CSCI 435 – Computer Vision

Lecture 2

Photometry and Colorimetry

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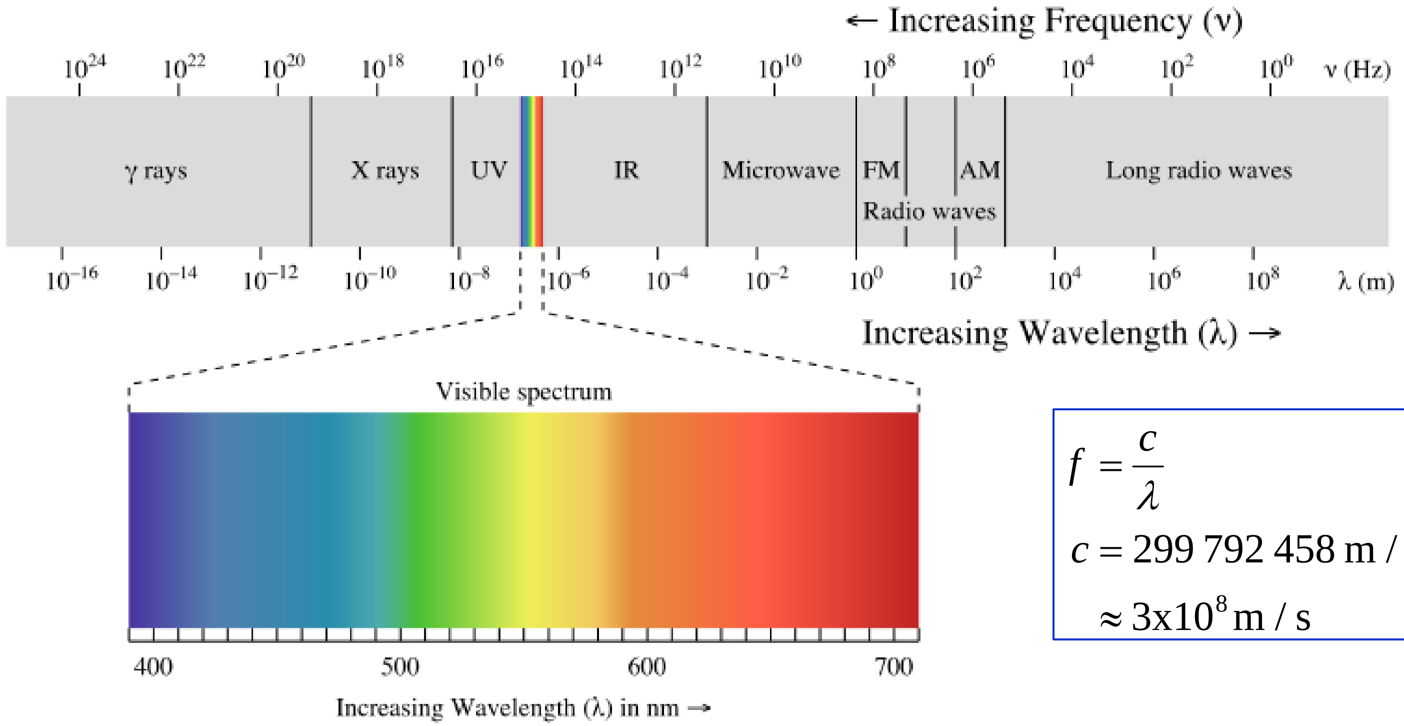
What is Light?



$$f = \frac{c}{\lambda}$$

$$c = 299\,792\,458 \text{ m / s}$$

$$\approx 3\text{x}10^{8} \text{ m / s}$$

- Light is electromagnetic radiation that travels as electromagnetic waves
- There is no fundamental difference between light and radio waves

Photometric Terms

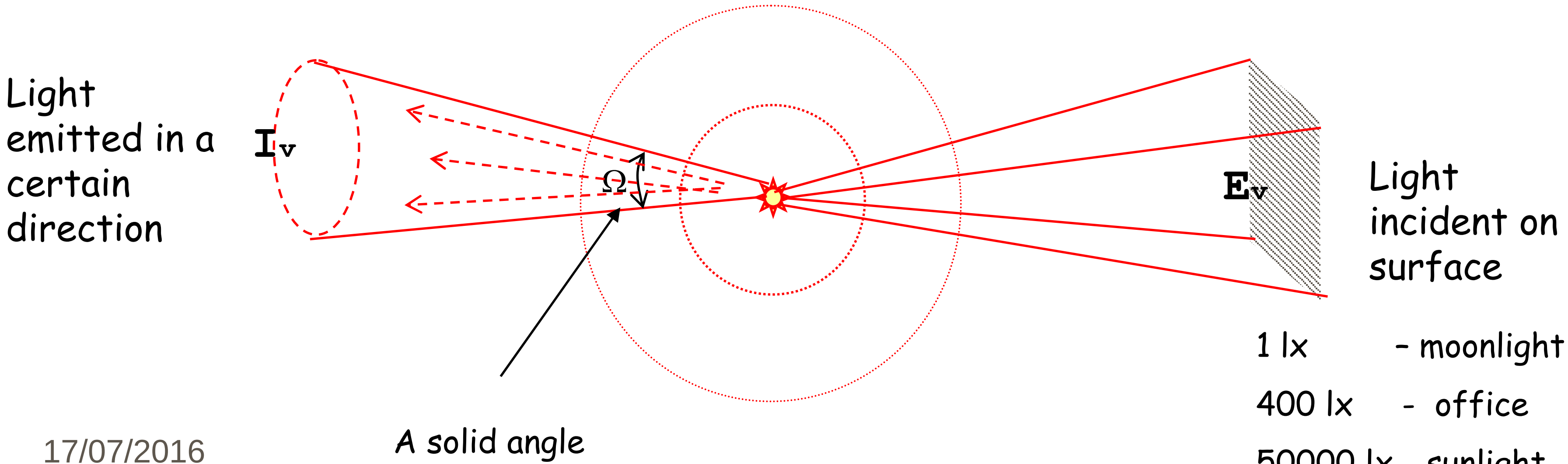
- To become a source of light an object must be heated
- Emission of light = emission of energy

Luminous Energy: Q_v

Luminous Flux: $F_v = dQ_v/dt$ (measured in Lumens lm)

Luminous Intensity: $I_v = dF_v/d\Omega$ (measured in $\mathrm{lm/radian}$)

Illuminance: $E_v = dF_v/dS$ (measured in lux $\mathrm{lx} = \mathrm{lm/m^2}$)



1 lx - moonlight

400 lx - office

50000 lx - sunlight

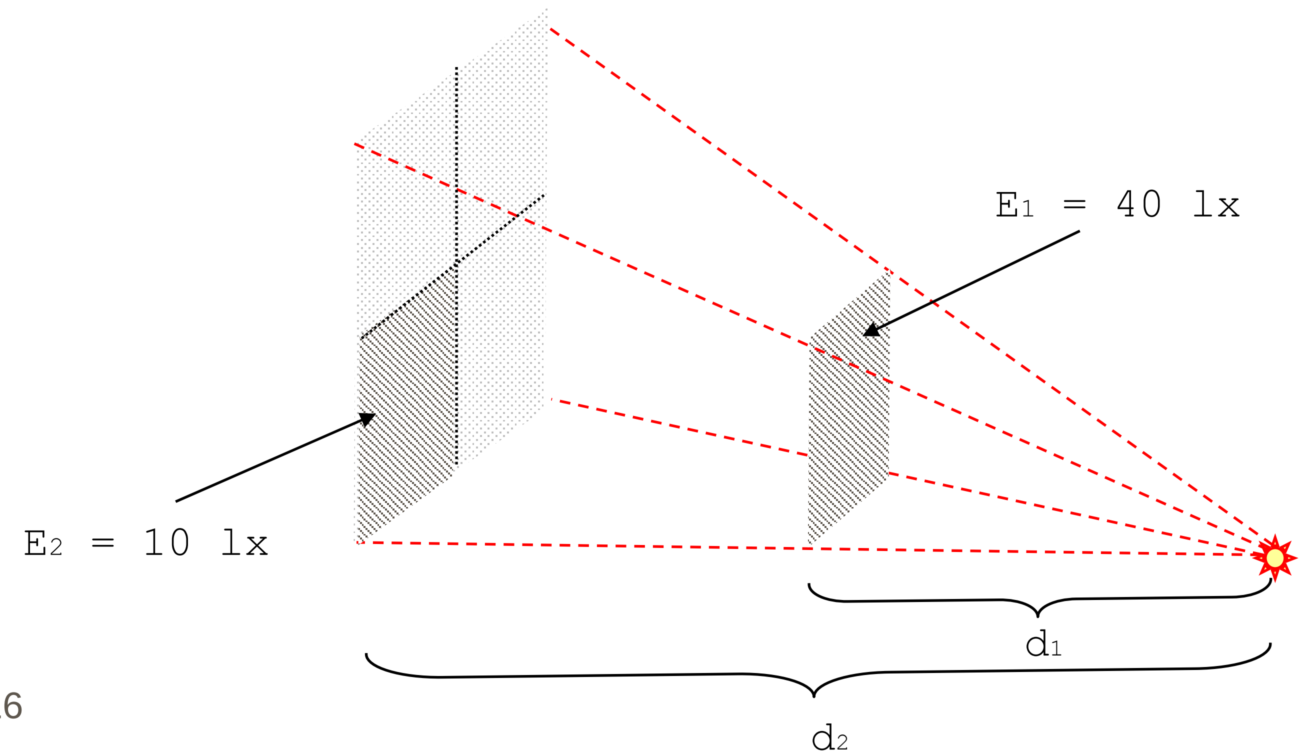
The Inverse Square Law

$E_2/E_1 = (d_1/d_2)^2$

thus,

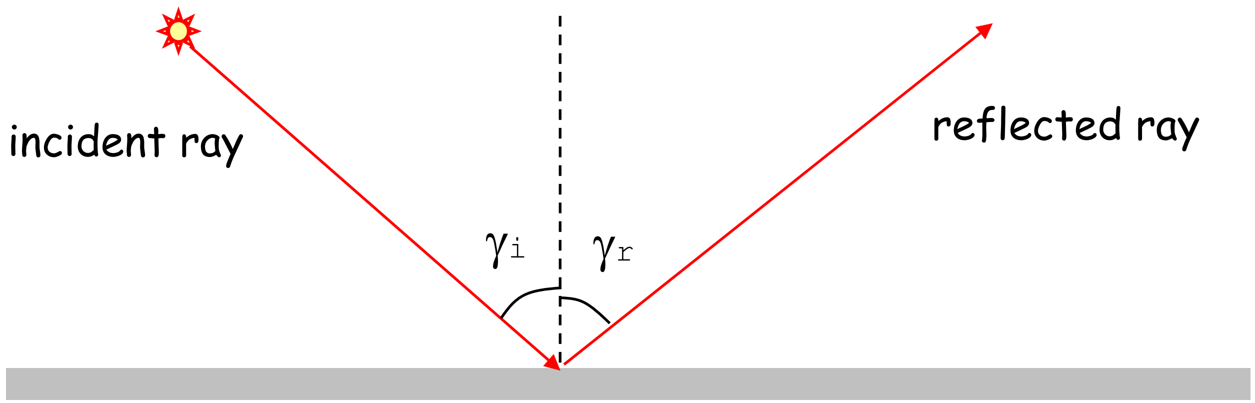
$E_2 = E_1 * (d_1/d_2)^2$

If illuminance of the first surface is known, the illuminance of other surfaces can be calculated



