Color
What is ‘Color’

**Color** is a fundamental attribute of human visual perception.

By fundamental we mean that it is so unique that its meaning cannot be fully appreciated without direct experience.

How would you describe color to a person who was blind since birth?
3 Properties of Color Perception

• **Hue**
  Qualitative, easily identified category of visual experience (Colloquially known as ‘color’; e.g. ‘red’, ‘green’, ‘blue’). Differs from black-gray-white. **Quickly now**: Name 10 ‘colors’…

• **Brightness**
  Intensity of the visual experience (e.g., ‘dim’, ‘bright’, ‘light’, ‘dark’)

• **Saturation**
  Purity of the hue experience (i.e., relative absence of ‘white’ or ‘gray’) (reciprocal of ‘added white’ required for a color-match-to-sample)
Color Stimulus Triad

- Illuminant Spectrum
- Surface Reflectance Spectrum
- Spectral Sensitivity of the Visual System
Illuminant Emission Spectra
“White” Light is a mixture of many different WAVELENGTHS

We perceive different wavelengths as different colors
Newtonian Light Spectrum
(ROY G BIV)
Spectra of Some Common Illuminants

- **Sunlight**
- **Tungsten light bulb**
- **Fluorescent light bulb**
- **Helium–neon laser**
Sunlight

Twilight/Overcast Sky

Clear Noon Sky

relative spectral power

wavelength (nm)
Incandescent Lamps
Surface Reflectance Spectra
Objects **REFLECT** some wavelengths but **ABSORB** others....
Surface Reflectance Spectra

- **Tomato**
  - Reflectance curve
  - Wavelength (nm): 400 to 700

- **Blue paper**
  - Reflectance curve
  - Wavelength (nm): 400 to 700

- **Violet rose**
  - Reflectance curve
  - Wavelength (nm): 400 to 700

- **Green paint**
  - Reflectance curve
  - Wavelength (nm): 400 to 700
The **Spectral Reflectance Profile** is the basic stimulus for Color Vision.
Visual Stimulus Spectrum = Illuminant x Surface Reflectance

- Tungsten light bulb
- Blue paper
- Colour signal
Additive vs. Subtractive Color Mixing

• Color Mixing Demo
Ideal “Yellow” Pigment

Ideal “Blue” Pigment

Residual “Green” Pigment resulting from mixing Yellow + Blue
Spectral Response of the Visual System
Newton’s Color Experiments

- Found that light was not “pure” but could be analyzed into separate component that appeared different in color [ROY G BIV]
- Combinations of “spectral colors” gave rise to perceived colors not observed in the spectrum
- “Non-spectral colors” were an emergent property of the human nervous system
- “Color wheel” is one of the first psychological theories in the classic scientific literature
Trichromatic Theory of Color

- Color perception emerges from the idiosyncratic discrimination of light wavelength in the retina

- Evidence strongly suggests that the retina must “encode” color based upon more than one type of wavelength-tuned photoreceptor

  \[\text{Univariance Principle}\]

- Additive color matching experiments suggest that three wavelength sensors are required

  [aka Trichromatic Theory]
Classic Color Demonstrations Explained by Trichromatic Mechanism

• Tristimulus Color Mixing Findings

  Maxwell Color Matching

• Fast Color Adaptation
  (Basis for Color Constancy)
Simulated Microspectrophotometry Analysis of Human Retina
3 Cones Revealed by MSP
Trichromatic Response to Spectral Stimulus

Colour signal

Absorption spectra

Cone signals

Signal Strength

Cone Type

Absorption spectra

Cone signals

Signal Strength

Cone Type
Color Metamers

**Colour signal**

![Graph showing energy vs. wavelength for blue paper](image)

**Cone signals**

![Bar chart showing signal strength for different cone types](image)
Color Specification Systems
(Hue, Saturation, Brightness)

- **CIE (1931) Chromaticity**
  \((x,y)\) captures hue x saturation

- **Munsell Color System**
  (18 Hues, 18 Chroma; 10 Values)

