Acquisition et Restitution de Données (ARD)

Part II : Photometry and colorimetry

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Topics

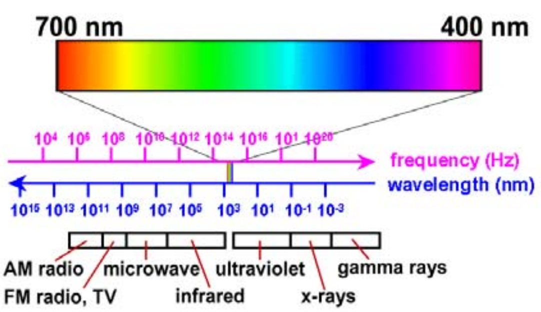
- Light sources and illumination
- Radiometry and photometry

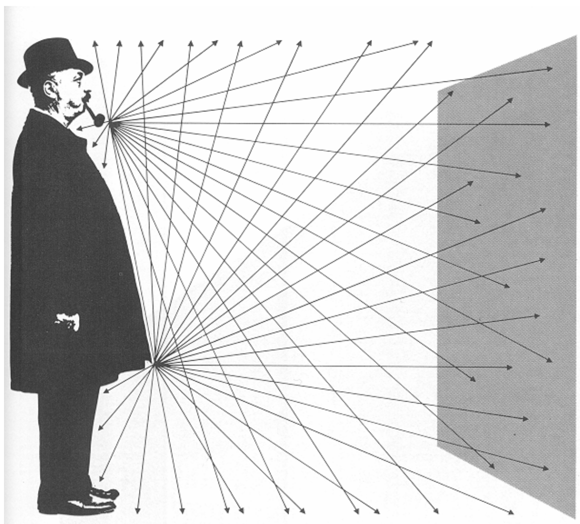
  Quantify spatial energy distribution
  - Radiant intensity
  - Irradiance
    - Inverse square law and cosine law
  - Radiance
  - Radiant exitance (radiosity)
  - Radiometry and Photometry Summary
- **Color**

Light sources and illumination

Light

- Visible electromagnetic radiation
- Power spectrum





- Polarization
- Photon (quantum effects)
- Wave (interference, diffraction)

Photons

- The basic quantity in lighting is the photon
- The energy (in Joule) of a photon with wavelength λ is: $\mathbf{q_\lambda = hc / \lambda}$
  - c is the speed of light
    - In vacuum, c = 299.792.458m/s
  - h ≈ 6.63×10^{-34}Js is Planck's constant

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Radiometry and Photometry

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Radiant Energy and Power

- **Power**: Watts vs. Lumens
  - Energy per unit time
  - Spectral

Φ

- **Energy**: Joules vs. Talbot
  - Exposure
    - Film response
    - Skin - sunburn

(Spectral) Radiant Energy

- The *spectral radiant energy, Q_λ*, in n_λ photons with wavelength λ is

$$Q_\lambda = n_\lambda q_\lambda$$

- The *radiant energy, Q,* is the energy of a collection of photons, and is given as the integral of Q_λ over all possible wavelengths:

$$Q = \int_0^\infty Q_\lambda d\lambda$$

Radiometry vs. Photometry

- **Radiometry** [Units = Watts]
  - Physical measurement of electromagnetic energy
- **Photometry and Colorimetry** [Lumen]
  - Sensation as a function of wavelength
  - Relative perceptual measurement
- **Brightness** [Brils] $B = Y^{1/3}$
  - Sensation at different brightness levels
  - Absolute perceptual measurement
  - Obeys Steven's Power Law

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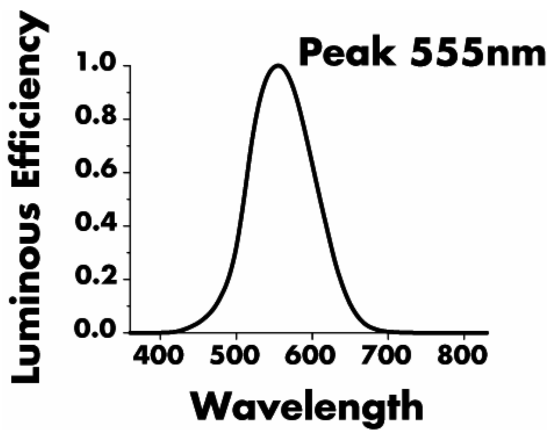
Radiometry vs. Photometry

- **Radiometry and photometry**

  Photometric quantity = product of the radiometric quantity by the luminous efficiency $V(\lambda)$

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



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Blackbody Radiation

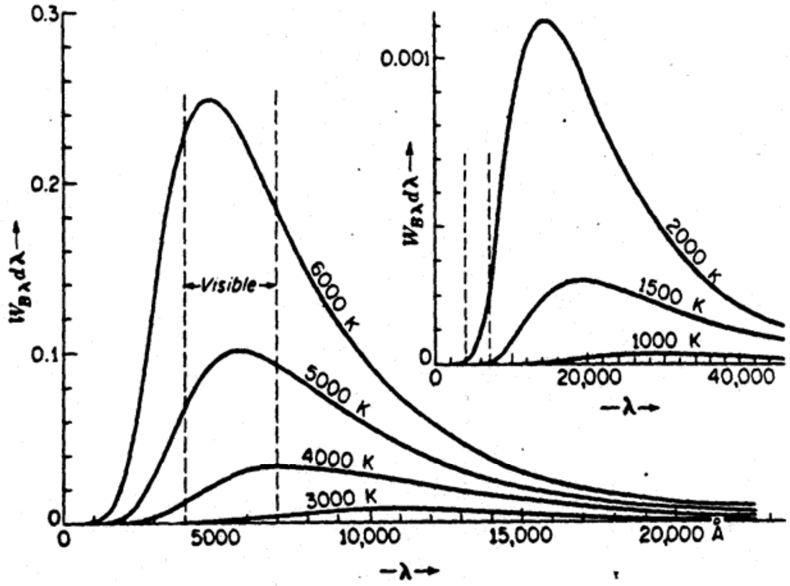


FIGURE 21F
Blackbody radiation curves plotted to scale. Ordinates give the energy in calories per square centimeter per second in a wavelength interval $d\lambda$ of 1 Å. For numerical values, see "Smithsonian Physical Tables," 8th ed., p. 314.

Tungsten Lamp

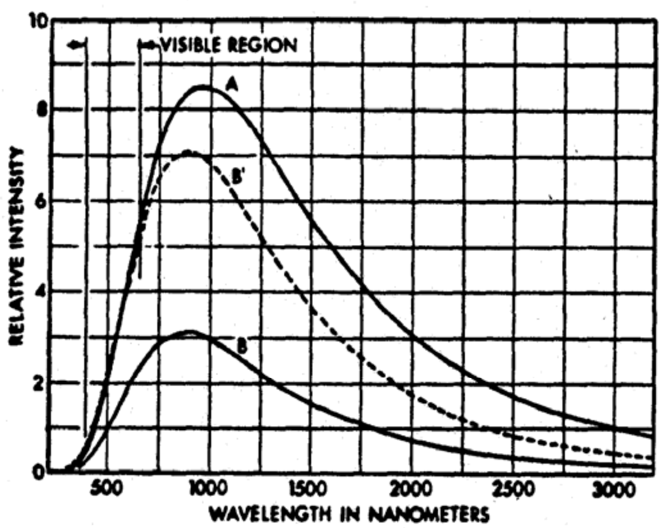
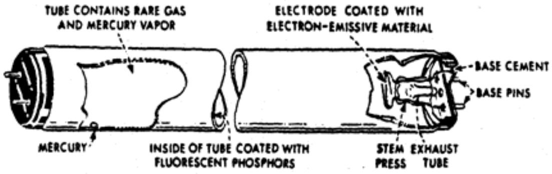


Fig. 8–1. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B′: radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.)

Fluorescent Bulb



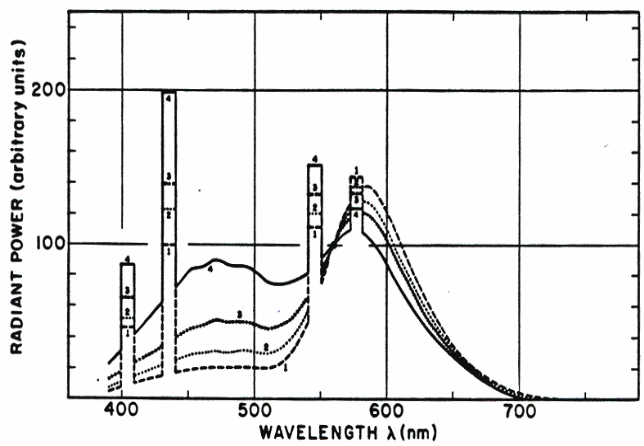


Fig. 3(1.2.3). Relative spectral radiant power distributions of common fluorescent lamps: (1) standard warm white; (2) white; (3) standard cool white; and (4) daylight. The distribution curves have been scaled by appropriate constant factors to provide a common value of 100 at $\lambda = 560$ nm.

Sunlight

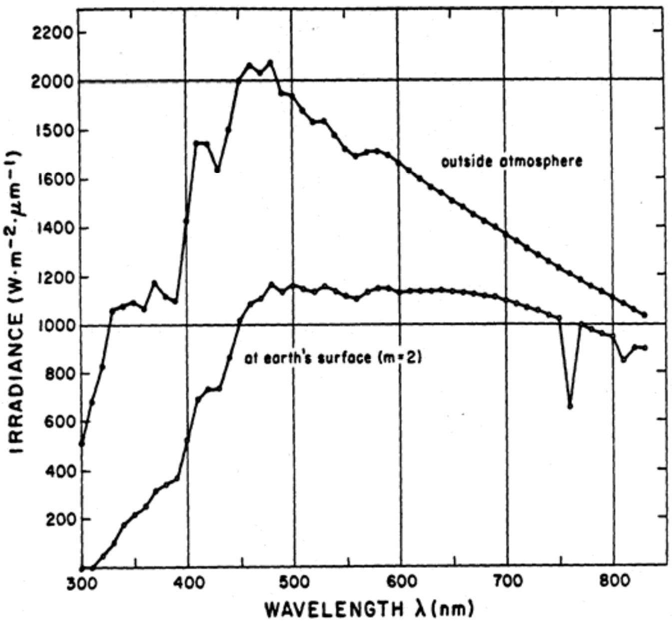


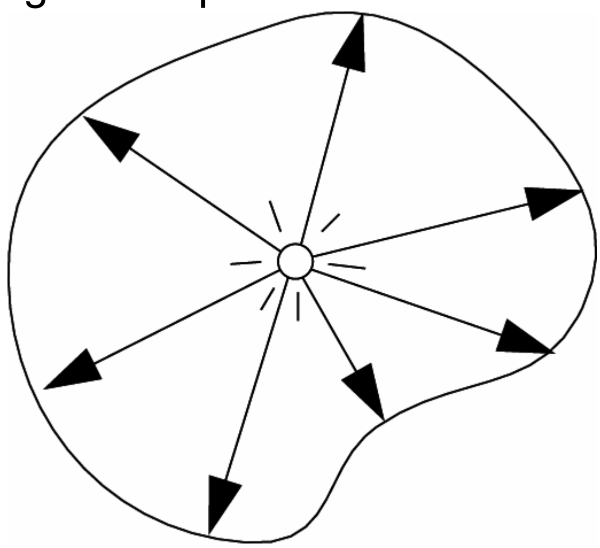
Fig. 1(1.2.1). NASA standard data of spectral irradiance ($W \cdot m^{-2} \cdot \mu m^{-1}$) for the solar disk measured outside the atmosphere (solid dots) and at the earth's surface at air mass 2 (open circles). Data points are those given in Table 1(1.2.1). Neighboring data points have been connected by straight lines for illustrative purposes only.

