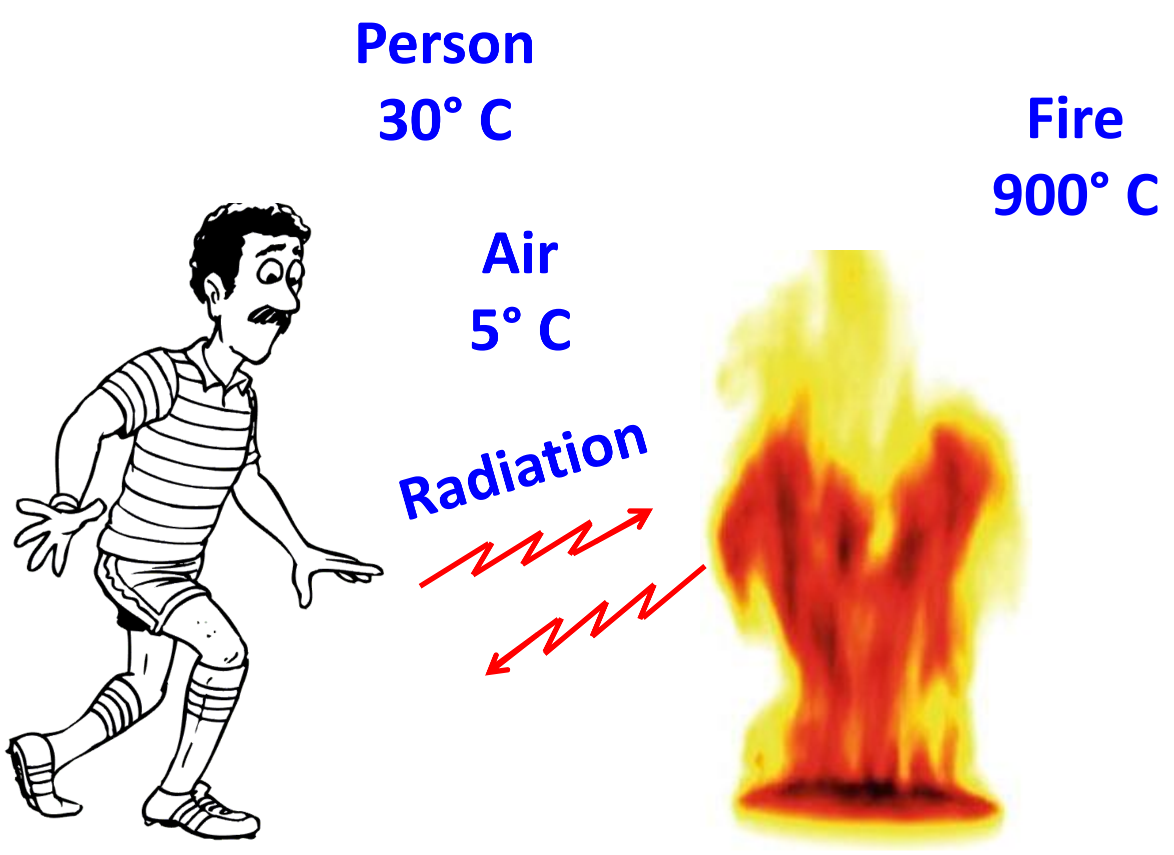
RADIATION: PROCESSES AND PROPERTIES

- Thermal radiation requires no matter
- Applications: Industrial heating, cooling and drying processes, energy conversion methods – fossil fuel combustion and solar radiation

OBJECTIVES

- MEANS BY WHICH THERMAL RADIATION IS GENERATED
- SPECIFIC NATURE OF RADIATION
- MANNER IN WHICH RADIATION INTERACTS WITH MATTER



Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even when they are separated by a medium colder than both.

Solar radiation reaches the earth after passing through cold air layers at high altitudes.

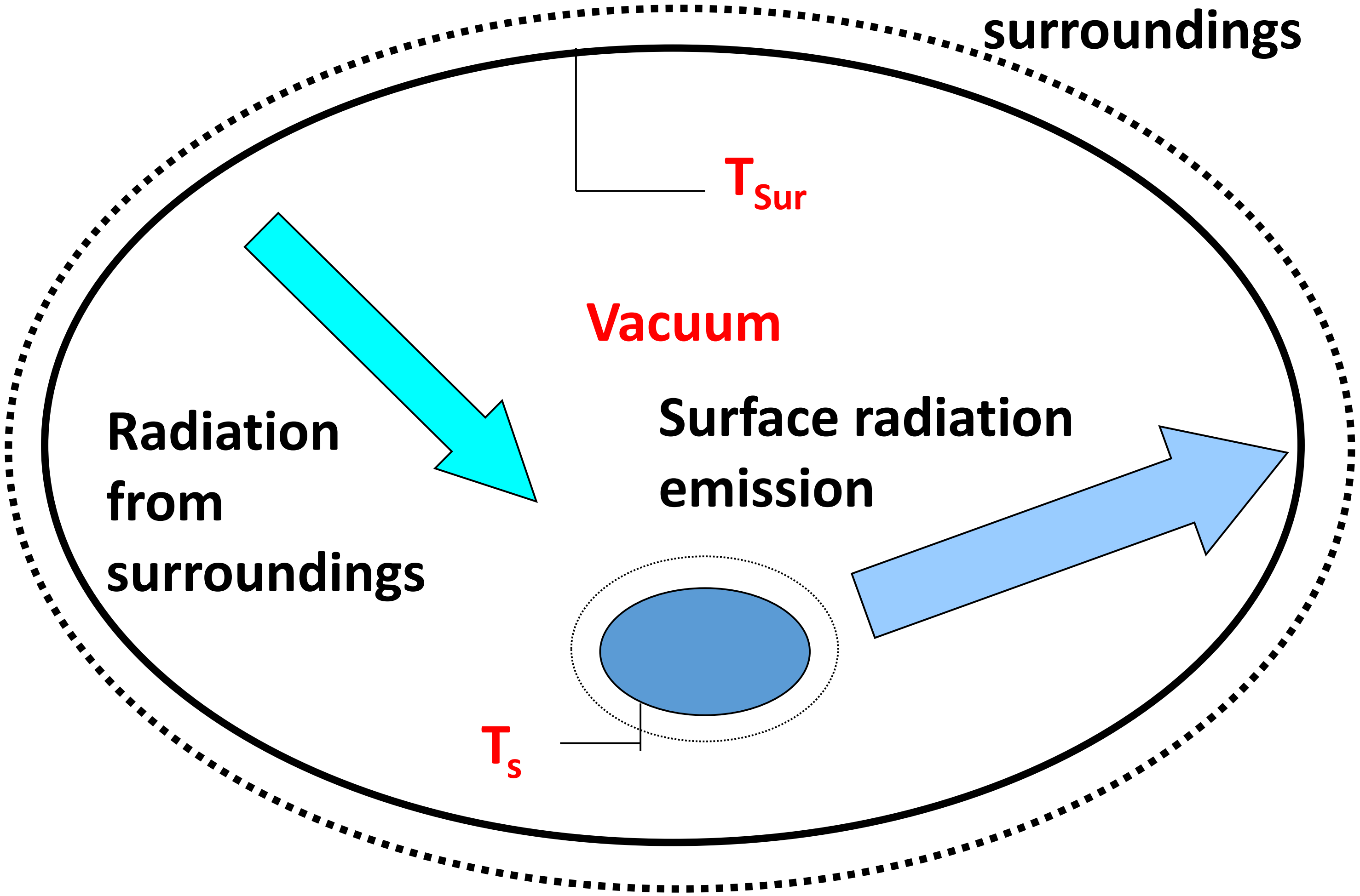
FUNDAMENTAL CONCEPTS

$T_S > T_{sur}$

No conduction or convection - still solid will cool

Solid gets cooled – emission of thermal radiation form the surface of the solid

Radiation cooling of a heated solid



Radiation – propogation of electromagnetic waves

J.C.Maxwell – accelerated charges or changing electric currents give rise to electric and magnetic fields. These moving fields are called ELECTROMAGNETIC WAVES OR ELECTROMAGNETIC RADIATION

Electro-magnetic Radiation – energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules

Characteristics of E.M.Radiation

$$\lambda = \frac{c}{\nu} \qquad c = \frac{c_o}{n}$$

Material	n
Air and most gases	1.0
Glass	1.5
Water	1.33

ν - Frequency (Hz - 1/sec)
λ - Wavelength (m)
c - Speed of propagation of wave in that medium
$c_o = 2.998 \times 10^8 \ m/s$ in vacuum
n - Refractive index

λ and c – Depend on the medium through which wave travels
ν - Independent of the medium Depends only on the source

Electromagnetic Radiation: Propogation of a discrete packets of energy called photons or quanta

Each photon of frequency ν is considered to have an energy of

$$e = h\nu = \frac{hc}{\lambda} \qquad \lambda = \frac{c}{\nu} \qquad c = \frac{c_o}{n}$$

Material	n
Air and most gases	1.0
Glass	1.5
Water	1.33

ν - Frequency (Hz - 1/sec)
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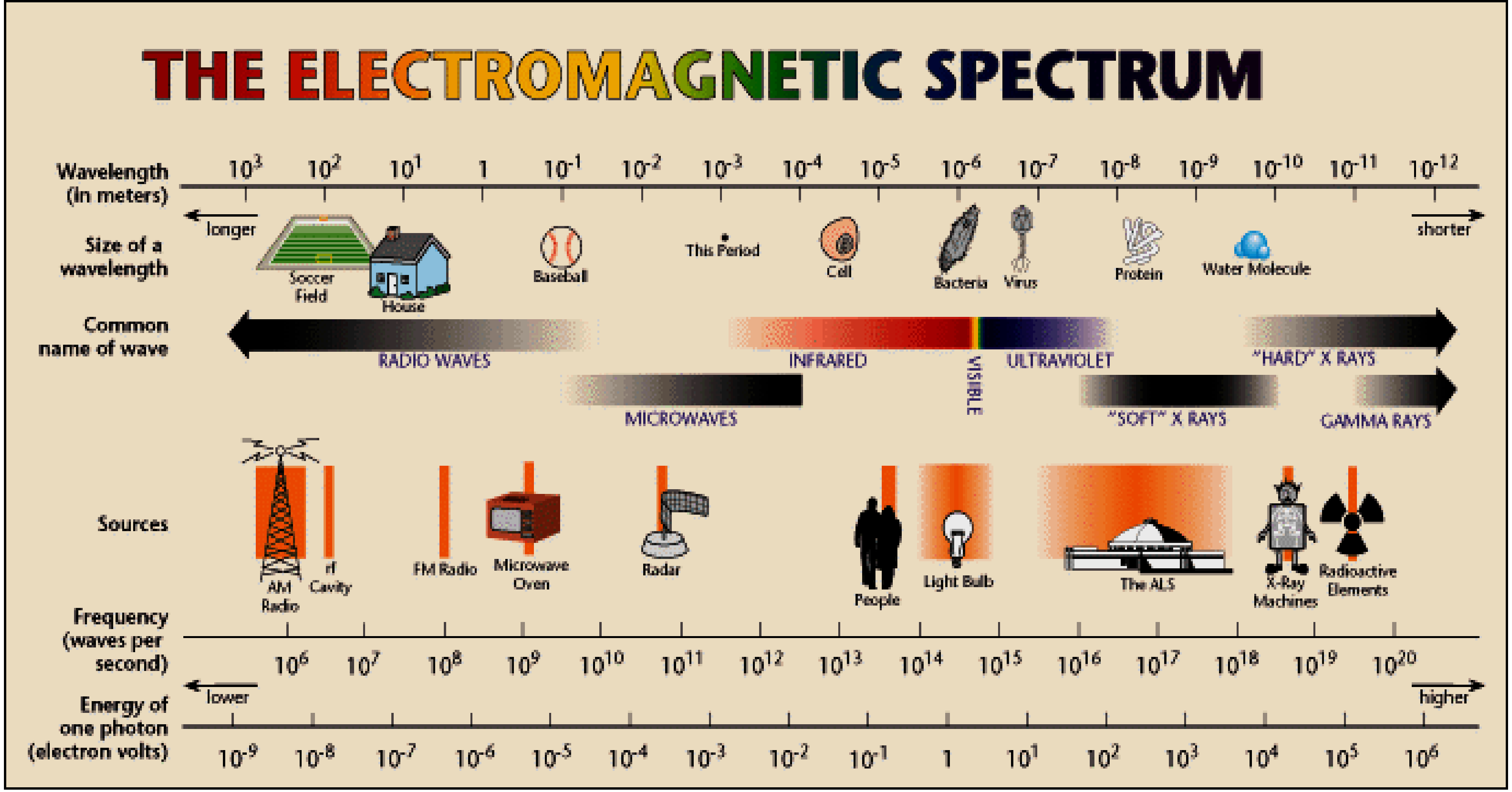
$c_o = 2.998 \times 10^8\ m/s$ in vacuum
n - Refractive index

h – Planck's Constant ($h = 6.625 \times 10^{-34}\ J.s$)

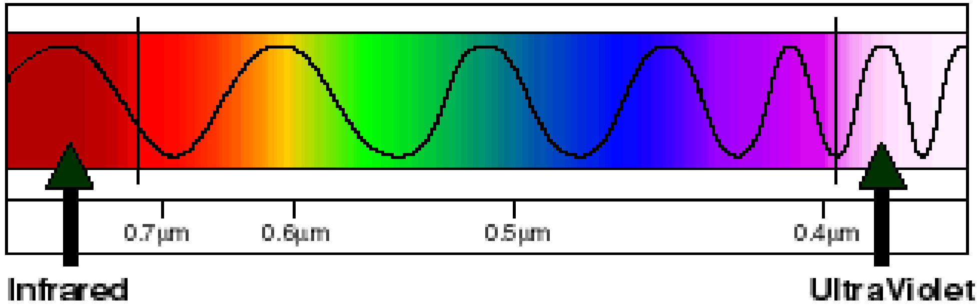
Energy of the photon – inversely proportional to its wavelength

