Using Color in Scientific Visualization

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"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

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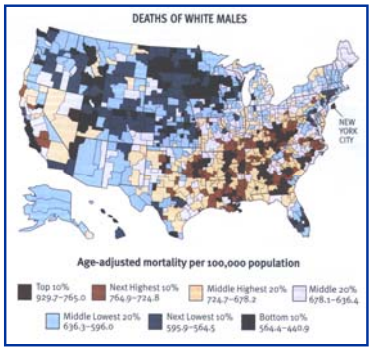
What's Wrong with this Picture?



Source: *Scientific American*, June 2000

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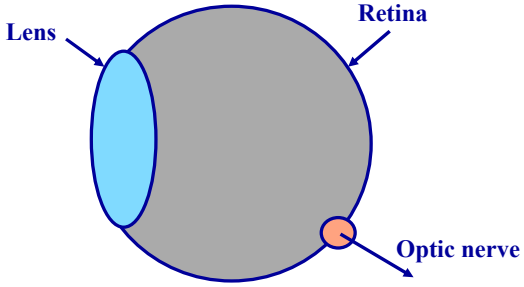
The Human Eye



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Cones

- ~7,000,000
- Concentrated near the center of the retina
- Sensitive to high, medium, and low wavelengths

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The Electromagnetic Spectrum

Blue: 380 nm

Red: 780 nm

Green: 520 nm

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Color Receptors in the Cones

Area of Spectrum:	Wavelength:	Approx. color:
Low	560 nm	Red
Medium	530 nm	Green
High	420 nm	Blue

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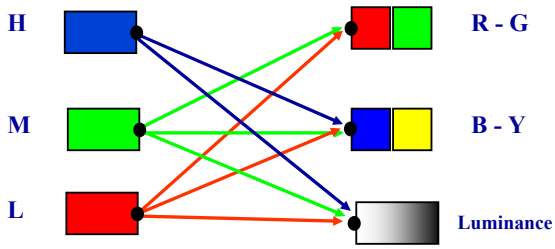
Combinations of Color To The Brain



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

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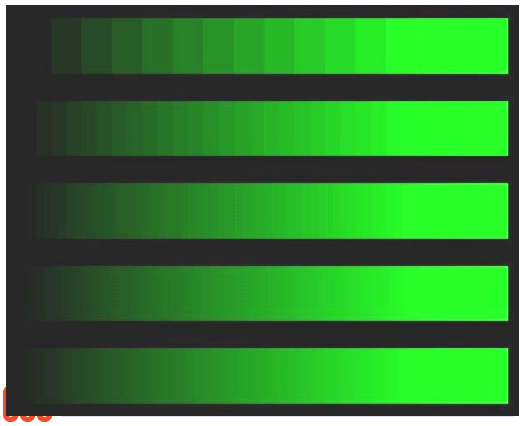

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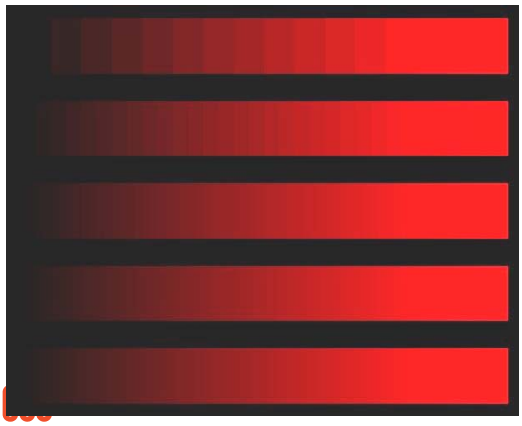

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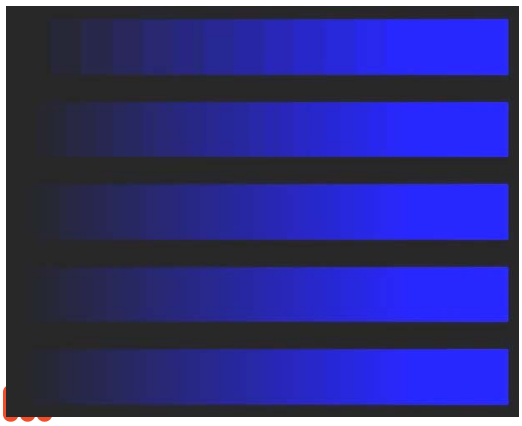

