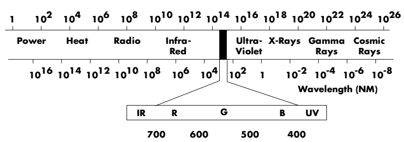
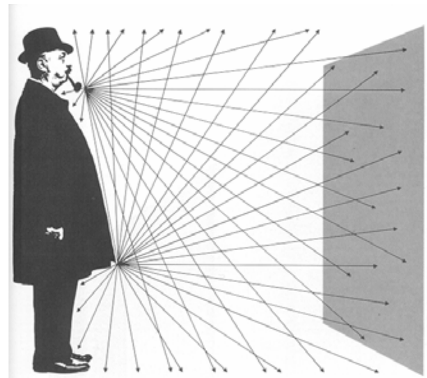
Light

Visible electromagnetic radiation

Power spectrum





From London and Upton

Polarization

Photon (quantum effects)

Wave (interference, diffraction)

Topics

Light sources and illumination

Radiometry and photometry

Quantify spatial energy distribution

- Radiant intensity
- Irradiance and radiant exitance (radiosity)
  - Inverse square law and cosine law
- Radiance

Illumination calculations

- Irradiance from environment

Radiometry and Photometry

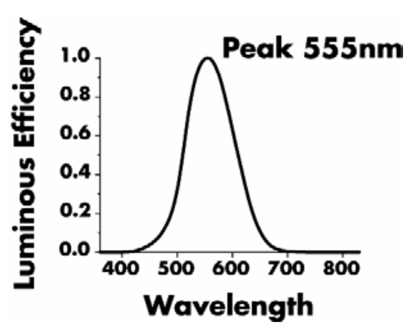
Radiant Energy and Power

Power: Watts vs. Lumens

Φ
- **Energy efficiency**
- **Spectral efficacy**

Energy: Joules vs. Talbot

- **Exposure**
  - **Film response**
  - **Skin - sunburn**



Luminance

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

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

Blackbody

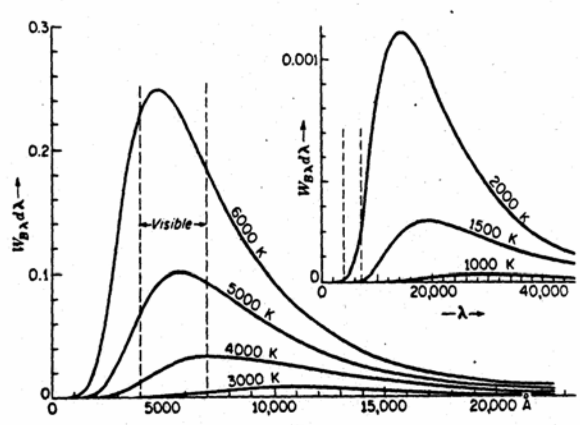


FIGURE 21F
Blackbody radiation curves plotted to scale. Ordinates give the energy in calories per square centimeter per second in a wavelength interval $d\lambda$ of 1 Å. For numerical values, see "Smithsonian Physical Tables," 8th ed., p. 314.

Tungsten

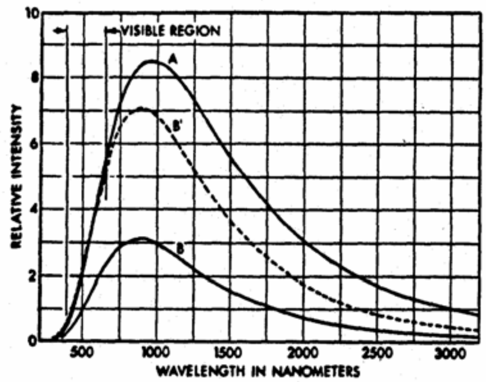
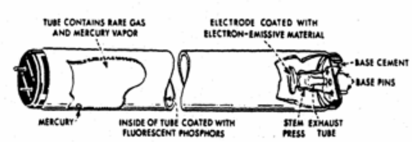


Fig. 8–1. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B′: radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region).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

Fluorescent



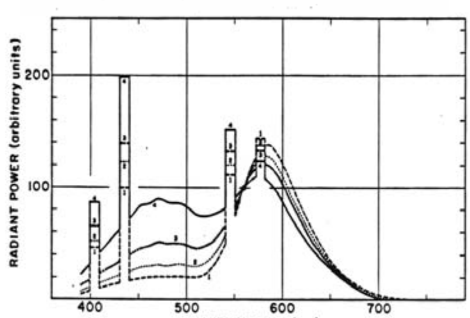


Fig. 3(1.2.3). Relative spectral radiant power distributions of common fluorescent lamps: (1) standard warm white; (2) white; (3) standard cool white; and (4) daylight. The distribution curves have been scaled by appropriate constant factors to provide a common value of 100 at $\lambda = 560$ nm.