Shorter wavelength radiation possess larger photon energies

No wonder, we try to avoid very short wavelength radiation such as gamma rays and X-rays since they are highly destructive

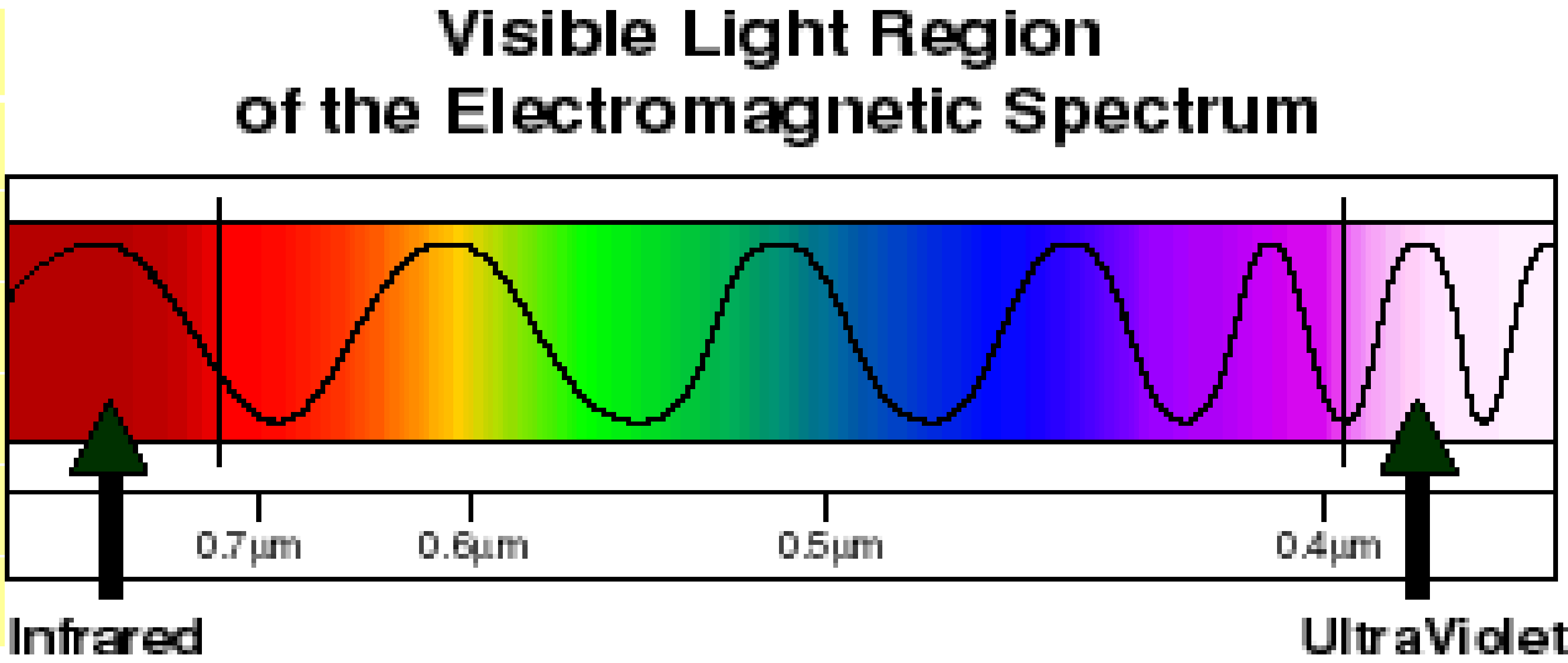


Visible Light Region of the Electromagnetic Spectrum



WAVELENGTH RANGE OF DIFFERENT COLOURS

Color	Wavelength Band (µm)
Violet	0.40 - 0.44
Blue	0.44 - 0.49
Green	0.49 – 0.54
Yellow	0.54 - 0.60
Orange	0.60 - 0.67
Red	0.63 - 0.76



Solar radiation:

Electromagnetic radiation emitted by sun

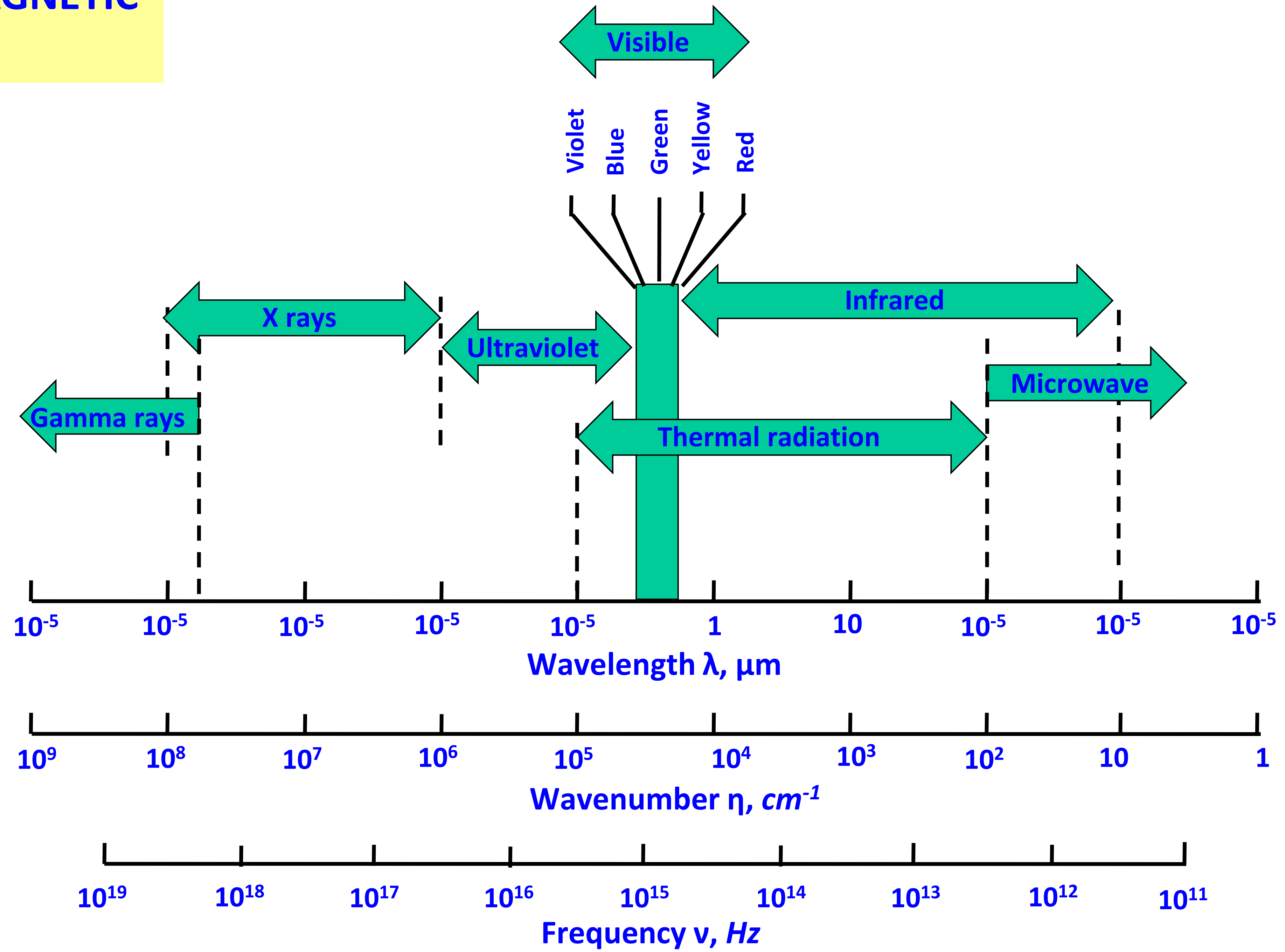
Wavelength band – 0.3 - 3µm

Half range is in the visible range

Other half range is in the ultraviolet and infrared range

IN HEAT TRANFER, WE ARE INTERESTED IN ENERGY EMITTED BY BODIES DUE TO THEIR TEMPERATURE ONLY – THERMAL RADIATION

ELECTROMAGNETIC SPECTRUM

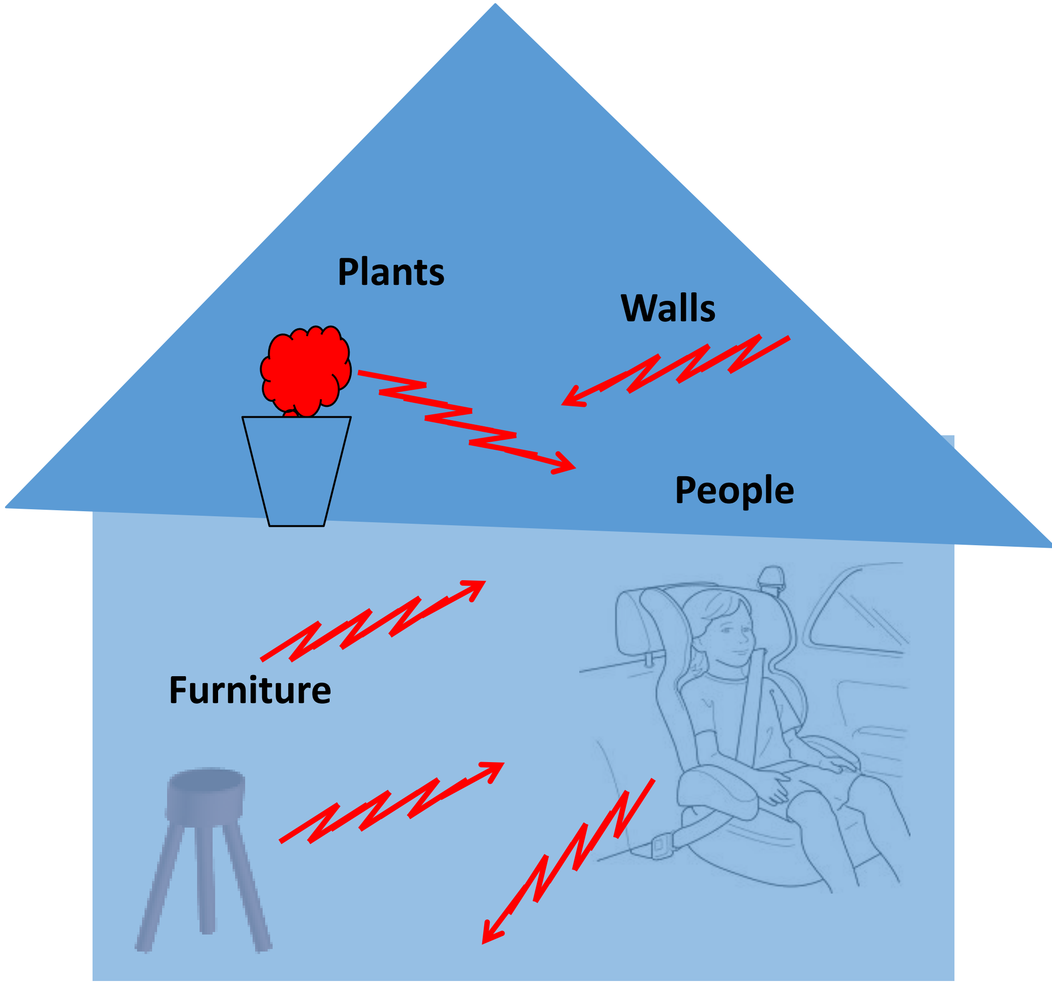


ALL BODIES EMIT RADIATION – RADIATION AT ABSOLUTE ZERO TEMP – ZERO

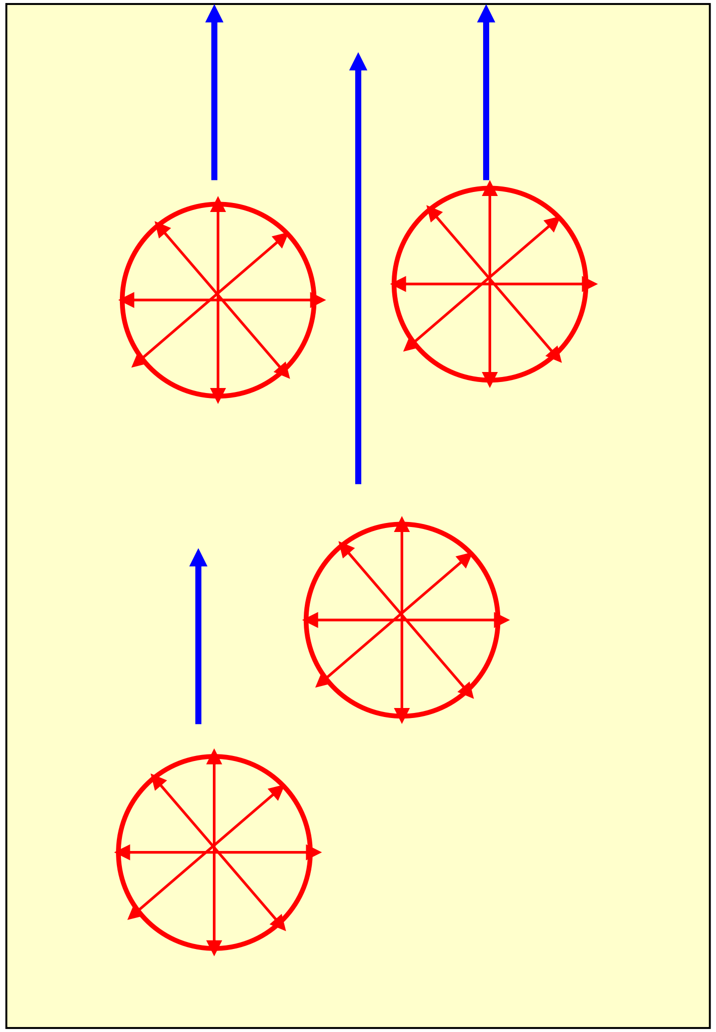
THERMAL RADIATION – Rate at which energy is emitted by matter as a result of its finite temperature

