Lecture 18: Radiation: Processes and Properties: Basic Principles and Definitions

Chapter 12

Sections 12.1 through 12.4

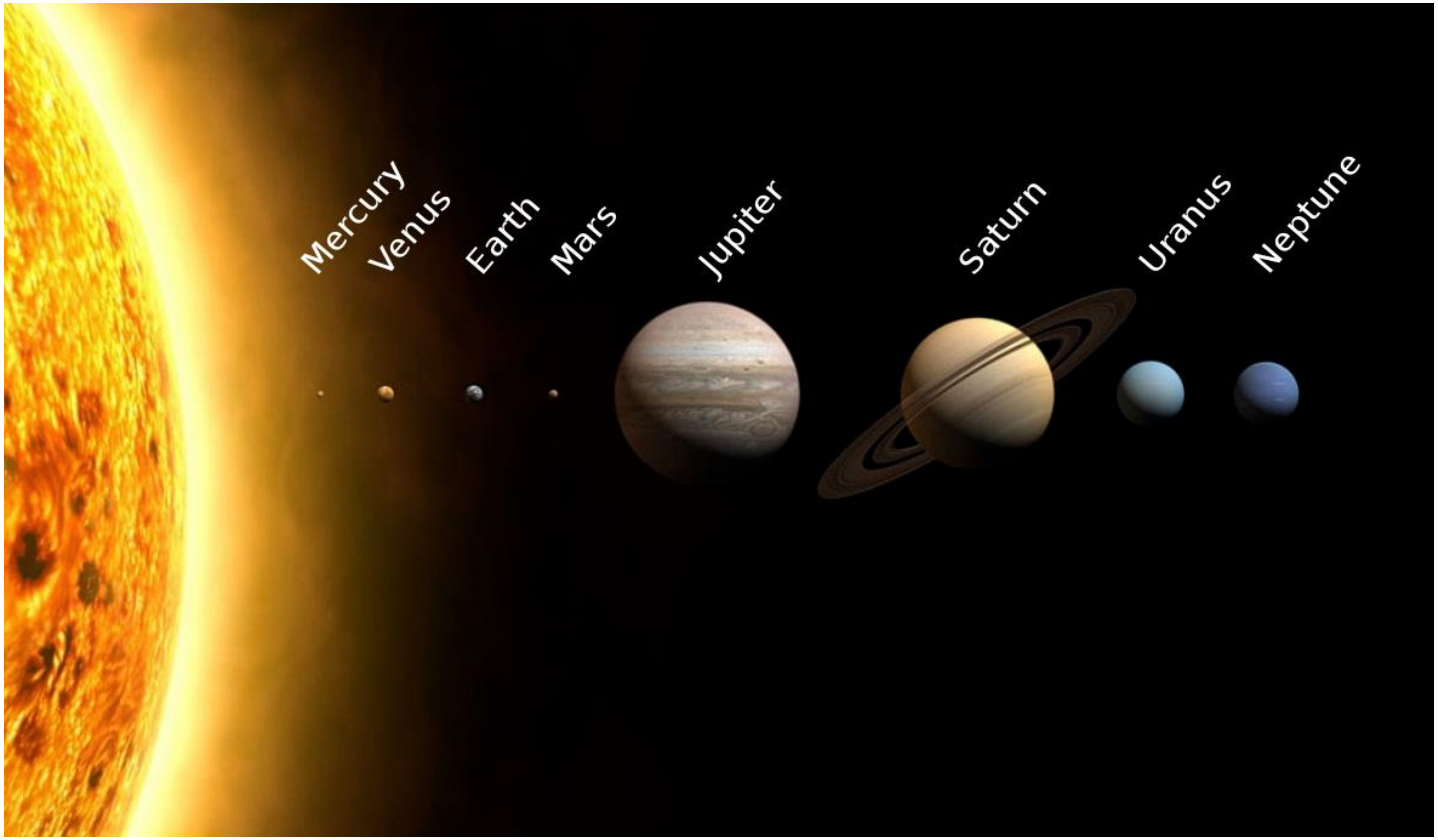
Announcement

- Exam02 next Wed. Everything on Convection!
- 2 sided cheat sheet.
  - Remember to include all your tables!!!

Content

1. What is the wavelength range for thermal radiation?
2. What is the physical origin of radiation emission?
3. How different is radiation from other forms of heat transfer?
4. What is the difference between radiative surface and volumetric phenomena?
5. What radiation characteristics are important when considering thermal radiation?
6. What can happen to radiation after it hits a surface?
7. How is the directionality handled in radiation?
8. How is the spectral nature handled in radiation?

Radiation vs Conduction and Convection

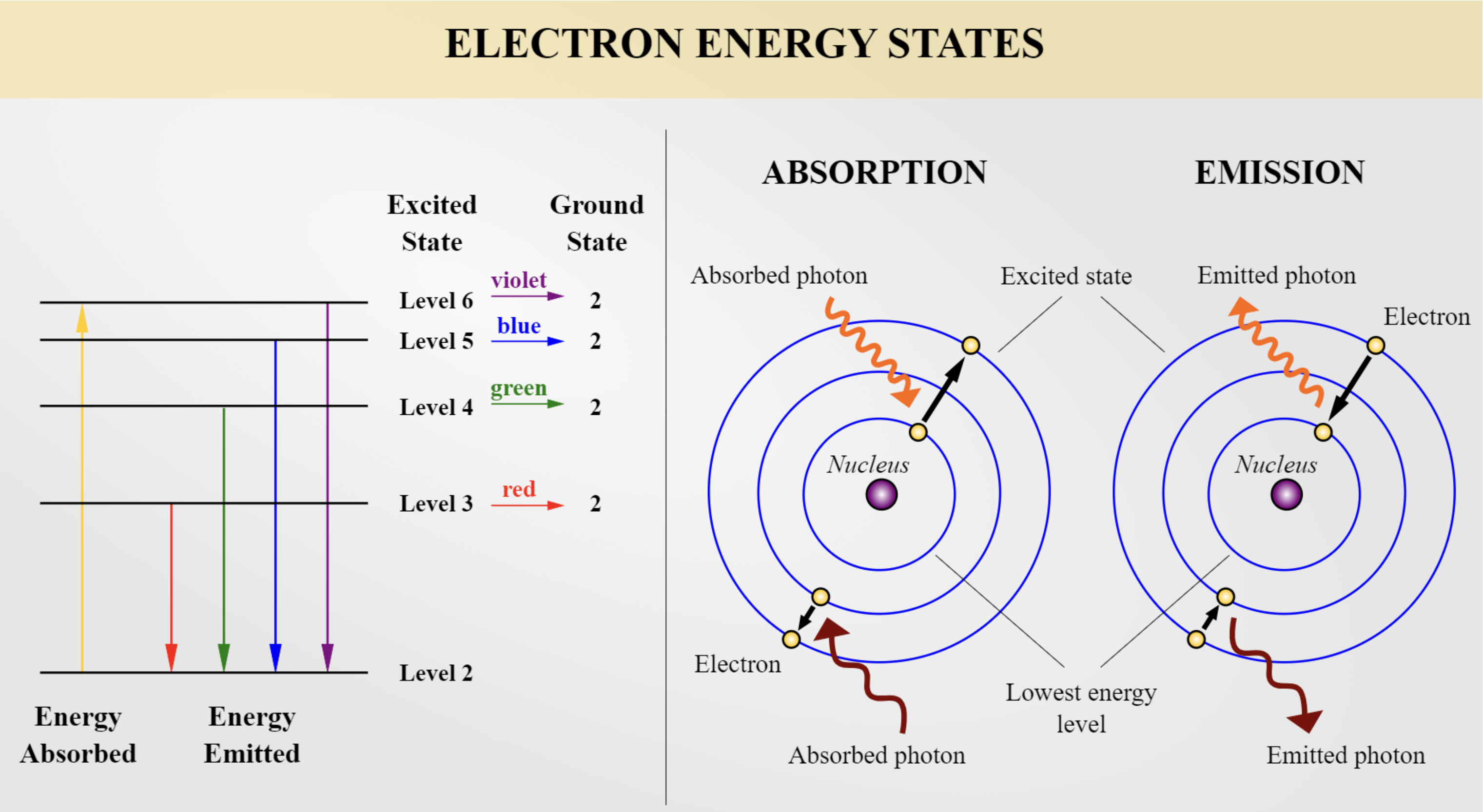


How does the Sun reach thermal equilibrium with its environment?

