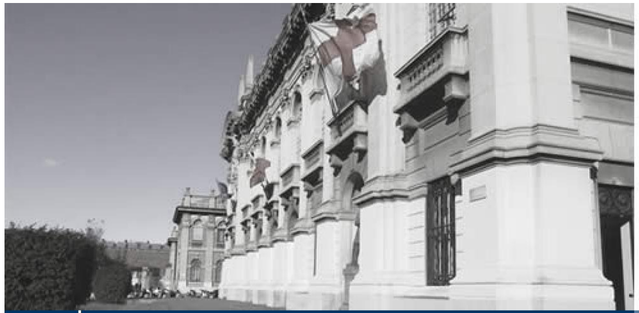


POLITECNICO DI MILANO





Heat Transfer Review: Radiation

Ref: Y. A. Cengel, Heat Transfer, a practical approach

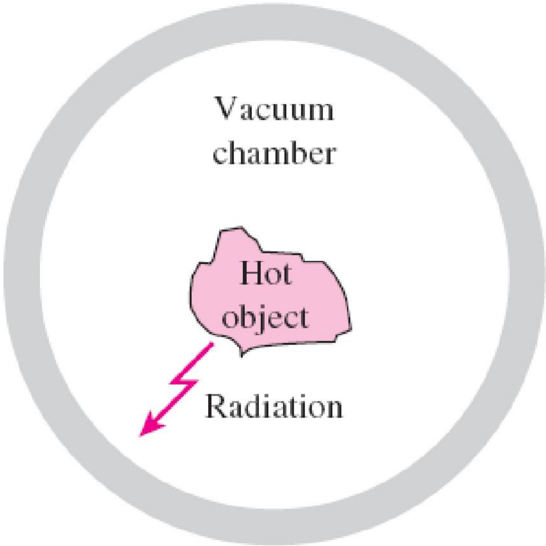
Energy and Environmental Technologies for Building Systems

Piacenza Campus, 2nd Semester 2016

B. Najafi

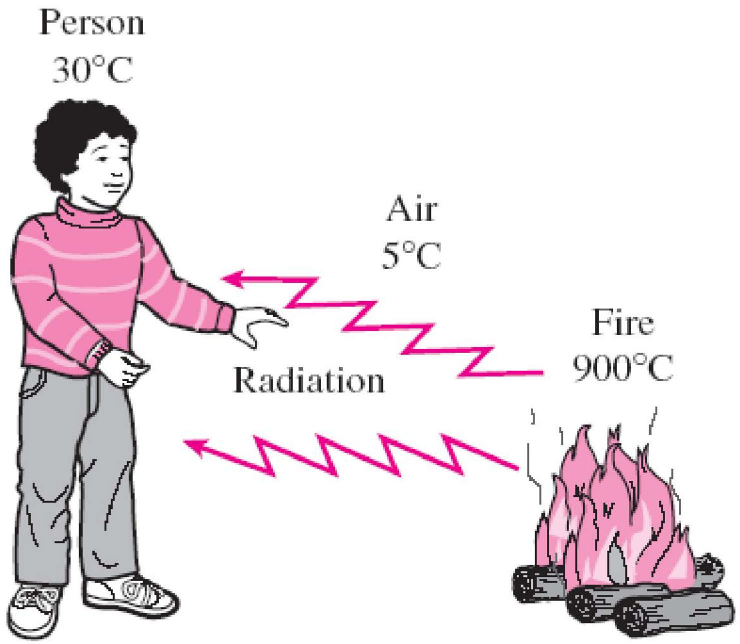
Introduction

❖The hot object in vacuum chamber will eventually cool down and reach thermal equilibrium with its surroundings by a heat transfer mechanism: radiation.



❖Radiation differs from conduction and convection in that it does not require the presence of a material medium to take place.

❖Radiation transfer occurs in solids as well as liquids and gases.



Introduction

❖Accelerated charges or changing electric currents give rise to electric and magnetic fields. These rapidly moving fields are called electromagnetic waves or electromagnetic radiation, and they represent the energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.

Electromagnetic waves transport energy just like other waves and they are characterized by their *frequency* ν or *wavelength* λ. These two properties in a medium are related by

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

$c = c_0 / n$

c, the speed of propagation of a wave in that medium

$c_0 = 2.9979 \times 10^8$ m/s, the *speed of light* in a vacuum

n, the *index of refraction* of that medium

$n = 1$ for air and most gases, $n = 1.5$ for glass, and n = 1.33 for water

❖It has proven useful to view electromagnetic radiation as the propagation of a collection of discrete packets of energy called photons or quanta.

In this view, each photon of frequency n is considered to have an energy of

$$e = h\nu = \frac{hc}{\lambda}$$

The energy of a photon is inversely proportional to its wavelength.

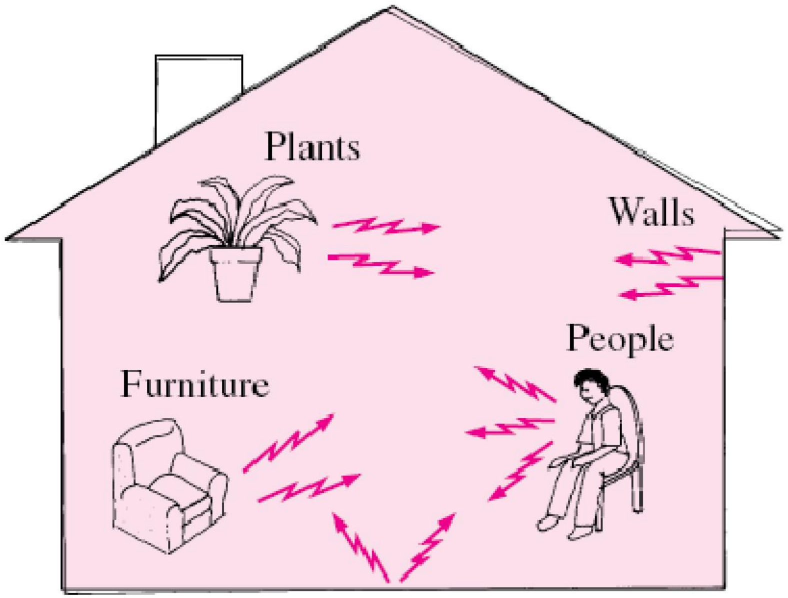
$h = 6.626069 \times 10^{-34}$ J · s is *Planck's constant*.

Thermal Radiation

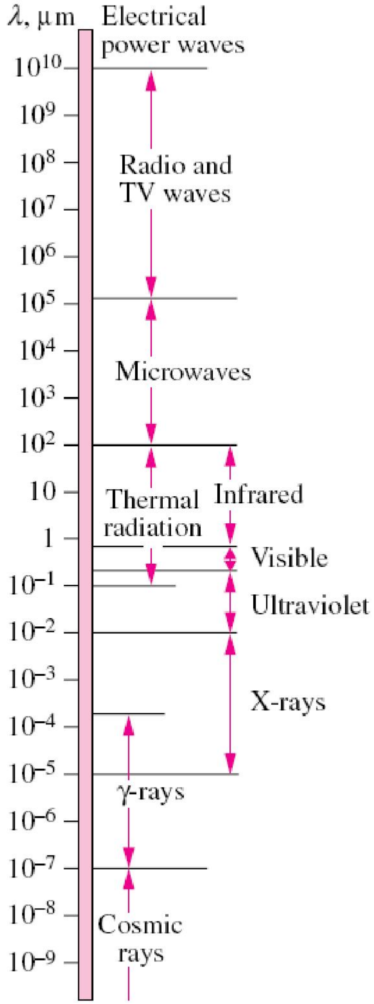
❖The type of electromagnetic radiation that is pertinent to heat transfer is the thermal radiation emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

❖Temperature is a measure of the strength of these activities at the microscopic level, and the rate of thermal radiation emission increases with increasing temperature.

❖Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero.



Everything around us constantly emits thermal radiation.



The electromagnetic wave spectrum.

Light

Light is simply the *visible* portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μm.

TABLE 12–1

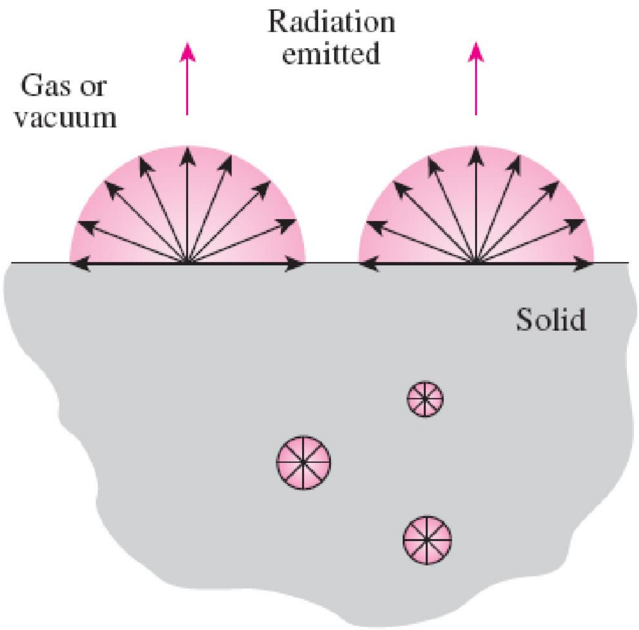
The wavelength ranges of different colors

Color	Wavelength band
Violet	0.40–0.44 μm
Blue	0.44–0.49 μm
Green	0.49–0.54 μm
Yellow	0.54–0.60 μm
Orange	0.60–0.67 μm
Red	0.63–0.76 μm

- A body that emits some radiation in the visible range is called a light source.
- The sun is our primary light source. The electromagnetic radiation emitted by the sun is known as solar radiation. Almost *half* of solar radiation is light (i.e., it falls into the visible range), with the remaining being ultraviolet and infrared.
- The radiation emitted by bodies at room temperature falls into the infrared region of the spectrum, which extends from 0.76 to 100 μm.
- The ultraviolet radiation includes the low-wavelength end of the thermal radiation spectrum and lies between the wavelengths 0.01 and 0.40 μm. Ultraviolet rays are to be avoided since they can kill microorganisms and cause serious damage to humans and other living beings.
- About 12 percent of solar radiation is in the ultraviolet range. The ozone (O_3) layer in the atmosphere acts as a protective blanket and absorbs most of this ultraviolet radiation.

❖In heat transfer studies, we are interested in the energy emitted by bodies because of their temperature only. Therefore, we limit our consideration to *thermal radiation*.

❖The electrons, atoms, and molecules of all solids, liquids, and gases above absolute zero temperature are constantly in motion, and thus radiation is constantly emitted, as well as being absorbed or transmitted throughout the entire volume of matter. That is, radiation is a volumetric phenomenon.