Reflection

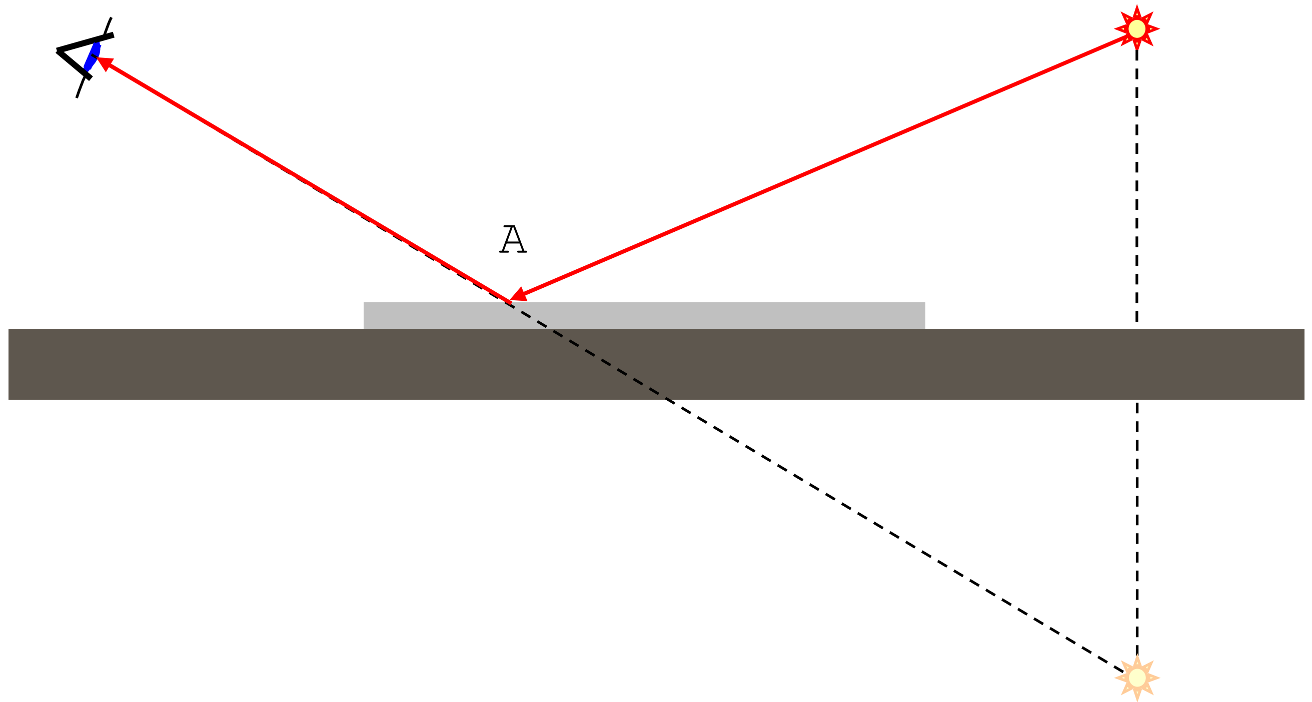
- When light falls upon a specular surface, it bounces off. This bouncing off is called reflection



- The angle of reflection γ_r is equal to the angle of incidence γ_i.

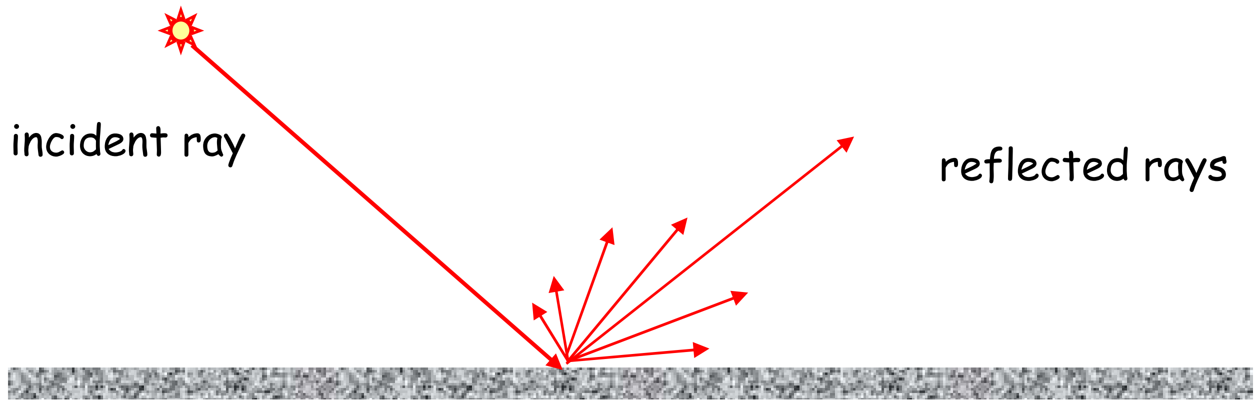
Quiz

- Find a point A on the surface where a ray reflected from the mirror falls into the eye



Diffuse Reflectance

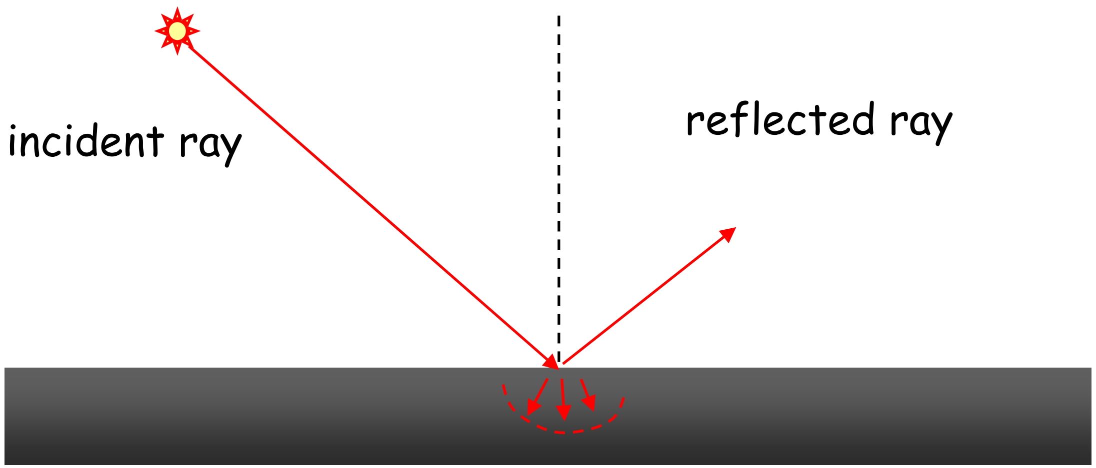
- Most materials do not have smooth specular reflecting surfaces
- Reflected rays are scattered in all directions
- There is a great variety how the reflected rays are distributed



- The surfaces which scatter equally in all directions are called Lambertian surfaces (cotton close, carpet, …)

Light Absorption

- Luminous Intensity of the reflected light may be les than Intensity of the incident light
- Some of the light wave energy is absorbed by the substance and converted into other forms of energy (thermal, chemical, electrical)



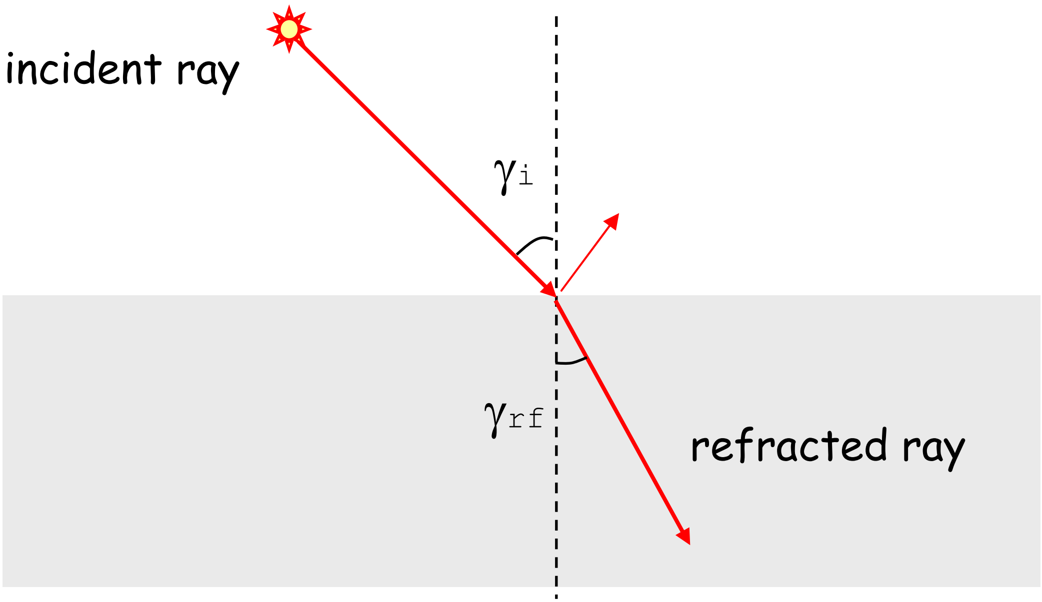
Absorption coefficient:

$$S(\lambda) = I_r(\lambda) / I_i(\lambda)$$

In general, it is wavelength dependent

Refraction

- Light has straight-line propagation only when it travels in one medium
- When light crosses a boundary between two transparent substances it changes direction. This phenomenon is called refraction



Refractive index:

$$n = \sin(\gamma_i) / \sin(\gamma_{rf})$$

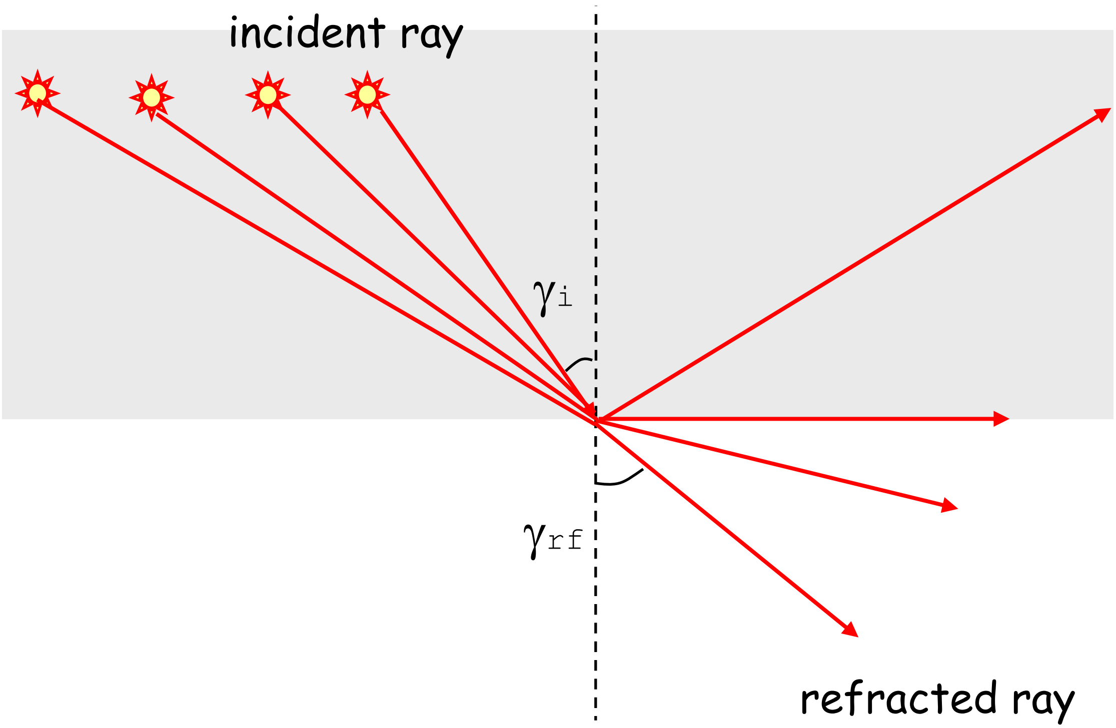
or

$$n = c_i / c_{rf}$$

where c_i and c_{rf} are corresponding velocities of light

Refraction

- When light travels from a more dense medium into a les dense medium, the ray bends away from the normal