Radiation: no matter needed

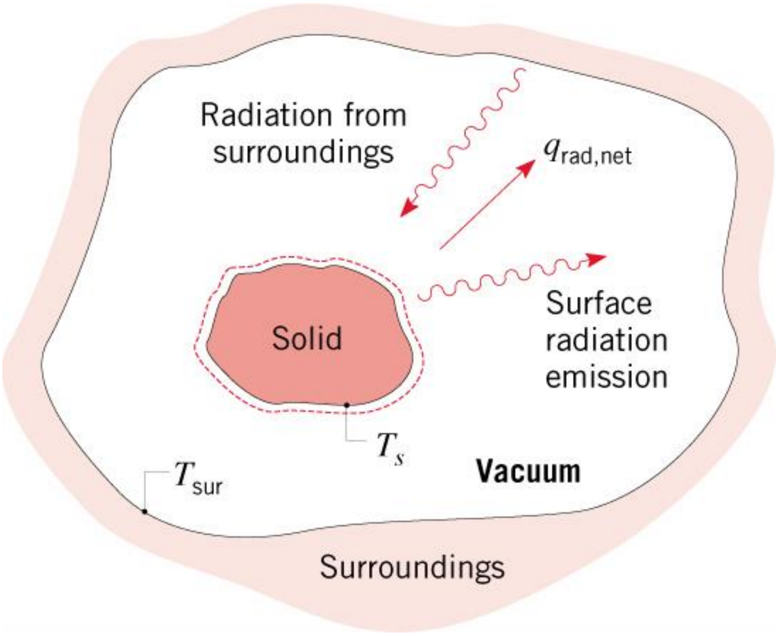
Thermal radiation

- Emission from matter with $T > 0\ K$
- Temperature causes electrons to jump across orbitals
- These high-energy electrons cool and relax back by emitting radiation
- Hence, thermal energy is transferred out



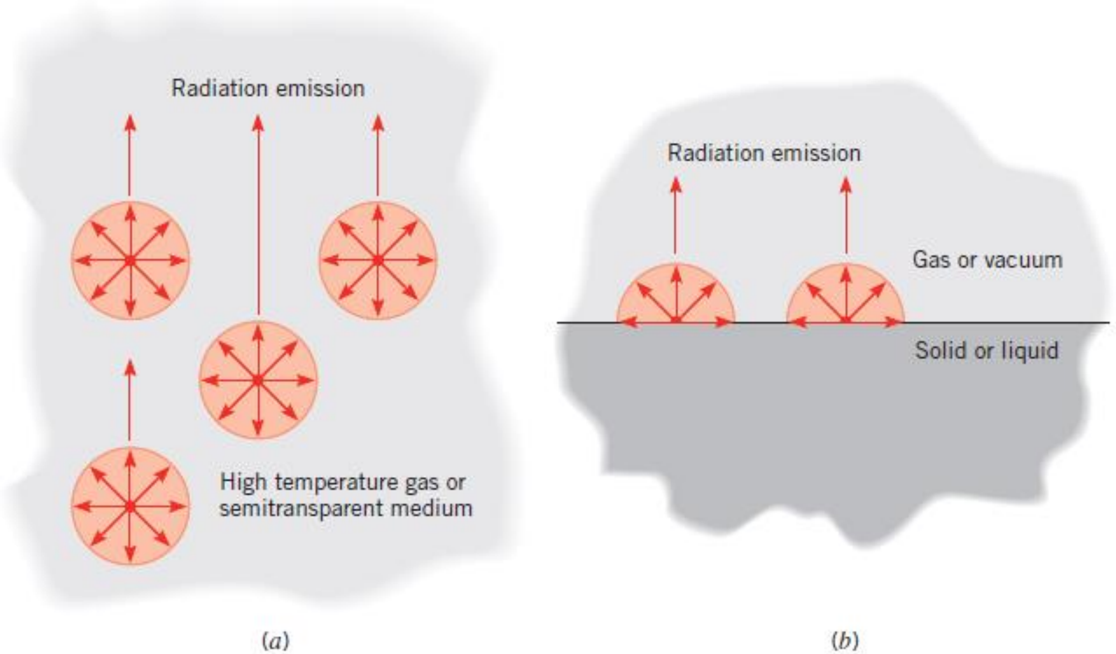
Radiation may also be intercepted and absorbed by matter, resulting in its increase in thermal energy

- Consider a solid with temperature T_s in an evacuated enclosure whose walls are at a fixed temperature T_{sur}:
  - What will occur if $T_s > T_{sur}$? Why?
  - What will occur if $T_s < T_{sur}$? Why?



Emission from

- opaque solid or liquid is treated as a surface phenomenon
- gas or a semitransparent solid or liquid is a volumetric phenomenon.



- But radiation within a solid is absorbed by neighboring atoms/molecules.
- Radiation usually originates from atoms and molecules within 1 μm of the surface => Surface phenomenon for most matter

Dual nature of radiation:

– In some cases, radiation is treated as particles (known as photons). (Quantum Mechanics)

– In other cases, radiation behaves as an electromagnetic wave. (Classical)

– In all cases, radiation has a wavelength λ and frequency ν, which are related through the speed of radiation propagates in the medium of interest:

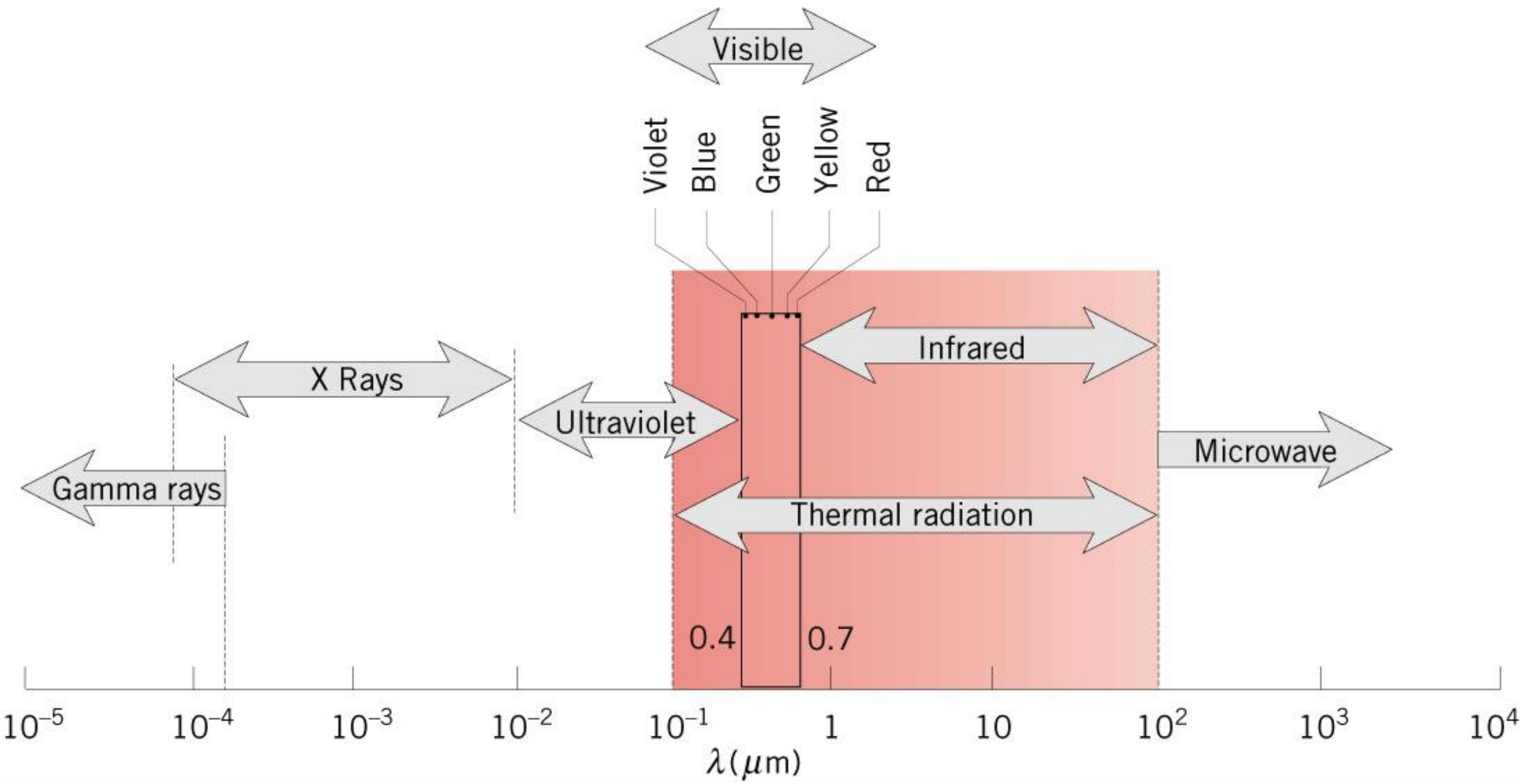
$$\lambda = \frac{c}{\nu}$$

For propagation in a vacuum,

$$c = c_o = 2.998 \ x \ 10^8 \ \text{m/s}$$

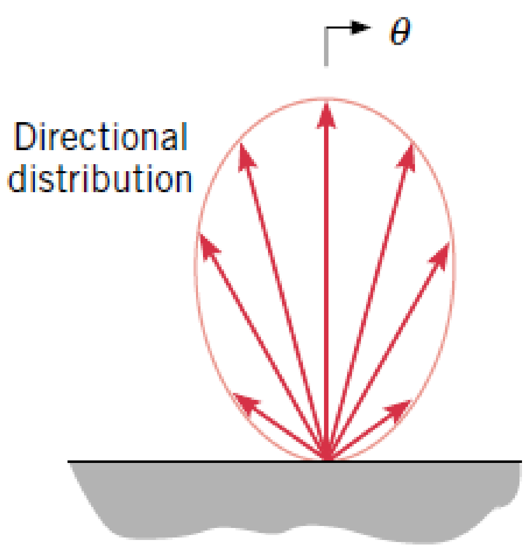
Spectral Nature:

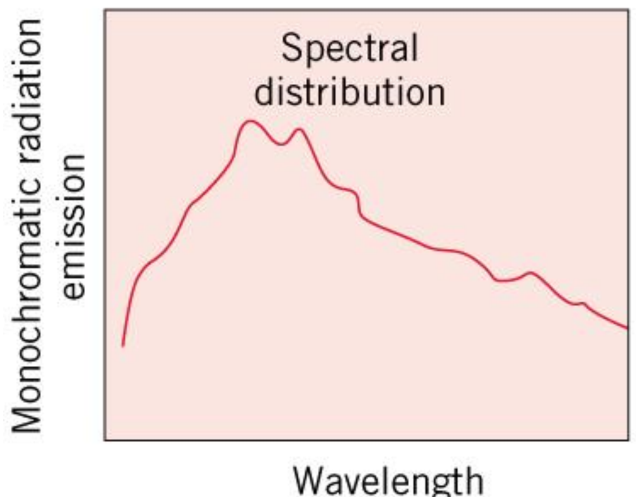
- Thermal radiation is confined to the infrared, visible and ultraviolet regions of the spectrum. $(0.1 < \lambda < 100\mu\text{m})$



Directionality

- The amount of radiation emitted by an opaque surface
  - Varies with wavelength
    - There is a spectral distribution
  - Varies with direction
    - A directional preference

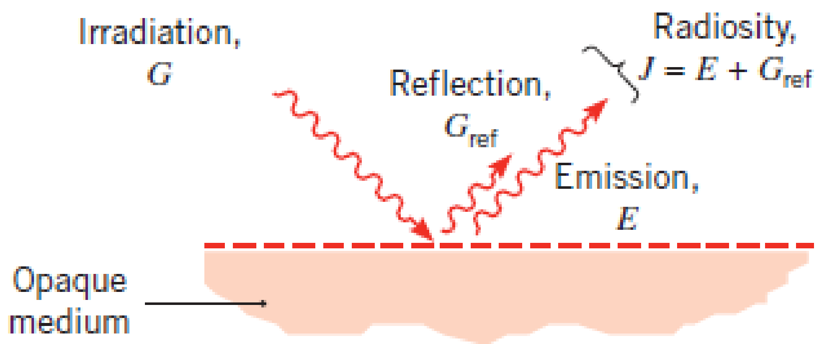




Radiation Heat Fluxes

Section 12.2

Radiation Heat Fluxes: Definitions



Define,

$\rho \rightarrow$ reflectivity $\rightarrow$ fraction of irradiation (G) reflected where $G_{ref} = \rho G$

$\alpha \rightarrow$ absorptivity $\rightarrow$ fraction of irradiation absorbed where $G_{abs} = \alpha G$

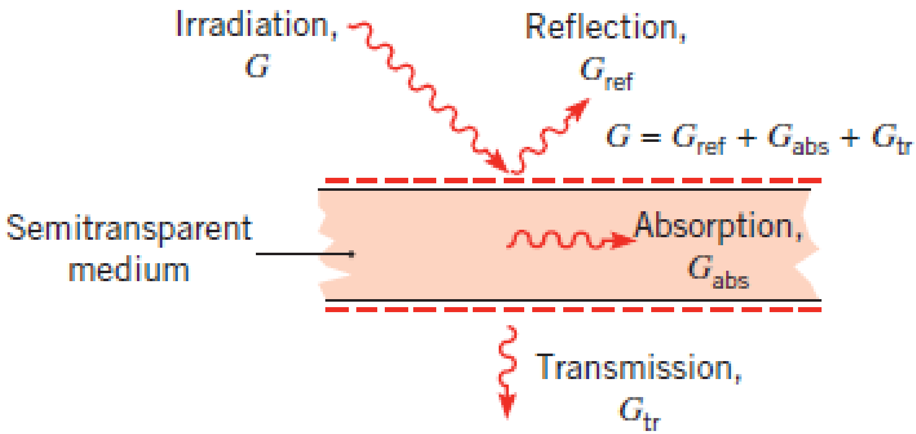
$\tau \rightarrow$ transmissivity $\rightarrow$ fraction of irradiation transmitted through the medium where $G_{tr} = \tau G$

