Radiometry

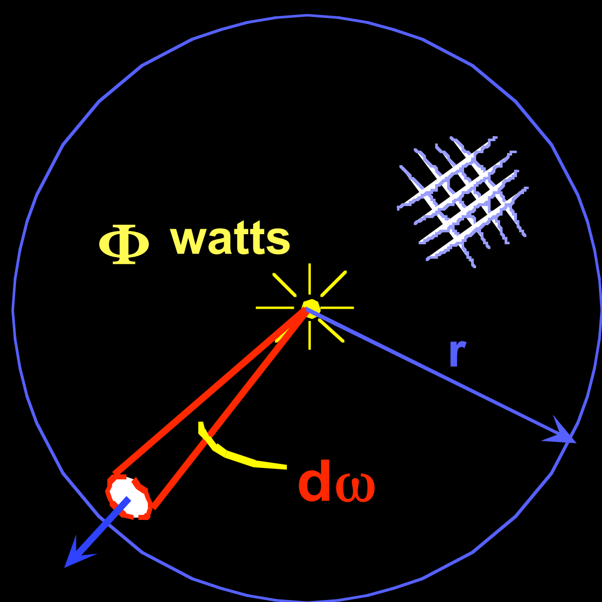
- Image: two-dimensional array of 'brightness' values.
- Geometry: where in an image a point will project.
- Radiometry: what the brightness of the point will be.
- Brightness: informal notion used to describe both scene and image brightness.
- Image brightness: related to energy flux incident on the image plane:

  IRRADIANCE
- Scene brightness: brightness related to energy flux emitted (radiated) from a surface.

  RADIANCE

Light

- Electromagnetic energy
- Wave model
- Light sources typically radiate over a frequency spectrum
- Φ watts radiated into 4π radians



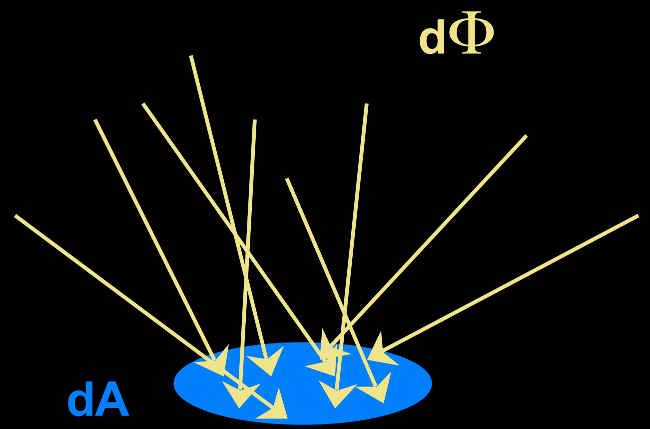
$$\Phi = \int_{sphere} d\Phi$$

$$R = \text{Radiant Intensity} = \frac{d\Phi}{d\omega}$$ Watts/unit solid angle (steradian)

(of source)

Irradiance

- Light falling on a surface from all directions.
- How much?

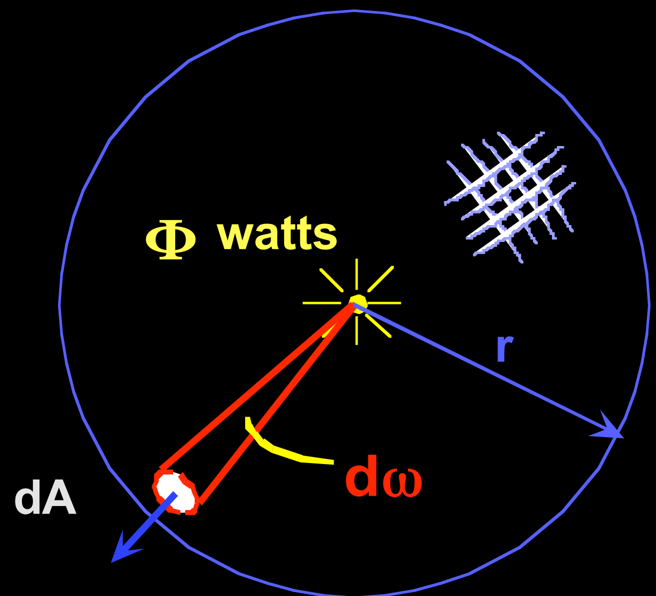


- Irradiance: power per unit area falling on a surface.

