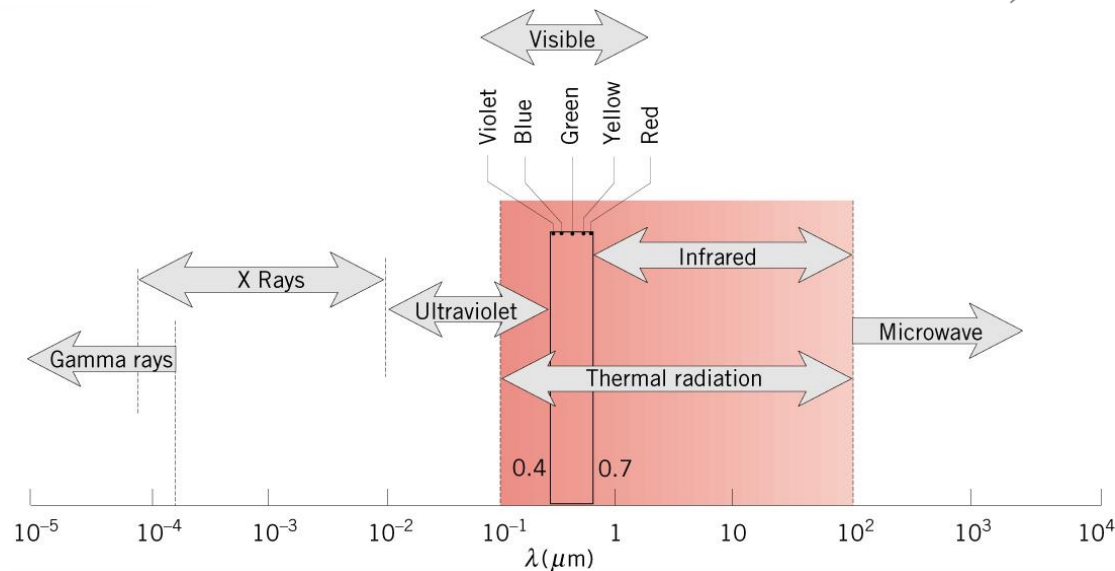
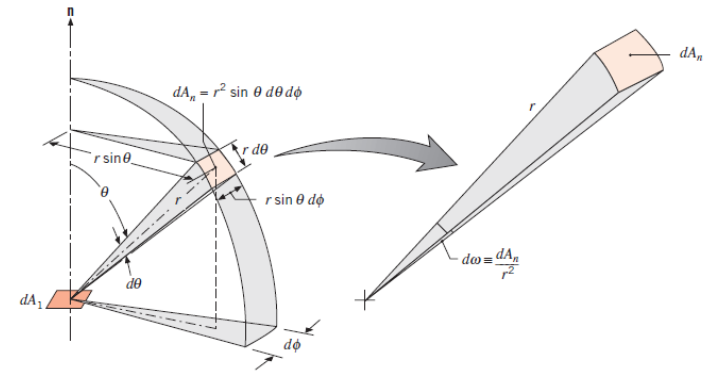
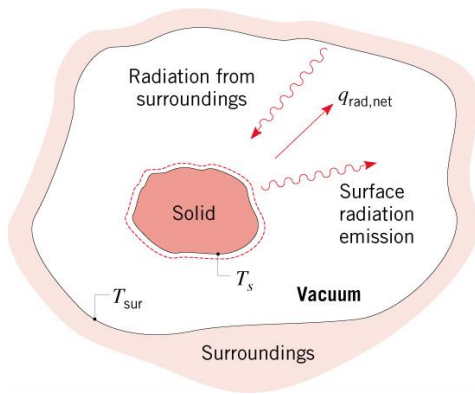
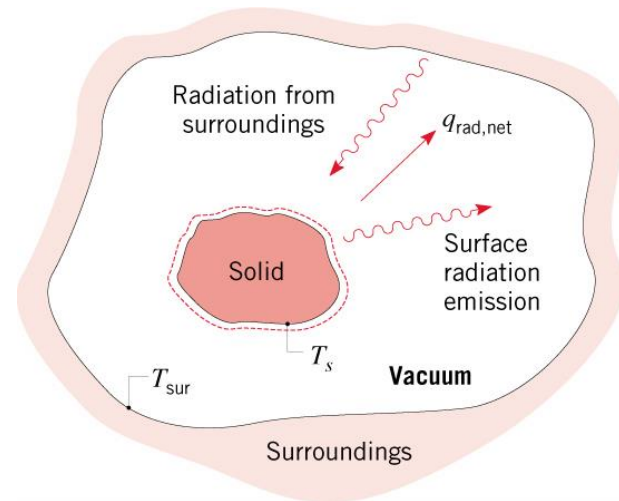


