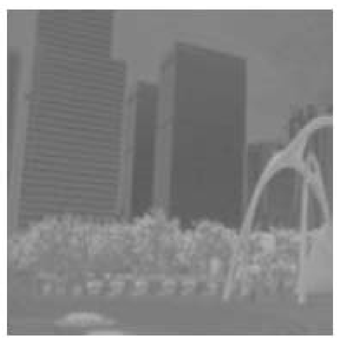
CIELab:

- L for luminance
- a for red-green
- b for yellow-blue

Lab

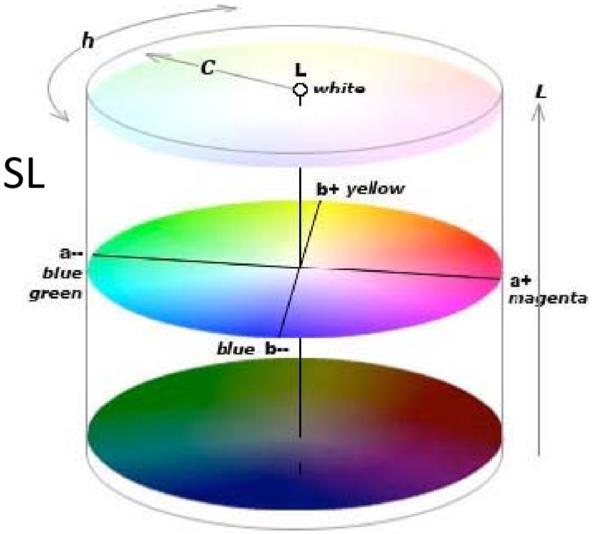
Luminance

a (red - green)

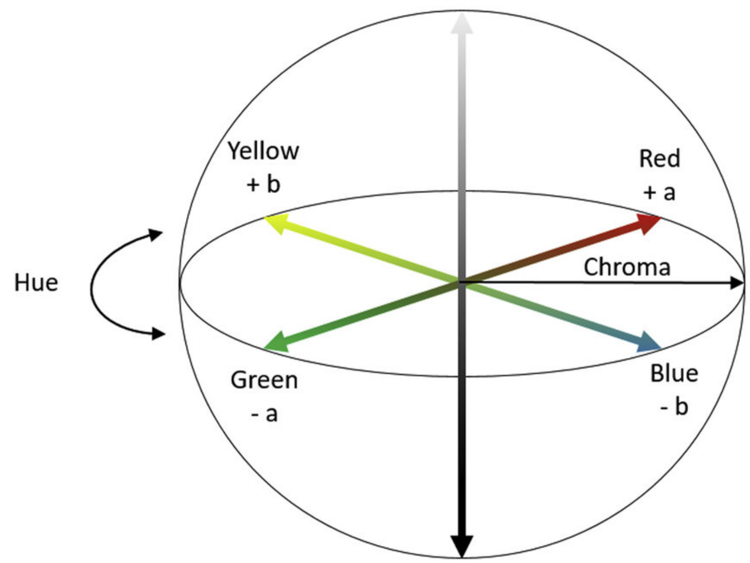


b (yellow - blue)

HSL



L = 100
(White)



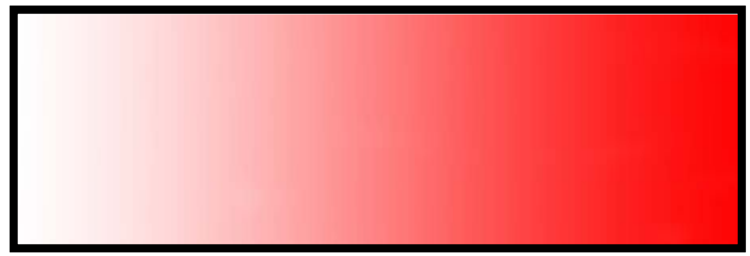
L = 0
(Black)

https://en.wikipedia.org/wiki/CIELAB_color_space

Use the right **Color Transfer Function** to represent different information

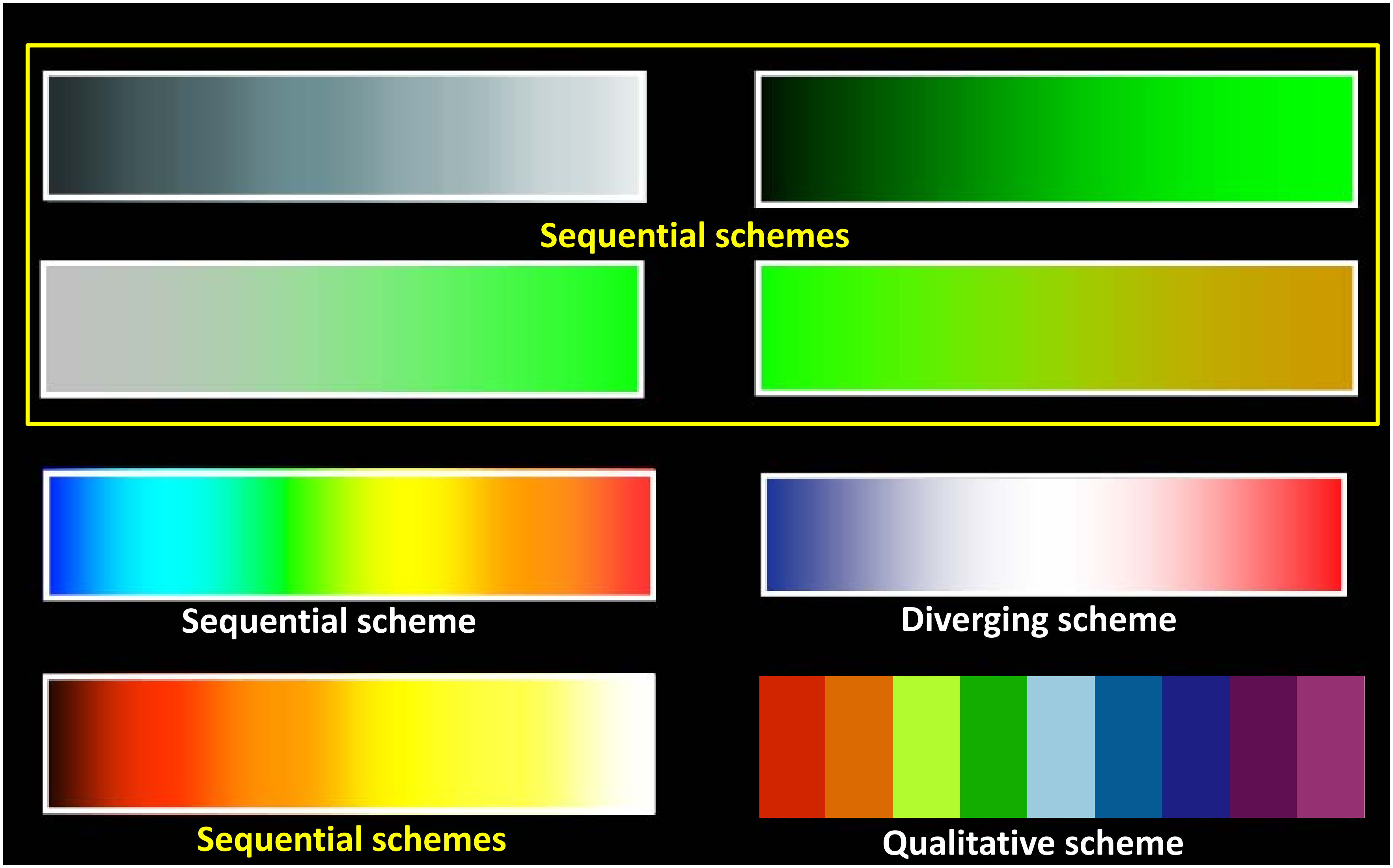
Hue: categorical

Saturation: ordinal and quantitative

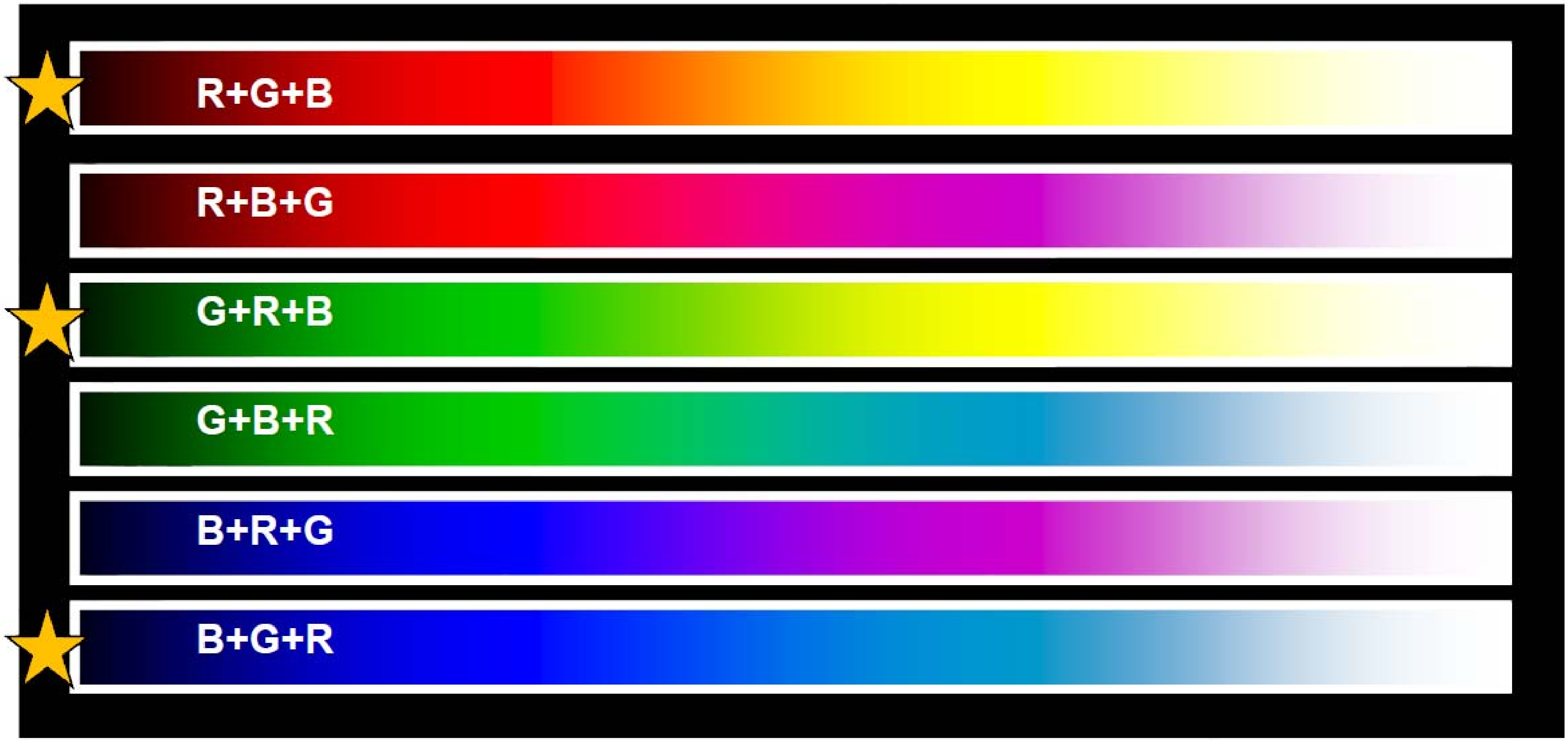


Luminance: ordinal and quantitative
Or brightness

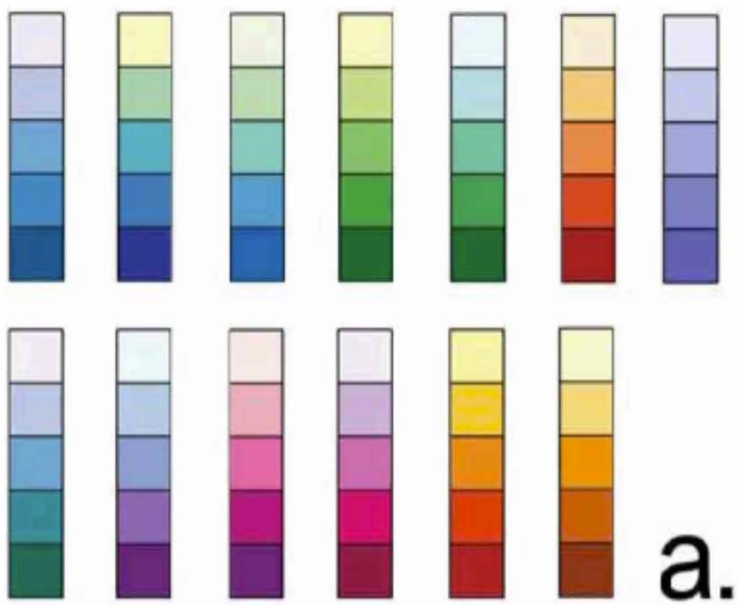
Different Types of Color Scales

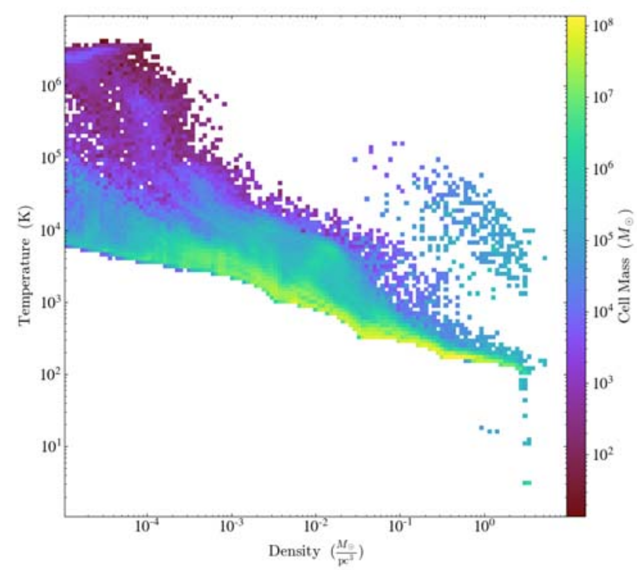


Using RGB color space to generate **sequential** color scheme
-- Add-One-Component at a time