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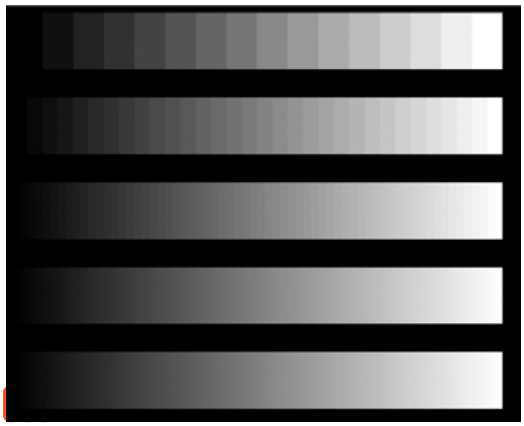
Rods

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



Sidebar: How Many Pixels Do You Need?

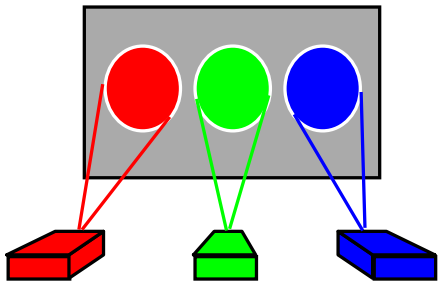
A person with 20/20 vision has a visual acuity of:
1 arc-minute = 1/60°

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

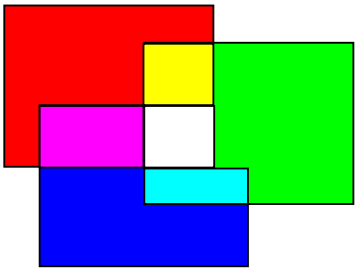
$$\Theta = 1/60° = .00029^R$$

Viewing Distance (inches)	Required Pixel Density (ppi)	1280x1024
36	95	19" monitor
31	111	16" monitor
24	143	
12	286	
9	400	
6	600	

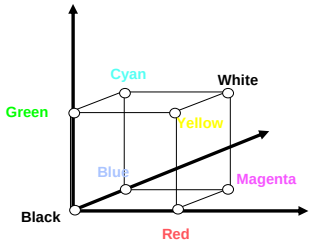
Monitors: Additive Colors



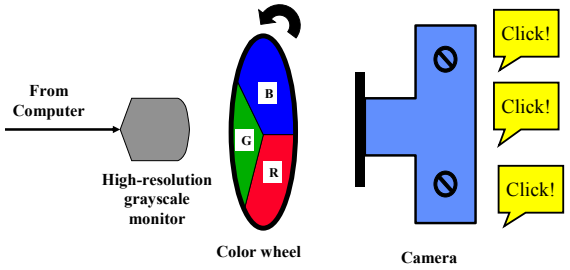
Additive Color (RGB)



RGB Color Space



Digital Film Recorders



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Digital Film Recorders

- Use additive colors
- Output resolution is limited by the quality of a grayscale monitor, not your display
- Typical resolutions currently available range from $2K^2$ to $32K^2$
- Many different film heads available: Polaroid, 16mm movies, 35mm slides and movies, 4x5 and 8x10 transparencies, 70mm movies (for IMAX and Omnimax)

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Lasergraphics Digital Film Recorder

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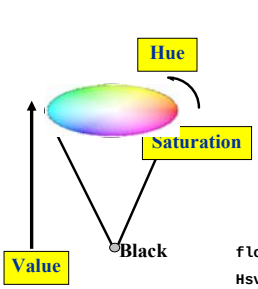
Is There a More Intuitive Way To Do Additive Colors Than RGB?