$$\text{Irradiance } E = \frac{d\Phi}{dA} \quad \text{watts/m}^2$$

Inverse Square Law

- Relationship between radiance (radiant intensity) and irradiance



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

$$E = \frac{d\Phi}{dA}$$

R: Radiant Intensity

E: Irradiance

Φ: Watts

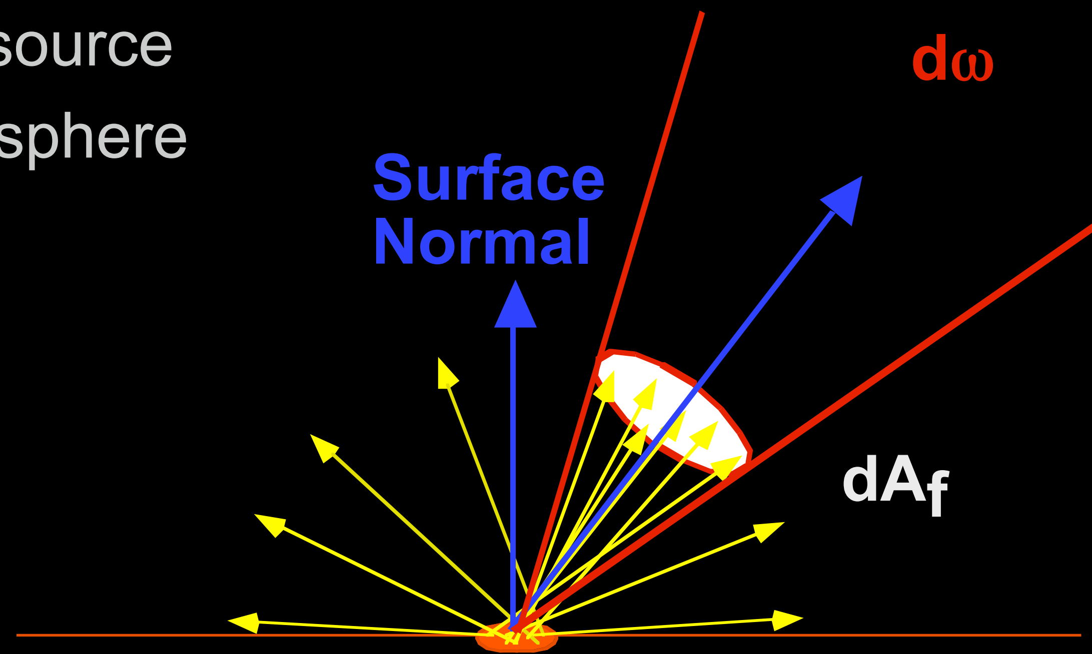
ω : Steradians

$$R = \frac{d\Phi}{d\omega} = \frac{r^2\, d\Phi}{dA} = r^2 E$$

$$E = \frac{R}{r^2}$$

Surface Radiance

- Surface acts as light source
- Radiates over a hemisphere



R: Radiant Intensity

E: Irradiance

L: Scene radiance

- Radiance: power per unit foreshortened area emitted into a solid angle

$$L = \frac{d^2\Phi}{dA_f \, d\omega}$$

(watts/m2 - steradian)

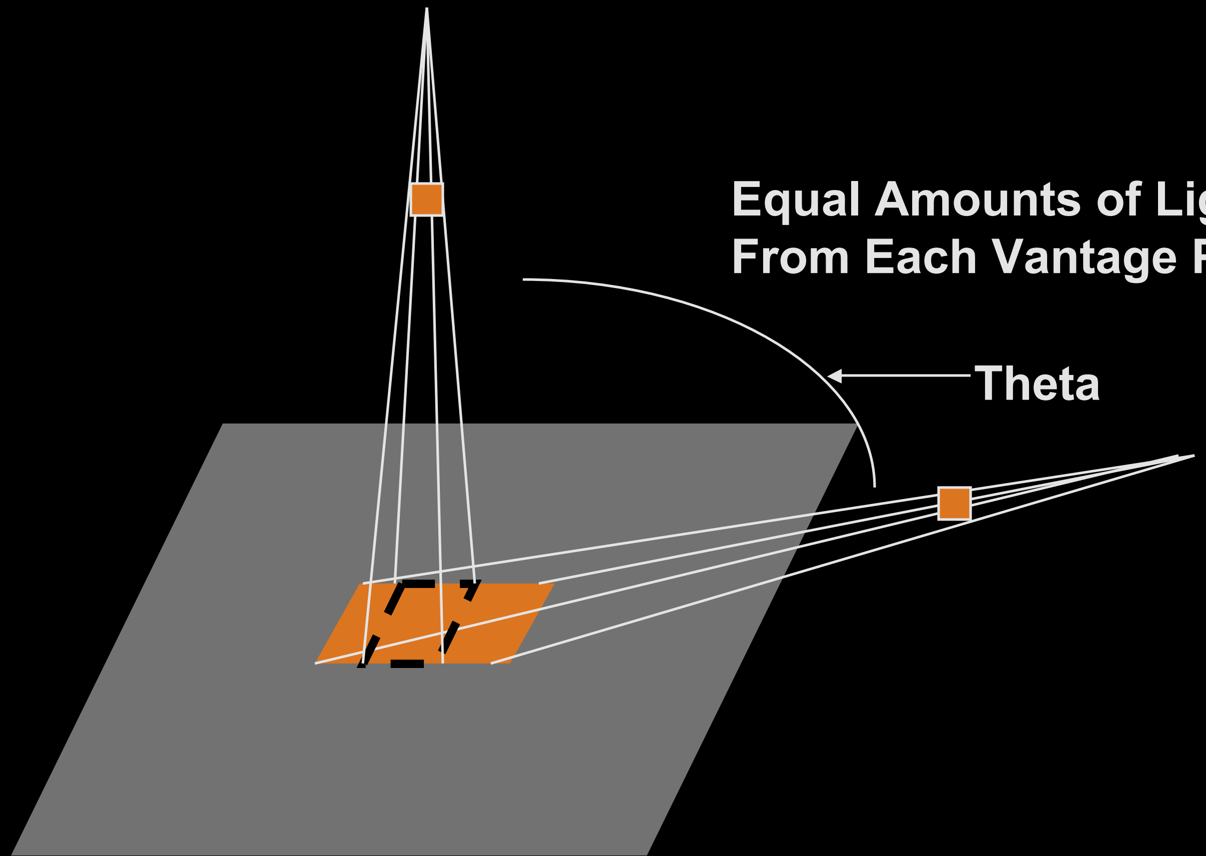
Pseudo-Radiance

- Consider two definitions:
  - Radiance:
    power per unit foreshortened area emitted into a solid angle
  - Pseudo-radiance
    power per unit area emitted into a solid angle
  - Why should we work with radiance rather than pseudo-radiance?
    - Only reason: Radiance is more closely related to our intuitive notion of “brightness”.