Black Body Radiation

- Different bodies may emit different amounts of radiation per unit surface area.
- A blackbody emits the *maximum* amount of radiation by a surface at a given temperature.
- It is an *idealized body* to serve as a standard against which the radiative properties of real surfaces may be compared.
- A blackbody is *a perfect emitter and absorber of radiation*.
- A blackbody absorbs *all* incident radiation, regardless of wavelength and direction.

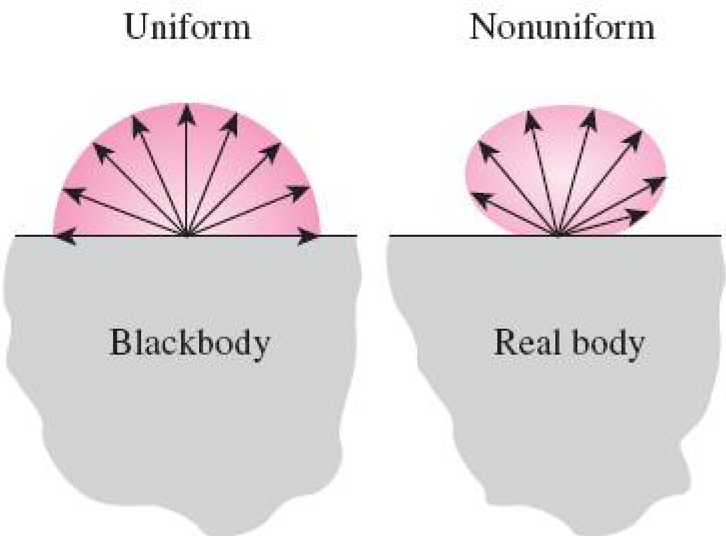
The radiation energy emitted by a blackbody:

$$E_b(T) = \sigma T^4 \qquad (\mathrm{W/m^2})$$

Blackbody emissive power

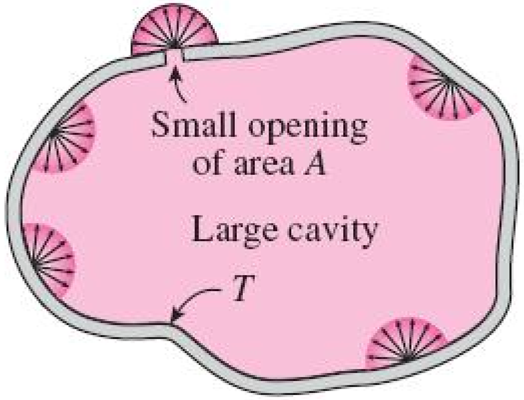
$$\sigma = 5.670 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$$

Stefan–Boltzmann constant



Spectral blackbody emissive Power:

The amount of radiation energy emitted by a blackbody at a thermodynamic temperature T per unit time, per unit surface area, and per unit wavelength about the wavelength λ.



A cavity which resembles black body

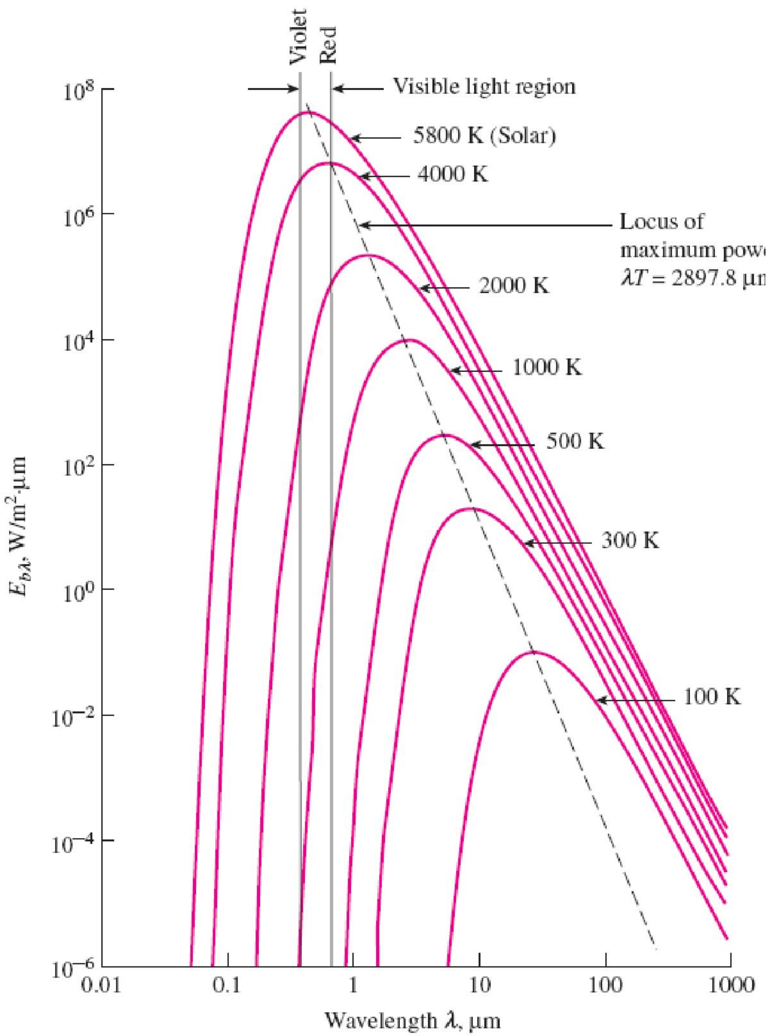
$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \quad (\mathrm{W/m^2 \cdot \mu m})$$ Planck's law

$$C_1 = 2\pi h c_0^2 = 3.74177 \times 10^8 \ \mathrm{W \cdot \mu m^4/m^2}$$

$$C_2 = hc_0/k = 1.43878 \times 10^4 \ \mathrm{\mu m \cdot K}$$

$$k = 1.38065 \times 10^{-23} \ \mathrm{J/K}$$ *Boltzmann's constant*

Black Body Radiation



The variation of the blackbody emissive power with wavelength for several temperatures.

The wavelength at which the peak occurs for a specified temperature is given by Wien's displacement law:

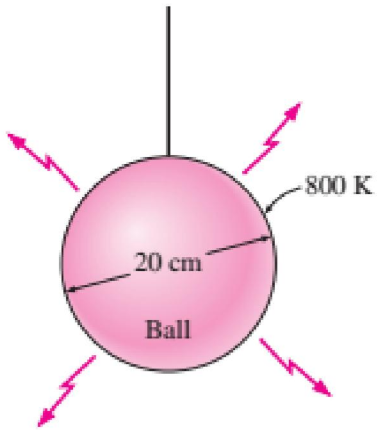
$$(\lambda T)_{\text{max power}} = 2897.8\ \mu\text{m} \cdot \text{K}$$

Important observations

- The emitted radiation is a continuous function of *wavelength*. At any specified temperature, it increases with wavelength, reaches a peak, and then decreases with increasing wavelength.
- At any wavelength, the amount of emitted radiation *increases* with increasing temperature.
- As temperature increases, the curves shift to the left to the shorter wavelength region. Consequently, a larger fraction of the radiation is emitted at *shorter wavelengths* at higher temperatures.
- The radiation emitted by the *sun*, which is considered to be a blackbody at 5780 K (or roughly at 5800 K), reaches its peak in the visible region of the spectrum. Therefore, the sun is in tune with our eyes.
- On the other hand, surfaces at $T < 800$ K emit almost entirely in the infrared region and thus are not visible to the eye unless they reflect light coming from other sources.

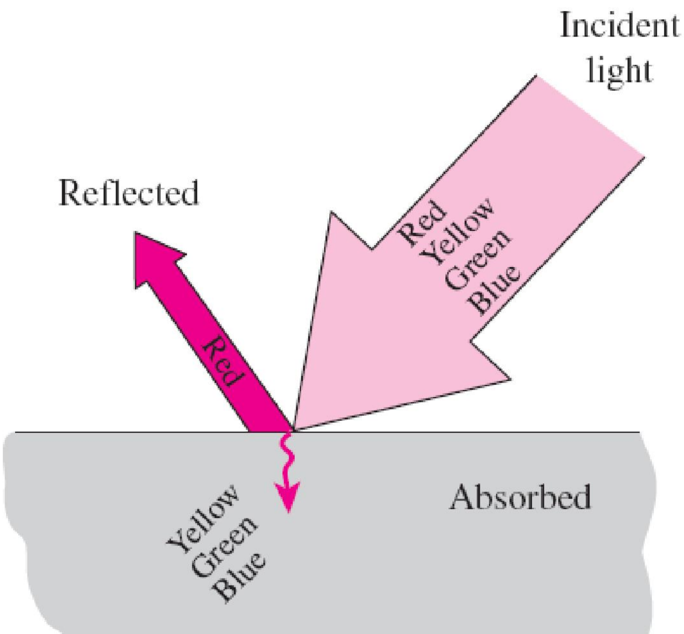
Example: Black Ball !

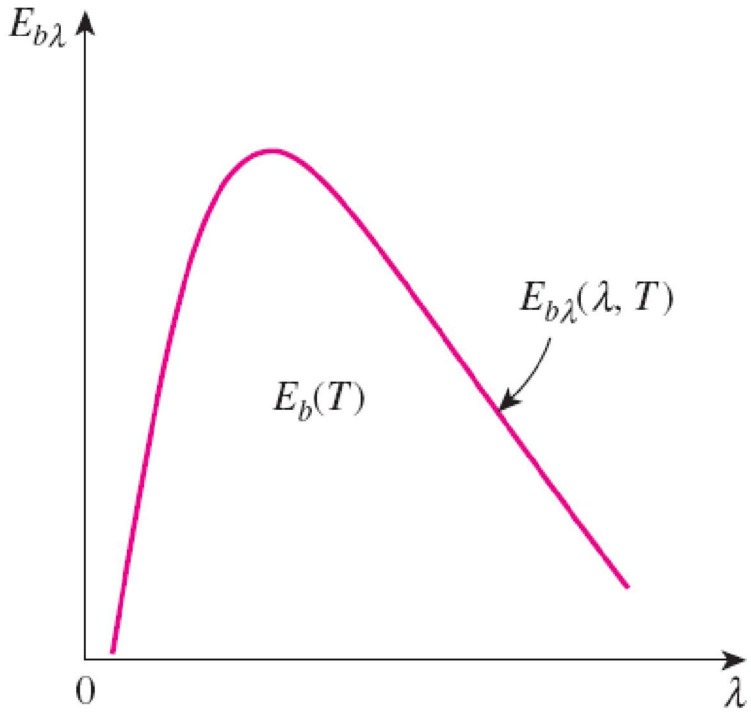
- Consider a 20-cm-diameter spherical ball at 800 K suspended in air. Assuming the ball closely approximates a blackbody, determine
- ✓ (*a*) the total blackbody emissive power
- ✓ (*b*) the total amount of radiation emitted by the ball in 5 min
- ✓ (*c*) the spectral blackbody emissive power at a wavelength of 3 μm