Radiation Processes and Properties

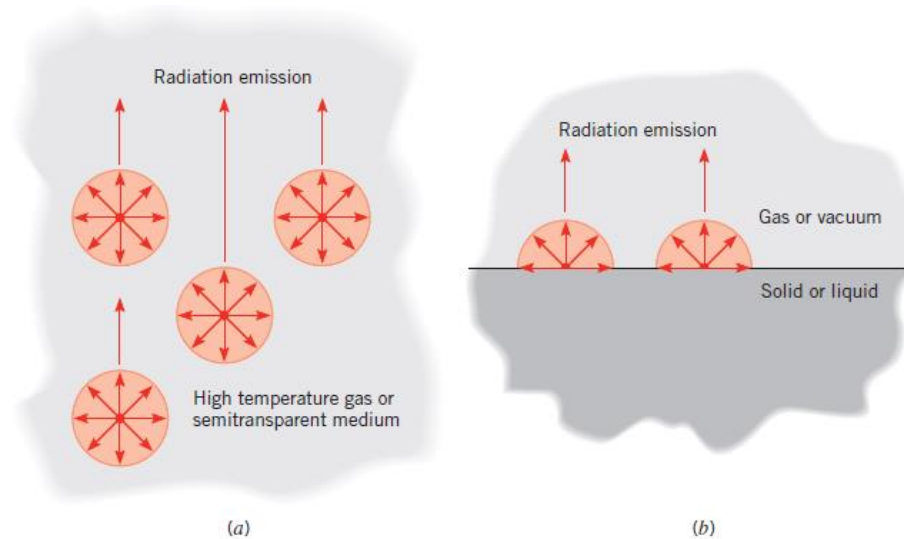


General Considerations

- Attention is focused on **thermal radiation**, whose origins are associated with **emission** from matter at an absolute temperature $T > 0$.
- Emission is **due to oscillations and transitions of** the many **electrons** that comprise matter, which are, in turn, sustained by the thermal energy of the matter.
- **Emission corresponds** to heat transfer from the matter and hence **to a reduction in its thermal energy**.
- **Radiation may also be** intercepted and **absorbed** by matter, resulting in its **increase in thermal energy**.
- Consider a solid of temperature T_s in an evacuated enclosure whose walls are at a fixed temperature T_{sur} :
 - What changes occur if $T_s > T_{\text{sur}}$? Why?
 - What changes occur if $T_s < T_{\text{sur}}$? Why?



- Emission from a gas or a semitransparent solid or liquid is a **volumetric phenomenon**. Emission from an opaque solid or liquid is treated as a **surface phenomenon**.



For an opaque solid or liquid, emission originates from atoms and molecules within $1\ \mu\text{m}$ of the surface.

- The **dual nature of radiation**:
 - In some cases, the physical manifestations of radiation may be explained by viewing it as **particles** (known as **photons** or **quanta**).
 - In other cases, radiation behaves as an **electromagnetic wave**.