Sunlight

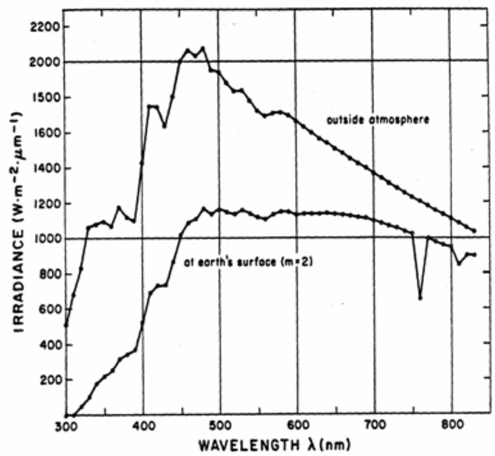


Fig. 1(1.2.1). NASA standard data of spectral irradiance ($W \cdot m^{-2} \cdot \mu m^{-1}$) for the solar disk measured outside the atmosphere (solid dots) and at the earth's surface at air mass 2 (open circles). Data points are those given in Table 1(1.2.1). Neighboring data points have been connected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

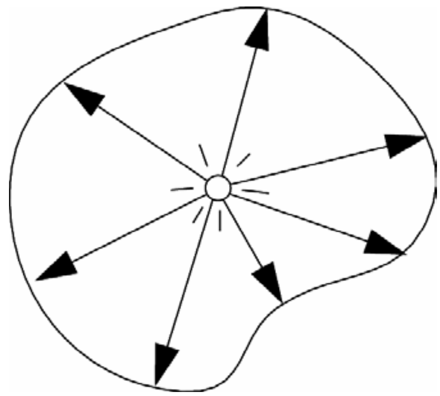
Radiant Intensity

Radiant Intensity

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

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

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



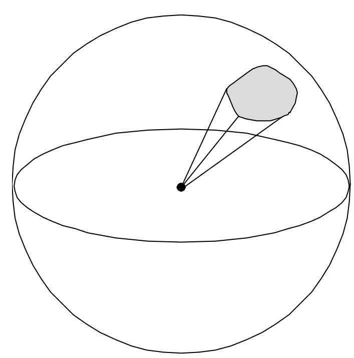
Angles and Solid Angles

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

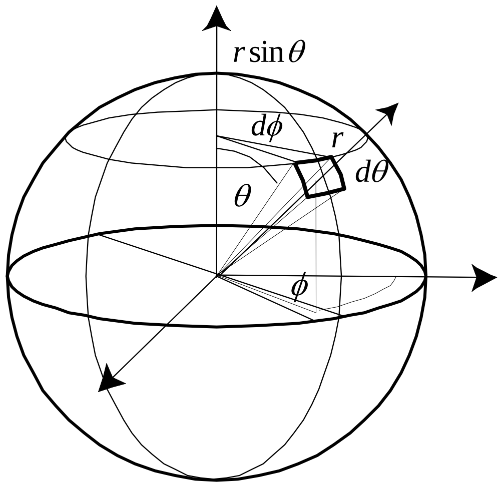
  $\Rightarrow$ **circle has 2π radians**

