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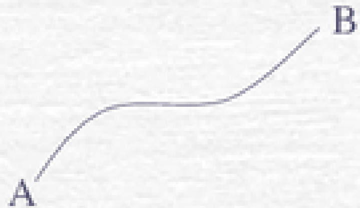
Basic display optics

- The Fermat Principle

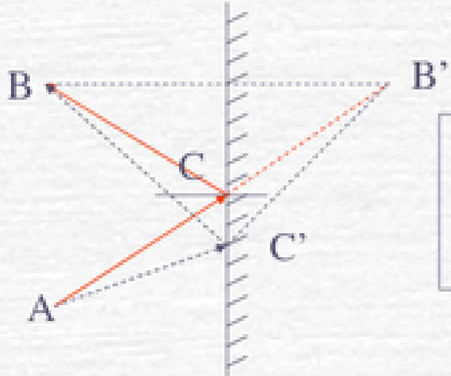
$$\delta \int_{A}^{B} n(s)ds = 0$$



- Light travels along the path of least time
- Or shortest Optical Path Length (OPL)

Reflection

- The reflected rays lies on the plane of incidence and the reflected angle equals the incident angle.

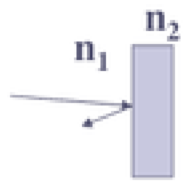


Ray ACB is shorter than AC'B; ACB' is the shortest possible path, a straight line.

- Nature chooses the shortest way.

Fresnel reflection

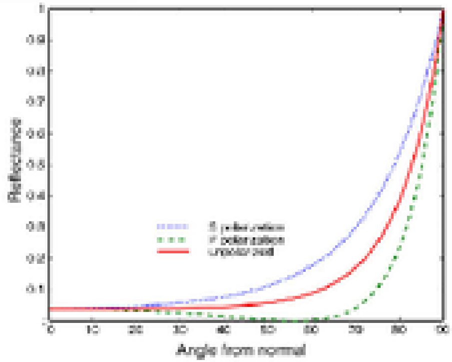
- Power reflectance at normal incidence



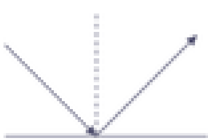
$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

At glass-air boundary, the reflectance is 4% (n_{glass} = 1.5)

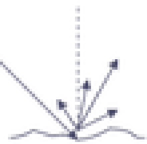
- At oblique incidence, TE wave (s-pol) will have a larger reflectance than the TM wave (p-pol)
- Total reflection keeps close to 4% even at large angles
- To enhance display contrast under ambient light, AR/ AG treatment is employed



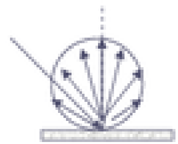
Specular and diffuse reflection



Specular reflection on smooth surface



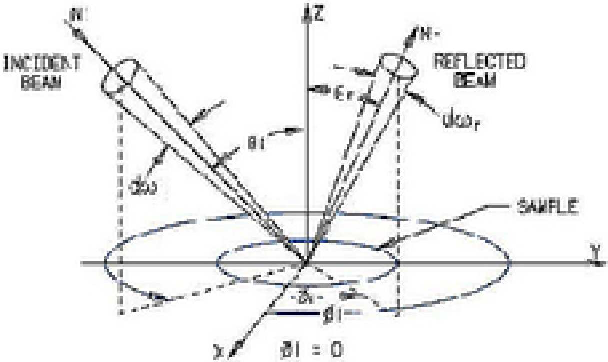
Diffuse reflection on rough surface

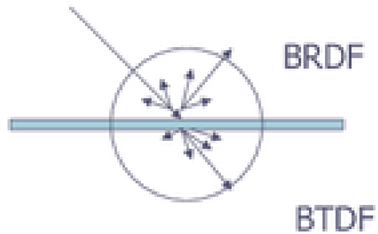


Lambertian reflection surface

- A Lambertian reflecting surface reflects incident light such that the reflected light has the same luminance when viewing from all directions.
- A diffuse white standard or interior surface of integrating sphere is close to Lambertian.