Important observations

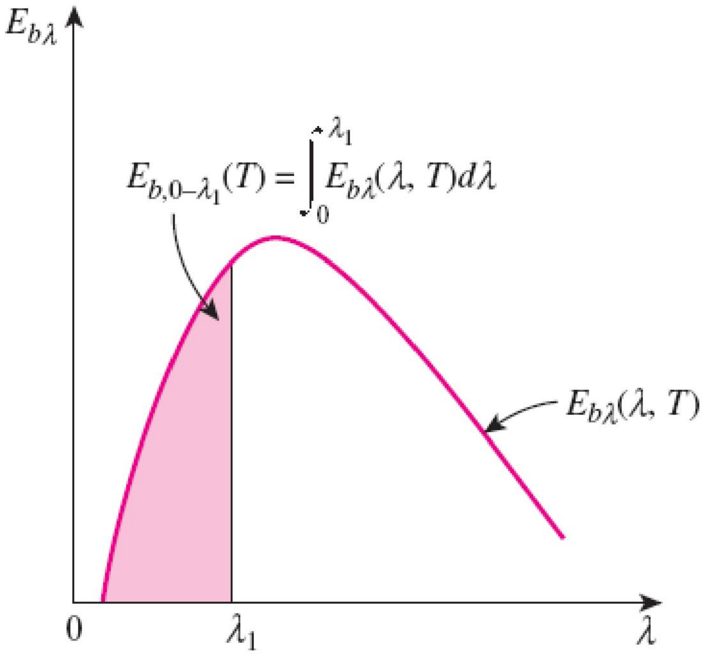
$$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T)\, d\lambda = \sigma T^4 \qquad (\mathrm{W/m^2})$$





The radiation energy emitted by a blackbody per unit area over a wavelength band from $\lambda = 0$ to λ is:

$$E_{b,\,0-\lambda}(T) = \int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda \qquad (\mathrm{W/m^2})$$



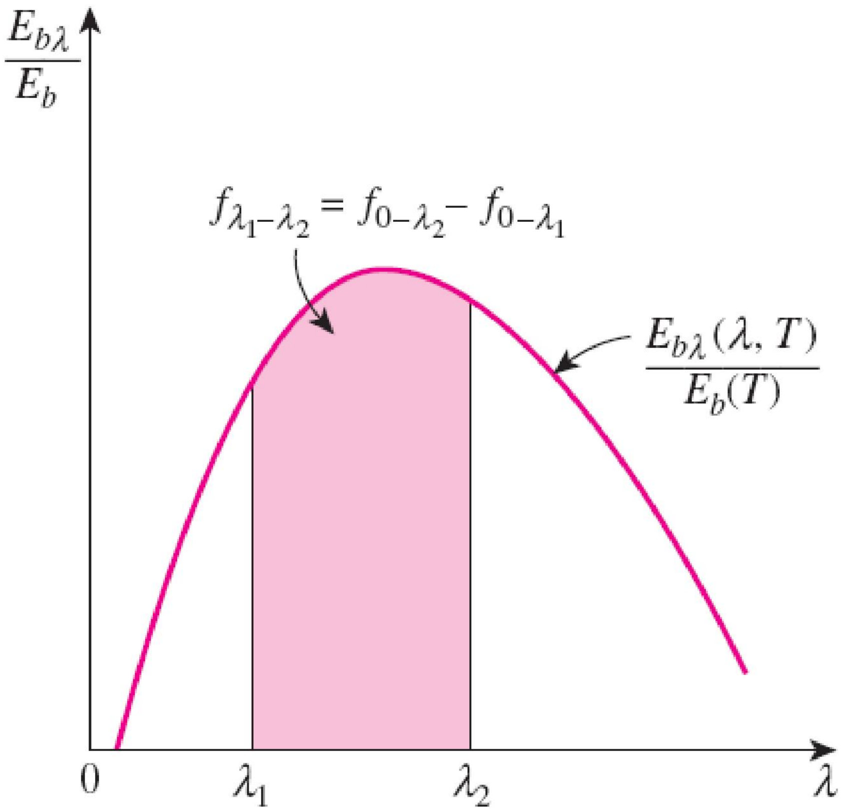
Blackbody radiation function f_λ:

The fraction of radiation emitted from a blackbody at temperature T in the wavelength band from $\lambda = 0$ to λ.

$$f_\lambda(T) = \frac{\int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4}$$

$$f_{\lambda_1-\lambda_2}(T) = f_{\lambda_2}(T) - f_{\lambda_1}(T)$$

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



Blackbody radiation functions f_λ

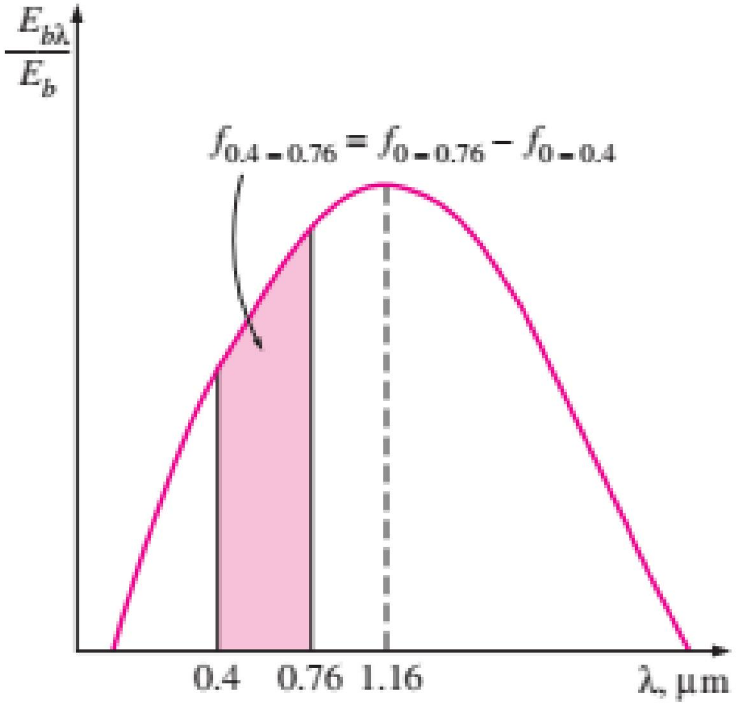
λT, μm·K	f_λ	λT, μm·K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905

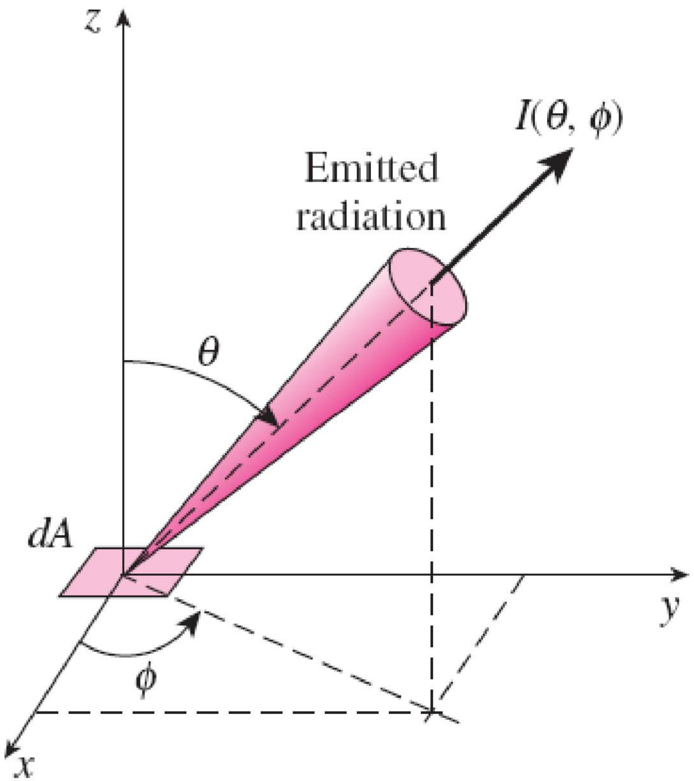
Example: Radiation from a light bulb

- The temperature of the filament of an incandescent light bulb is 2500 K. Assuming the filament to be a blackbody, determine the fraction of the radiant energy emitted by the filament that falls in the visible range. Also, determine the wavelength at which the emission of radiation from the filament peaks.

Example: Radiation from a light bulb

- The temperature of the filament of an incandescent light bulb is 2500 K. Assuming the filament to be a blackbody, determine the fraction of the radiant energy emitted by the filament that falls in the visible range. Also, determine the wavelength at which the emission of radiation from the filament peaks.

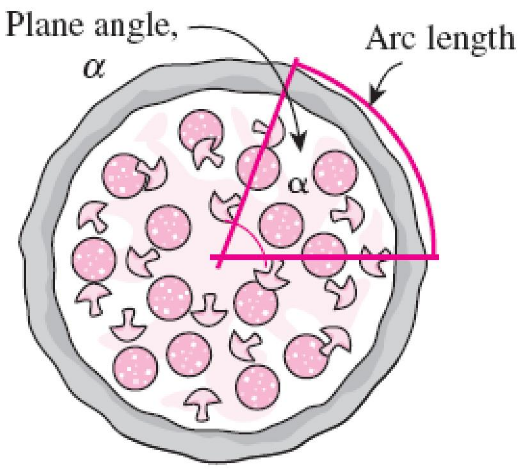




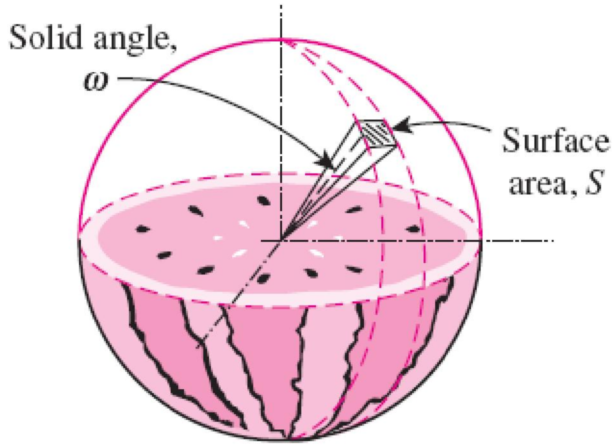
❖Radiation is emitted by all parts of a plane surface in all directions into the hemisphere above the surface, and the directional distribution of emitted (or incident) radiation is usually not uniform.

❖ Therefore, we need a quantity that describes the magnitude of radiation emitted (or incident) in a specified direction in space. This quantity is *radiation intensity,* denoted by *I*.