At certain incident angle the refracted ray lies along the boundary

- The angle of incidence for which the angle of refraction is 90° is called the critical angle

$$\sin(\gamma_i) = 1/n$$

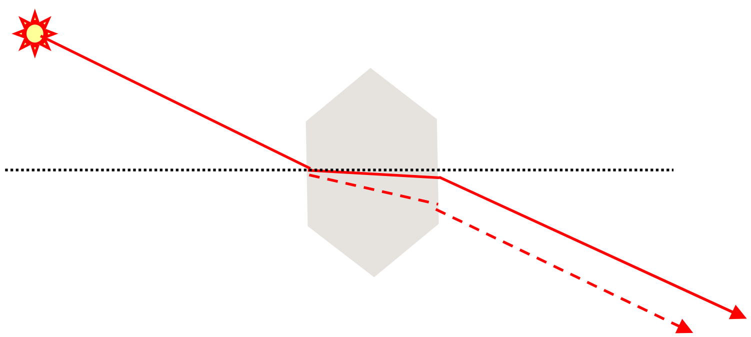
If the angle of incidence exceeds the critical angle the light is totally reflected

Quiz

- The table below shows refractive indices of various media

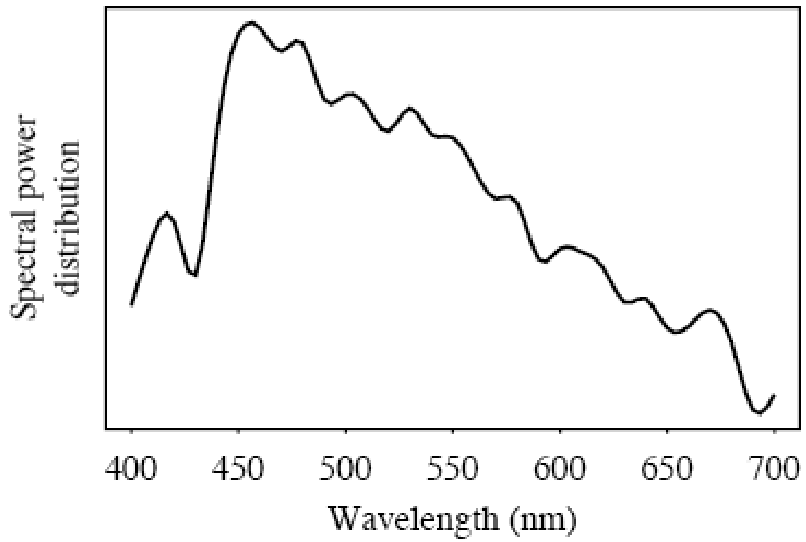
Vacuum	1.0000
Air	1.0003
Water	1.33
Glass	1.5
Diamond	2.42

Given a precious stone, how to distinguish a diamond from a glass fake?



Typical Outdoor Light

- The figure below shows the relative power in each wavelength interval for typical outdoor light on a sunny day. This type of curve is called a Spectral Power Distribution (**SPD**) or a **spectrum**.

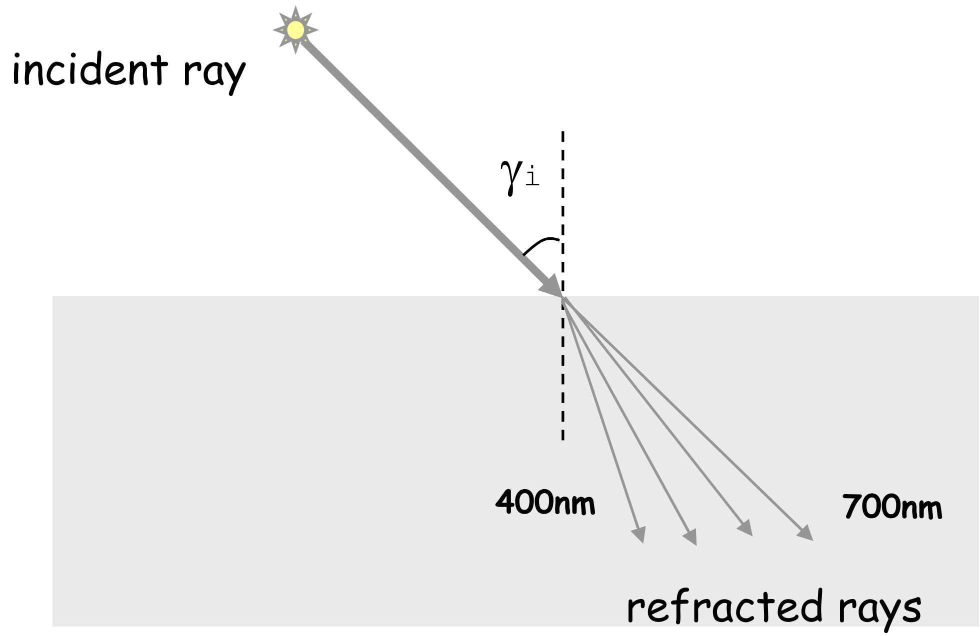


Spectral power distribution of daylight.

Outdoor light is a mixture of waves with various wavelengths

Dispersion

- Refractive indices are wavelength dependent



Refractive index:

$n = c_i / c_{rf}$

where $c_i = f * \lambda_i$ and

$c_{rf} = f * \lambda_{rf}$

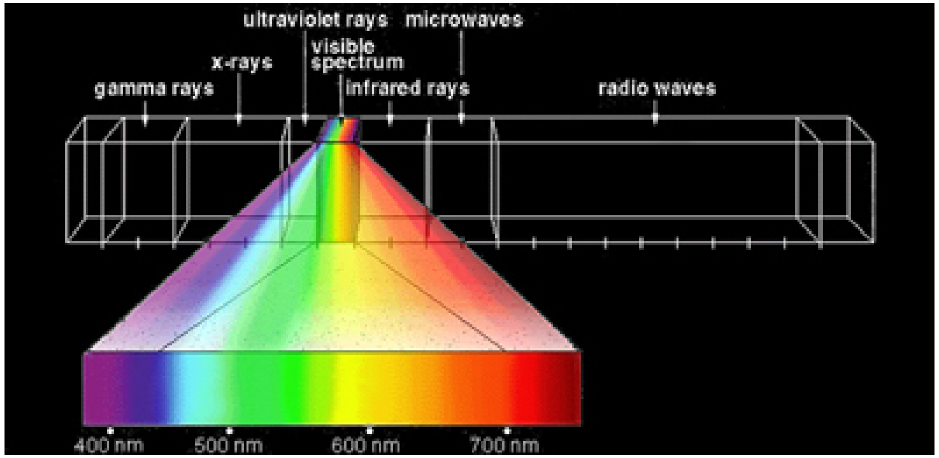
thus,

$\mathbf{n = \lambda_i / \lambda_{rf}}$

- *An incident multi-spectral ray is split into several rays according to wavelengths of individual spectral components*

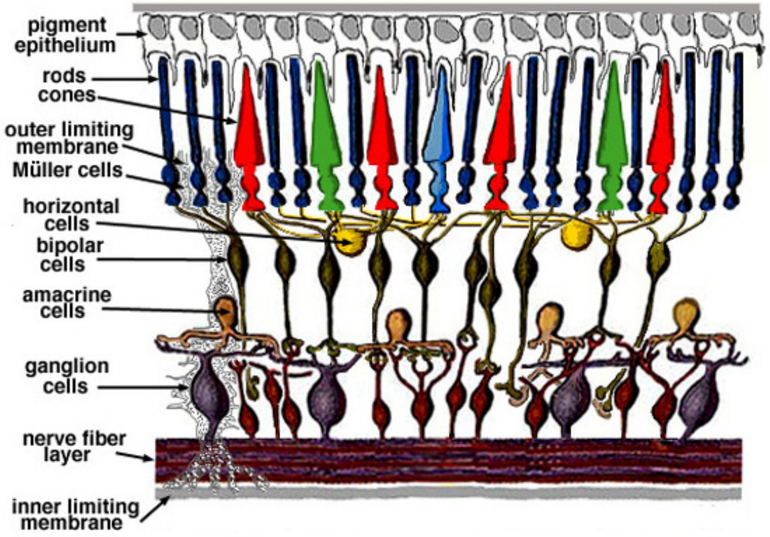
What is Colour?

- Colour is a subjective sensation produced in the brain when the eyes are exposed to light
- Colour is characterized by the wavelength content of the light
  - Laser light consists of a single wavelength: e.g., a ruby laser produces a bright-red beam.
  - Short wavelengths produce a blue sensation, long wavelengths produce a red one



Receptors

- Human eyes have two types of receptors
  - Rods
    - night vision
    - cannot distinguish color
  - Cones
    - color vision
    - comes in three different sorts that respond to three different groups of wavelengths of light (**tristimulus theory**)



Simple diagram of the organization of the retina.

Sensitivity of Receptors

- The eye is most sensitive to light in the middle of the visible spectrum.
  - The sensitivity of our *receptors* is also a function of wavelength

