Causes of colour

• The sensation of colour is caused by the brain.
• One way to get it is the response of the eye to the presence/absence of light at various wavelengths.
  • Dreaming, hallucination, etc.
  • Pressure on the eyelids
• Light could be
  • emitted with wavelengths absent (flourescent light vs. incandescent light)
  • differentially reflected - e.g. paint on a surface
  • differentially refracted - e.g. Newton’s prism
  • subject to wavelength dependent specular reflection (most metals).
  • Flourescence -
    • invisible wavelengths absorbed and reemitted at visible wavelengths.
  • Phosphorescence (ditto, energy, longer timescale)
<table>
<thead>
<tr>
<th>XXXXX</th>
<th>BLUE</th>
<th>YELLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXXXX</td>
<td>GREEN</td>
<td>BLUE</td>
</tr>
<tr>
<td>XXXXX</td>
<td>RED</td>
<td>GREEN</td>
</tr>
<tr>
<td>XXXXX</td>
<td>YELLOW</td>
<td>RED</td>
</tr>
<tr>
<td>XXXXX</td>
<td>BLUE</td>
<td>GREEN</td>
</tr>
<tr>
<td>XXXXX</td>
<td>RED</td>
<td>BLUE</td>
</tr>
<tr>
<td>XXXXX</td>
<td>GREEN</td>
<td>BLUE</td>
</tr>
<tr>
<td>XXXXX</td>
<td>BLUE</td>
<td>YELLOW</td>
</tr>
<tr>
<td>XXXXX</td>
<td>YELLOW</td>
<td>RED</td>
</tr>
<tr>
<td>XXXXX</td>
<td>RED</td>
<td>GREEN</td>
</tr>
</tbody>
</table>
Sunlight
Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

from “Colour in nature”, P. Farrant
Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

from “Colour in nature”, P. Farrant
Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

from “Colour in nature”, P. Farrant
from “Colour in nature”, P. Farrant
Fig. 1.16 Transmission: light waves of all colours pass through a colourless transparent medium.
from “Colour in nature”, P. Farrant
Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).
Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).
Fig. 10.1 The iridescence-producing structure of peacock feathers comprises evenly spaced melanin rods and air spaces, embedded in keratin.

from “Colour in nature”, P. Farrant
Fig. 10.2 The iridescence-producing structure of (a) sunbirds’ feathers comprises layers of solid melanin platelet embedded in keratin, whereas that of (b) hummingbirds’ consists of hollow melanin-line flat discs, also embedded in keratin.

Fig. 10.3 Iridescence in morpho butterflies is due to sloping layers within ridges on the wing.
PL. 10.3 Melanin platelets between layers of keratin provide the structural basis of iridescence in sunbirds. Photo W. Farrant

from “Colour in nature”, P. Farrant
PL. 10.5 In pigeons, relatively large granules of melanin produce some interference colours.
Photo: P. Farrant.

from “Colour in nature”, P. Farrant
PL. 10.2 Goatfish with iridescent eyes; light is reflected from regular layers of guanine particles.

from “Colour in nature”, P. Farrant
Scattering (again) causing Tyndall Blue

(notice because scattering occurs at an interface, all media could be translucent e.g. fresh snow)
from “Colour in nature”, P. Farrant
from “Colour in nature”, P. Farrant
Radiometry for colour

- All definitions are now “per unit wavelength”
- All units are now “per unit wavelength”
- All terms are now “spectral”
- Radiance becomes spectral radiance
  - watts per square meter per steradian per unit wavelength
- Radiosity --- spectral radiosity
Color: film color mode

• Hering, Helmholtz: Color appearance is strongly affected by other nearby colors, by adaptation to previous views, and by “state of mind”

• Film color mode:
  • View a colored surface through a hole in a sheet, so that the colour looks like a film in space; controls for nearby colors, and state of mind.
    • Other modes:
      • Surface colour
      • Volume colour
      • Mirror colour
      • Illuminant colour
Trichromacy

- By experience, it is possible to match almost all colors, viewed in film mode using only three primary sources - the principle of trichromacy
- Other modes may have more dimensions
  - Glossy-matte
  - Rough-smooth
  - Most of what follows discusses film mode.
Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - e.g. Kodak yellow, painting a house.
- Of the order of 10 color names are widely recognized by English speakers - other languages have fewer/more, but not much more.
  - There’s a great deal of structure to the way colour is spoken about (Berlin-Kay), but not much precision
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - Choosing pixel values to reproduce/evoke experiences, e.g. an architectural model.
  - Consistency in user interfaces, monitor-printer consistency, monitor-lino consistency, etc.
Additive and subtractive matching

- Choose colors A, B, C such that no two can be mixed to match the third - Primaries.
  - Many colors can be represented as a mixture of A, B, C: \( M = aA + bB + cC \)
  - This is additive matching.
  - Gives a color description system - two people who agree on A, B, C need only supply \((a, b, c)\) to describe a color.

