Light and colour

Advanced Graphics

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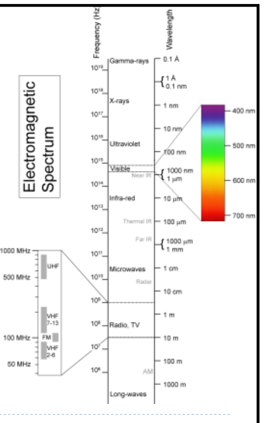
From light to colour spaces

Electromagnetic spectrum

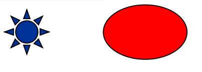
- Visible light
  - Electromagnetic waves of wavelength in the range 380nm to 730nm
  - Earth's atmosphere lets through a lot of light in this wavelength band
  - Higher in energy than thermal infrared, so heat does not interfere with vision



Colour

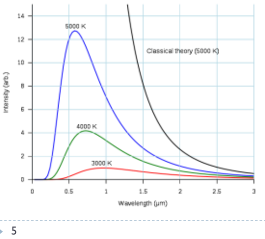
- There is no physical definition of colour – colour is the result of our perception

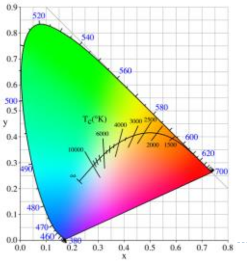
colour = perception(illumination * reflectance)



Black body radiation

- Electromagnetic radiation emitted by a perfect absorber at a given temperature
  - Graphite is a good approximation of a black body



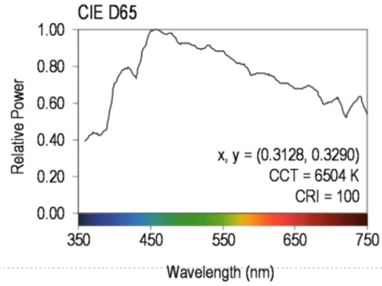


Correlated colour temperature

- The temperature of a black body radiator that produces light most closely matching the particular source
- Examples:
  - Typical north-sky light: 7500 K
  - Typical average daylight: 6500 K
  - Domestic tungsten lamp (100 to 200 W): 2800 K
  - Domestic tungsten lamp (40 to 60 W): 2700 K
  - Sunlight at sunset: 2000 K
- Useful to describe colour of the **illumination** (source of light)

Standard illuminant D65

- Mid-day sun in Western Europe / Northern Europe
- Colour temperature approx. 6500 K



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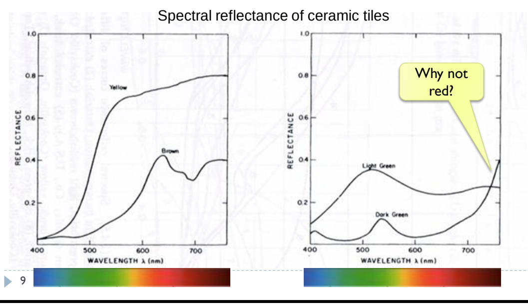
Reflectance

- Most of the light we see is reflected from objects
- These objects absorb a certain part of the light spectrum



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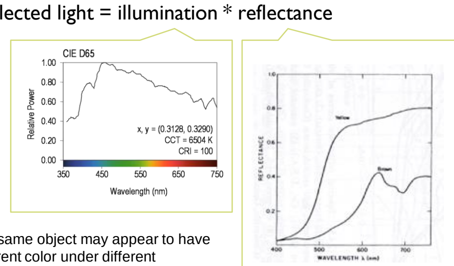
Reflected light

$$L(\lambda) = I(\lambda) \times R(\lambda)$$

- Reflected light = illumination * reflectance



The same object may appear to have different color under different illumination.

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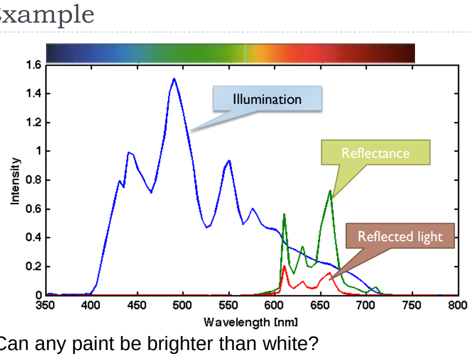
Example



Can any paint be brighter than white?