Radiant Intensity

Radiant Intensity

- **Definition**: The *radiant* (*luminous*) *intensity* is the power per unit solid angle emanating from a point source.

$$I(\omega) \equiv \frac{d\Phi}{d\omega}$$



$$\left[\frac{W}{sr}\right]\left[\frac{lm}{sr} = cd = candela\right]$$

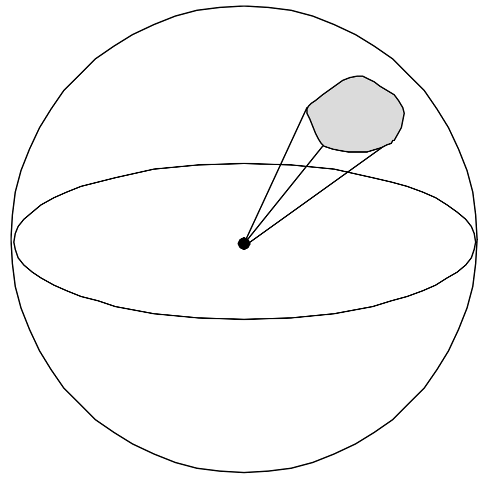
Angles and Solid Angles

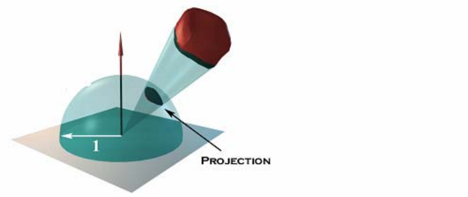
- Angle $\theta = \frac{l}{r}$

  $\Rightarrow$ **circle has 2π radians**

- Solid angle $\Omega = \frac{A}{R^2}$

  $\Rightarrow$ **sphere has 4π steradians**





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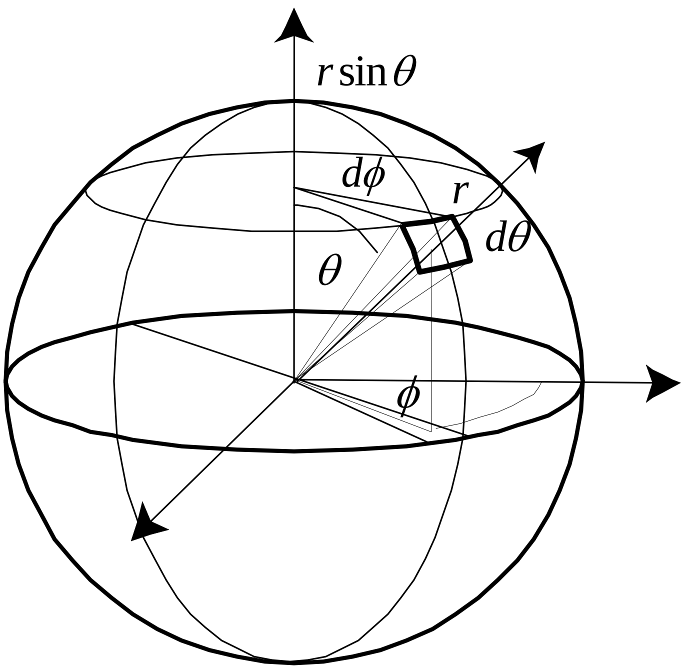
Differential Solid Angles



$$dA = (r\,d\theta)(r\sin\theta\,d\phi)$$
$$= r^2 \sin\theta\,d\theta\,d\phi$$

$$d\omega = \frac{dA}{r^2} = \sin\theta\,d\theta\,d\phi$$

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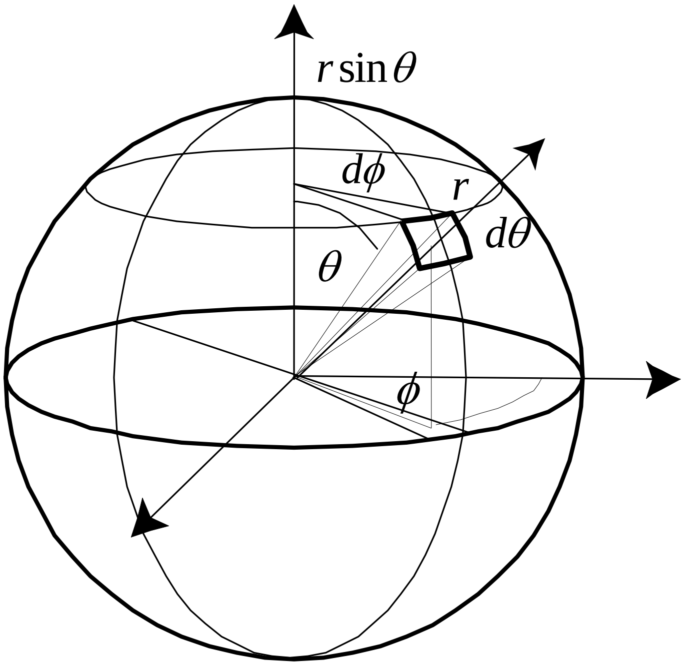
Differential Solid Angles



$$d\omega = \frac{dA}{r^2} = \sin\theta \, d\theta \, d\phi$$

$$\Omega = \int_{S^2} d\omega$$

$$= \int_0^{\pi} \int_0^{2\pi} \sin\theta \, d\theta \, d\phi$$

$$= \int_{-1}^{1} \int_0^{2\pi} d\cos\theta \; d\phi$$

$$= 4\pi$$

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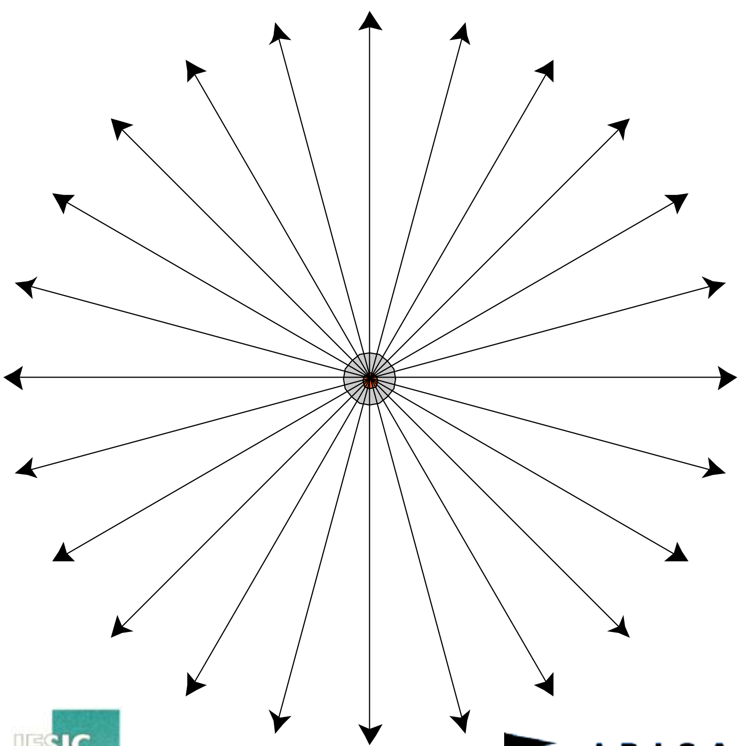
Isotropic Point Source



$$\Phi = \int_{S^2} I \, d\omega$$

$$= 4\pi I$$

$$I = \frac{\Phi}{4\pi}$$

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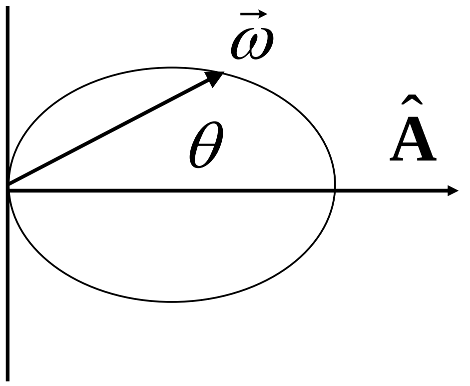
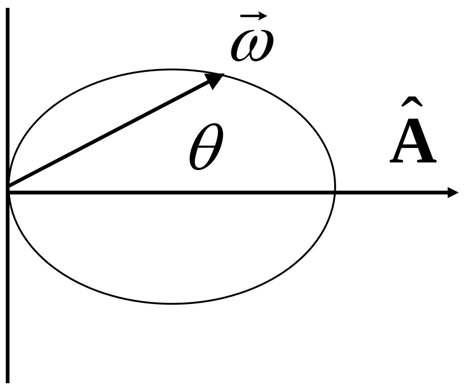
Warn's Spotlight



$$I(\omega) = \cos^s \theta = (\vec{\omega} \bullet \hat{\mathbf{A}})^s$$

$$\Phi = \int_0^{2\pi} \int_0^1 I(\omega)\, d\cos\theta\, d\varphi$$

Warn's Spotlight

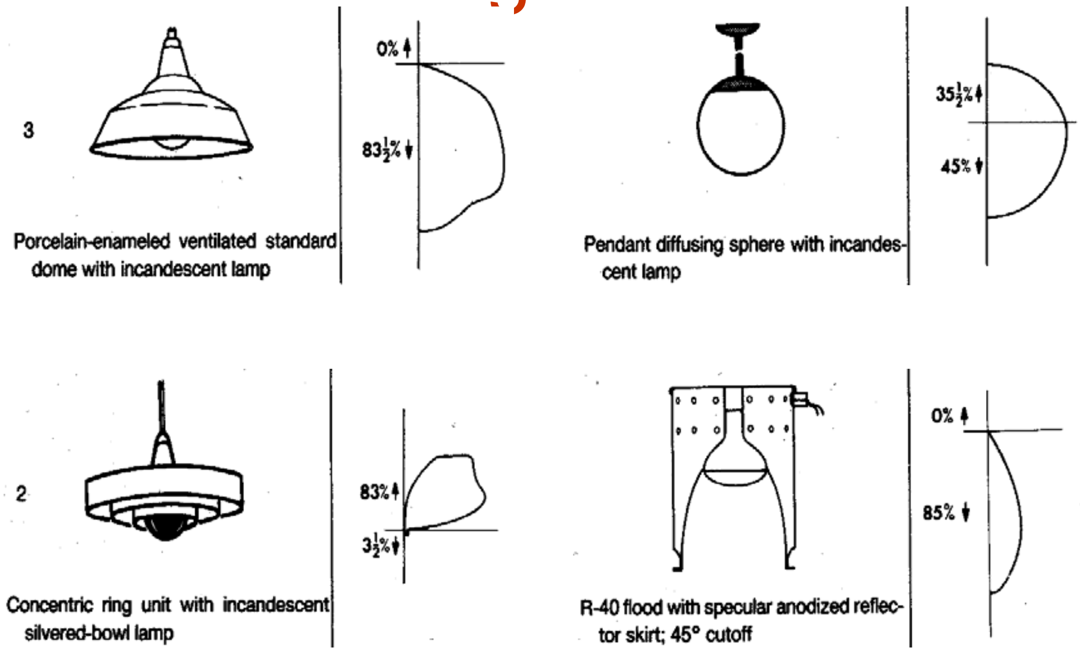


$$I(\omega) = \cos^s \theta = (\vec{\omega} \bullet \hat{\mathbf{A}})^s$$

$$\Phi = \int_0^{2\pi} \int_0^1 I(\omega)\, d\cos\theta\, d\varphi = 2\pi \int_0^1 \cos^s \theta\, d\cos\theta = \frac{2\pi}{s+1}$$