Lambertian Surfaces

- A particular point P on a Lambertian (perfectly matte) surface appears to have the same brightness no matter what angle it is viewed from.
  - Piece of paper
  - Matte paint
- Doesn't depend upon incident light angle.
- What does this say about how they emit light?

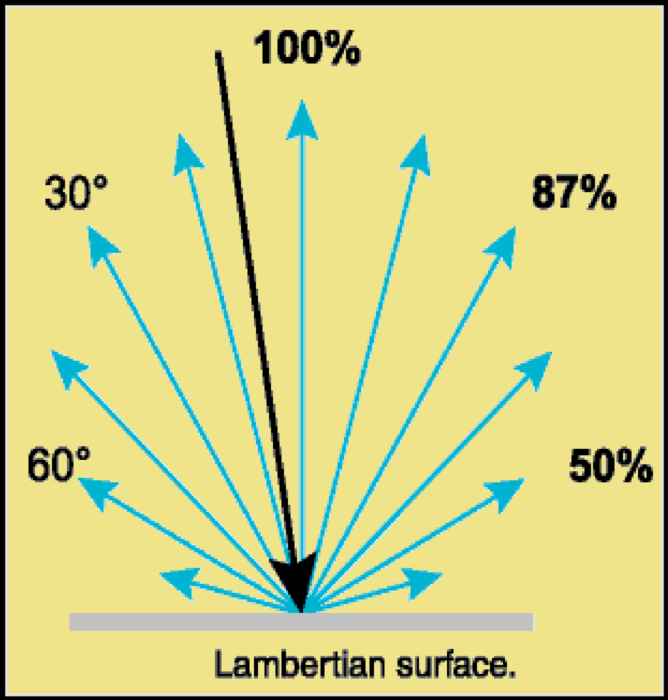
Lambertian Surfaces



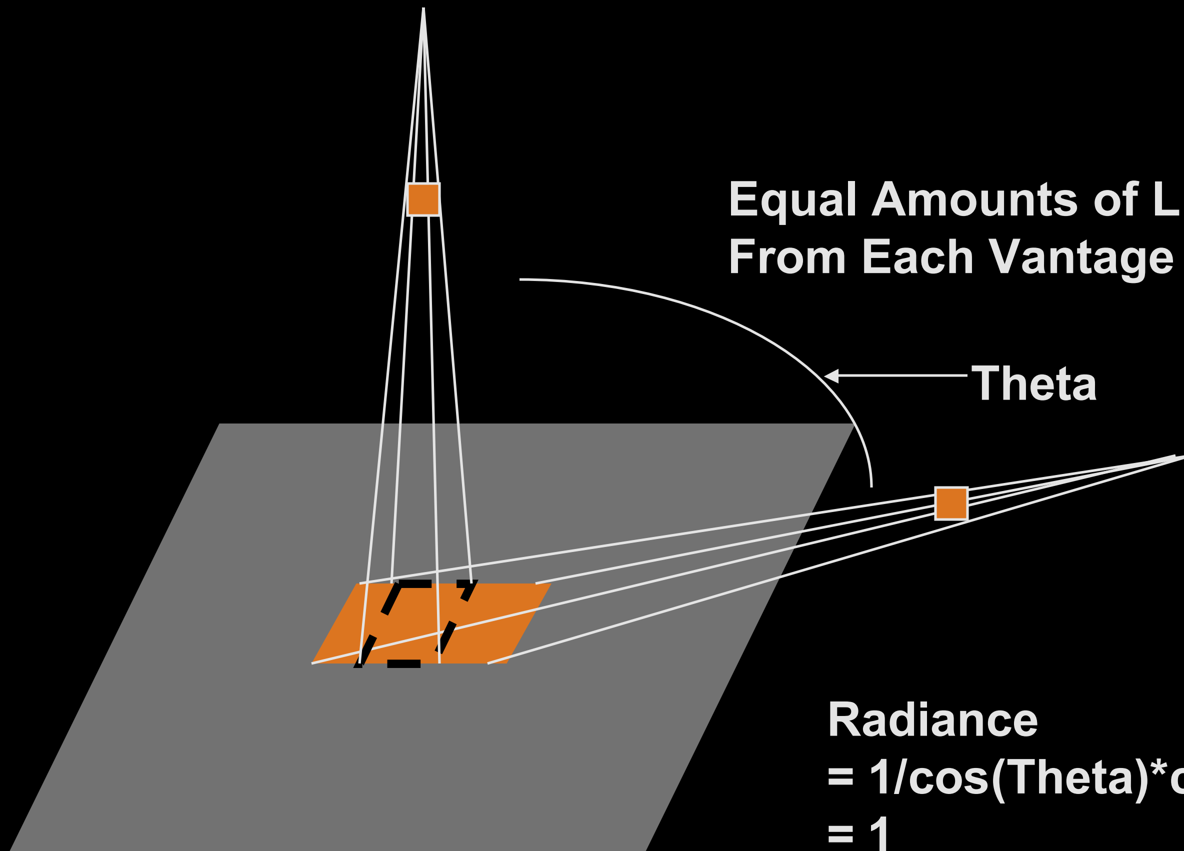
Area of black box = 1
Area of orange box = 1/cos(Theta)
Foreshortening rule.