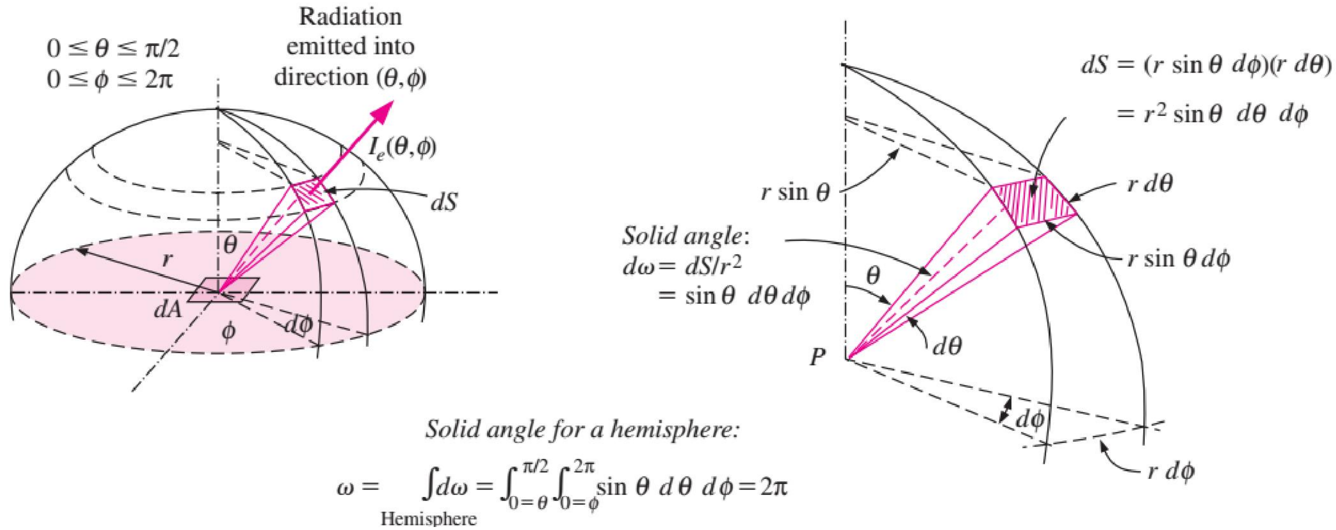
Solid Angle



A slice of pizza of plane angle α



A slice of watermelon of solid angle ω



$$S = \int_{\text{sphere}} dS = \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} r^2 \sin\theta d\theta\phi = 2\pi r^2 \int_{\theta=0}^{\pi} \sin\theta d\theta = 4\pi r^2$$

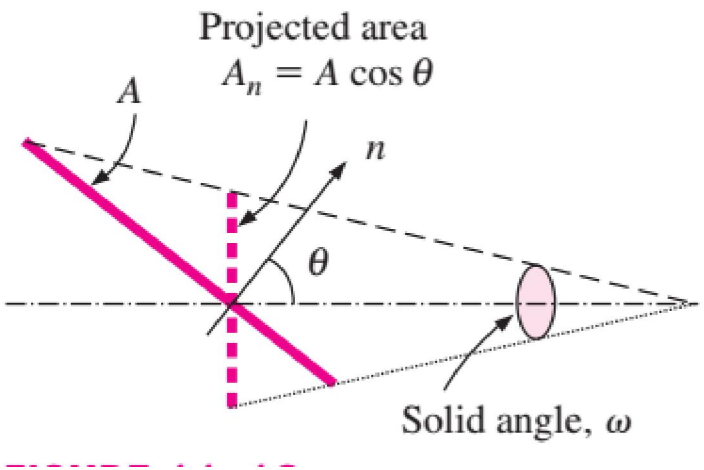
$$d\omega = \frac{dS}{r^2} = \sin\theta d\theta d\phi$$

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

Solid Angle: tilted surfaces

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

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



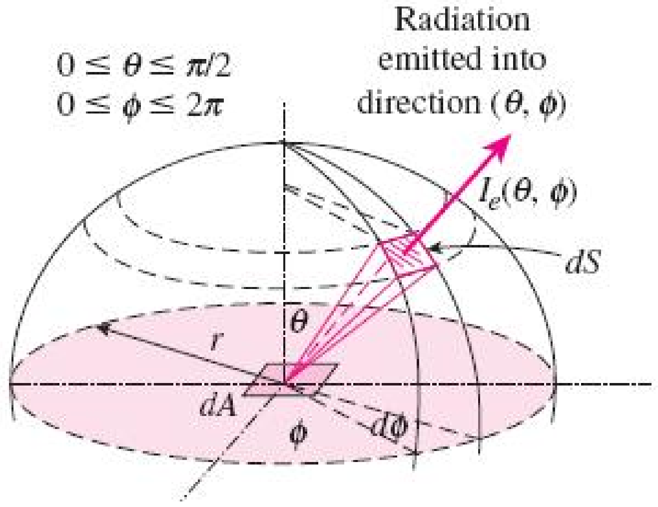
Example: solid angle of a small surface

- Find the solid angle subtended by a 5 cm2 plane surface when viewed from a point O at a distance of 80 cm along the normal of the surface
- Find the solid angle for the same case while the surface is tilted so that the normal of the surface makes an angle of 60° with the line connecting point O to the center of the surface,

Intensity of Emitted Radiation

The **radiation intensity** for emitted radiation is defined as the rate at which radiation energy is emitted in the direction per unit area normal to this direction and per unit solid angle about this direction:

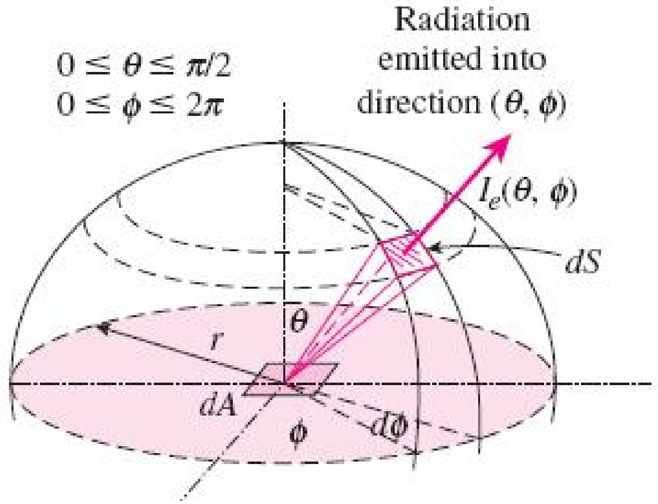
$$I_e(\theta, \phi) = \frac{d\dot{Q}_e}{dA \cos\theta \cdot d\omega} = \frac{d\dot{Q}_e}{dA \cos\theta \sin\theta d\theta d\phi} \qquad (\text{W/m}^2 \cdot \text{sr})$$



Emissive Power

The **radiation flux** for emitted radiation is the **emissive power E** (the rate at which radiation energy is emitted per unit area of the emitting surface), which can be expressed in differential form as
:

$$dE = \frac{d\dot{Q}_e}{dA} = I_e(\theta, \phi) \cos\theta \sin\theta d\theta d\phi$$



Emissive Power

Noting that the hemisphere above the surface will intercept all the radiation rays emitted by the surface, the emissive power from the surface into the hemisphere surrounding it can be determined by integration as:

$$E = \int_{\text{hemisphere}} dE = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I_e(\theta, \phi) \cos\theta \sin\theta d\theta d\phi \qquad (\text{W/m}^2)$$

The intensity of radiation emitted by a surface, in general, varies with direction (especially with the zenith angle). But many surfaces in practice can be approximated as being diffuse. For a diffusely emitting surface, the intensity of the emitted radiation is independent of direction and thus the emissivity is constant:

$$\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \cos\theta \sin\theta d\theta d\phi = \pi$$

Diffusely emitting surface: $\quad E = \pi I_e$

Emissive Power: Black Body

Since the emissive power of the black body was previously defined, the corresponding intensity can be determined:

Blackbody: $$E_b = \pi I_b$$

Blackbody: $$I_b(T) = \frac{E_b(T)}{\pi} = \frac{\sigma T^4}{\pi} \qquad (\mathrm{W/m^2 \cdot sr})$$

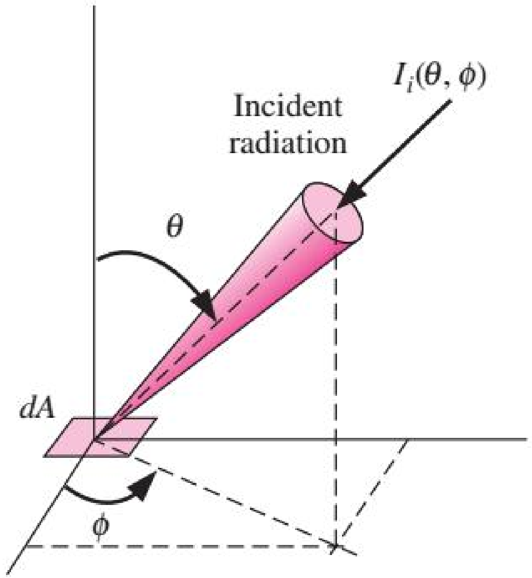
Incident radiation

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

❖The intensity of incident radiation is defined as the rate at which radiation energy dG is incident from a specific direction per unit area of the receiving surface normal to this direction and per unit solid angle about this direction.

❖The radiation flux incident on a surface from all directions is called **irradiation** G, and is expressed as:

$$G = \int_{\text{hemisphere}} dG = \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} I_i(\theta, \phi)\cos\theta \sin\theta\, d\theta\, d\phi \qquad (\mathrm{W/m^2})$$



❖Considering a diffuse surface:

Diffusely incident radiation: $\quad G = \pi I_i \qquad (\mathrm{W/m^2})$

Radiosity

❖Surfaces emit radiation as well as reflecting it, and thus the radiation leaving a surface consists of emitted and reflected components

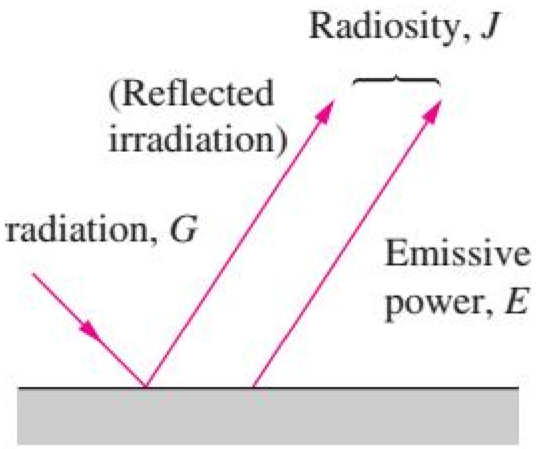
❖The calculation of radiation heat transfer between surfaces involves the total radiation energy streaming away from a surface, with no regard for its origin.