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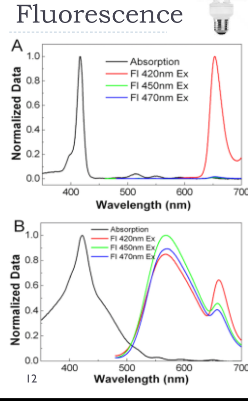
Fluorescence



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Colour

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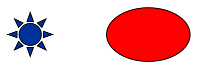
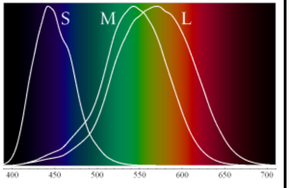
colour = perception(illumination * reflectance)



Colour vision

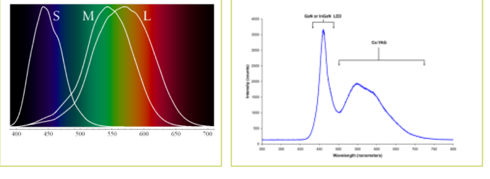
- Cones are the photoreceptors responsible for color vision
  - Only daylight, we see no colors when there is not enough light
- Three types of cones
  - S – sensitive to short wavelengths
  - M – sensitive to medium wavelengths
  - L – sensitive to long wavelengths



Sensitivity curves – probability that a photon of that wavelengths will be absorbed by a photoreceptor

Perceived light

- cone response = sum(sensitivity * reflected light)



Although there is an infinite number of wavelengths, we have only three photoreceptor types to sense differences between light spectra

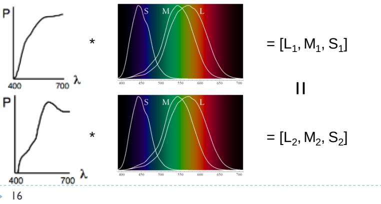
Formally

$$R_S = \int_{380}^{730} S_S(\lambda) \cdot L(\lambda) d\lambda$$

Index S for S-cones

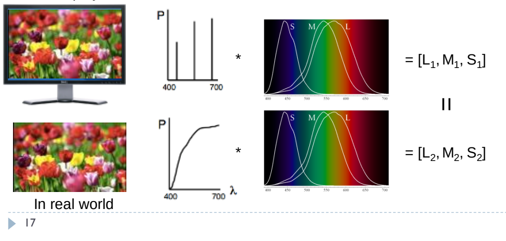
Metamers

- Even if two light spectra are different, they may appear to have the same colour
- The light spectra that appear to have the same colour are called **metamers**
- Example:

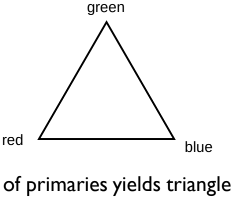


Practical application of metamerism

- Displays do not emit the same light spectra as real-world objects
- Yet, the colours on a display look almost identical



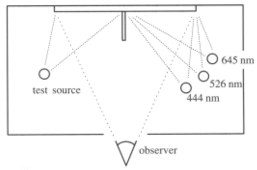
Tristimulus Colour Representation

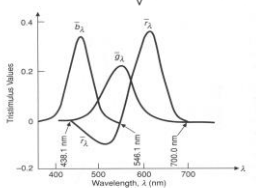


- Interpolation of primaries yields triangle of colours
- Making use of the three cones and their weighting functions

Tristimulus Colour Representation

- Observation
  - Any colour can be matched using three linear independent reference colours
  - May require "negative" contribution to test colour
  - Matching curves describe the value for matching mono-chromatic spectral colours of equal intensity
    - With respect to a certain set of primary colours



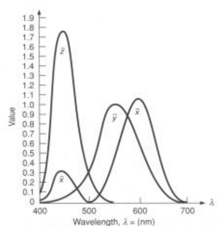


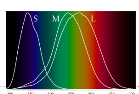
Standard Colour Space CIE-XYZ

- CIE Experiments [Guild and Wright, 1931]
  - Colour matching experiments
  - Group ~12 people with „normal" colour vision (from London area)
  - 2 degree visual field (fovea only)
  - Other Experiment in 1964
    - 10 degree visual field, ~50 people (with foreigners)
    - More appropriate for larger field of view but rarely used
- CIE-XYZ Colour Space
  - Goals
    - Abstract from concrete primaries used in experiment
    - All matching functions are positive
    - One primary is roughly proportionally to light intensity

Standard Colour Space CIE-XYZ

- Standardized imaginary primaries CIE XYZ (1931)
  - Could match all physically realizable colour stimuli
  - Y is roughly equivalent to luminance
    - Shape similar to luminous efficiency curve
  - Monochromatic spectral colours form a curve in 3D XYZ-space