Bidirectional Reflection Distribution Function (BRDF)



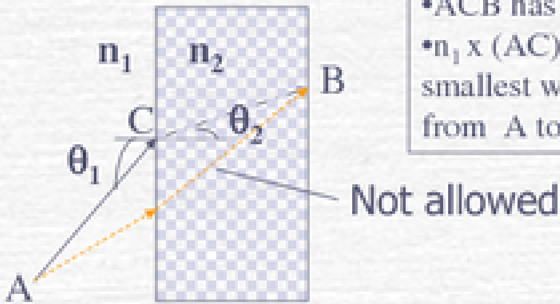


- The BRDF describes the reflection distribution as a function of the incident light direction
- For transmission, BTDF can be defined in similar way
- The BRDF/BTDF values are useful for diffuser/ backlight design

Refraction-Snell's law

- The refracted rays lies on the plane of incidence and the refracted angle is related to the incident angle by

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



•ACB has the shortest OPL
•n_1 x (AC) + n_2 x (CB) is smallest when traveling from A to B

- n1, n2: refractive index of medium 1 and 2
- θ1, θ2: angle to the interface normal in medium 1 and 2

Light as an EM Wave

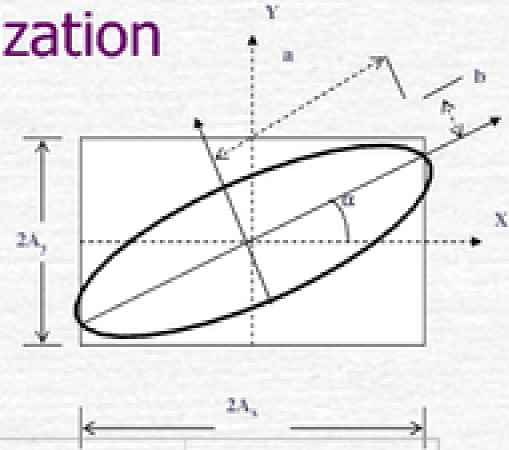
$$\nabla^2 \Psi = \frac{1}{v^2}\frac{\partial^2 \Psi}{\partial t^2}$$

- Plane wave solution

$$\Psi(\vec{r},t) = Ae^{i(\vec{k}\bullet\vec{r}-\omega t)}$$

- A: amplitude→ brightness
- (kr-ωt)→ phase
- *k* → propagating direction
- ω → frequency (color)

Light Polarization



$$E_x = A_x \cos(\omega t - kz + \delta_x)$$

$$E_y = A_y \cos(\omega t - kz + \delta_y)$$

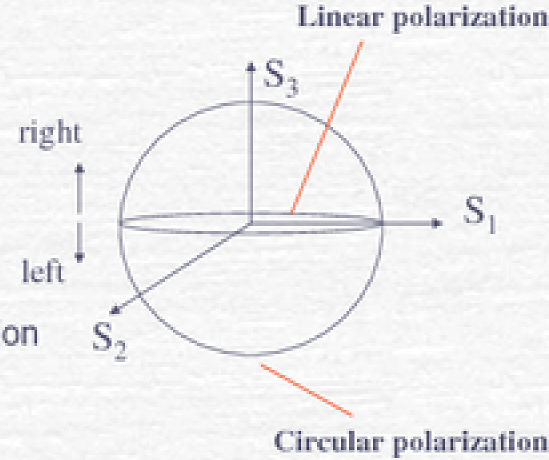
$$\frac{E_x^{\ 2}}{A_x^{\ 2}} + \frac{E_y^{\ 2}}{A_y^{\ 2}} - 2\frac{E_x E_y}{A_x A_y}\cos\delta = \sin^2\delta$$

	$\delta = 0, \pi$	$\delta = +\pi/2, -\pi/2$	Else
$A_x = A_y$	Linear (±45°)	Circular (LH, RH)	Elliptical (45°)
$A_x \neq A_y$	Linear $(\pm\tan^{-1}(A_y/A_x))$	Elliptical ($\alpha = 0$)	Elliptical (general)