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

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

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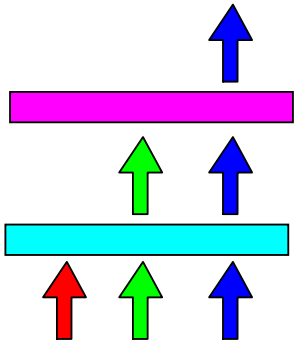
Subtractive Colors



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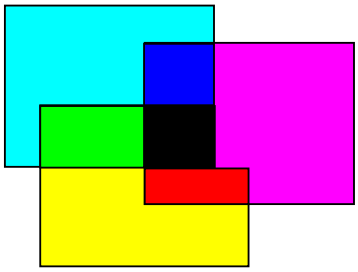
Subtractive Color (CMYK)



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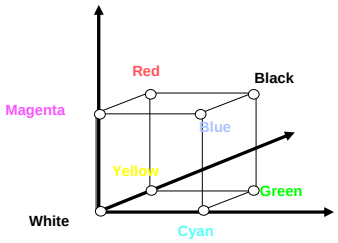
CMY Color Space



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Color Paper Printing

- Uses subtractive colors
- Uses 3 or 4 passes

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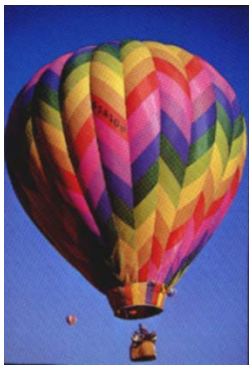
How Do Color Separations Work in Color Printing?



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

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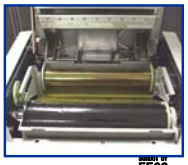
Printing the Four Colors

Wax

Toner

Toner



Sheets

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Color Paper Printing

- Uses subtractive colors
- Uses 3 or 4 passes
- Resolution ranges from 200 DPI to 600 DPI
- Considerable variation in quality between products
- Considerable variation in color *gamut* between products

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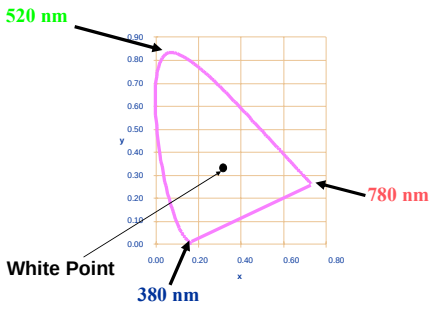
CIE Chromaticity Diagram



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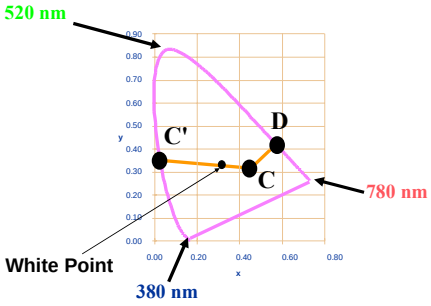
CIE Chromaticity Diagram



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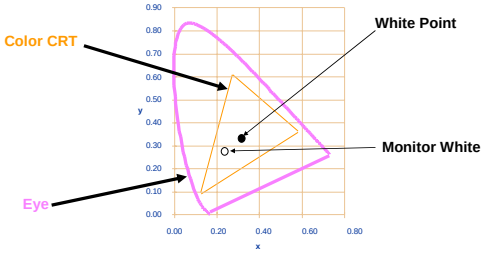
Color Gamut for an SGI Monitor



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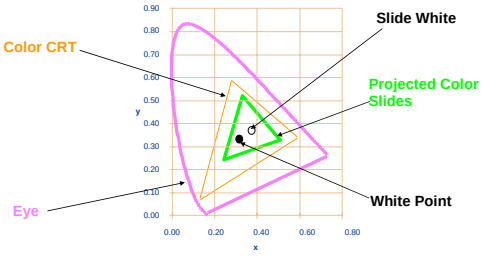
Color Gamut for a Monitor and Color Slides