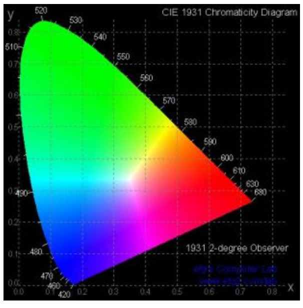


Cone sensitivity curves can be obtained by a linear transformation of CIE XYZ

CIE Chromaticity diagram

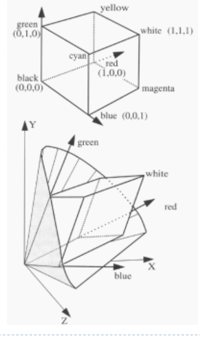
- **Normalization:**
  - Concentrate on colour, not light intensity
  - Relative colour coordinates
  - $x = \dfrac{X}{X+Y+Z}$ etc

    Chromaticity diagram: 2D-Plot over x and y
  - Points in diagram are called „colour locations"
  - White point: ~(0.3, 0.3)
    - Device dependent
    - Adaptation of the eye

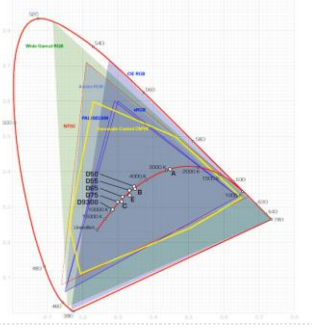


Monitor Color Gamut

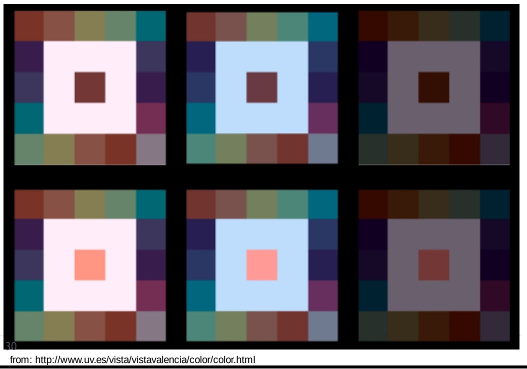
- CIE XYZ gamut
  - Device-independent
- Device color gamut
  - Cube inside CIE color space with additive color blending



Different Color Gamuts



Colour constancy



from: http://www.uv.es/vista/vistavalencia/color/color.html

Chromatic adaptation = colour constancy

- Visual system "estimates" the colour of the illuminant
  - and then attempts to discount it
- This works well if the scene fills the entire field of view
  - But is less effective for images
  - E.g. image on the computer monitor or developed print
- Therefore photographs require **white balance**
  - To discount the illuminant that is not discounted by the visual system

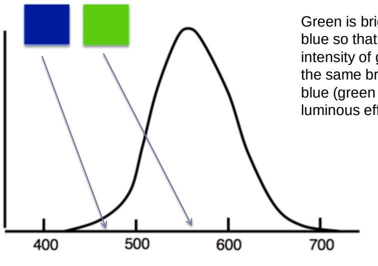
from Wikipedia

White point

- Displays are expected to have the white point D65
  - This corresponds to the color temperature of 6500K
  - But most displays do not strictly adhere to this specification
  - It is often possible to adjust the white point of a display
- Digital cameras need to discount illuminant
  - They estimate the color of white and make it D65 so that it looks white on displays
  - This is called white balance

From: http://en.wikipedia.org/wiki/File:Incand-3500-5500-color-temp-comparison.png

Luminous efficiency function



Green is brighter than blue so that lower intensity of green gives the same brightness as blue (green has higher luminous efficiency)

To match the brightness of colors produced by the light of different wavelength

Photometric units

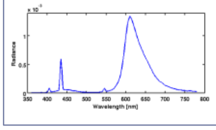
- Luminance – perceived brightness of light, adjusted for the sensitivity of the visual system to wavelengths

Luminance

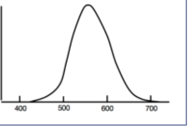
$$L_V = \int_0^\infty L(\lambda) \times V(\lambda) d\lambda$$

ISO Unit: cd/m²

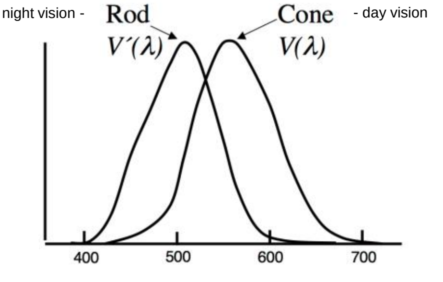
Light spectrum (radiance)