Stokes parameters and the Poincare sphere

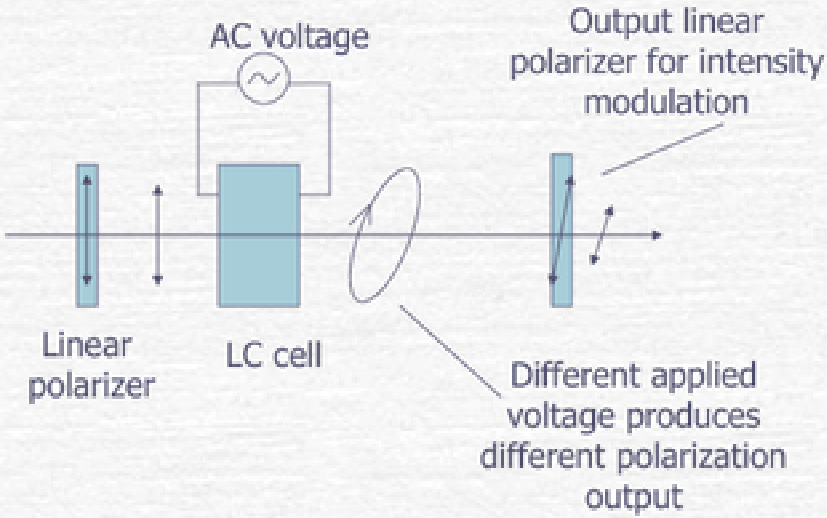
- A light beam can be completely characterized by A_x, A_y, δ_x, δ_y
- Or equivalently by the four Stokes parameters S_0, S_1, S_2, S_3

$$S_0 = A_x^{\,2} + A_y^{\,2}$$
$$S_1 = A_x^{\,2} - A_y^{\,2}$$
$$S_2 = A_x A_y \cos(\delta_y - \delta_x)$$
$$S_3 = A_x A_y \sin(\delta_y - \delta_x)$$



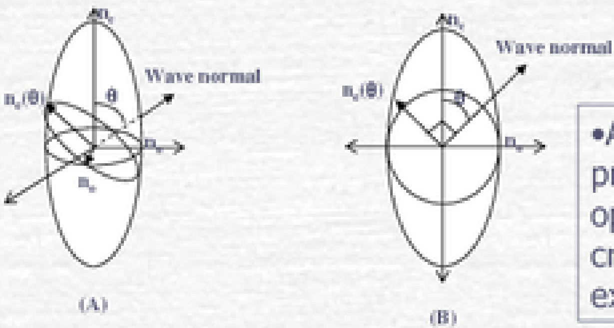
- The Stokes vector $S=[S_0, S_1, S_2, S_3]$ describes the intensity and polarization state of the light beam
- The Poincare sphere surface represents all possible pure polarization states

Most LC devices work by manipulating polarization states



Refractive Index and Birefringence

- Isotropic material→ single R.I. n e.g. *glass*
- Uniaxial material → two R.I. n_e, n_o (birefringence) e.g. *Liquid crystals*
- Biaxial material →three R.I. n_x, n_y, n_z e.g. *some compensation films*



$$n_e(\theta) = \left(\frac{\cos^2\theta}{n_o^{\;2}} + \frac{\sin^2\theta}{n_e^{\;2}}\right)^{-1/2}$$

•Angle between the wave propagation direction and the optical axis (of a uniaxial crystal) determines the extraordinary index value

Retardation

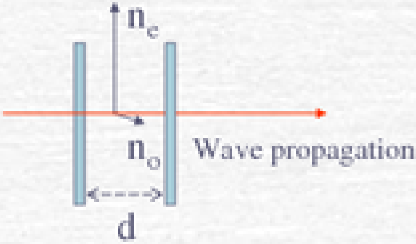
- Optical path difference and phase change

$$OPD = d \times n_e - d \times n_o = d \times (n_e - n_o) = d \times \Delta n$$

$$Phase\ change = OPD \times 2\pi / \lambda$$

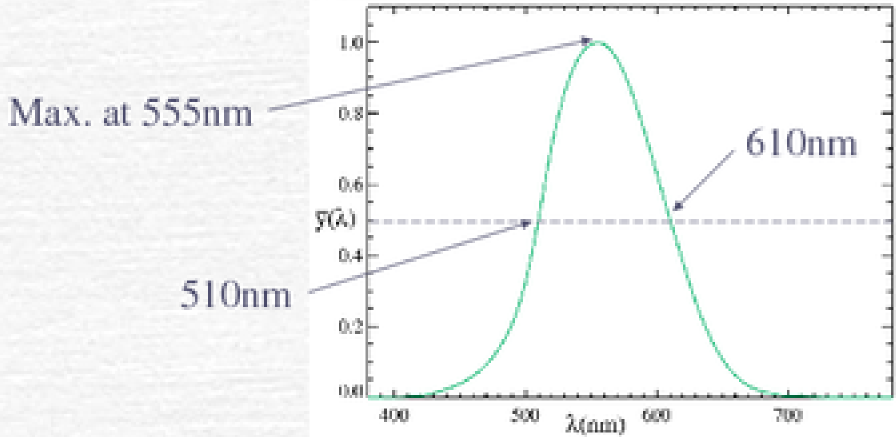
- In LCD, retardation of LC cell refers to OPD regardless of the twist angle

