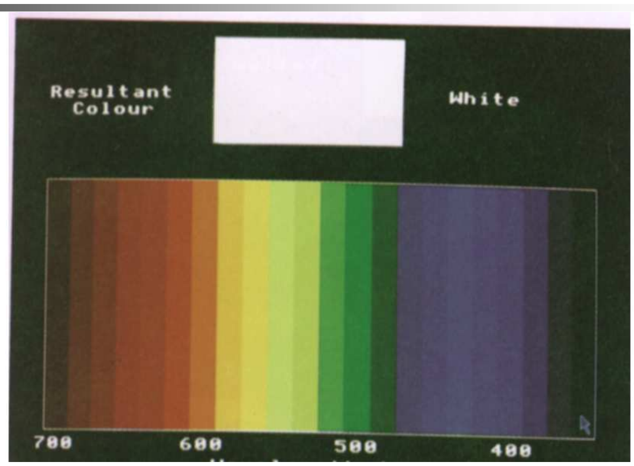
Why Care About Color?

- Accurate color reproduction is commercially valuable - e.g. Kodak yellow, painting a house
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art
- Color provides useful information for many aspects of computer vision
  - Segmentation – deciding which pieces of image represent which things
  - Recognition - deciding what something is
  - Image synthesis – e.g., texture synthesis

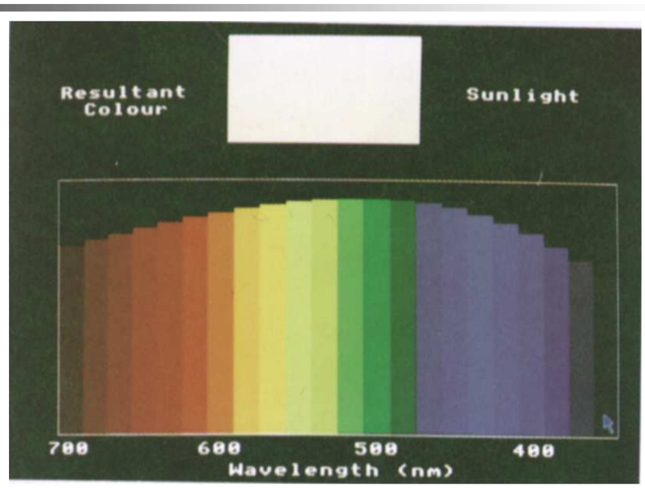
Light and Color

- The *distribution of frequencies of light* determines its "color"
  - The distribution is called the *spectrum* of the light
  - Frequency, wavelength, energy all related