Luminous efficiency function (weighting)

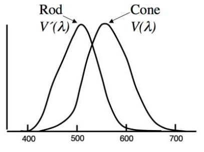


Rod and cone luminous efficiency functions



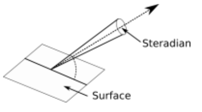
Purkinje shift (effect)

- A shift in spectral sensitivity associated with the transition of cone to rod vision
- Blue appears brighter and red appears darker in twilight
- And the reverse is observed in daylight

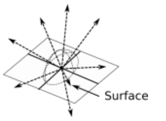


Photometric units

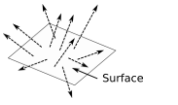
Quantity	Units	Symbol
Luminance	candela per sq. meter [cd/m²=lm/(sr*m²)]	L_V
Illuminance	lux [lx = lm/m² = cd*sr/m²]	E_V
Luminous flux	lumen [lm = cd*sr]	F



Luminance – light emitted from a point on a surface in a particular direction



Illuminance – light emitted from a point on a surface in all directions



Luminous flux – light emitted from the entire surface in all directions

All these units can measure either incoming or emitted light

Luminous flux - lumens

- Total light emitted
- Useful to measure and compare light sources
  - For example fluorescent and incandescent light bulbs
- But also used for digital projectors

Integrating sphere – to measure all light emitted

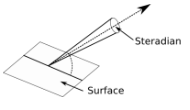
Illuminance - lux

- Measures light coming (or emitted) from all directions
- Useful to measure lighting conditions
  - Whether street lighting is bright enough, etc.

Illuminance meter

Luminance – candela per square meter

- Light emitted (or incomming) from a point in a particular direction
- Luminance is the same regardless of the distance to the emitter
- The light sensed by our eyes is relative to luminance



Radiometric vs. Photometric units

Photometry	Radiometry
Luminance [cd m⁻²]	Radiance [W sr⁻¹ m⁻²]
Illuminance [lx = lm m⁻² = cd sr m⁻²]	Irradiance / Exitance / Radiosity [W m⁻²]
Luminous flux [lm = cd sr]	Radiant flux [W]

- Radiometric units integrate light over **all wavelengths** (visible and invisible)
- **Spectral radiance / irradiance / radiant flux** describe light for a single wavelength
- But, in computer graphics radiometric units are often assumed to capture a quantity integrated over a spectral basis function (e.g. red, green, blue)
- In color science, the product of radiance with a colour matching function is called **trichromatic colour value**

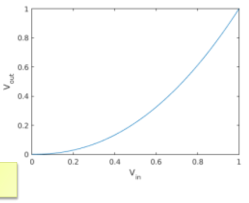
Gamma correction

- Gamma correction is used to encode luminance or tri-stimulus color values (RGB) in imaging systems (displays, printers, cameras, etc.)

Gain — Gamma (usually =2.2)

$$V_{out} = a \times V_{in}^{\gamma}$$

(relative) Luminance — Luma



For color images: $R = a \times (R')^{\gamma}$ and the same for green and blue

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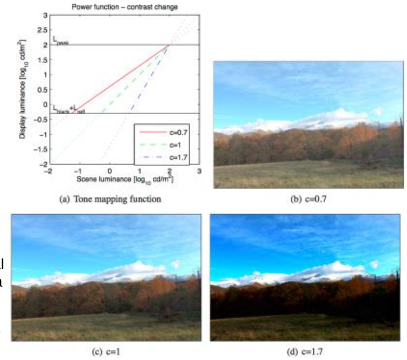
Gamma



Lower gamma

Original gamma

Higher gamma

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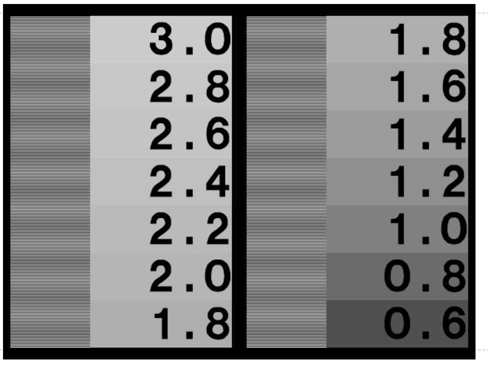
Gamma Testing Chart



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Why is gamma needed?