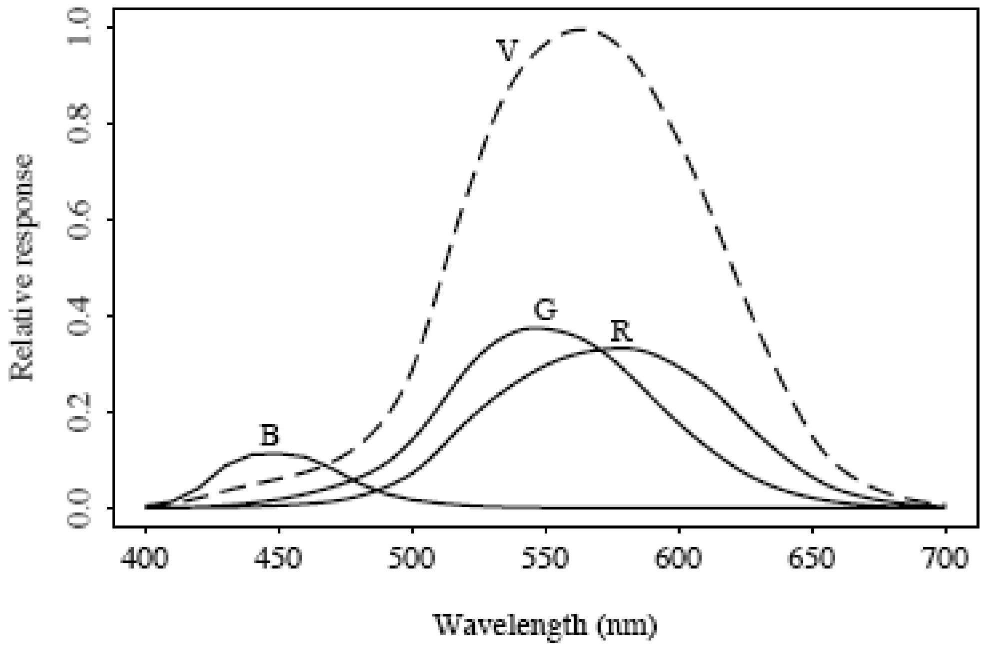


Image Formation

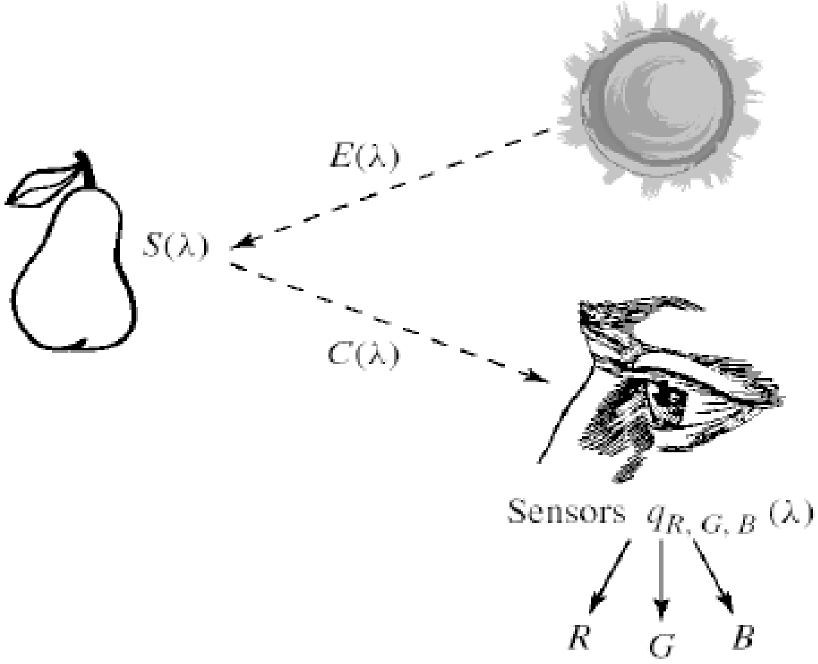
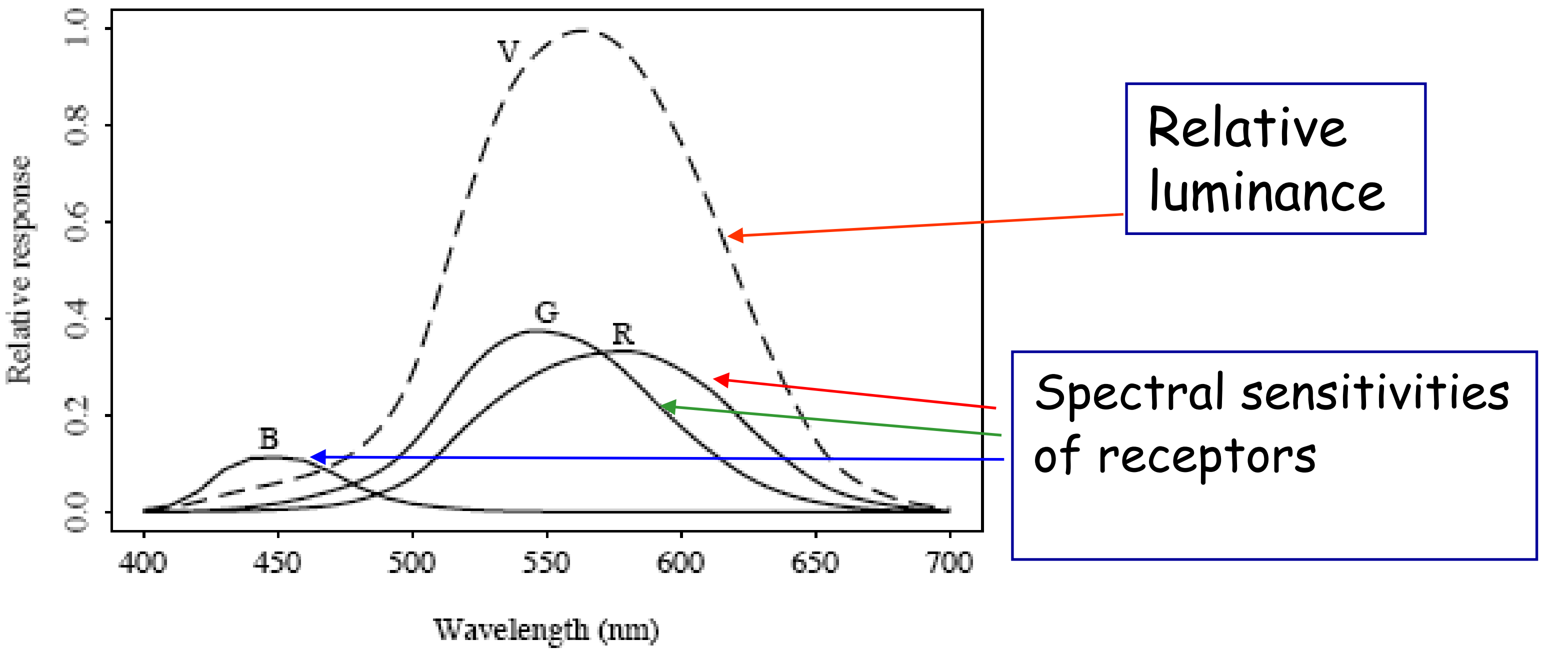


Image formation model.

- Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces.

$$C(\lambda) = E(\lambda)\, S(\lambda).$$

Luminance or Intensity



$$L = \int C(\lambda) V(\lambda) d\lambda$$

Perceptual brightness is not the same as luminance ***L***

Weber's Law

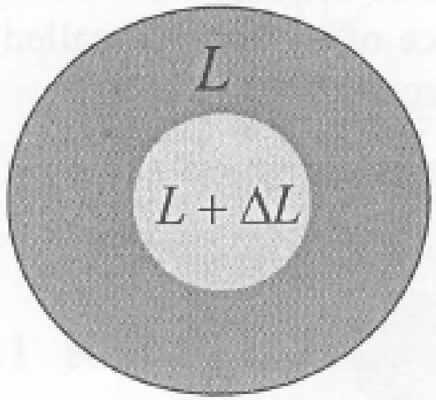


Figure 3.6. Contrast and luminance

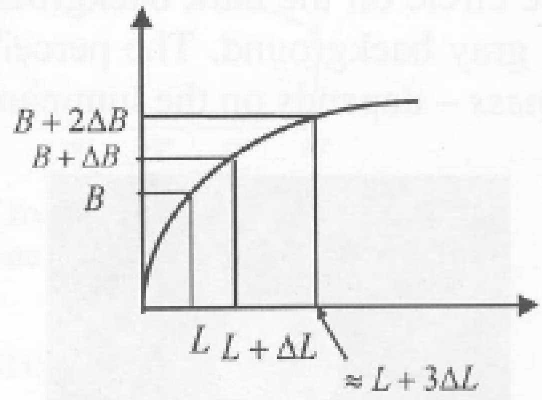


Figure 3.7. Brightness (B) and luminance (L)

- If ΔL is zero, the two regions are indistinguishable.
- If we slowly increase ΔL from zero. For a certain value of ΔL, the contrast of the two region will just be noticeable.
- Let this value be denoted as ΔL_N

Weber's Law…

- Weber-Fechner found that the ratio between ΔL_N and L is a constant (Weber's Law)

$$\frac{\Delta L_N}{L} = k$$

- k is about 0.02

- Weber's law also leads to the logarithmic relationship between the brightness and luminance

$$B = c \log L + d$$

Color Perception Of Objects

- Given three spectral sensitivity functions $q_R(\lambda)$, $q_G(\lambda)$ and $q_B(\lambda)$

Illuminance perceived by the receptors can be calculated as

$$R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, S(\lambda)\, q_G(\lambda)\, d\lambda$$

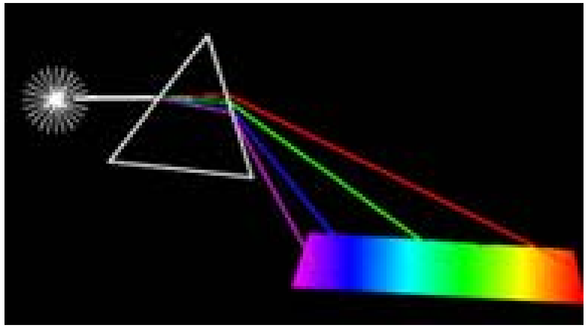
$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$$

Regardless how complex the spectrum $E(\lambda)$ is, it is perceived as the tristimulus R, G, B

Color Representation

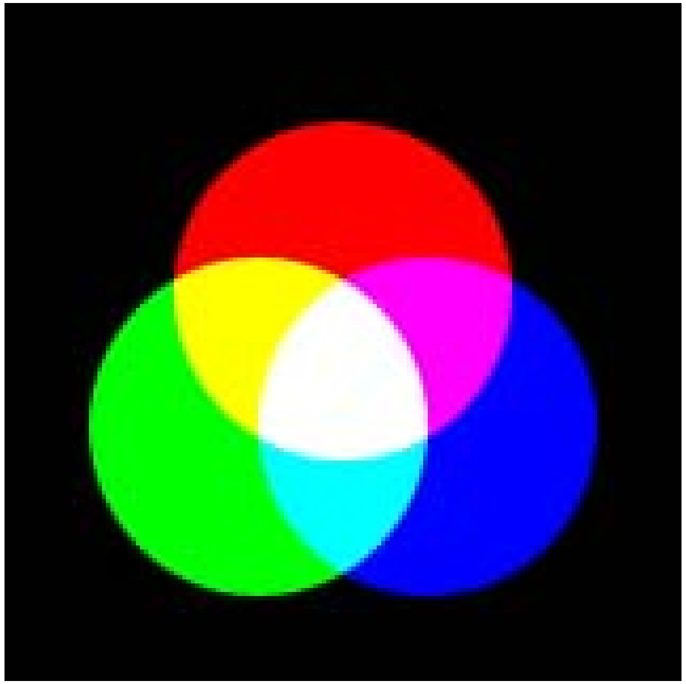
- The *tristimulus theory* suggests that any color (but this does not mean any spectrum) can be represented as three values R, G and B

- These three components are called ***primary colors*** form ***color space***



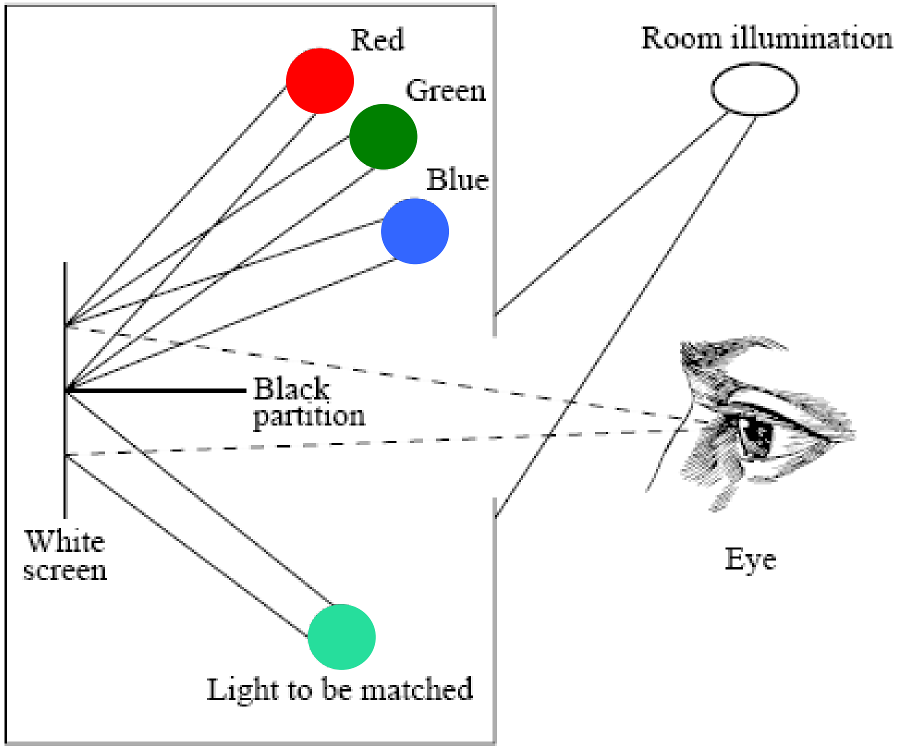
RGB color space

- Color Primaries
  - Red
  - Green
  - Blue
- Any color can be represented or reproduced as a linear combination of R, G and B
- How much R, G and B needed for a particular color?
  - Color matching experiments using colorimeter