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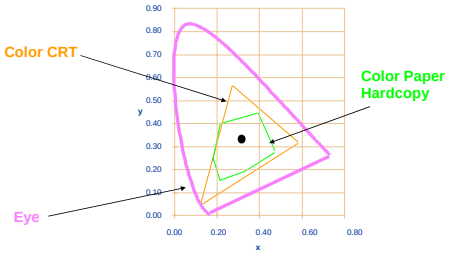
Color Gamut for a Monitor and Color Printer



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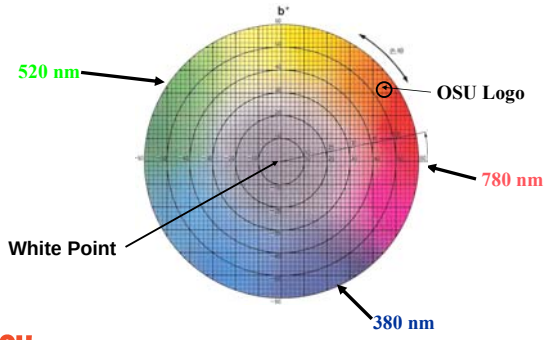
La*b* Diagram



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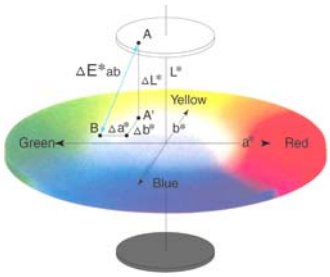
La*b* Diagram



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Some Good Rules of Thumb When Using Color for Scientific Visualization

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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
- Knowing 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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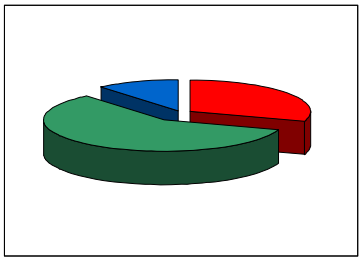
The Luminance Equation

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



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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

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≈ 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

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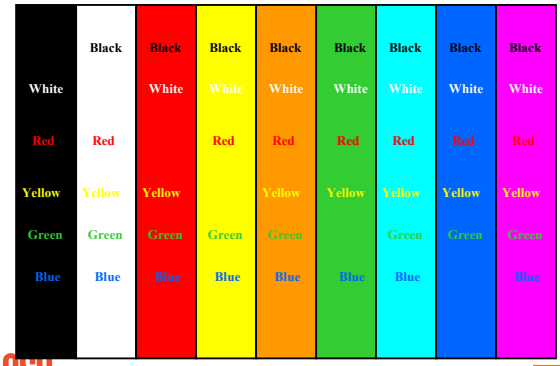

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Do Not Attempt to Fight Pre-Established Color Meanings

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Pre-Established Color Meanings

Red:

Stop
On
Off
Dangerous
Hot
High stress
Oxygen
Shallow
Money loss

Green:

On
Plants
Carbon
Moving

Blue:

Cool
Safe
Deep
Nitrogen

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Use the Right Color Interpolation Method

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

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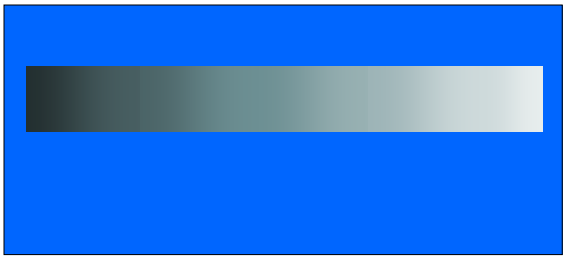
Gray Scale



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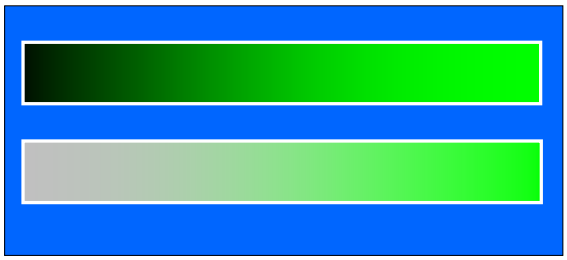
Intensity and Saturation Color Scales