❖Thus, we need to define a quantity that represents the rate at whichradiation energy leaves a unit area of a surface in all directions. This quantity is called the radiosity J, and is expressed as:

$$J = \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} I_{e+r}(\theta, \phi)\cos\theta\sin\theta d\theta d\phi \qquad (\text{W/m}^2)$$

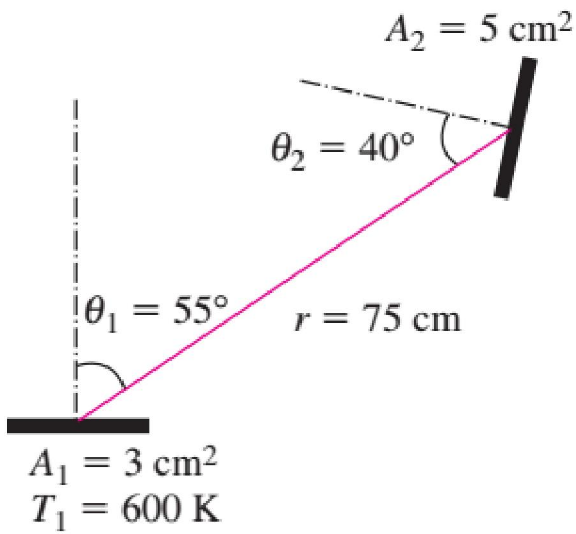
❖Considering a diffuse surface:

Diffuse emitter and reflector: $J = \pi I_{e+r} \qquad (\text{W/m}^2)$



Example

❖A small surface of area $A1$=3 cm2 emits radiation as a blackbody at $T1$ = 600 K. Part of the radiation emitted by $A1$ strikes another small surface of area $A2$ = 5 cm2 oriented as shown in Figure 11–23. Determine the solid angle subtended by $A2$ when viewed from $A1$, and the rate at which radiation emitted by $A1$ that strikes $A2$.



Spectral Quantiles

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

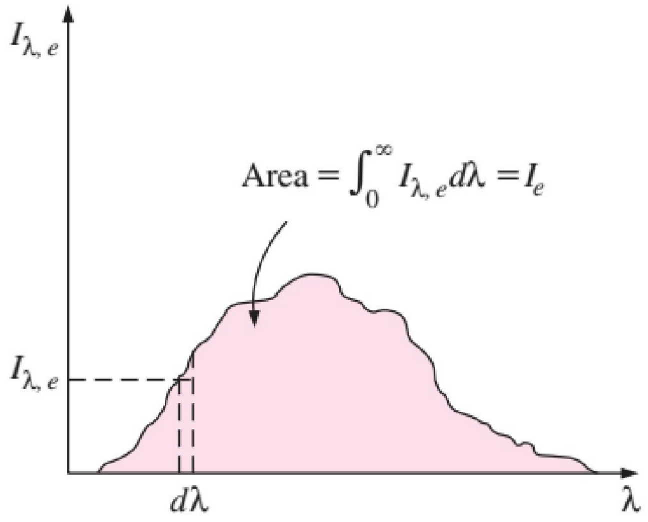
❖This lumped approach is adequate for many radiation problems encountered in practice.

❖But sometimes it is necessary to consider the variation of radiation with wavelength as well as direction, and to express quantities at a certain wavelength or per unit wavelength interval . Such quantities are referred to as spectral quantities to draw attention to wavelength dependence. The modifier "spectral" is used to indicate "at a given wavelength.
Which radiation energy leaves a unit area of a surface in all directions. This quantity is called the radiosity J, and is expressed as:

$$I_{\lambda,e}(\lambda,\theta,\phi) = \frac{d\dot{Q}_e}{dA\cos\theta \cdot d\omega \cdot d\lambda} \qquad (\mathrm{W/m^2 \cdot sr \cdot \mu m})$$

❖Spectral emissive power:

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



Radiative Properties

- Most materials encountered in practice, such as metals, wood, and bricks, are *opaque* to thermal radiation, and radiation is considered to be a *surface phenomenon* for such materials.
- Radiation through *semitransparent* materials such as glass and water cannot be considered to be a surface phenomenon since the entire volume of the material interacts with radiation.
- A blackbody can serve as a convenient *reference* in describing the emission and absorption characteristics of real surfaces.

Emissivity

- Emissivity: *The ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature.* $0 \leq \varepsilon \leq 1$.
- Emissivity is a measure of how closely a surface approximates a blackbody ($\varepsilon = 1$).
- The emissivity of a real surface varies with the *temperature* of the surface as well as the *wavelength* and the *direction* of the emitted radiation.
- The emissivity of a surface at a specified wavelength is called *spectral emissivity* ε_λ. The emissivity in a specified direction is called *directional emissivity* ε_θ where θ is the angle between the direction of radiation and the normal of the surface.

Emissivity

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T)=\frac{I_{\lambda,e}(\lambda,\theta,\phi,T)}{I_{b\lambda}(\lambda,T)}$$ spectral directional emissivity

$$\varepsilon_{\theta}(\theta,\phi,T)=\frac{I_{e}(\theta,\phi,T)}{I_{b}(T)}$$ total directional emissivity

$$\varepsilon_{\lambda}(\lambda,T)=\frac{E_{\lambda}(\lambda,T)}{E_{b\lambda}(\lambda,T)}$$ spectral hemispherical emissivity

$$\varepsilon(T)=\frac{E(T)}{E_{b}(T)}$$ total hemispherical emissivity

$$\varepsilon(T)=\frac{E(T)}{E_{b}(T)}=\frac{\int_0^\infty \varepsilon_{\lambda}(\lambda,T)E_{b\lambda}(\lambda,T)d\lambda}{\sigma T^4}$$

The ratio of the total radiation energy emitted by the surface to the radiation emitted by a blackbody of the same surface area at the same temperature

Emissivity

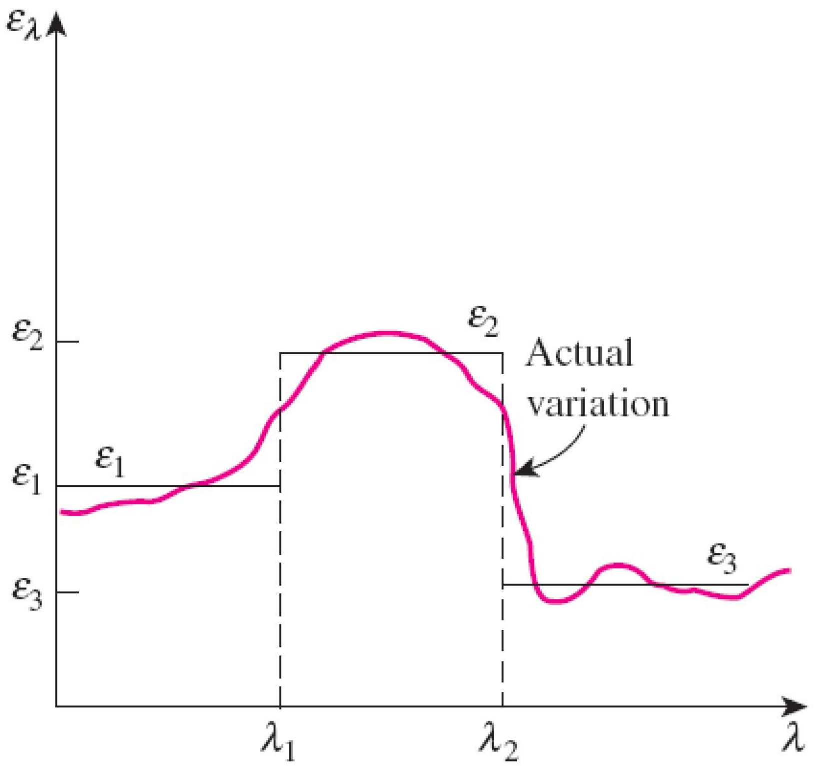


FIGURE 12–24

Approximating the actual variation of emissivity with wavelength by a step function.

$$\varepsilon_\lambda = \begin{cases} \varepsilon_1 = \text{constant}, & 0 \leq \lambda < \lambda_1 \\ \varepsilon_2 = \text{constant}, & \lambda_1 \leq \lambda < \lambda_2 \\ \varepsilon_3 = \text{constant}, & \lambda_2 \leq \lambda < \infty \end{cases}$$

$$\varepsilon(T) = \frac{\varepsilon_1 \int_0^{\lambda_1} E_{b\lambda}\, d\lambda}{E_b} + \frac{\varepsilon_2 \int_{\lambda_1}^{\lambda_2} E_{b\lambda}\, d\lambda}{E_b} + \frac{\varepsilon_3 \int_{\lambda_2}^{\infty} E_{b\lambda}\, d\lambda}{E_b}$$

$$= \varepsilon_1 f_{0-\lambda_1}(T) + \varepsilon_2 f_{\lambda_1-\lambda_2}(T) + \varepsilon_3 f_{\lambda_2-\infty}(T)$$

Emissivity

❖A surface is said to be *diffuse* if its properties are *independent of direction*, and *gray* if its properties are *independent of wavelength*.

Real surface:

$\varepsilon_\theta \neq$ constant

$\varepsilon_\lambda \neq$ constant

Diffuse surface:

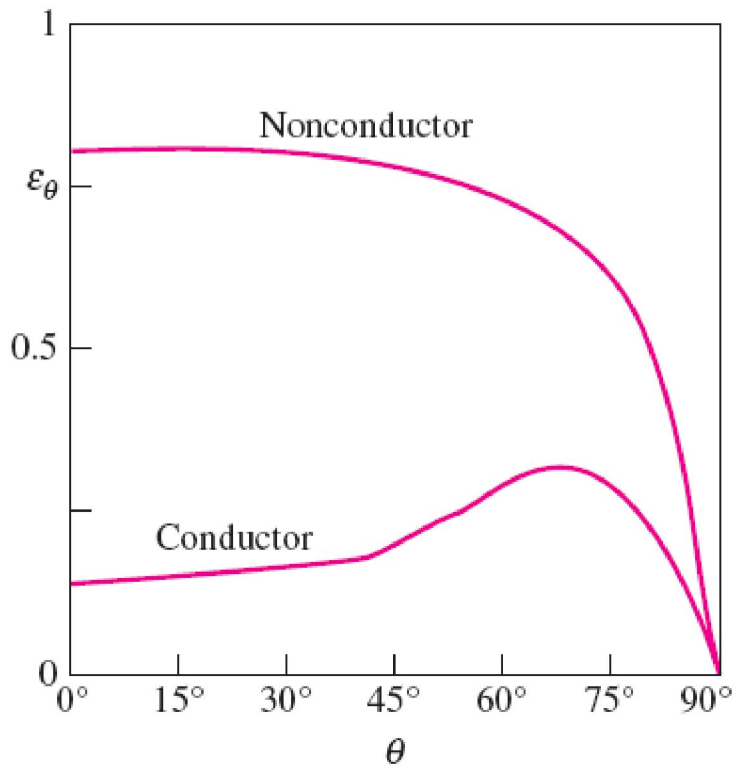
$\varepsilon_\theta =$ constant

Gray surface:

$\varepsilon_\lambda =$ constant

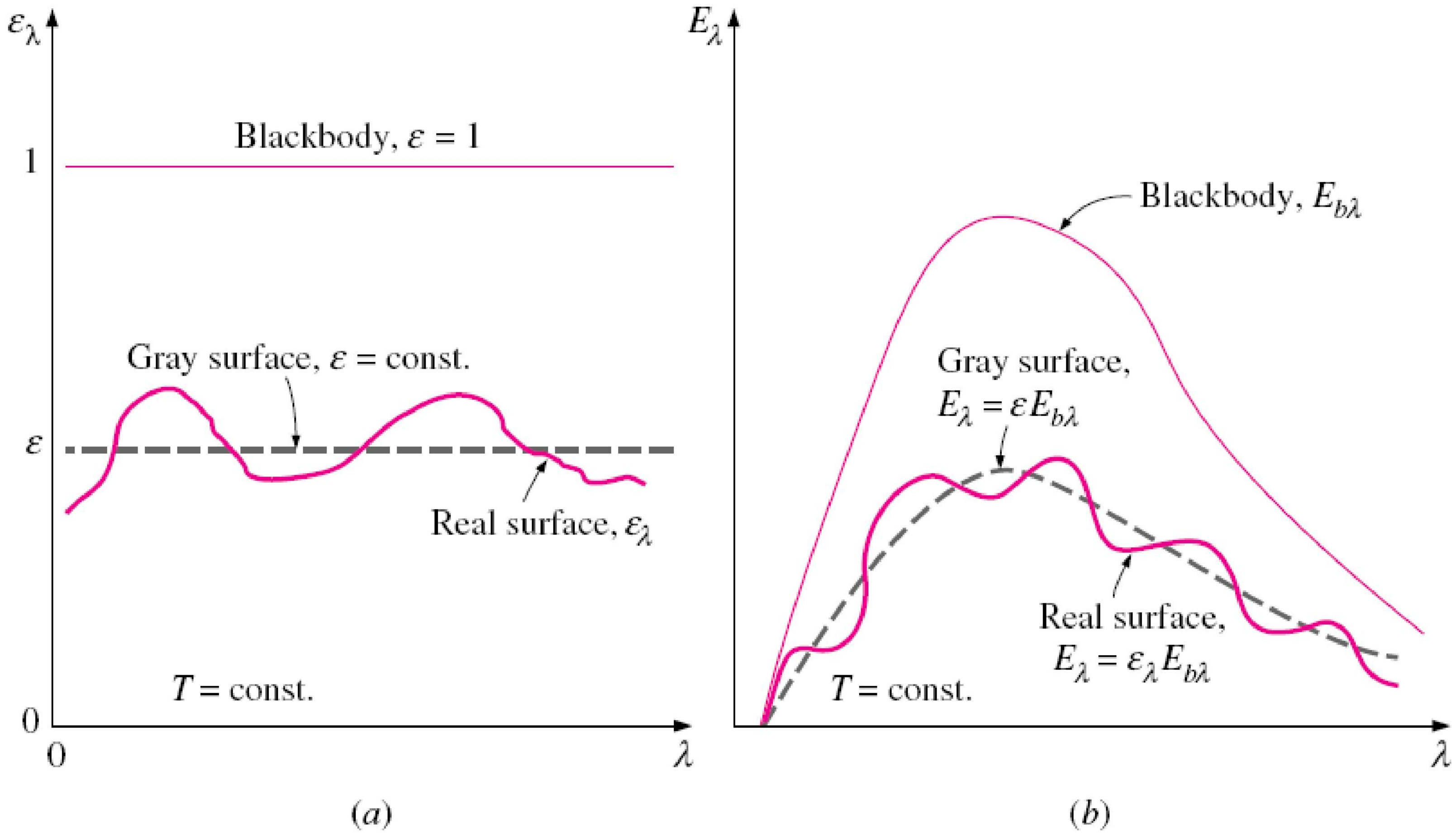
Diffuse, gray surface:

$\varepsilon = \varepsilon_\lambda = \varepsilon_\theta =$ constant

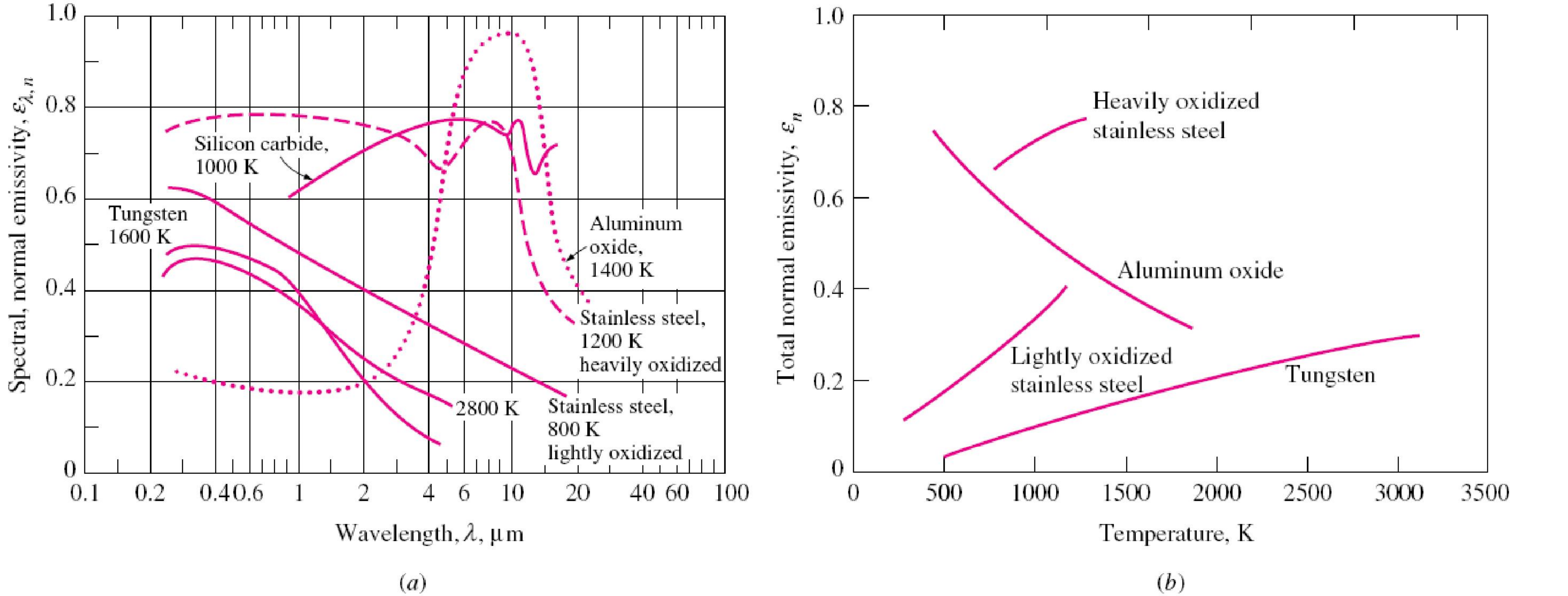


θ is the angle measured from the normal of the surface

Emissivity

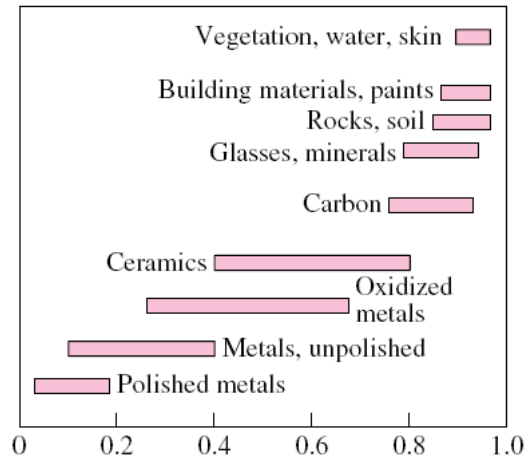

ε_λ
Blackbody, ε = 1
1
Gray surface, ε = const.
ε
Real surface, ε_λ
T = const.
0
0
λ
(a)
E_λ
Blackbody, $E_{b\lambda}$
Gray surface,
$E_\lambda = \varepsilon E_{b\lambda}$
Real surface,
$E_\lambda = \varepsilon_\lambda E_{b\lambda}$
T = const.
λ
(b)

Emissivity



The variation of normal emissivity with (*a*) wavelength and (*b*) temperature for various materials.

Typical ranges of emissivity for various materials.



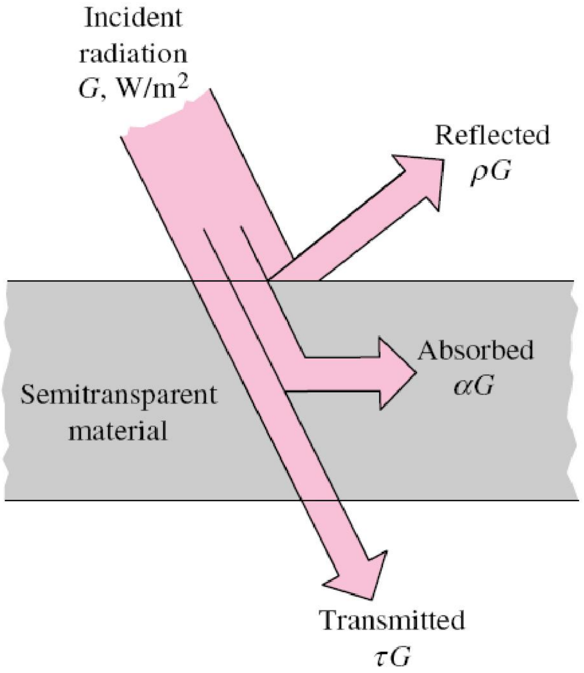
Absorptivity, Reflectivity, Transmissivity

Absorptivity: $\alpha = \dfrac{\text{Absorbed radiation}}{\text{Incident radiation}} = \dfrac{G_{abs}}{G}, \quad 0 \leq \alpha \leq 1$

Reflectivity: $\rho = \dfrac{\text{Reflected radiation}}{\text{Incident radiation}} = \dfrac{G_{ref}}{G}, \quad 0 \leq \rho \leq 1$

Transmissivity: $\tau = \dfrac{\text{Transmitted radiation}}{\text{Incident radiation}} = \dfrac{G_{tr}}{G}, \quad 0 \leq \tau \leq 1$

Irradiation, G: Radiation flux *incident on a surface.*



$$G_{abs} + G_{ref} + G_{tr} = G$$

$$\alpha + \rho + \tau = 1$$

$\alpha + \rho = 1$ for opaque surfaces

Spectral and directional properties

$$\alpha_\lambda(\lambda) = \frac{G_{\lambda,\,\mathrm{abs}}(\lambda)}{G_\lambda(\lambda)}$$ spectral hemispherical absorptivity

$$\rho_\lambda(\lambda) = \frac{G_{\lambda,\,\mathrm{ref}}(\lambda)}{G_\lambda(\lambda)}$$ spectral hemispherical reflectivity

$$\tau_\lambda(\lambda) = \frac{G_{\lambda,\,\mathrm{tr}}(\lambda)}{G_\lambda(\lambda)}$$ spectral hemispherical transmissivity

spectral directional absorptivity

$$\alpha_{\lambda,\,\theta}(\lambda,\theta,\phi) = \frac{I_{\lambda,\,\mathrm{abs}}(\lambda,\theta,\phi)}{I_{\lambda,\,i}(\lambda,\theta,\phi)}$$