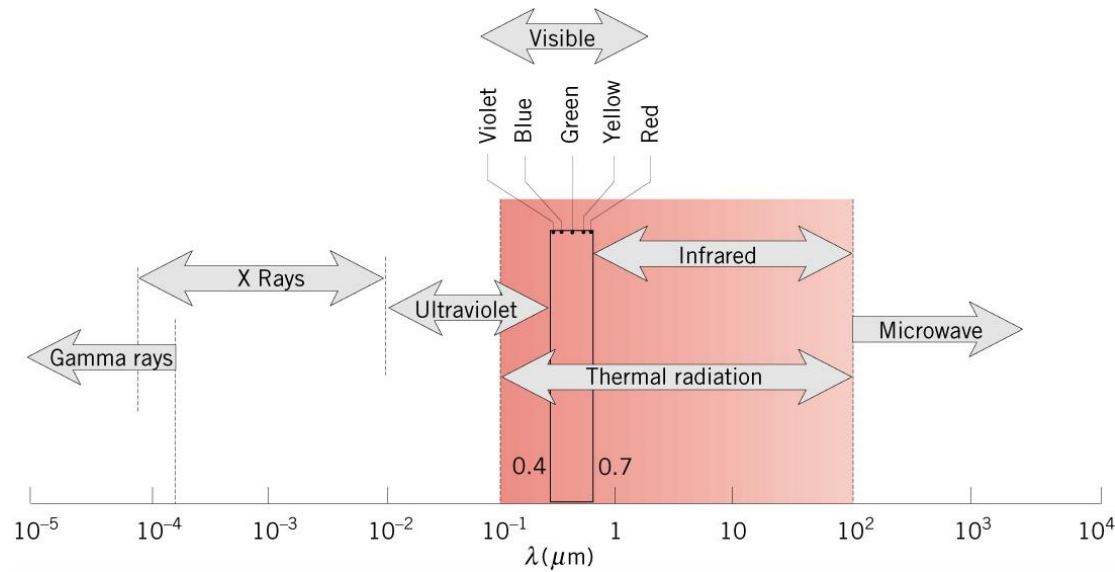
- In all cases, radiation can be characterized by a **wavelength** λ and **frequency** ν , which are related through the speed at which radiation propagates in the medium of interest:

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

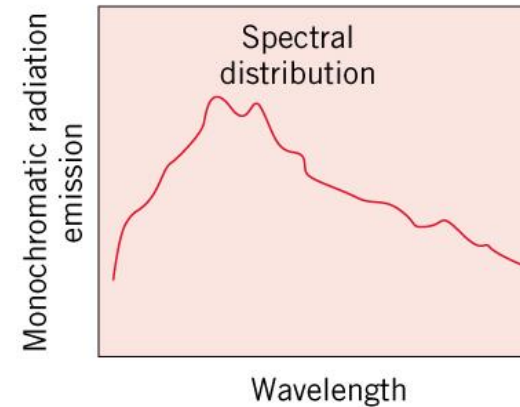
For propagation in a vacuum,

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

The Electromagnetic Spectrum

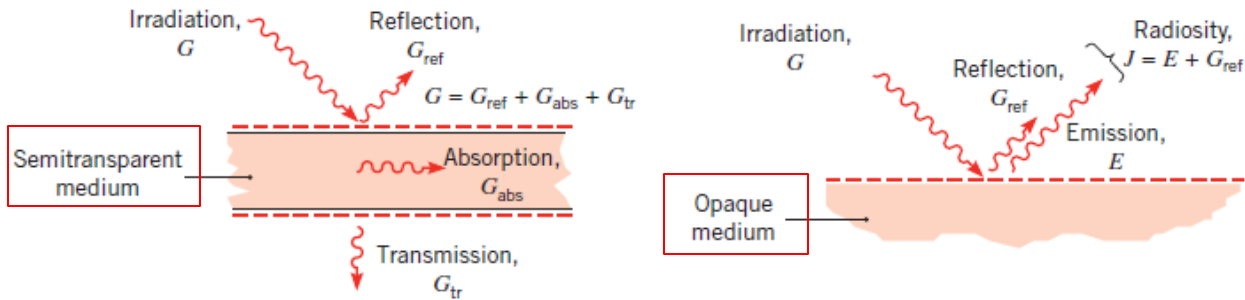


- Thermal radiation is confined to the **infrared**, **visible** and **ultraviolet** regions of the spectrum ($0.1 < \lambda < 100 \mu\text{m}$) .
- The amount of radiation emitted by an opaque surface varies with wavelength, and we may speak of the **spectral distribution** over all wavelengths or of **monochromatic/spectral components** associated with particular wavelengths.



Radiation Heat Fluxes and Material Properties

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 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 $q''_{\text{rad}} = \varepsilon \sigma T_s^4 - \alpha G$



$\rho \rightarrow$ **reflectivity** \rightarrow fraction of irradiation (G) reflected.
 $\alpha \rightarrow$ **absorptivity** \rightarrow fraction of irradiation absorbed.
 $\tau \rightarrow$ **transmissivity** \rightarrow fraction of irradiation transmitted through the medium.