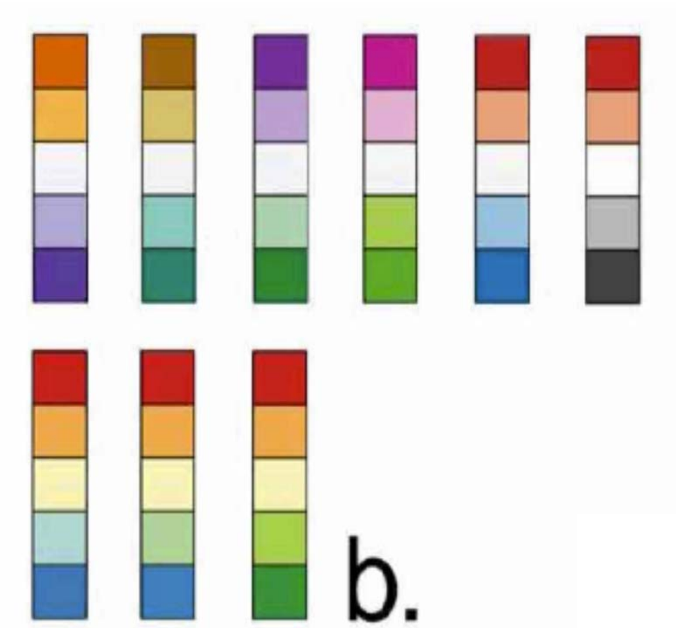


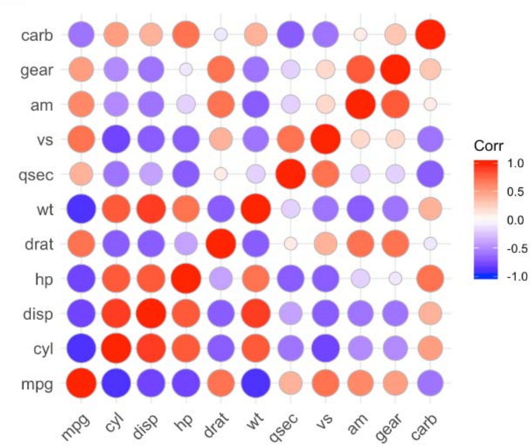
Other Sequential Color Schemes



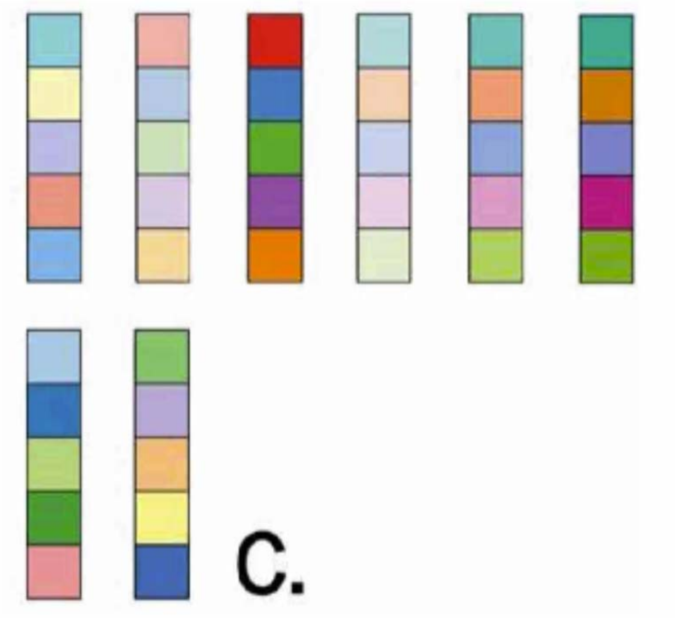


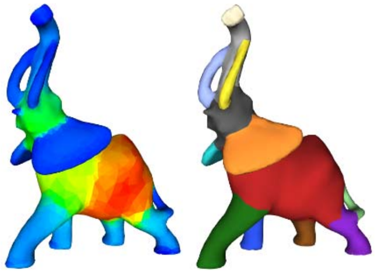
Other Divergence Color Schemes

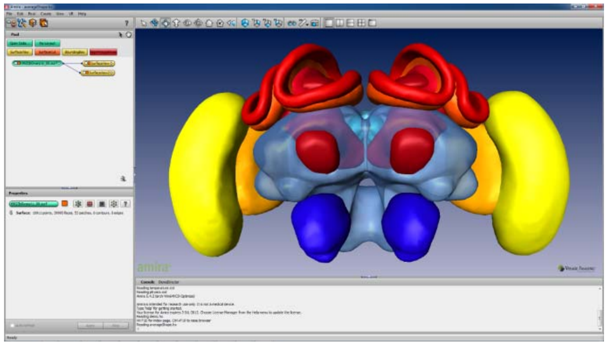


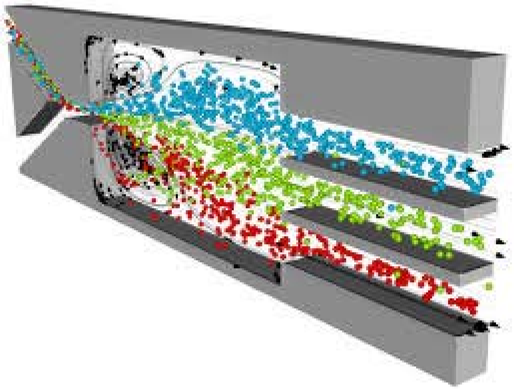


Other Qualitative Color Schemes





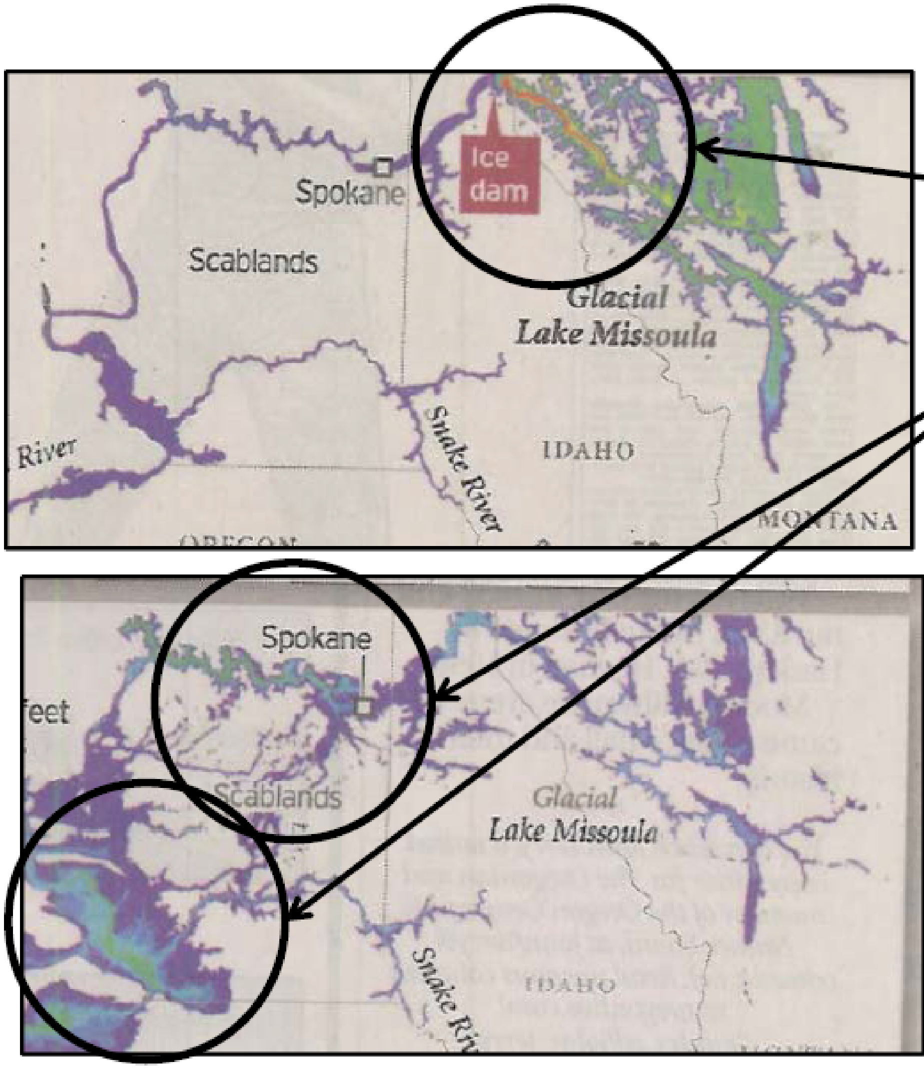




For visualizing <u>quantitative information</u>, Here is What Really Important

Given any 2 colors, make it *intuitively obvious* which color represents “higher” and which represents “lower”

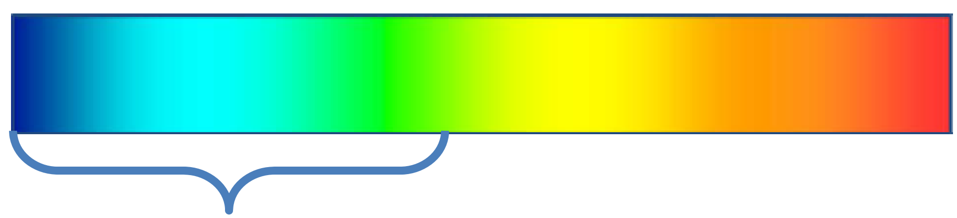
Pay attention to the dynamic range issue.



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

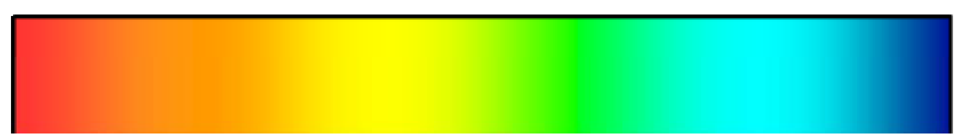
As-shown:

< 150 | 1050 | 1650



I'd like to try:

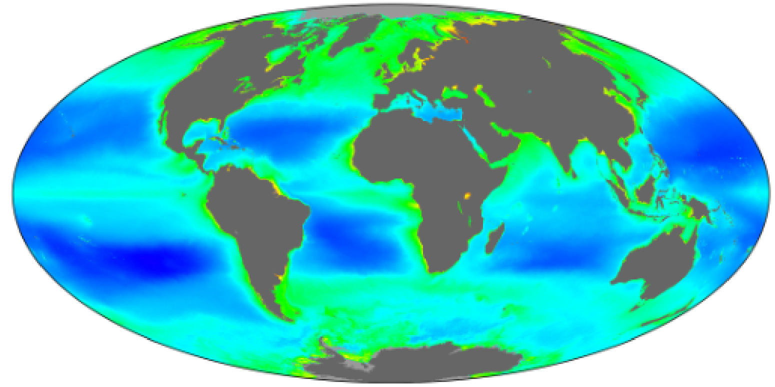
< 150 | 700 | > 1200



Issues with some common color schemes

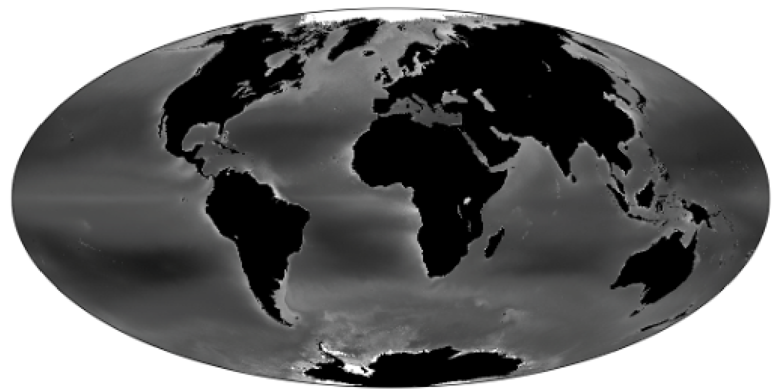
Transitions between some colors, green and red, for example, occur very rapidly **VISUALLY**, leading to false contrast. Other transitions, especially green to blue, are gradual, and there is a loss of detail. Rainbow palettes have another deficiency: because the overall brightness of the colors increases and decreases over the range of hues there is no natural progression of values.

Rainbow palette



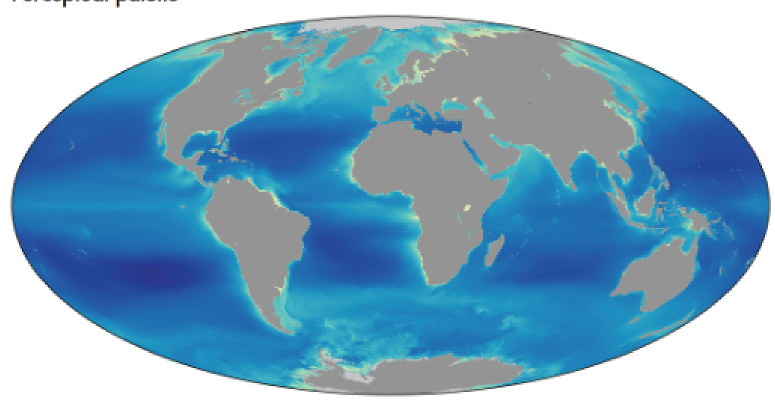
An alternative is to only use brightness, not color, to encode value, but surrounding tones can significantly alter the perceived values
of pixels. Grayscale palettes are best limited to black and white reproductions.

Grayscale palette



A better approach is to use a color scheme that spirals through a perceptual color space, with each step equally different in hue, saturation,
and brightness.