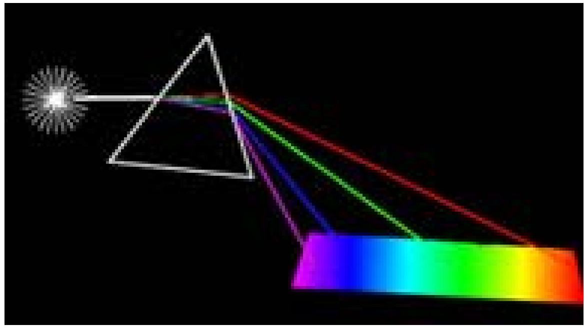
Red+Green+Blue=White

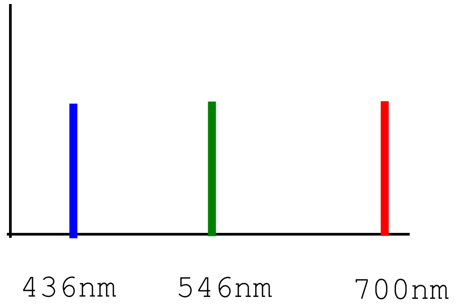
Colorimeter Experiment



Colorimeter experiment.

What Red, Green **and** Blue **are?**

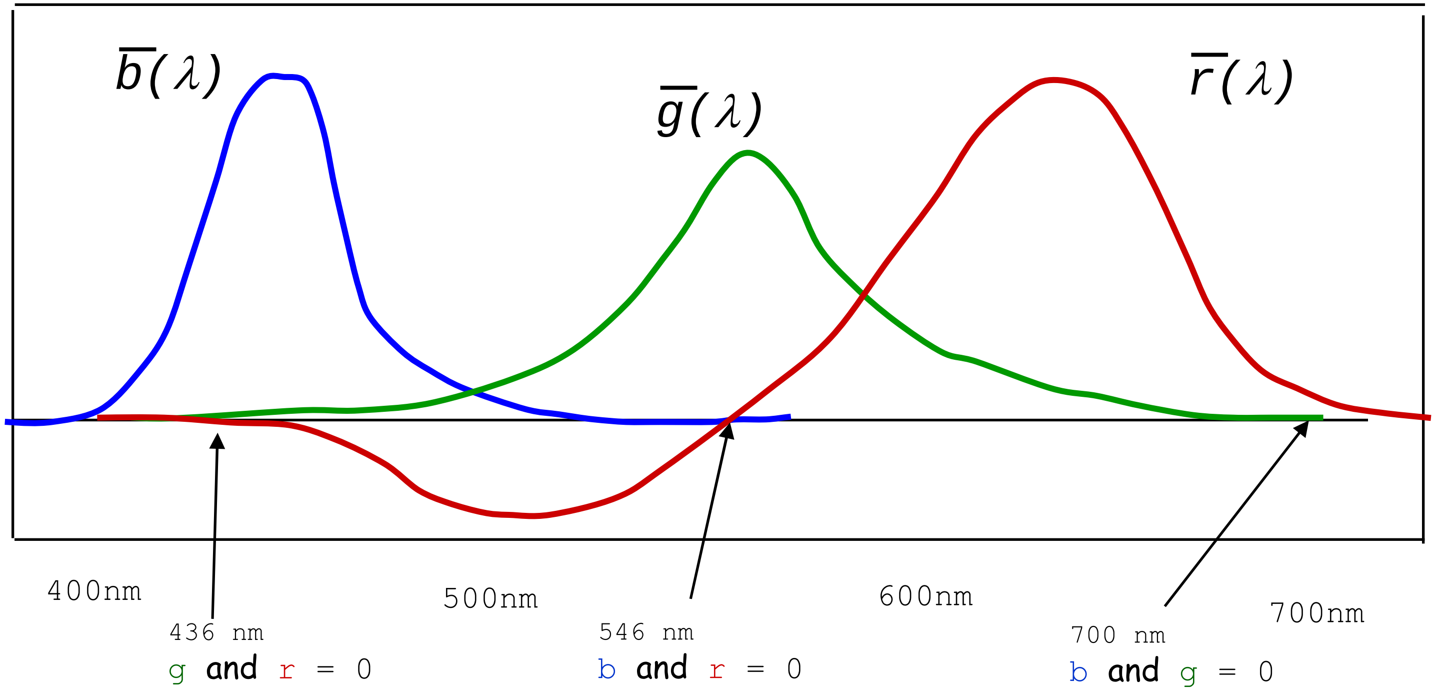




Blue, Green and **red** stimuli standardised by CIE

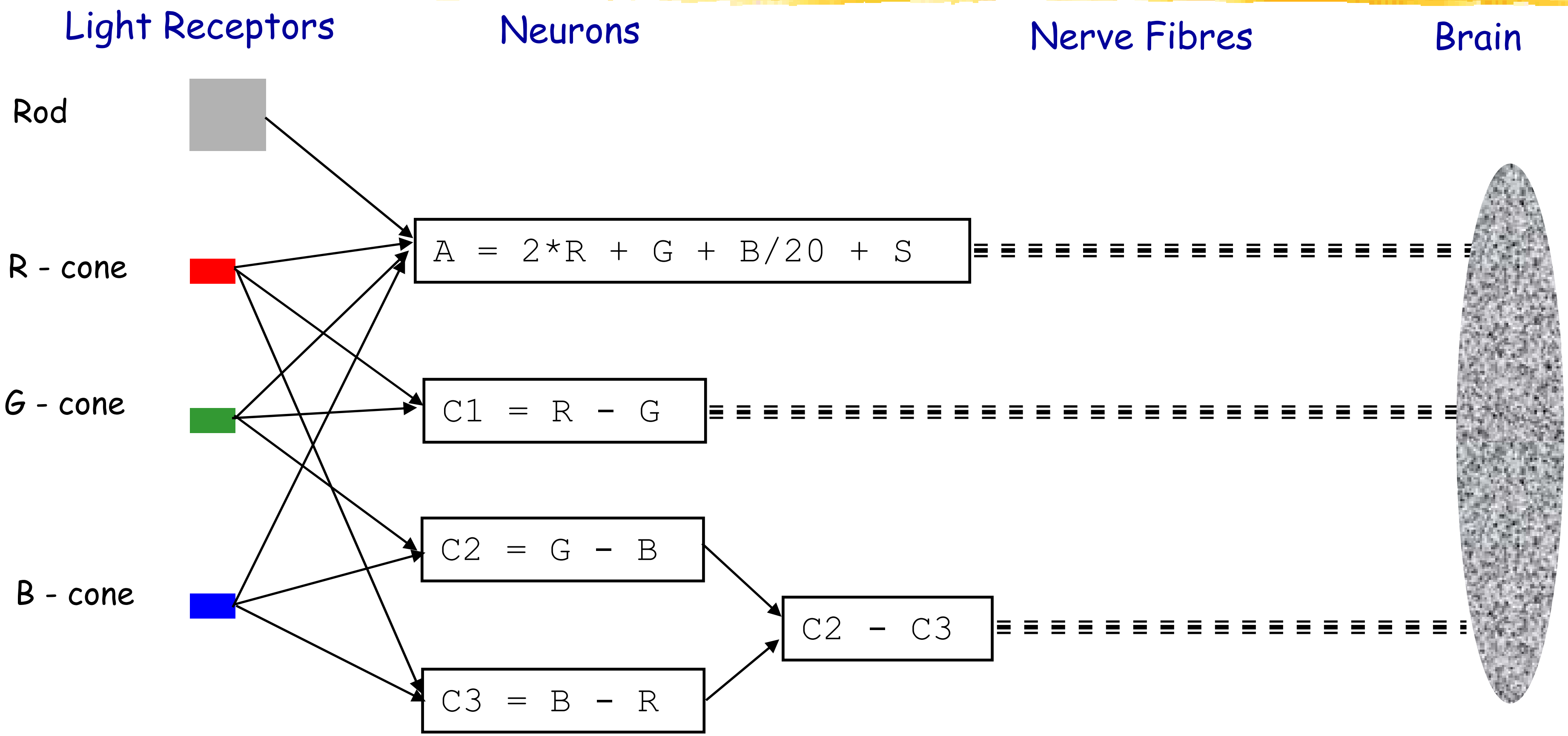
CIE Color Matching Functions

- In 1931 CIE (Commission Internationale de L'Eclarirage) run experiments to measure $q_R(\lambda)$, $q_G(\lambda)$ and $q_B(\lambda)$



The measured colour matching functions $\overline{b}(\lambda)$, $\overline{g}(\lambda)$ and $\overline{r}(\lambda)$ differ from spectral sensitivity of receptors $q_R(\lambda)$, $q_G(\lambda)$ and $q_B(\lambda)$

Visual Data Transmission



Shape of colour matching functions depends on spectral sensitivity of receptors, neuron processing and brain

Major Conclusions

1. Some of the colour matching functions have negative values. As a result, physical devices (TV, displays, etc) cannot reproduce some colours

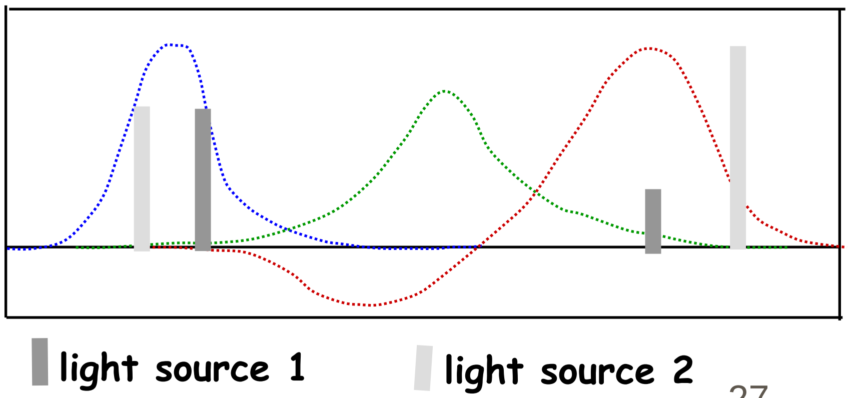
2. If a TV, or a monitor uses R, G, B emitters with parameters different from those standardised by CIE, the colour matching functions have to be corrected

3. Integrated stimulation of cones may create identical r, g, b from light sources with different spectrums. Different colours (in terms of their spectral composition) which look identical are called **metameric**

$$r = \int S_1(\lambda)\,\bar{r}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$g = \int S_1(\lambda)\,\bar{g}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

