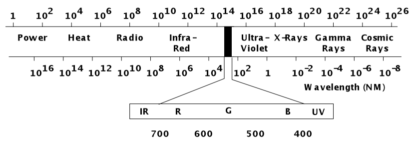
Light

Visible electromagnetic radiation

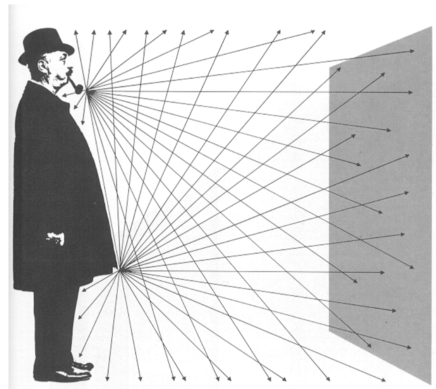
Power spectrum



Polarization

Photon (quantum effects)

Wave (interference, diffraction)



From London and Upton

Radiometry and Photometry

Measuring spatial properties of light

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

Goal is to perform lighting calculations in the physically correct way

Radiometry and Photometry

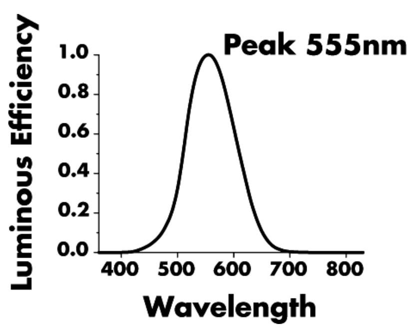
Radiant Energy and Power

Power: Watts (radiometry)

vs. Lumens (photometry)

Φ

- Spectral efficacy
- Energy efficiency



Energy: Joules vs. Talbot

- Exposure
  - Film response
  - Skin - sunburn

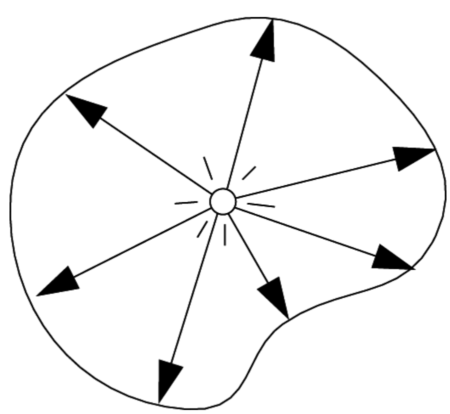
Photometric luminance

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

Radiant Intensity

Radiant Intensity

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



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

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

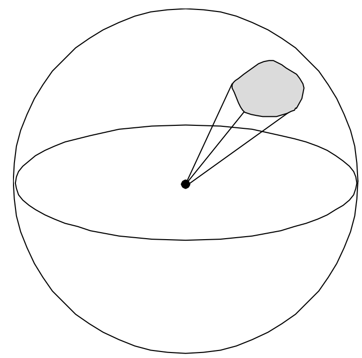
Angles and Solid Angles

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

  $\Rightarrow$ circle has 2π radians

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

  $\Rightarrow$ sphere has 4π steradians



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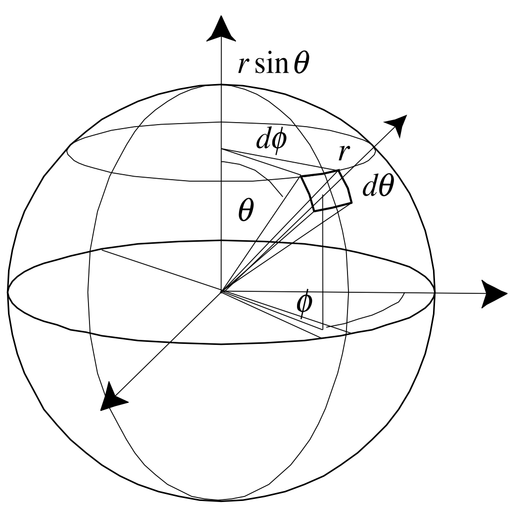
Differential Solid Angles