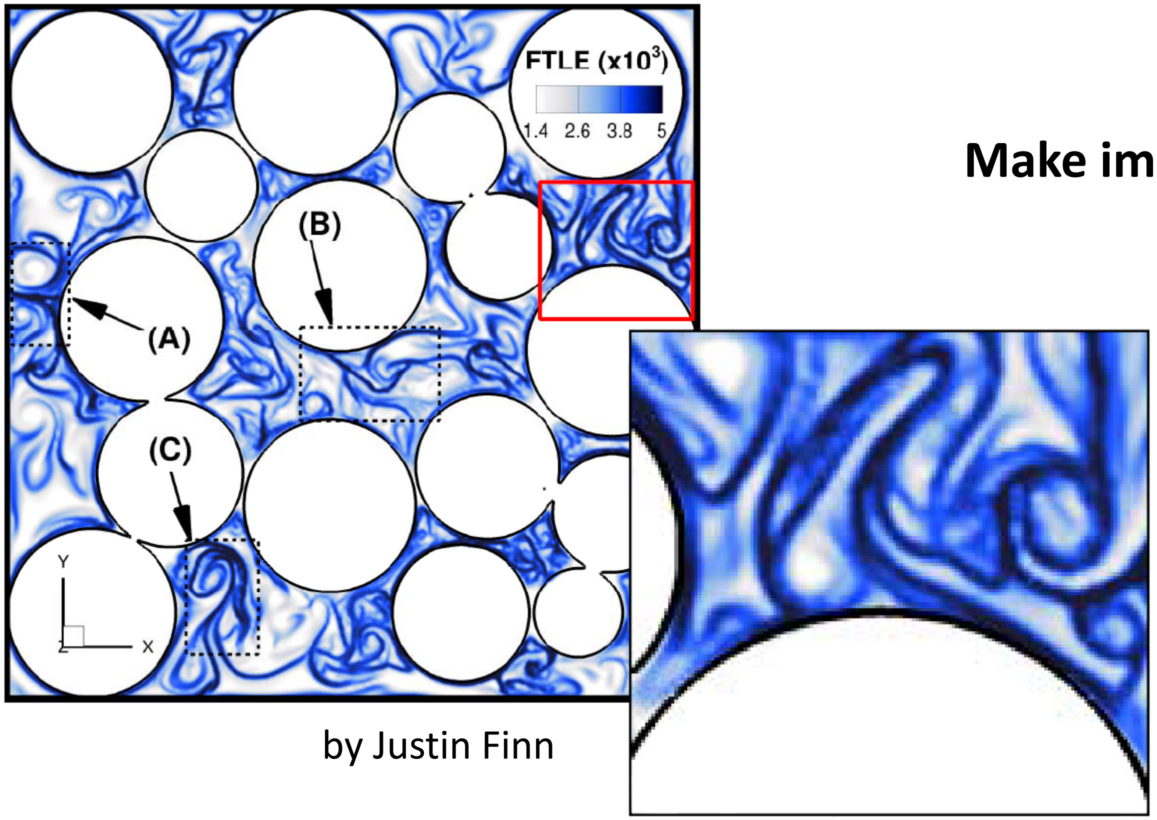
Perceptual palette



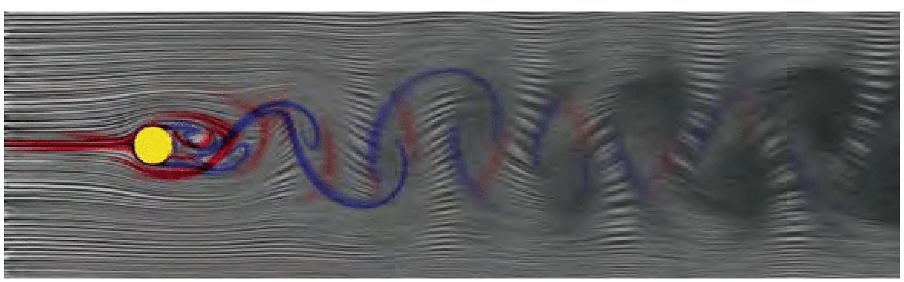
https://programmingdesignsystems.com/color/perceptually-uniform-color-spaces/

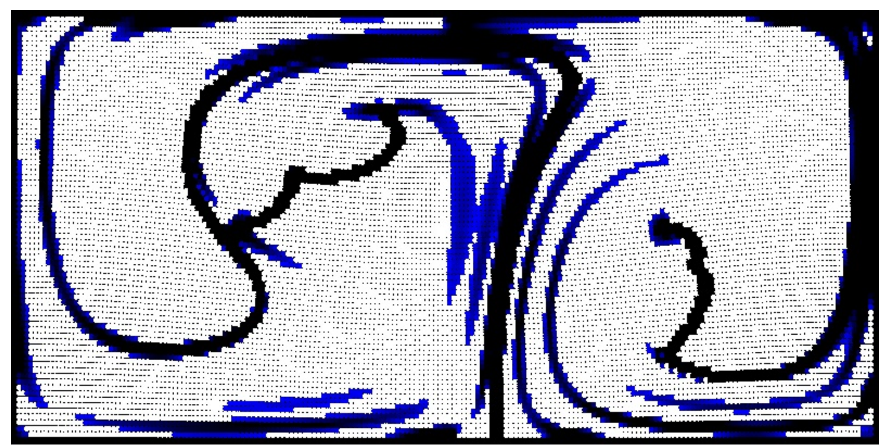
Importance of contrast

Make important features pop up!



by Justin Finn





by Wei Cao

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 gray scale photocopy of your color hardcopy

Color Alone Doesn't Cut It

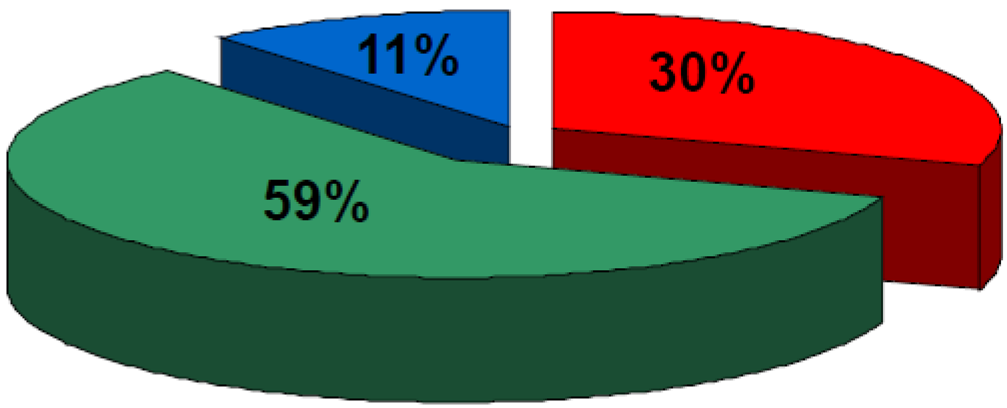
I sure hope that my life does not depend on being able to read this quickly and accurately!

Luminance Contrast is Crucial

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

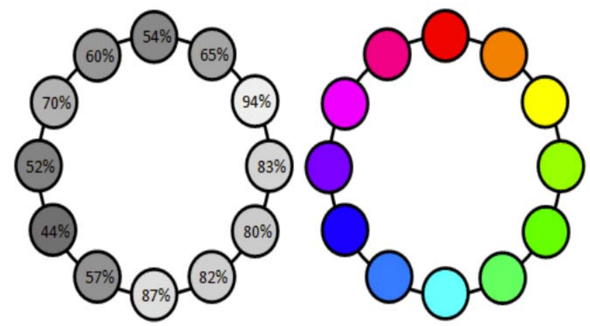
The Luminance Equation

$$Y = 0.3 \times Red + 0.59 \times Green + 0.11 \times Blue$$



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



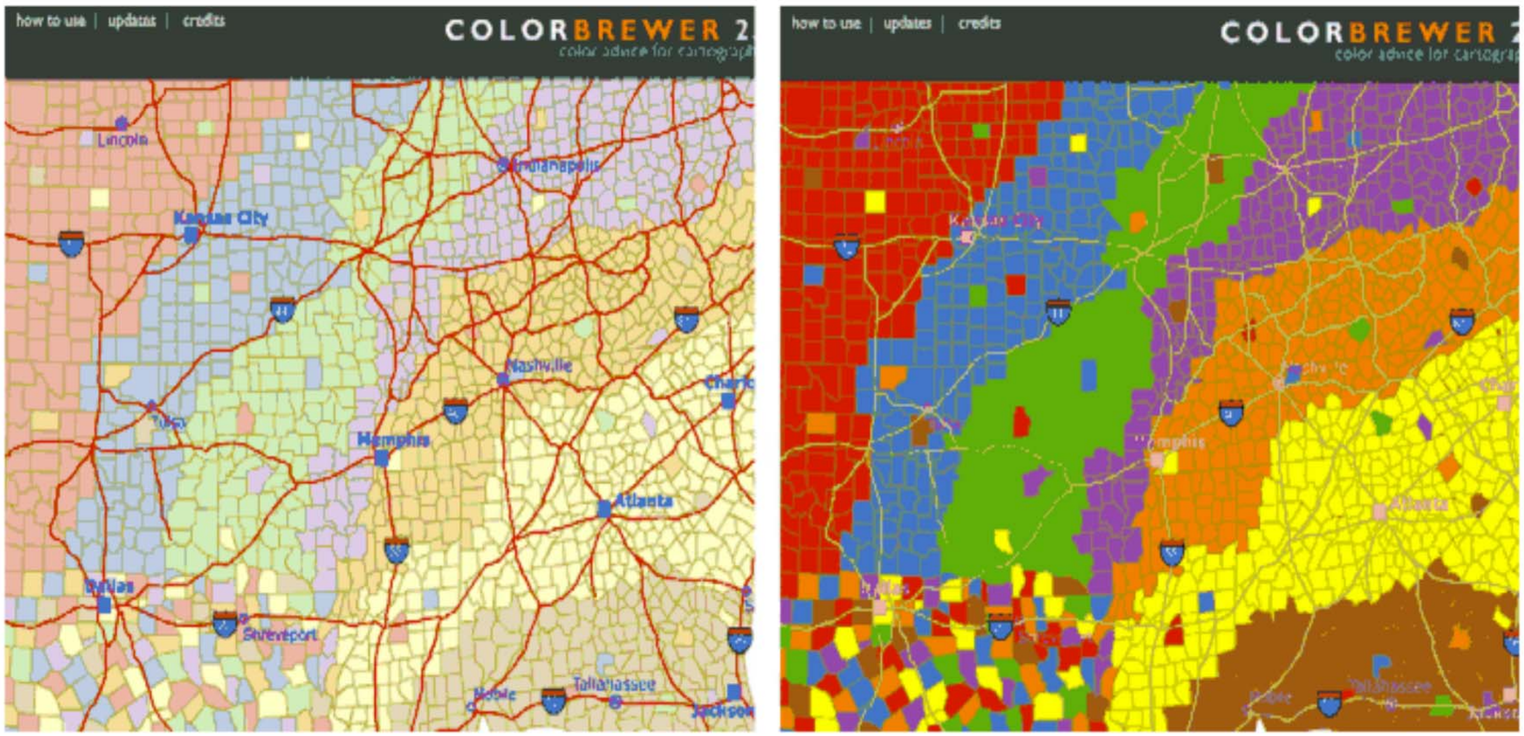
≈ Contrast Table

	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

ΔL* of about 0.40 are highlighted and recommended

	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

Importance of using proper contrast of colors in visualization



Highlighting: make small subset clearly distinct from the rest

Some useful guidelines

- Use more saturated colors for **small** symbols, thin lines, or small areas (maybe important).
- Use less saturated colors for large areas (background, context…)

Some Good Rules of Thumb
When Using Colors for Visualization

Do Not Attempt to Fight Pre-Established Color Meanings

Pre-Established Color Meanings

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

Limit the Total Number of Colors if viewers are to <u>Discern Information Quickly</u>

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 • • •

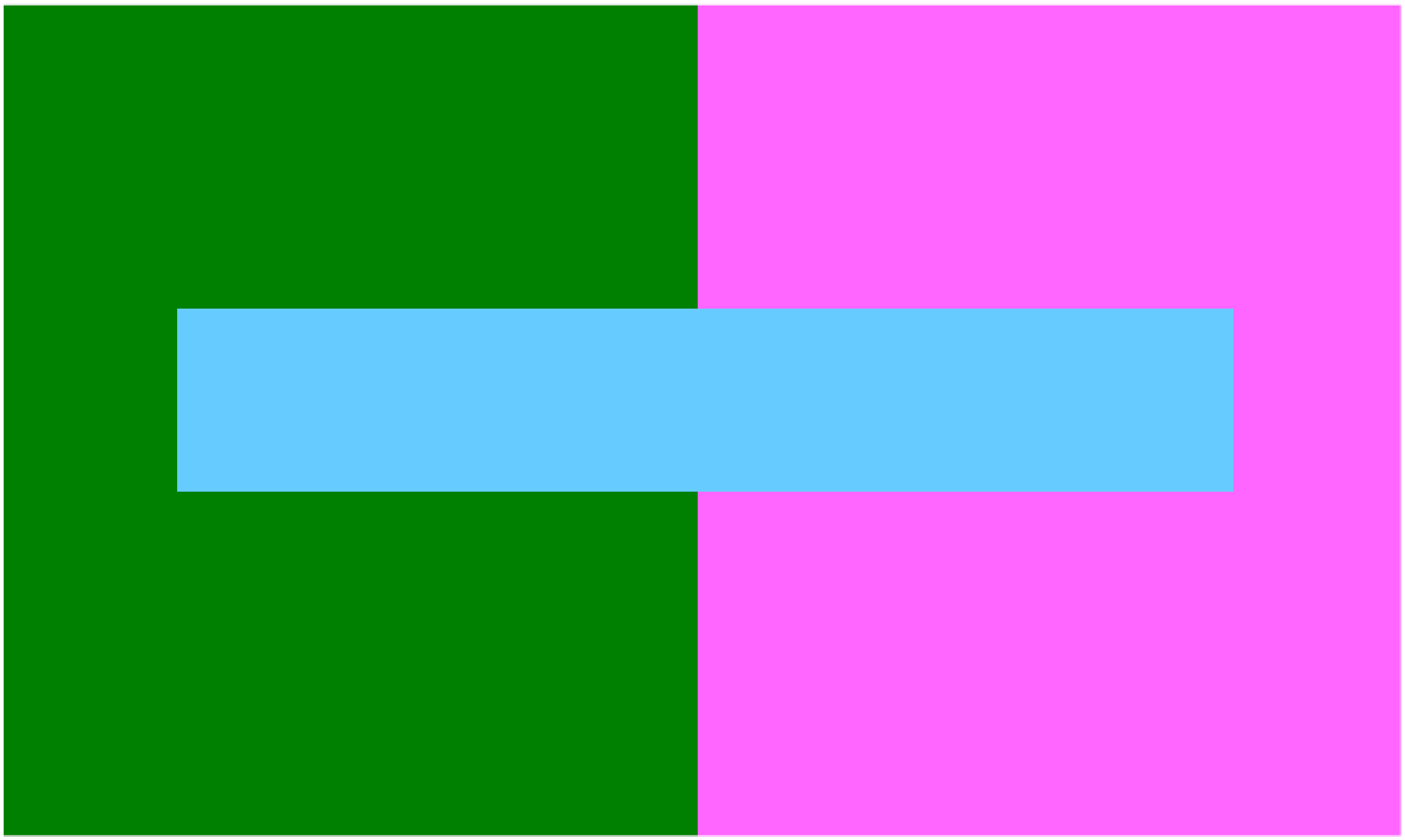
?

