ME 476
Solar Energy

UNIT TWO
THERMAL RADIATION

Unit Outline

- Electromagnetic radiation
- Thermal radiation
- Blackbody radiation
- Radiation emitted from a real surface
- Irradiance
- Kirchhoff's Law
- Diffuse and gray surface
- View factor
- Radiation exchange between black bodies
- Radiation from a diffuse, gray surface

Electromagnetic Radiation

- The electromagnetic energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.
- Electromagnetic radiation energy is transported by waves
- These waves have a frequency (ν) and wavelength (λ).

Electromagnetic Radiation

- Frequency ν and wavelength λ Are related by:

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

where,

$C = C_0 / n$

C: the speed of propagation of a wave in the medium

C_0 = 2.9979×10^8 m/s, the *speed of light* in a vacuum

n, the *index of refraction* of that medium

Examples:

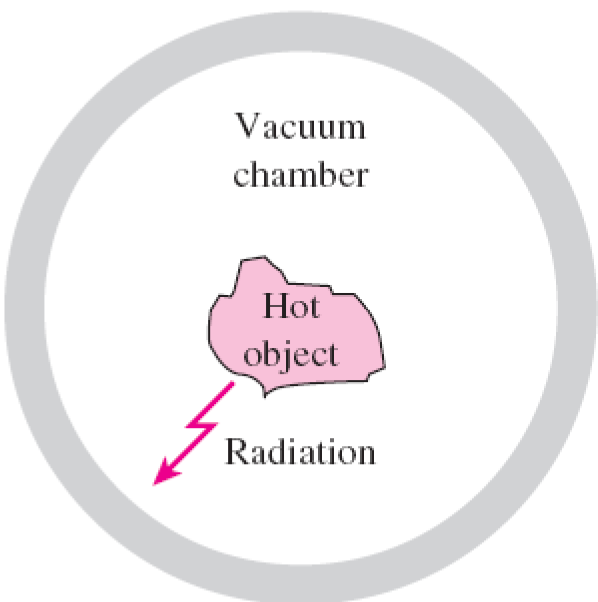
n =1 (air and most gases)

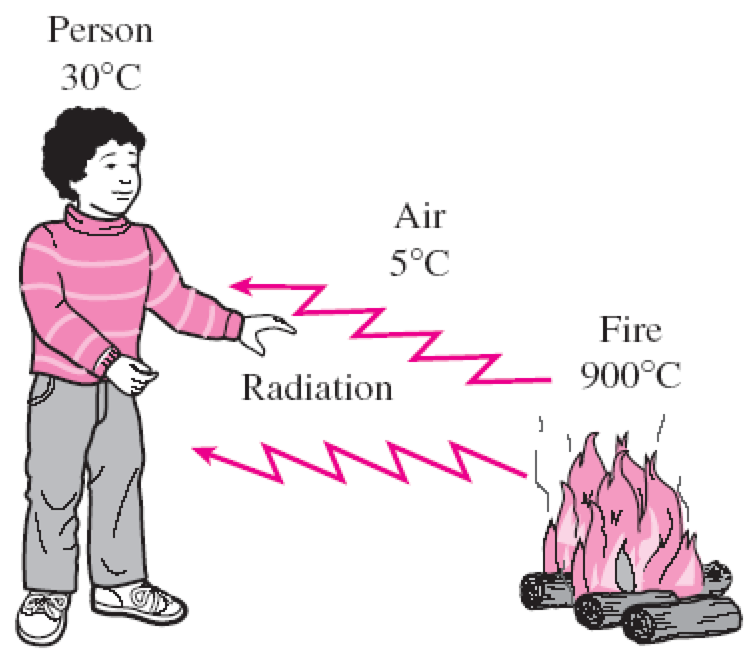
n = 1.5 (glass)

n = 1.33 (water)

Electromagnetic Radiation

- Radiation differs from conduction and convection
- It does not require the presence of a material medium
- Radiation transfer occurs in all types of matter (solid, liquid, or gas)





Electromagnetic Radiation

- Electromagnetic radiation can be viewed 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:

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

where *h* is called Planck's constant

$h = 6.6256 \times 10^{-34}$ J.s

- This means that the energy of a photon is inversely proportional to its wavelength