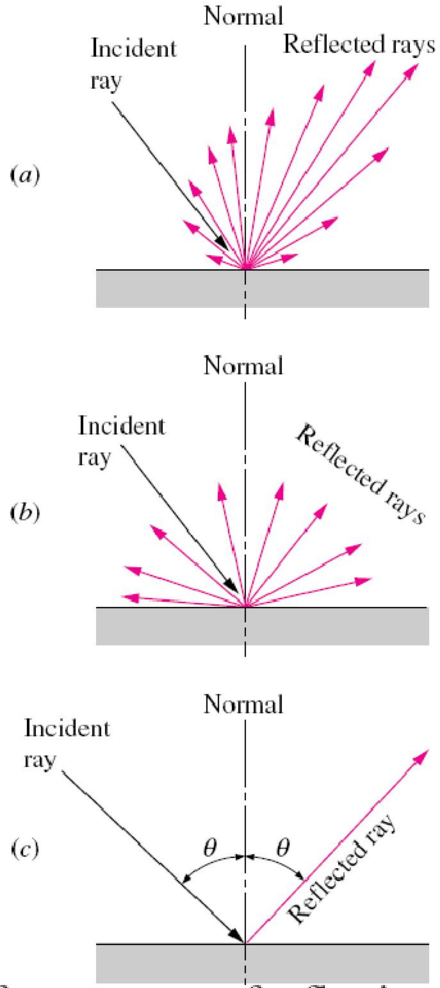
spectral directional reflectivity

$$\rho_{\lambda,\,\theta}(\lambda,\theta,\phi) = \frac{I_{\lambda,\,\mathrm{ref}}(\lambda,\theta,\phi)}{I_{\lambda,\,i}(\lambda,\theta,\phi)}$$

G_λ: the spectral irradiation, W/m^2·µm

Average absorptivity, reflectivity, and transmissivity of a surface:

$$\alpha = \frac{\int_0^\infty \alpha_\lambda G_\lambda\, d\lambda}{\int_0^\infty G_\lambda\, d\lambda}, \qquad \rho = \frac{\int_0^\infty \rho_\lambda G_\lambda\, d\lambda}{\int_0^\infty G_\lambda\, d\lambda}, \qquad \tau = \frac{\int_0^\infty \tau_\lambda G_\lambda\, d\lambda}{\int_0^\infty G_\lambda\, d\lambda}$$



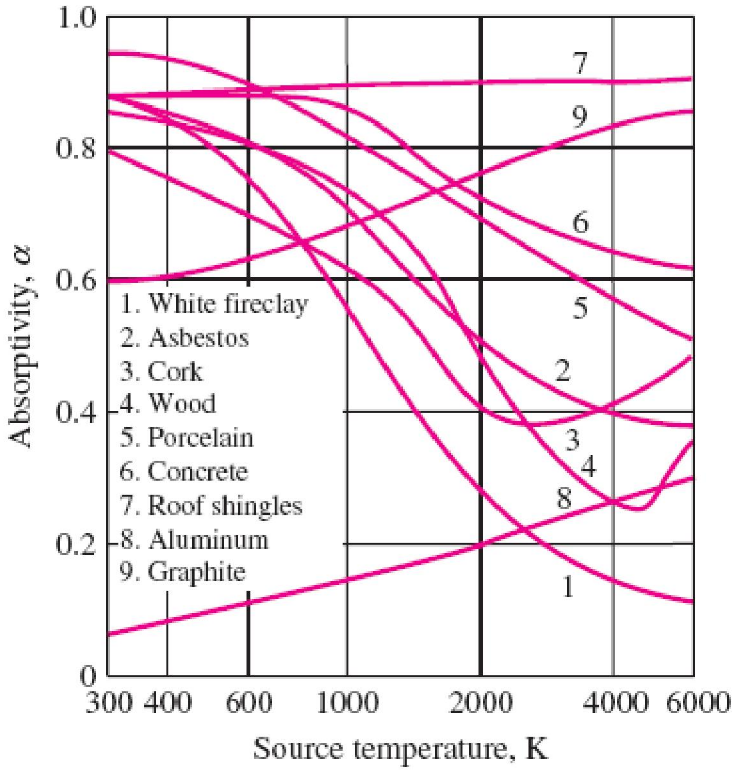
Different types of reflection from a surface: (*a*) actual or irregular, (*b*) diffuse, and (*c*) specular or mirrorlike.

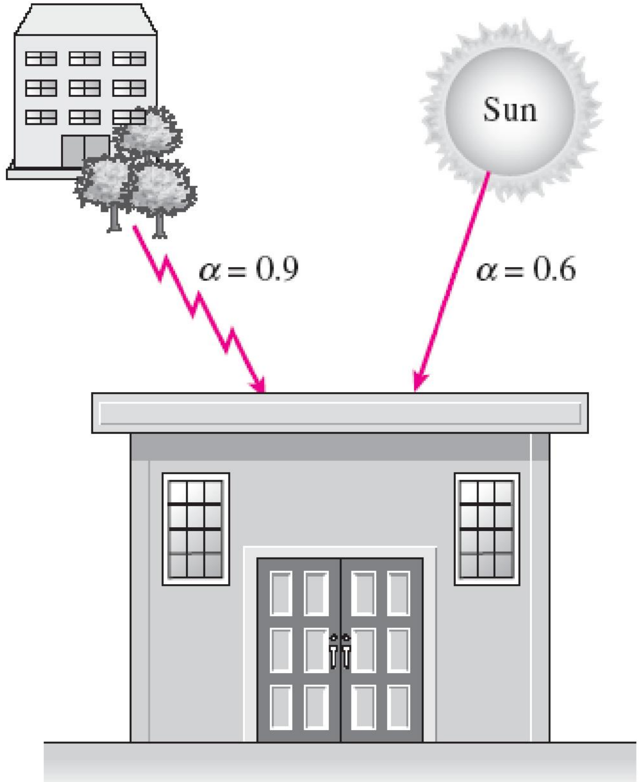
In practice, surfaces are assumed to reflect in a perfectly specular or diffuse manner.

Specular (or mirrorlike) reflection: The angle of reflection equals the angle of incidence of the radiation beam.

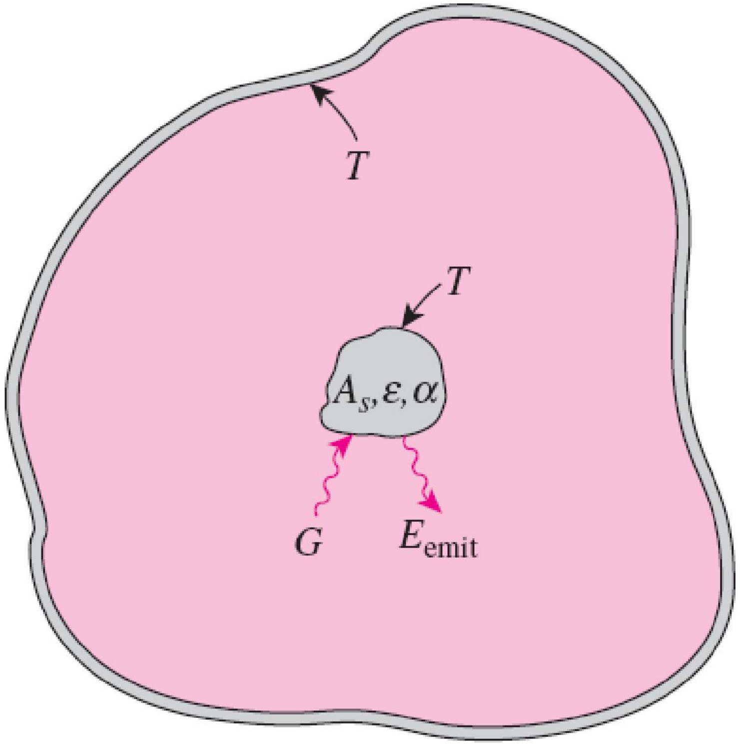
Diffuse reflection:

Radiation is reflected equally in all directions.





The absorptivity of a material may be quite different for radiation originating from sources at different temperatures.



$$G_{abs} = \alpha G = \alpha \sigma T^4$$

$$E_{emit} = \varepsilon \sigma T^4$$

$$A_s \varepsilon \sigma T^4 = A_s \alpha \sigma T^4$$

$\varepsilon(T) = \alpha(T)$ Kirchhoff's law

The total hemispherical emissivity of a surface at temperature T is equal to its total hemispherical absorptivity for radiation coming from a blackbody at the same temperature.

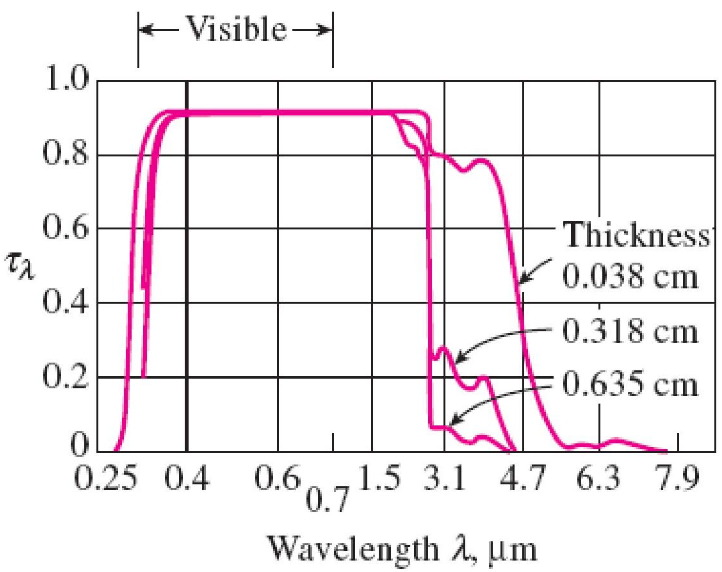
$\varepsilon_\lambda(T) = \alpha_\lambda(T)$ *spectral* form of Kirchhoff's law

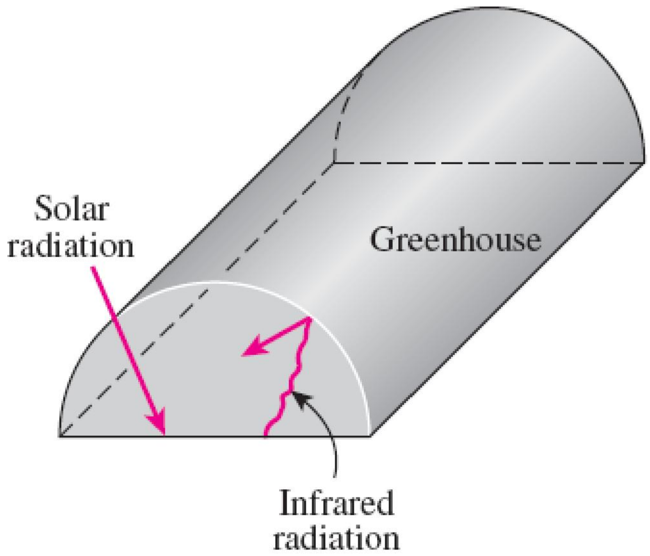
$\varepsilon_{\lambda,\theta}(T) = \alpha_{\lambda,\theta}(T)$ The emissivity of a surface at a specified wavelength, direction, and temperature is always equal to its absorptivity at the same wavelength, direction, and temperature.