Other Color Facts

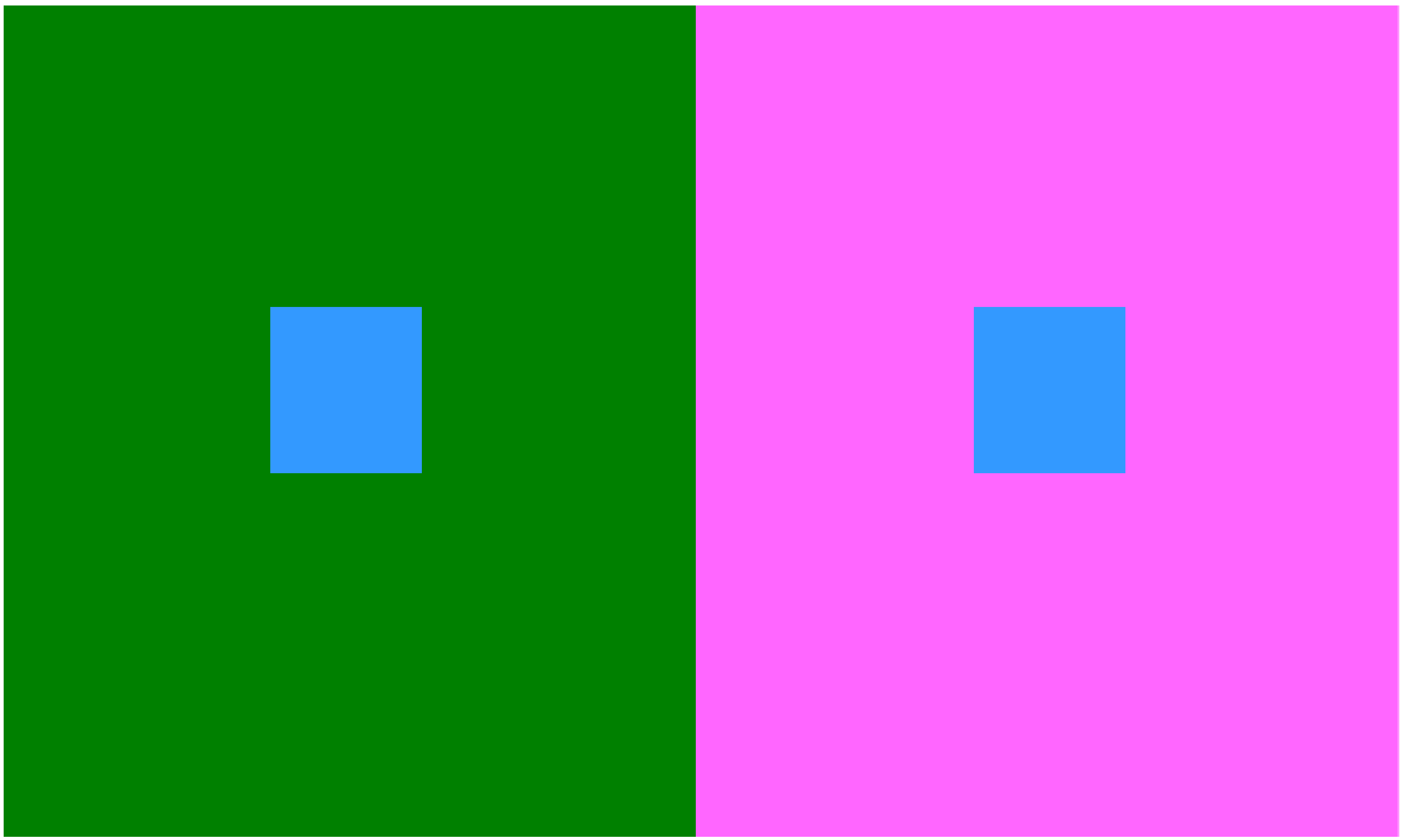
In visualization applications, we must be aware that *<u>our perception of color changes</u>* with:

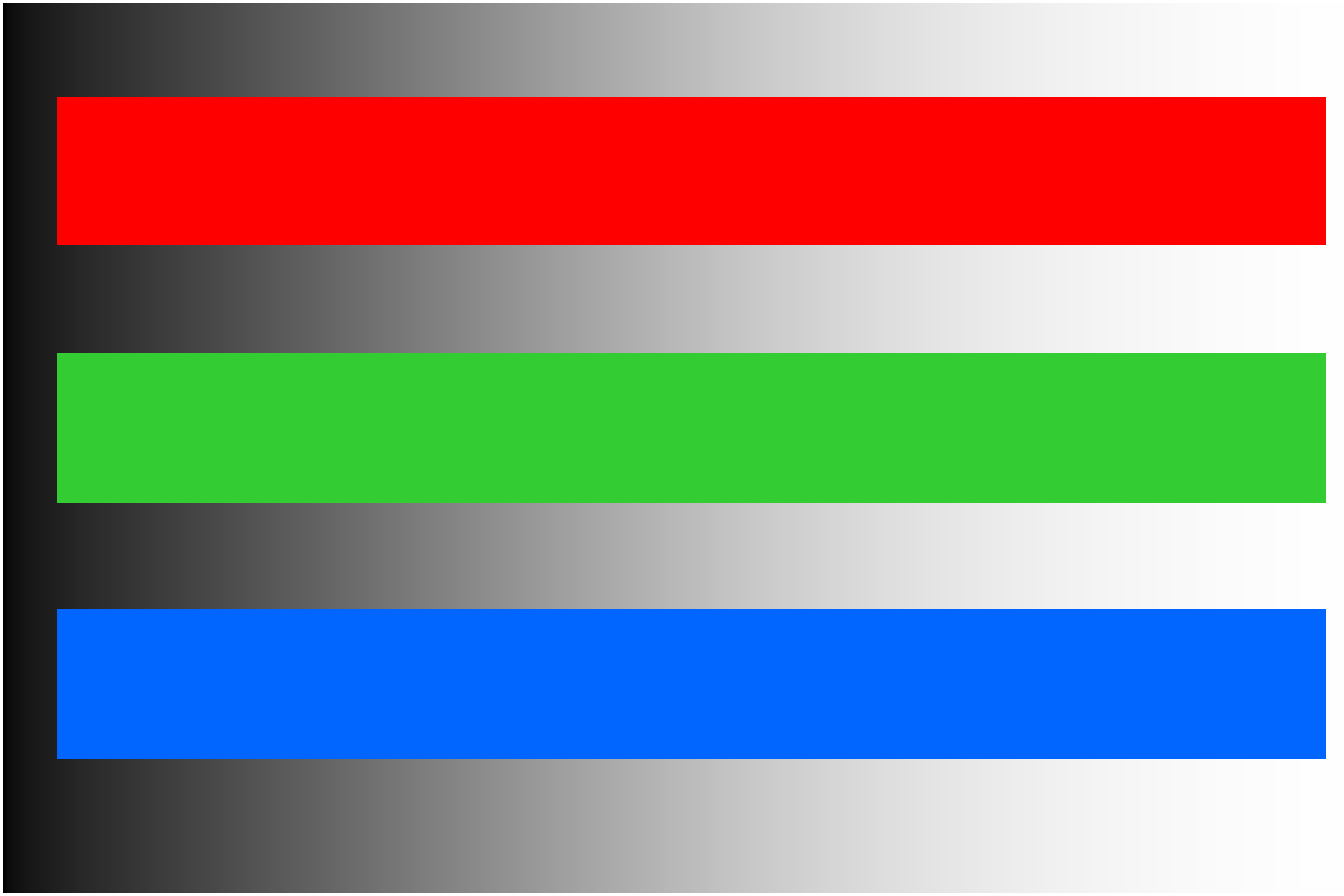
- The surrounding color
- How close two objects are
- How long you have been staring at the color
- Sudden changes in the color intensity

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



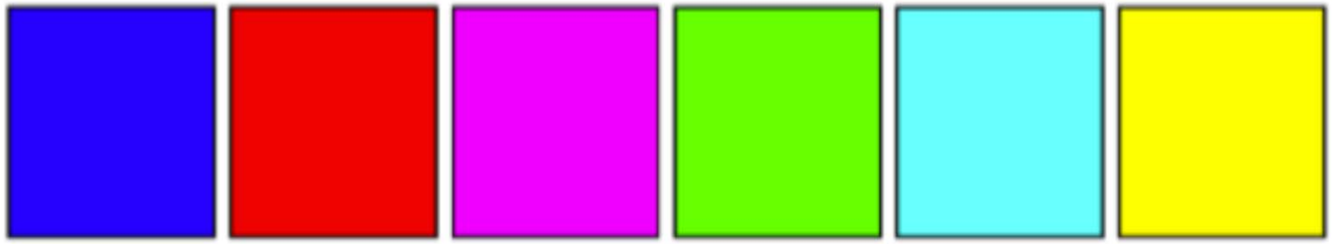
The Ability to Discriminate Colors Changes with Surrounding Color: “Simultaneous Contrast”





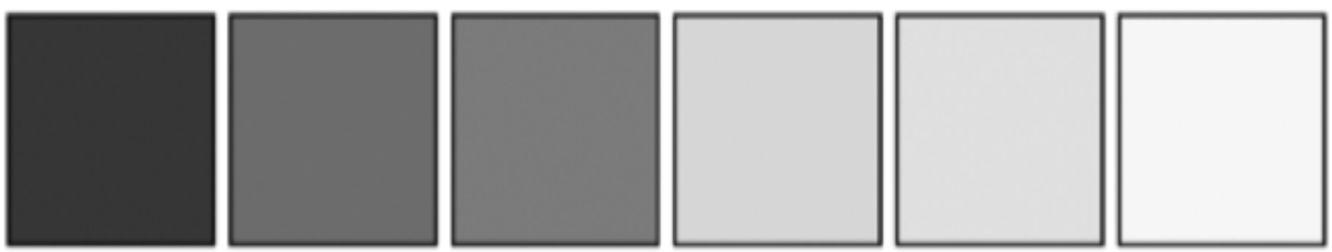
All colors are equal

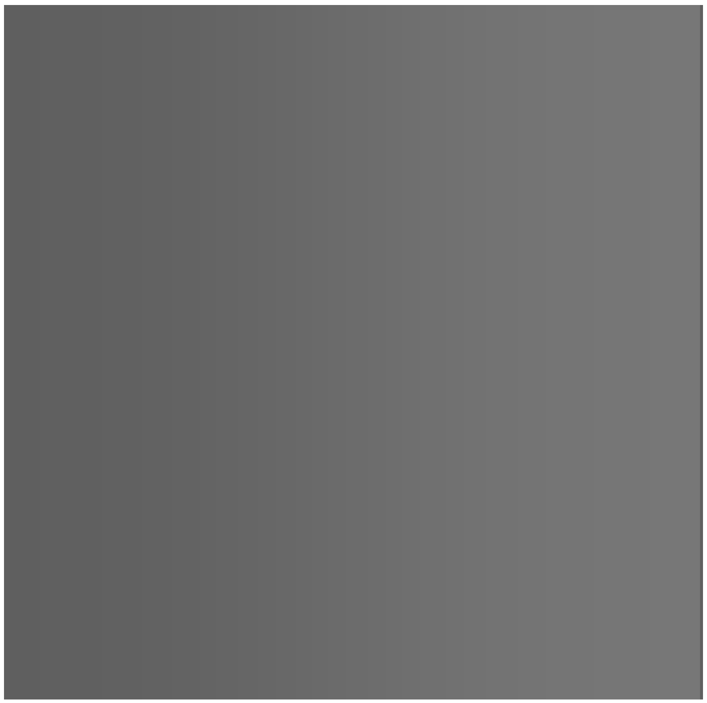
… but they are not perceived as the same