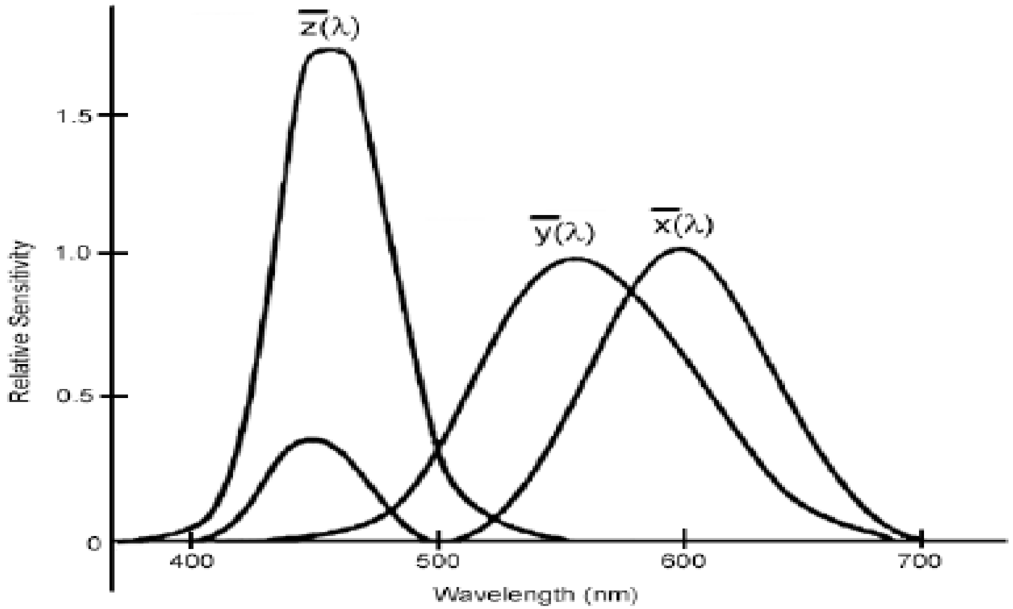
$$b = \int S_1(\lambda)\,\bar{b}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{b}(\lambda)\,d\lambda$$



CIE XYZ Color Matching Functions

Derived from $b(\lambda)$, $g(\lambda)$ and $r(\lambda)$ **to eliminate negative values**

[X Y Z] = [r g b]***T**   where **T** is 3x3 transformation matrix



CIE standard XYZ color-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$.

Any colour can be represented using positive XYZ primaries

However, X Y Z primaries are not real

CIE XYZ can only be used for theoretical analysis

CIE Chromaticity

- We go to 2D by factoring out the magnitude of vectors (X, Y, Z); we could divide by $\sqrt{X^2+Y^2+Z^2}$, but instead we divide by the sum $X+Y+Z$ to make the **chromaticity**:

$$\begin{aligned} x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ z &= Z/(X+Y+Z) \end{aligned} \qquad (4.7)$$

- This effectively means that one value out of the set (x, y, z) is redundant since we have

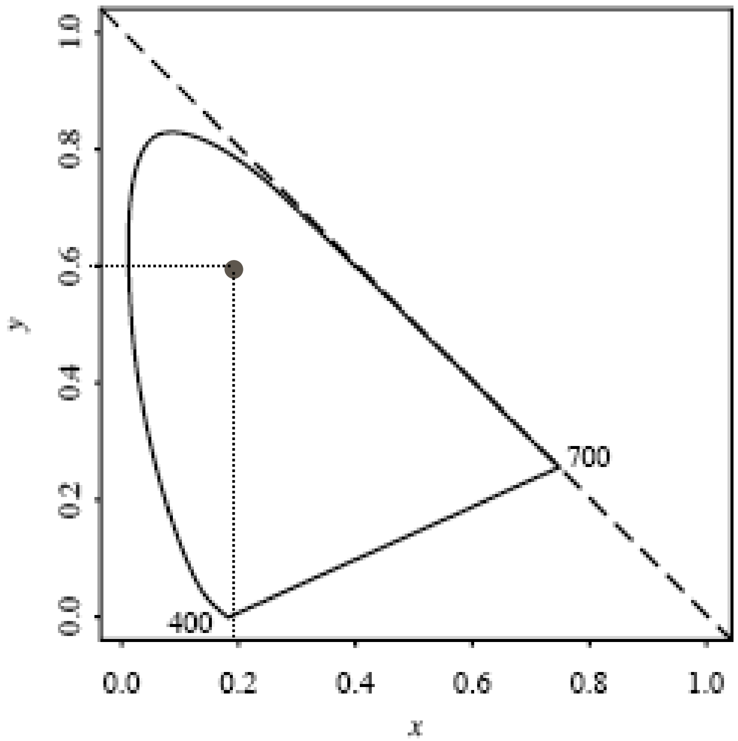
$$x+y+z = \frac{X+Y+Z}{X+Y+Z} \equiv 1 \qquad (4.8)$$

so that

$$z = 1 - x - y \qquad (4.9)$$

Values *x, y* are called **chromaticity coordinates**

CIE Chromaticity Diagram



CIE chromaticity diagram.

The third component z is calculated

z = 1 − x − y

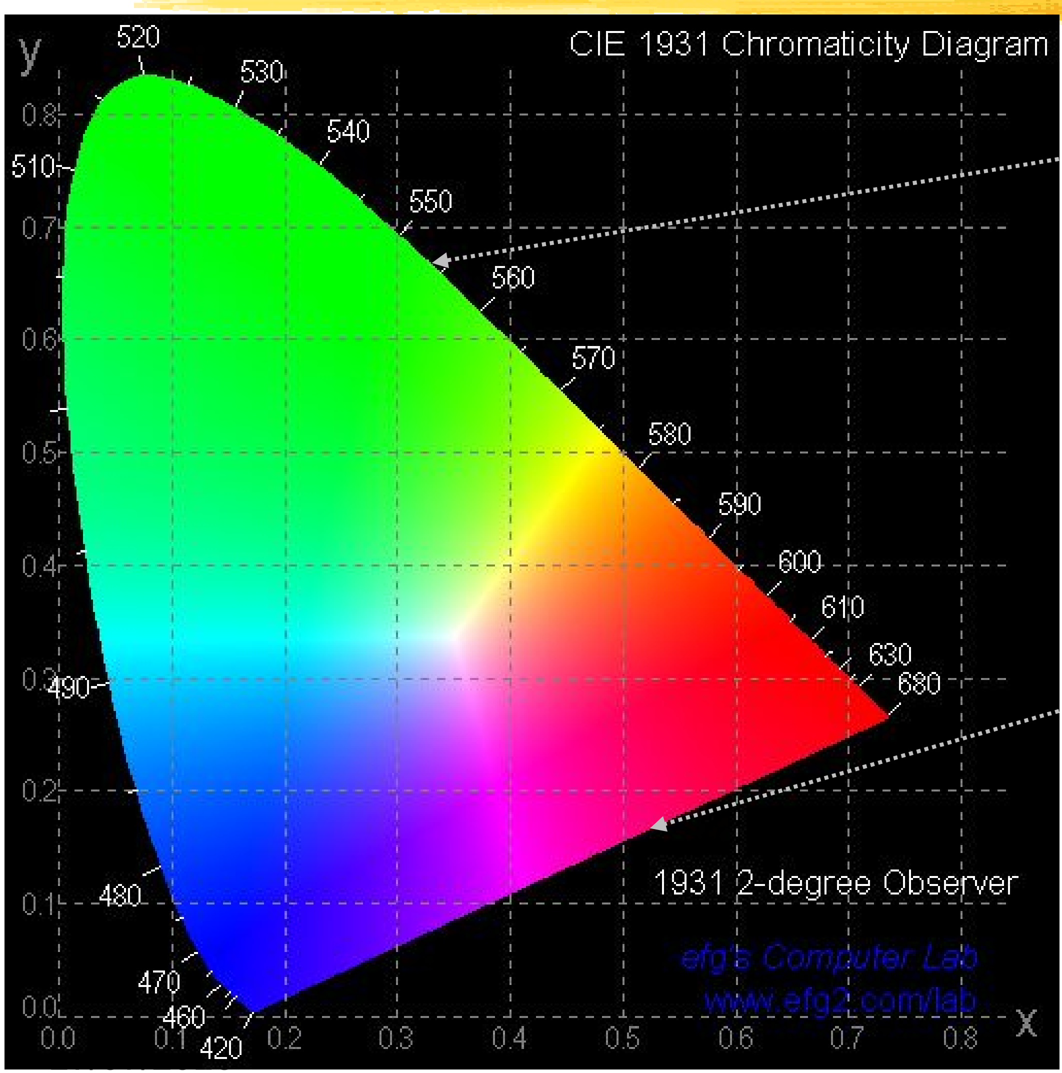
Example:

Z = 1 -0.6 -0.2 = 0.2

All visible colours lie inside the spectral locus

CIE Chromaticity Diagram

(the gamut of human vision)



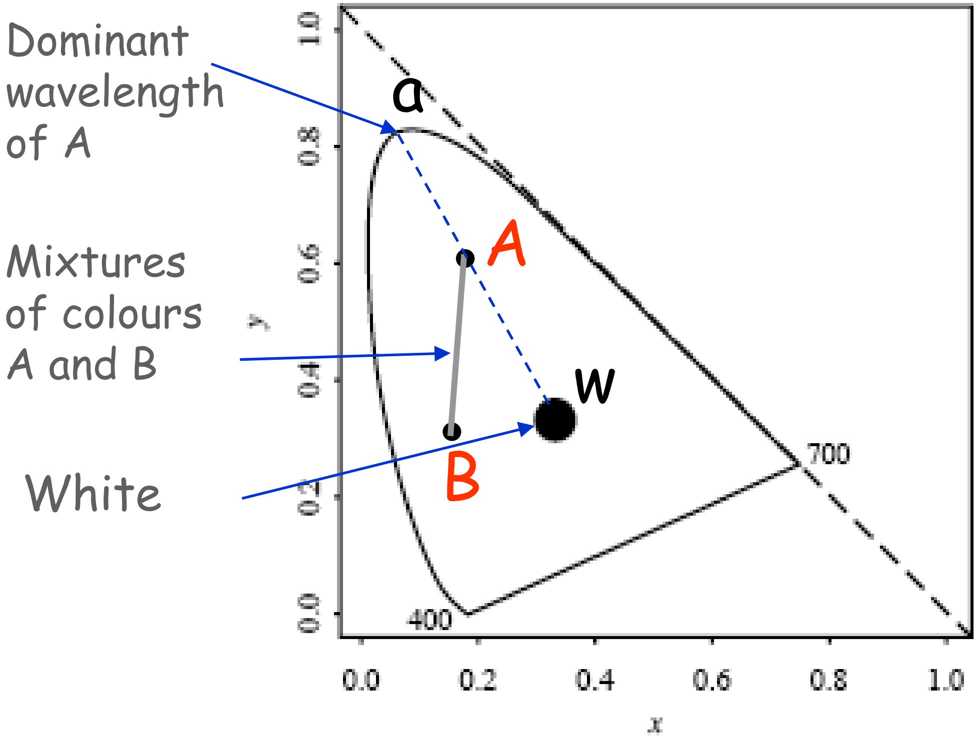
The spectral locus

It contains all monochromatic lights

The line of purples

There are no monochromatic light sources to reproduce these colours

Colour Mixtures



CIE chromaticity diagram.