Lambertian Surfaces

Relative magnitude of light scattered in each direction.
Proportional to cos (Theta).



Lambertian Surfaces

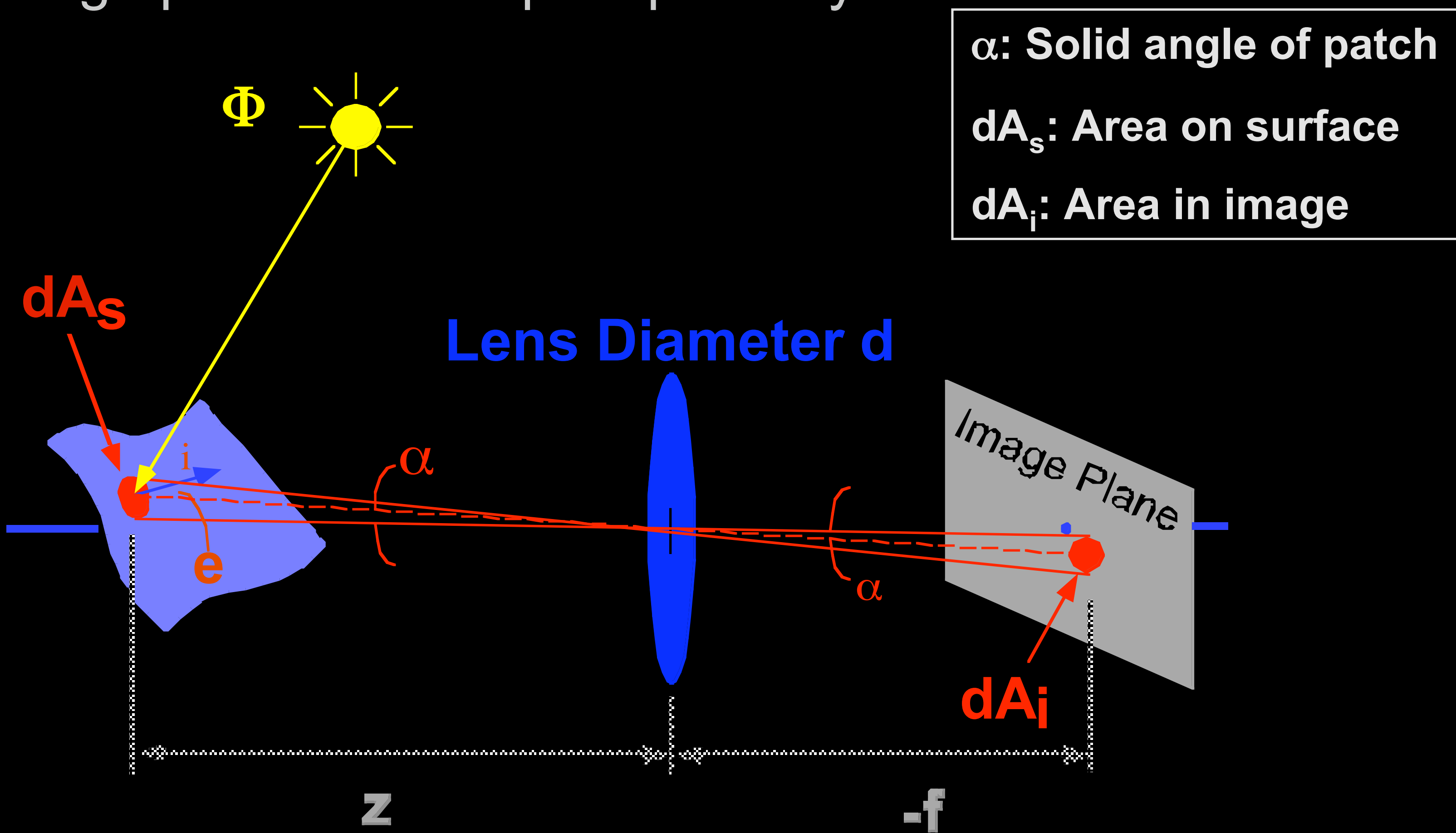


Equal Amounts of Light Observed
From Each Vantage Point

Radiance
= 1/cos(Theta)*cos(Theta)
= 1

Area of black box = 1
Area of orange box = 1/cos(Theta)
Foreshortening rule.