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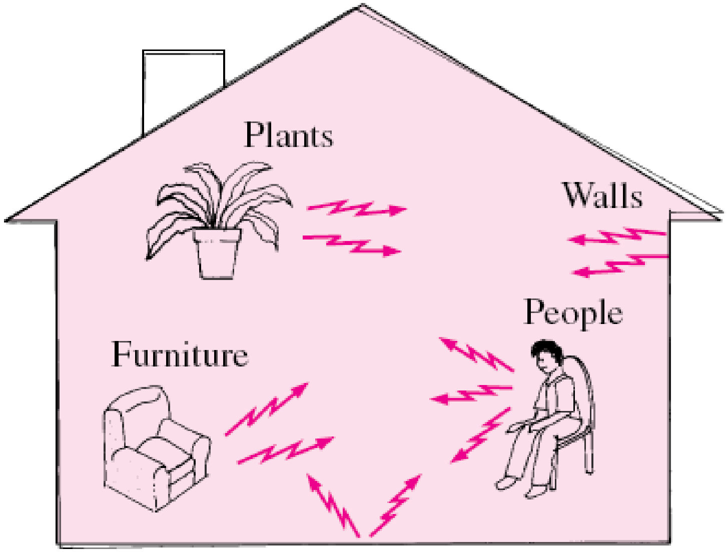
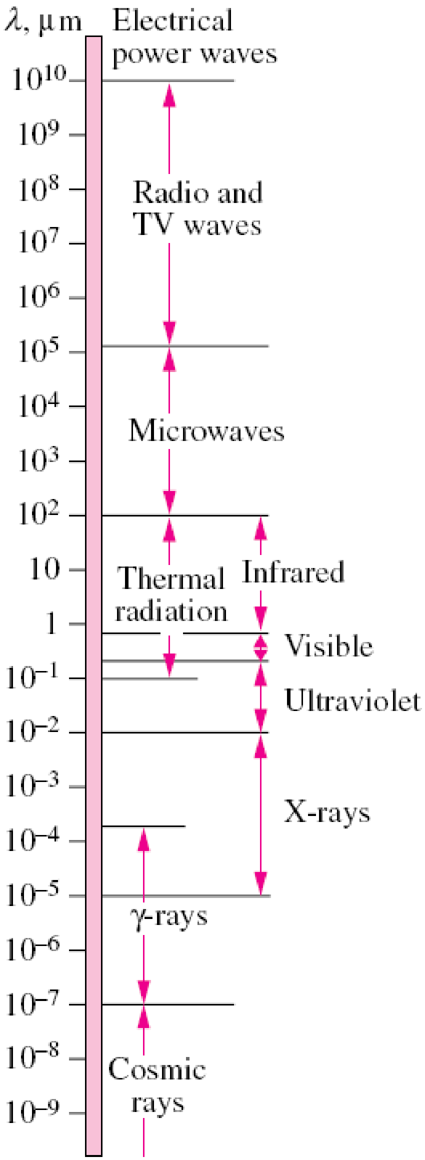
Thermal Radiation

- Thermal radiation is the part of electromagnetic radiation that primarily creates a heating effect.
- Thermal radiation is 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
- Therefore, thermal radiation emission increases with increasing temperature

Thermal Radiation

- Thermal radiation mainly covers:
  - **Infrared radiation**
  - **Visible light**
  - **Ultraviolet radiation**
- Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero.





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Blackbody Radiation

- A blackbody is a body that absorbs ***all*** the incident radiation regardless of wavelength and direction **AND** emits the ***maximum*** amount radiation 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.

Blackbody Radiation

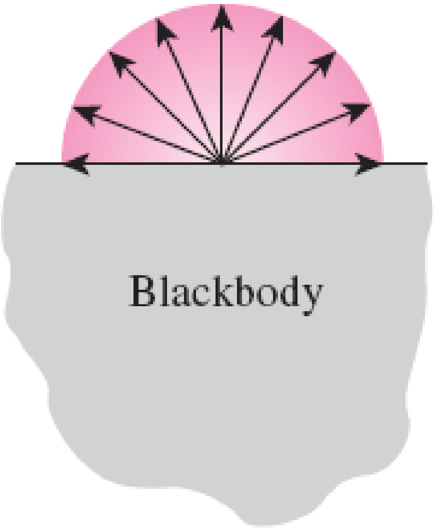
- The amount of radiation emitted by a blackbody is given by **Planck's Law**:

$$E_{\lambda b} = \frac{2\pi h C_o^2}{\lambda^5[\exp(hC_o/\lambda kT) - 1]}$$

where,

k = 1.381 x 10^{-23} J/K (Boltzmann's Constant)

- Planck's Law shows that the energy emitted from a blackbody does not depend on direction.
- Blackbody radiation is ***diffuse***.