$$I(\omega) = \Phi \frac{s+1}{2\pi} \cos^s \theta$$

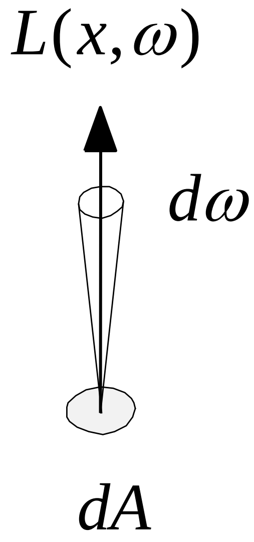
Light Source Goniometric Diagrams



Radiance (Luminance)

Radiance

- **Definition**: The surface *radiance* (*luminance*) is the intensity per unit area leaving a surface



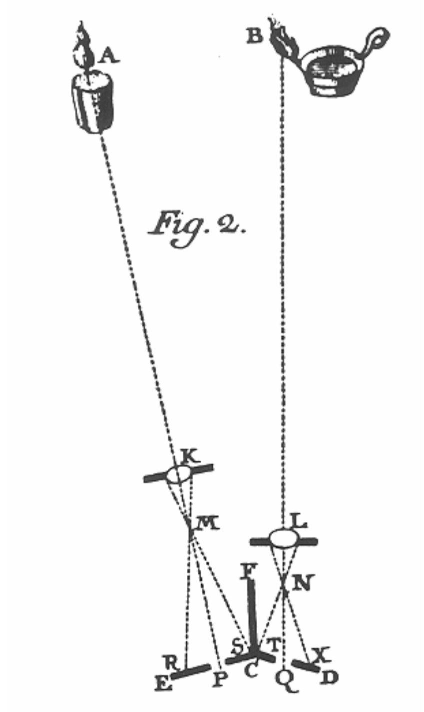
$$L(x,\omega) \equiv \frac{dI(x,\omega)}{dA}$$

$$= \frac{d^2\Phi(x,\omega)}{d\omega dA}$$

$$\left[\frac{W}{sr\,m^2}\right]\left[\frac{cd}{m^2} = \frac{lm}{sr\,m^2} = nit\right]$$

Irradiance (illuminance)

The Invention of Photometry



- Bouguer's classic experiment
  - Compare a light source and a candle
  - Intensity is proportional to ratio of distances squared
- Definition of a candela
  - Originally a "standard" candle
  - Currently 550 nm laser w/ 1/683 W/sr
  - 1 of 6 fundamental SI units

Irradiance

- Definition: The *irradiance* (*illuminance*) is the power per unit area incident on a surface.

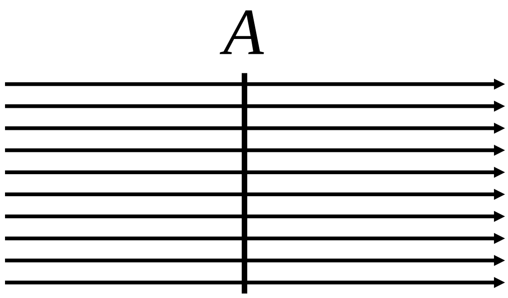
$$E(x) \equiv \frac{d\Phi_i}{dA}$$

$$\left[\frac{W}{m^2}\right] \left[\frac{lm}{m^2} = lux\right]$$

- Sometimes referred to as the radiant (luminous) incidence.

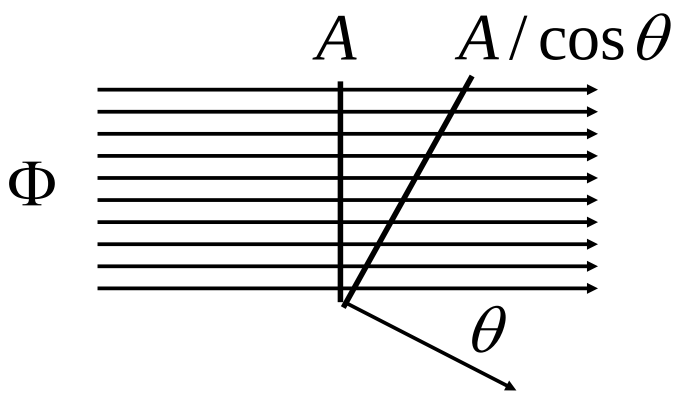
Lambert's Cosine Law

$$\Phi = EA$$



$$E = \frac{\Phi}{A}$$

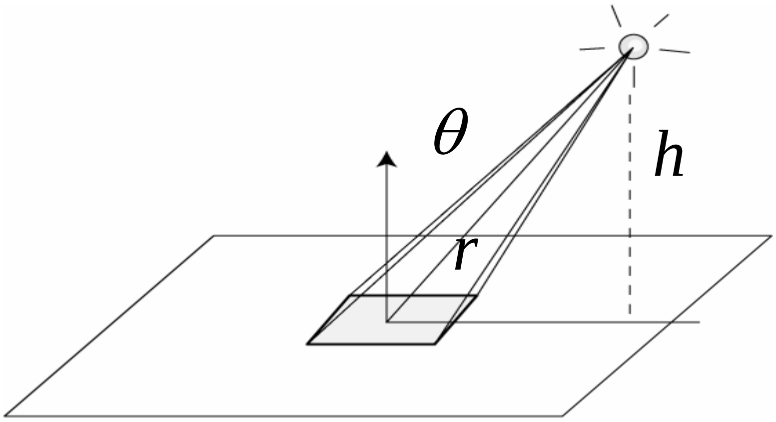
Lambert's Cosine Law



$$E = \frac{\Phi}{A/\cos\theta} = \frac{\Phi}{A}\cos\theta$$

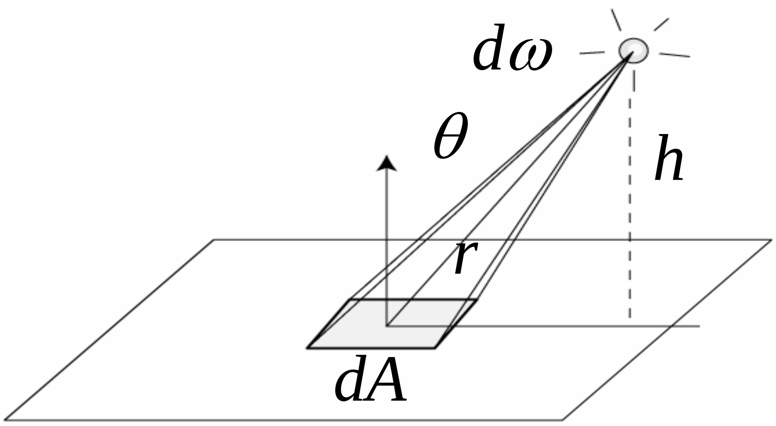
Irradiance: Isotropic Point Source

$$I = \frac{\Phi}{4\pi}$$



Irradiance: Isotropic Point Source

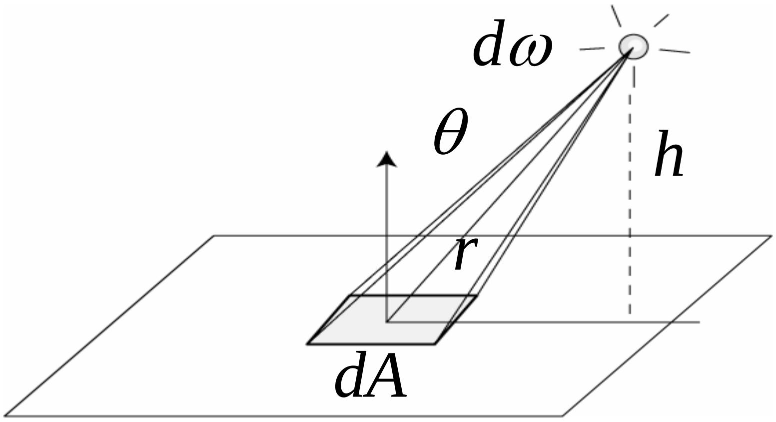
$$I = \frac{\Phi}{4\pi}$$



$$d\Phi = I\, d\omega$$

Irradiance: Isotropic Point Source

$$I = \frac{\Phi}{4\pi}$$



$$d\omega = \frac{\cos\theta}{r^2} dA$$

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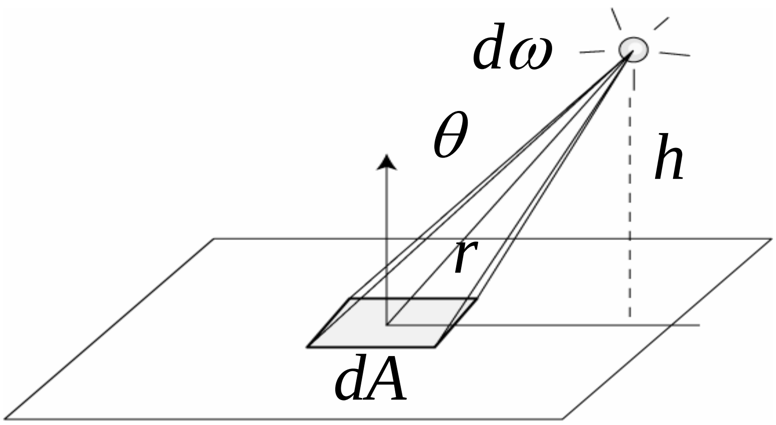
Irradiance: Isotropic Point Source

$$I = \frac{\Phi}{4\pi}$$



$$I\, d\omega = \frac{\Phi}{4\pi} \frac{\cos\theta}{r^2} dA$$

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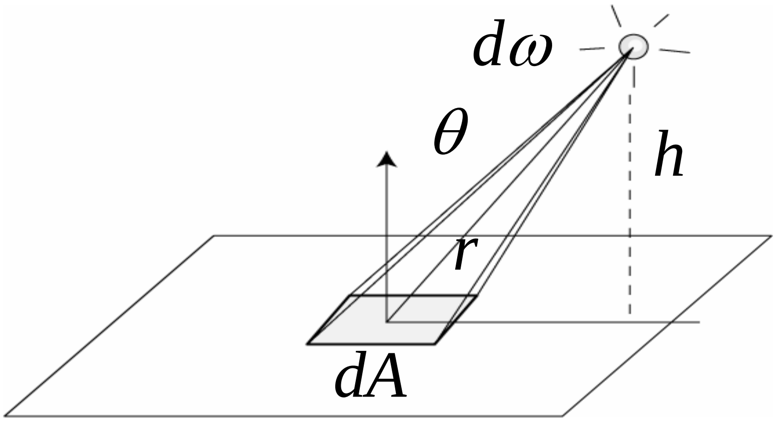
Irradiance: Isotropic Point Source