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

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



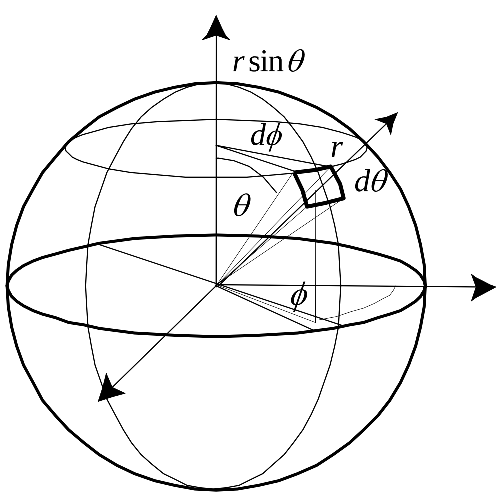
Differential Solid Angles



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

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

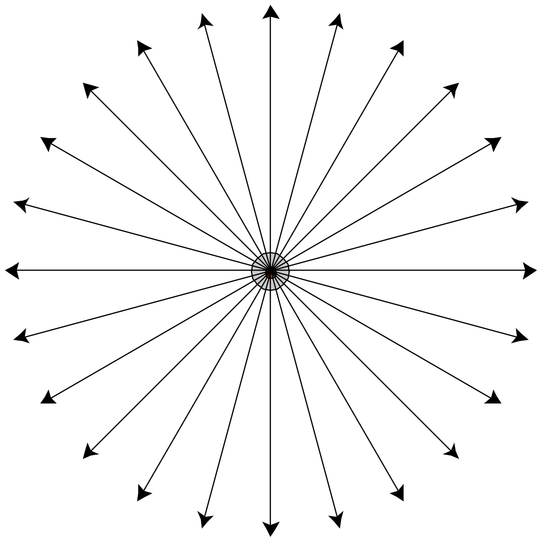
Differential Solid Angles



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

$$\Omega = \int_{S^2} d\omega$$
$$= \int_0^{\pi}\int_0^{2\pi} \sin\theta\,d\theta\,d\phi$$
$$= \int_{-1}^{1}\int_0^{2\pi} d\cos\theta\;d\phi$$
$$= 4\pi$$

Isotropic Point Source



$$\Phi = \int_{S^2} I \, d\omega$$
$$= 4\pi I$$

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

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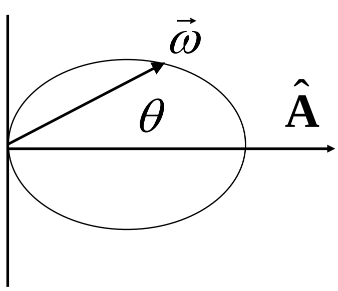
Warn's Spotlight



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

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

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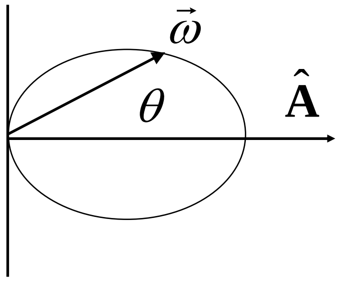
Warn's Spotlight

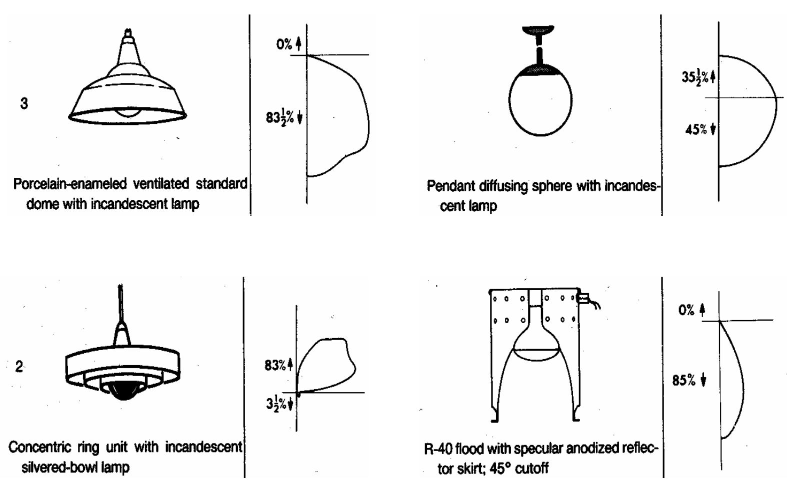


$$I(\omega) = \cos^s \theta = (\vec{\omega} \bullet \hat{\mathbf{A}})^s$$

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

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

Light Source Goniometric Diagrams



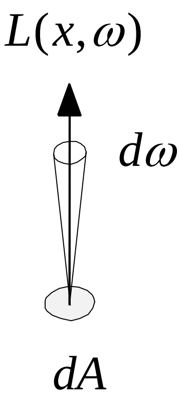
PIXAR Light Source


```
UberLight( )
{
  Clip to near/far planes
  Clip to shape boundary
  foreach superelliptical blocker
      atten *= …
  foreach cookie texture
      atten *= …
  foreach slide texture
      color *= …
  foreach noise texture
      atten, color *= …
  foreach shadow map
      atten, color *= …
  Calculate intensity fall-off
  Calculate beam distribution
}
```