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

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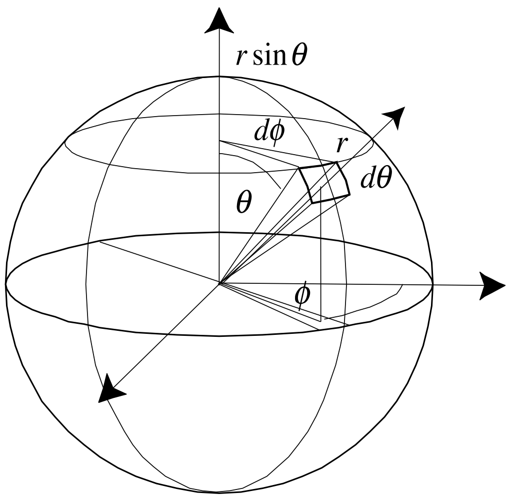
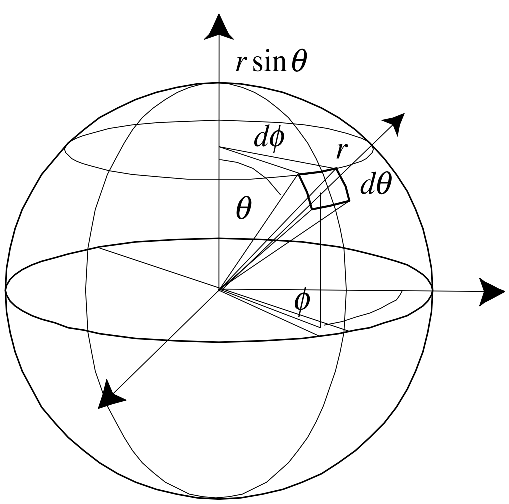
Differential Solid Angles