MECHANISM OF EMISSION – energy released as a result of oscillations of many electrons that constitute matter

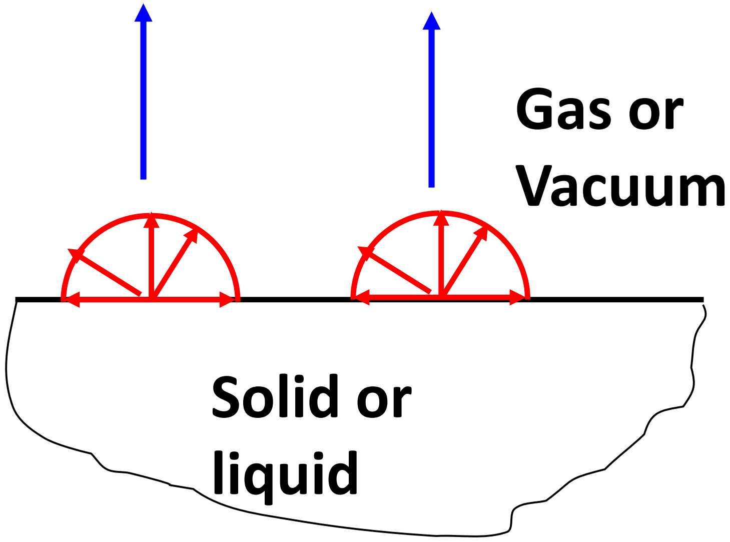
Radiation is a volumetric phenomena
Radiation is considered as surface phenomena
Radiation – interior molecules – absorbed by adjoining molecules
Radiation that is emitted from a solid or a liquid originates from molecules that within a distance of 1 μm from the exposed surface



Radiation emission



High Temperature gas or semi-transparent medium



Radiation is a volumetric phenomena

Radiation is considered as surface phenomena

Radiation – interior molecules – absorbed by adjoining molecules

Emission Process

a. Volumetric Phenomenon

b. Surface Phenomenon

Radiation that is emitted from a solid or a liquid originates from molecules that within a distance of 1 μm from the exposed surface

DESCRIPTION OF THE THERMAL RADIATION – SPECTRAL AND DIRECTIONAL DISTRIBUTION

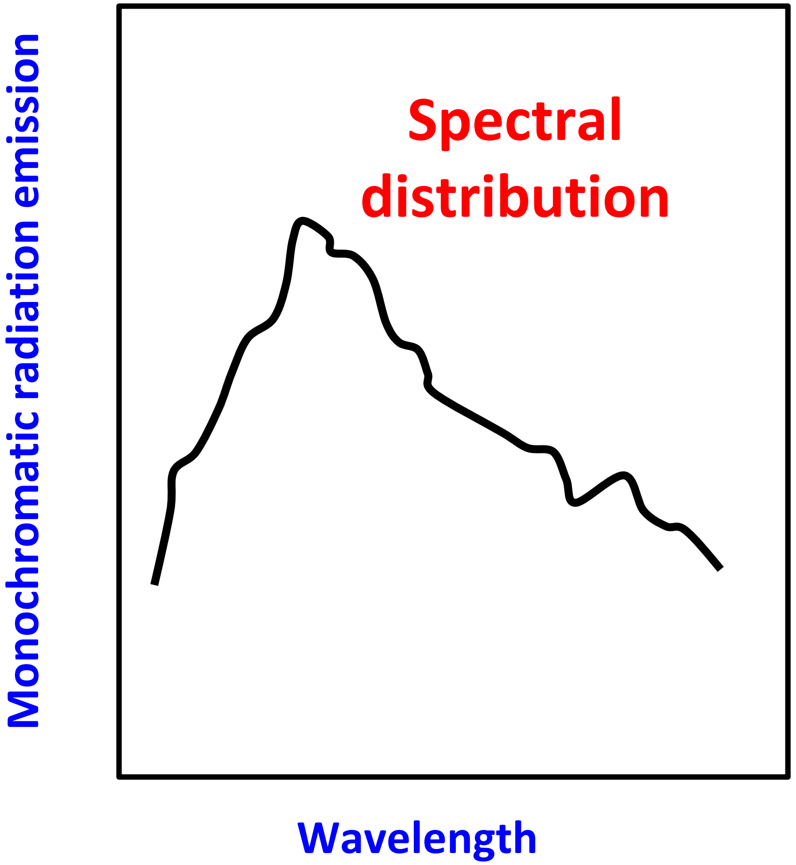
Spectral Distribution

Emitted Radiation – continuous, non-uniform distribution of mono-chromatic (single wavelength) components

Spectral distribution depends on

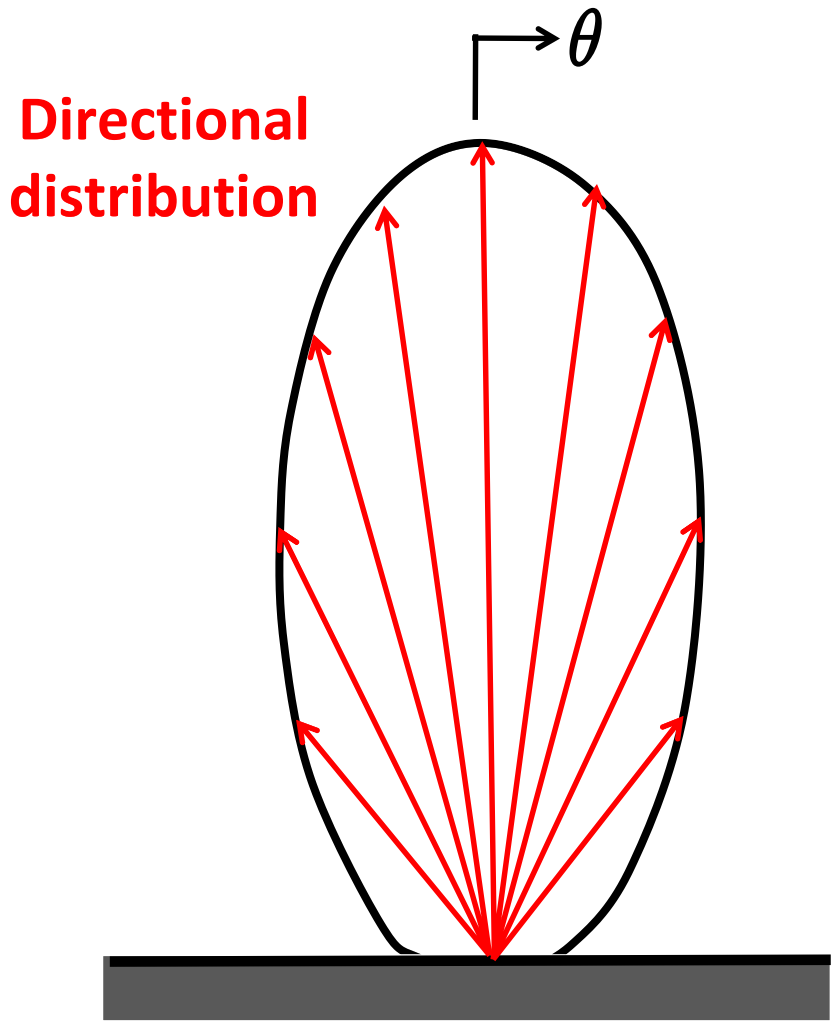
Nature of the emitting surface

Temperature of the emitting surface



(a)

Spectral distribution



(b)

Directional distribution

RADIATION INTENSITY

Radiation emitted by a surface propagates in all directions

Radiation incident on the surface may come from different directions

Response of the surface to the radiation depends on the direction

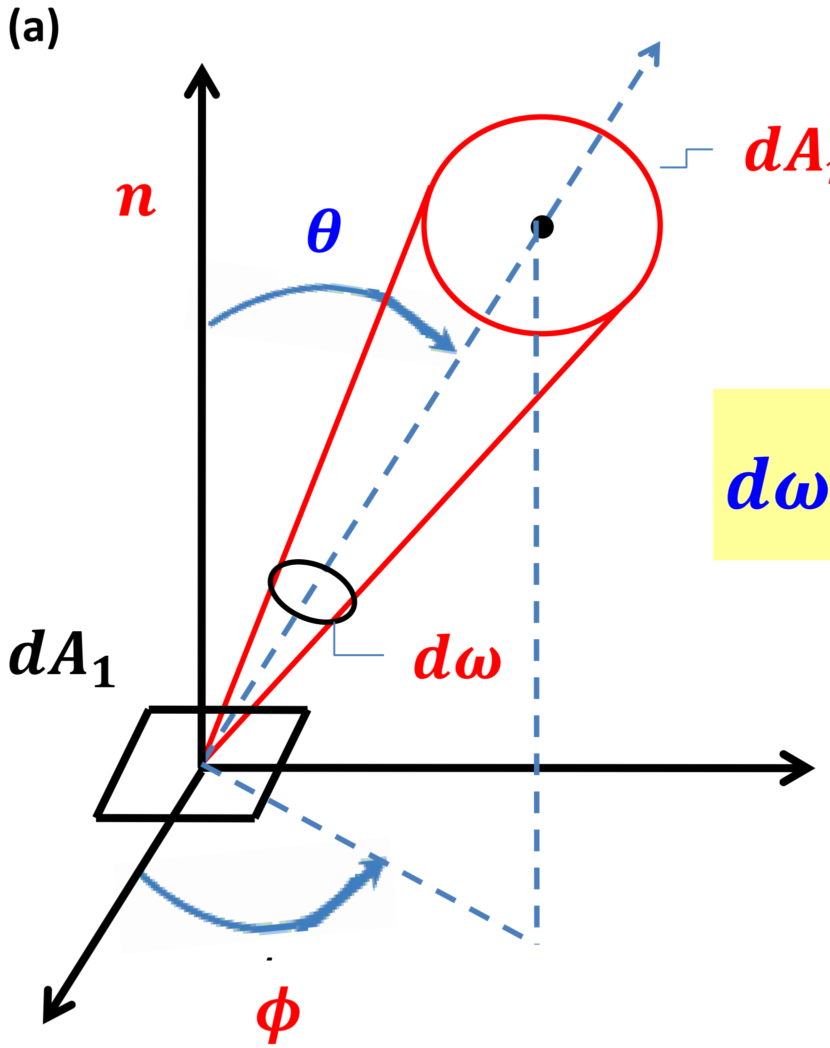
Directional effects – concept – RADIATION INTENSITY

Definitions (Concepts)

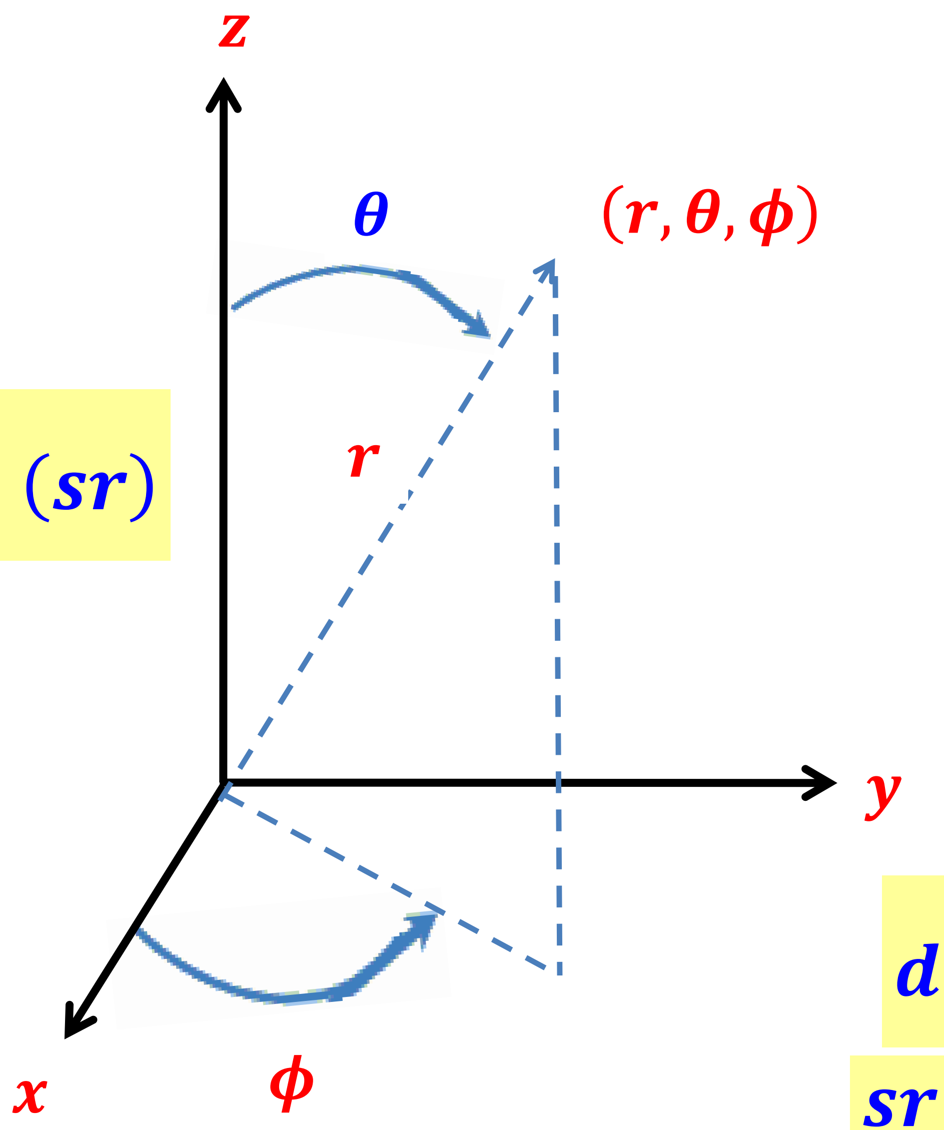
- Solid Angle
- Intensity of Emitted Radiation
- Incident Radiation (Irradiation)
- Radiosity
- Spectral Emissive Power, Spectral Irradiation, Spectral Radiosity

