“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 Picture?

Source:  
Scientific American, June 2000

The Human Eye

Lens

Retina

Optic nerve
Cones

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

The Electromagnetic Spectrum

Blue: 380 nm  Red: 780 nm  Green: 520 nm
### Color Receptors in the Cones

<table>
<thead>
<tr>
<th>Area of Spectrum</th>
<th>Wavelength:</th>
<th>Approx. color:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>560 nm</td>
<td>Red</td>
</tr>
<tr>
<td>Medium</td>
<td>530 nm</td>
<td>Green</td>
</tr>
<tr>
<td>High</td>
<td>420 nm</td>
<td>Blue</td>
</tr>
</tbody>
</table>

### Combinations of Color To The Brain

- **H** (Blue) + **M** (Green) = **R - G** (Red - Green)
- **M** (Green) + **L** (Red) = **B - Y** (Blue - Yellow)
- All colors combined = **Luminance**
How Many Shades of Different Colors Are We Able to Detect?
**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°

Density = \frac{1}{\Theta}

\Theta = 1/60° = 0.00029°

<table>
<thead>
<tr>
<th>Viewing Distance (inches)</th>
<th>Required Pixel Density (ppi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>95</td>
</tr>
<tr>
<td>31</td>
<td>111</td>
</tr>
<tr>
<td>24</td>
<td>143</td>
</tr>
<tr>
<td>12</td>
<td>286</td>
</tr>
<tr>
<td>9</td>
<td>400</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
</tr>
</tbody>
</table>

Monitors: Additive Colors
Additive Color (RGB)

RGB Color Space

- Red
- Green
- Blue
- Magenta
- Cyan
- Yellow
- White
- Black
- Green
- Cyan
- White
- Magenta
- Yellow
- Blue
- Red
- Black
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 2K² to 32K²
- Many different film heads available: Polaroid, 16mm movies, 35mm slides and movies, 4x5 and 8x10 transparencies, 70mm movies (for IMAX and Omnimax)
Is There a More Intuitive Way To Do Additive Colors Than RGB?

- **Hue**: The color type, ranging from 0 to 360 degrees.
- **Saturation**: The intensity of the color, ranging from 0 to 1.
- **Value**: The brightness of the color, ranging from 0 to 1.

```
float hsv[3], rgb[3];
HsvRgb(hsv, rgb);
0.0 ≤ s, v, r, g, b ≤ 1.0
0.0 ≤ h ≤ 360.0
```
Subtractive Colors

Subtractive Color (CMYK)
CMY Color Space

Color Paper Printing

- Uses subtractive colors
- Uses 3 or 4 passes
How Do Color Separations Work in Color Printing?

Printing the Four Colors

Wax

Toner

Toner

Sheets
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

CIE Chromaticity Diagram

- White Point
- 380 nm
- 520 nm
- 780 nm
CIE Chromaticity Diagram

Color Gamut for an SGI Monitor
La*b* Diagram

520 nm

White Point

780 nm

380 nm

OSU Logo

La*b* Diagram

ΔE\text{ab}^* \quad ΔL^* \quad Δa^* \quad Δb^*

Green \quad Yellow \quad Red \quad Blue
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 \( \Delta \) luminance
- Knowing this also helps if someone makes a grayscale photocopy of your color hardcopy
I sure hope that my life does not depend on being able to read this quickly and accurately!

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

\[ Y = 0.30 \times \text{Red} + 0.59 \times \text{Green} + 0.11 \times \text{Blue} \]

Luminance Table

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>White</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Red</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Green</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.59</td>
</tr>
<tr>
<td>Blue</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.70</td>
</tr>
<tr>
<td>Magenta</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.41</td>
</tr>
<tr>
<td>Orange</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Yellow</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.89</td>
</tr>
</tbody>
</table>
### ≈ Contrast Table

<table>
<thead>
<tr>
<th></th>
<th>Black</th>
<th>White</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0.00</td>
<td>1.00</td>
<td>0.30</td>
<td>0.59</td>
<td>0.11</td>
<td>0.70</td>
<td>0.41</td>
<td>0.60</td>
<td>0.89</td>
</tr>
<tr>
<td>White</td>
<td>1.00</td>
<td>0.00</td>
<td>0.70</td>
<td>0.41</td>
<td>0.89</td>
<td>0.30</td>
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<td>0.11</td>
</tr>
<tr>
<td>Red</td>
<td>0.30</td>
<td>0.70</td>
<td>0.00</td>
<td>0.29</td>
<td>0.19</td>
<td>0.40</td>
<td>0.11</td>
<td>0.30</td>
<td>0.59</td>
</tr>
<tr>
<td>Green</td>
<td>0.59</td>
<td>0.41</td>
<td>0.29</td>
<td>0.00</td>
<td>0.48</td>
<td>0.11</td>
<td>0.18</td>
<td>0.01</td>
<td>0.30</td>
</tr>
<tr>
<td>Blue</td>
<td>0.11</td>
<td>0.89</td>
<td>0.19</td>
<td>0.48</td>
<td>0.00</td>
<td>0.59</td>
<td>0.30</td>
<td>0.49</td>
<td>0.78</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.70</td>
<td>0.30</td>
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<td>0.00</td>
<td>0.29</td>
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<td>0.30</td>
<td>0.00</td>
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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
Use the Right Color Interpolation Method

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

R+G+B
R+B+G
G+R+B
G+B+R
B+R+G
B+G+R

Blue-White-Red Color Scale
A Gallery of Color Scales
Something Relatively New – The Haxby Color Scale

Here’s What’s Important:

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

Obvious:

Not obvious:
What in the World was *The Oregonian* Thinking When They Chose This Color Scale?

Source: 
The Oregonian, 
January 11, 2006

Fortunately, They Got Better At It …

Source: 
The Oregonian, 
October 31, 2006
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

[Diagram showing the effect of surrounding color on the perception of blue squares]
Color Receptors in the Cones

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<tr>
<td>High</td>
<td>420 nm</td>
<td>Blue</td>
</tr>
</tbody>
</table>

Beware of Mach Banding
Beware of Mach Banding

Actual Intensity

Perceived Intensity
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

• There is 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

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.
Do Not Display High Spatial Frequencies in Color

Be Aware of the Differences Between Color Gamuts –

Adapt by Deciding What is Most Important for Your Visualization
Color Gamut for a Monitor and Color Printer

Color CRT

Color Paper Hardcopy

Eye

Color-Preserving vs. Contrast-Preserving Gamut Mappings

Monitor colors to be printed

White Point

1 → 3
1
2
2

2 → 3 ?
2 → 4 ?
Some Basic Rules for Using NTSC Video

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
NTSC Cycles-of-Encoding per Scanline

<table>
<thead>
<tr>
<th>What</th>
<th>Cycles/Scanline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>267</td>
</tr>
<tr>
<td>Orange-Blue</td>
<td>96</td>
</tr>
<tr>
<td>Purple-Green</td>
<td>35</td>
</tr>
</tbody>
</table>

Gratuitous Color Pollution

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

\[ \text{doesn't mean you must use them all} \]
Good Color and Perception References