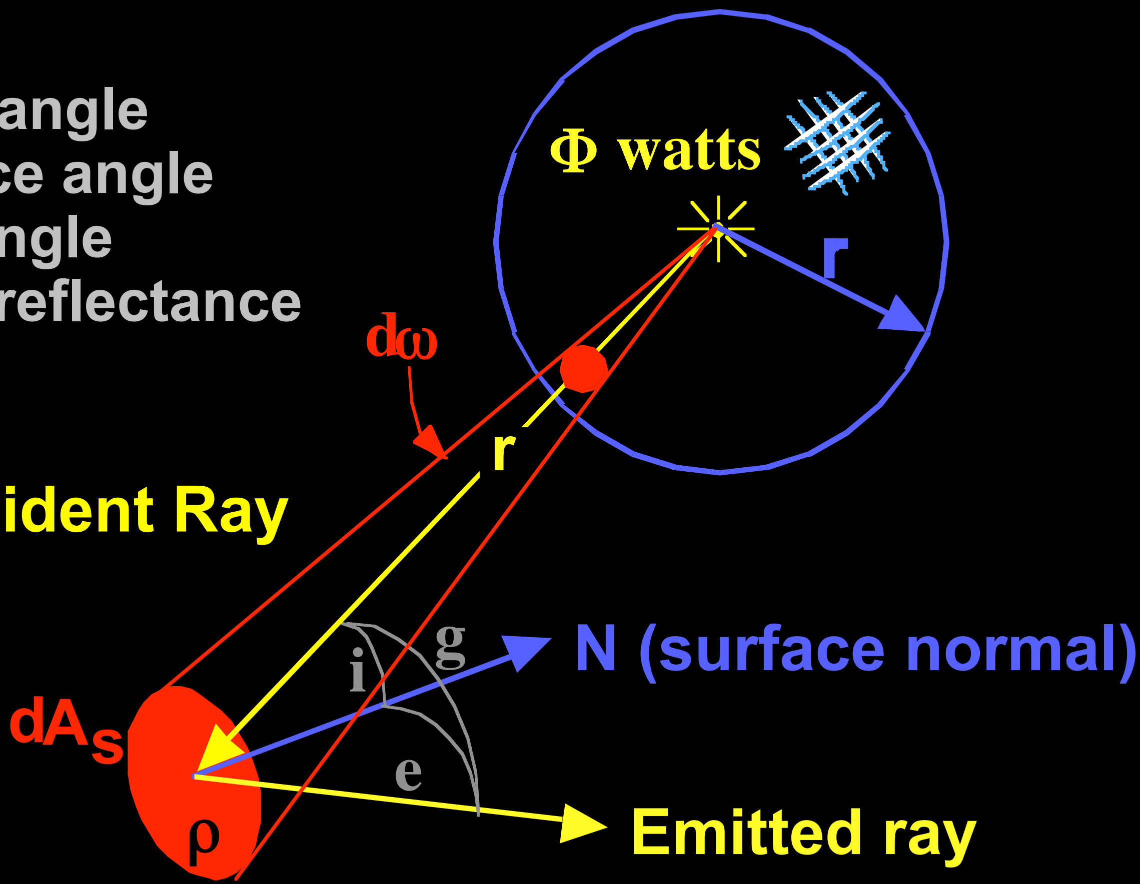
- Goal: Relate the radiance of a surface to the irradiance in the image plane of a simple optical system.



Light at the Surface

- E = flux incident on the surface (irradiance) = $\frac{d\Phi}{dA}$

i = incident angle
e = emittance angle
g = phase angle
ρ = surface reflectance



- We need to determine dΦ and dA

Reflections from a Surface I

dA

- $dA = dA_s \cos i$ {foreshortening effect in direction of light source}

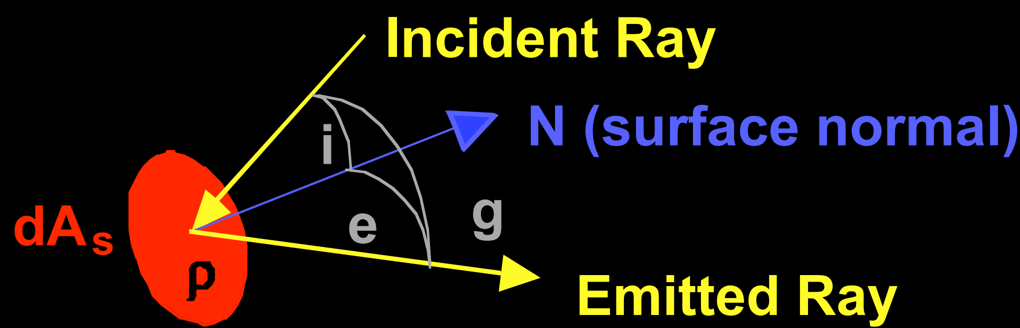
$d\Phi$

- $d\Phi$ = flux intercepted by surface over area dA
  - dA subtends solid angle $d\omega = dA_s \cos i / r^2$
  - $d\Phi = R\, d\omega = R\, dA_s \cos i / r^2$
  - $E = d\Phi / dA_s$

Surface Irradiance: $E = R \cos i / r^2$

Reflections from a Surface II

- Now treat small surface area as an emitter
  - ….because it is bouncing light into the world
- How much light gets reflected?