❖Glass has a transparent window in the wavelength range 0.3 μm < λ < 3 μm in which over 90% of solar radiation is emitted. The entire radiation emitted by surfaces at room temperature falls in the infrared region (λ > 3 μm).

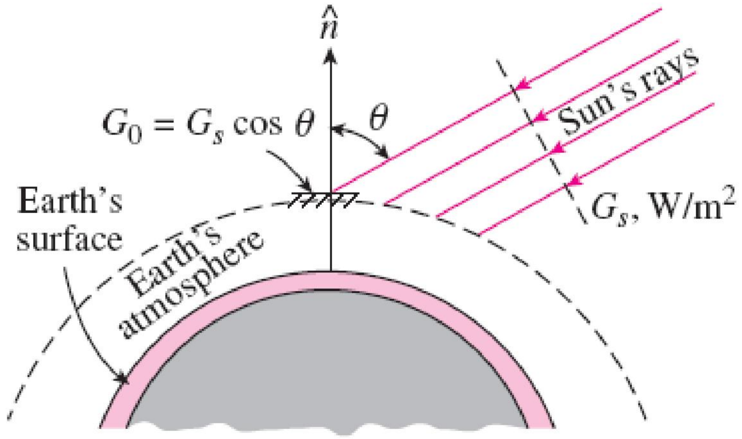
❖Glass allows the solar radiation to enter but does not allow the infrared radiation from the interior surfaces to escape. This causes a rise in the interior temperature as a result of the energy buildup in the car.

❖This heating effect, which is due to the non-gray characteristic of glass (or clear plastics), is known as the greenhouse effect.





❖*Atmospheric radiation:* The radiation energy emitted or reflected by the constituents of the atmosphere.



❖The energy of the sun is due to the continuous *fusion* reaction during which two hydrogen atoms fuse to form one atom of helium.

❖Therefore, the sun is essentially a *nuclear reactor,* with temperatures as high as 40,000,000 K in its core region.

❖The temperature drops to about 5800 K in the outer region of the sun, called the convective zone, as a result of the dissipation of this energy by radiation.

Total solar irradiance G_s: The solar energy reaching the earth's atmosphere is called the

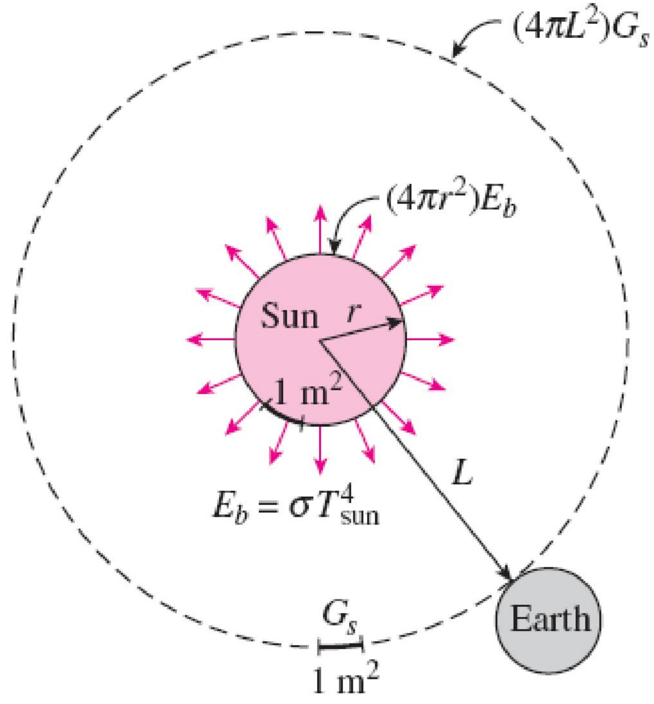
$$G_s = 1373 \text{ W/m}^2$$

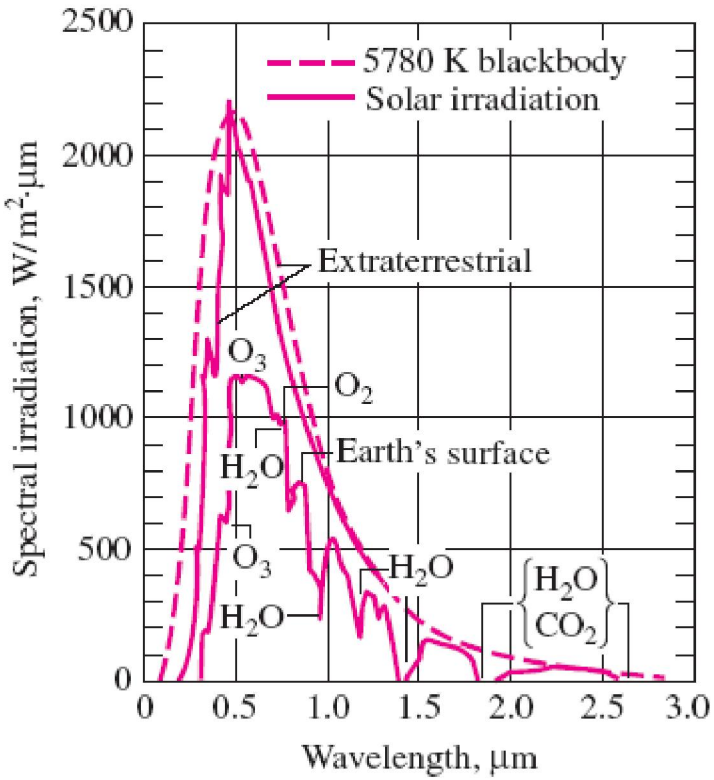
❖Solar constant: The total solar irradiance. It represents the rate at which solar energy is incident on a surface normal to the sun's rays at the outer edge of the atmosphere when the earth is at its mean distance from the sun

The value of the total solar irradiance can be used to estimate the effective surface temperature of the sun from the requirement that

The sun can be treated as a blackbody at a temperature of 5780 K.

$$(4\pi L^2)G_s = (4\pi r^2)\,\sigma T_{sun}^4$$



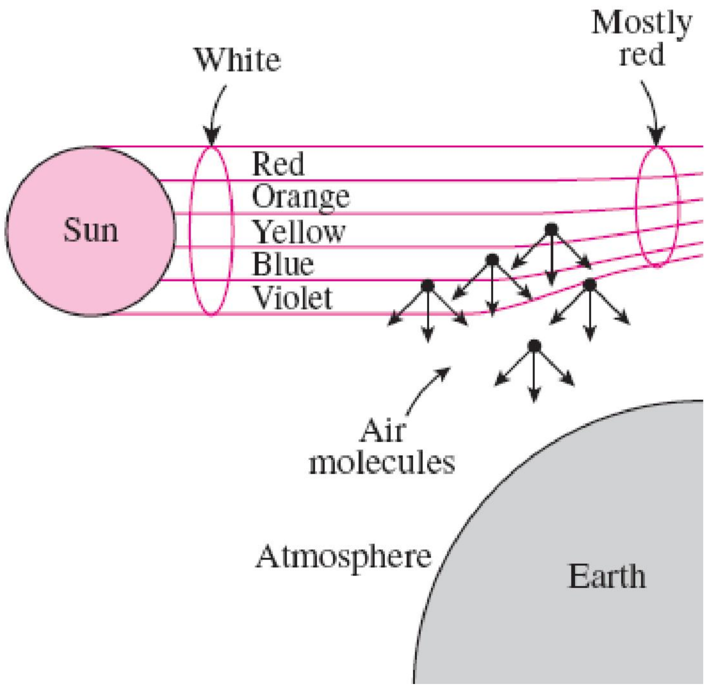


The solar energy incident on a surface on earth is considered to consist of *direct* and *diffuse* parts.

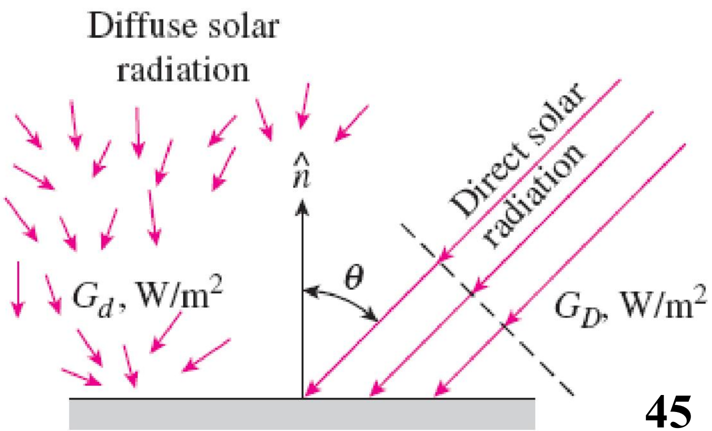
Direct solar radiation G_D: The part of solar radiation that reaches the earth's surface without being scattered or absorbed by the atmosphere.

Diffuse solar radiation G_d: The scattered radiation is assumed to reach the earth's surface uniformly from all directions.

The *total* solar energy incident on the unit area of a *horizontal surface* on the ground is



$$G_{solar} = G_D \cos\theta + G_d \qquad (\mathrm{W/m^2})$$



❖it is found convenient in radiation calculations to treat the atmosphere as a blackbody at some lower fictitious temperature that emits an equivalent amount of radiation energy. This fictitious temperature is called the effective sky temperature T_{sky}.

❖The radiation emission from the atmosphere to the earth's surface is

$$G_{sky} = \sigma T_{sky}^4 \qquad (W/m^2)$$

❖The value of T_{sky} depends on the atmospheric conditions. It ranges from about 230 K for cold, clear-sky conditions to about 285 K for warm, cloudy-sky conditions.

$$E_{sky,\ absorbed} = \alpha G_{sky} = \alpha\sigma T_{sky}^4 = \varepsilon\sigma T_{sky}^4 \qquad (W/m^2)$$

❖Net rate of radiation heat transfer to a surface exposed to solar and atmospheric radiation

$$\begin{aligned}\dot{q}_{net,\ rad} &= \Sigma E_{absorbed} - \Sigma E_{emitted} \\ &= E_{solar,\ absorbed} + E_{sky,\ absorbed} - E_{emitted} \\ &= \alpha_s G_{solar} + \varepsilon\sigma T_{sky}^4 - \varepsilon\sigma T_s^4 \\ &= \alpha_s G_{solar} + \varepsilon\sigma (T_{sky}^4 - T_s^4) \qquad (W/m^2)\end{aligned}$$