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

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

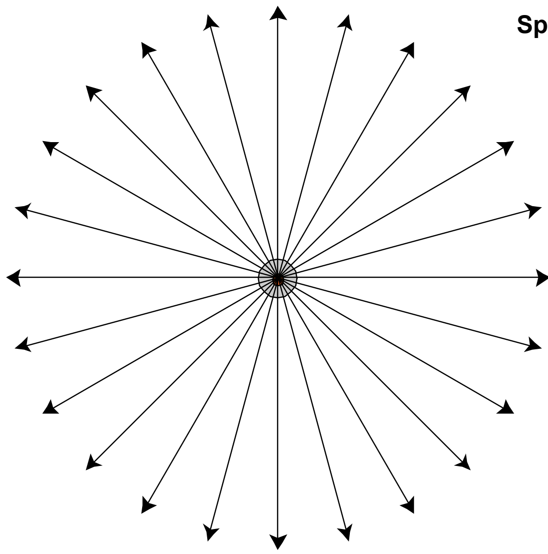
Differential Solid Angles



$$d\omega = \sin\theta\,d\theta\,d\phi$$

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

Isotropic Point Source

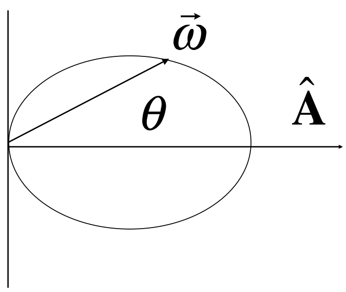


Sphere S^2

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

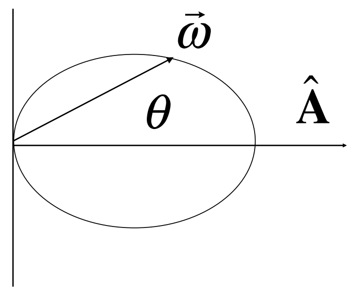
$$I = \frac{\Phi}{4\pi}$$

Warn's Spotlight



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

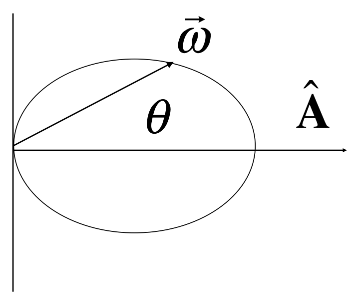
Warn's Spotlight



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

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

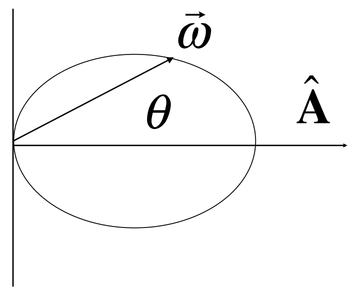
Warn's Spotlight



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

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

Warn's Spotlight



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

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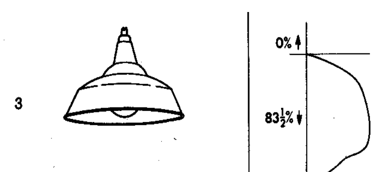
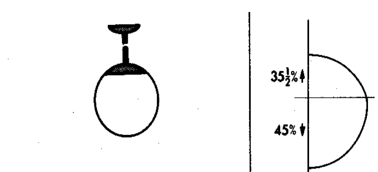
$$I(\omega) = \Phi \frac{s+1}{2\pi} \cos^s \theta$$

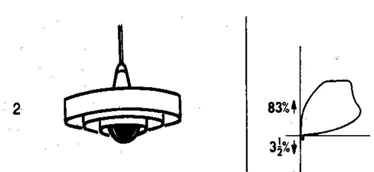
Light Source Goniometric Diagrams



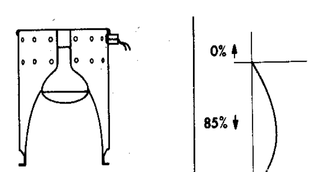
Porcelain-enameled ventilated standard dome with incandescent lamp



Pendant diffusing sphere with incandescent lamp



Concentric ring unit with incandescent silvered-bowl lamp



R-40 flood with specular anodized reflector skirt; 45° cutoff

Irradiance

Irradiance

<u>Definition</u>: 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.

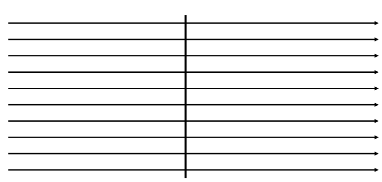
Typical Values of Illuminance [lm/m²]

