Causes of color

- The sensation of color is caused by the brain.
- Some ways to get this sensation include:
  - Pressure on the eyelids
  - Dreaming, hallucinations, etc.
- Main way to get it is the response of the visual system to the presence/absence of light at various wavelengths.

- Light could be produced in different amounts at different wavelengths (compare the sun and a fluorescent light bulb).
- Light could be differentially reflected (e.g. some pigments).
- It could be differentially refracted - (e.g. Newton’s prism)
- Wavelength dependent specular reflection - e.g. shiny copper penny (actually most metals).
- Fluorescence - light at invisible wavelengths is absorbed and reemitted at visible wavelengths.
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
Black body radiators

• Construct a hot body with near-zero albedo (black body)
  – Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.

• The spectral power distribution of light leaving this object is a simple function of temperature

\[ E(l) = \frac{1}{\lambda^5 \exp(hc/\lambda kT) - 1} \]

• This leads to the notion of color temperature --- the temperature of a black body that would look the same
Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow". Mnemonic is "Richard of York got blisters in Venice".
Relative spectral power of two standard illuminant models --- D65 models sunlight, and illuminant A models incandescent lamps. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the “colors of the rainbow”.

Violet    Indigo Blue   Green   Yellow   Orange   Red
Measurements of relative spectral power of four different artificial illuminants, made by H. Sugiura. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm.
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.
The appearance of colors

• Color appearance is strongly affected by (at least):
  – other nearby colors,
  – adaptation to previous views
  – “state of mind”
• We show several demonstrations in what follows.

• **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
The appearance of colors

- 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
- 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.
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Why specify color numerically?

• Accurate color reproduction is commercially valuable
  – Many products are identified by color (“golden” arches;
• Few color names are widely recognized by English speakers -
  – About 10; other languages have fewer/more, but not many more.
  – It’s common to disagree on appropriate color names.

• Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  – How do we ensure that everyone sees the same color?
Color matching experiments - I

- Show a split field to subjects; one side shows the light whose color one wants to measure, the other a weighted mixture of primaries (fixed lights).
- Each light is seen in film color mode.
Color matching experiments - II

• Many colors can be represented as a mixture of A, B, C

• write

\[ M = a \, A + b \, B + c \, C \]

where the = sign should be read as “matches”

• 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.
Subtractive matching

• Some colors can’t be matched like this: instead, must write
  \[ M + a \ A = b \ B + c \ C \]

• 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
The principle of trichromacy

• Experimental facts:
  – Three primaries will work for most people if we allow subtractive matching
    • Exceptional people can match with two or only one primary.
    • This could be caused by a variety of deficiencies.
  – Most people make the same matches.
    • There are some anomalous trichromats, who use three primaries but make different combinations to match.
Grassman’s Laws

• For colour matches made in film colour mode:
  – symmetry: \[ U=V \iff V=U \]
  – transitivity: \[ U=V \text{ and } V=W \implies U=W \]
  – proportionality: \[ U=V \iff tU=tV \]
  – additivity: if any two (or more) of the statements
    \[
    U=V, \\
    W=X, \\
    (U+W)=(V+X)
    \]
    are true, then so is the third

• These statements are as true as any biological law. They mean that color matching in film color mode is linear.
Linear color spaces

- A choice of primaries yields a linear color space --- the coordinates of a color are given by the weights of the primaries used to match it.
- Choice of primaries is equivalent to choice of color space.

- **RGB:** primaries are monochromatic energies are 645.2nm, 526.3nm, 444.4nm.
- **CIE XYZ:** Primaries are imaginary, but have other convenient properties. Color coordinates are (X,Y,Z), where X is the amount of the X primary, etc.
  - Usually draw x, y, where
    - $x = X/(X+Y+Z)$
    - $y = Y/(X+Y+Z)$
Color matching functions

- Choose primaries, say A, B, C
- Given energy function, 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.

Then our match is:

\[
\{ a(l)E(l)dl \} A + \{ b(l)E(l)dl \} B + \{ c(l)E(l)dl \} C
\]
RGB: primaries are monochromatic, energies are 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

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$
A qualitative rendering of the CIE (x,y) space. The blobby region represents visible colors. There are sets of (x, y) coordinates that don’t represent real colors, because the primaries are not real lights (so that the color matching functions could be positive everywhere).
A plot of the CIE (x,y) space. We show the spectral locus (the colors of monochromatic lights) and the black-body locus (the colors of heated black-bodies). I have also plotted the range of typical incandescent lighting.
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
Uniform color spaces

• McAdam ellipses (next slide) demonstrate that differences in x,y are a poor guide to differences in color
• Construct color spaces so that differences in coordinates are a good guide to differences in color.
Variations in color matches on a CIE x, y space. At the center of the ellipse is the color of a test light; the size of the ellipse represents the scatter of lights that the human observers tested would match to the test color; the boundary shows where the just noticeable difference is. The ellipses on the left have been magnified 10x for clarity; on the right they are plotted to scale. The ellipses are known as MacAdam ellipses after their inventor. The ellipses at the top are larger than those at the bottom of the figure, and that they rotate as they move up. This means that the magnitude of the difference in x, y coordinates is a poor guide to the difference in color.
CIE $u'v'$ which is a projective transform of $x, y$. We transform $x, y$ so that ellipses are most like one another. Figure shows the transformed ellipses.
Color receptors and color deficiency

- Trichromacy is justified - in color normal people, there are three types of color receptor, called cones, which vary in their sensitivity to light at different wavelengths (shown by molecular biologists).
- Deficiency can be caused by CNS, by optical problems in the eye, or by absent receptor types
  - Usually a result of absent genes.
- Some people have fewer than three types of receptor; most common deficiency is red-green color blindness in men.
- Color deficiency is less common in women; red and green receptor genes are carried on the X chromosome, and these are the ones that typically go wrong. Women need two bad X chromosomes to have a deficiency, and this is less likely.
Color receptors

• **Principle of univariance:** cones give the same kind of response, in different *amounts*, to different wavelengths. The output of the cone is obtained by summing over wavelengths. Responses are measured in a variety of ways (comparing behaviour of color normal and color deficient subjects).