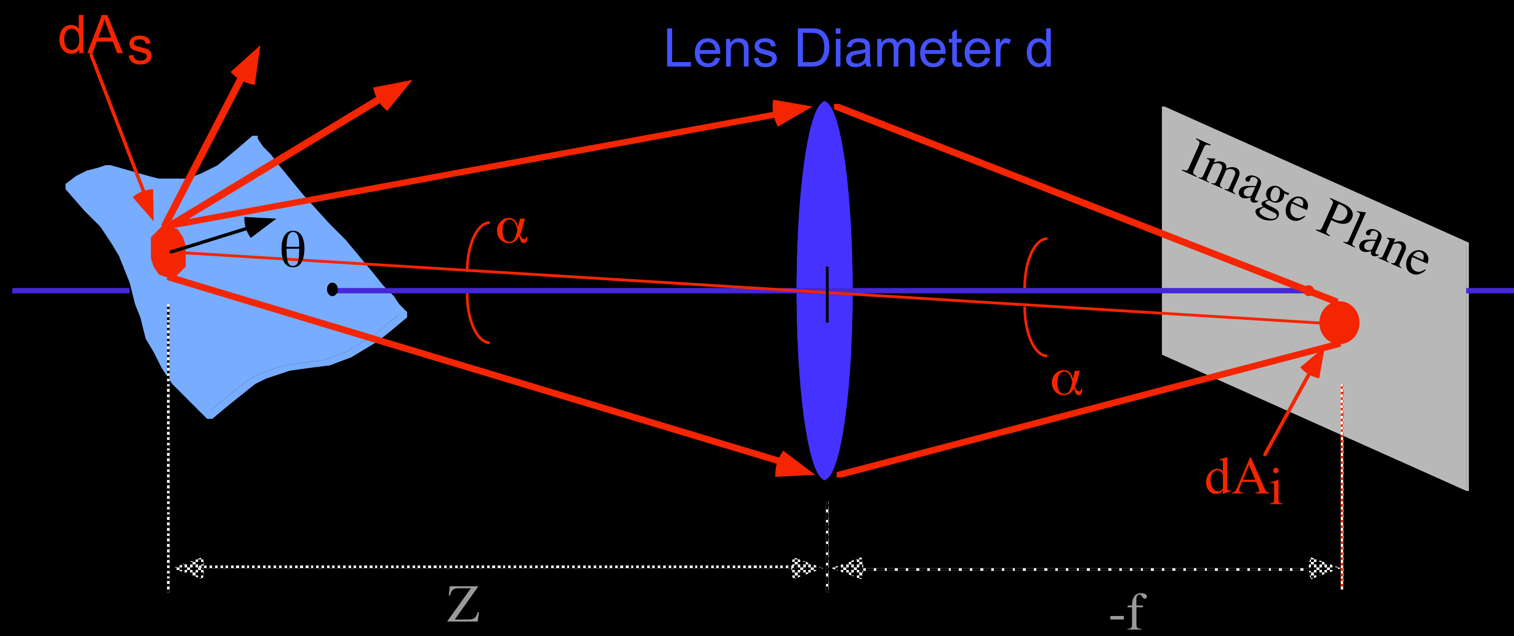


- E is the surface irradiance
- L is the surface radiance = luminance
- They are related through the surface reflectance function:

$$\frac{L_s}{E} = \rho(i,e,g,\lambda)$$

May also be a function of the wavelength of the light

Power Concentrated in Lens



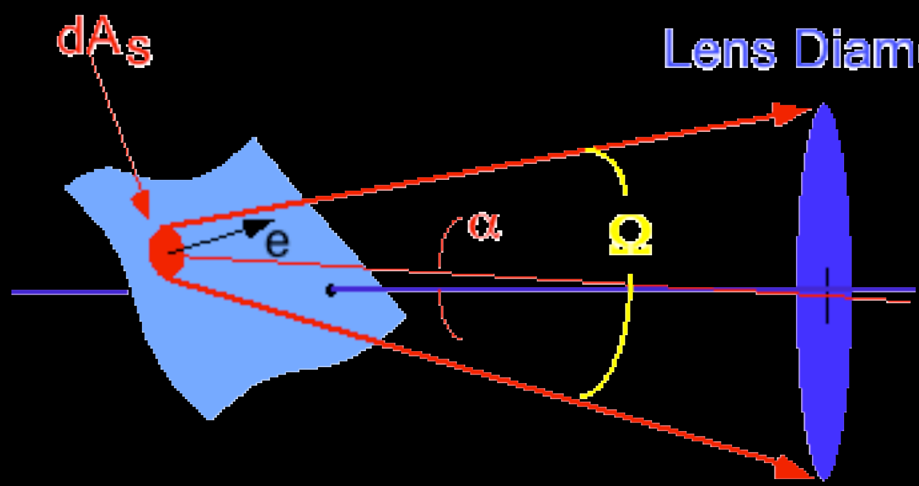
$$L_s = \frac{d^2\Phi}{dA_s d\omega}$$

Luminance of patch (known from previous step)

What is the power of the surface patch as a source in the direction of the lens?

$$d^2\Phi = L_s dA_s d\omega$$

Through a Lens Darkly



- In general:
  - L_s is a function of the angles i and e.
  - Lens can be quite large
  - Hence, must integrate over the lens solid angle to get $d\Phi$

$$d\Phi = dA_s \int_{\Omega} L_s \, d\Omega$$

Simplifying Assumption

- Lens diameter is small relative to distance from patch

$$d\Phi = dA_s \int_{\Omega} L_s \, d\Omega$$

L_s is a constant and can be removed from the integral

$$d\Phi = dA_s L_s \int_{\Omega} d\Omega$$

Surface area of patch in direction of lens

$$= dA_s \cos e$$

Solid angle subtended by lens in direction of patch

$$= \frac{\text{Area of lens as seen from patch}}{(\text{Distance from lens to patch})^2}$$