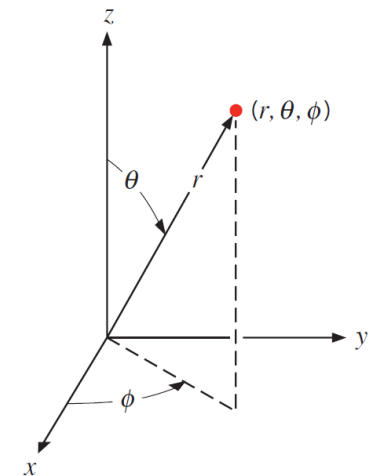
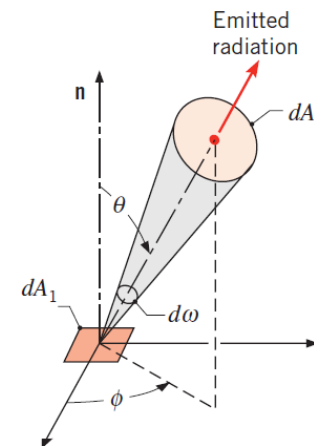
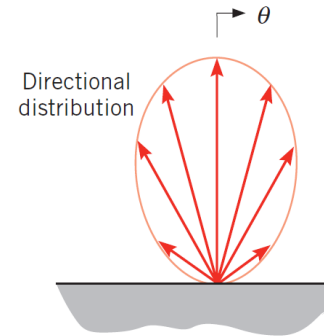
$\rho + \alpha + \tau = 1$ for any medium. $\rho + \alpha = 1$ for an **opaque** medium.

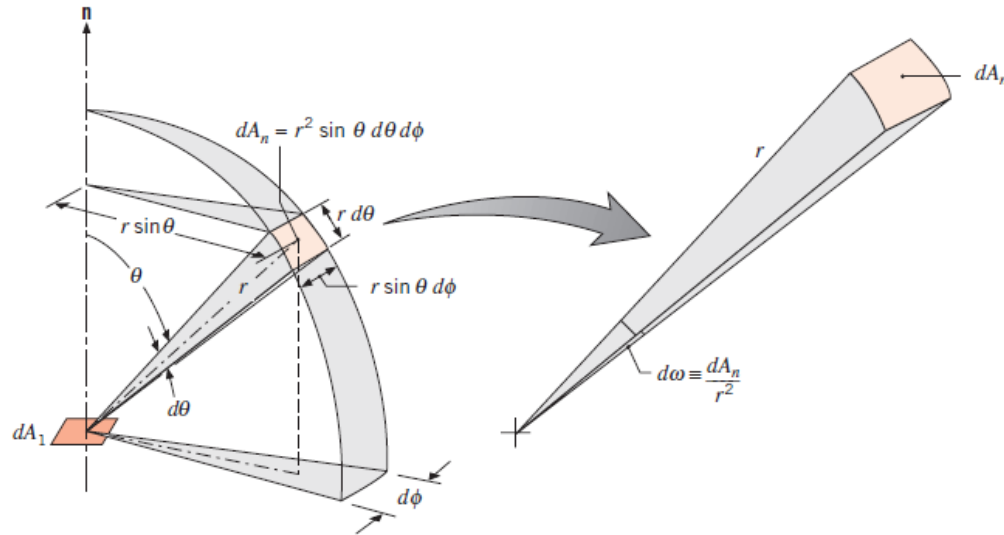
Directional Considerations and Radiation Intensity

- In general, radiation fluxes can be determined only from knowledge of the directional and spectral nature of the radiation.
- Radiation emitted by a surface will be in all directions associated with a hypothetical hemisphere about the surface and is characterized by a **directional distribution**.
- Direction may be represented in a spherical coordinate system characterized by the zenith or 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** associated with the direction.

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

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





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

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

- The solid angle ω has units of **steradians (sr)**.
- The solid angle associated with a complete hemisphere is

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

- **Spectral Intensity**: A quantity used to specify the radiant **heat flux** (W/m^2) **within a unit solid angle** about a prescribed direction ($\text{W/m}^2 \cdot \text{sr}$) and **within a unit wavelength interval** about a prescribed wavelength ($\text{W/m}^2 \cdot \text{sr} \cdot \mu\text{m}$).