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Two-Color Interpolation

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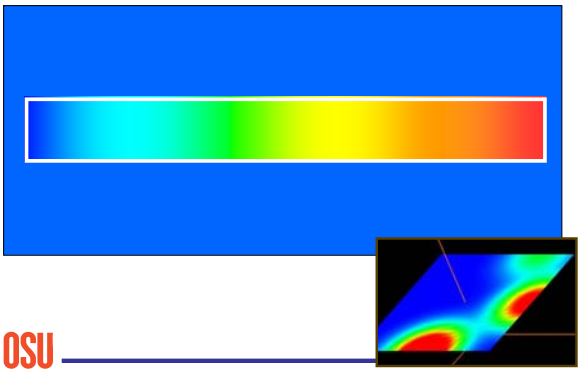
Rainbow Color Scale



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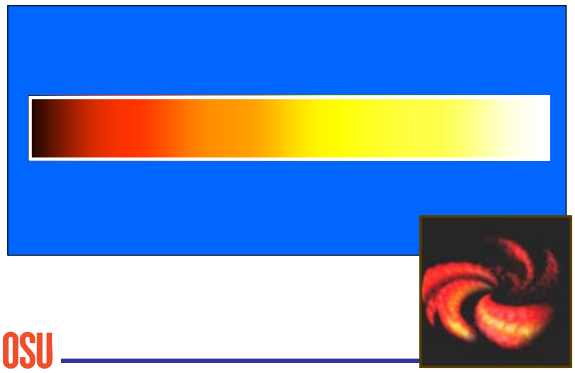
Heated Object Color Scale



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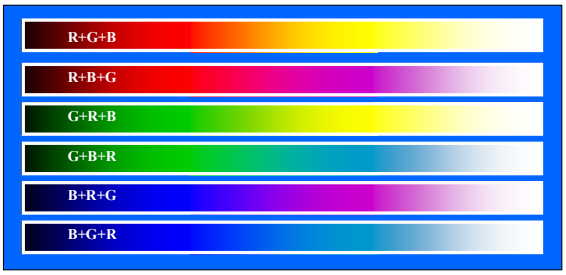
A Gallery of Add-One-More-Component Color Scales



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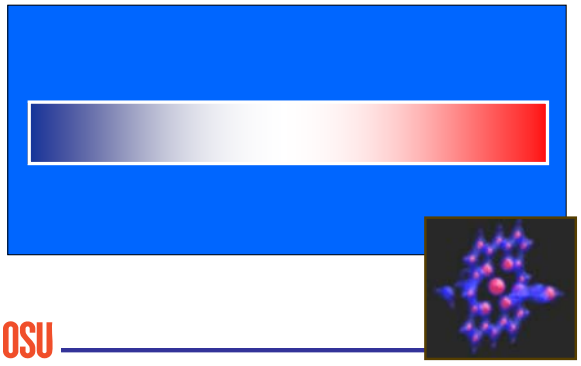
Blue-White-Red Color Scale



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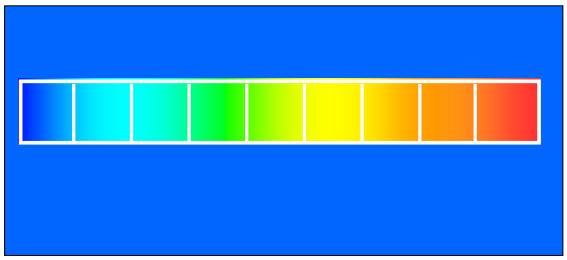
Color Scale Contours



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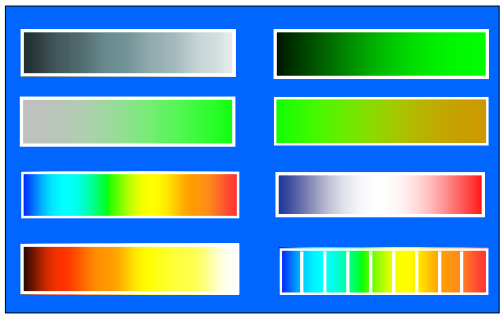
A Gallery of Color Scales