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

Beam Power in Terms of Irradiance

$$\Phi = EA$$

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

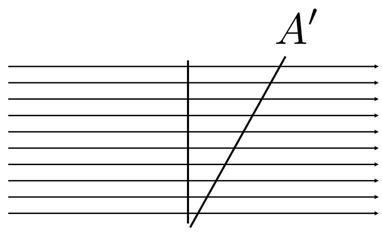


A

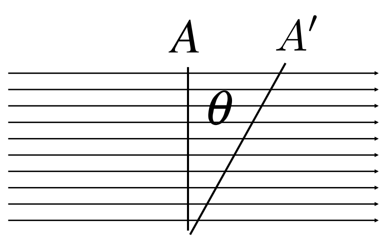
Beam Power Falling on the Surface

$$\Phi' = E' A'$$

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



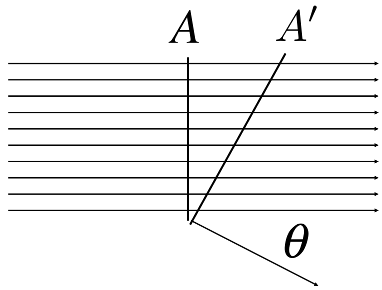
Projected Area



$$A = A' \cos\theta$$

Conservation of Energy

$$A = A' \cos\theta$$

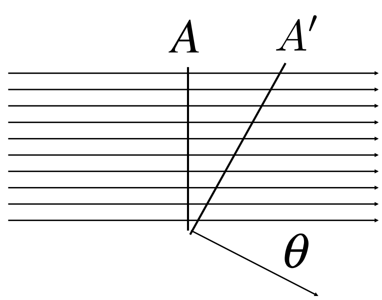


$$\Phi = \Phi'$$

Lambert's Cosine Law

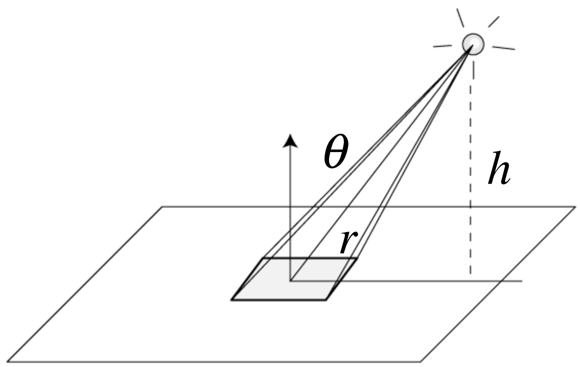
$$A = A' \cos\theta$$

$$\Phi = \Phi'$$



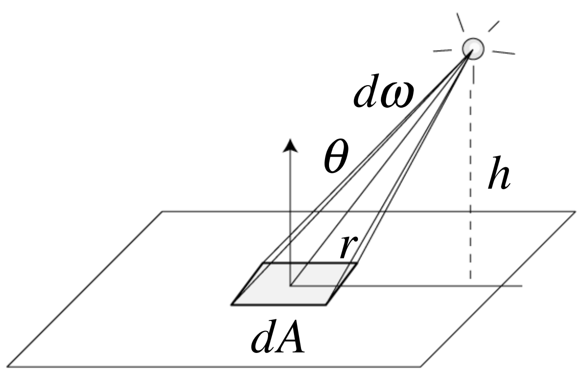
$$E' = \frac{\Phi'}{A'} = \frac{\Phi}{A}\cos\theta = E\cos\theta$$

Irradiance: Isotropic Point Source



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

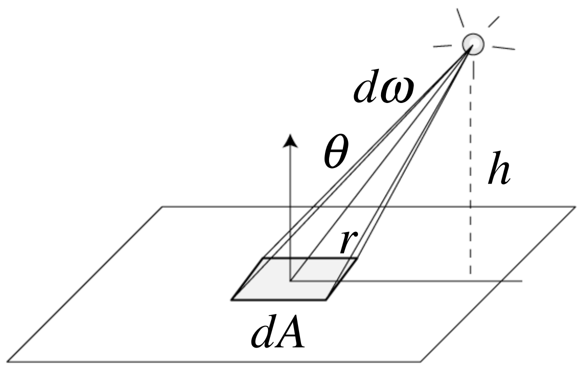
Irradiance: Isotropic Point Source



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

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

Irradiance: Isotropic Point Source



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

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

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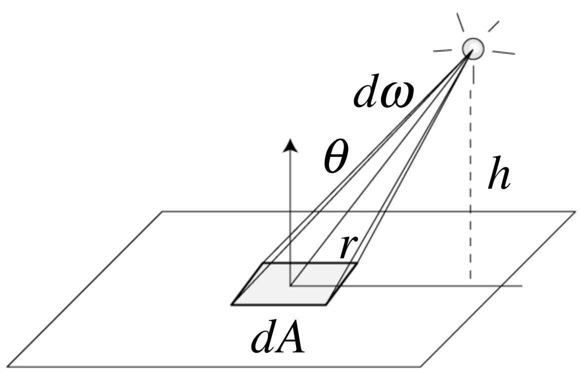
Irradiance: Isotropic Point Source



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

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

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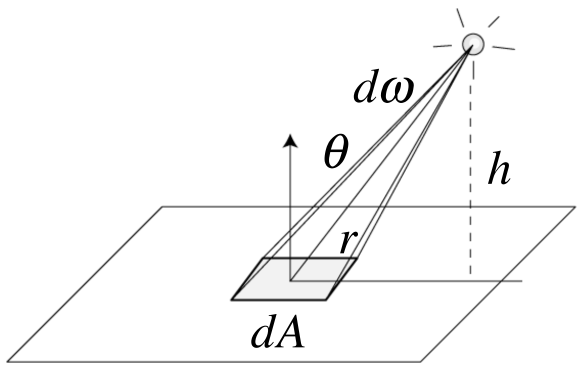
Irradiance: Isotropic Point Source