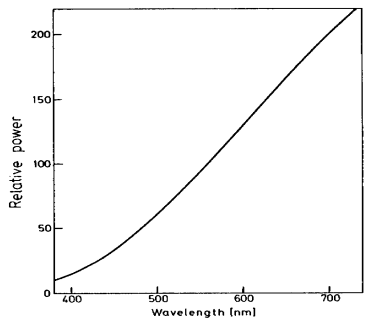
White Light Spectrum



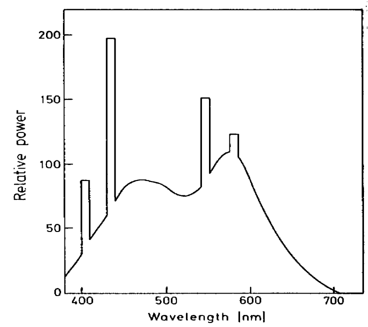
Sunlight Spectrum



More spectra



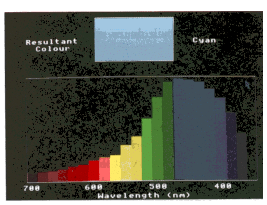
Tungsten-filament lamp



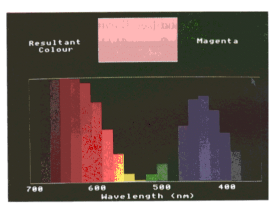
Daylight fluorescent lamp

Absorption spectra: real pigments

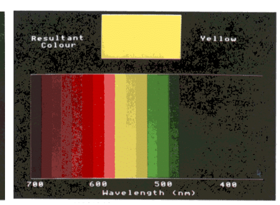
cyan



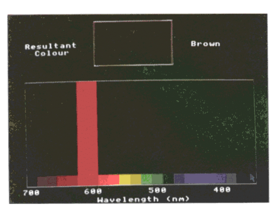
magenta



yellow

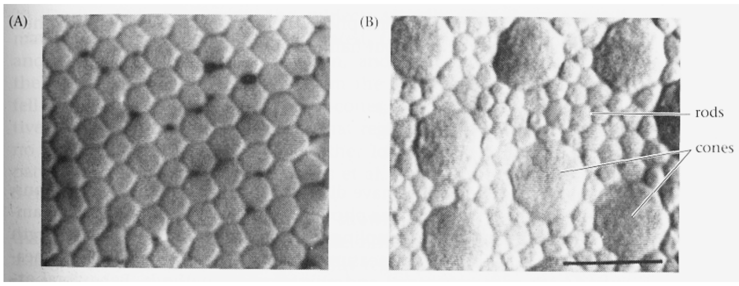


brown



Seeing in Color

- The eye contains rods and cones
  - Rods work at low light levels and do not see color
  - Cones come in three types (experimentally and genetically proven), each responds in a different way to a given spectrum

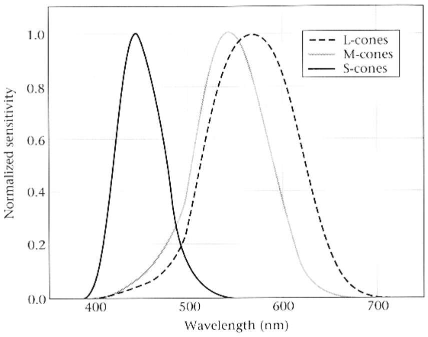


Color receptors

- Output of cone is obtained by summing over wavelengths:

$$\int \rho_k(\lambda) E(\lambda) d\lambda$$

- Experimentally determined in a variety of ways



Color Perception

- Colors may be perceived differently:
  - Affected by other nearby colors
  - Affected by adaptation to previous views
  - Affected by "state of mind"
- Experiment:
  - Subject views a colored surface through a hole in a sheet, so that the color looks like a film in space
  - Investigator controls for nearby colors, and state of mind

Color Deficiency

- Some people are missing one type of receptor
  - Most common 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
  - If you're missing the red or green receptor, which colors can't you distinguish?
- Other color deficiencies
  - Anomalous trichromacy, Achromatopsia, Macular degeneration
  - Deficiency can be caused by central nervous system, by optical problems in the eye, or by absent receptors

Trichromacy

- Experiment:
  - Show a target color beside a user controlled color
  - User has knobs that add primary sources to their color
  - Ask the user to match the colors
- By experience, it is possible to match almost all colors using only three primary sources - the principle of trichromacy
  - Sometimes, have to add light to the target
- How many numbers do we need to specify a color completely? What else must we know?
- What aspect of computer monitors, TVs, flat panel-displays, color digital cameras, etc. does this explain?

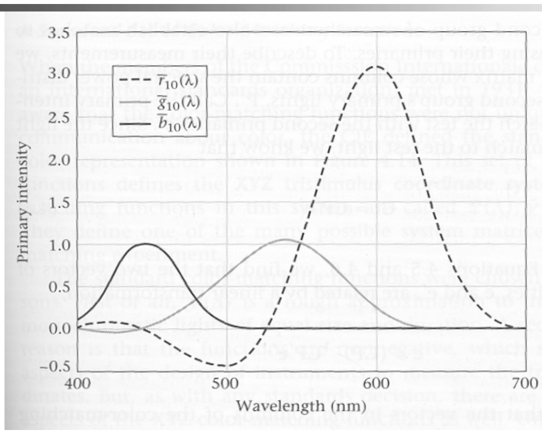
The Math of Trichromacy

- Write primaries as A, B and C
- Many colors can be represented as a mixture of A, B, C: M=aA+bB+cC (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, write: M+aA=bB+cC (Subtractive matching)
  - Interpret this as (-a, b, c)
  - Problem for reproducing colors! Why?