Grassmann's Law:

If colours $A(X_a, Y_a, Z_a)$ and $B(X_b, Y_b, Z_b)$ are mixed to obtain colour $C(X_c, Y_c, Z_c)$

$$X_c = X_a + X_b$$

$$Y_c = Y_a + Y_b$$

$$Z_c = Z_a + Z_b$$

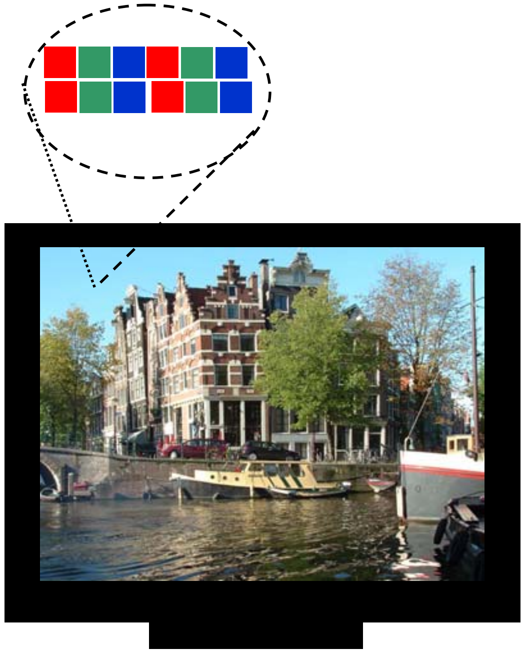
Chromaticity coordinates (x,y,z) are obtained as a liner weighted sum of components (equation of a straight line)

Colour purity of A:

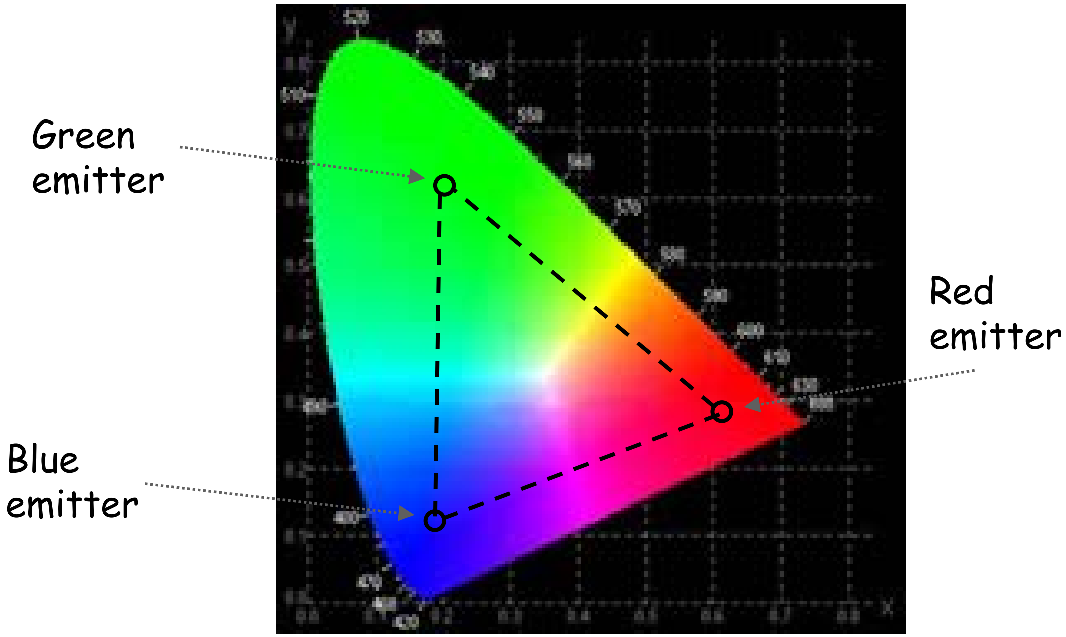
$$P_a = |WA| / |Wa|$$

Gamut

- Gamut is a range of colors that a device can produce



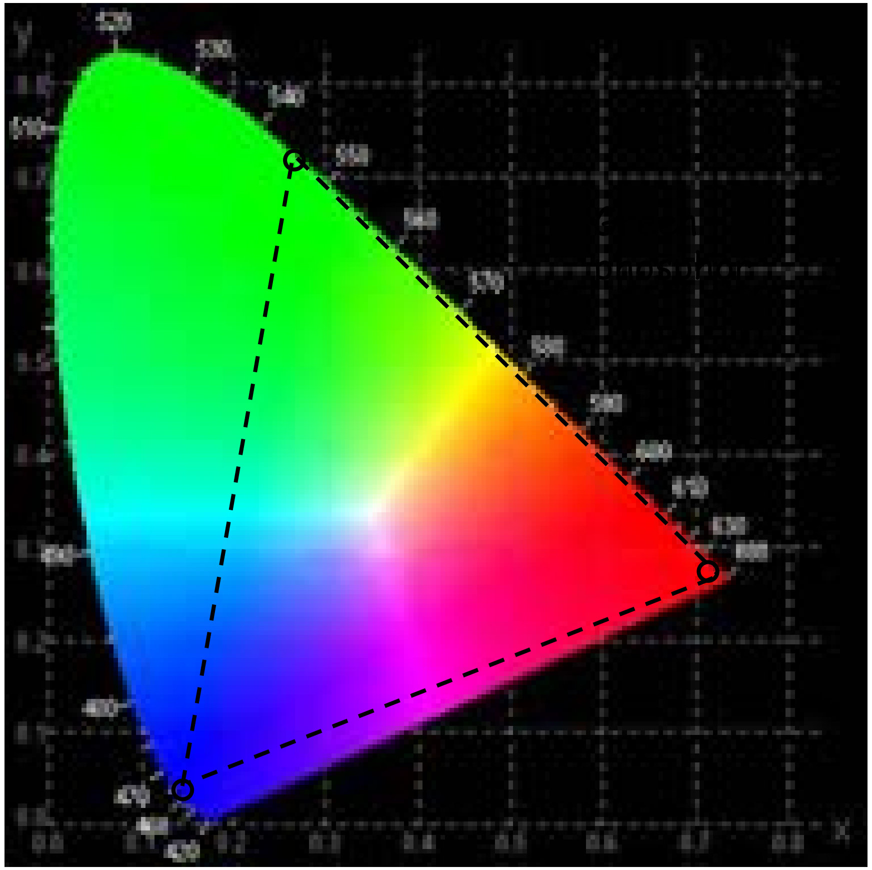
TVs and monitors use 3-colour light emission screens



Only colours limited by the triangle can be reproduced by a TV with these three emitters

Gamut

- Gamut for R, G, B primaries 436nm, 546nm and 700nm

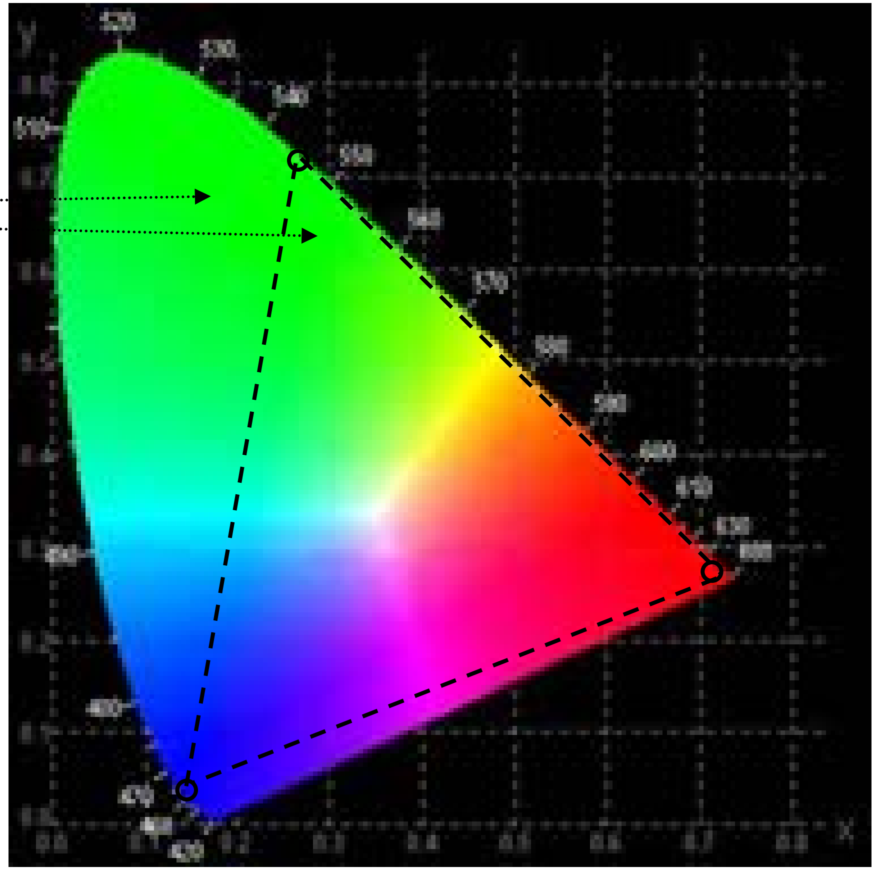


- Only colours limited by the triangle can be reproduced
- If other primaries are used, the chromaticity diagram will have different coordinates for the same colours. However, this diagram will not be CIE Standard compliant
- Chromaticity coordinates of a colour in terms of any second set of primaries can be calculated from the coordinates that correspond to the first set of primaries.

Thus, CIE Chromaticity Diagram provides a device independent model for colour analysis and gamut comparison

Quiz

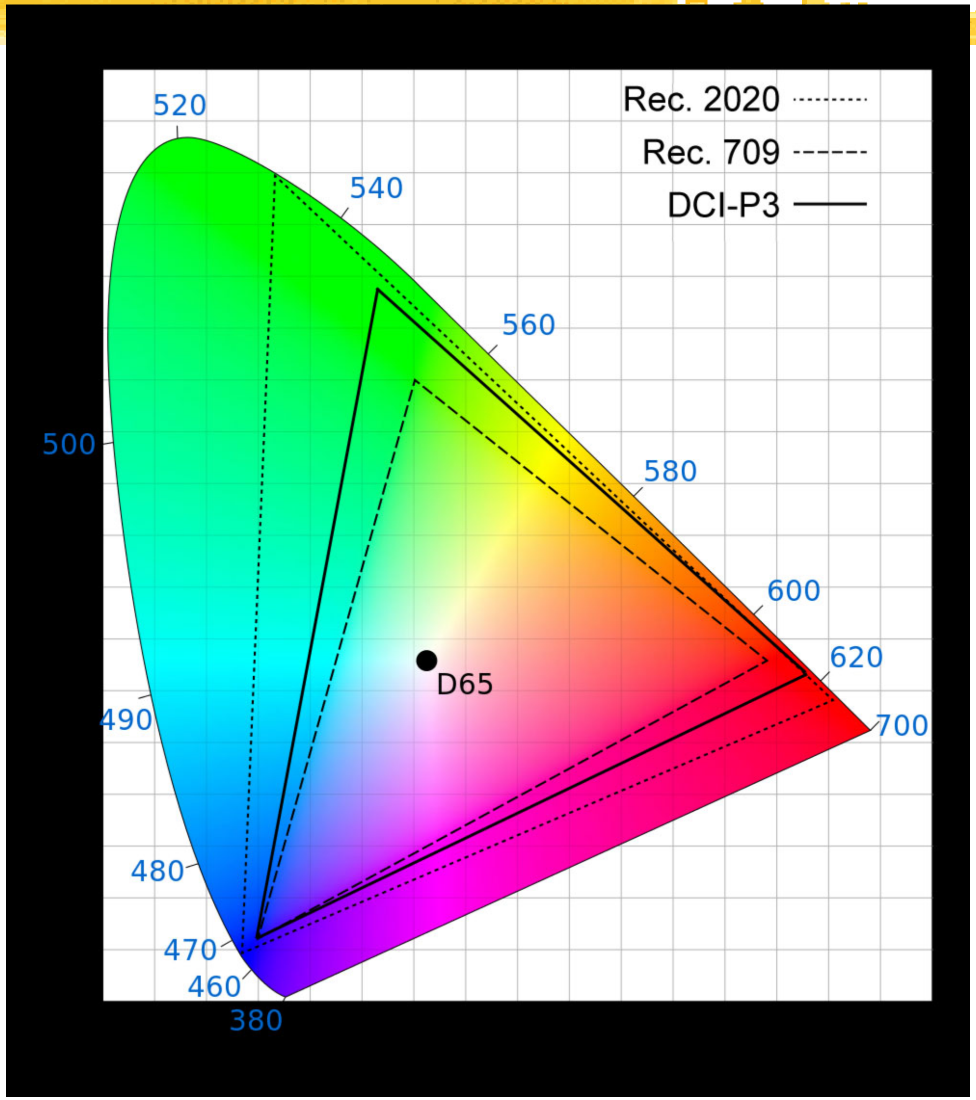
What can you say about the perceptual difference between these two colours if you compare them visually?