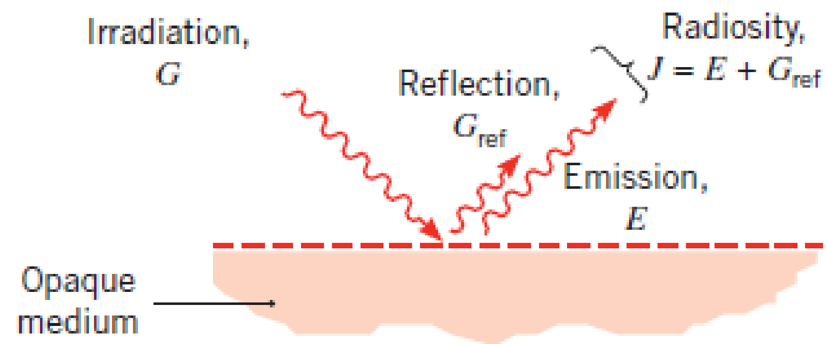
Hence,

$\rho + \alpha + \tau = 1$ for any medium.

$\rho + \alpha = 1$ for an opaque medium.

Radiation Heat Fluxes: Definitions





Ignoring Emission

Define,

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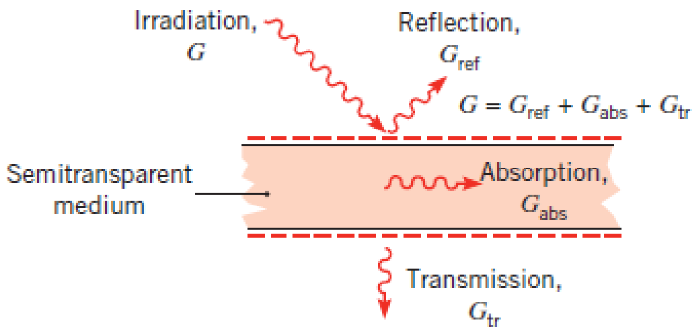
Hence,

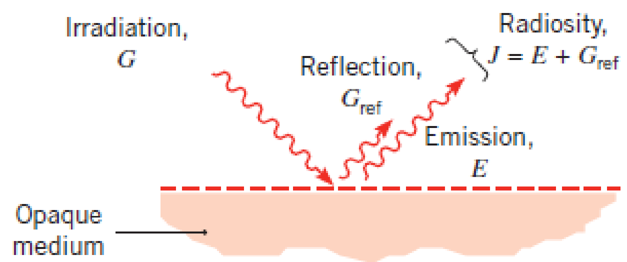
$\rho + \alpha + \tau = 1$ for any medium.

$\rho + \alpha = 1$ for an opaque medium.

Radiation Heat Fluxes: Definitions

Flux (W/m^2)	Description	Comment
Emissive power, E	Rate at which radiation is emitted from a surface per unit area	$E = \varepsilon\sigma T_s^4$
Irradiation, G		Irradiation can be reflected, absorbed, or transmitted
Radiosity, J		For an opaque surface $J = E + \rho G$
Net radiative flux, $q''_{rad} = J - G$		For an opaque surface $q''_{rad} = \varepsilon\sigma T_s^4 - \alpha G$

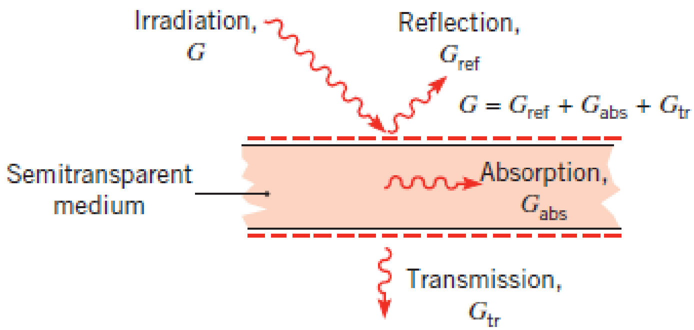


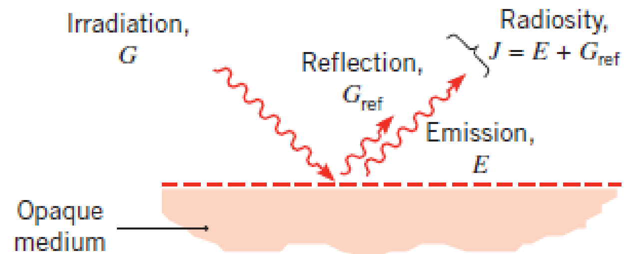


- From $q''_{rad} = J - G$ how to get $q''_{rad} = \varepsilon\sigma T_s^4 - \alpha G$?
- Directionality is considered by comparing with radiation intensity
- Spectral effect is considered by comparing with Blackbody radiation

Radiation Heat Fluxes: Definitions

Flux (W/m^2)	Description	Comment
Emissive power, E	Rate at which radiation is emitted from a surface per unit area	$E = \varepsilon\sigma T_s^4$
Irradiation, G	Rate at which radiation is incident upon a surface per unit area	Irradiation can be reflected, absorbed, or transmitted
Radiosity, J	Rate at which all radiation leaves a surface per unit area	For an opaque surface $J = E + \rho G$
Net radiative flux, $q''_{\text{rad}} = J - G$	Net rate of radiation leaving a surface per unit area	For an opaque surface $q''_{\text{rad}} = \varepsilon\sigma T_s^4 - \alpha G$





- From $q''_{rad} = J - G$ how to get $q''_{rad} = \varepsilon\sigma T_s^4 - \alpha G$?
- Directionality is considered by comparing with radiation intensity
- Spectral effect is considered by comparing with Blackbody radiation

Radiation Intensity
I and E, G, J, q

Section 12.3

Content

1. What is a solid angle? How is it defined? What is its unit?
2. What is intensity?
3. What is the difference between spectral and total radiation?
4. What is the difference between directional and hemispherical radiation?
5. What is spectral emissive intensity? What is emissive power?
6. What is irradiation?
7. What is radiosity?