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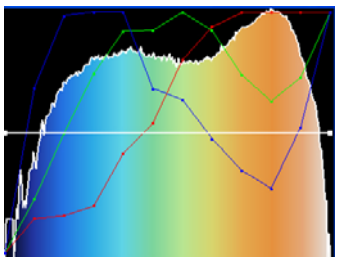
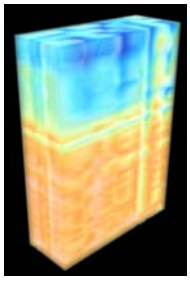
Something Relatively New – The Haxby Color Scale





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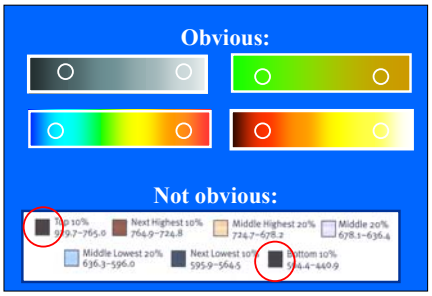
Here's What's Important:

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



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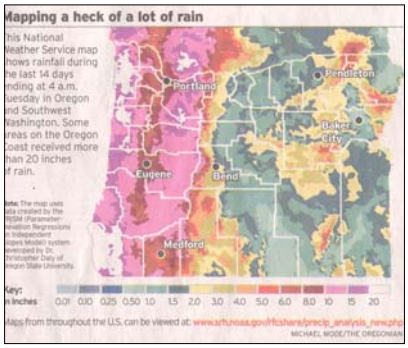
What in the World was *The Oregonian* Thinking When They Chose This Color Scale?



Source:
The Oregonian,
January 11, 2006

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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 • • •

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?

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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**

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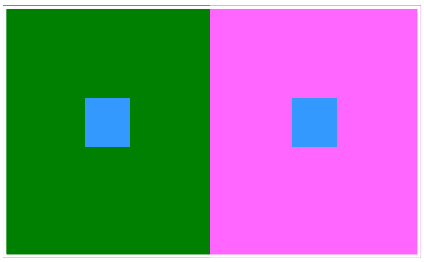
The Ability to Discriminate Colors Changes with Surrounding Color



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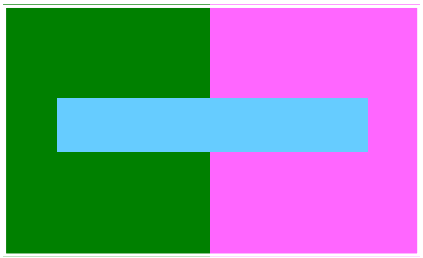