$$Retardation = d \times \Delta n$$



Basic Photometry

- Visible light: 360nm-780nm
- Eye's response to light- Photopic vision



Four basic photometric quantities

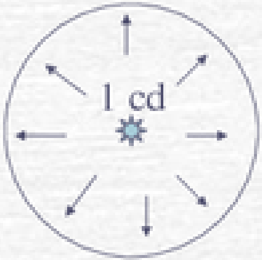
- Flux (lumen)- the Luminous power

  1 watt 555nm light produces 683 lm flux

- Intensity (candela)- lumen/steradian

$$I = \frac{dF}{d\omega}$$

- **An isotropic source with 1 cd luminous intensity in all directions produces a total flux of 4π lumen**

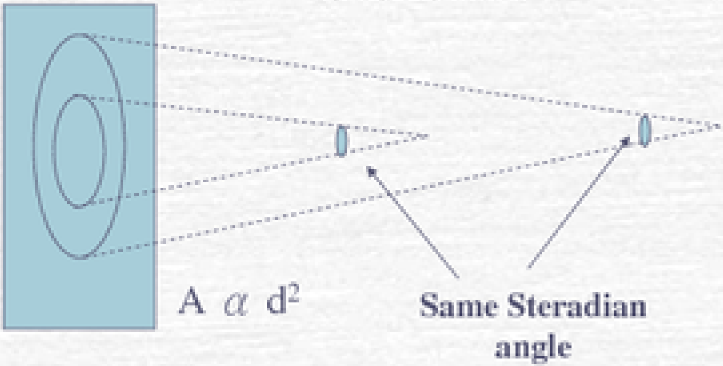


4π lm

1 sphere = 4π Steradian angle

- Luminance (cd/m^2)- density of luminous intensity
- It is the quantity that tells how " bright" an object is

$$L = \frac{d^2 F}{dA d\Omega d \cos\theta}$$



Luminance is independent of distance

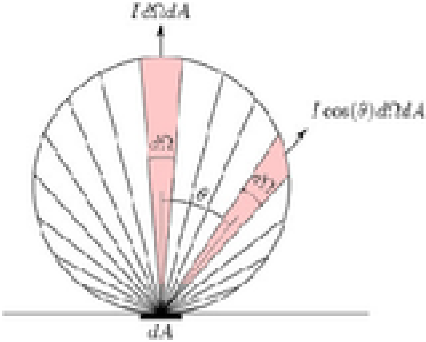
- Illuminance (lux)-total flux per unit area $E = \frac{F}{A}$

The inverse square law of Illuminance by a point source

$$E = \frac{I \cos\theta}{d^2}$$

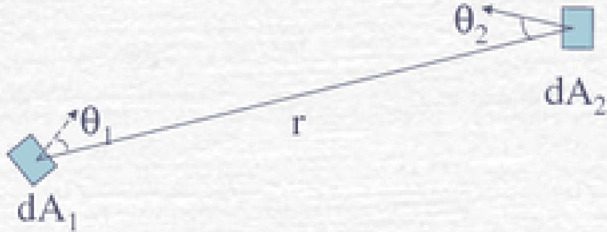
Lamberts' cosine law

states that the *luminous intensity* from an element of a perfectly diffusing surface varies as the cosine of the angle between that direction and the *normal vector* of the surface. As a consequence, the *luminance* of that surface is the same regardless of the viewing direction.