Color Matching

- The most common primaries in computer science are Red (645.16nm), Green (526.32nm) and Blue (444.44nm)
- Given a spectrum, how do we determine how much each of R, G and B to use to match it?
- First step:
  - For a light of unit intensity at each wavelength, ask people to match it with R, G and B primaries
  - Result is three functions, r(λ), g(λ) and b(λ), the RGB *color matching functions*

RGB Color Matching Functions



4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

Computing the Matching

- The spectrum function that we are trying to match, E(λ), gives the amount of energy at each wavelength
- The RGB color matching functions tell us how much of each primary is needed to match at each wavelength
- Hence, if the "color" due to E(λ) is E, the match is:

$$\mathrm{E}=\left(\int r(\lambda)E(\lambda)d\lambda\right)\mathrm{R}+\left(\int g(\lambda)E(\lambda)d\lambda\right)\mathrm{G}+\left(\int b(\lambda)E(\lambda)d\lambda\right)\mathrm{B}$$

The amount of red to use

The amount of blue to use

The amount of green to use

Color Spaces

- Taking linear combinations of R, G and B defines the RGB color space
  - The range of perceptible colors generated by adding some part each of R, G and B
- If R, G and B correspond to a monitor's phosphors (monitor RGB), then the space is the range of colors displayable on the monitor
  - Note that the color matching functions will *always* tell you how much RGB you need for any spectrum, but you may not have enough power to provide it, or you might need negative light

RGB Color Space

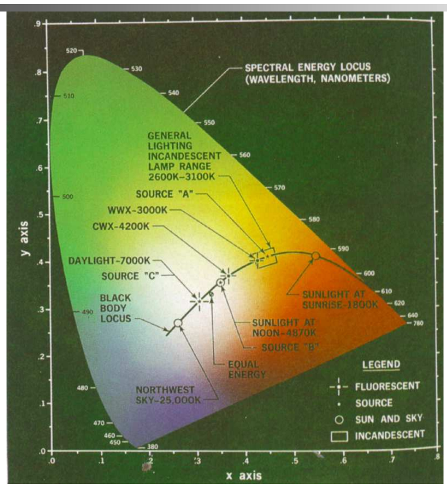
Problems with RGB

- Only a small range of the potential perceivable colors can be represented (particularly for monitor RGB)
- Perceptually non-linear
  - Two points a certain distance apart in one part of the space may be perceptually different
  - Two other point, the same distance apart in another part of the space, may be perceptually the same
  - In other words, a sensible distance metric on the space is almost impossible to come up with
  - A broader question is: How do you measure the difference between colors? How far is red from green? From blue?

CIE XYZ Color Space

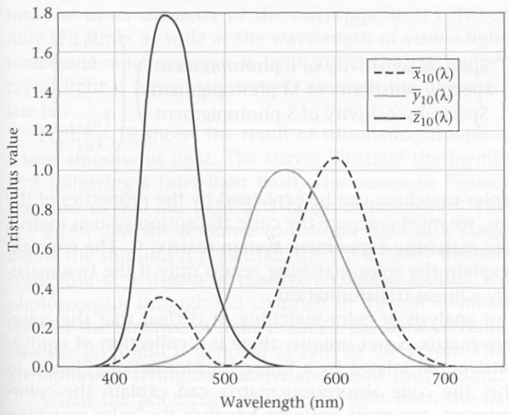
- Defined in 1931 to describe the full space of perceptible colors
  - Revisions now used by color professionals
- Color matching functions are everywhere positive
  - Cannot produce the primaries – need negative light!
  - But, can still describe a color by its matching weights
  - Y component intended to correspond to intensity
- Most frequently set x=X/(X+Y+Z) and y=Y(X+Y+Z)
  - x,y are coordinates on a constant brightness slice

CIE x, y



Note: This is a representation on a projector with limited range, so the right colors are not being displayed

CIE Matching Functions



4.14 THE XYZ STANDARD COLOR-MATCHING FUNCTIONS. In 1931 the CIE standardized a set of color-matching functions for image interchange. These color-matching functions are called $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Industrial applications commonly describe the color properties of a light source using the three primary intensities needed to match the light source that can be computed from the XYZ color-matching functions.

