Matching is only for "aperture" color

- When color is viewed in the context of other colors numerous effects occur which complicate the characterization of color (simultaneous contrast, color constancy, etc)
- Other complications include chromatic aberration in the eye and different spatial resolution for different colors (these are linked)

Colour Reproduction

Key point--color reproduction is based on "metamerism"

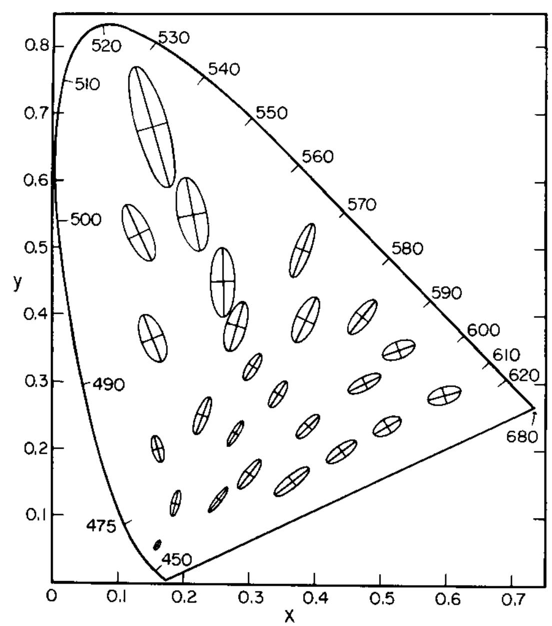
Metameric match--colors which match, despite different spectra.

Duplicating spectra would work, but for practical reasons, we duplicate the match.

For reflective surfaces, e.g prints, this means that the match can change if the illumination changes.

The quest for uniform colour spaces

- Uniform: equal (small!) steps give the same perceived color changes.
- XYZ is not uniform!
- Uniformity only applied to small differences. There is no theory for numerically deciding if yellow is perceptually closer to green or red.



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

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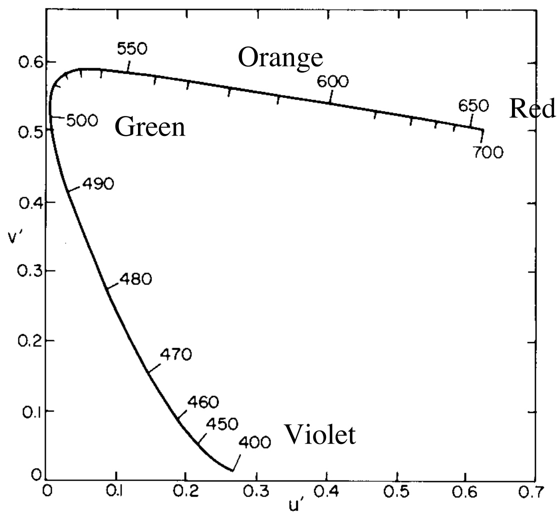

CIE u'v' is a linear colour space where colour differences are more uniform

(u', v') =(4 X/(X+15 Y +3 Z), 9 Y/(X+15Y+3 Z))

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Non-linear colour spaces

- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - hue relations are naturally expressed in a circle
  - popular in graphics
  - a variety of similar but different formulas are available for converting between RGB and HSV
- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light
- L*a*b: Another attempt to approximate uniformity
  - popular in colour science

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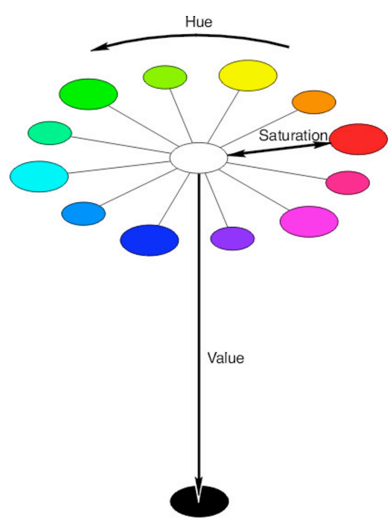
HSV (cont)