SOLID ANGLE $d\omega$

- Emission of radiation from a differential area dA_1 into a solid angle $d\omega$ subtended by dA_n at a point on dA_1



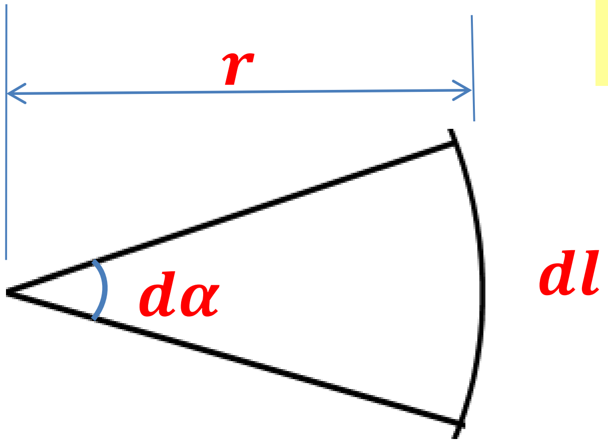
$$d\omega = \frac{dA_n}{r^2}\ (sr)$$



$$d\omega = \frac{dA_n}{r^2}\ (sr)$$

$sr\ -Steridians$

Plain angle

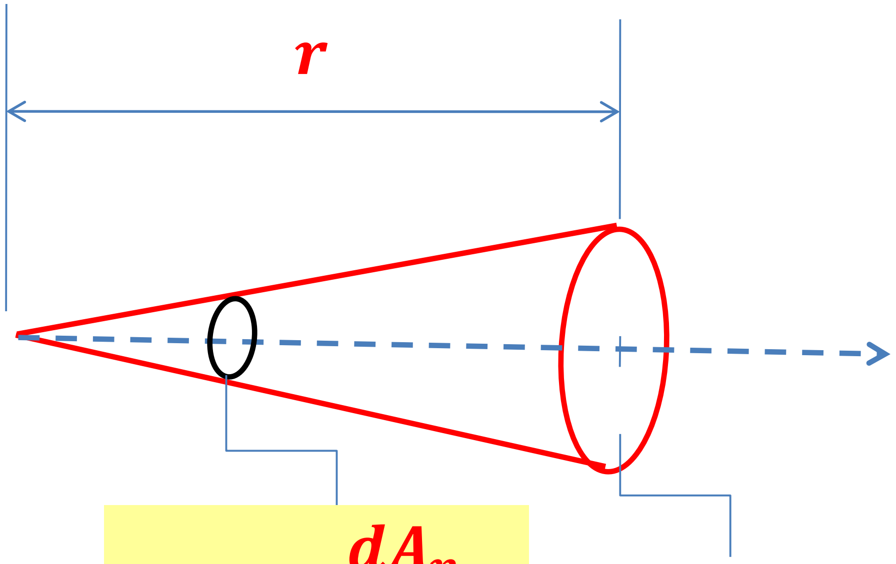


$$d\alpha = \frac{dl}{r}$$

Quantifying the slice of a pizza of plane angle α

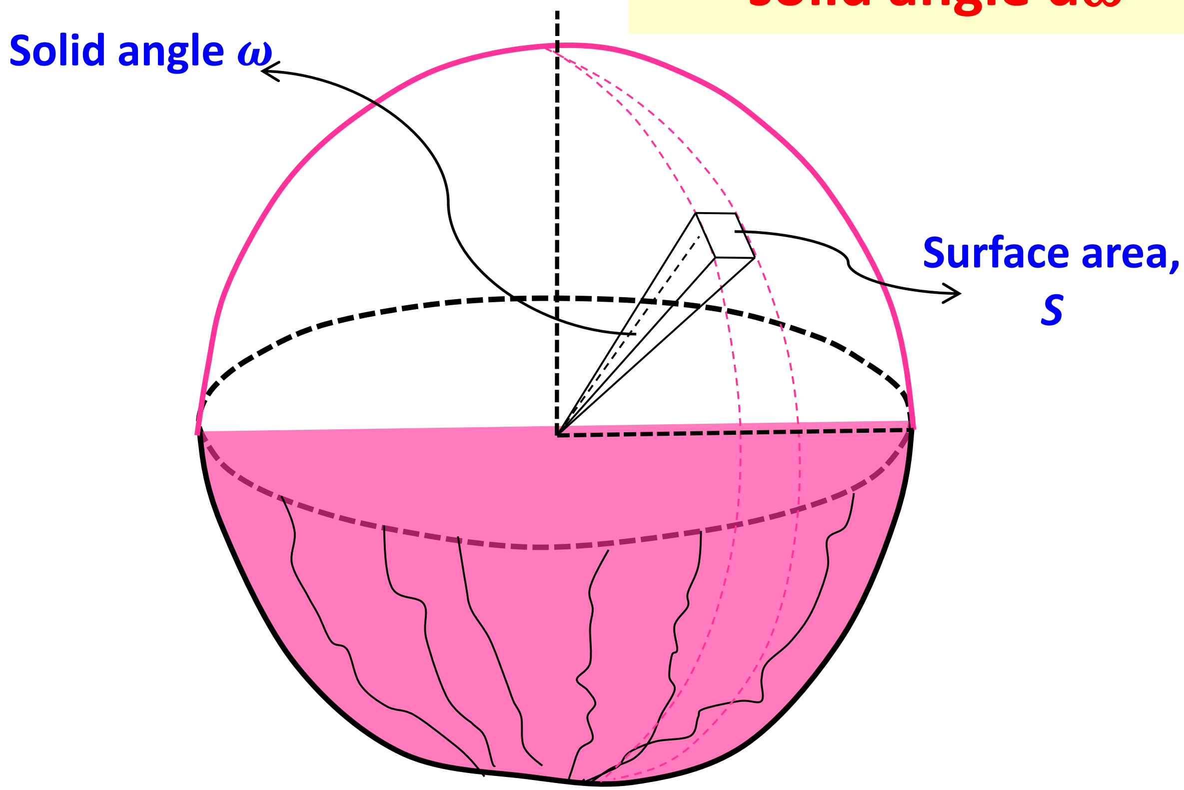
Quantifying the slice of a water melon of solid angle dω

Solid angle

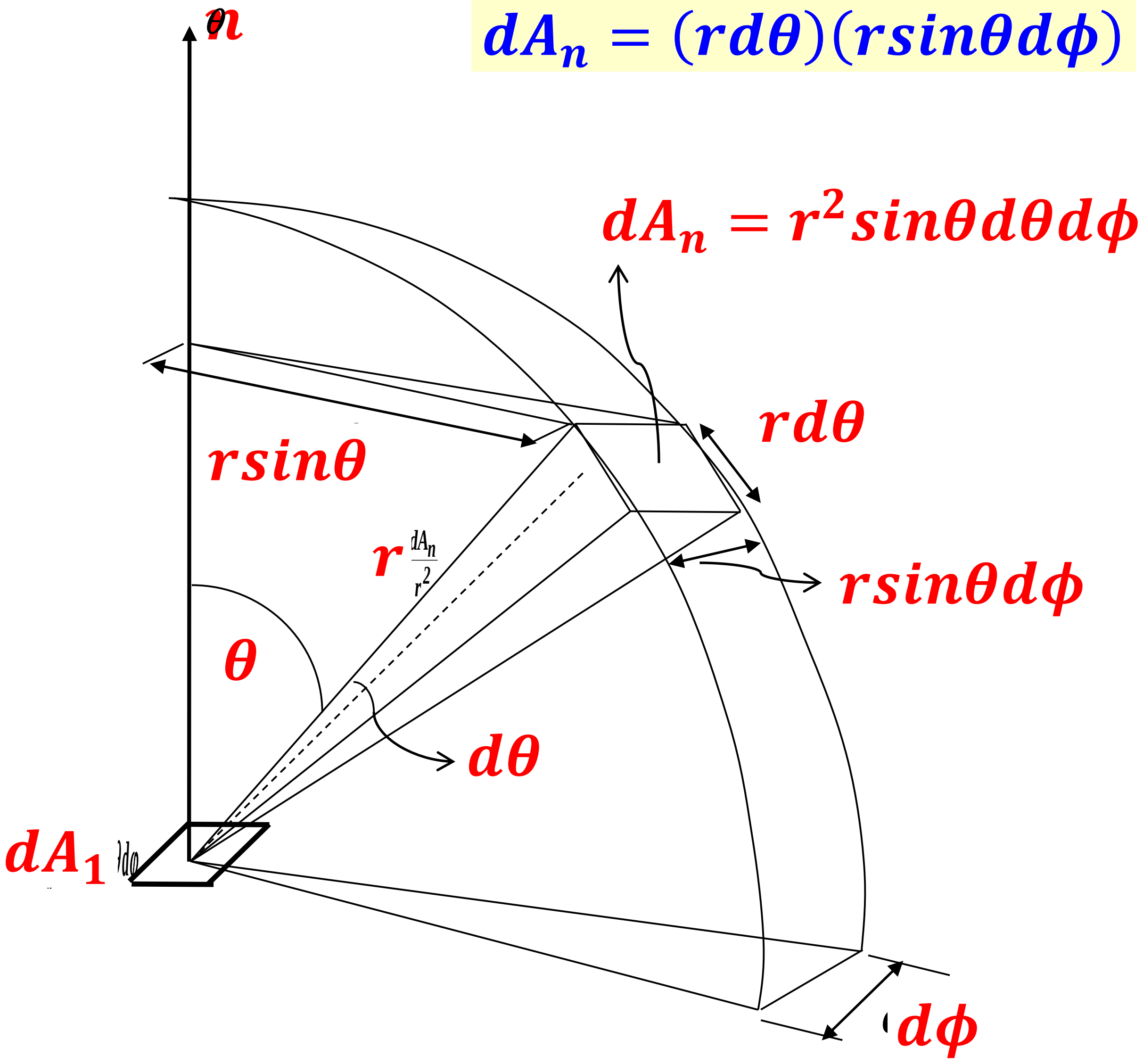


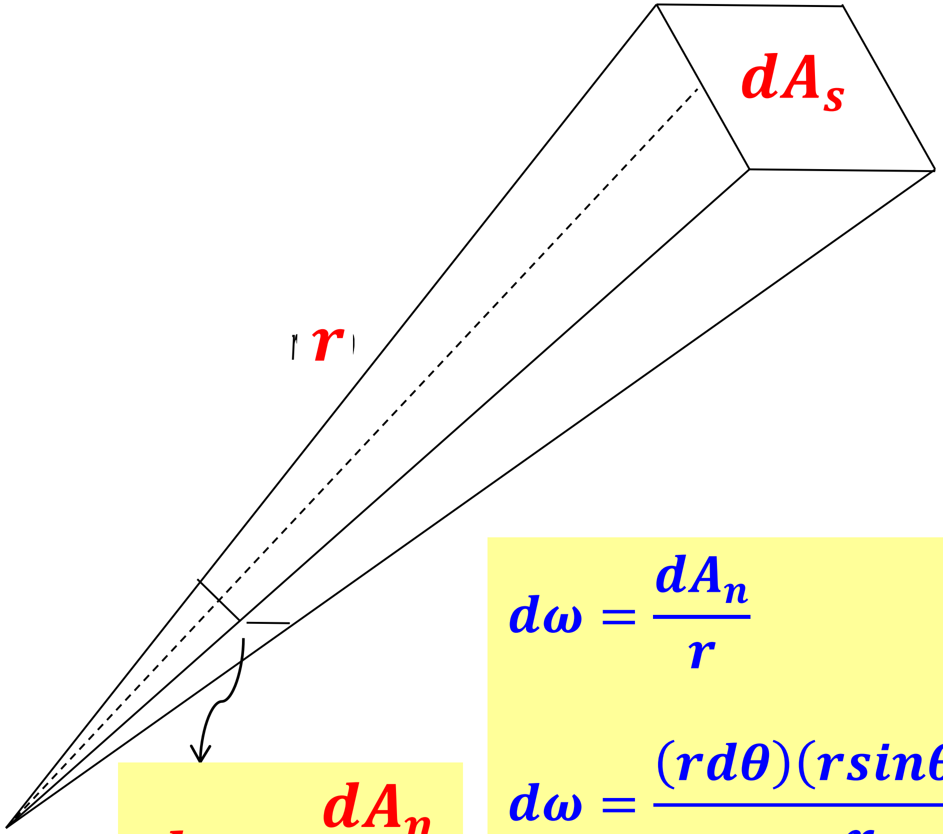
$$d\omega = \frac{dA_n}{r^2}$$

dA_n



$$dA_n = (rd\theta)(rsin\theta d\phi)$$





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

$$d\omega = \frac{dA_n}{r}$$

$$d\omega = \frac{(rd\theta)(rsin\theta d\phi)}{r}$$

$$d\omega = rsin\theta d\theta d\phi$$

Differential area dA_n is normal to (θ, ϕ)direction as in figure

dA_n is normal to the direction of viewing since dA_n is viewed from the center of the sphere