$$= \frac{\pi (d/2)^2 \cos \alpha}{(z / \cos \alpha)^2}$$

Putting it Together

$$d\Phi = dA_s \int_{\Omega} L_s \, d\Omega$$

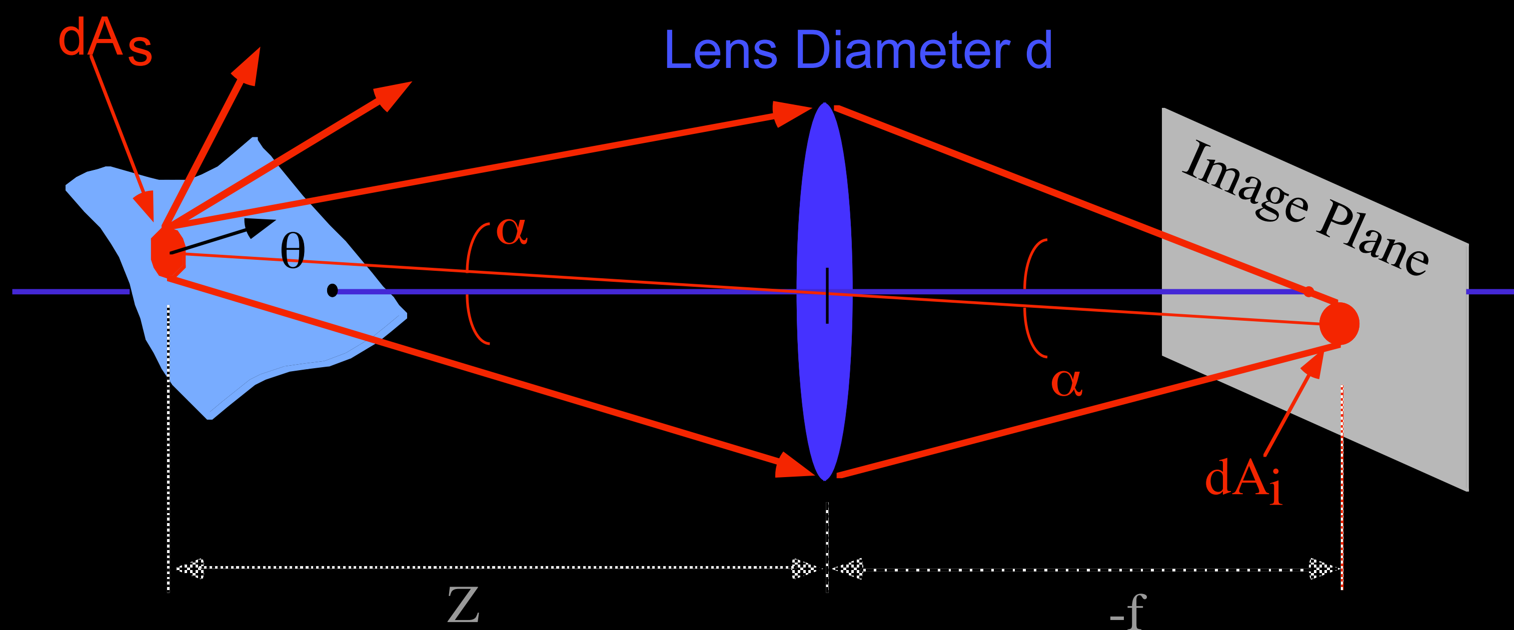
$$= dA_s \cos e \; L_s \frac{\pi (d/2)^2 \cos \alpha}{(z / \cos \alpha)^2}$$

- Power concentrated in lens:

$$d\Phi = \frac{\pi}{4} L_s \, dA_s \left[\frac{d}{z}\right]^2 \cos e \cos^3 \alpha$$

- Assuming a lossless lens, this is also the power radiated by the lens as a source.