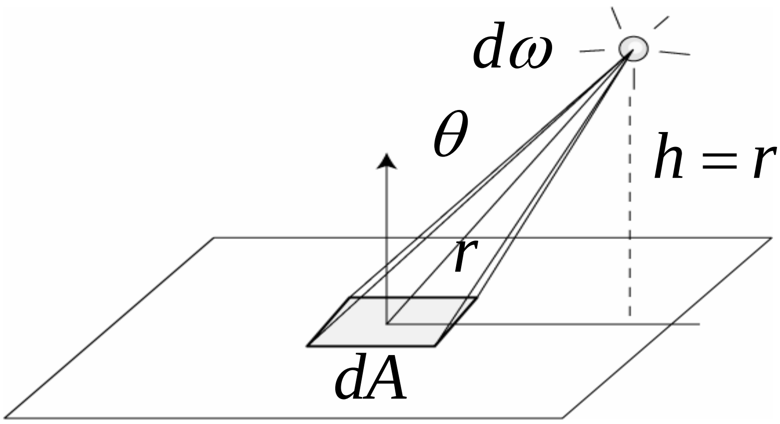


$$I = \frac{\Phi}{4\pi}$$

$$I\,d\omega = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2}dA = E\,dA$$

$$E = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2}$$

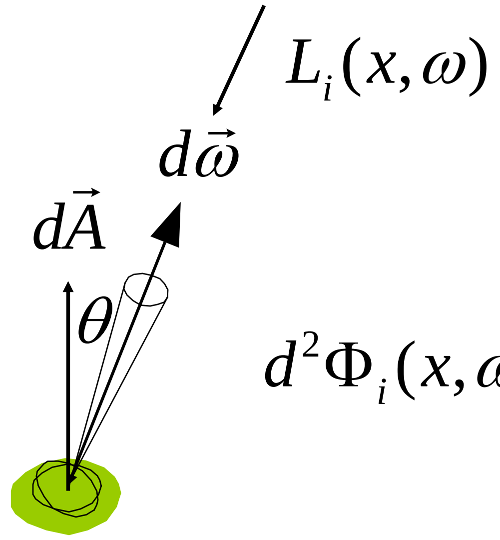
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$E = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2} = \frac{\Phi}{4\pi}\frac{\cos^3\theta}{h^2}$$

Directional Power Arriving at a Surface



- $$d^2\Phi_i(x,\omega) = L_i(x,\omega)\cos\theta\, dA\, d\omega$$

$$\cos\theta\, dA\, d\omega = d\vec{A} \cdot d\vec{\omega}$$

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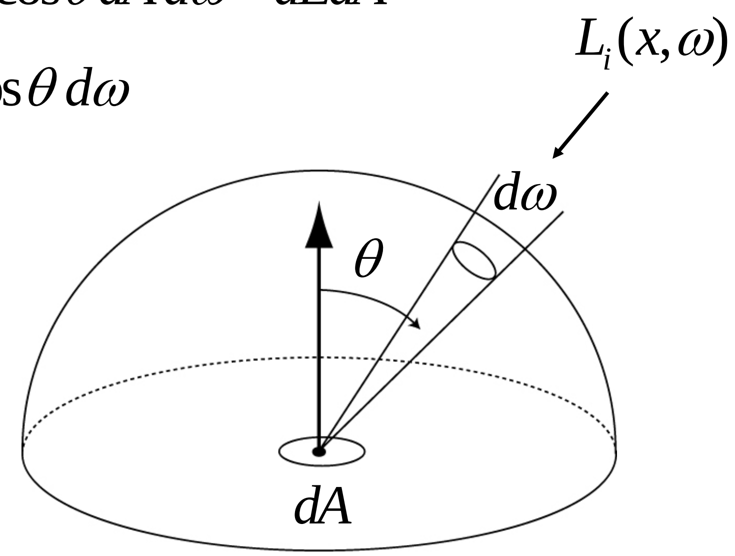
Irradiance from the Environment

$$d^2\Phi_i(x,\omega) = L_i(x,\omega)\cos\theta\, dA\, d\omega = dE\, dA$$

$$dE(x,\omega) = L_i(x,\omega)\cos\theta\, d\omega$$



Light meter

$$E(x) = \int_{H^2} L_i(x,\omega)\cos\theta\, d\omega$$

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Typical Values of Illuminance [lm/m^2]

Sunlight plus skylight	100,000 lux
Sunlight plus skylight (overcast)	10,000
Interior near window (daylight)	1,000
Artificial light (minimum)	100
Moonlight (full)	0.02
Starlight	0.0003

Radiant Exitance Or Radiosity or Emitance

Radiant Exitance

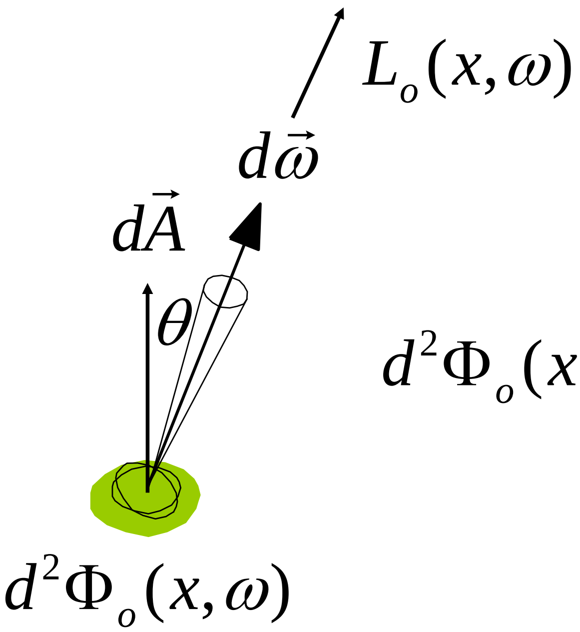
- **Definition**: The *radiant* (*luminous*) *exitance* is the energy per unit area leaving a surface.

$$M(x) \equiv \frac{d\Phi_o}{dA}$$

$$\left[\frac{W}{m^2}\right] \left[\frac{lm}{m^2} = lux\right]$$

- In computer graphics, this quantity is often referred to as the ***radiosity*** *(B)*

Directional Power Leaving a Surface

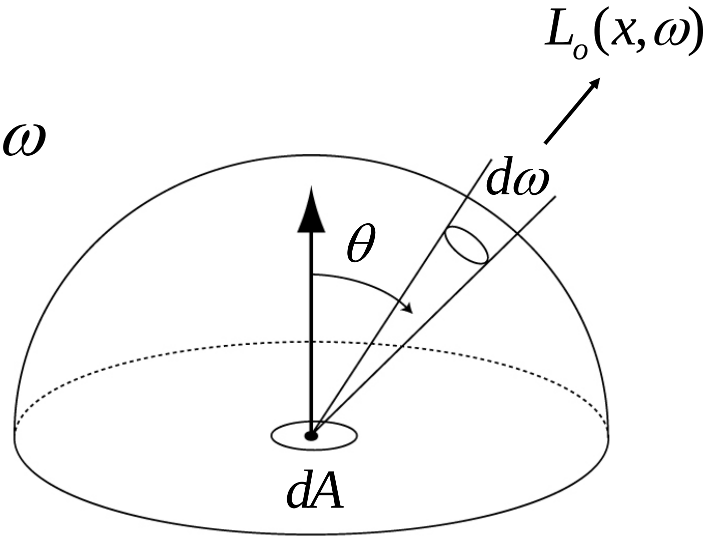


- $$d^2\Phi_o(x,\omega) = L_o(x,\omega)\cos\theta \, dA \, d\omega$$

Uniform Diffuse Emitter

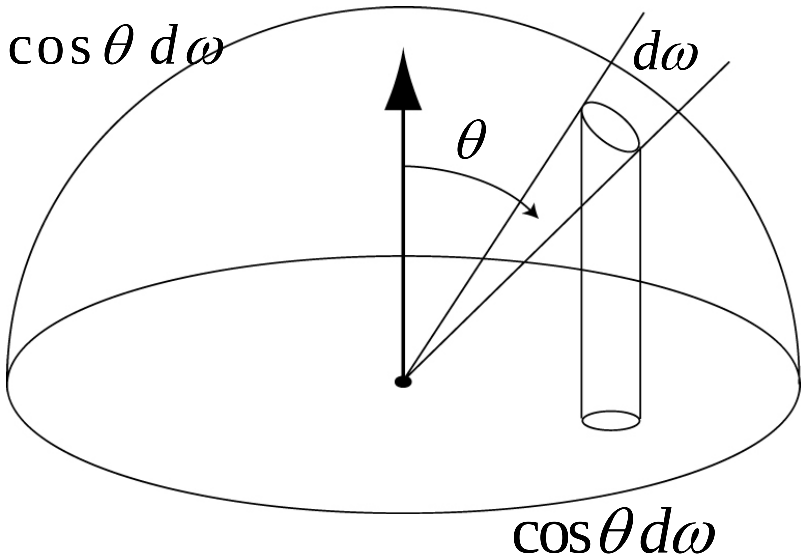
$$M = \int_{H^2} L_o \cos\theta \, d\omega$$

$$= L_o \int_{H^2} \cos\theta \, d\omega$$



Projected Solid Angle

$$\tilde{\Omega} \equiv \int_{\Omega} \cos\theta \, d\omega$$



$$\tilde{\Omega} = \int_{H^2} \cos\theta \, d\omega = \pi$$

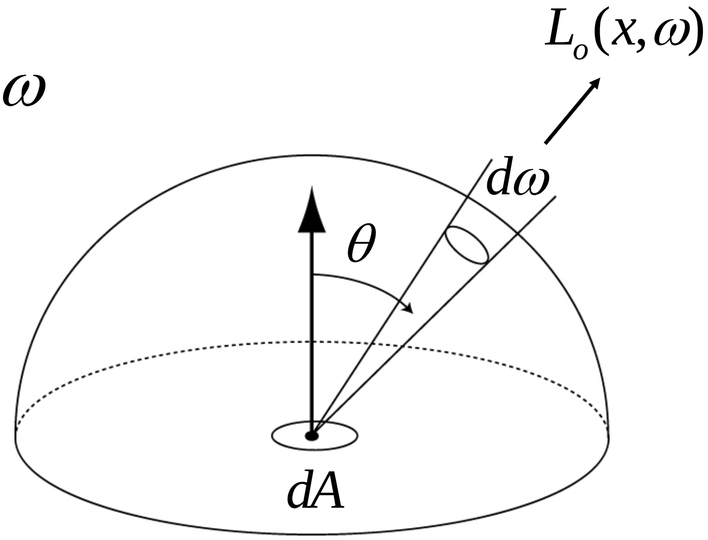
Uniform Diffuse Emitter

$$M = \int_{H^2} L_o \cos\theta \, d\omega$$

$$= L_o \int_{H^2} \cos\theta \, d\omega$$

$$= \pi L_o$$

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



Radiometry and Photometry Summary

Radiometric and Photometric Terms

Physics	Radiometry	Photometry
Energy	Radiant Energy	Luminous Energy
Flux (Power)	Radiant Power	Luminous Power
Flux Density	Irradiance Radiosity	Illuminance Luminosity
Angular Flux Density	Radiance	Luminance
Intensity	Radiant Intensity	Luminous Intensity