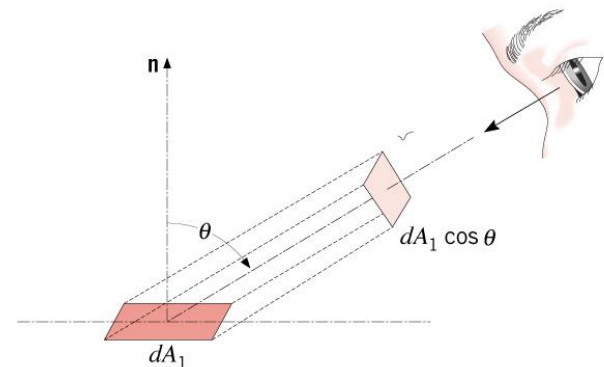
- The spectral intensity $I_{\lambda,e}$ associated with emission from a surface element dA_1 in the solid angle $d\omega$ about θ, ϕ and the wavelength interval $d\lambda$ about λ is defined as:

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

- The rationale for defining the radiation flux in terms of the **projected surface area** ($dA_1 \cos \theta$) stems from the existence of surfaces for which, to a good approximation, $I_{\lambda,e}$ is independent of direction. Such surfaces are termed **diffuse**, and the radiation is said to be **isotropic**.

➤ The projected area is how dA_1 would appear if observed along θ, ϕ .

- What is the projected area for $\theta = 0$?
- What is the projected area for $\theta = \pi / 2$?



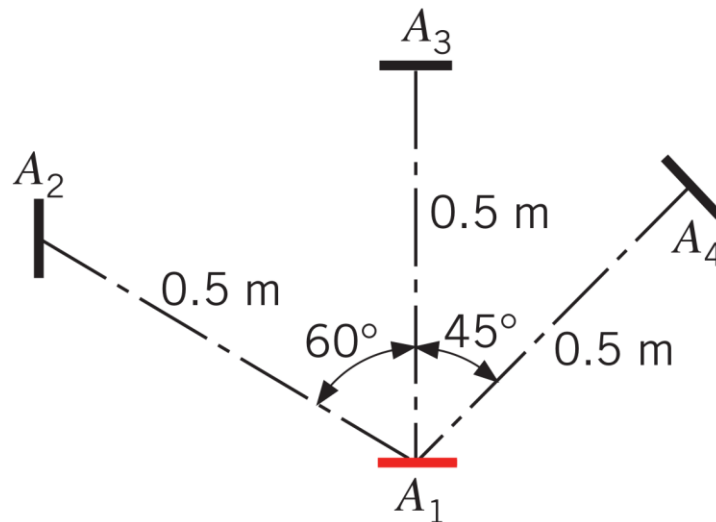
- The spectral heat rate and heat flux associated with emission from dA_1 are, respectively,

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

$$dq''_\lambda = I_{\lambda,e}(\lambda, \theta, \phi) \cos \theta d\omega = I_{\lambda,e}(\lambda, \theta, \phi) \cos \theta \sin \theta d\theta d\phi$$

Example 1

A small surface of area $A_1 = 10^{-3} \text{ m}^2$ is known to emit diffusely, and from measurements the total intensity associated with emission in the normal direction is $I_n = 7000 \frac{\text{W}}{\text{m}^2 \text{ sr}}$. Radiation emitted from the surface is intercepted by three other surfaces of area $A_2 = A_3 = A_4 = 10^{-3} \text{ m}^2$, 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?



Relation of Intensity to Emissive Power, Irradiation, and Radiosity

- The **spectral emissive power** ($\text{W/m}^2 \cdot \mu\text{m}$) corresponds to spectral emission overall possible directions.

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

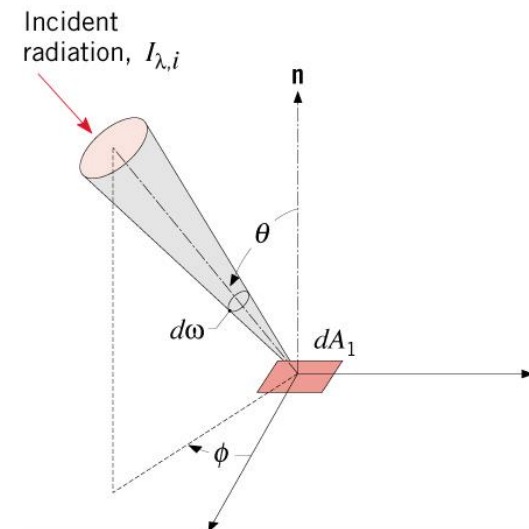
- The **total emissive power** (W/m^2) corresponds to emission over all directions and wavelengths.