Radiance

Radiance

<u>Definition</u>: The surface *radiance* (*luminance*) is the intensity per unit area leaving a surface



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

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

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

Typical Values of Luminance [cd/m2]

Surface of the sun	**2,000,000,000 nit**
Sunlight clouds	**30,000**
Clear day	**3,000**
Overcast day	**300**
Moon	**0.03**

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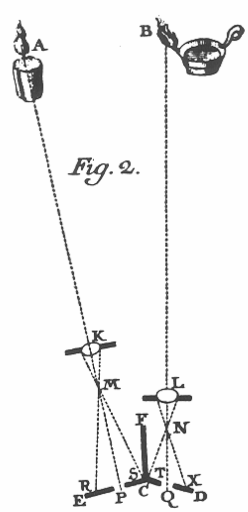
Irradiance

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.

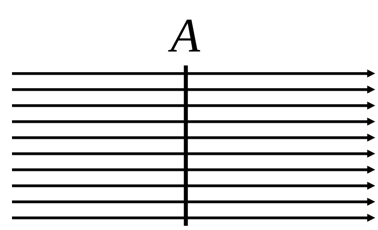
$$E(x) \equiv \frac{d\Phi_i}{dA}$$

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

Sometimes referred to as the radiant (luminous) incidence.

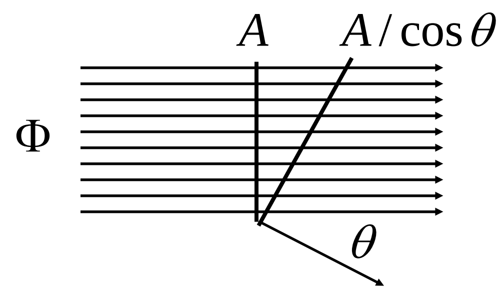
Lambert's Cosine Law

$$\Phi = EA$$



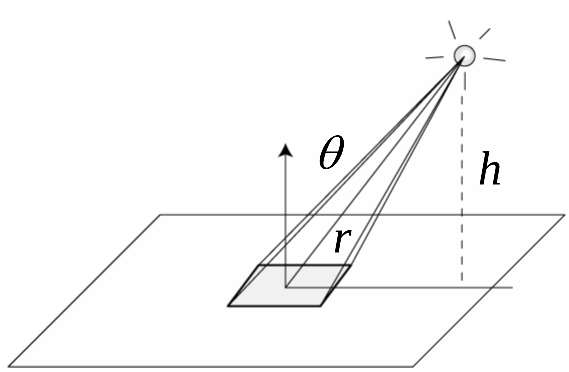
$$E = \frac{\Phi}{A}$$

Lambert's Cosine Law



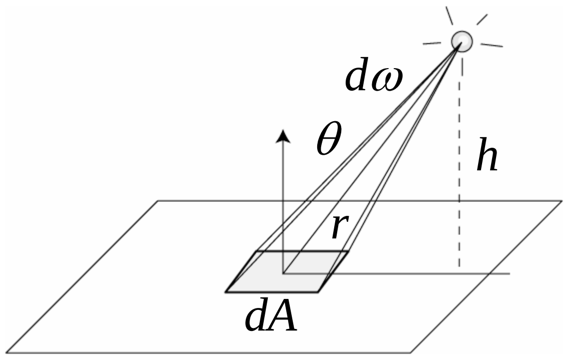
$$E = \frac{\Phi}{A/\cos\theta} = \frac{\Phi}{A}\cos\theta$$