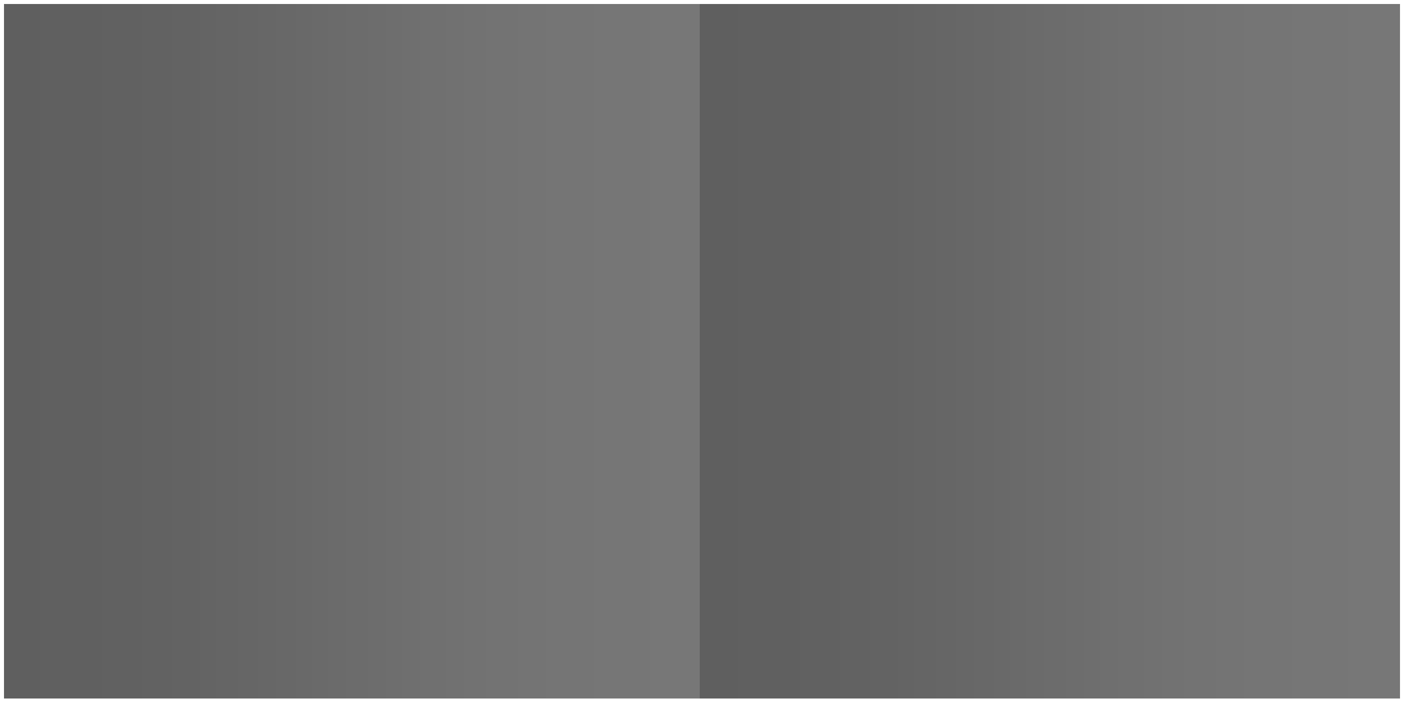


Luminance values

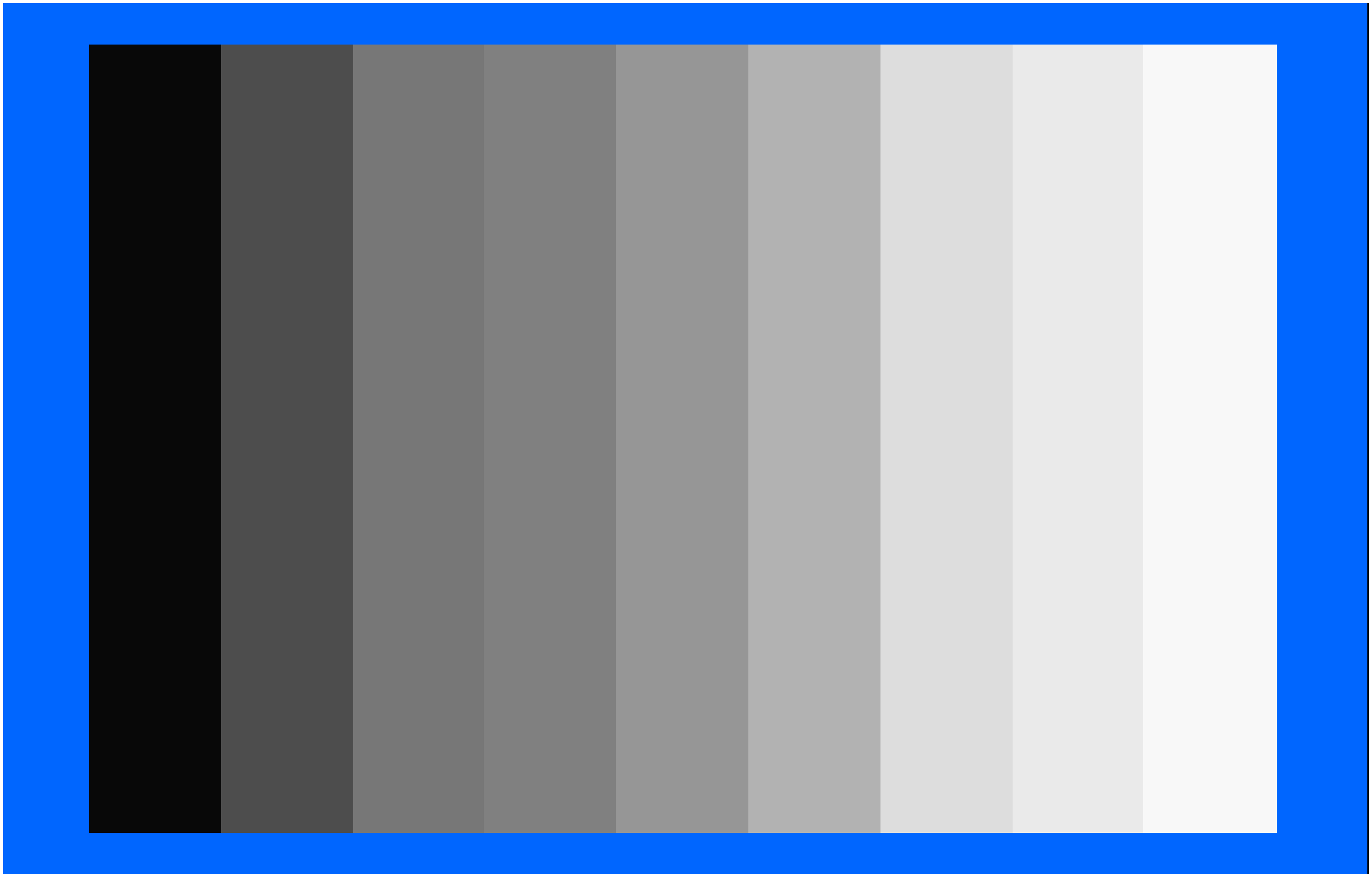
Perceived lightness



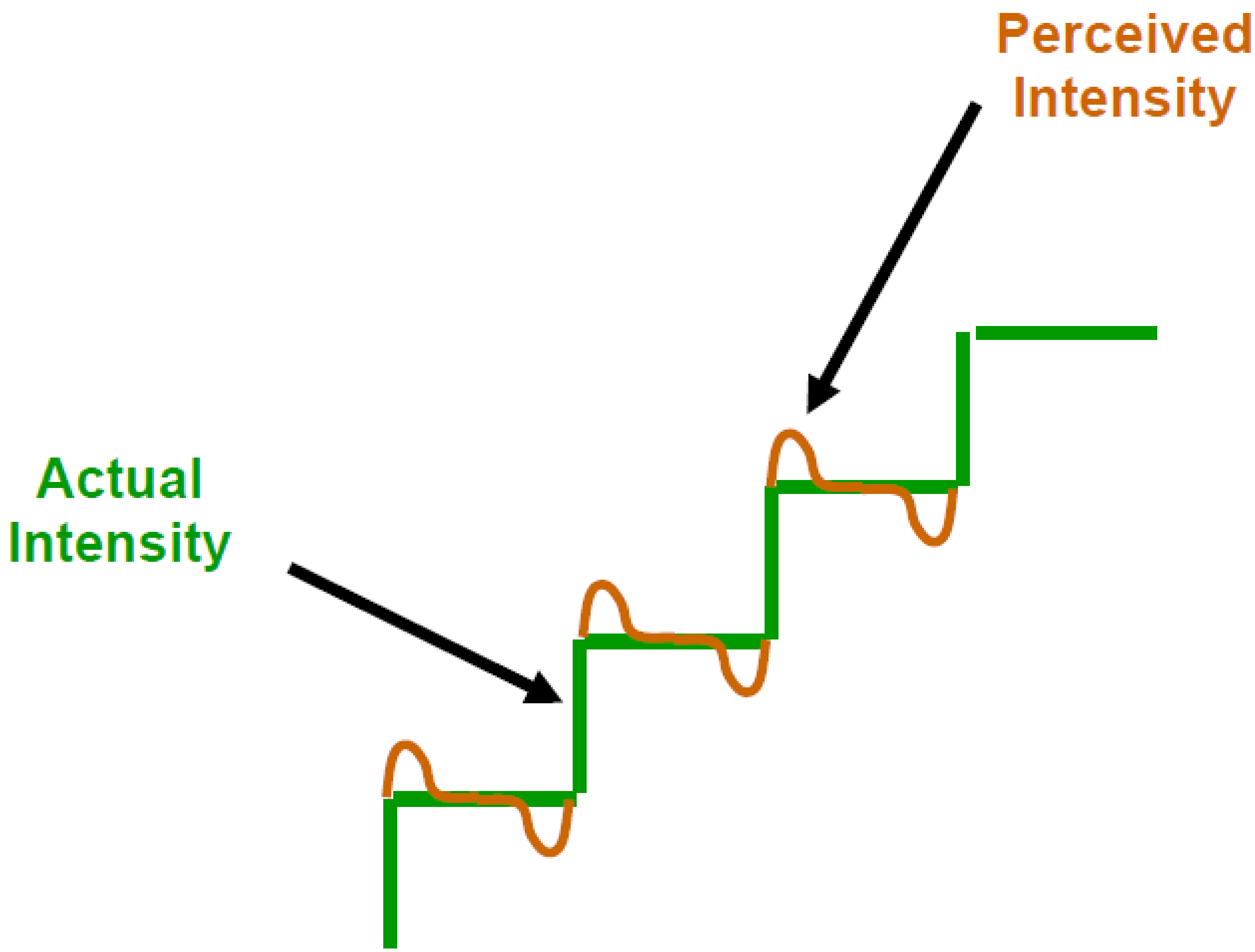




Beware of Mach Banding

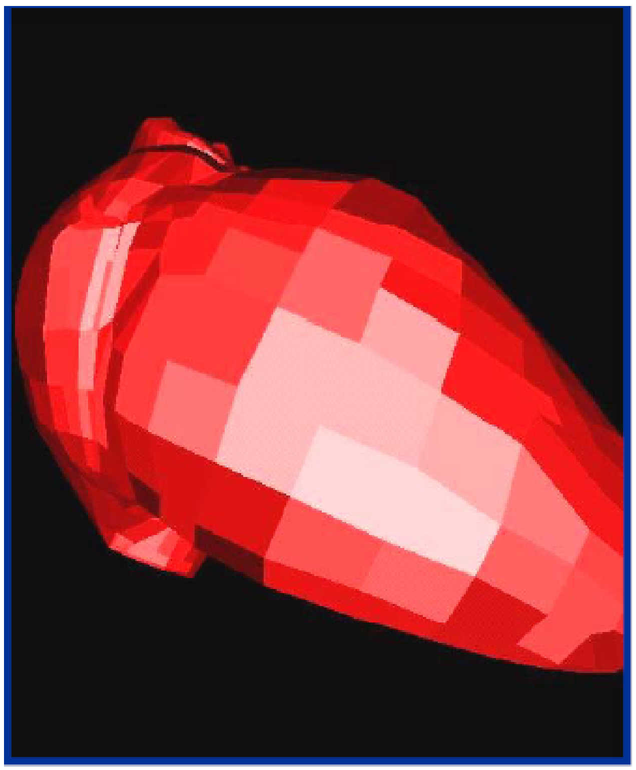


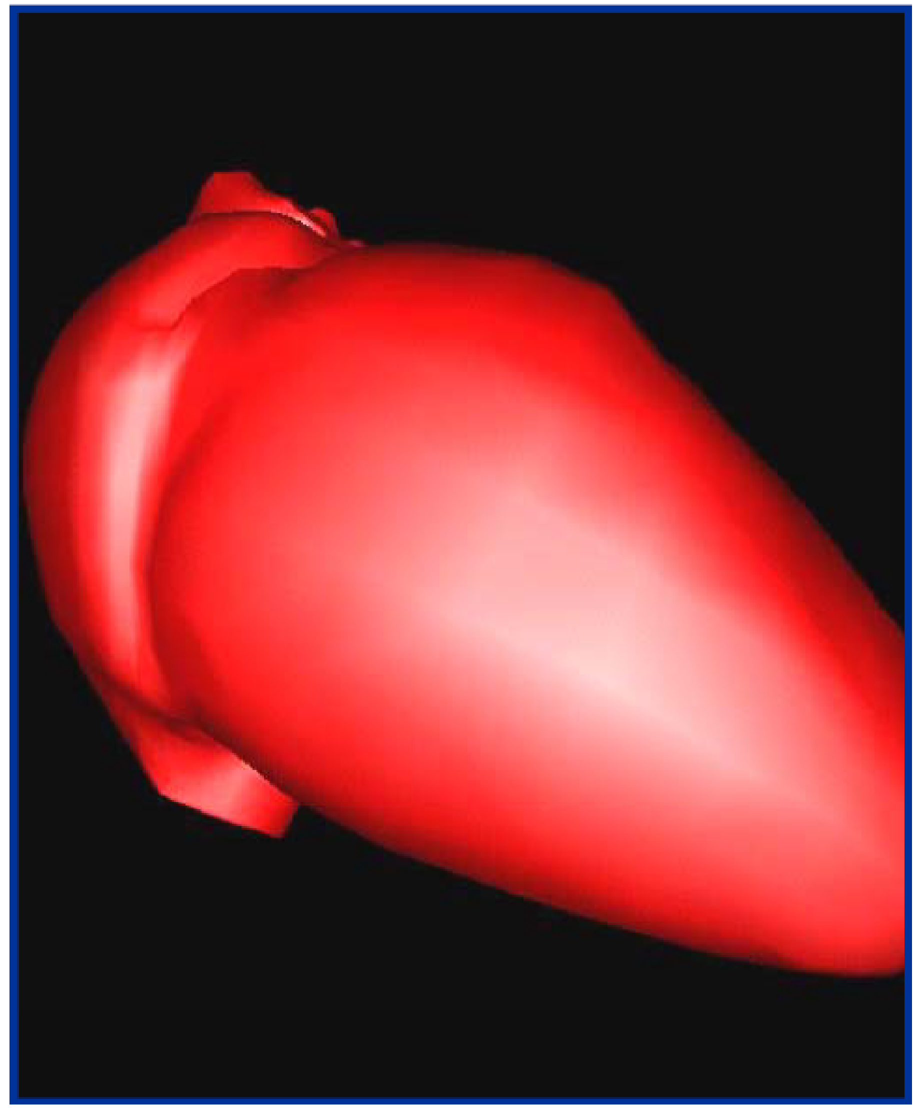
Beware of Mach Banding

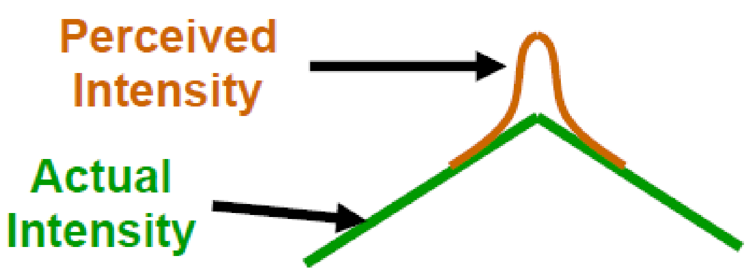


We are good at telling the boundaries/border!!!