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

- For a **diffuse surface**, **emission is isotropic** and

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

- 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 surface, $dA_1 \cos\theta$.



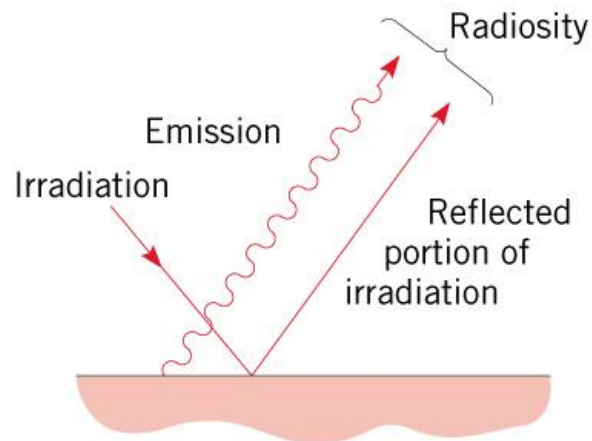
- The **spectral irradiation** ($\text{W/m}^2 \cdot \mu\text{m}$) is then:

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

and the **total irradiation** (W/m^2) is

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

- The **radiosity** of an opaque surface accounts for all of the radiation leaving the surface in all directions and may include contributions from both **reflection** and **emission**.



- With $I_{\lambda,e+r}$ designating the spectral intensity associated with radiation emitted by the surface and the reflection of incident radiation, the **spectral radiosity** ($\text{W/m}^2 \cdot \mu\text{m}$) is:

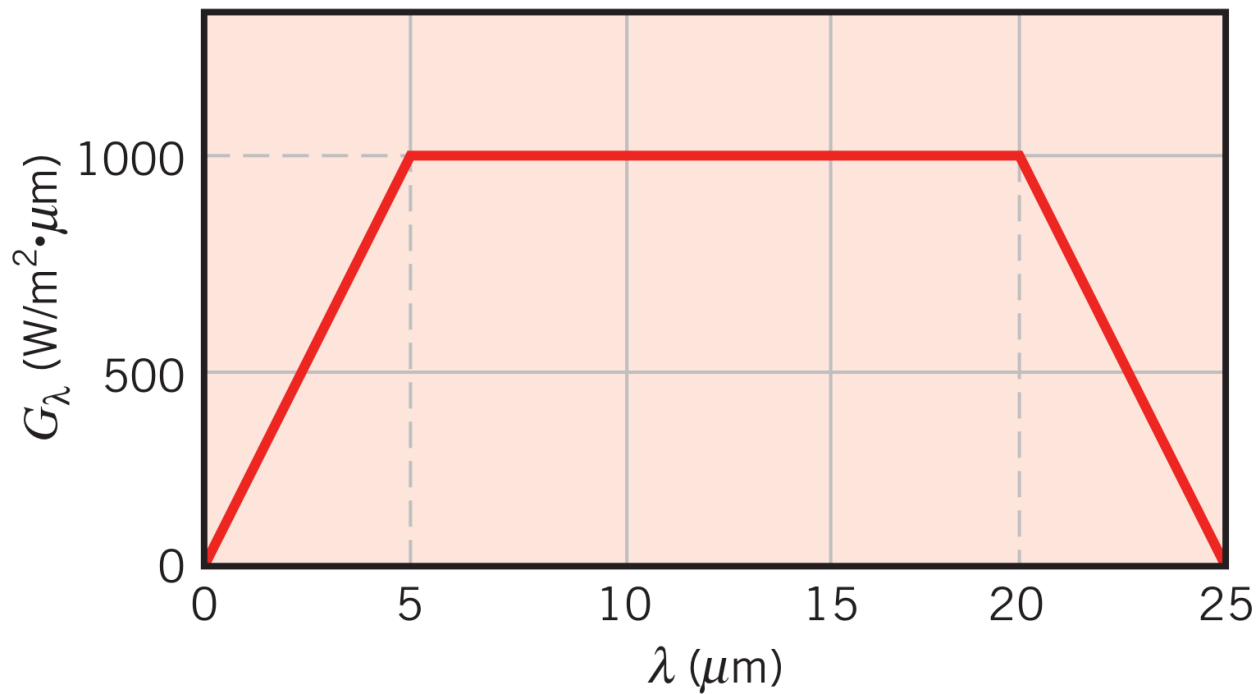
$$J_{\lambda}(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e+r}(\lambda, \theta, \phi) \cos \theta \sin \theta d\theta d\phi$$