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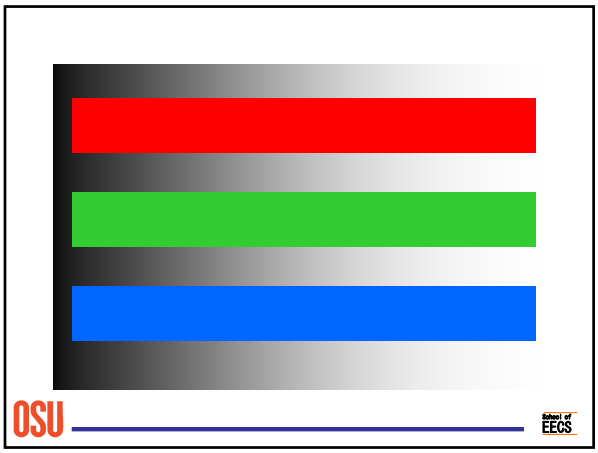
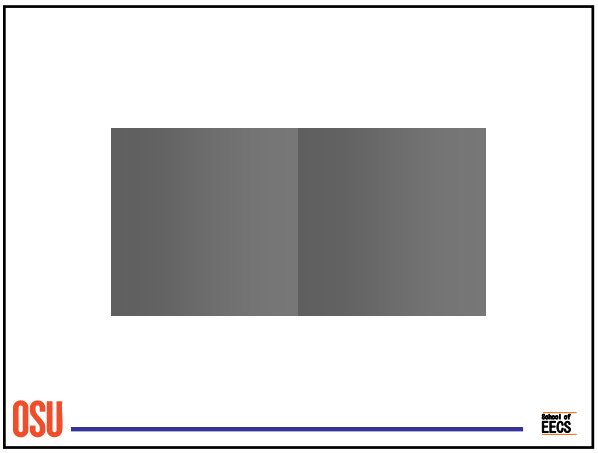
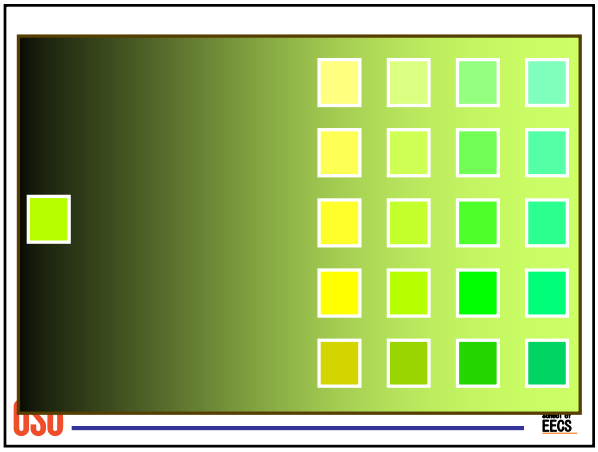
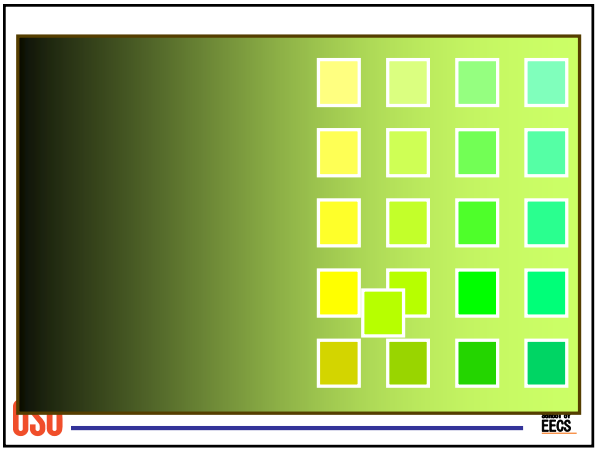
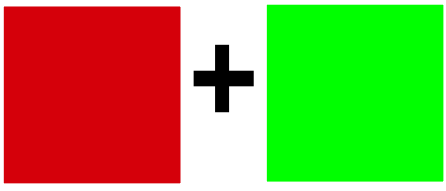








Afterimages

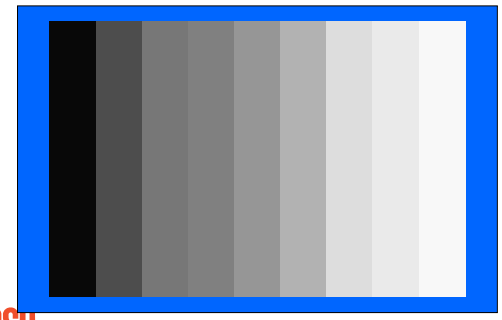


Afterimages

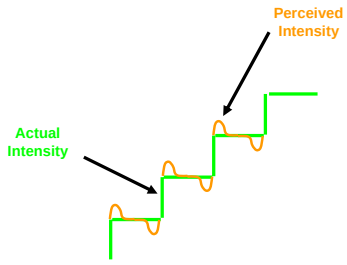
Color Receptors in the Cones

Area of Spectrum:	Wavelength:	Approx. color:
Low	560 nm	Red
Medium	530 nm	Green
High	420 nm	Blue