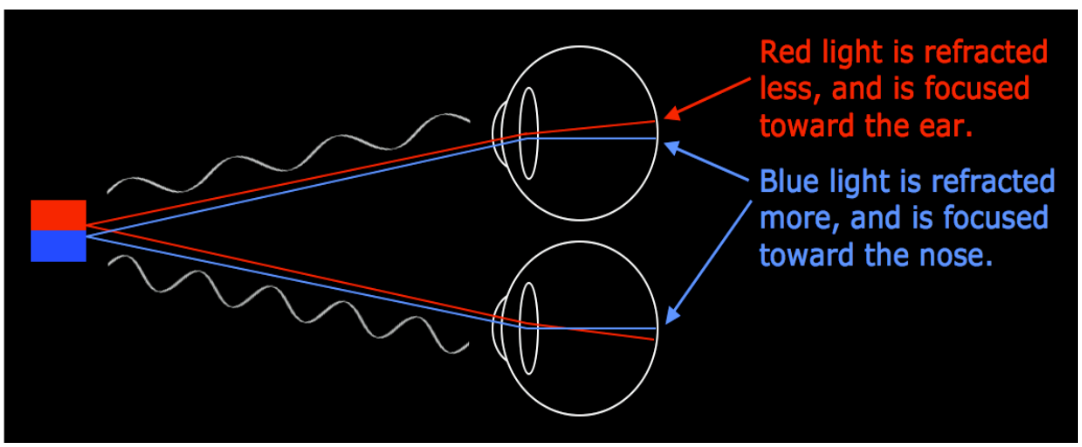
Beware of Mach Banding





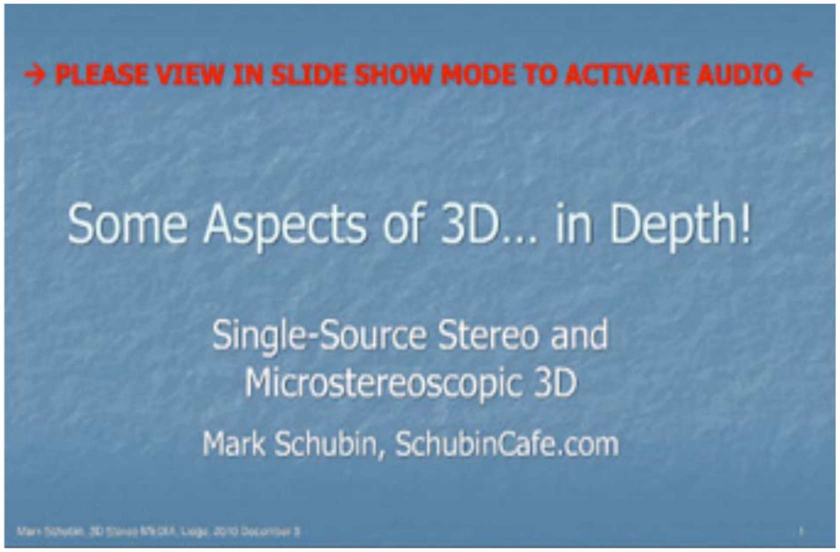


Chromostereopsis

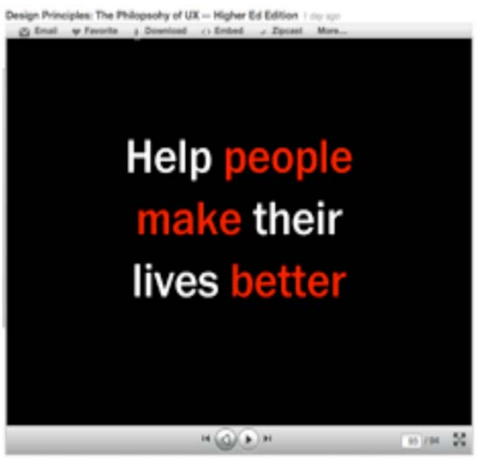


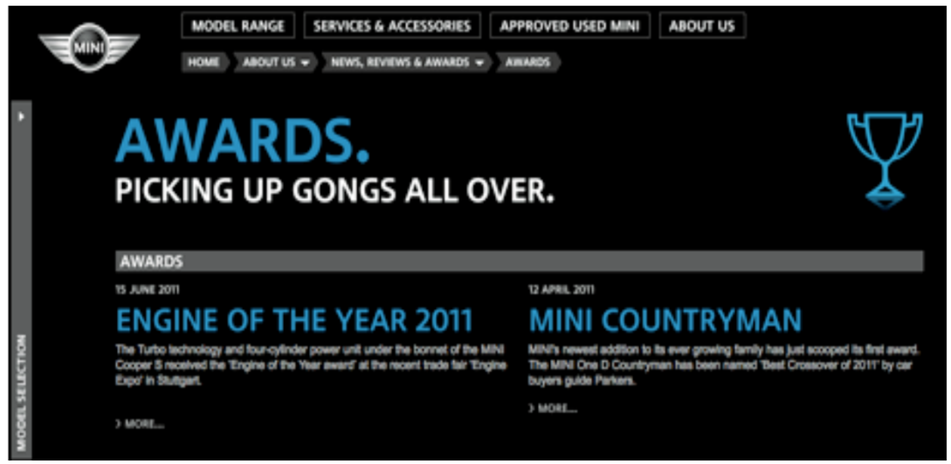
Easy to read?

Many beginning designers, however, find themselves overwhelmed by the palettes available on most comptuers, and begin choosing colors for the palette of their designed based on favorites. However, results like that can be disastrous.



Good or bad?


Help people
make their
lives better


MODEL RANGE
SERVICES & ACCESSORIES
APPROVED USED MINI
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HOME
ABOUT US
NEWS, REVIEWS & AWARDS
AWARDS
AWARDS.
PICKING UP GONGS ALL OVER.
AWARDS
ENGINE OF THE YEAR 2011
MINI COUNTRYMAN

Some useful guidelines for Chromostereopsis

- Beware of interactions between some colors (e.g., red/blue)
- Can be useful: for highlighting, creating 3D effect, etc.
- Resolve if unintended by
  - Using colors that are less saturated
  - Surrounding the contrasting colors with a background that moderates the effect of their different wavelengths
  - Separating the contrasting colors

Do different colors affect your mood?

https://www.factmonster.com/color-meanings-and-moods

by David Johnson

Like death and taxes, there is no escaping color. It is ubiquitous. Yet what does it all mean? Why are people more relaxed in green rooms? Why do weightlifters do their best in blue gyms?

Colors often have different meanings in various cultures. And even in Western societies, the meanings of various colors have changed over the years. But today in the U.S., researchers have generally found the following to be accurate.

Black

Black is the color of authority and power. It is popular in fashion because it makes people appear thinner. It is also stylish and timeless. Black also implies submission. Priests wear black to signify submission to God. Some fashion experts say a woman wearing black implies submission to men. Black outfits can also be overpowering, or make the wearer seem aloof or evil. Villains, such as Dracula, often wear black.

White

Brides wear white to symbolize innocence and purity. White reflects light and is considered a summer color. White is popular in decorating and in fashion because it is light, neutral, and goes with everything. However, white shows dirt and is therefore more difficult to keep clean than other colors. Doctors and nurses wear white to imply sterility.

Red

The most emotionally intense color, red stimulates a faster heartbeat and breathing. It is also the color of love. Red clothing gets noticed and makes the wearer appear heavier. Since it is an extreme color, red clothing might not help people in negotiations or confrontations. Red cars are popular targets for thieves. In decorating, red is usually used as an accent.

Related Links

- Color Psychology Quiz
- Color: Psychology, Symbolism, and Interesting Facts
- What Is Color?
- The History of Color
- Seasonal Color Analysis
- What Colors Mean - *from FactMonster.com*
- Color Blindness
- Academic Colors
- Color Printing
- Astronomical Color

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

The Ability to Discriminate Colors Changes with Ambient Light

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

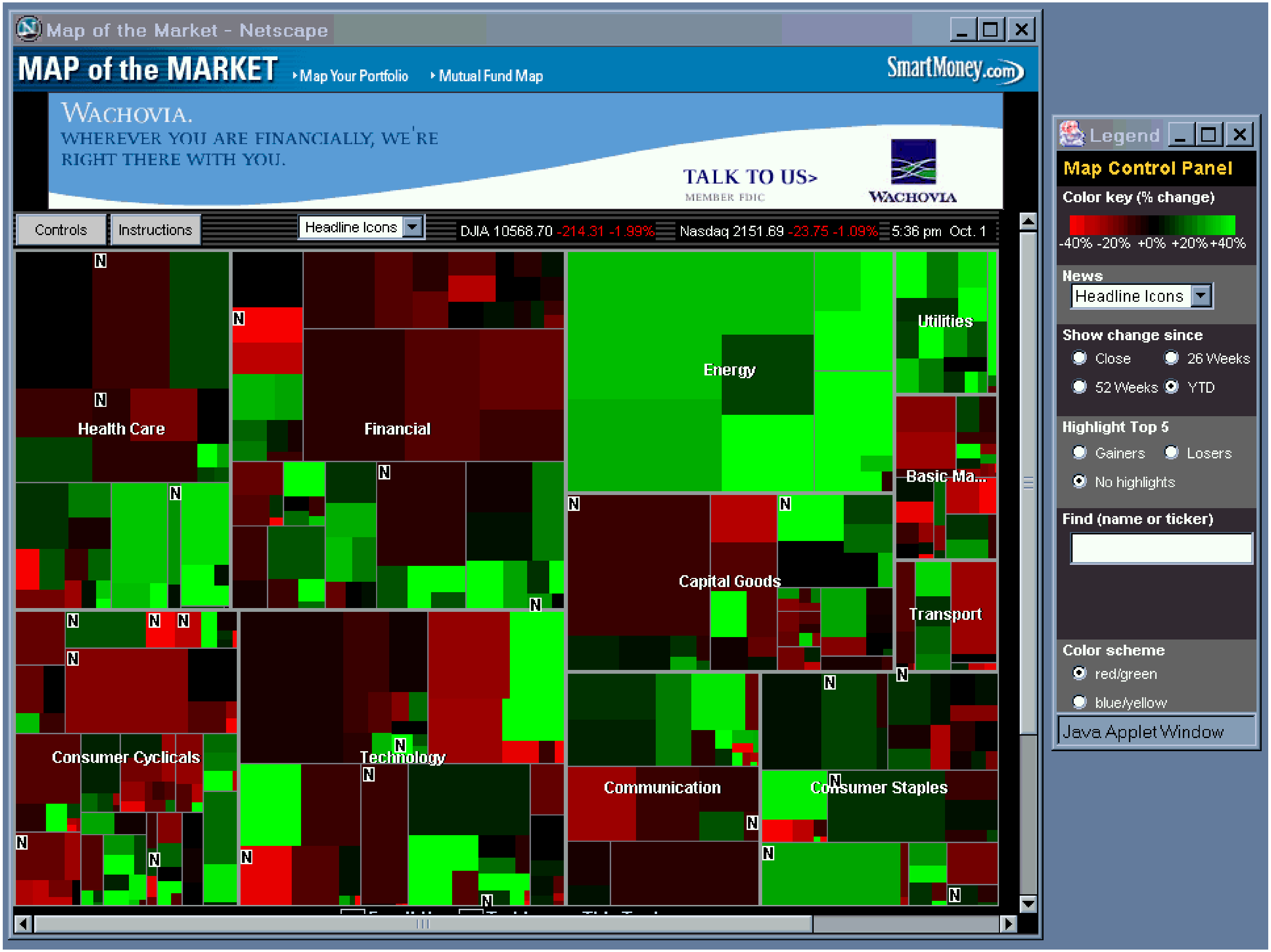
Be Aware of Color Vision Deficiencies (CVD)

- 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

Be Aware of Color Vision Deficiencies (CVD)

- Code Information Redundantly: **Color + …**
  - Different fonts
  - Symbols
  - Fill pattern
  - Outline pattern
  - Outline thickness

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



Map of the Market - Netscape
MAP of the MARKET
Map Your Portfolio
Mutual Fund Map
SmartMoney.com
WACHOVIA.
WHEREVER YOU ARE FINANCIALLY, WE'RE RIGHT THERE WITH YOU.
TALK TO US>
MEMBER FDIC
WACHOVIA
Controls
Instructions
Headline Icons
DJIA 10568.70 -214.31 -1.99%
Nasdaq 2151.69 -23.75 -1.09%
5:36 pm Oct. 1
Health Care
Financial
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Utilities
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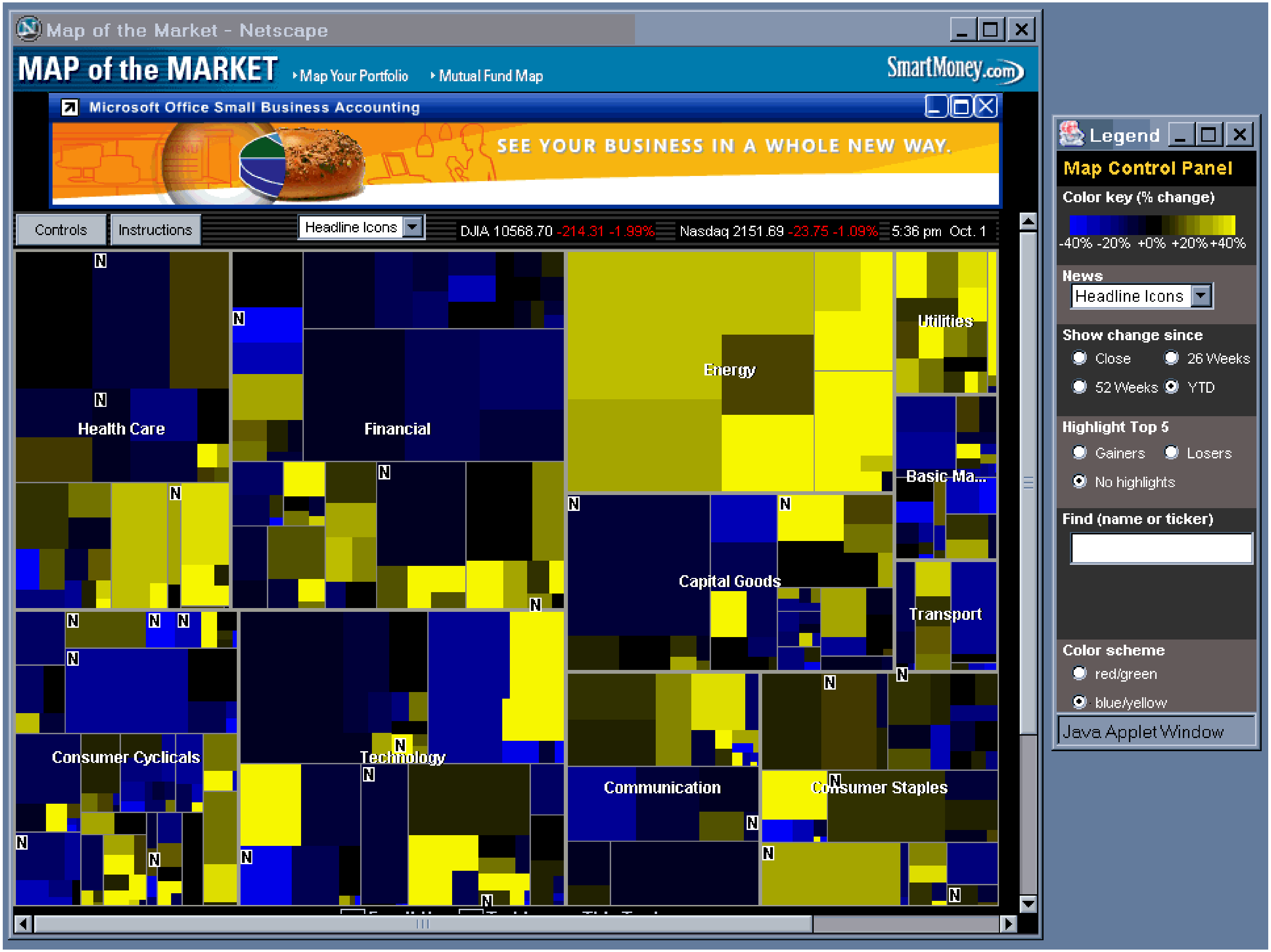
Capital Goods
Transport
Consumer Cyclicals
Technology
Communication
Consumer Staples
Legend
Map Control Panel
Color key (% change)
-40% -20% +0% +20% +40%
News
Headline Icons
Show change since
Close
26 Weeks
52 Weeks
YTD
Highlight Top 5
Gainers
Losers
No highlights
Find (name or ticker)
Color scheme
red/green
blue/yellow
Java Applet Window