Solid angle of a sphere

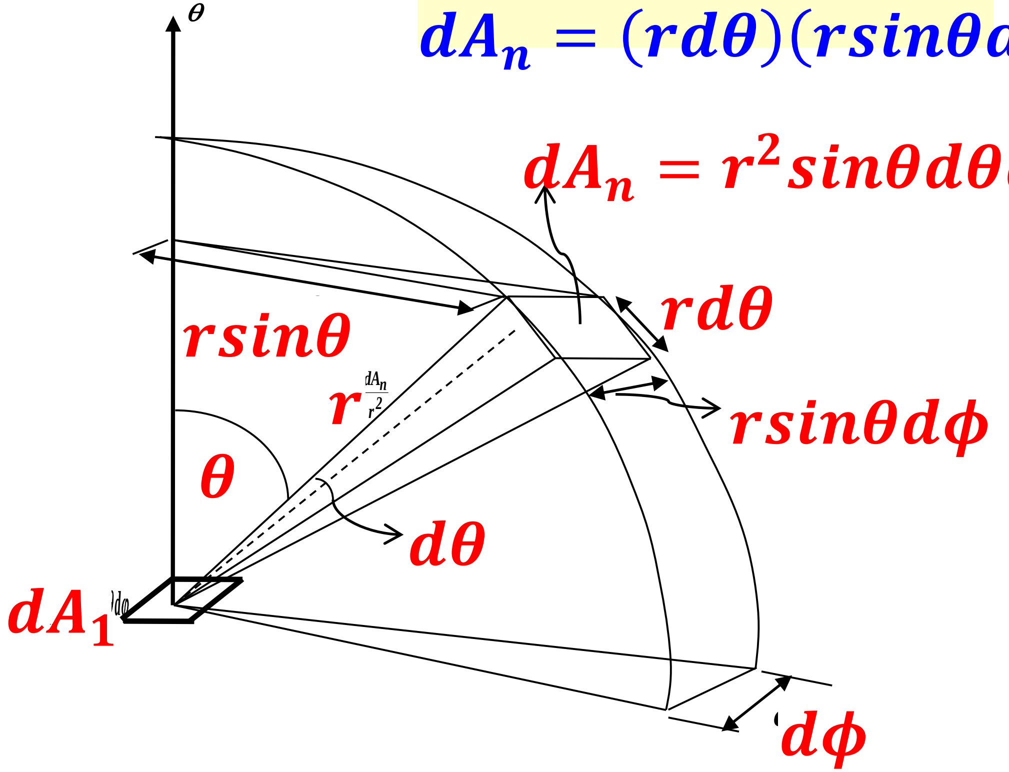
$$A_n = \int_{sphere} dA_n = \int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi} r^2 sin\theta d\theta d\phi = 2\pi r^2 \int_{\theta=0}^{\theta=\pi} sin\theta d\theta = 2\pi r^2 \left(-cos\theta\right)\Big|_{\theta=0}^{\theta=\pi}$$

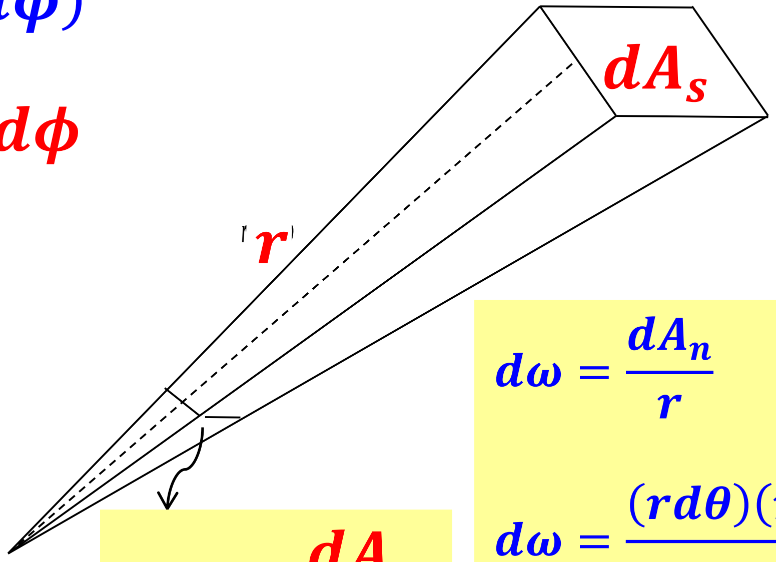
$$A_n = 4\pi r^2$$

For a sphere with unit radius, solid angle is 4π

$$dA_n = (rd\theta)(rsin\theta d\phi)$$

$$dA_n = r^2 sin\theta d\theta d\phi$$





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

$$d\omega = \frac{dA_n}{r}$$

$$d\omega = \frac{(rd\theta)(rsin\theta d\phi)}{r}$$

$$d\omega = rsin\theta d\theta d\phi$$

Differential solid angle $d\omega$ subtended by a differential surface area dA when viewed from a point at a distance r from dA is expressed as

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

where α is the angle between the normal to the surface and the direction of viewing, and thus $dA_n = dA\cos\alpha$ is the normal (or projected) area to the direction of viewing

Small surfaces viewed from relatively a large distances can approximately treated as differential areas in solid angle calculations. For example, the solid angle subtended by 6 cm^2 plane surface when viewed from a point at a distance of 90 cm along the normal of the surface

$$d\omega = \frac{dA_n}{r^2} = \frac{6}{90^2} = 7.41 \times 10^{-4}\ sr$$

If the surface is tilted so that the normal of the surface makes an angle of 60° with the line connecting the point of viewing to the centre of the surface, the projected area would be $dA_n = dA\cos\alpha = 6\cos 60 = 3\ cm^2$ and the solid angle in this case would be half of the value just determined.

INTENSITY OF EMITTED RADIATION

- Consider the emission of radiation by a differential area element dA_1 of a surface
- Radiation is emitted in all directions into the hemispherical surface and the radiation streaming through the surface area dA_n is proportional to the solid angle $d\omega$ subtended by area dA_n

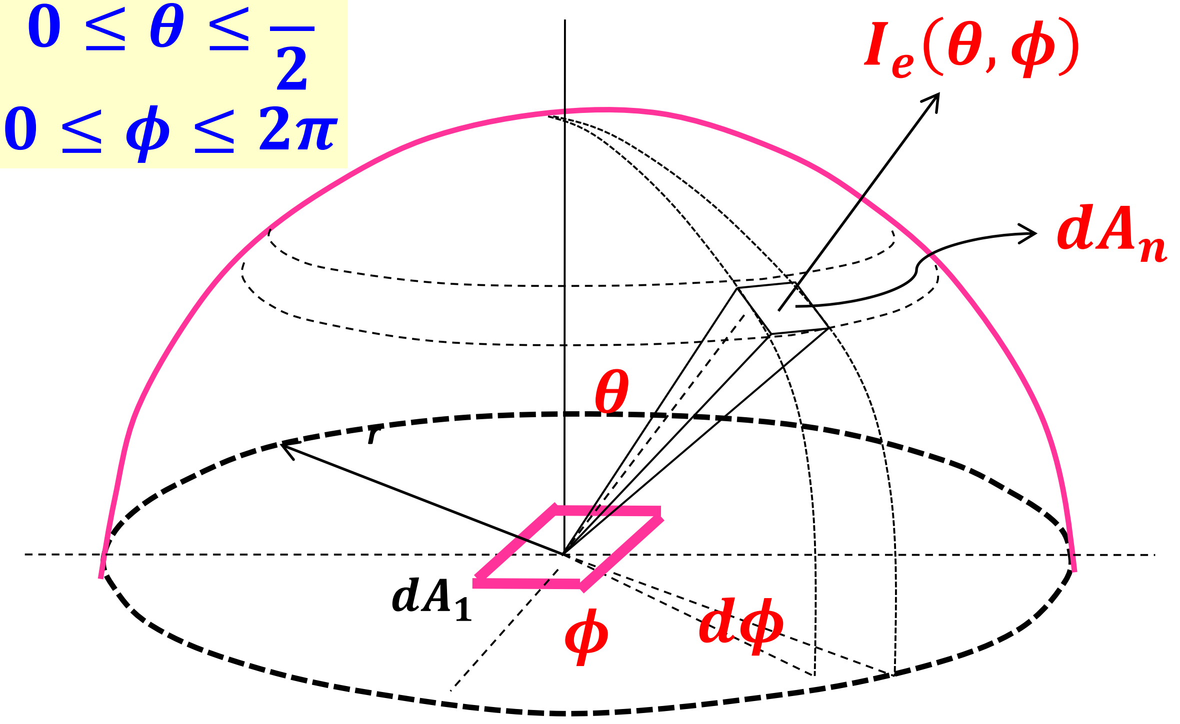
Radiation is also proportional to the radiating area dA_1 as seen by an observer on dA_n

Radiation varies from a maximum of dA_1 when dA_n is at the top directly above dA_1 ($\theta = 0^o$) to a minimum of zero when dA_n is at the bottom ($\theta = 90^o$)

The effective area of dA_1 for emission in the direction of θ is projection of dA_1 on a plane normal to θ, which is $dA_1 cos\theta$

Radiation emitted into direction (θ, ϕ)

$$0 \leq \theta \leq \frac{\pi}{2}$$
$$0 \leq \phi \leq 2\pi$$



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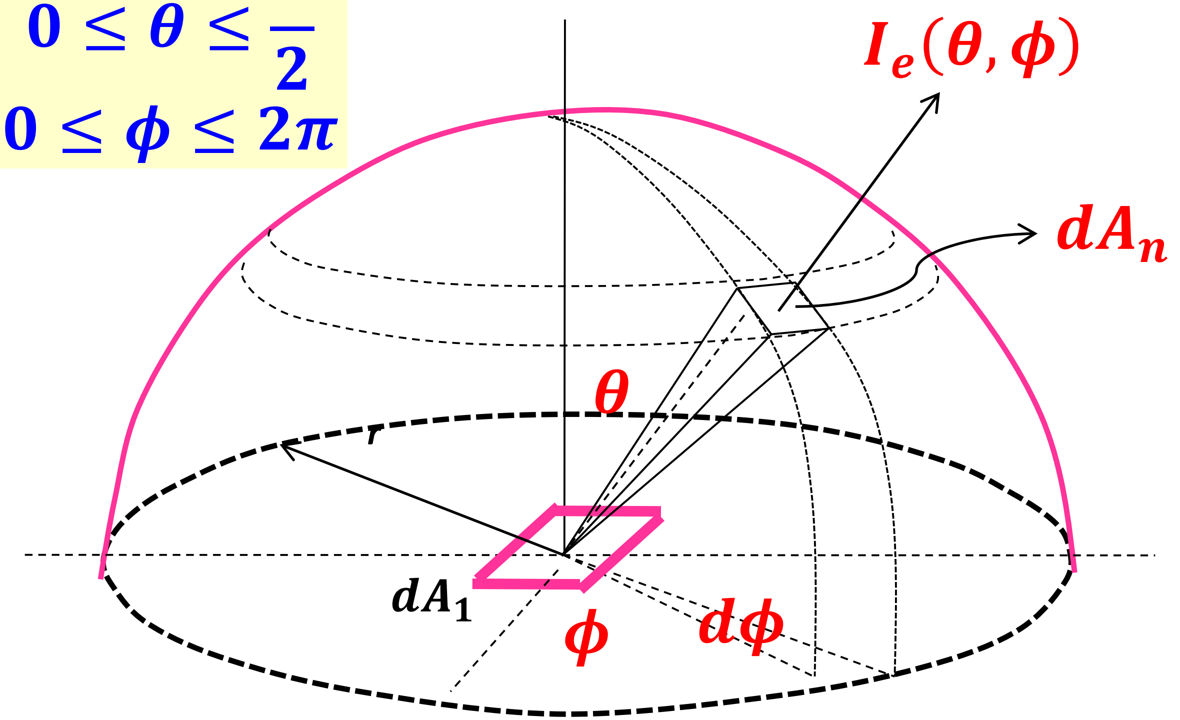
Radiation intensity for emitted radiation $I_e(\theta, \phi)$ is defined as the rate at which the radiation energy dq is emitted in the (θ, ϕ) direction per unit area normal to this direction and per unit solid angle about this direction

$$I_e(\theta, \phi) = \frac{dq}{(dA_1 cos\theta)(d\omega)} \quad \left(\frac{W}{m^2 sr}\right)$$

$$I_e(\theta, \phi) = \frac{dq}{(dA_1 cos\theta)(sin\theta d\theta d\phi)}$$

Radiation emitted into direction (θ, ϕ)

$$0 \le \theta \le \frac{\pi}{2}$$
$$0 \le \phi \le 2\pi$$



$$I_e(\theta,\phi) = \frac{dq}{(dA_1 cos\theta)(sin\theta d\theta d\phi)}$$

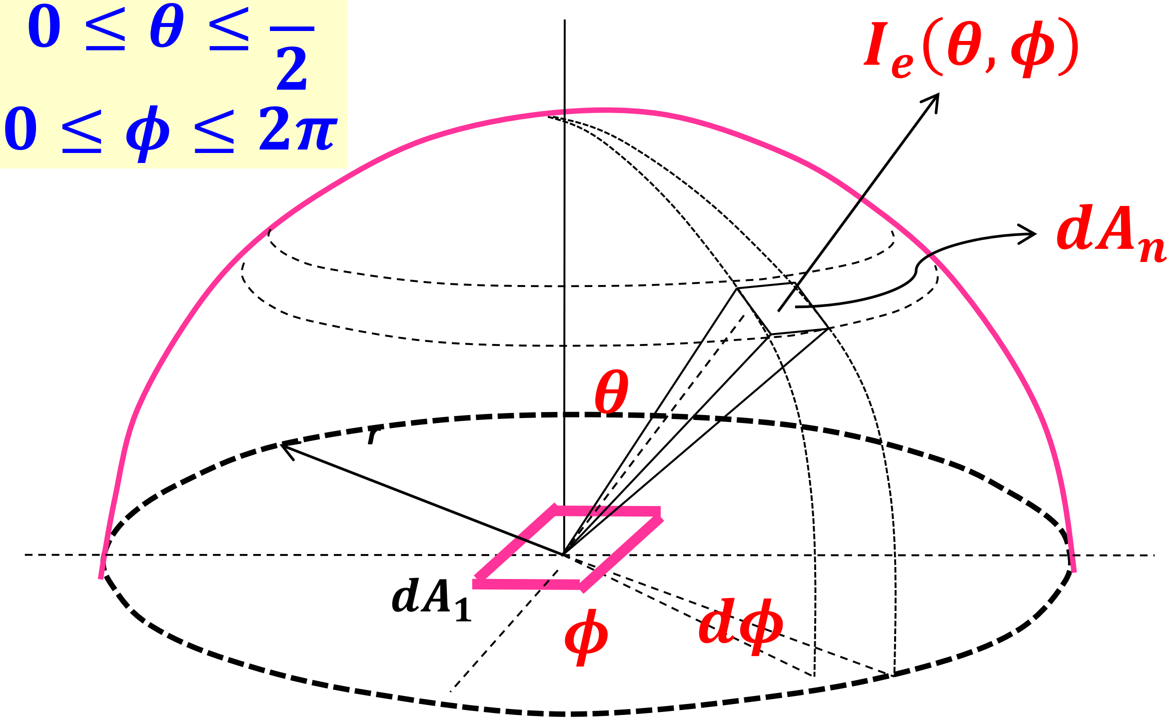
Radiation flux for emitted radiation is the **EMISSIVE POWER** (E) – rate at which radiation energy is emitted per unit area of the emitting surface which is expressed in the differential form

$$\frac{dq}{dA_1} = I_e(\theta,\phi) cos\theta sin\theta d\theta d\phi$$

Radiation emitted into direction (θ,ϕ)

$$0 \le \theta \le \frac{\pi}{2}$$

$$0 \le \phi \le 2\pi$$



Hemisphere above the surface intercepts all the radiation rays emitted by the surface, the emissive power from the surface into the hemisphere surrounding it is given by

$$E = \int_{hemisphere} dE = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_e(\theta,\phi) cos\theta sin\theta d\theta d\phi$$

The intensity of radiation emitted by a surface, in general, varies with direction (especially with zenith angle θ. But, many surfaces in practice can be approximated as DIFFUSE.