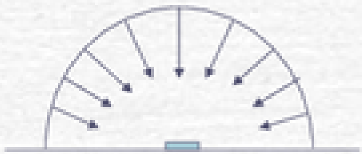
Flux transfer equation

$$dF = \frac{L\cos\theta_1 dA_1 \cos\theta_2 dA_2}{r^2}$$



Exitance

$$L = \frac{M}{\pi}$$

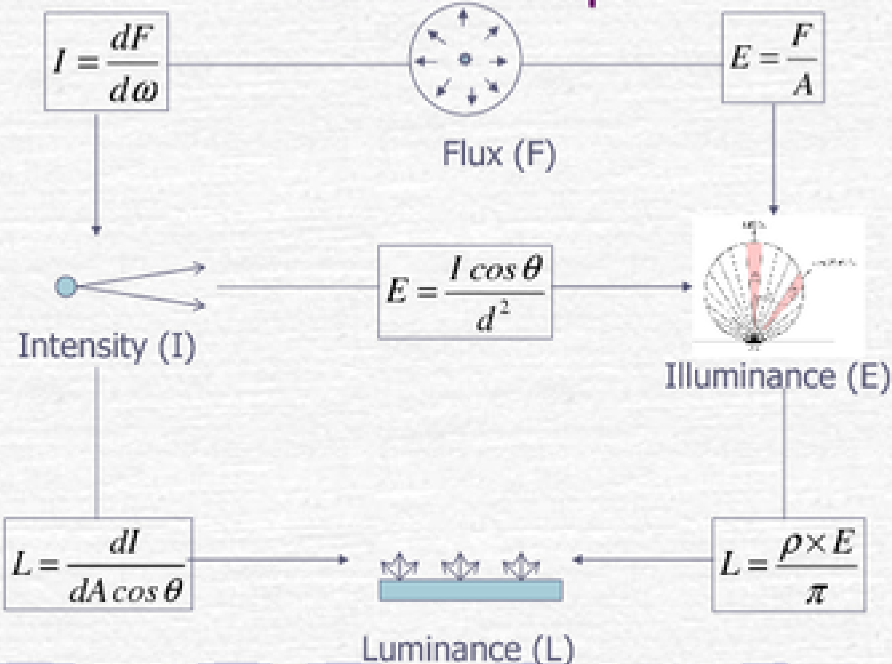


Lambertian source

$$E = \pi \times L$$

$$E = \pi \times L \times \sin^2\frac{\theta}{2}$$

Relationships



Typical photometric values

- Flux: 100W incandescent lamp→1360 lm
  20W Halogen→ 320 lm
  35W Fluorescent tube→ 3300 lm
  1W power white LED→ 45 lm
- Intensity: normal red→10 mcd
  high bright red→ 300 mcd
  super bright red→3000 mcd
  20W 60° spot halogen→450 cd
  1 mW HeNe laser→10^5 cd

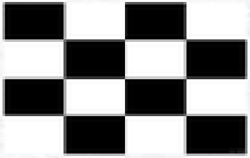
- Illuminance: Office→ 300~750 lx
  Work place→750~1500 lx
  Moonlight→ 0.2 lx
  Sunlight→ 100K lx
- Luminance: CRT TV→300 cd/m^2
  LCD monitor→ 150 cd/m^2
  LCD TV→ 500 cd/m^2
  BLU→100-10000 cd/m^2
  full moon→ 2500 cd/m^2
  Sun→ 10^9 cd/m^2

- Common Contrast Ratio definition

$$CR = \frac{L_o - L_b}{L_b}$$

- Contrast Ratio in displays

$$CR = \frac{L_{Bright\ State}}{L_{Dark\ State}}$$



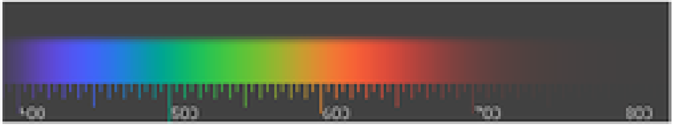
• usually use $L_{full\ on} / L_{full\ off}$

•ANSI uses checker board pattern

CR values:	TN ~30:1, STN ~10:1
	CRT~700:1
	LCD Monitor~250:1to 1000:1
	LCD TV~1000:1 up
	Plasma >5000:1 up *Ref ONLY

Basic Colourimetry

- The colour spectrum

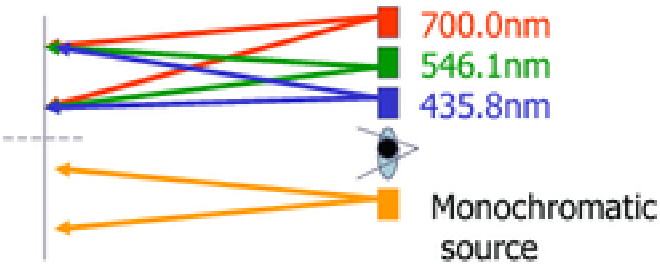


Violet	380–450 nm
Blue	450–495 nm
Green	495–570 nm
Yellow	570–590 nm
Orange	590–620 nm
Red	620–750 nm

For monochromatic light wavelength determines the colour

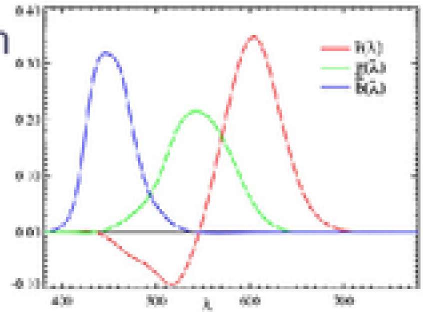
How to specify colour?