Content

I – Intensity

E – Emission

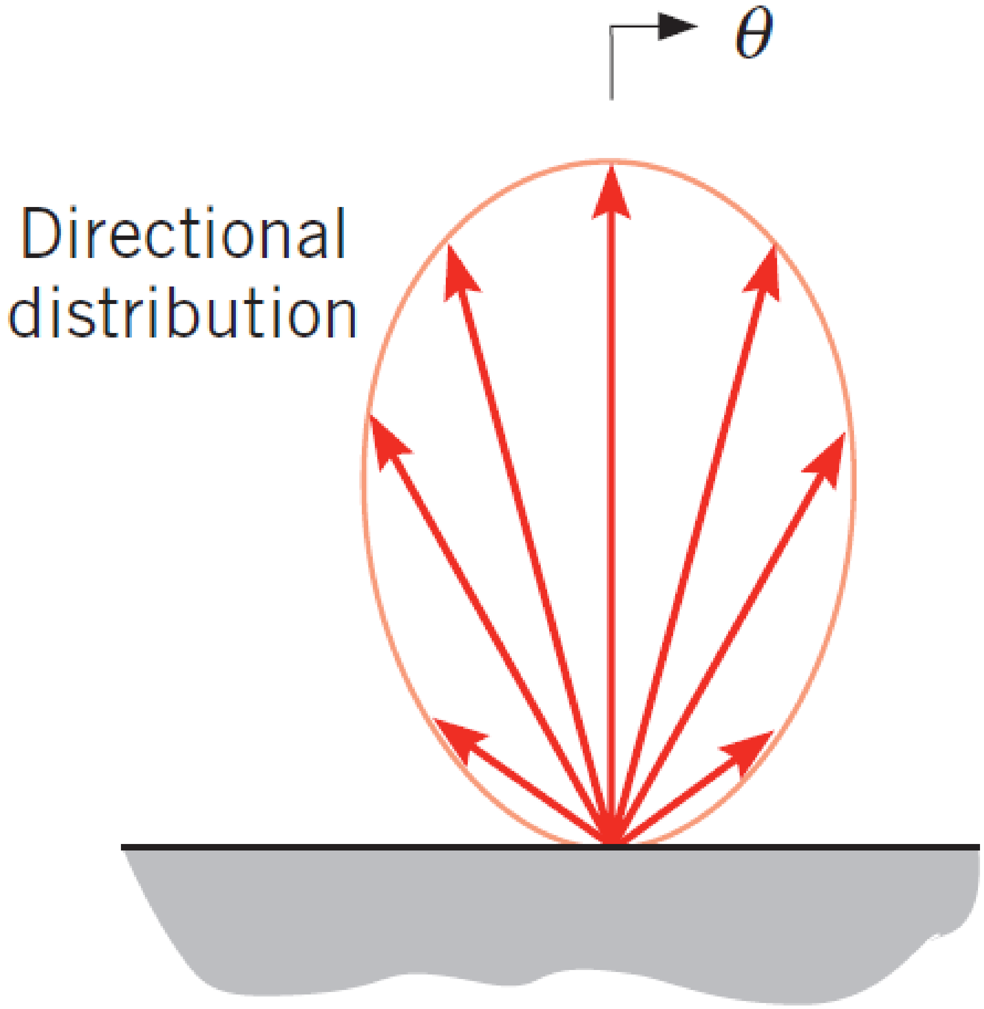
G – Irradiation

J – Radiosity

q – net radiation heat rate

What are the relationships between them? How to calculate each of them?

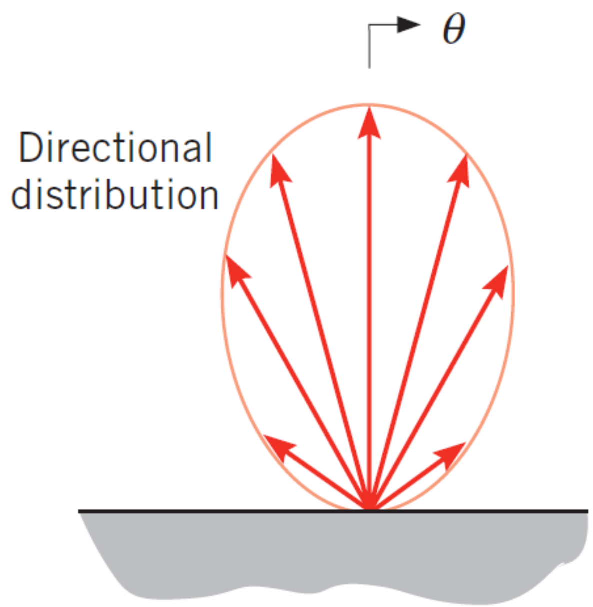
Directional Considerations



Directional Considerations

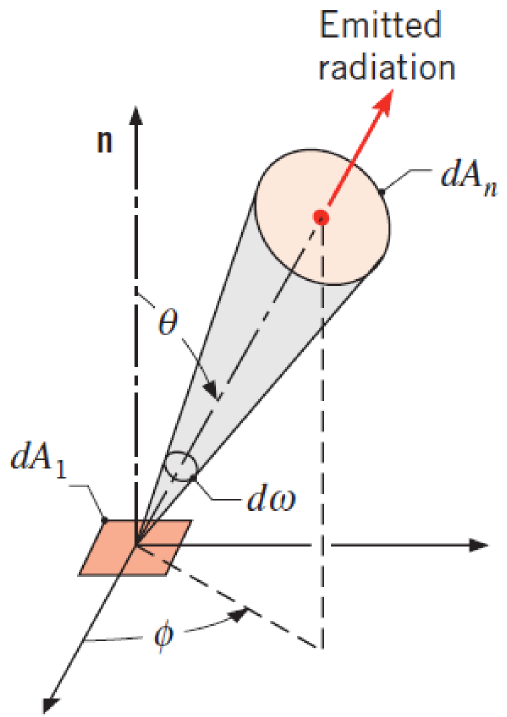
In general, radiation fluxes (q''_{rad}) can be determined only from knowledge of the directional and spectral nature of the radiation.

- Radiation emitted by a surface is in all directions and compared to a hypothetical hemisphere about the surface and is characterized by a directional distribution.



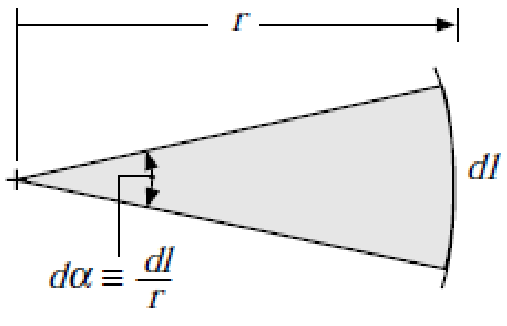
- Direction may be represented in a spherical coordinate system characterized by polar angle θ and the azimuthal angle ϕ.

The amount of radiation emitted from a surface, dA_1, and propagating in a particular direction, θ,ϕ, is quantified in terms of a differential solid angle, $d\omega$ associated with the direction.

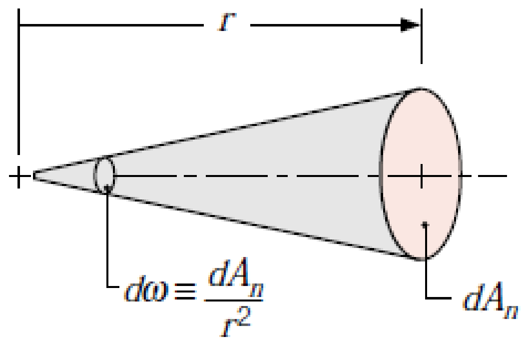


$$d\omega \equiv \frac{dA_n}{r^2}$$

$dA_n \rightarrow$ unit element of surface on a θ,ϕ hypothetical sphere and normal to the direction.