- **Pantone**
  (Proprietary Color Matching Standards)
CIE Color Matching Paradigm
(Specifying Tristimulus Values)
CIE Maxwellian Color Matching Functions
CIE (1931) Standardized Tristimulus Color Matching Functions
TRISTIMULUS VALUE = X,Y,Z

Normalization of XYZ into (x,y) Chromaticity Coordinates:

\[
\begin{align*}
x &= \frac{X}{X+Y+Z} \\
y &= \frac{Y}{X+Y+Z} \\
z &= \frac{Z}{X+Y+Z}
\end{align*}
\]

Since \( z = 1 - x - y \) then XYZ can be fully specified in the (x,y) plane.
Munsell = (Hue, Value, Chroma)

Munsell Hues
Munsell Book of Colors

Hue 5RP (Red-Purple)
(Most saturated: 5RP 5/26)

Hue 10YR (Yellow-Red)

Hue  
Value  
Chroma
Problems with Trichromatic Theory

• Hue Cancellation Effects (Hurvich & Jameson)
  Red+Green $\rightarrow$ Yellow (not reddish-green)
  Yellow+Blue $\rightarrow$ White (not yellow-blue)

• Complementary Color Afterimages

• Complex Color Contrast Effects (Land)

• “Blue” light discounted in Brightness Perception
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Complementary Color
Afterimages
Challenge for Simple Trichromatic Theory
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Experiments in Color Vision

Edwin Land
Scientific American (1960)
LONG AND SHORT RECORDS are provided by transparencies of these black-and-white photographs made through a red filter (top) and a green filter (bottom). In projection the long record (top) is illuminated by the longer of two wavelengths or bands of wavelengths, and the short record is illuminated by the shorter wavelengths or band of wavelengths.
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Opponent Process Theory

Information from Red, Green and Blue Cones is organized into three discrete channels before ascending to the visual cortex:

Two pairs of **OPPONENT COLOR channels** code for HUE

- Red vs. Green channel \( \text{L} \leftrightarrow \text{M} \) cones
- Blue vs. Yellow channel \( \text{S} \leftrightarrow \text{L}+\text{M} \) cones

One **ACHROMATIC channel** codes for BRIGHTNESS

- Black vs. White \( \text{L}+\text{M} \) in center-surround antagonism
DeValois & DeValois (1975)

Color-Opponent Cells in the LGN
Red-Green Ganglion Cell

Receptive field

Ganglion cell

Cones

M M L L M M L L M M L L
Blue-Yellow Ganglion Cell

Receptive field

Ganglion cell

Cone types: M, L, S

To LGN

B+  Y-  To LGN

Y+  B-  To LGN

B/Y  E  Y/B  E

M L S S  L M  S S L M S S
Achromatic Ganglion Cell
(Notice that Blue Light is “Discounted”)
Psychophysical vs. Physiological Results

DeValois & DeValois (1975)
Monkey LGN data

Boynton & Gordon’s (1965)
Color Naming Results

Present brief-flash of monochromatic light; Identify appearance using four color categories: RED, YELLOW, GREEN or BLUE
Bornstein (1975) Infant Color Vision Study

White light

Prism

Visible light spectrum

350 Violet
500 Green
600 Yellow
700 Red

Ultraviolet
Gamma rays
X rays
Ultra-violet rays
Infrared rays

Wavelength in nanometers

Physical properties of light
- Wavelength
- Amplitude
- Purity

Related perceptions
- Hue (color)
- Brightness
- Saturation

(a) Wavelength
(b) Physical properties of light
Dichromatic Color “Blindness”

Only TWO cone types available
3D color-space reduced to 2D color-space
(i.e., diminished color discrimination capability)

Prevalence

<table>
<thead>
<tr>
<th>Phenotype</th>
<th>Cone Deficiency</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protanopia</td>
<td>Missing L-cones</td>
<td>2%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Deuteranopia</td>
<td>Missing M-cones</td>
<td>6%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Tritanopia</td>
<td>Missing S-cones</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>
Trichromat

Red/Green

Dichromat

Source: www.vischeck.com/daltonize