Qualitative features of CIE x, y

- Linearity implies that colors obtainable by mixing lights with colors A, B lie on line segment with endpoints at A and B
- Monochromatic colors (spectral colors) run along the “Spectral Locus”
- Dominant wavelength = Spectral color that can be mixed with white to match
- Purity = (distance from C to spectral locus)/(distance from white to spectral locus)
- Wavelength and purity can be used to specify color.
- Complementary colors=colors that can be mixed with C to get white

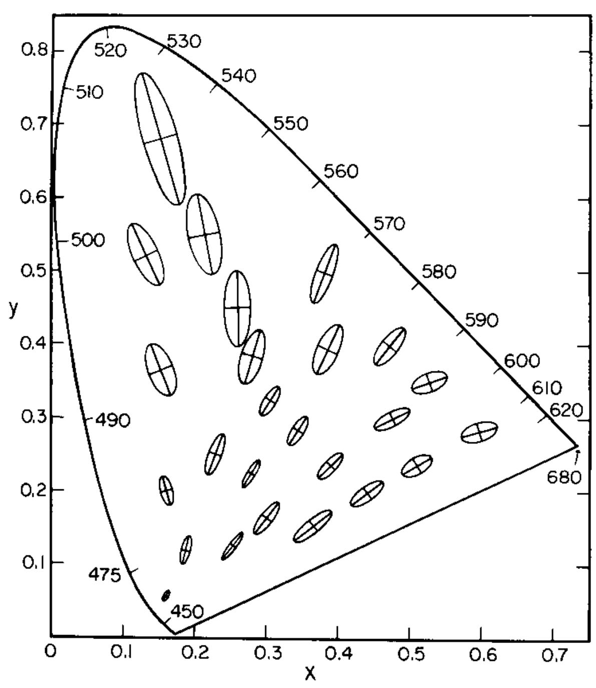
HSV Color Space (Alvy Ray Smith, 1978)

- Hue: the color family: red, yellow, blue…
- Saturation: The purity of a color: white is totally unsaturated
- Value: The intensity of a color: white is intense, black isn't
- Space looks like a cone
  - Parts of the cone can be mapped to RGB space
- Idea is that HSV coordinates directly capture the relevant properties of the color

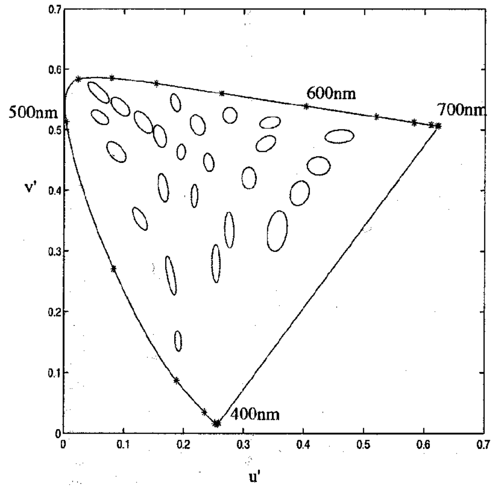
HSV Color Space

Uniform Color Spaces

- Color spaces in which distance in the space corresponds to perceptual "distance"
- Only works for local distances
  - How far is red from green? Is it further than red from blue?
- Use MacAdams ellipses to define perceptual distance



MacAdam Ellipses (scaled by a factor of 10) on CIE x, y



CIE u'v'
is a non-linear
color space
where color
differences are
more uniform

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \frac{1}{X + 15Y + 3Z} \begin{bmatrix} 4X \\ 9Y \end{bmatrix}$$