Map of the Market - Netscape
MAP of the MARKET
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Mutual Fund Map
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Microsoft Office Small Business Accounting
SEE YOUR BUSINESS IN A WHOLE NEW WAY.
Controls
Instructions
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DJIA 10568.70 -214.31 -1.99%
Nasdaq 2151.69 -23.75 -1.09%
5:36 pm Oct. 1
Health Care
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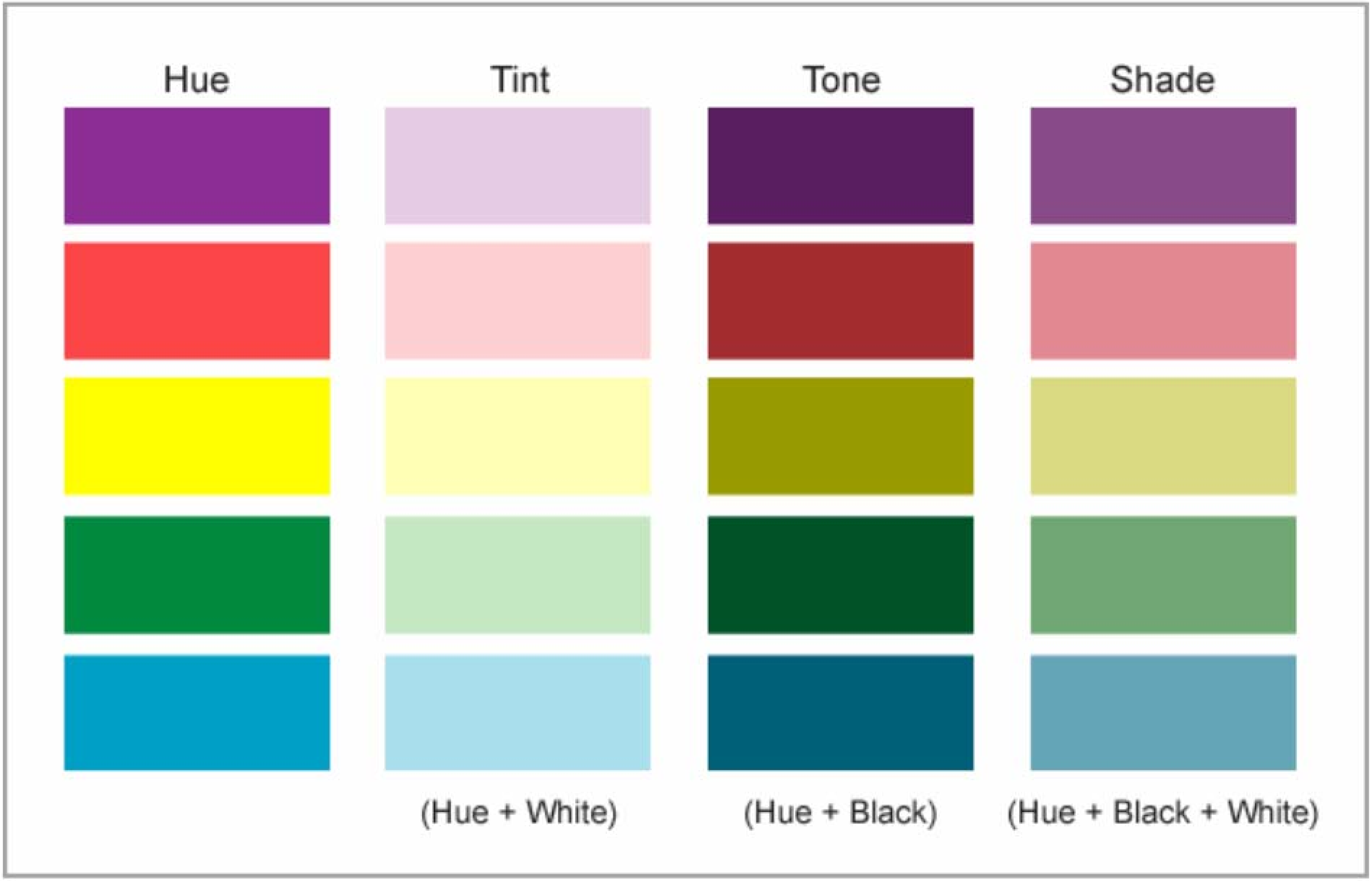
Utilities
Basic Ma...
Capital Goods
Transport
Consumer Cyclicals
Technology
Communication
Consumer Staples
Legend
Map Control Panel
Color key (% change)
-40% -20% +0% +20% +40%
News
Headline Icons
Show change since
Close
26 Weeks
52 Weeks
YTD
Highlight Top 5
Gainers
Losers
No highlights
Find (name or ticker)
Color scheme
red/green
blue/yellow
Java Applet Window