For a diffusely emitting surface, the intensity of emitted radiation is independent of direction and thus $I_e = constant$

$$E = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_e(\theta,\phi) cos\theta sin\theta d\theta d\phi = I_e(\theta,\phi) \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} cos\theta sin\theta d\theta d\phi$$

$$E = I_e(\theta,\phi)(2\pi) \int_{\theta=0}^{\theta=\frac{\pi}{2}} cos\theta sin\theta d\theta = I_e(\theta,\phi)(2\pi) \int_{\theta=0}^{\theta=\frac{\pi}{2}} \frac{sin2\theta}{2} d\theta = I_e(\theta,\phi)(\pi) \left.\frac{-cos2\theta}{2}\right|_0^{\frac{\pi}{2}}$$

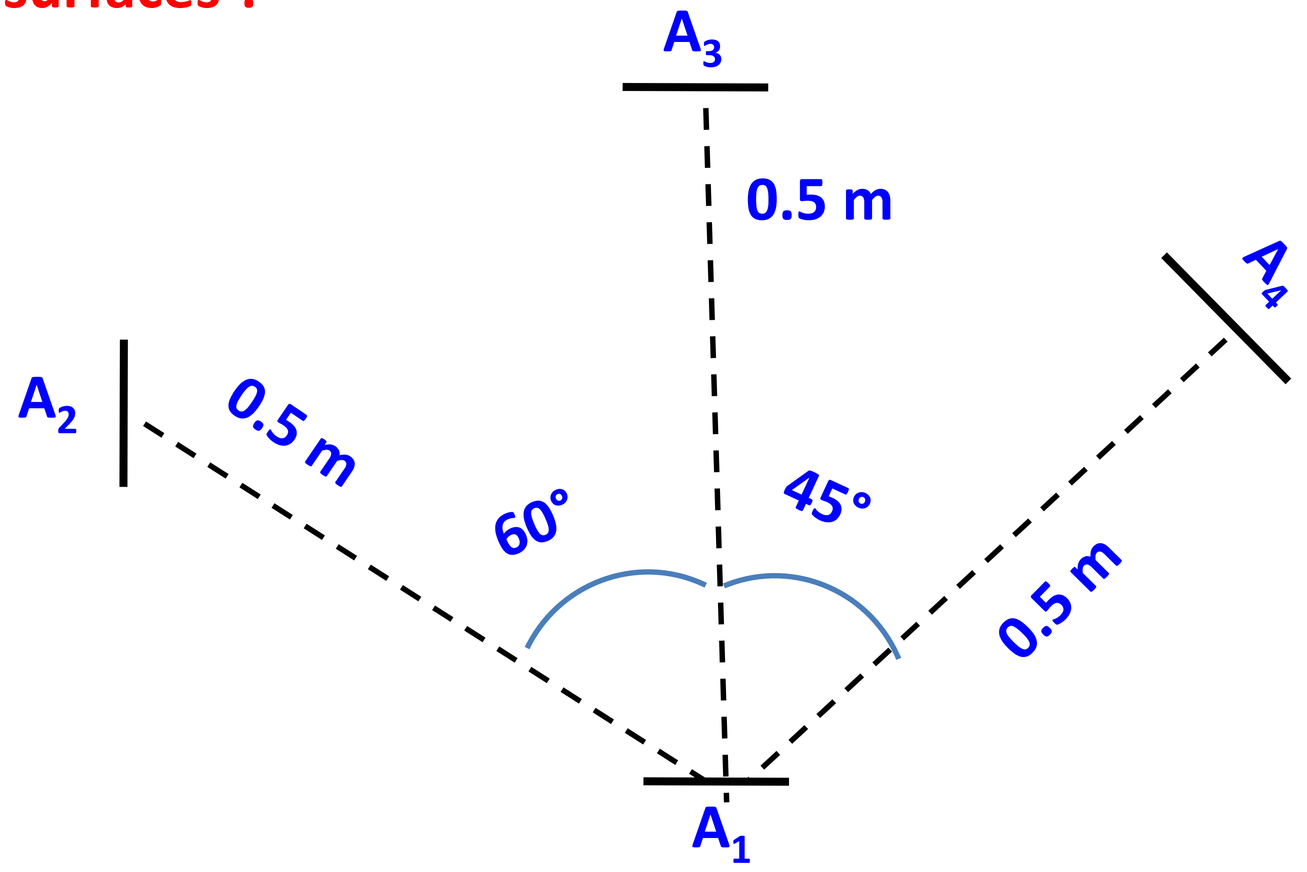
$$E = I_e(\theta,\phi)(-\pi)\left(\frac{cos\pi - cos0}{2}\right) = I_e(\theta,\phi)(-\pi)\left(\frac{-1-1}{2}\right) = I_e(\theta,\phi)(\pi)$$

$$E = \pi I_e$$

For diffuse emitter $\frac{W}{m^2}$

Problem: A small surface of area $A_1 = 10^{-3}\, m^2$ is known to emit diffusely and from measurements the total intensity associated with emission in the normal direction is $I_n = 7000\ W/m^2.sr$. Radiation emitted from the surface is intercepted by other surfaces of area $A_2 = A_3 = A_4 = 10^{-3}\, m^2$, which are 0.5 m from A_1 and are oriented as shown. What is the intensity associated with emission in each of the three directions ? What are the solid angles subtended by the three surfaces when viewed from A_1? What is the rate at which radiation emitted by A_1 is intercepted by the three surfaces ?

Known: Normal intensity of diffuse emitter of area A_1 and orientation of three surfaces relative to A_1



Find

1. Intensity of emission in each of the three directions
2. Solid angles subtended by the three surfaces
3. Rate at which radiation is intercepted by the three surfaces

Assumptions

1. Surface A_1 emits diffusely
2. A_1, A_2, A_3, A_4 may be approximated as differential surfaces $\left(A_i/r_j^2 \ll 1\right)$

Analysis

1. From the definition of a diffuse emitter, we know that the intensity of the emitted radiation is independent of direction. Hence

$$I_e = 7000\, W/m^2.sr$$

for each of the three directions

2. Treating A_2, A_3, and A_4 as differential surface areas, the solid angles may be computed by

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

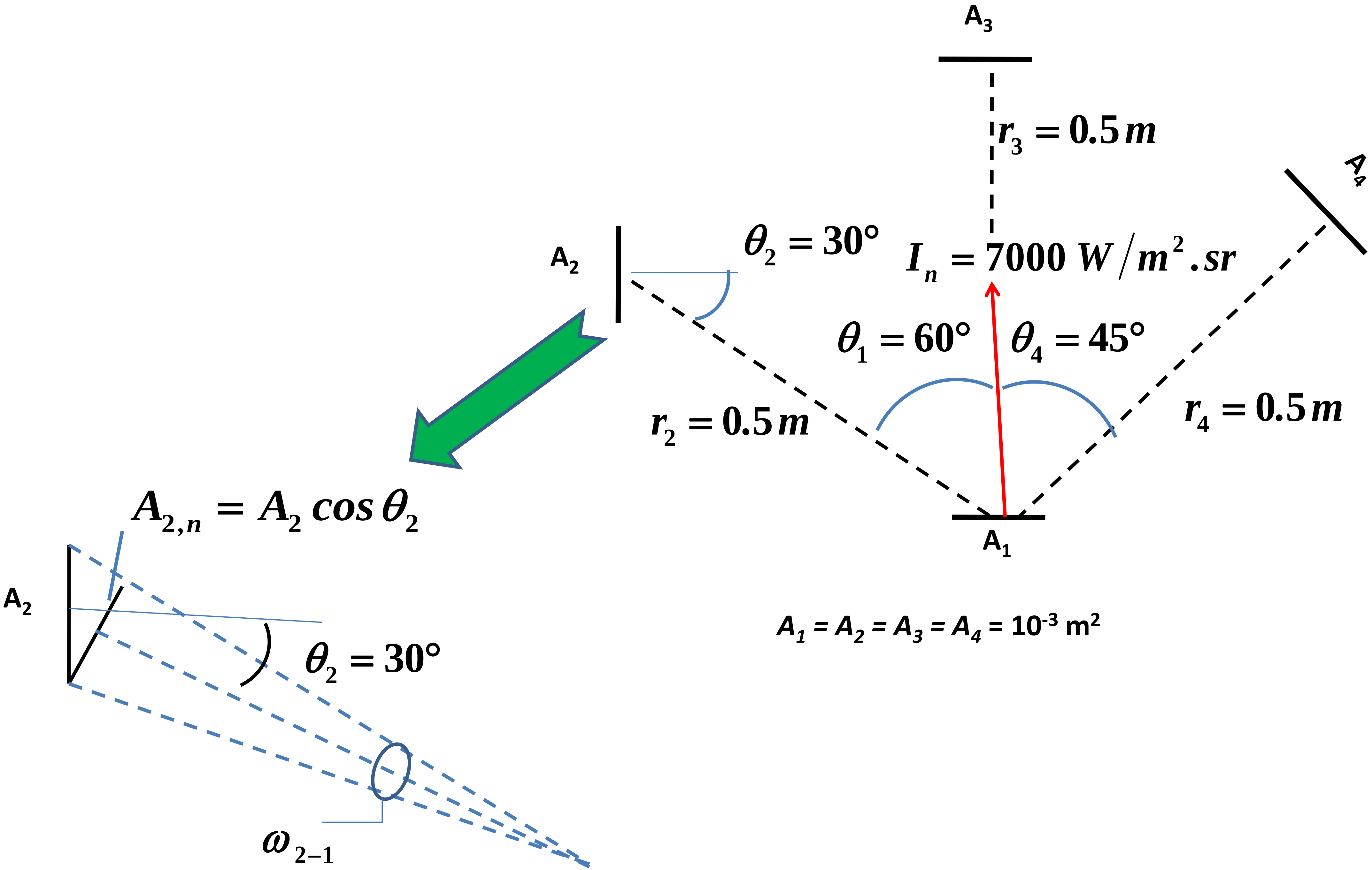
where dA_n is the projection of the surface normal to the direction of the radiation.

Since surfaces A_3 and A_4 are normal to the direction of radiation, the solid angles subtended by these surfaces can be directly found from this equation

$$\omega_{3-1} = \omega_{4-1} = \frac{A_3}{r^2} = \frac{10^{-3}}{0.5^2} = 4 \times 10^{-3}\ sr$$

Since surface A_2 is not normal to the direction of radiation, we use $dA_{n,2} = dA_2 cos\theta_2$, where θ_2 is the angle between the surface normal and the direction of the radiation. Thus

$$\omega_{2-1} = \frac{A_2 cos\theta_2}{r^2} = \frac{10^{-3} \times cos30}{0.5^2} = 3.46 \times 10^{-3}\ sr$$



$A_1 = A_2 = A_3 = A_4 = 10^{-3}\ m^2$

3. Approximating A_1 as a differential surface, the rate at which radiation is intercepted by each of the three surfaces may be found from the following equation

$$q_{1-j} = I \times A_1 cos\theta \times \omega_{j-1}$$

where θ_1 is the angle between the normal to the surface 1 and the direction of the radiation.

$$\omega_{2-1} = 3.46 \times 10^{-3}\ sr \qquad \omega_{3-1} = \omega_{4-1} = 4 \times 10^{-3}\ sr$$

$$q_{1-2} = 7000 \frac{W}{m^2 sr} \times \left(10^{-3} m^2 \times cos60\right) \times 3.46 \times 10^{-3}\ sr = 12.1 \times 10^{-3}\ W$$

$$q_{1-3} = 7000 \frac{W}{m^2 sr} \times \left(10^{-3} m^2 \times cos0\right) \times 4 \times 10^{-3}\ sr = 28.0 \times 10^{-3}\ W$$

$$q_{1-4} = 7000 \frac{W}{m^2 sr} \times \left(10^{-3} m^2 \times cos45\right) \times 4 \times 10^{-3}\ sr = 19.8 \times 10^{-3}\ W$$

Even though the intensity of the emitted radiation is independent of direction, the rate at which radiation is intercepted by the three surfaces differs significantly due to differences in the solid angles and projected areas.