and the **total radiosity** (W/m^2) is

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

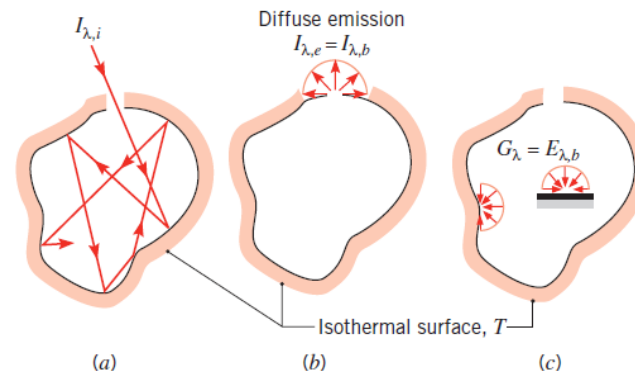
Example 2

The spectral distribution of surface irradiation is shown below. What is the total irradiation?



Blackbody Radiation and Its Intensity

- The **Blackbody**
 - An **idealization** providing limits on radiation emission and absorption by matter.
 - For a prescribed temperature and wavelength, no surface can emit more radiation than a blackbody: the **ideal emitter**.
 - A blackbody is a **diffuse emitter**.
 - A blackbody absorbs all incident radiation: the **ideal absorber**.
- The **Isothermal Cavity**



- (a) After multiple reflections, virtually **all radiation entering the cavity is absorbed**.
- (b) **Emission** from the aperture is the maximum possible emission achievable for the temperature associated with the cavity and is **diffuse**.

- (c) The cumulative effect of radiation emission from and reflection off the cavity wall is to provide diffuse irradiation corresponding to emission from a blackbody ($G_{\lambda} = E_{\lambda,b}$) for any surface in the cavity.

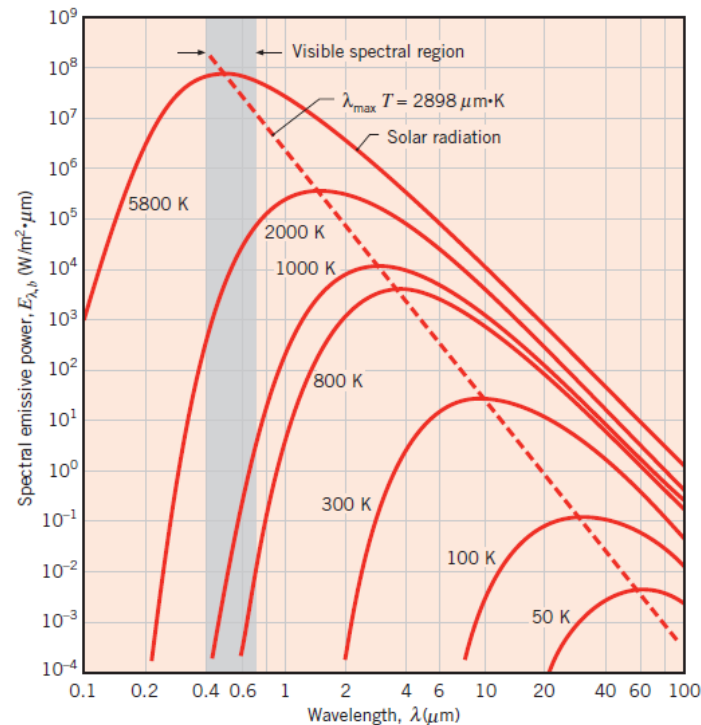
The Spectral (Planck) Distribution of Blackbody Radiation

- The spectral distribution of the blackbody emissive power (determined theoretically and confirmed experimentally) is

$$E_{\lambda,b}(\lambda, T) = \pi I_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5 [\exp(C_2 / \lambda T) - 1]}$$

First radiation constant: $C_1 = 3.742 \times 10^8 \text{ W} \cdot \mu\text{m}^4 / \text{m}^2$

Second radiation constant: $C_2 = 1.439 \times 10^4 \mu\text{m} \cdot \text{K}$



- $E_{\lambda,b}$ (and $I_{\lambda,b}$) varies continuously with λ and increases with T .
- The distribution is characterized by a maximum for which λ_{max} is given by **Wien's displacement law**:

$$\lambda_{\text{max}} T = C_3 = 2898 \mu\text{m} \cdot \text{K}$$

- The **fractional** amount of total blackbody emission appearing at lower wavelengths increases with increasing T .