(a) 2D angle



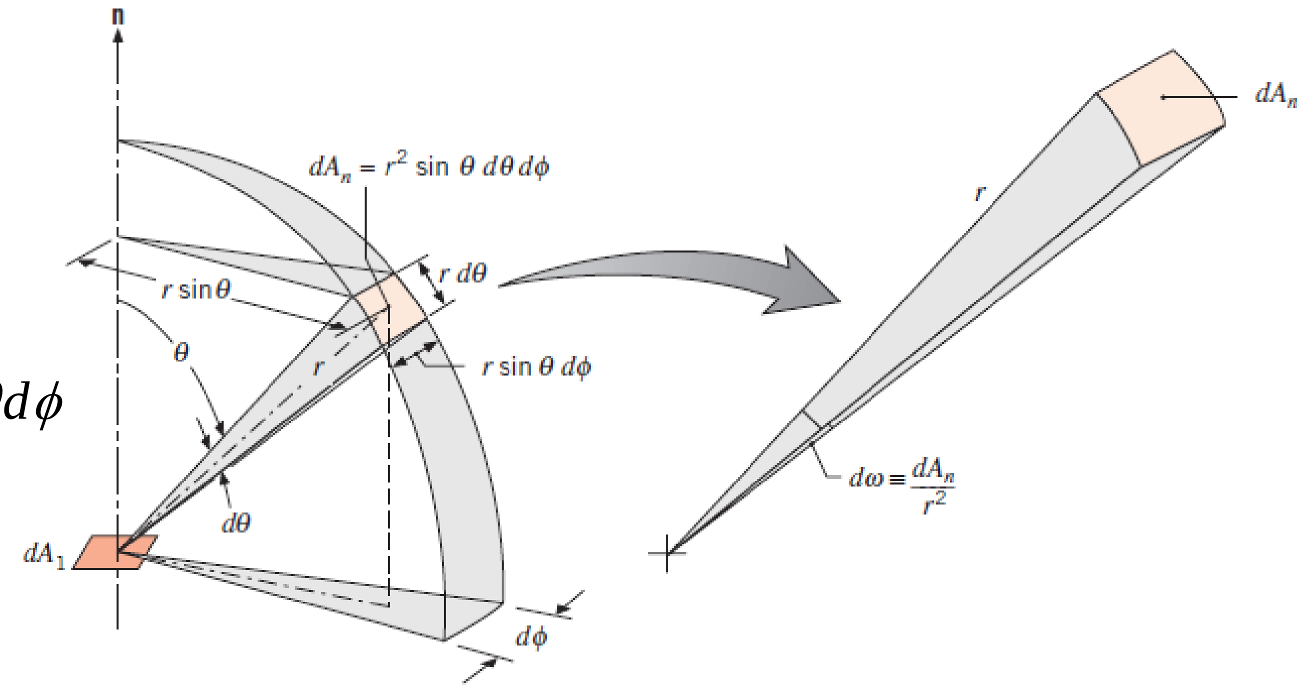
(b) 3D angle

But,

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

So,

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



– The solid angle associated with a complete hemisphere is

$$\omega_{\text{hemi}} = \int_0^{2\pi} \int_0^{\pi/2} \sin\theta d\theta d\phi = 2\pi \text{ sr}$$

– The solid angle ω has units of steradians (sr).

Intensity ?

- How powerful it is over a small area
- The radiant heat flux $\left(\mathrm{W/m^2}\right)$ within a unit solid angle about a prescribed direction $\left(\mathrm{W/m^2 \cdot sr}\right)$

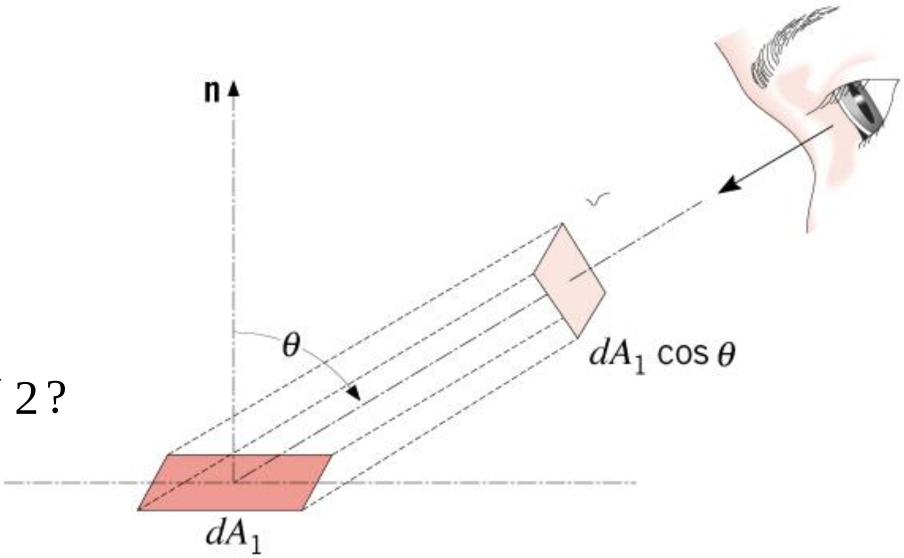
- Intensity is considered
  - For emission, irradiation, and radiosity
  - **Depends on the direction (ϕ, θ) and wavelength of radiation (λ)**

Spectral Intensity (I_λ) => radiation of a certain wavelength at a certain direction per unit wavelength per unit solid angle [$W/(m^2 \cdot sr \cdot \mu m)$].

- The area for ***I*** is the area perpendicular to the radiation direction. This is known as the projected area, $dA_1 \cos\theta$
- So, $I_\lambda(\lambda,\theta,\phi) = \dfrac{dq}{dA_1 cos\theta \, d\omega \, d\lambda}$

  – What is the projected area for $\theta = 0$?

  – What is the projected area for $\theta = \pi / 2$?

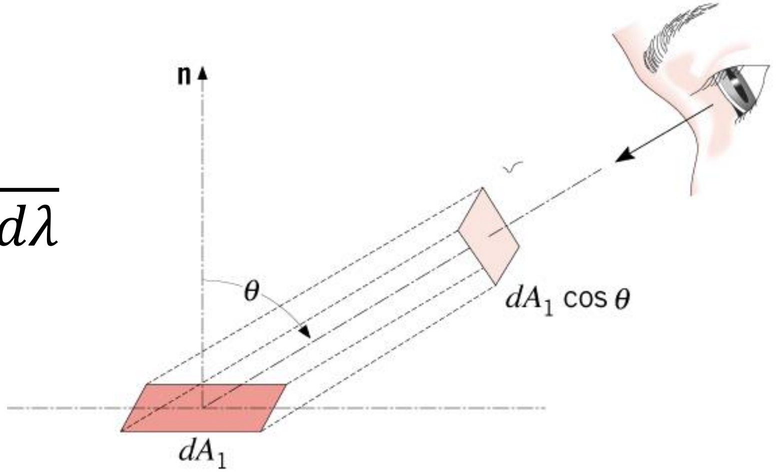


Spectral Emissive intensity, $I_{\lambda,e}$

Spectral emissive intensity $\boldsymbol{I_{\lambda,e}}$ $[\mathrm{W/(m^2 \cdot sr \cdot \mu m)}]$

- due to emission from a surface element dA_1 in the solid angle $d\omega$ about θ,ϕ and the wavelength interval $d\lambda$ about λ is defined as (similar to infront):

$$\boldsymbol{I_{\lambda,e}(\lambda,\theta,\phi)} \equiv \frac{dq}{(dA_1 \cos\theta)\cdot d\omega \cdot d\lambda}$$