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Photometric Units

Photometry	Units		
	MKS	CGS	British
Luminous Energy	Talbot		
Luminous Power	Lumen		
Illuminance Luminosity	Lux	Phot	Footcandle
Luminance	Nit Apostilb, Blondel	Stilb Lambert	 Footlambert
Luminous Intensity	Candela (Candle, Candlepower, Carcel, Hefner)		

"Thus one nit is one lux per steradian is one candela per square meter is one lumen per square meter per steradian. Got it?", *James Kajiya*

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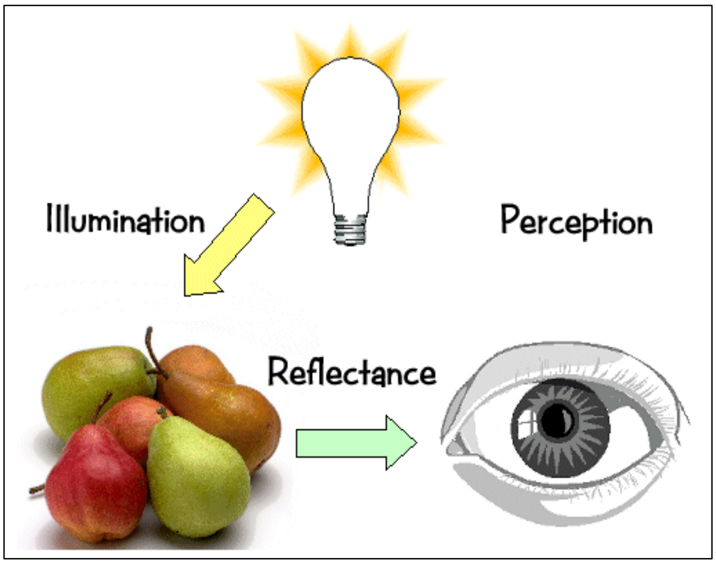
Color science

The Elements of Colour



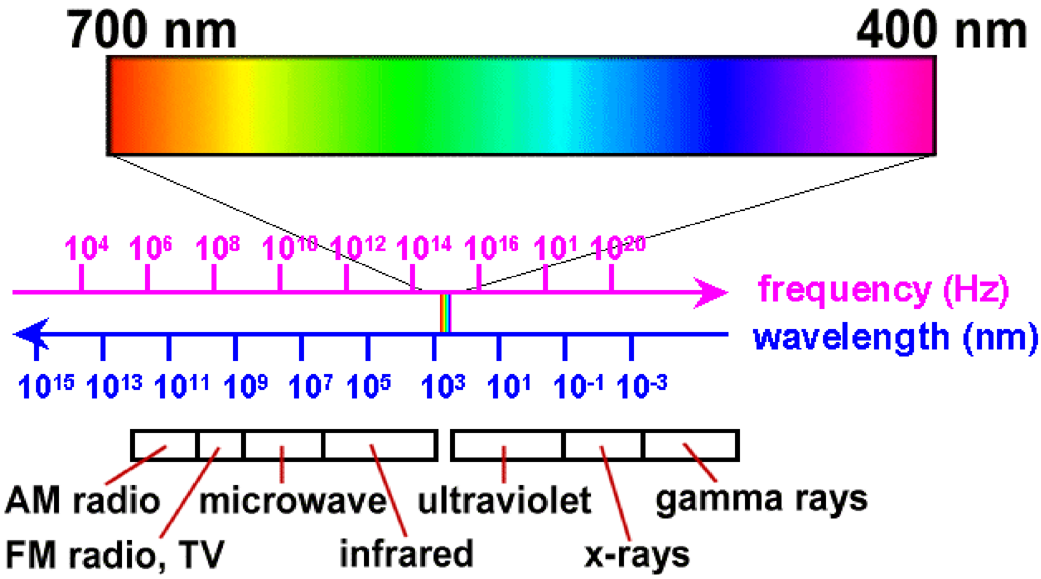
Perceived light of different wavelengths is in approximately equal weights – *achromatic*.

>80% incident light from white source reflected from white object.

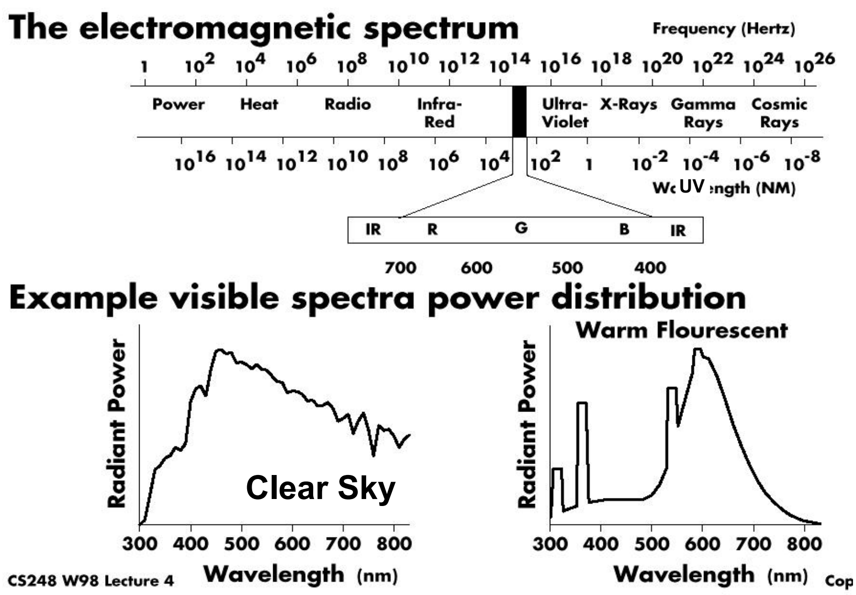
<3% from black object.

Narrow bandwidth reflected – perceived as colour

The Visible Spectrum



Daylight Vision



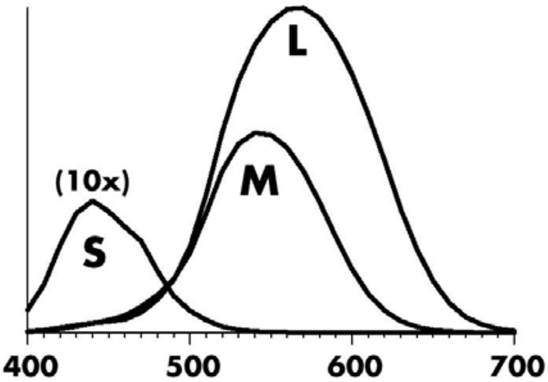
Human Colour Vision

- There are 3 light sensitive pigments in your cones (L,M,S), each with different *spectral response curve.*

$$L = \int L(\lambda) \cdot E(\lambda)$$

$$M = \int M(\lambda) \cdot E(\lambda)$$

$$S = \int S(\lambda) \cdot E(\lambda)$$



Colour Matching is Linear!

Grassman's Laws

- Scaling the colour and the primaries by the same factor preserves the match :

2C=2R+2G+2B

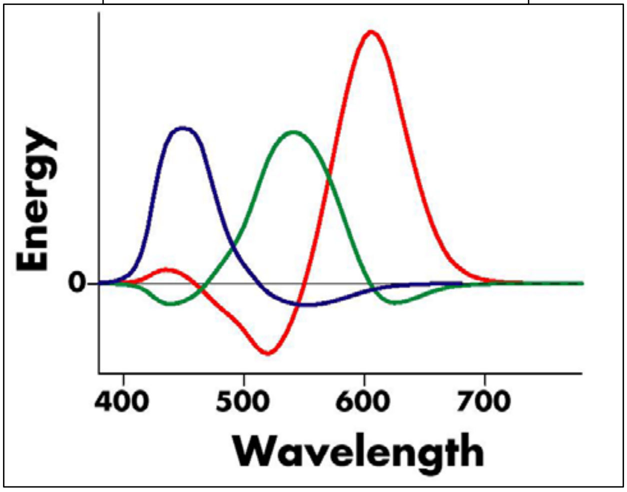
- To match a colour formed by adding two colours, add the primaries for each colour

$$C_1+C_2=(R_1+R_2)+(G_1+G_2)+(B_1+B_2)$$

Spectral Matching Curves

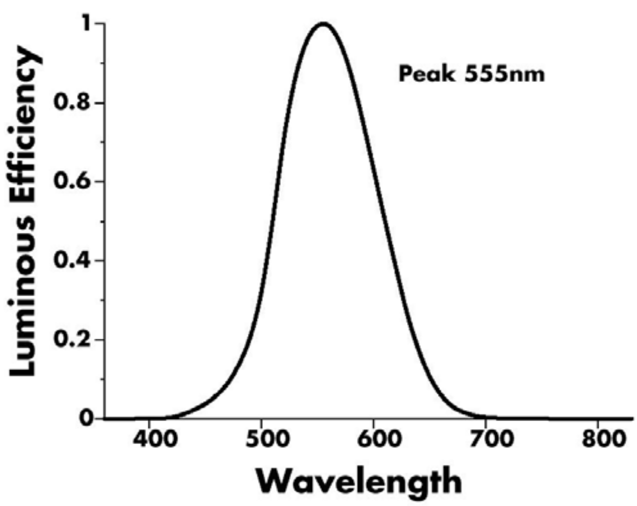
Match each pure colour in the visible spectrum with the 3 primaries, and record the values of the three as a function of wavelength.

Red, Green & Blue primaries.



Note : We need to specify a negative amount of one primary to represent all colours.