- Some colors can’t be matched like this:
  - Instead, must write: \( M + aA = bB + cC \)
  - This is subtractive matching.
  - Interpret this as \((-a, b, c)\)
  - Problem for building monitors: Choose R, G, B such that positive linear combinations match a large set of colors
Grassman’s Laws

- For colour matches made in film colour mode:
  - symmetry: \( A=B \iff B=A \)
  - transitivity: \( A=B \) and \( B=C \) \( \implies \) \( A=C \)
  - proportionality: \( A=B \iff tA=tB \)
  - additivity: if any two (or more) of the statements
    - \( A=B \),
    - \( C=D \),
    - \( (A+C)=(B+D) \) are true, then so is the third
Color matching functions

• Choose primaries, say A, B, C
• Given energy function, $E$
  • What amounts of primaries will match it?
  • For each wavelength, determine how much of A, of B, and of C is needed to match light of that wavelength alone.
  • Now match each wavelength in $E$, and sum
Color spaces

- **Linear color spaces**
  - describe colors as linear combinations of primaries
  - Choice of primaries=choice of color matching functions=choice of color space
  - Color matching functions all within linear transformations
- **RGB:**
  - primaries are monochromatic, 645.2nm, 526.3nm, 444.4nm.
  - Color matching functions have negative parts
  - some colors can be matched only subtractively.
- **CIE XYZ:**
  - Color matching functions are positive everywhere, but primaries are imaginary.
  - Usually draw x, y, where $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$
CIE x, y
Non-linear colour spaces

- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - because hue relations are naturally expressed in a circle

- Uniform: equal (small!) steps give the same perceived color changes.

- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light
HSV hexcone
CIE $u'v'$ which is a projective transform of $x, y$
Munsell color space
Color books

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table shows a grid with various color samples arranged in a pattern.
Subtractive mixing

- Inks subtract light from white, whereas phosphors glow.
- Linearity depends on pigment properties - often hugely non-linear.
- Inks:
  - Cyan=White-Red,
  - Magenta=White-Green,
  - Yellow=White-Blue.
- For a good choice of inks, and good registration, matching is linear and easy
  - eg. C+M+Y=White-White=Black    C+M=White-Yellow=Blue
  - Usually require CMY and Black, because colored inks are more expensive, and registration is hard
Mixing pigments in CIE with Titanium Dioxide
The color of objects

- Colored light arriving at the camera involves two effects
  - The color of the light source
  - The color of the surface
  - Changes caused by different colored light sources can be large
Leaf reflectances
Different red flowers

Petal reflectances

![Graph showing petal reflectances for different red flowers.](image)
Petal reflectances
Different lights on uniform reflectances
Different lights on blue flower
Different lights on green leaf
Color receptors and color deficiency

- **Trichromacy is justified** -
  - in color normal people, there are three types of color receptor (shown by molecular biologists).

- **Some people have fewer;**
  - most common deficiency is red-green color blindness in men. Red and green receptor genes are carried on the X chromosome. Most red-green color blind men have two red genes or two green genes. Yields an evolutionary story.

- **Deficiency**
  - can be caused by CNS, by optical problems in the eye, or by absent receptors

- **Other color deficiencies:**
  - Anomalous trichromacy
  - Achromatopsia
  - Macular degeneration
Color receptors

Principle of univariance: cones give the same kind of response, in different amounts, to different wavelengths. Output of cone is obtained by summing over wavelengths. Responses measured in a variety of ways.
Finding Specularities

• Assume we are dealing with dielectrics
  • specularly reflected light is the same colour as the source
• Reflected light has two components
  • diffuse
  • specular
  • and we see a weighted sum of these two
Illuminant color

Diffuse component
Diffuse region

Boundary of specularity
Constancy

- We observe the colour of the light reflected from surfaces
- But we want surface colour
- problem is known as colour constancy
- Multiple types of report
  - The colour of paint I would use is
  - The colour of the surface is
  - The colour of the light is

- Problem is well understood, and largely solved
  - solutions not currently used very widely
Land’s Demonstration

White light

Photometer reading (1, .3, .3)

Audience name "Red"

Coloured light

Photometer reading (1, .3, .3)

Audience name "Blue"
Lightness Constancy

- Lightness constancy
  - how light is the surface, independent of the brightness of the illuminant
  - issues
    - spatial variation in illumination
    - absolute standard
  - Human lightness constancy is very good
- Assume
  - frontal 1D “Surface”
  - slowly varying illumination
  - quickly varying surface reflectance
Thresholded $\frac{d \log p}{dx}$

Integrate This to get
Lightness Constancy in 2D

- Differentiation, thresholding are easy
  - integration isn’t
  - problem - gradient field may no longer be a gradient field
- One solution
  - Choose the function whose gradient is “most like” thresholded gradient
  - This yields a minimization problem
  - How do we choose the constant of integration?
    - average lightness is grey
    - lightest object is white
    - ?
Simplest colour constancy

- Adjust three receptor channels independently
  - Von Kries
  - Where does the constant come from?
    - White patch
    - Averages
    - Some other known reference (faces, nose)
We need a model of interaction between illumination and surface colour

- finite dimensional linear model seems OK
- FDLM
  - surface spectral albedo is a weighted sum of basis functions
  - illuminant spectral exitance is a weighted sum of basis functions
  - This gives a quite simple form to interaction between the two
General strategies

• Determine what image would look like under white light
• Assume
  • that we are dealing with flat frontal surfaces
  • We’ve removed specularities
  • no variation in illumination
• We need some form of reference
  • brightest patch is white
  • spatial average is known
  • gamut is known
  • specularities