- From above:

$$dq_\lambda \equiv \frac{dq}{d\lambda} = I_{\lambda,e}(\lambda,\theta,\phi)\, dA_1 \cos\theta \, d\omega$$

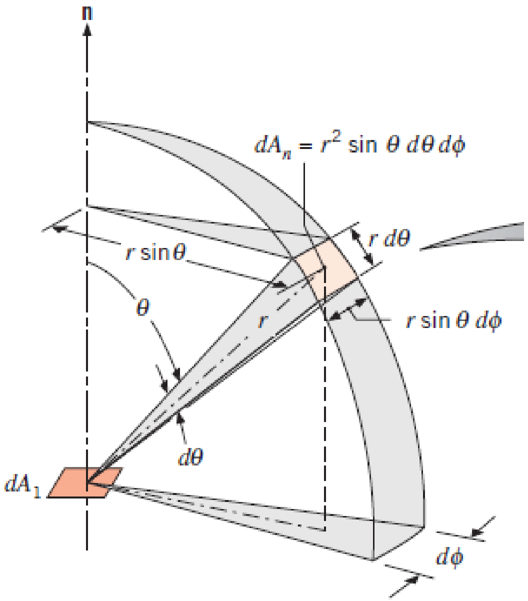
$$\begin{aligned} dq''_\lambda &= I_{\lambda,e}(\lambda,\theta,\phi) \cos\theta \, d\omega \\ &= I_{\lambda,e}(\lambda,\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi \end{aligned}$$ as $d\omega = \dfrac{dA_n}{r^2} = \sin\theta d\theta d\phi$

Emissive Power, E

The spectral hemispherical emissive power $(\mathrm{W/m^2 \cdot \mu m})$ of a surface corresponds to spectral emission over all possible directions => $\boldsymbol{E_\lambda}$ **is based on actual surface area**.

$$\boxed{E_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi}$$

- Why over all possible directions, the $d\theta$ is only from 0 to 90°?



Emissive Power, E

The total hemispherical emissive power $\left(\mathrm{W/m^2}\right)$ corresponds to emission over all directions and wavelengths => ***E* is also based on actual surface area**.

$$\boxed{E = \int_0^\infty E_\lambda(\lambda)\, d\lambda}$$

- For a diffuse surface, emission is independent of directions => isotropic:

$$E_\lambda(\lambda) = \pi I_{\lambda,e}(\lambda) \qquad\qquad E = \pi I_e$$

  – Why it is a π not 2π ?

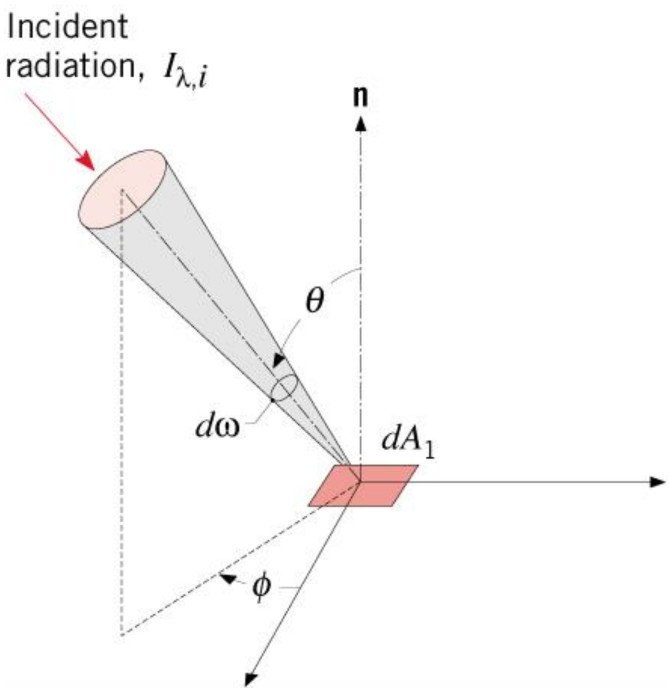
Spectral Irradiation intensity, $I_{\lambda,i}$

The spectral intensity of radiation incident on a surface, $I_{\lambda,i}$

- is defined in terms of the unit solid angle about the direction of incidence, the wavelength interval $d\lambda$ about λ, and the projected area of the receiving/intercepting surface, $dA_1 \cos\theta$.

- Same definition as emission but now the radiation is hitting the surface.

- What is the formula of $I_{\lambda,i}$?



Irradiation, G

The spectral irradiation $\left(\mathrm{W/m^2}\cdot\mu\mathrm{m}\right)$ is then:

$$\boxed{G_\lambda(\lambda)=\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi}$$

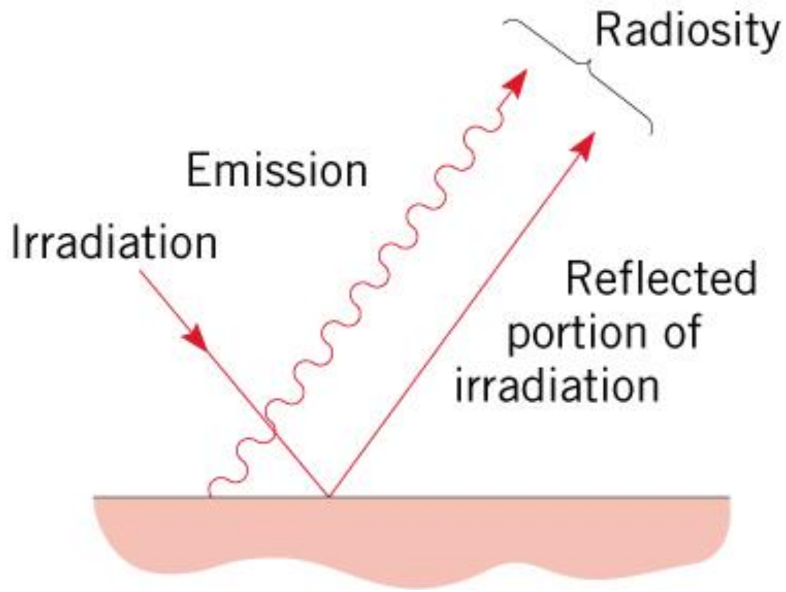
and the total irradiation $\left(\mathrm{W/m^2}\right)$ is

$$\boxed{G=\int_0^{\infty} G_\lambda(\lambda)\, d\lambda}$$

- How may G_λ and G be expressed if the incident radiation is diffuse (i.e., independent of directions)?
- Note: **G_λ and G are also based on actual surface area**

The radiosity of an opaque surface == all of the radiation leaving the surface in all directions

- Include contributions from both reflection and emission.
  - $J = \rho G + E$



Radiosity, J

$I_{\lambda,e+r}$ **includes the spectral intensity from radiation emitted by the surface and the reflection of incident radiation**, the spectral radiosity $\left(\mathrm{W/m^2}\cdot\mu\mathrm{m}\right)$ is:

$$\boxed{J_\lambda(\lambda)=\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e+r}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi}$$

and the total radiosity $\left(\mathrm{W/m^2}\right)$ is

$$\boxed{J=\int_0^\infty J_\lambda(\lambda)\,d\lambda}$$

- How may J_λ and J be expressed if the surface emits and reflects diffusely?