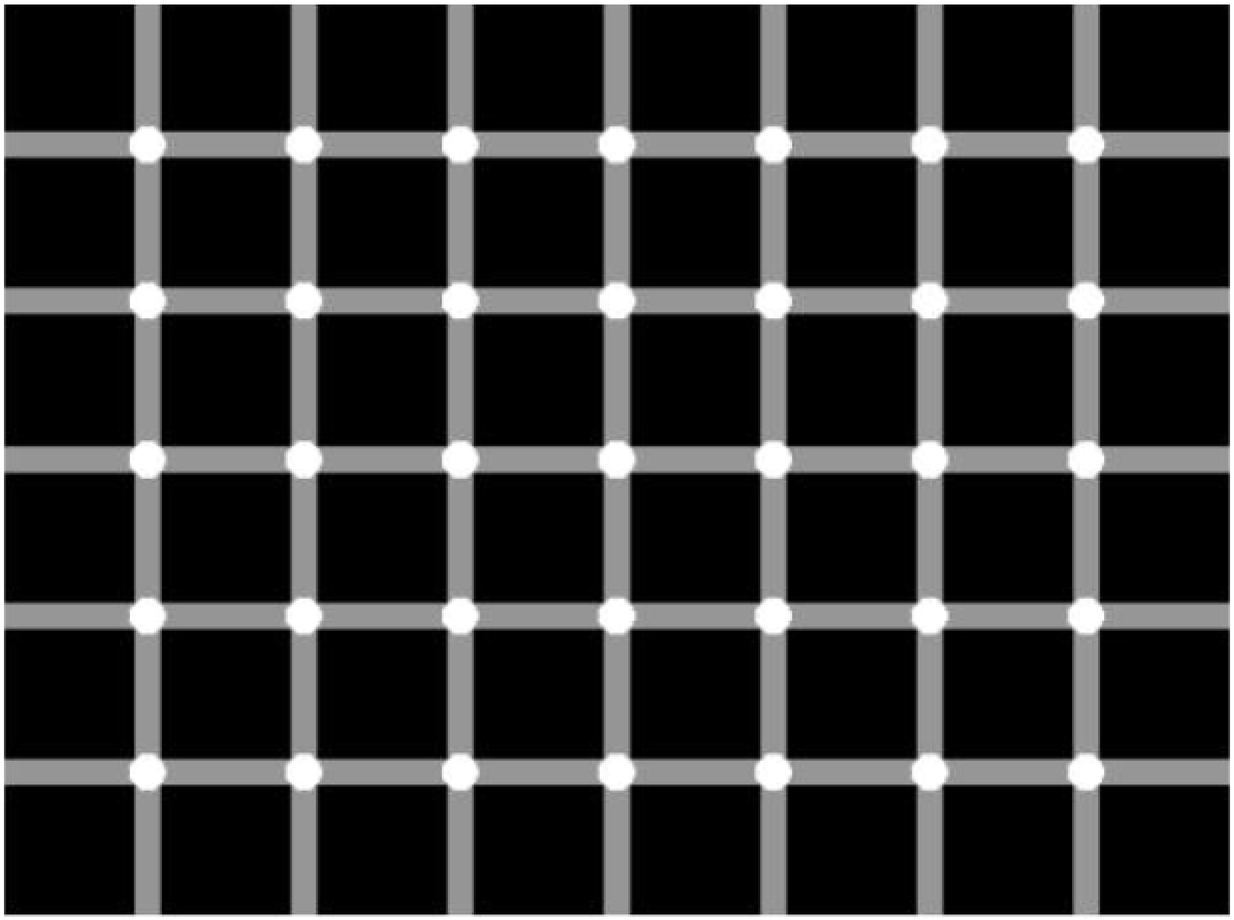
Adding more variations using HSV

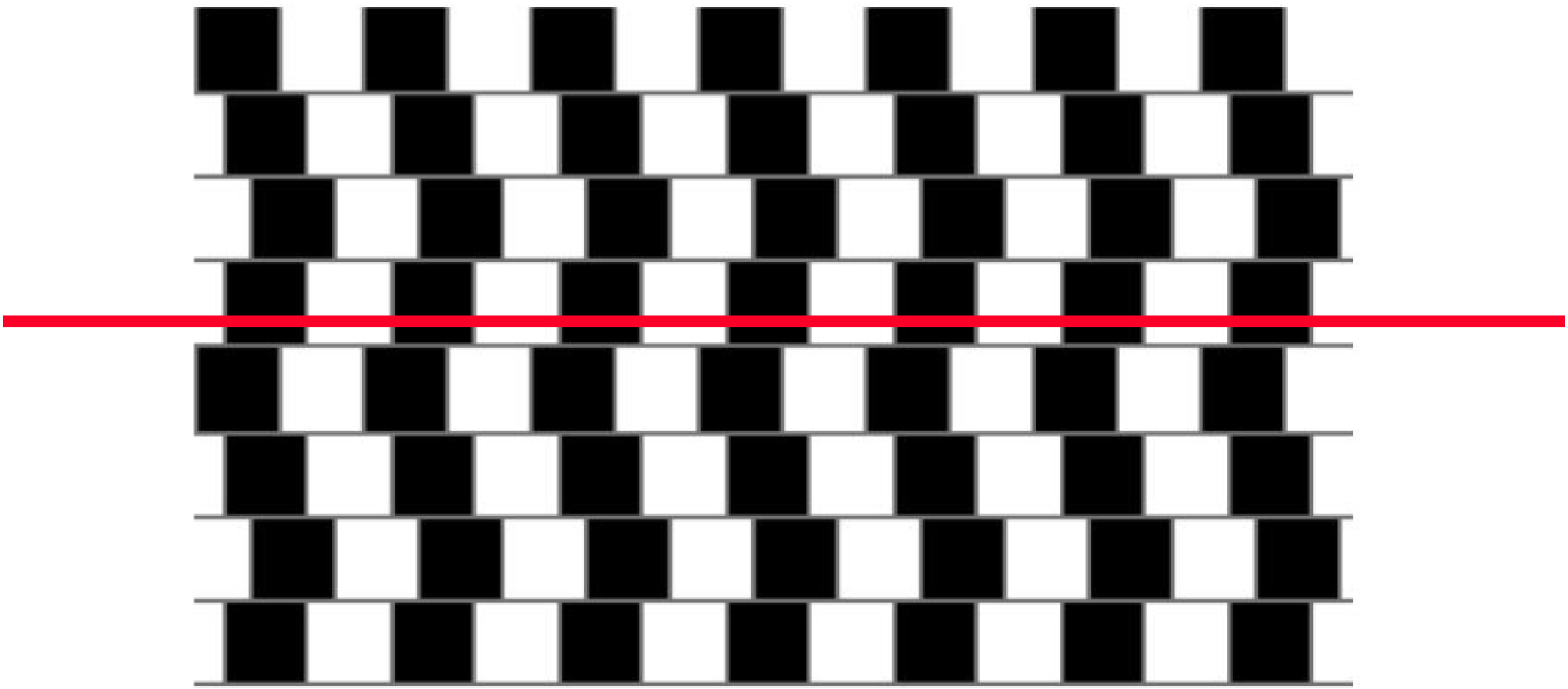


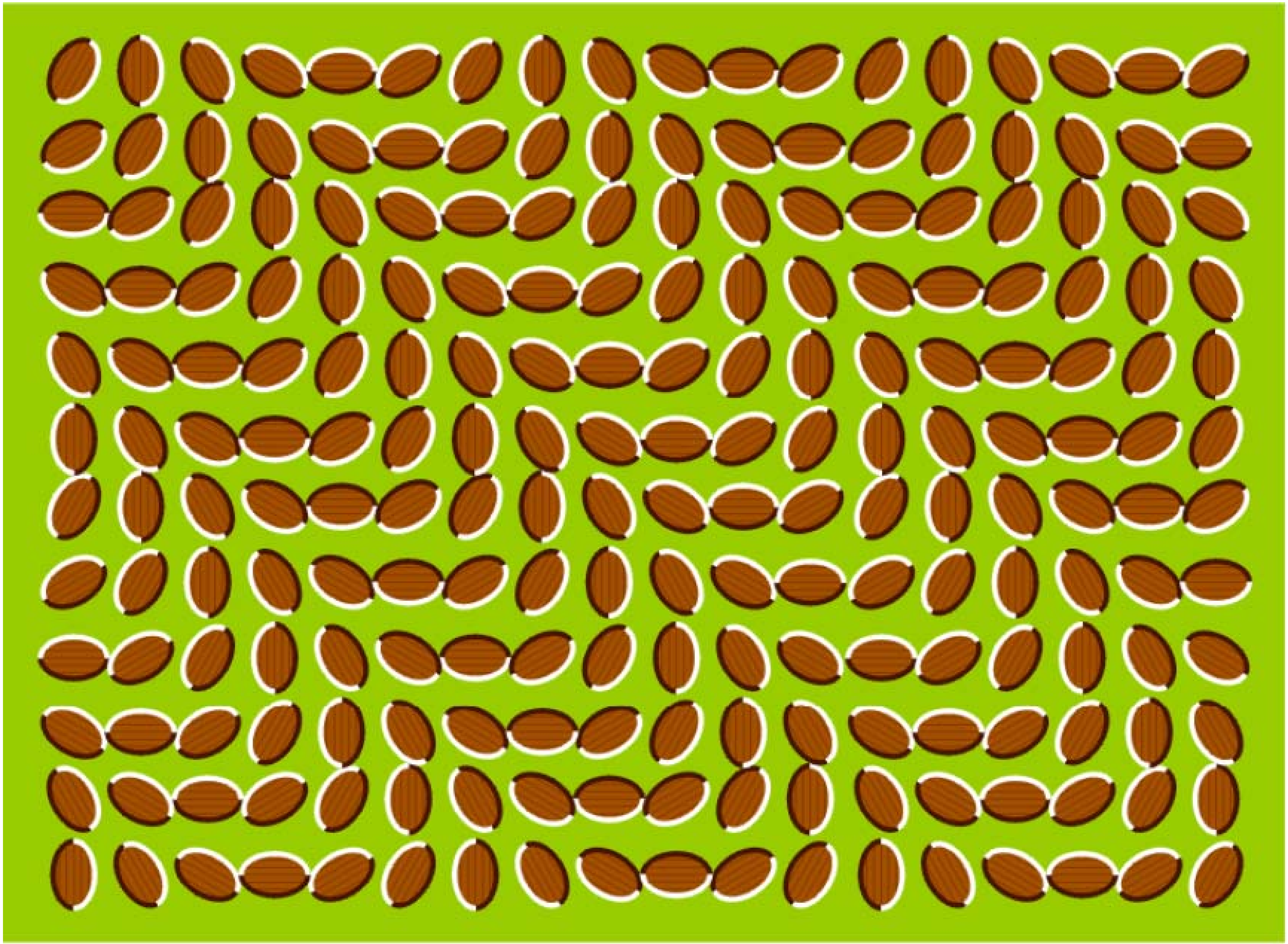
Beware of Color Pollution

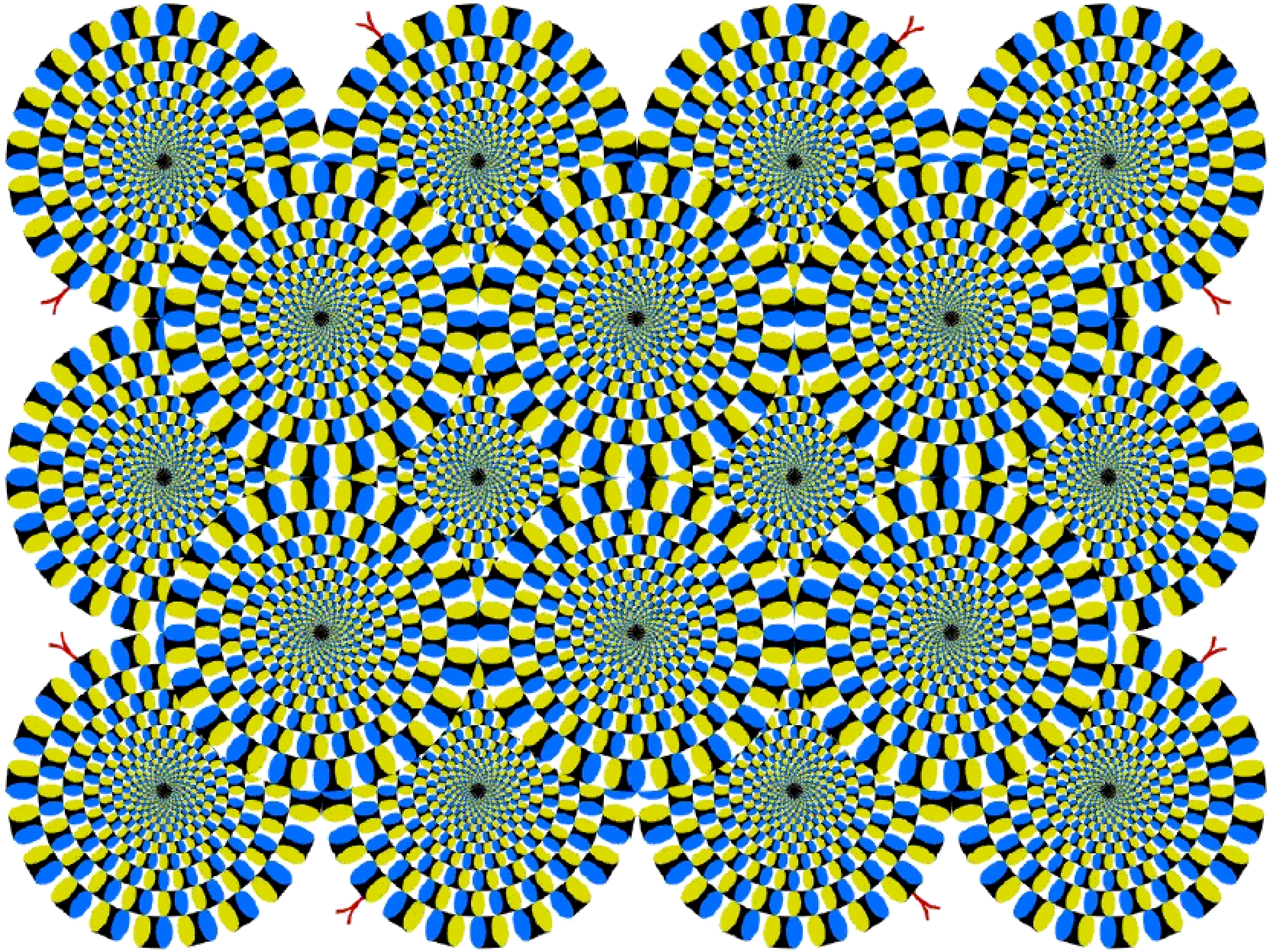
Just because you have millions of colors to choose from

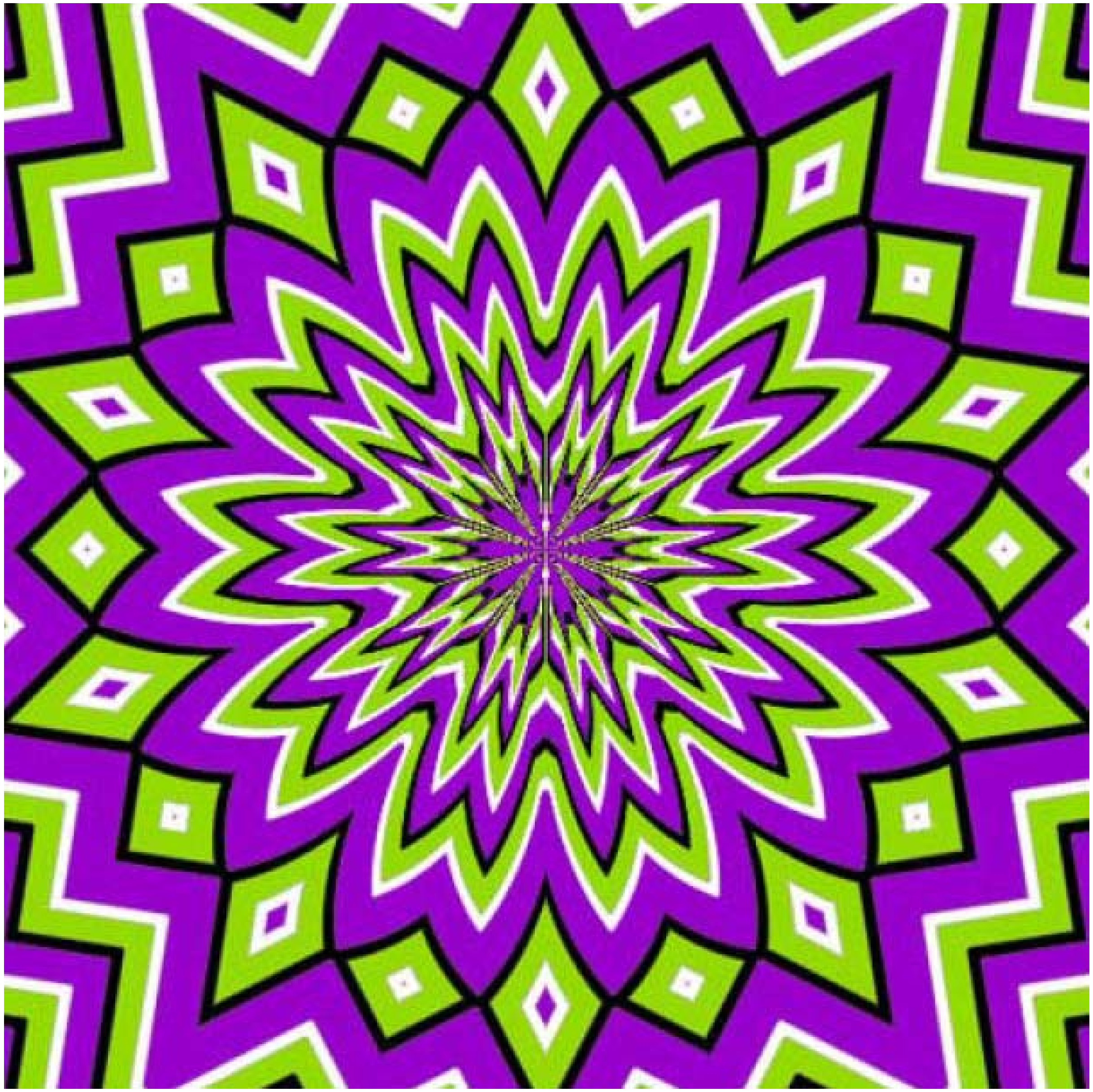
doesn't mean you must use them all •••

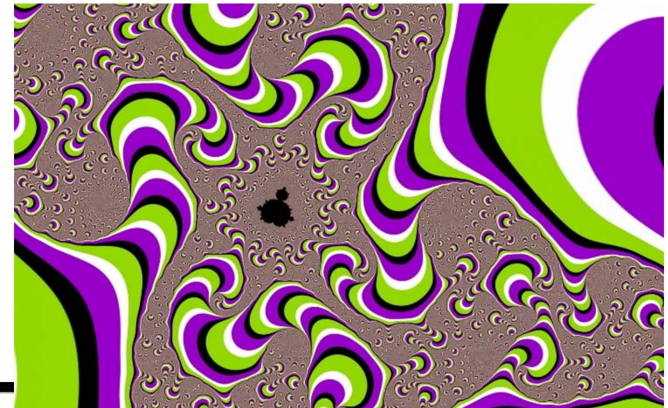


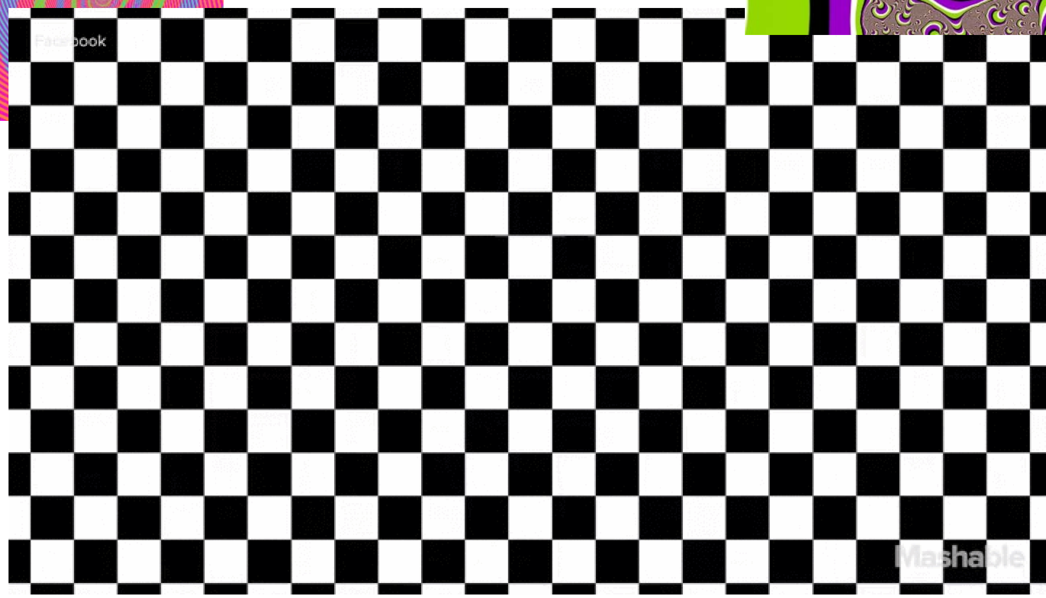












Additional links to the color perception

http://mashable.com/2015/03/26/f8-oculus-optical-illusions/#6493oMF2Hgqg

http://www.weirdoptics.com/melting-colors-optical-illusion/

Additional Reading

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- Danielle Albers Szafir, *Modeling Color Difference for Visualization Design*, IEEE VIS 2017.
- C Ware, *Information Visualization: Perception for design*. Chapters 3-5, 2013.
- Maureen Stone, *A Field Guide to Digital Color*, AK Peters, 2003.
- Roy Hall, *Illumination and Colors*, *in Computer Generated Imagery*, Springer-Verlag, 1989.
- 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.