Incident Radiation (Irradiation)

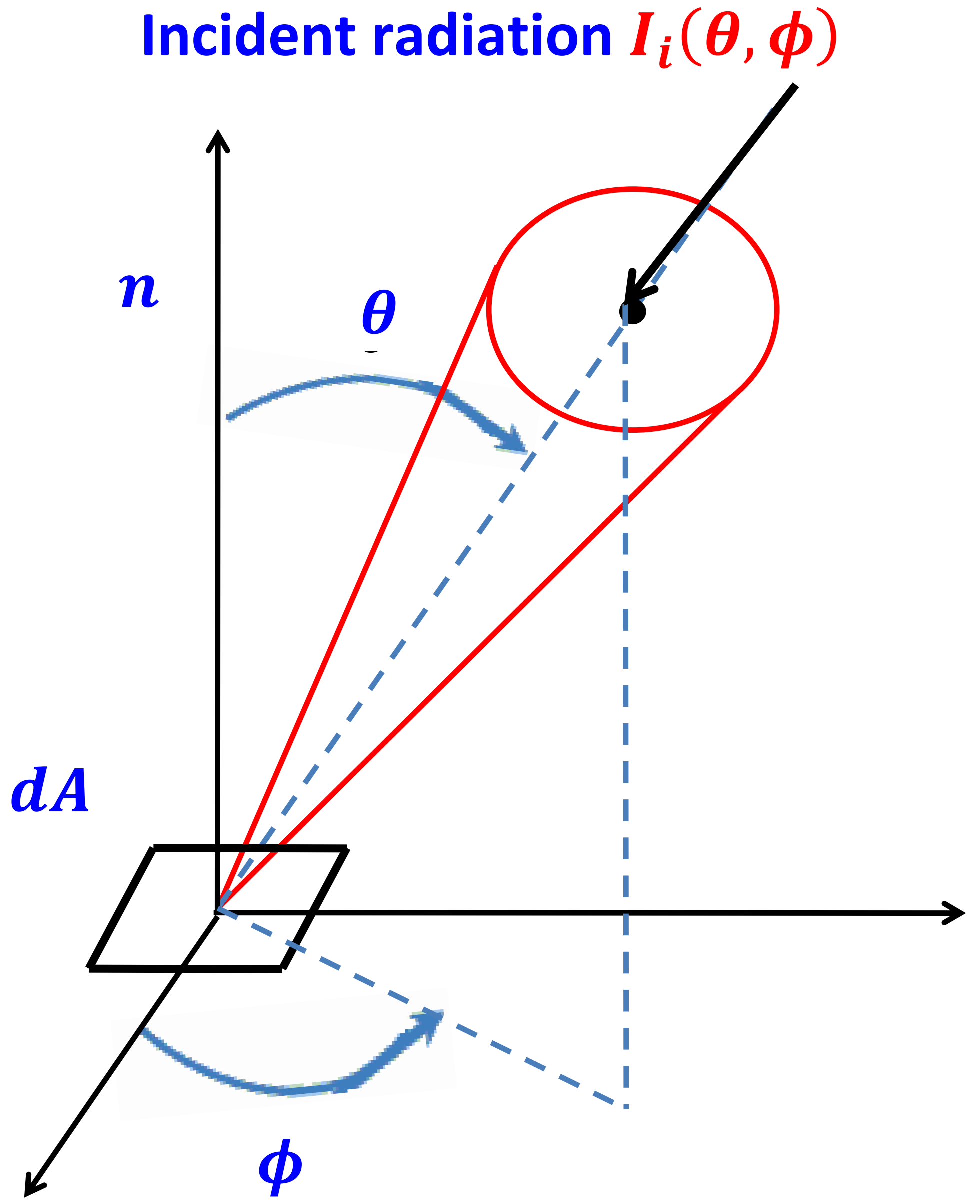
All surface emit radiation, but they also receive radiation emitted or reflected by other surfaces

The intensity of incident radiation $I_i(\theta,\phi)$ is defined as the rate at which radiation energy dG is incident from the (θ,ϕ) direction per unit area of the receiving surface normal to this direction and per unit solid angle about this direction.

θ is the angle between the direction of incident radiation and the normal to the surface

The radiation flux incident on a surface from all directions is called Irradiation G

$$G = \int_{hemisphere} dG = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_i(\theta,\phi) cos\theta sin\theta d\theta d\phi$$



Incident Radiation (Irradiation)

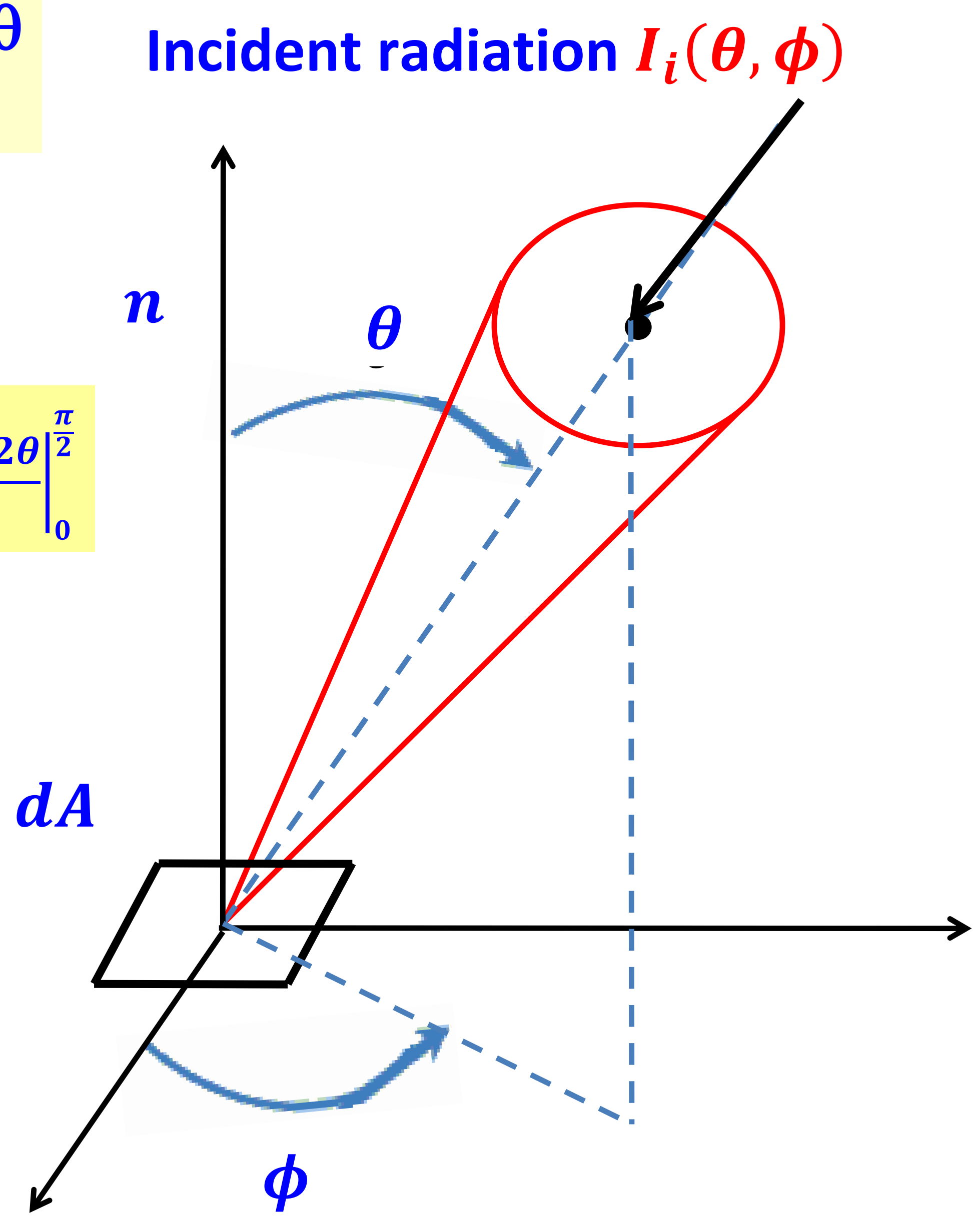
If the incident radiation is diffuse, I_i is independent of θ and ϕ and thus $I_i = constant$

$$G = \int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\frac{\pi}{2}} I_i(\theta,\phi)cos\theta sin\theta d\theta d\phi = I_i(\theta,\phi)\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\frac{\pi}{2}} cos\theta sin\theta d\theta d\phi$$

$$G = I_i(\theta,\phi)(2\pi)\int_{\theta=0}^{\theta=\frac{\pi}{2}} cos\theta sin\theta d\theta = I_i(\theta,\phi)(2\pi)\int_{\theta=0}^{\theta=\frac{\pi}{2}} \frac{sin2\theta}{2}d\theta = I_i(\theta,\phi)(\pi)\left.\frac{-cos2\theta}{2}\right|_0^{\frac{\pi}{2}}$$

$$G = I_i(\theta,\phi)(-\pi)\left(\frac{cos\pi - cos0}{2}\right) = I_i(\theta,\phi)(-\pi)\left(\frac{-1-1}{2}\right)$$

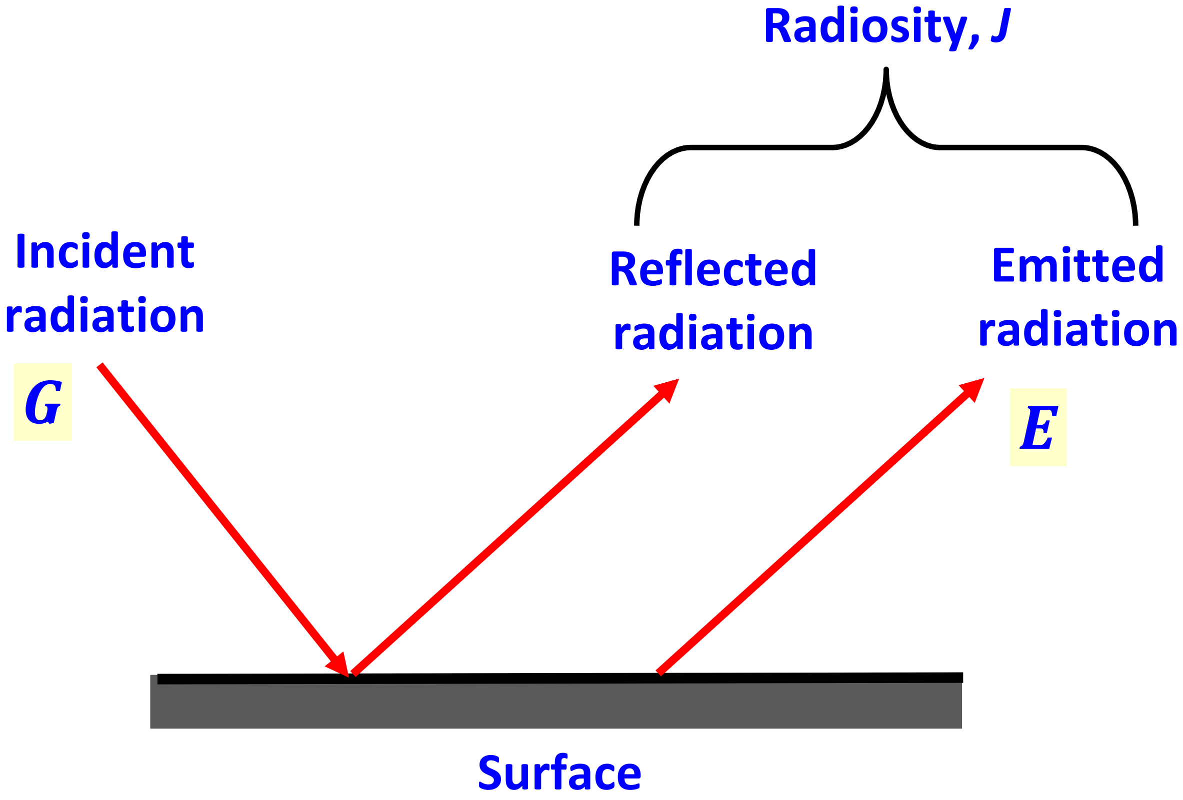
$$G = \pi I_i \quad \frac{W}{m^2}$$



RADIOSITY

Radiosity – accounts for all the radiant energy leaving a surface

Radiosity - The rate at which radiation energy leaves a unit area of a surface in all directions



$$J = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_{e+r}(\theta,\phi) cos\theta sin\theta d\theta d\phi$$

$I_{e+r}(\theta,\phi)$ **is the sum of the emitted and reflected intensities**

If the surface is both a diffuse reflector and a diffuse emitter, $I_{e+r}(\theta,\phi)$ **is independent of** θ **and** ϕ

$$J = \pi I_{e+r} \quad \frac{W}{m^2}$$

SPECTRAL QUANTITIES – wavelength dependence

So far we considered total radiation quantities (quantities integrated over all wavelengths), and made no reference to wavelength dependence.