• All experimental evidence suggests that the response of the k’th type of cone can be written as

\[
\int \rho_k(l)E(l)dl
\]

where \( \rho_k(l) \) is the sensitivity of the receptor and spectral energy density of the incoming light.
Color receptors

- Plot shows relative sensitivity as a function of wavelength, for the three cones. The S (for short) cone responds most strongly at short wavelengths; the M (for medium) at medium wavelengths and the L (for long) at long wavelengths.
- These are occasionally called B, G and R cones respectively, but that’s misleading - you don’t see red because your R cone is activated.
Adaptation phenomena

- The response of your color system depends both on spatial contrast and what it has seen before (adaptation).
- This seems to be a result of coding constraints --- receptors appear to have an operating point that varies slowly over time, and to signal some sort of offset. One form of adaptation involves changing this operating point.
- Common example: walk inside from a bright day; everything looks dark for a bit, then takes its conventional brightness.
Viewing coloured objects

- Assume diffuse+specular model

- Specular
  - specularities on dielectric objects take the colour of the light
  - specularities on metals can be coloured

- Diffuse
  - colour of reflected light depends on both illuminant and surface
  - people are surprisingly good at disentangling these effects in practice (colour constancy)
  - this is probably where some of the spatial phenomena in colour perception come from
When one views a colored surface, the spectral radiance of the light reaching the eye depends on both the spectral radiance of the illuminant, and on the spectral albedo of the surface. We’re assuming that camera receptors are linear, like the receptors in the eye. This is usually the case.
Subtractive mixing of inks

• Inks subtract light from white, whereas phosphors glow.
• Linearity depends on pigment properties
  – inks, paints, 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
• For good choice of inks, there is a linear transform between XYZ and CMY
Finding Specularities

• Assume we are dealing with dielectrics
  – specularly reflected light is the same color as the source

• Reflected light has two components
  – diffuse
  – specular
  – and we see a weighted sum of these two

• Specularities produce a characteristic dogleg in the histogram of receptor responses
  – in a patch of diffuse surface, we see a color multiplied by different scaling constants (surface orientation)
  – in the specular patch, a new color is added; a “dog-leg” results
Computer Vision - A Modern Approach
Set: Color
Slides by D.A. Forsyth
Color constancy

- Assume we’ve identified and removed specularities
- The spectral radiance at the camera depends on two things
  - surface albedo
  - illuminant spectral radiance
  - the effect is much more pronounced than most people think (see following slides)
- We would like an illuminant invariant description of the surface
  - e.g. some measurements of surface albedo
  - need a model of the interactions
- Multiple types of report
  - The colour of paint I would use is
  - The colour of the surface is
  - The colour of the light is
Notice how the color of light at the camera varies with the illuminant color; here we have a uniform reflectance illuminated by five different lights, and the result plotted on CIE x,y.
Notice how the color of light at the camera varies with the illuminant color; here we have the blue flower illuminated by five different lights, and the result plotted on CIE x,y. Notice how it looks significantly more saturated under some lights.
Notice how the color of light at the camera varies with the illuminant color; here we have a green leaf illuminated by five different lights, and the result plotted on CIE x,y.
Computer Vision - A Modern Approach
Set: Color
Slides by D.A. Forsyth
Computer Vision - A Modern Approach
Set: Color
Slides by D.A. Forsyth
Land’s Demonstration

Photometer reading (1, .3, .3)

Audience name "Red"

White light

Computer Vision - / Set: Slides by D

Coloured light

Audience name "Blue"

Photometer reading (1, .3, .3)
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)
Colour Constancy - I

• We need a model of interaction between illumination and surface colour
  – finite dimensional linear model seems OK

• Finite Dimensional Linear Model (or 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
Finite Dimensional Linear Models

Receptor response of k'th receptor class

\[ \int \sigma(\lambda) \rho(\lambda) E(\lambda) d\lambda \]

Incoming spectral radiance \( E(\lambda) \)

Outgoing spectral radiance \( E(\lambda) \rho(\lambda) \)

Spectral albedo \( \rho(\lambda) \)
General strategies

• Determine what image would look like under white light
• Assume
  – that we are dealing with flat frontal surfaces
  – We’ve identified and removed specularities
  – no variation in illumination

• We need some form of reference
  – brightest patch is white
  – spatial average is known
  – gamut is known
  – specularities
Obtaining the illuminant from specularities

- Assume that a specularity has been identified, and material is dielectric.
- Then in the specularity, we have

Assuming
- we know the sensitivities and the illuminant basis functions
- there are no more illuminant basis functions than receptors
- This linear system yields the illuminant coefficients.
Obtaining the illuminant from average color assumptions

- Assume the spatial average reflectance is known
- We can measure the spatial average of the receptor response to get
- Assuming
  - \( g_{ijk} \) are known
  - average reflectance is known
  - there are not more receptor types than illuminant basis functions
- We can recover the illuminant coefficients from this linear system
Computing surface properties

- Two strategies
  - compute reflectance coefficients
  - compute appearance under white light.
- These are essentially equivalent.
- Once illuminant coefficients are known, to get reflectance coefficients we solve the linear system.

- to get appearance under white light, plug in reflectance coefficients and compute.