Through a Lens Darkly

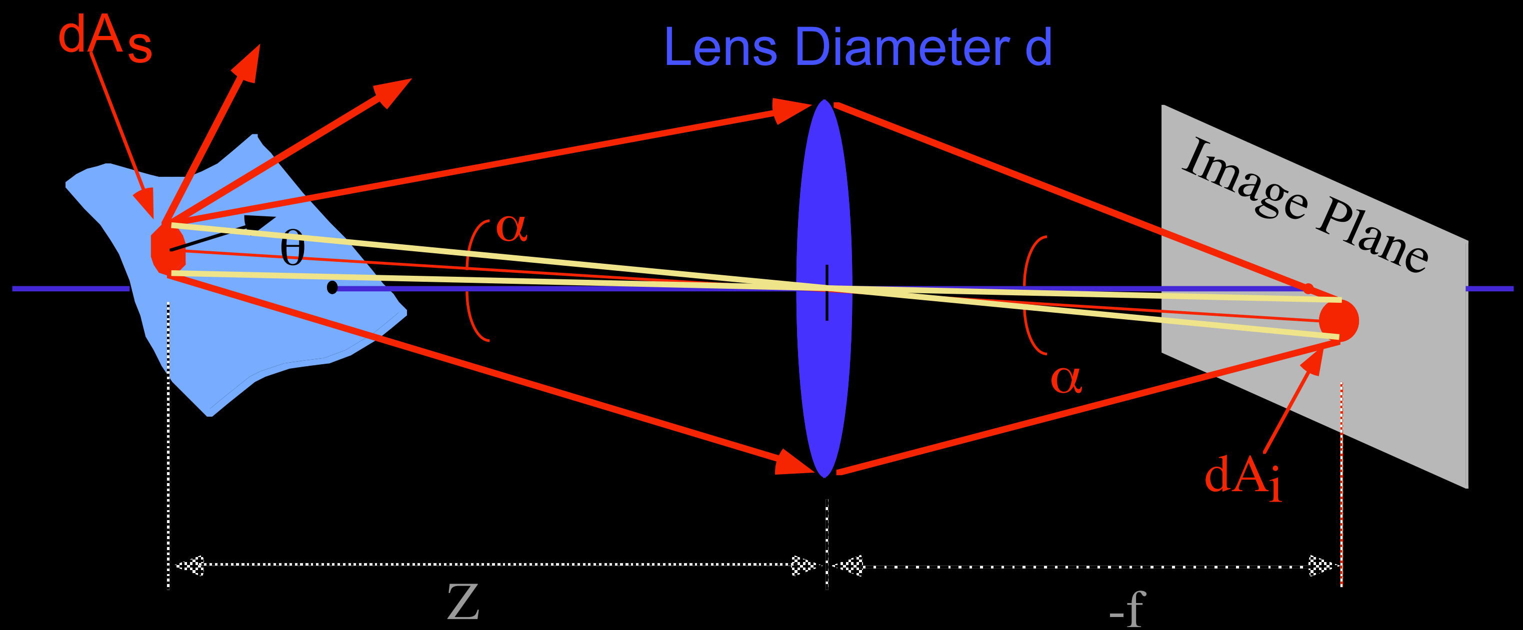


- Image irradiance at $dA_i = \frac{d\Phi}{dA_i} = E_i$

$$E_i = L_s \frac{dA_s}{dA_i} \frac{\pi}{4} \left[\frac{d}{Z} \right]^2 \cos e \cos^3 \alpha$$

ratio of areas

Patch ratio



The two solid angles are equal

$$\frac{dA_s \cos e}{(Z/\cos\alpha)^2} = \frac{dA_i \cos\alpha}{(-f/\cos\alpha)^2} \Rightarrow \frac{dA_s}{dA_i} = \frac{\cos\alpha}{\cos e}\left(\frac{Z}{-f}\right)^2$$

The Fundamental Result

- Source Radiance to Image Sensor Irradiance:

$$\frac{dA_s}{dA_i} = \frac{\cos\alpha}{\cos e}\left(\frac{Z}{-f}\right)^2$$

$$E_i = L_s \frac{dA_s}{dA_i} \frac{\pi}{4}\left(\frac{d}{Z}\right)^2 \cos e \cos^3\alpha$$

$$E_i = L_s \frac{\cos\alpha}{\cos e}\left(\frac{Z}{-f}\right)^2 \frac{\pi}{4}\left(\frac{d}{Z}\right)^2 \cos e \cos^3\alpha$$

$$E_i = L_s \frac{\pi}{4}\left(\frac{d}{-f}\right)^2 \cos^4\alpha$$

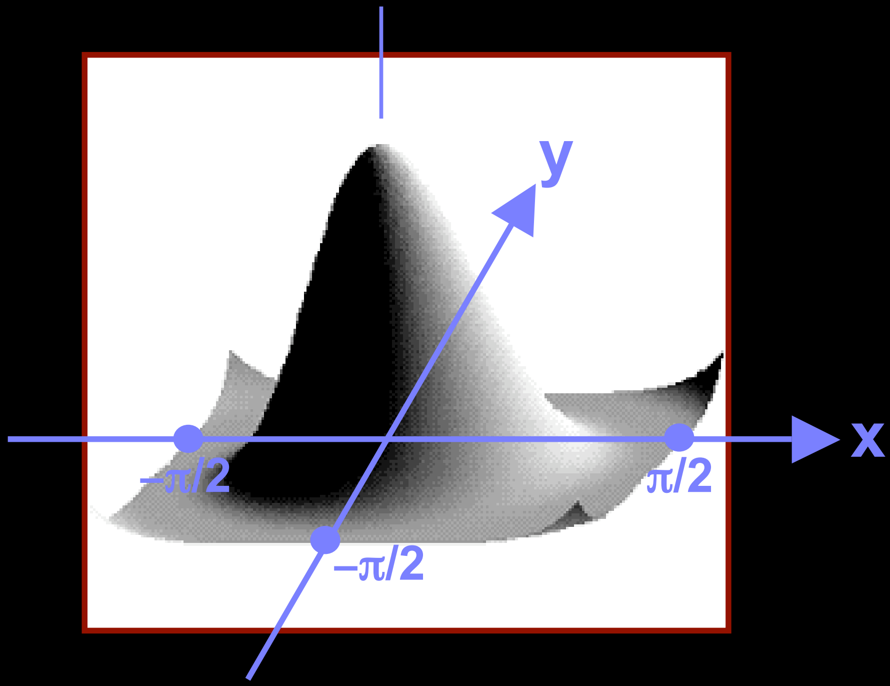
Radiometry Final Result

$$E_i = L_s \frac{\pi}{4} \left(\frac{d}{-f} \right)^2 \cos^4 \alpha$$

- Image irradiance is a function of:
  - Scene radiance L_s
  - Focal length of lens f
  - Diameter of lens d
    - f/d is often called the 'effective focal length' of the lens
  - Off-axis angle α

$\cos^4 \alpha$ Light Falloff

Lens Center



Top view shaded by height