- Note: J_λ and J are based on actual surface area but $I_{\lambda,e+r}$ is based on projected area

Net Radiative Flux, q''_{rad}

Difference between the outgoing radiosity *J* and incoming irradiation *G*,

$$\boxed{q''_{rad} = J - G}$$

- Can be simplified by expressing using blackbody radiation and emissivity, absorptivity, and reflectivity.

Summary

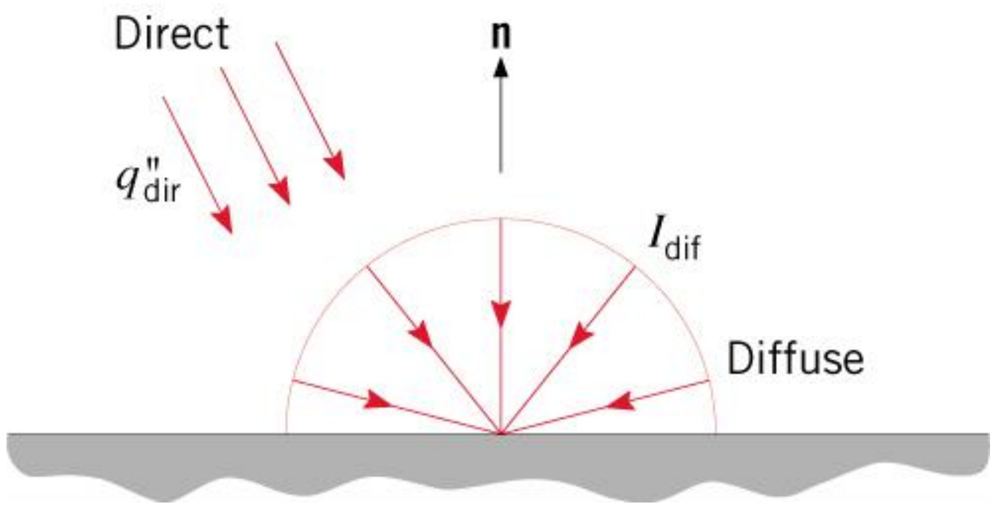
Radiation

- **Nature of Radiation**
  - What causes it?
  - Spectral + Directionality

- **Emission**
- **Irradiation**
- **Radiosity**
- **Net q_{rad}**

Example 1: Solar Irradiation

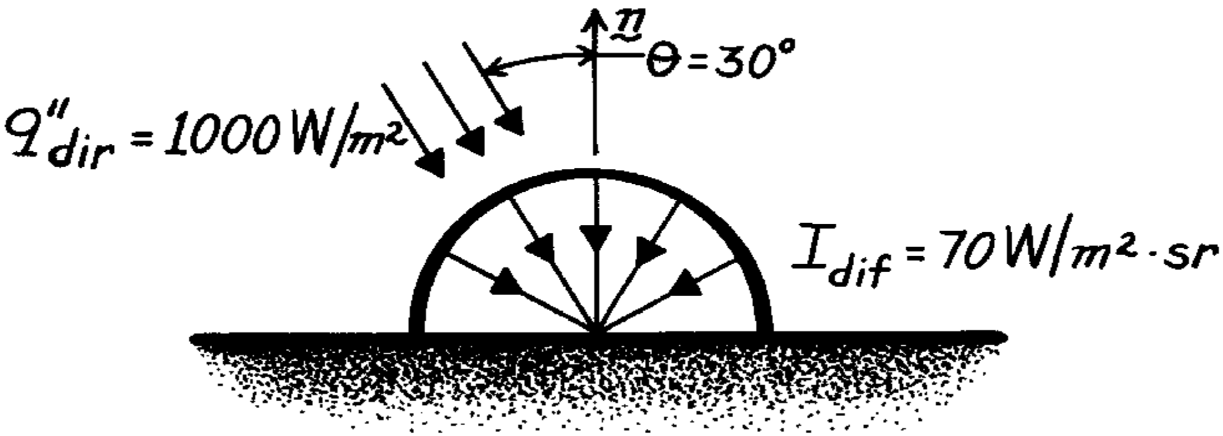
Problem 12.93: Evaluation of total solar irradiation at the earth's surface when direct incident radiation is at $\theta = 30^{o}$ with a total flux (area normal to the rays) q''_{dir} = 1000 W/m^2, as well as a total intensity of the diffuse radiation is I_{dif} = 70 W/m^{2}sr. What is the total solar irradiation at the earth's surface?



KNOWN: Flux and intensity of direct and diffuse components, respectively, of solar irradiation.

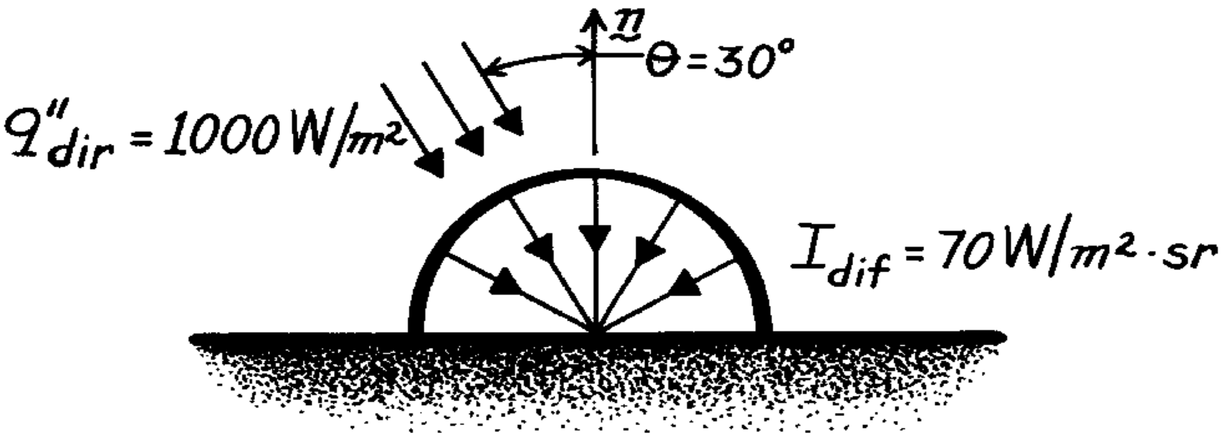
FIND: Total irradiation.

SCHEMATIC:



- **Total irradiation comes from?**
- **Irradiation, *G* is based on what area?**
- **Intensity, *I* is based on what area?**
- **How to combine them?**

SCHEMATIC:



ANALYSIS: Since the irradiation is based on the actual surface area, the contribution due to the direct solar radiation is

$$G_{\mathrm{dir}} = q''_{\mathrm{dir}} \cdot \cos\theta.$$

For the contribution due to the diffuse radiation

$$G_{\mathrm{dif}} = \pi I_{\mathrm{dif}}.$$

Hence

$$G = G_{\mathrm{dir}} + G_{\mathrm{dif}} = q''_{\mathrm{dir}} \cdot \cos\theta + \pi I_{\mathrm{dif}}$$

or

$$G = 1000\,\mathrm{W/m^2} \times 0.866 + \pi\mathrm{sr} \times 70\,\mathrm{W/m^2} \cdot \mathrm{sr}$$

$$G = (866 + 220)\,\mathrm{W/m^2}$$

$$G = 1086\ \mathrm{W/m^2}.$$

COMMENTS: Although a diffuse approximation is often made for the non-direct component of solar radiation, the actual directional distribution deviates from this condition, providing larger intensities at angles close to the direct beam.