The Stefan-Boltzmann Law and Band Emission

- The **total emissive power of a blackbody** is obtained by integrating the Planck distribution over all wavelengths.

$$E_b = \pi I_b = \int_0^{\infty} E_{\lambda,b} d\lambda = \sigma T^4$$

————→ the **Stefan-Boltzmann law**, where

$$\sigma = 5.670 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 \rightarrow \text{the Stefan-Boltzmann constant}$$

- The fraction of total blackbody **emission** that is **in a prescribed wavelength interval** or **band** ($\lambda_1 < \lambda < \lambda_2$) is

$$F_{(\lambda_1-\lambda_2)} = F_{(0-\lambda_2)} - F_{(0-\lambda_1)} = \frac{\int_0^{\lambda_2} E_{\lambda,b} d\lambda - \int_0^{\lambda_1} E_{\lambda,b} d\lambda}{\sigma T^4}$$

where, in general,

$$F_{(0-\lambda)} = \frac{\int_0^{\lambda} E_{\lambda,b} d\lambda}{\sigma T} = f(\lambda T)$$

and numerical results are given in Table 13.1.

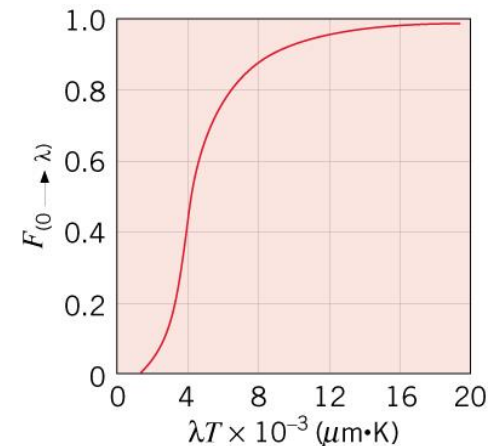


Table 13.1

$\lambda T (\mu m K)$	$F_{(0 \rightarrow \lambda)}$	$I_{\lambda,b}(\lambda, T) / \sigma T^5 (\mu m K sr)^{-1}$	$\frac{I_{\lambda,b}(\lambda, T)}{I_{\lambda,b}(\lambda_{max}, T)}$
200	0.000000	$0.375034E - 27$	0.000000
400	0.000000	$0.490335E - 13$	0.000000
600	0.000000	$0.104046E - 8$	0.000014
800	0.000016	$0.991126E - 7$	0.001372
1000	0.000321	$0.118505E - 5$	0.016406
1200	0.002134	$0.523927E - 5$	0.072534
1400	0.007790	$0.134411E - 4$	0.186082
1600	0.019718	$0.249130E - 4$	0.344904
1800	0.039341	$0.375568E - 4$	0.519949
2000	0.066728	$0.493432E - 4$	0.683123
2200	0.100888	$0.589649E - 4$	0.816329
2400	0.140256	$0.658866E - 4$	0.912155
2600	0.183120	$0.701292E - 4$	0.970891
2898	0.250108	$0.722318E - 4$	1.000000
3000	0.273232	$0.720254E - 4$	0.997143
3400	0.361735	$0.681544E - 4$	0.943551
3800	0.443382	$0.615225E - 4$	0.851737
4200	0.516014	$0.540394E - 4$	0.748139

Note ability to readily determine $I_{\lambda,b}$ and its relation to the maximum intensity from the 3rd and 4th columns, respectively.

- If emission from the sun may be approximated as that from a blackbody at 5800 K, at what wavelength does peak emission occur?
- Would you expect radiation emitted by a blackbody at 800 K to be discernible by the naked eye?
- As the temperature of a blackbody is increased, what color would be the first to be discerned by the naked eye?

Example 3

Consider a large isothermal enclosure that is maintained at a uniform temperature of 2000K. Calculate the emissive power of the radiation that emerges from a small aperture on the enclosure surface. What is the wavelength λ_1 below which 10% of the emission is concentrated? What is the wavelength λ_2 above which 10% of the emission is concentrated? Determine the maximum spectral emissive power and the wavelength at which this emission occurs. What is the irradiation incident on a small object placed inside the enclosure?