Irradiance: Isotropic Point Source



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

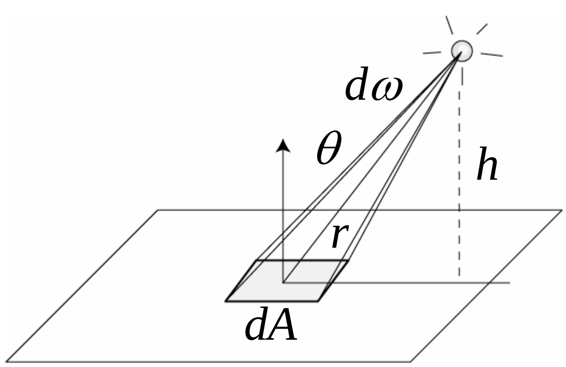
Irradiance: Isotropic Point Source



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

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

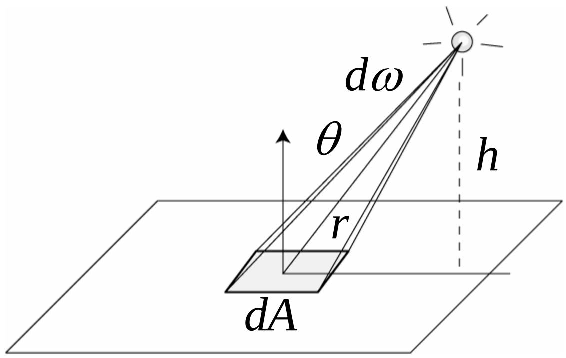
Irradiance: Isotropic Point Source



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

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

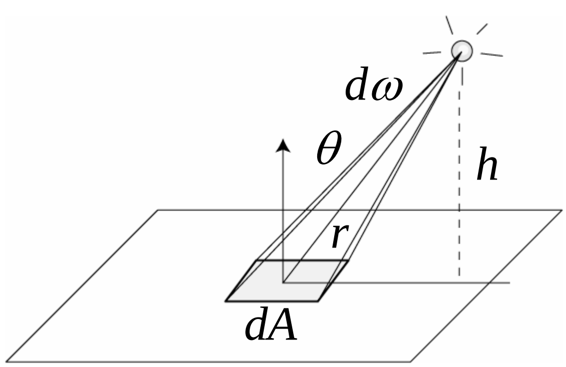
Irradiance: Isotropic Point Source



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

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

Irradiance: Isotropic Point Source

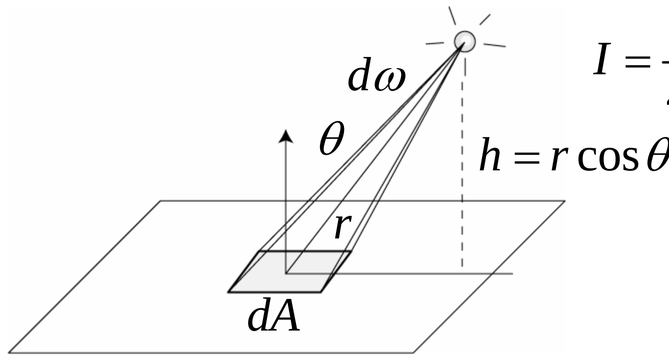


$$I = \frac{\Phi}{4\pi}$$

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

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

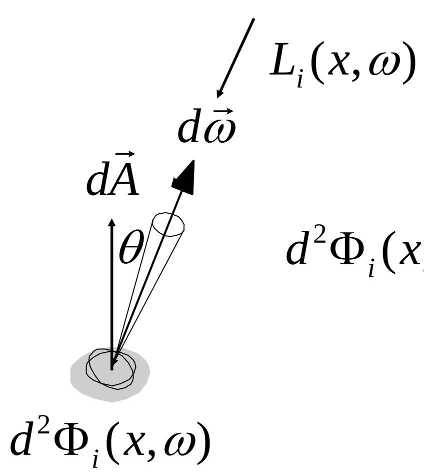
Irradiance: Isotropic Point Source



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

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

Directional Power Arriving at a Surface



$$\begin{aligned} d^2\Phi_i(x,\omega) &= L_i(x,\omega)\cos\theta\, dA\, d\omega \\ &= L_i(x,\omega)\, d\vec{A}\bullet d\vec{\omega} \end{aligned}$$

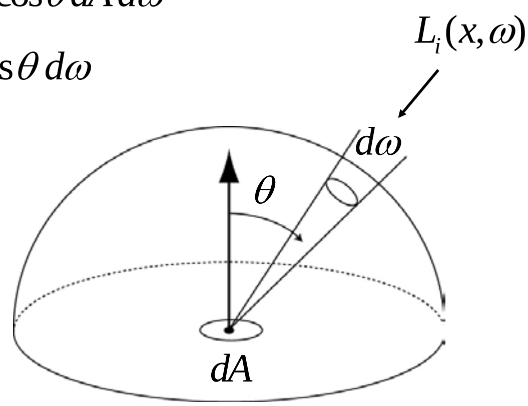
$$d\vec{A}\bullet d\vec{\omega} = \cos\theta\, dA\, d\omega$$