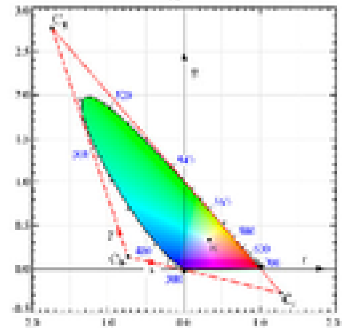
- Tri-stimulus values of the spectrum
- Colour mixing of RGB primaries



The Experiment

Results

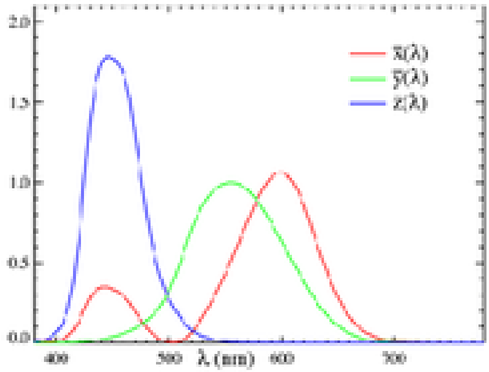




The colour matching functions

- From rgb to xyz
  - --Eliminates negative values
  - --Force one of the curve = V(λ)

→



The CIE1931 colour coordinates

$$X = k\int_{380nm}^{780nm} S(\lambda)\bar{x}(\lambda)\,d\lambda$$

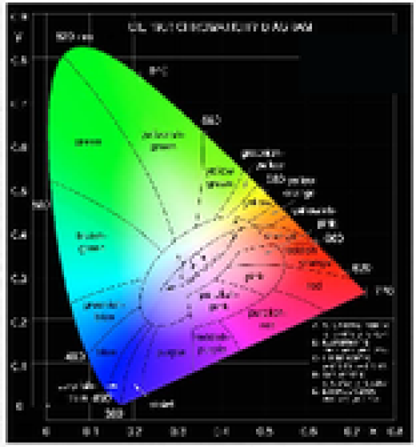
$$Y = k\int_{380nm}^{780nm} S(\lambda)\bar{y}(\lambda)\,d\lambda$$

$$Z = k\int_{380nm}^{780nm} S(\lambda)\bar{z}(\lambda)\,d\lambda$$

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

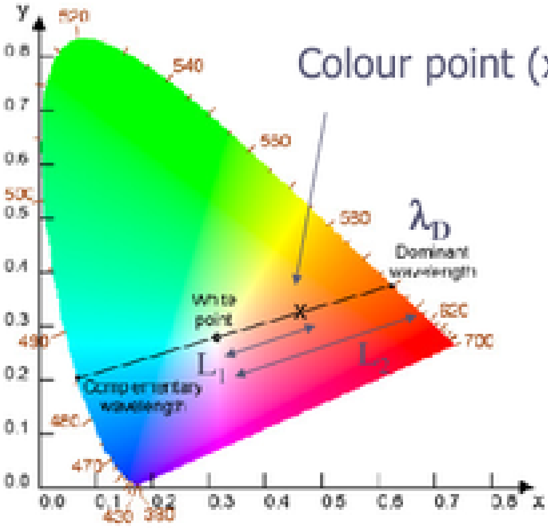
$$y = \frac{Y}{X+Y+Z}$$

$$z = 1 - x - y$$



- CIE1931 chromaticity diagram

Dominant wavelength and colour purity



The CIE 1976 UCS diagram and CIELUV

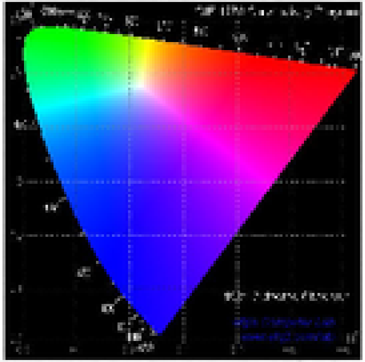
- From XYZ to L*u*v*

$$L^* = 116(Y/Y_o)^{1/3} - 16$$
$$u^* = 13L^*(u' - u'_o)$$
$$v^* = 13L^*(v' - v'_o)$$