Gamut of digital TV

- ITU-R Rec. 709 HDTV standard defines a set of non-monochromatic primaries that limit the gamut. Also, recalculation of R,G,B values is needed as the primaries are different from those defined by CIE 1931

- ITU-R Rec. 2020 UHDTV standard defines monochromatic primaries with wavelengths similar to those defined by CIE 1931 covering 76% of the chromaticity diagram



Colour Transformations

- Given the tristimulus values $R_1 \quad G_1 \quad B_1$ of a colour in terms of the first set of primaries, how to get the tristimulus values $R_2 \quad G_2 \quad B_2$ of the same colour in terms of the second set of primaries

- In general: $$\begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} = \mathbf{M} * \mathbf{T} * \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

where,

$\mathbf{T}$ is a $3x3$ matrix that converts RGB of the first set of primaries into CIE XYZ colour space

$\mathbf{M}$ is a $3x3$ matrix that converts CIE XYZ into RGB colour space of the second set of primaries

- Two 3x3 matrixes can be multiplied to produce $\mathbf{C} = \mathbf{M} * \mathbf{T}$

Colour Transformations

- *Example:* ITU-R Rec. 709 specifies primaries which are different from CIE 1931 primaries

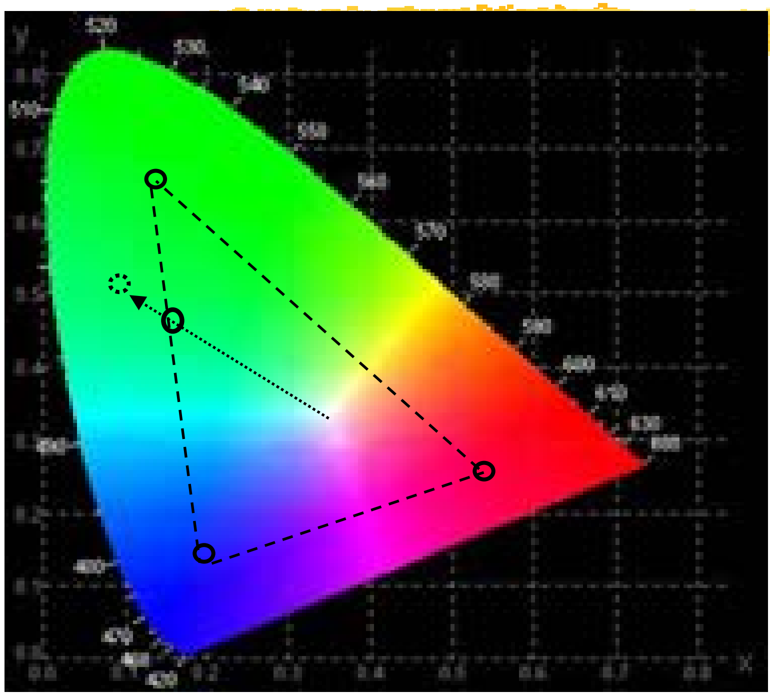
1. Given a colour A in CIE XYZ colour space, how to get its RGB components in Rec. 709 primaries colour space?

$$\begin{bmatrix} R_A \\ G_A \\ B_A \end{bmatrix} = \begin{bmatrix} 3.24 & -1.54 & -0.5 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{bmatrix} * \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix}$$

2. Given a colour A in Rec. 709 primaries colour space, how to get its CIE XYZ Colour coordinates?

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{bmatrix} * \begin{bmatrix} R_A \\ G_A \\ B_A \end{bmatrix}$$

Out of Gamut Colors



An out-of-gamut colour is approximated by an in-gamut one

Although different TV standards specify different sets of primaries, all of them can be expressed in XYZ coordinates

Chromaticities and White Points of Monitor Specifications

System	Red		Green		Blue		White Point	
	x_r	y_r	x_g	y_g	x_b	y_b	x_W	y_W
NTSC	0.67	0.33	0.21	0.71	0.14	0.08	0.3101	0.3162
SMPTE	0.630	0.340	0.310	0.595	0.155	0.070	0.3127	0.3291
EBU	0.64	0.33	0.29	0.60	0.15	0.06	0.3127	0.3291

HSB Color Space

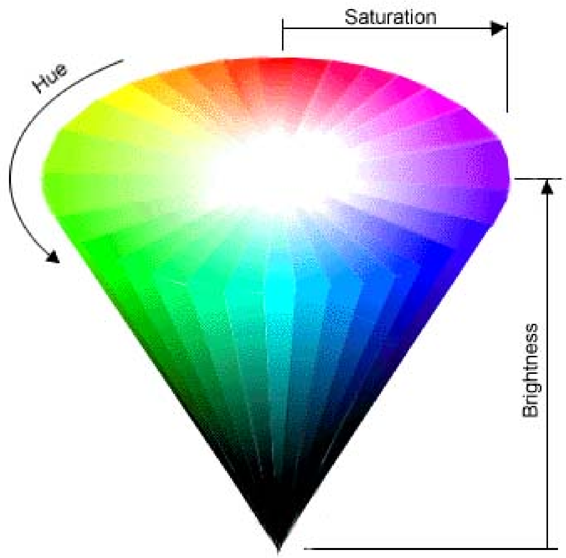
Besides RGB and xyz, there are other colour models

- Hue, Saturation and Brightness
  - **Hue** is the wavelength at which most of the energy of the light is concentrated (the *dominant wavelength*)
  - Saturation is a measure of the purity of a color

    A hue can be "diluted" by mixing a pure colour with white. The dominant wavelength remains the same, but the presence of other hues makes the color paler
  - Brightness is a measure of how light or dark it is
    - A color's appearance will be modified by the intensity of the light. Less light intensity makes it appear darker

HSB Color Space

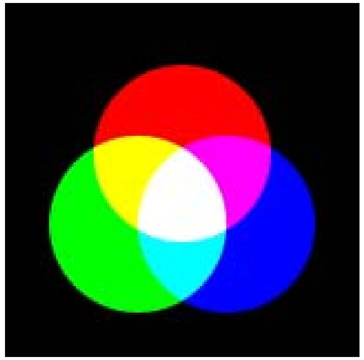
- **Hue** is the actual colour. It is measured in angular degrees around the cone starting and ending at red = 0 or 360 (so yellow = 60, green = 120, etc.).
- **Saturation** is the purity of the colour, measured in percent from the centre of the cone (0) to the surface (100). At 0% saturation, hue is meaningless.
- **Brightness** is measured in percent from black (0) to white (100). At 0% brightness, both hue and saturation are meaningless.



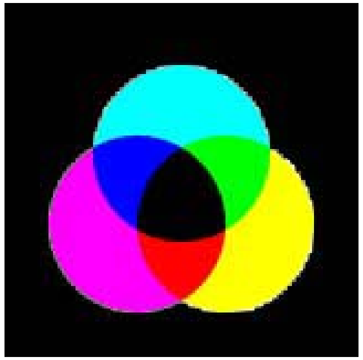
Additive and Subtractive Colour Models

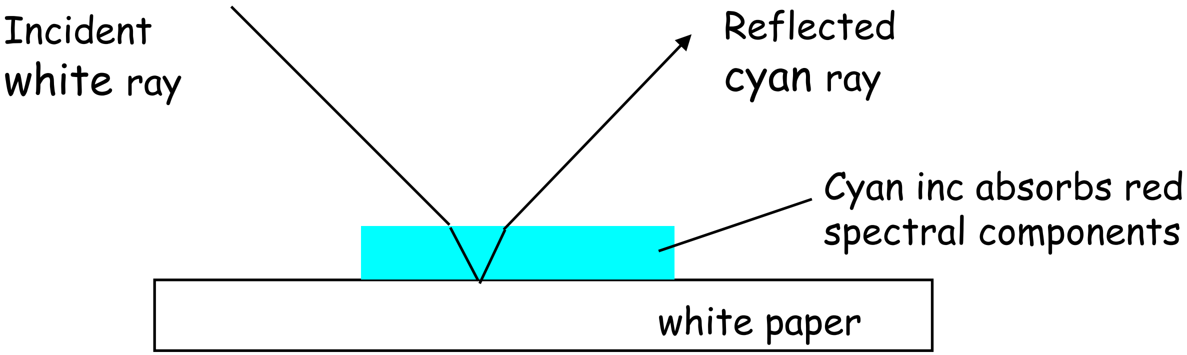
- R, G, B colour model describes intensities of components which are *emitted* to produce a given color. Components are added together

(TV tubes, LSD and Plasma screens)



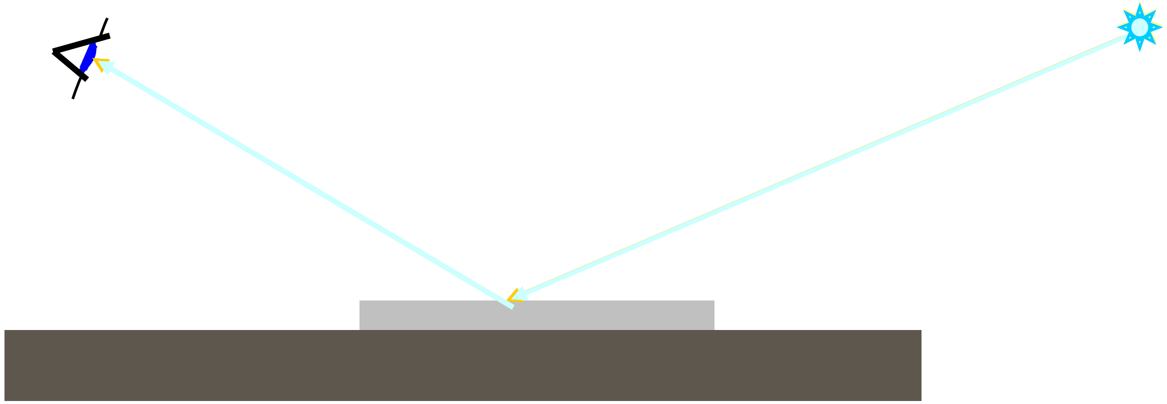
- Printed images use completely different model for colour rendering. Colour components a subtracted from white light





C = W − R
M = W − G
Y = W − B

Colour Constancy



$$r_1 = \int S_1(\lambda)\,\overline{r}(\lambda)\,d\lambda$$
$$g_1 = \int S_1(\lambda)\,\overline{g}(\lambda)\,d\lambda$$
$$b_1 = \int S_1(\lambda)\,\overline{b}(\lambda)\,d\lambda$$

$$r_2 = \int S_2(\lambda)\,\overline{r}(\lambda)\,d\lambda$$
$$g_2 = \int S_2(\lambda)\,\overline{g}(\lambda)\,d\lambda$$
$$b_2 = \int S_2(\lambda)\,\overline{b}(\lambda)\,d\lambda$$

According to the formulas, if two sources of light have different spectrums, a white object should change its colour

However. the **perceived** color of objects remains relatively constant under varying illumination conditions

The mechanism of adaptation of the human vision to illumination conditions is still not fully understood

Textbook

- D Forsyth, *Computer Vision. A Modern Approach*

  Chapters
  - 1 Radiometry
  - 3 Colour