Luminance



Compare colour source to a grey source

- Luminance

Y = .30R + .59G + .11B

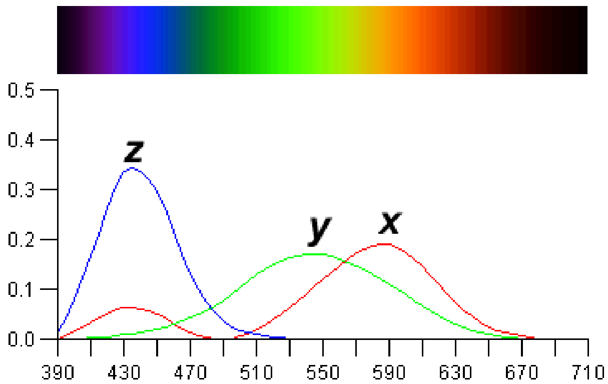
Colour signal on a B&W TV
(Except for gamma, of course)

- Perceptual measure : Lightness

$$L = Y^{1/3}$$

CIE Colour Space

For only positive mixing coefficients, the CIE (Commission Internationale d'Eclairage) defined 3 new hypothetical light sources x, y and z (as shown) to replace red, green and blue.

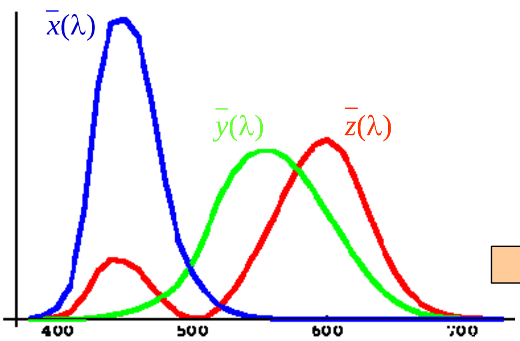


Primary Y intentionally has same response as luminance response of the eye.

The weights X, Y, Z form the 3D CIE XYZ space (see next slide).

CIE-XYZ Color Space

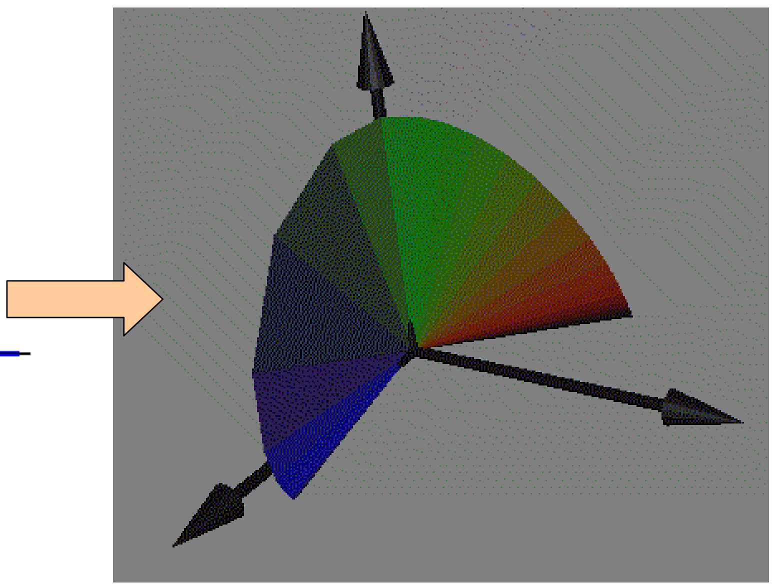
Color-matching curves



$$X = \int_{380}^{780} C(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_{380}^{780} C(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_{380}^{780} C(\lambda)\bar{z}(\lambda)d\lambda$$



Chromaticity Diagram

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$

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

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

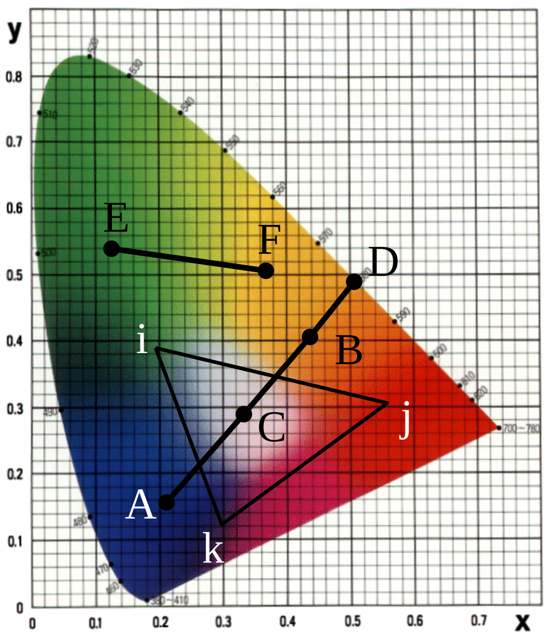
$$z = \frac{Z}{X+Y+Z}$$

Normalise by the total amount of light energy.

Often convenient to work in 2D colour space, so 3D colour space projected onto the plane X+Y+Z=1 to yield the *chromaticity diagram.*

The projection is shown opposite and the diagram appears on the next slide.

CIE Chromaticity Diagram



C is “white” and close to x=y=z=1/3

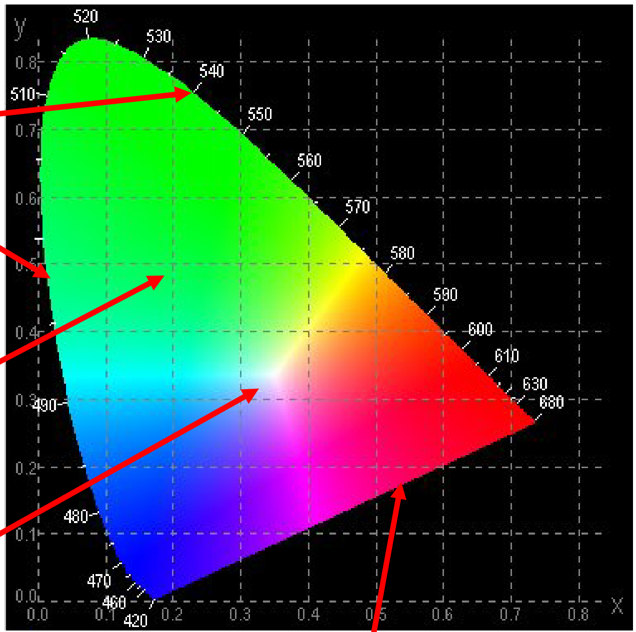
The dominant wavelength of a colour, eg. B, is where the line from C through B meets the spectrum, 580nm for B (tint).

A and B can be mixed to produce any colour along the line AB here including white. True for EF (no white this time).

True for ijk (includes white)

The Colors in the Chromaticity Diagram

Spectrally pure colors (monochromatic or prismatic) on the contour



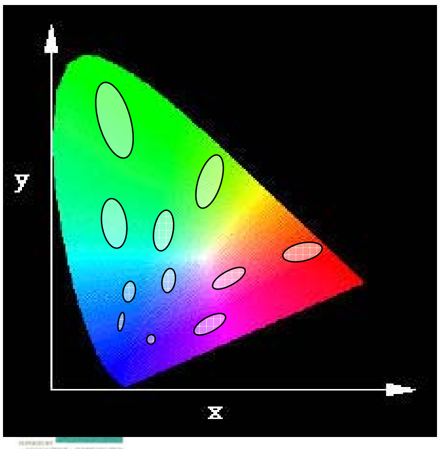
Visible spectrum

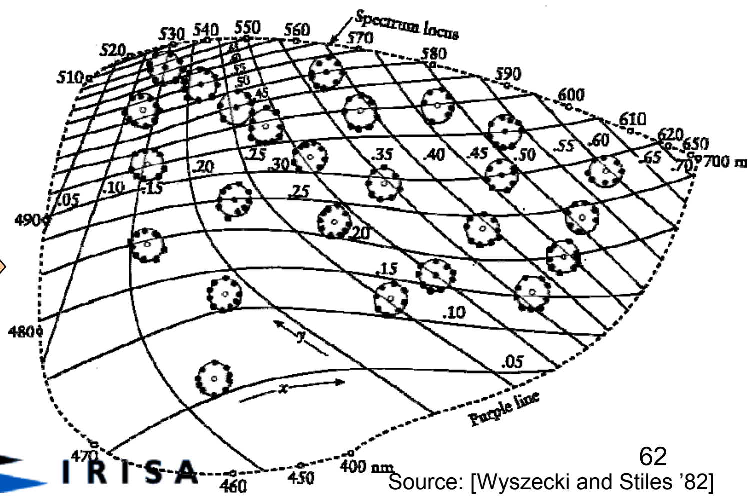
Neutral illuminant white

Non-spectral colors (purples and magentas) no dominant wavelength

Perceptually Uniform Space: MacAdam

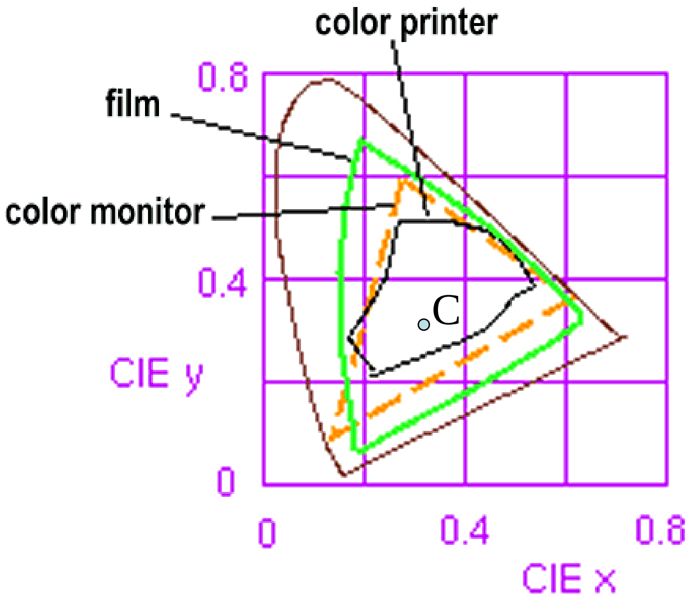
- In color space CIE-XYZ, the perceived distance between colors is not equal everywhere
- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors
- MacAdam ellipses (areas of unperceivable differences) become circles





Source: [Wyszecki and Stiles '82]

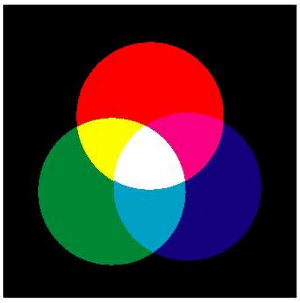
Some device colour "gamuts"

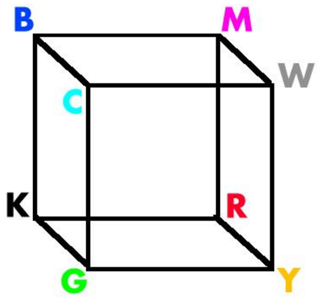


The diagram can be used to compare the gamuts of various devices. Note particularly that a colour printer can't reproduce all the colours of a colour monitor. Note no triangle can cover all of visible space.