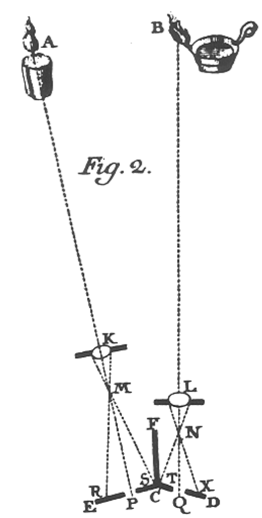


$$I = \frac{\Phi}{4\pi}$$

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

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

The Invention of Photometry



Bouguer's classic experiment

- **Compare a light source and a candle**
- **Move until they both appear equally bright**
- **Intensity is proportional to ratio of distances squared**

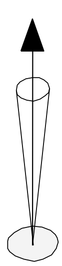
Definition of a candela

- **Originally a "standard" candle**
- **Currently 550 nm laser with 1/683 W/sr**
- **1 of 6 fundamental SI units**

Radiance

Area Lights – Surface Radiance

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



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

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

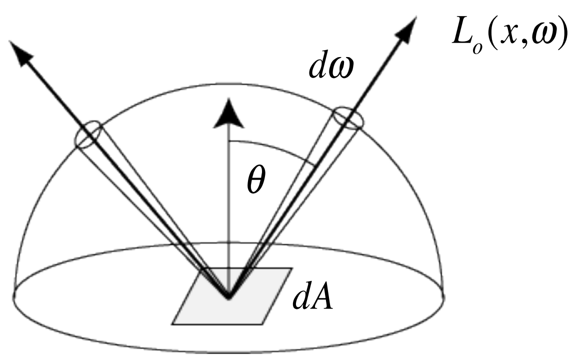
$$\left[\frac{W}{sr\, m^2}\right]\left[\frac{cd}{m^2} = \frac{lm}{sr\, m^2} = nit\right]$$

Typical Values of Luminance [cd/m²]

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

Directional Power Leaving a Surface

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



Same *dA* for all directions

Radiant Exitance

(Radiosity)

Radiant Exitance

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

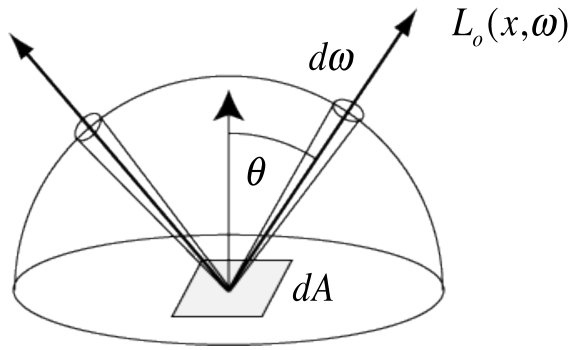
$$M(x) \equiv \frac{d\Phi_o}{dA}$$

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

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

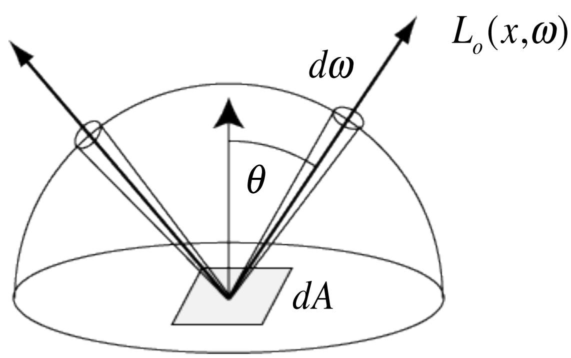
Area Light Source

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



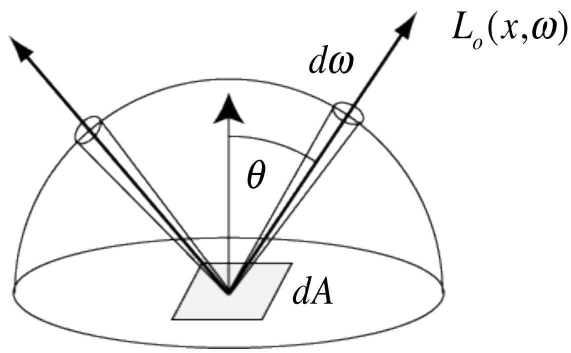
Area Light Source

$$dM(x,\omega) = \frac{d^2\Phi_o(x,\omega)}{dA} = L_o(x,\omega)\cos\theta\, d\omega$$