Irradiance from the Environment

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

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

Light meter

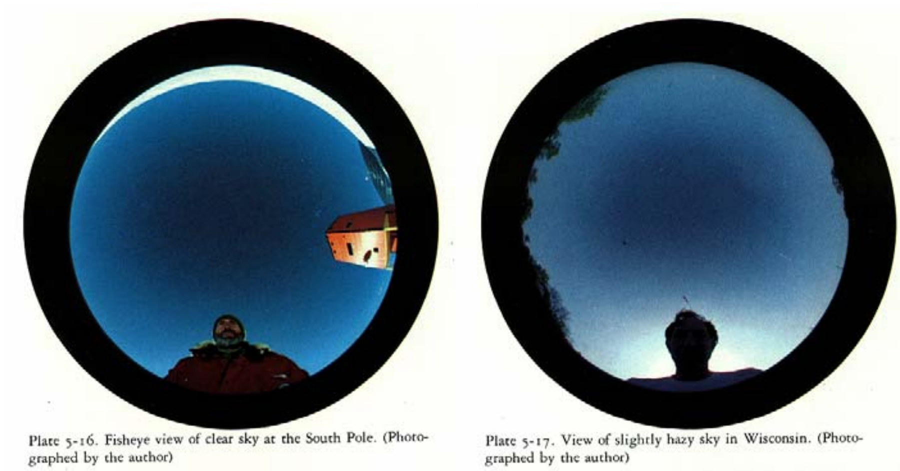


$$E(x) = \int_{H^2} L_i(x,\omega)\cos\theta \, d\omega$$

Typical Values of Illuminance [lm/m²]

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**

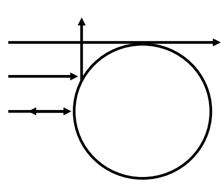
The Sky Radiance Distribution



From Greenler, Rainbows, halos and glories

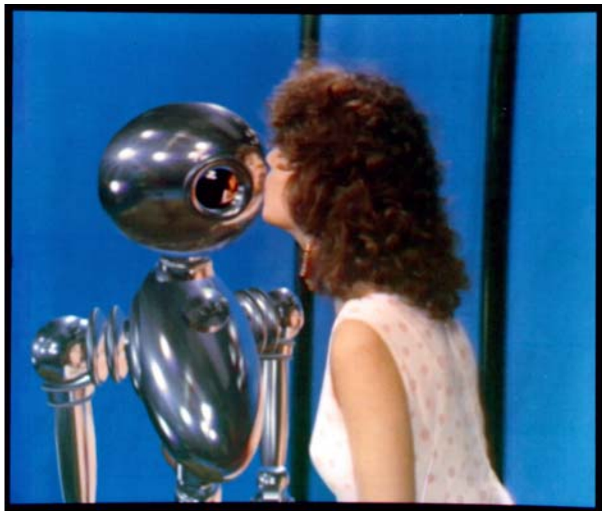
Gazing Ball ⇒ Environment Maps

Miller and Hoffman, 1984



- Photograph of mirror ball
- Maps all directions to a to circle
- *Reflection indexed by normal*
- Resolution function of orientation

Environment Maps



Interface, Chou and Williams (ca. 1985)

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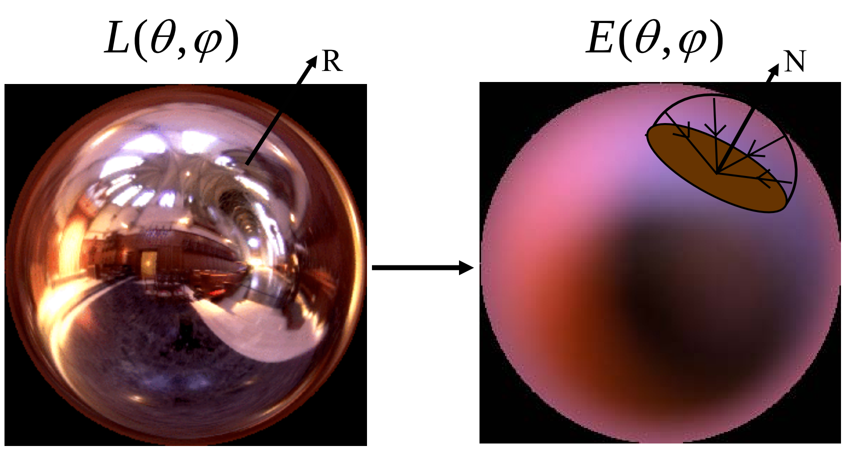
Irradiance Environment Maps