Colour Cube

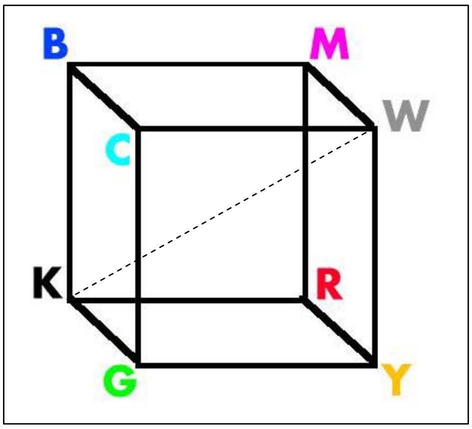
R,G,B model is *additive*, i.e we add amounts of 3 primaries to get required colour.

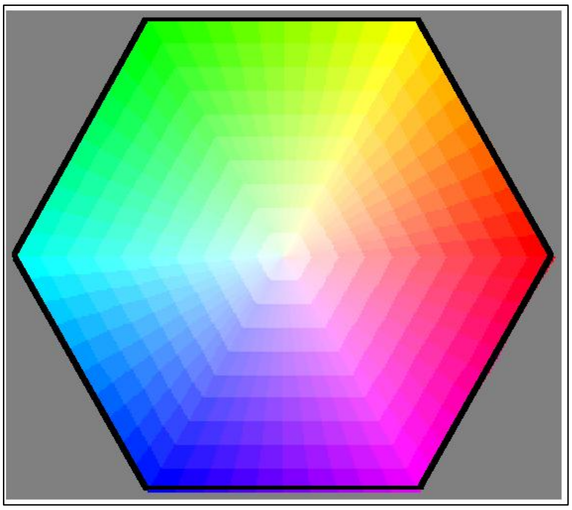




Can visualize RGB space as cube, grey values occur on diagonal K to W.

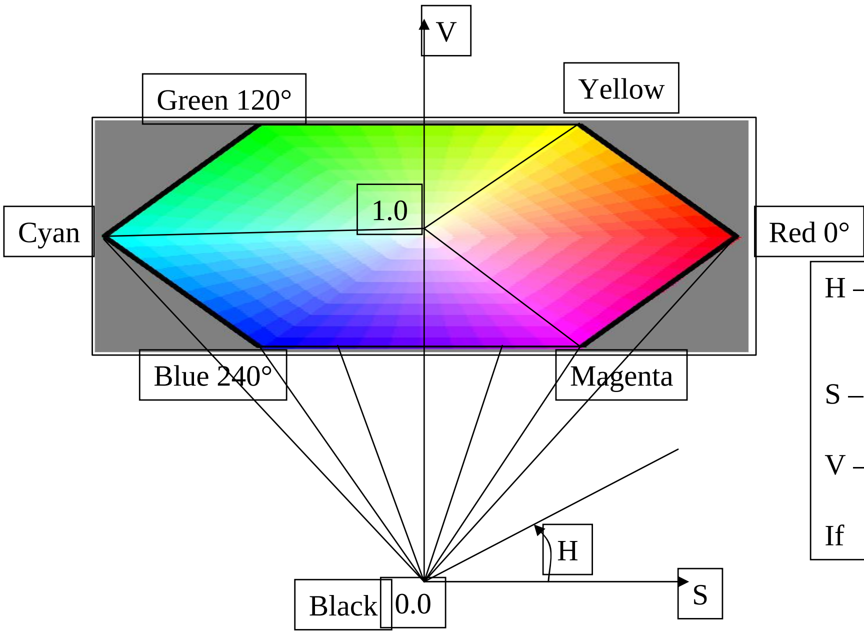
Intuitive Colour Spaces





Hexagon is a diagonal Cross-Section of the 3D Colour Cube.

The HSV Colour Space



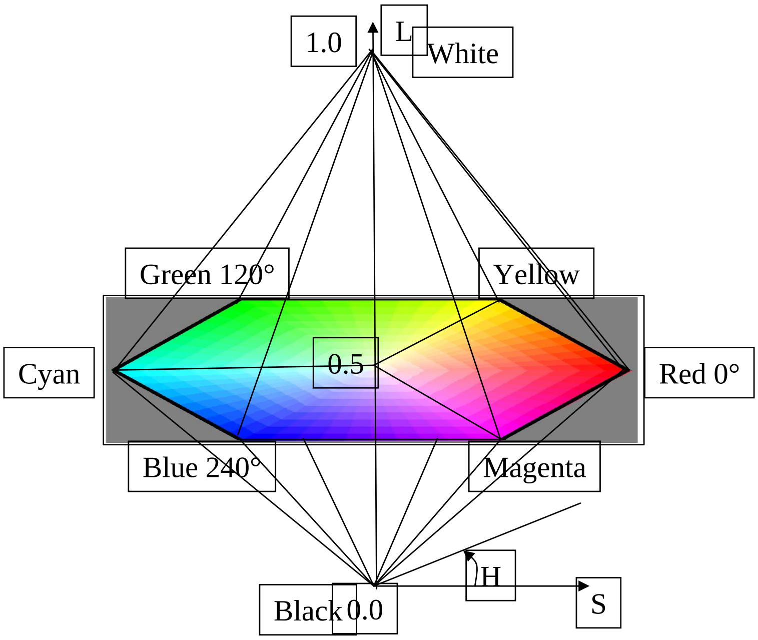
H – Hue, or the colour of the pure pigment.

S – Saturation of the colour.

V – Value, or brightness.

If V = 0, H is Undefined.

The HSL Colour Space



H – Hue, or the colour of the pure pigment.

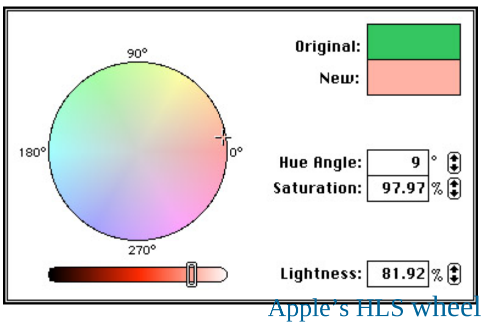
S – Saturation of the colour.

L – Lightness, or brightness.

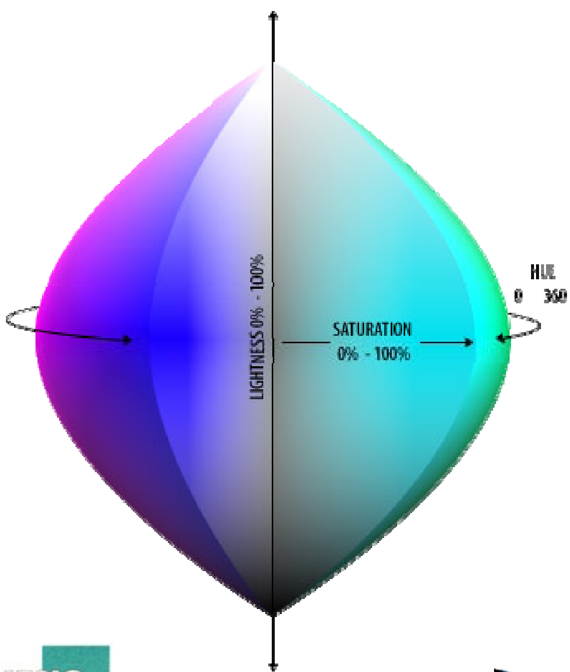
If L = 0,1 H is Undefined.