with

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

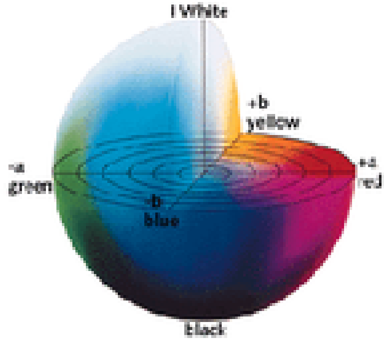
- The values with a 'o' refer to the chromaticity coordinates of the reference white or CIE standard illuminants



The CIELAB and colour difference

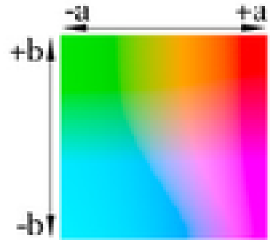
- From XYZ to L*a*b*

$$L^* = 116(Y/Y_o)^{1/3} - 16$$
$$a^* = 500\left[(X/X_o)^{1/3} - (Y/Y_o)^{1/3}\right]$$
$$b^* = 200\left[(Y/Y_o)^{1/3} - (Z/Z_o)^{1/3}\right]$$



- Colour difference

$$\Delta E^*(L^*a^*b^*) = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$$



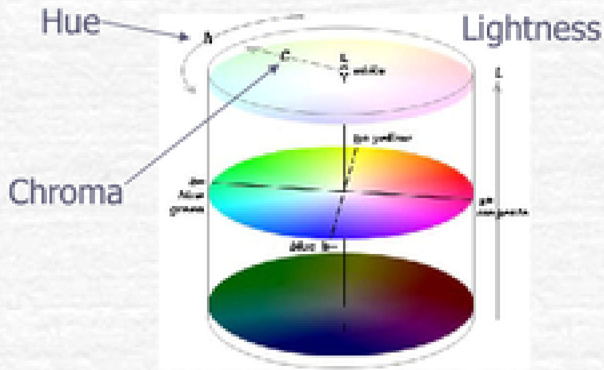
- The CIELAB system is now universally used for colour an color difference spec.
  Hue (a*,b*) is commonly used in polarizer spec

Hue, Value and Chroma

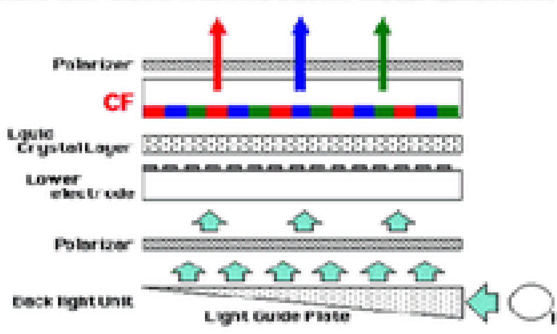
- Hue- the term for classification of red, yellow, blue etc.
- Chroma- how saturate or vivid a colour is
- Value (or Lightness)- refer to the brightness

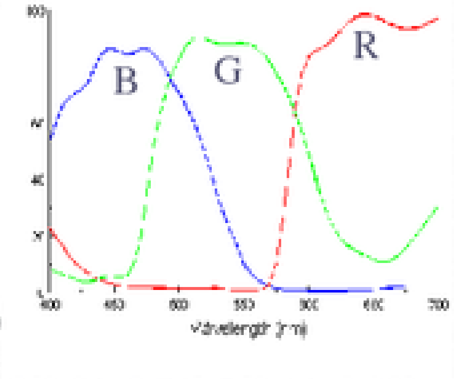
$$C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

$$Hue\ Angle\ h_{ab} = \tan^{-1}\left(\frac{a^*}{b^*}\right)$$



LCD colour filter





- NTSC colour gamut: R(0.67, 0.33) G(0.21, 0.71) B(0.14, 0.08) (FCC 1953, white point C)
- PAL/SECAM color gamut: R(0.64, 0.334) G(0.291, 0.6) B(0.147, 0.06) (EBU 3213, white point D65)