From http://www2.ncsu.edu:8010/scivis/lessons/colormodels/

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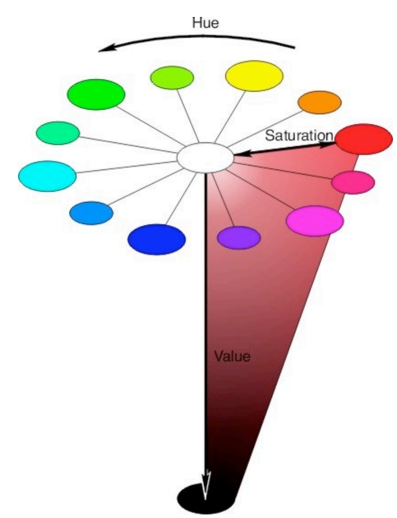
HSV (cont)



From http://www2.ncsu.edu:8010/scivis/lessons/colormodels/

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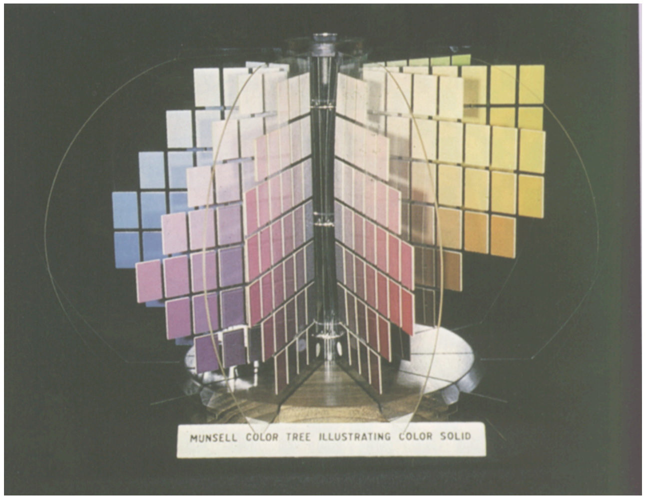
Munsell color space



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Monitor Gamma

A typical image encoding is **NOT** linear. Often a gamma correction is included. This leads to no end of confusion.

A “gamma” corrected image is ready to drive a CRT monitor, and has advantages that quantization (8 bits) errors are *roughly* uniformly distributed--that fact that this works is a convenient accident.

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Monitor Gamma

Due to the physics involved, CRT monitor brightness is proportional to voltage^(2.5)

This is further hacked to give the “standard” gamma of 2.2

So, if an image looks good on a CRT, it is likely to be non-linear by pow(1/2.2)

LCD--more linear, but then hardware/software can be hacked to be like CRT

Confusing? Yes!

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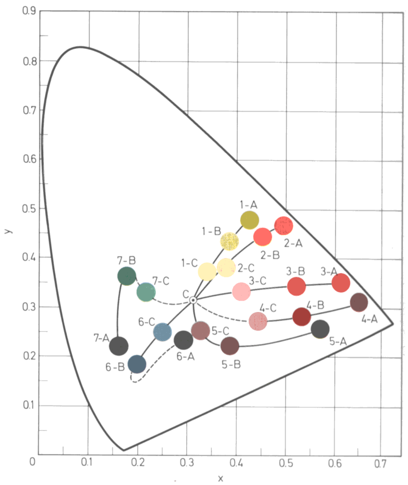
Subtractive mixing

- Treatment so far has been for additive mixing
- Inks subtract light from white.
- Linearity depends on pigment properties - often non-linear!
- Typical system (printers)
  - Cyan = White – Red
  - Magenta = White – Green
  - Yellow = White – Blue.
- Usually have black also, because colored inks are more expensive, black is very comon, and registration is hard
- For a good choice of inks, matching is not too from linear
- Printers can have both additive and subtractive qualities

Mixing pigments in CIE



Color matching is linear, but combining pigments is not necessarily linear like mixing light .