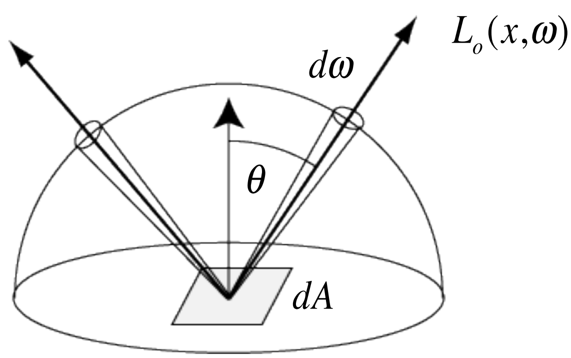
Area Light Source

$$dM(x,\omega) = L_o(x,\omega)\cos\theta \, d\omega$$



Area Light Source

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



H^2 **Hemisphere**

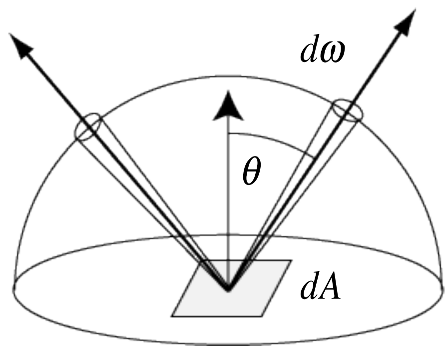
Uniform Diffuse Emitter

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

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

Uniform means L_o is not a function of direction

$$L_o(x,\omega) = L_o$$



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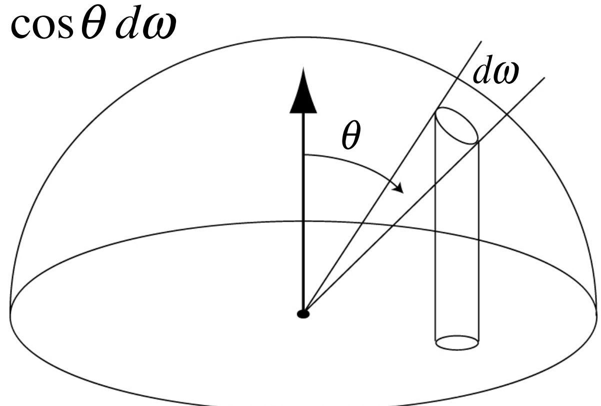
Projected Solid Angle

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



$$\cos\theta \, d\omega$$

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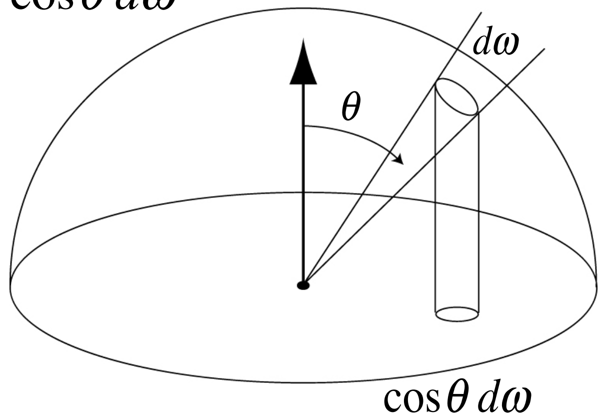
Projected Solid Angle

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



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

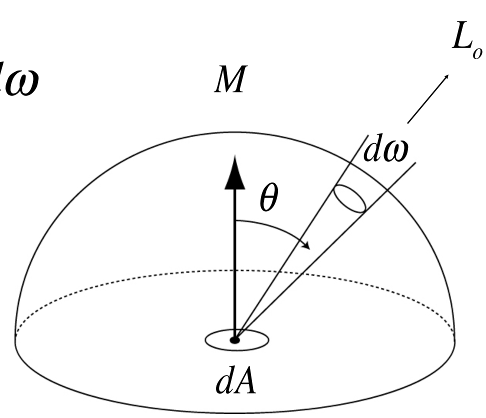
Uniform Diffuse Emitter

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

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

$$= \pi L_o$$

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



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

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***