Spectral quantities – variation of radiation with wavelength as well direction, and to express quantities at a certain wavelength λ or per unit wavelength interval about λ

Spectral Radiation intensity for emitted radiation $I_{\lambda,e}(\lambda,\theta,\phi)$ is defined as the rate at which the radiation energy dq is emitted at the wavelength λ in the (θ,ϕ) direction per unit area normal to this direction and per unit solid angle about this direction

$$I_{\lambda,e}(\lambda,\theta,\phi) = \frac{dq}{(dA_1 cos\theta)(d\omega)(d\lambda)} \quad \left(\frac{W}{m^2.sr.\mu m}\right)$$

Spectral emissive power is

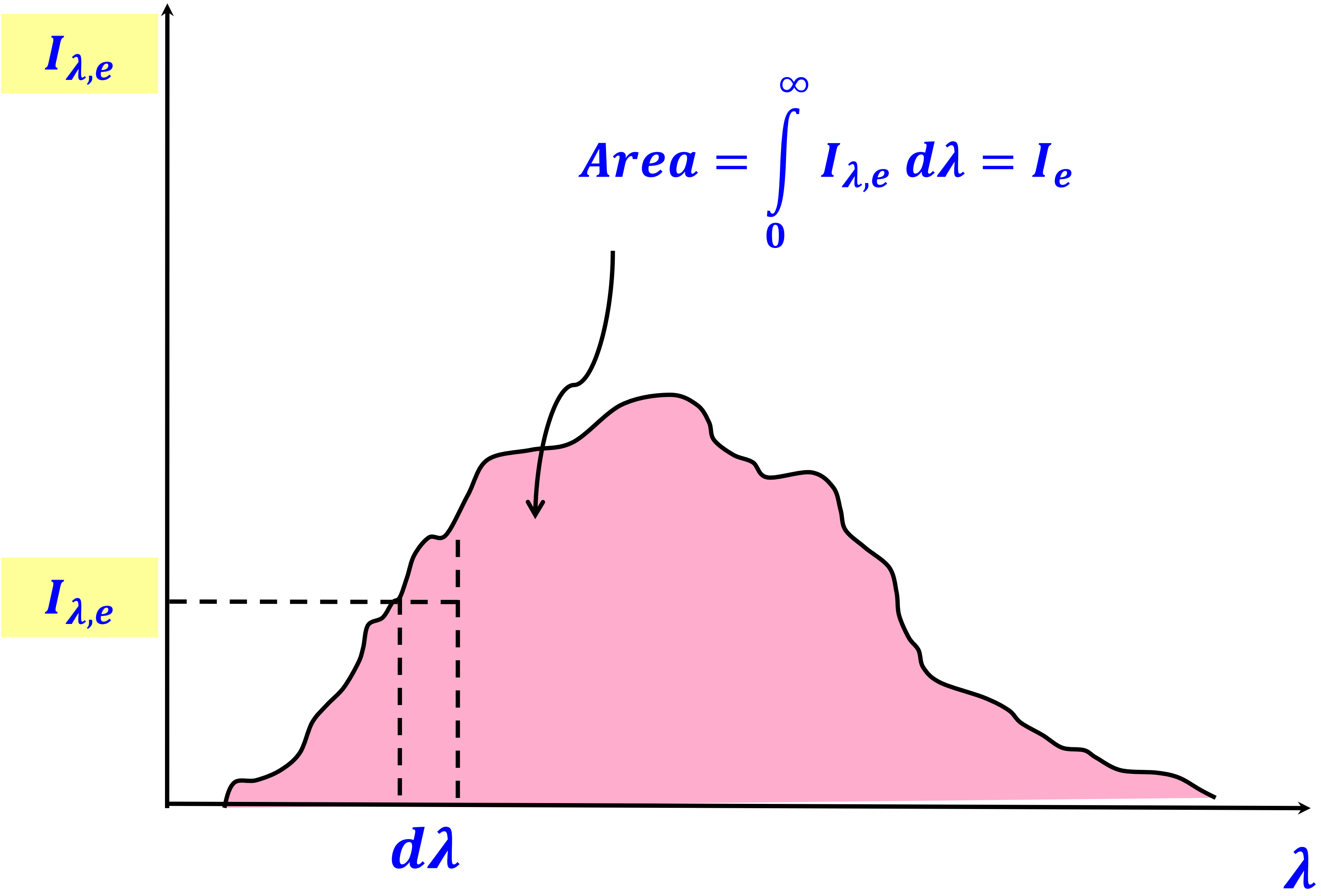
$$E_\lambda = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_{\lambda,e}(\theta,\phi) cos\theta sin\theta d\theta d\phi \quad \frac{W}{m^2}$$

When the variation of spectral radiation intensity with I_λ wavelength λ, the total radiation intensity I for emitted, incident and emitted and reflected radiation can be determined by integration over the entire wavelength spectrum as

$$I_e = \int_0^\infty I_{\lambda,e}\, d\lambda$$

$$I_i = \int_0^\infty I_{\lambda,i}\, d\lambda$$

$$I_{e+r} = \int_0^\infty I_{\lambda,e+r}\, d\lambda$$



$$E = \int_{\lambda=0}^{\lambda=\infty} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_{\lambda,e}(\theta,\phi) cos\theta sin\theta d\theta d\phi d\lambda$$

$$G = \int_{\lambda=0}^{\lambda=\infty} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_{\lambda,i}(\theta,\phi) cos\theta sin\theta d\theta d\phi d\lambda$$

$$J = \int_{\lambda=0}^{\lambda=\infty} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} I_{\lambda,e+r}(\theta,\phi) cos\theta sin\theta d\theta d\phi d\lambda$$

Similarly, when the variations of spectral radiation fluxes E_λ, G_λ, J_λ with wavelength are known, the total radiation fluxes can be determined by integration over the entire wavelength spectrum

$$E = \int_{\lambda=0}^{\lambda=\infty} E_\lambda d\lambda \qquad G = \int_{\lambda=0}^{\lambda=\infty} G_\lambda d\lambda$$

$$J = \int_{\lambda=0}^{\lambda=\infty} J_\lambda d\lambda$$

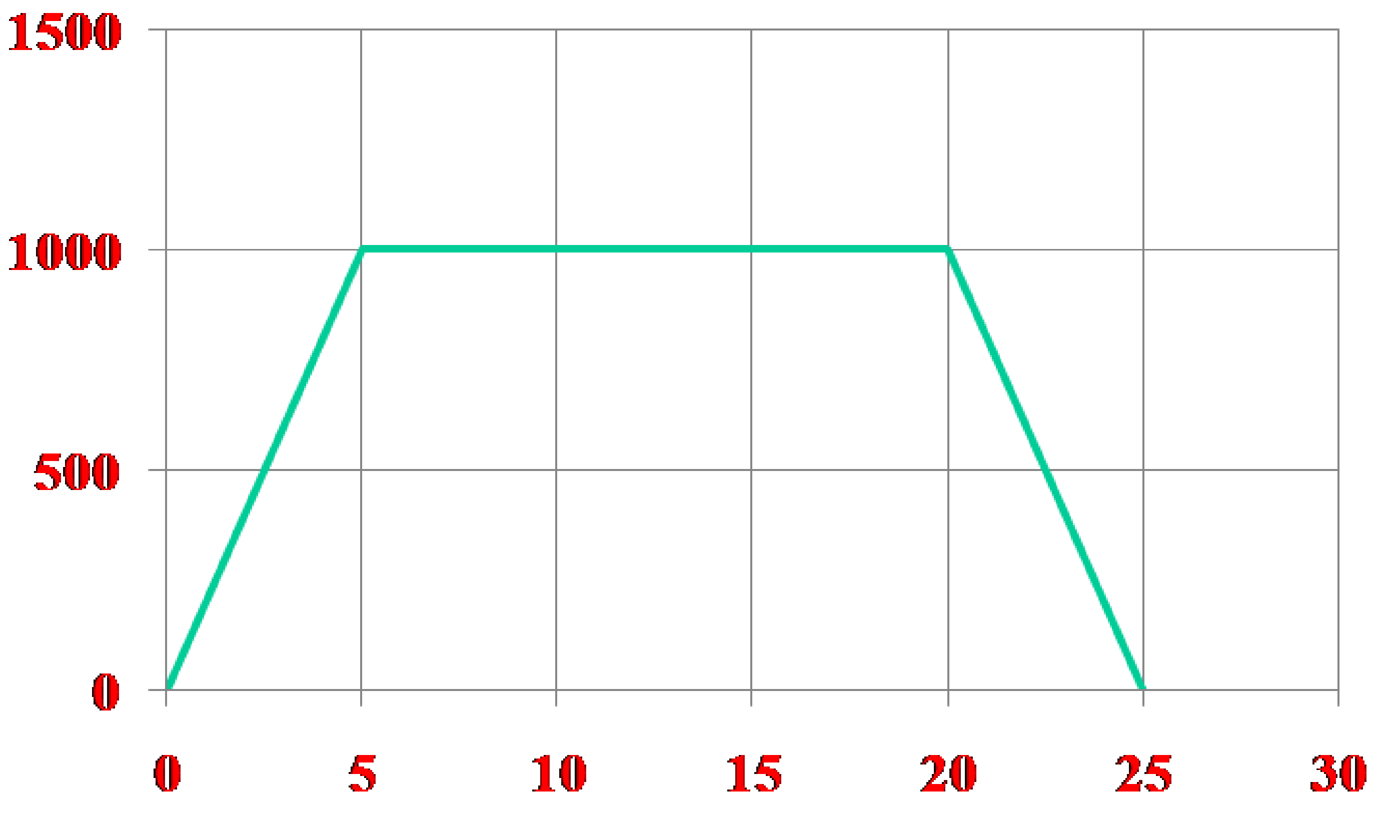
When the surfaces and the incident radiation are diffuse, the spectral radiation fluxes are related to spectral intensities

$$E_\lambda = \pi I_{\lambda,e} \qquad G_\lambda = \pi I_{\lambda,i} \qquad J_\lambda = \pi I_{\lambda,e+r}$$

Note that the relations for spectral and total radiation quantities are of the same form

What is the total irradiation

$$G_\lambda\left(\frac{W}{m.\mu m}\right)$$



$$\lambda(\mu m)$$

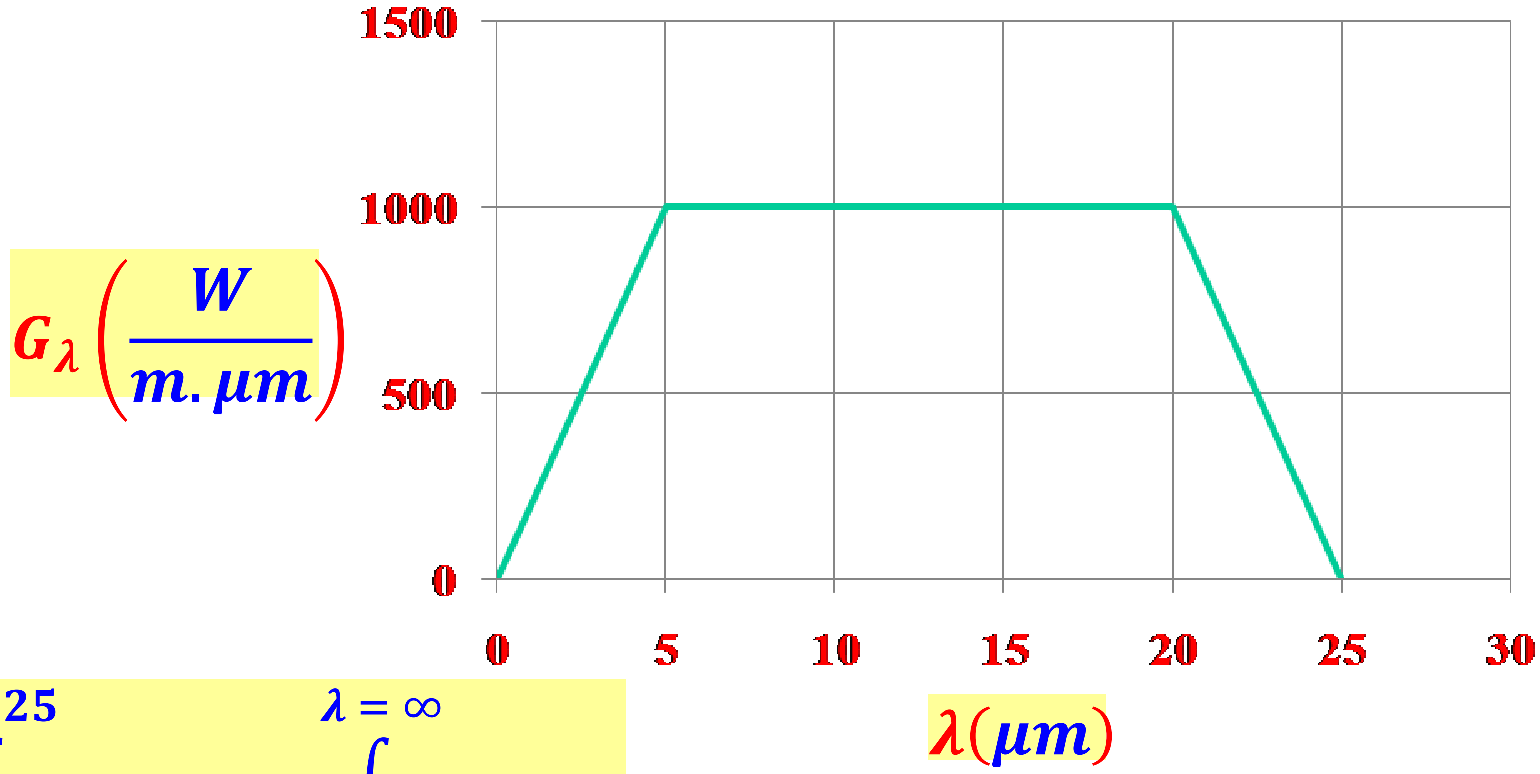
Known: spectral distribution of surface irradiation

Find: Total irradiation

Analysis : The total irradiation may be obtained from

$$G = \int_{\lambda=0}^{\lambda=\infty} G_\lambda d\lambda$$

$$G = \int_{\lambda=0}^{\lambda=5} G_\lambda d\lambda + \int_{\lambda=5}^{\lambda=20} G_\lambda d\lambda + \int_{\lambda=20}^{\lambda=25} G_\lambda d\lambda + \int_{\lambda=25}^{\lambda=\infty} G_\lambda d\lambda$$



$$G = \int_{\lambda=0}^{\lambda=5} G_\lambda d\lambda + \int_{\lambda=5}^{\lambda=20} G_\lambda d\lambda + \int_{\lambda=20}^{\lambda=25} G_\lambda d\lambda + \int_{\lambda=25}^{\lambda=\infty} G_\lambda d\lambda$$

$$G = \frac{1}{2}(1000)(5-0) + (1000)(20-5) + \frac{1}{2}(1000)(25-20) + 0$$

$$G = 2500 + 15000 + 2500 + 0$$

$$G = 20000\ \frac{W}{m^2}$$

Comments: Generally, radiation sources do not provides such a regular spectral distribution for the irradiation. However, the procedure of computing the total irradiation from knowledge of the spectral distribution remains the same, although evaluation of the integral is likely to involve more detail.