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Device independent colour imaging

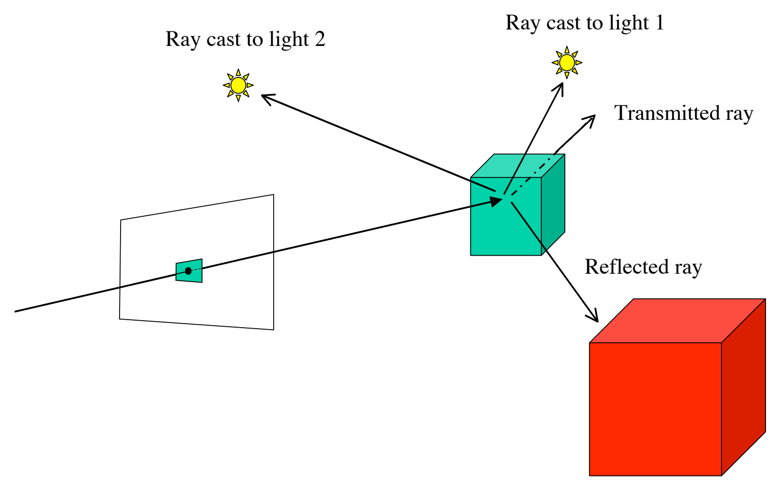
- Problem: ensure that colours on a display, printer, etc. give the same experience that a viewer would have seeing relevant light spectra
- Difficulty: limited gamuts of most output devices
- Strategy: exploit a model of human experience
  - Simple model: The CIE XYZ matching paradigm
    - Being implemented in “Color Management Systems”
  - These try to relieve the user of the different color capabilities of devices
  - Complicated because every device needs to register properly with the CMS
- Deficiencies--as we have seen, the CIE systems does not count for spatial effects, illumination environments, etc., and these are important
- Some progress is being made but the models tend to be complicated

Shading values for colored surfaces

- Simplest:
  - Use appropriate shading model in 3 channels, instead of one
  - Implies red albedo, green albedo, blue albedo, etc.
  - Works because the shading model is independent of wavelength.
  - Can lead to somewhat inaccurate colour reproduction in some cases - particularly coloured light on coloured surfaces
- Better
  - Use appropriate shading model at many different wavelength samples - 7 is usually enough
  - Estimate receptor response in eye using sum over wavelength
  - Set up pixel value to generate that receptor response

Recursive ray tracing

H&B, page 597



Recursive ray tracing rendering algorithm

- Cast ray from pinhole (projection center) through pixel, determine nearest intersection
- Compute components by casting rays
  - to sources = shadow ray (diffuse and for specular lobe)
  - along reflected direction = reflected ray
  - along transmitted dir = refracted ray
- Determine each component and add them up with contribution from ambient illumination.
- To determine some of the components, the ray tracer must be called **recursively**.

Recursive ray tracing rendering (cont)

- Recursion needs to stop at some point!
- Contributions die down after multiple bounces---there is no such thing as a perfect reflector---so we either set mirror reflections to be less than 100% (even if the user asks for 100%), or simply include an attenuation factor for each new ray.
- Can also model absorbtion due to light traveling in medium
  - Usually ignored in air, but depends on the application
  - Translucent absorption is exponential in depth

$$I = I_0 e^{-\alpha d}$$

- Recursion is stopped when contributions are too small
  - need to track the cumulative effect
  - common to also limit the depth explicitly

Mechanics

- Primary issue is intersection computations.
  - E.g. sphere, triangle.
- Polygon (should feel familiar!)
- Find point on plane of polygon and then determine if it is inside
  - One way is to make an argument with angles
  - Another way---thinking of the polygon as a surface of a polyhedra---is to check if the point is on the inside side of each of the other planes of the polyhedra.
- Sphere, relatively simple algebra (see book page 602)