<- Pixel value (luma)

<- Luminance

- "Gamma corrected" pixel values give a scale of brightness levels that is more perceptually uniform
- At least 12 bits (instead of 8) would be needed to encode each color channel without gamma correction
- And accidentally it was also the response of the CRT gun

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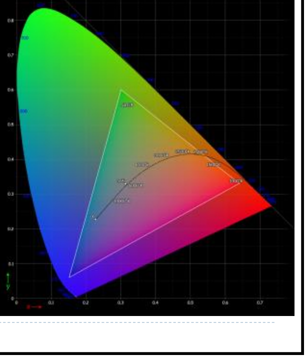
sRGB color space (LDR)

- "RGB" color space is not a standard. Colors may differ depending on the choice of the primaries
- "sRGB" is a standard color space, which most displays try to mimic (standard for HDTV)

Chromaticity	Red	Green	Blue	White point
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583

- The chromacities above are also known as Rec. 709



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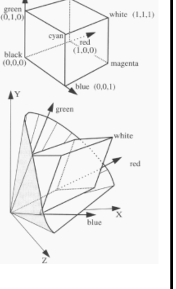
sRGB color space

- Two step XYZ – sRGB transformation:
  - Step 1: Linear color transform

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

  - Step 2: Non-linearity

$$C_{\text{srgb}} = \begin{cases} 12.92 C_{\text{linear}}, & C_{\text{linear}} \le 0.0031308 \\ (1+a) C_{\text{linear}}^{1/2.4} - a, & C_{\text{linear}} > 0.0031308 \end{cases}$$



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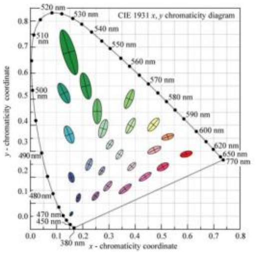
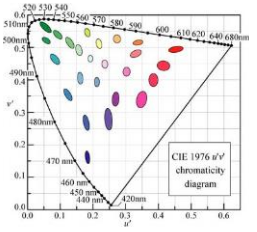
Perceptually uniformity

- MacAdam ellipse - visually indistinguishable colours

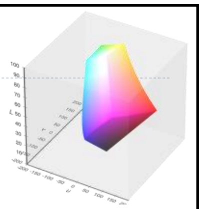


In CIE xy chromatic coordinates



In CIE u'v' chromatic coordinates

CIE L*u*v* and u'v'



sRGB in CIE L'u'v'

- Approximately perceptually uniform
- u'v' chromacity

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}$$
$$v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}$$

- CIE LUV

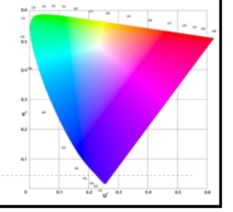
Lightness:
$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 Y/Y_n, & Y/Y_n \le \left(\frac{6}{29}\right)^3 \\ 116(Y/Y_n)^{1/3} - 16, & Y/Y_n > \left(\frac{6}{29}\right)^3 \end{cases}$$

Chromacity coordinates:
$$u^* = 13L^* \cdot (u' - u'_n)$$
$$v^* = 13L^* \cdot (v' - v'_n)$$

Colours less distinguishable when dark

- Hue and chroma

$$C^*_{uv} = \sqrt{(u^*)^2 + (v^*)^2}$$
$$h_{uv} = \operatorname{atan2}(v^*, u^*),$$



CIE L*a*b* colour space

- Another approximately perceptually uniform colour space

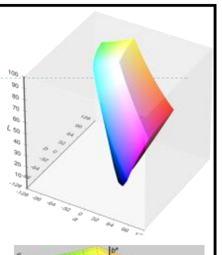
$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$
$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$
$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

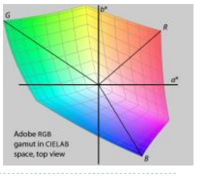
Trichromatic values of the white point, e.g.
$X_n = 95.047,$
$Y_n = 100.000,$
$Z_n = 108.883$

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$
$$\delta = \frac{6}{29}$$

- Chroma and hue

$$C^* = \sqrt{a^{*2} + b^{*2}}, \qquad h^\circ = \arctan\left(\frac{b^*}{a^*}\right)$$





References

- Well written textbook
  - Fairchild, M. D. (2005). *Color Appearance Models* (second.). John Wiley & Sons.
- More detailed introduction to light and colour phenomena
  - Erik Reinhard, Erum Arif Khan, Ahmet Oguz Akyuz, G. J. (2008). *Color Imaging: Fundamentals and Applications*. CRC Press.