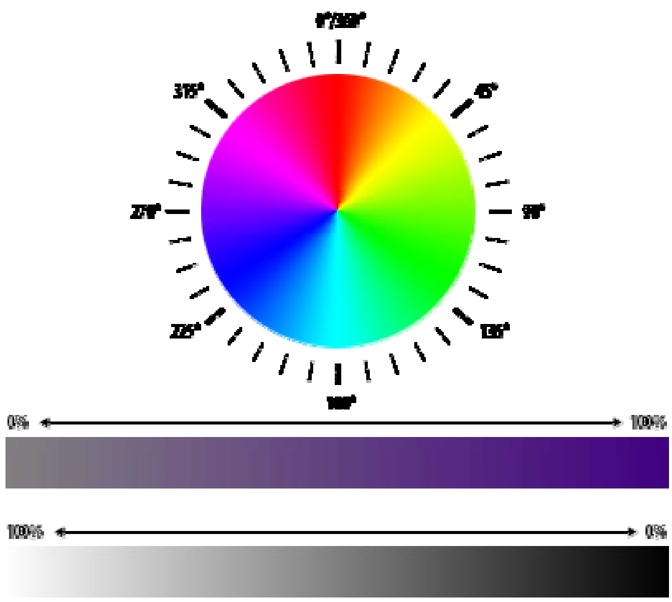
Maximum saturation occurs when L = 0.5

Color Pickers: HLS

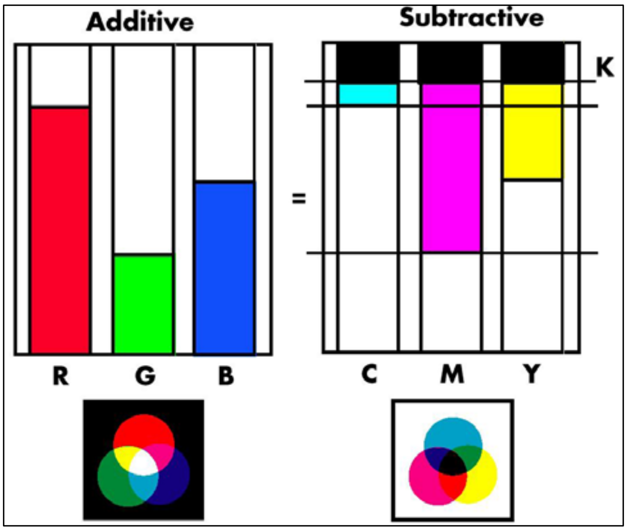


Apple's HLS wheel





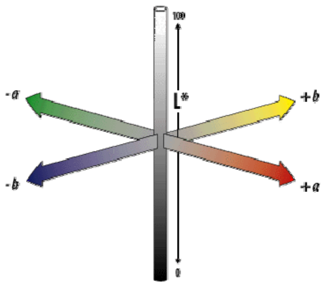
CMYK – Subtractive Colour Model

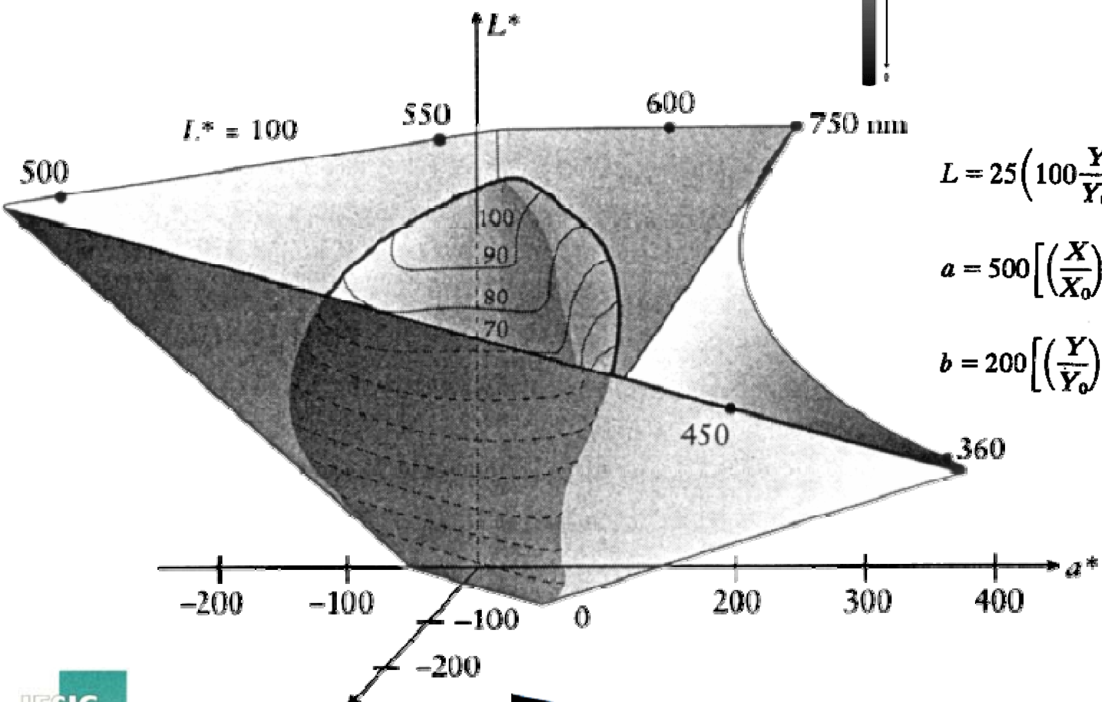


R = (1-C) (1-K) W
G = (1-M) (1-K) W
B = (1-Y) (1-K) W

K = G(1-max(R,G,B))
C = 1 - R/(1-K)
M = 1 - G/(1-K)
Y = 1 - B/(1-K)

CIE-LAB





$$L = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

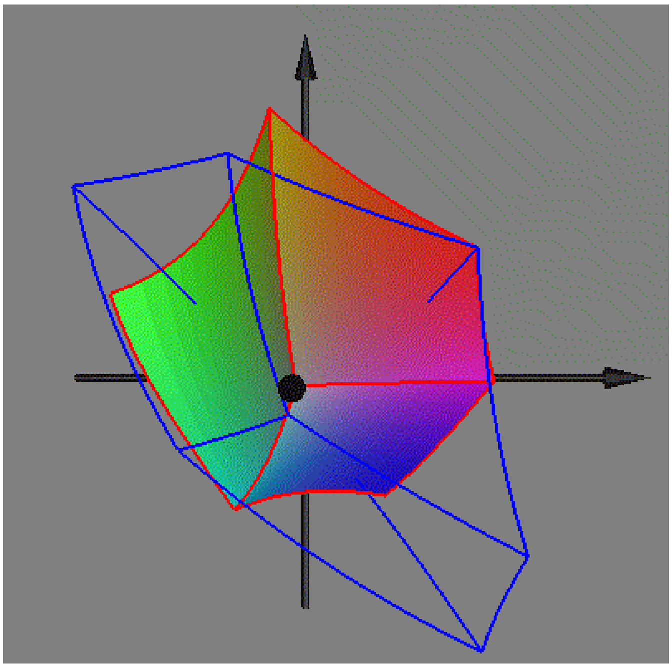
Source: [Wyszecki and Stiles '82]

Gamut Mapping

CIE-LAB

Perceptually-uniform Color space

- Color gamut of different processes may be different (e.g. CRT display and 4-color printing process)
- Need to map one 3D color space into another



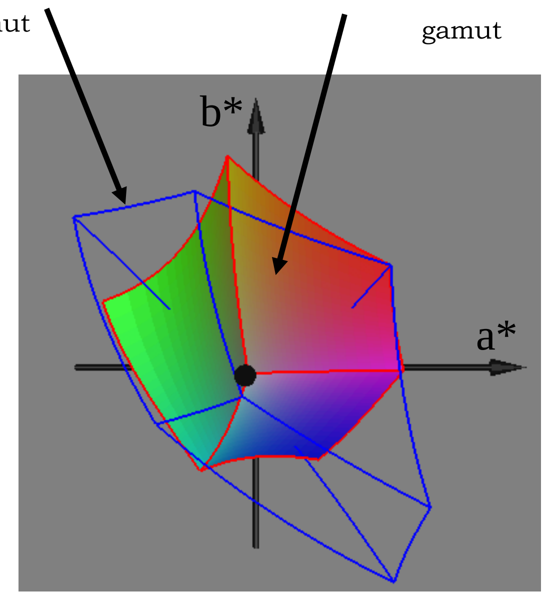
Typical CRT gamut

4-color printing gamut

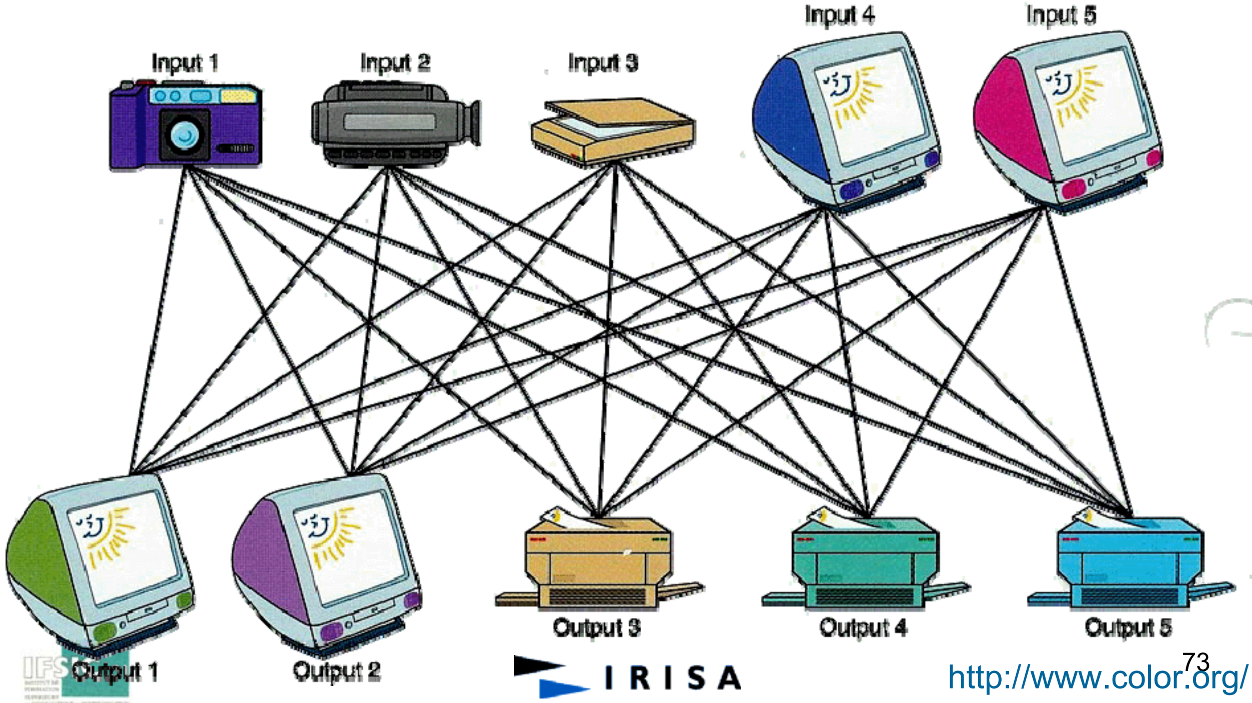
Gamut Mapping

Typical CRT gamut

4-color CMYK printing gamut



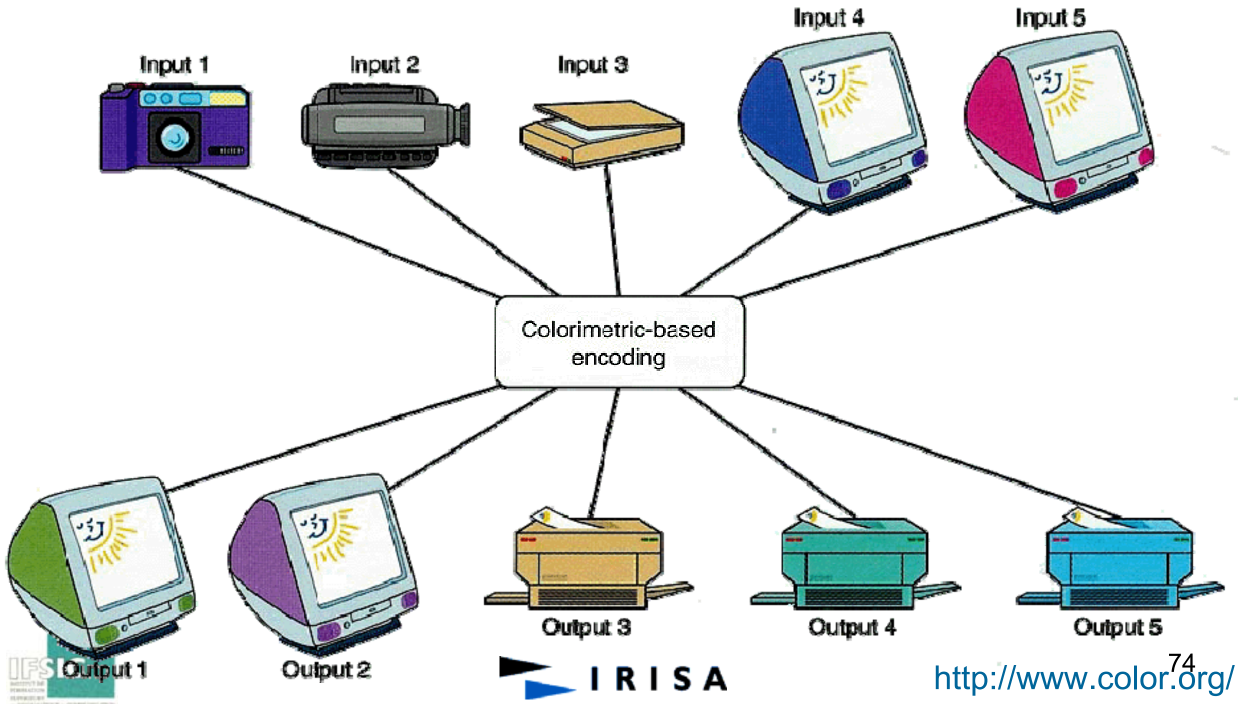
Device-Dependent Color



IRISA

http://www.color.org/

Device-Independent Color



IRISA

http://www.color.org/

Colour, Physics & Light - Summary

- Humans have tri-chromatic vision.
- All visible colours represented in CIE colour diagram.
- No three selected primaries in CIE colour space can generate all visible colours.
- Intuitive colour spaces.
- Subtractive colour models for hard copy.