Radiance Environment Map

Irradiance Environment Map

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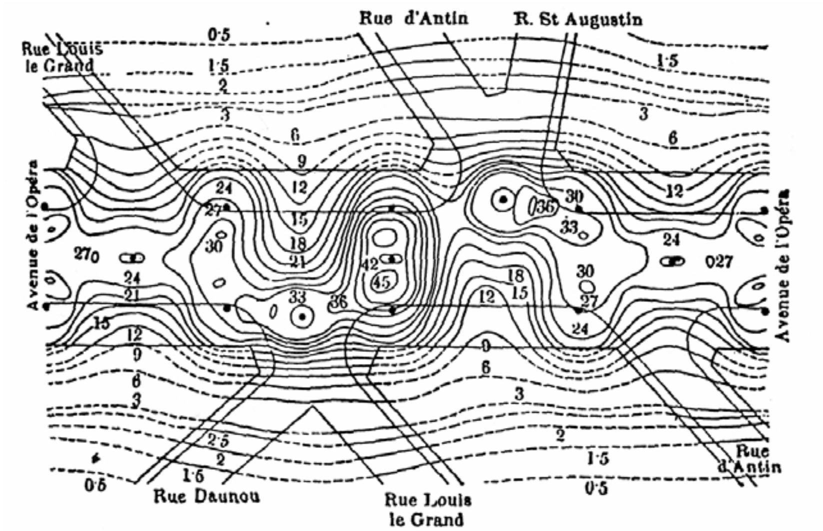
Irradiance Map or Light Map



Isolux contours

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Radiant Exitance (Radiosity)

Radiant Exitance

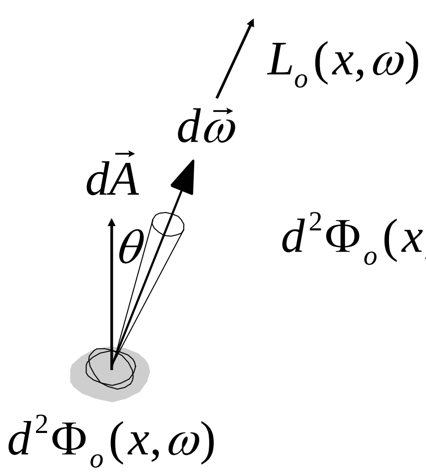
Definition: **The *radiant* (*luminous*) *exitance* is the energy per unit area leaving a surface.**

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

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

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

Directional Power Leaving a Surface



$$d^2\Phi_o(x,\omega) = L_o(x,\omega)\cos\theta dAd\omega$$
$$= L_o(x,\omega)\, d\vec{A} \bullet d\vec{\omega}$$

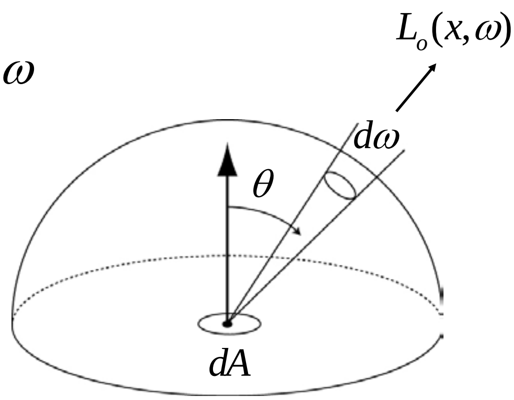
Uniform Diffuse Emitter

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

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

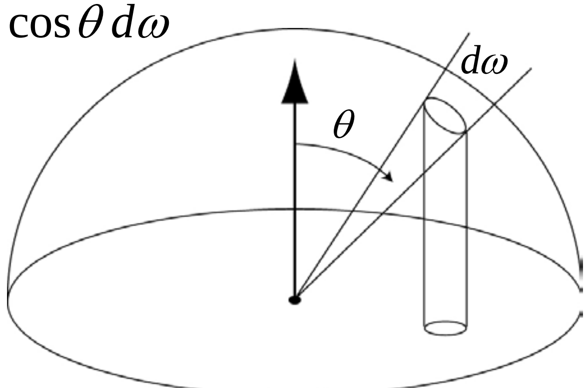
$$= \pi L_o$$

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



Projected Solid Angle

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



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

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

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***