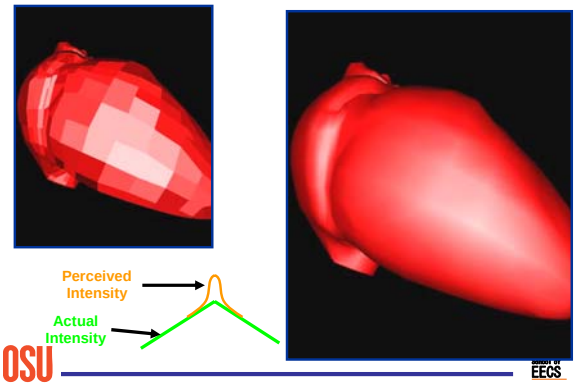
Beware of Mach Banding



Beware of Mach Banding



Beware of Mach Banding



Beware of Lots of Other Stuff

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 Recognition Deficiencies

- Actually no such thing as "color blindness"
- ~10% of Caucasian men
- ~4% of non-Caucasian men
- ~0.5% of women

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...

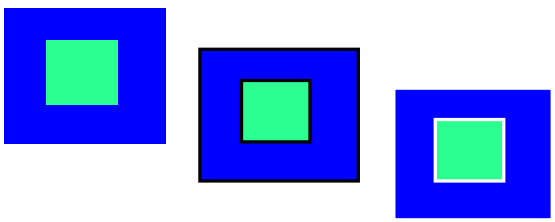
Four score and seven years ago, our forefathers brought forth upon this continent a new nation...

Code Information Redundantly: Color + ...

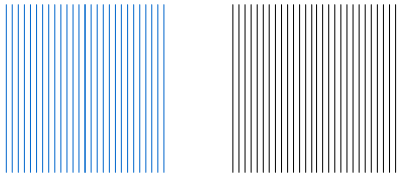
- Different fonts
- Symbols
- Fill pattern
- Outline pattern
- Outline thickness

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



Watch the Use of Saturated Blues for Fast-Moving Items or Fine Detail



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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.

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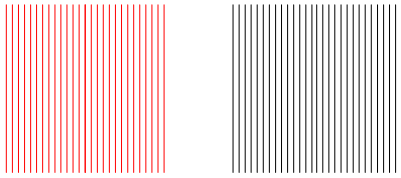
Do Not Display High Spatial Frequencies in Color



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Be Aware of the Differences Between Color Gamuts –

Adapt by Deciding What is Most Important for Your Visualization

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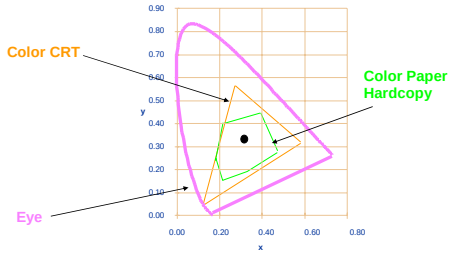
Color Gamut for a Monitor| and Color Printer



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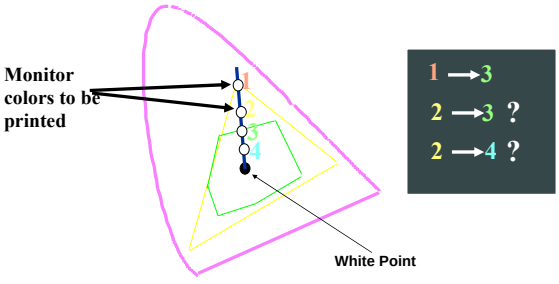
Color-Preserving vs. Contrast-Preserving Gamut Mappings



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Some Basic Rules for Using NTSC Video

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Understand the Limitations of going from Workstations to NTSC

- 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

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NTSC Cycles-of-Encoding per Scanline

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

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Gratuitous Color Pollution

Just because you have 2^{24} different colors,

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

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Good Color and Perception References

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- Edward Tufte, *The Visual Display of Quantitative Information*, Graphics Press, 1983.
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