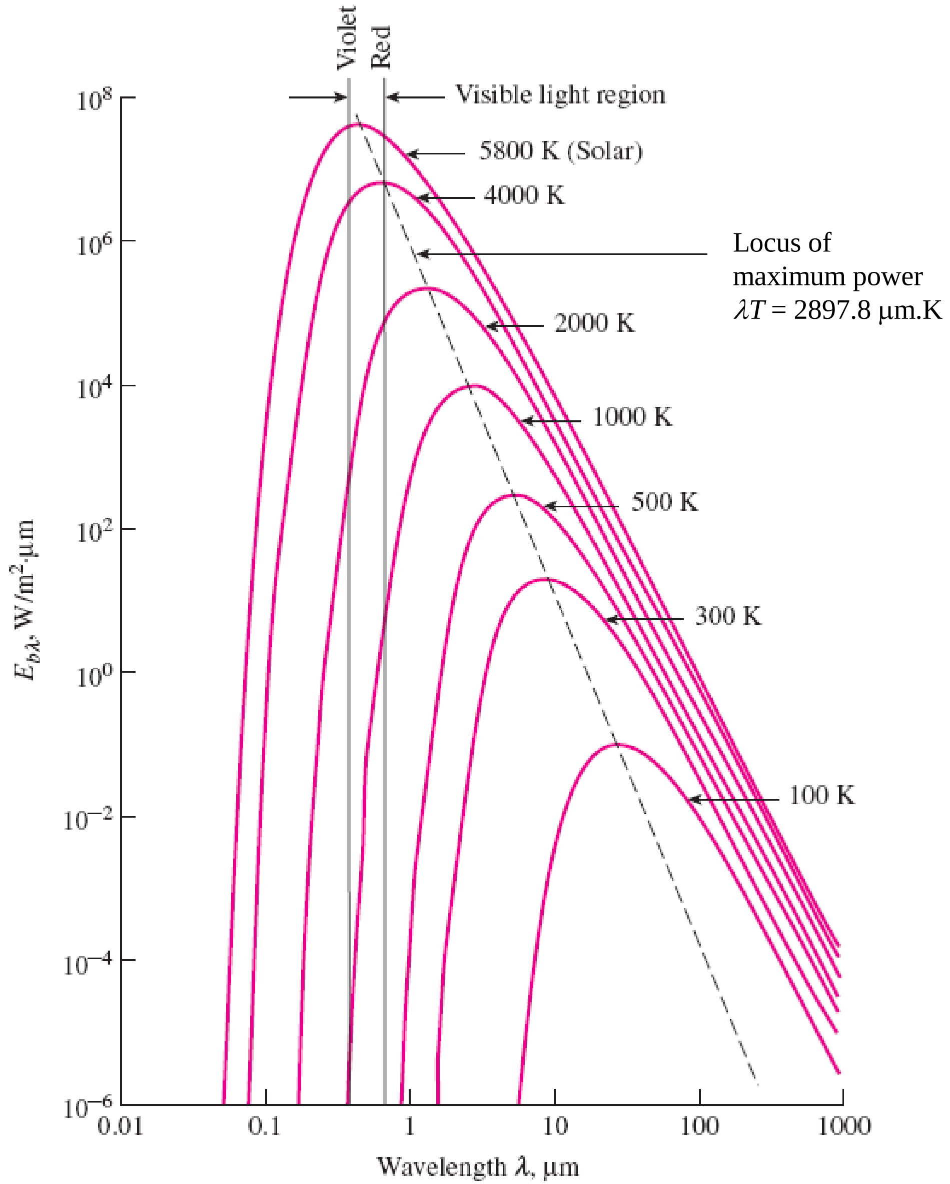


Blackbody Radiation

- From Planck's Law, we can find the wavelength at which the maximum radiation is emitted by a blackbody
- This is done by taking the derivative of $E_{\lambda b}$ and setting it to zero
- The result is called Wien's displacement law:

$$\lambda_{\max} T = 2897.8 \ \mu\text{m K}$$

Blackbody Radiation



Blackbody Radiation

- Integrating Planck's Law yields Stefan-Boltzmann's Equation:

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

where,

σ = 5.67 x 10^{-8} W/m^2.K^4 (Stefan-Boltzmann Constant)

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Radiation Emitted from a Real Surface

- A real surface does not emit as much energy as a blackbody.
- A real surface does not emit energy uniformly in all directions.
- The amount of energy emitted by a real surface is quantified by **emittance**.
- ***Emittance*** is the ratio of radiation emitted by a real surface to the radiation emitted by a blackbody at the same temperature.
- When the energy emitted in all directions and at all wavelengths is integrated, the result is the **“*total hemispherical emittance*”**

$$\varepsilon(T) = \frac{E(T)}{E_b(T)}$$

- Emittance ranges from 0 to 1.

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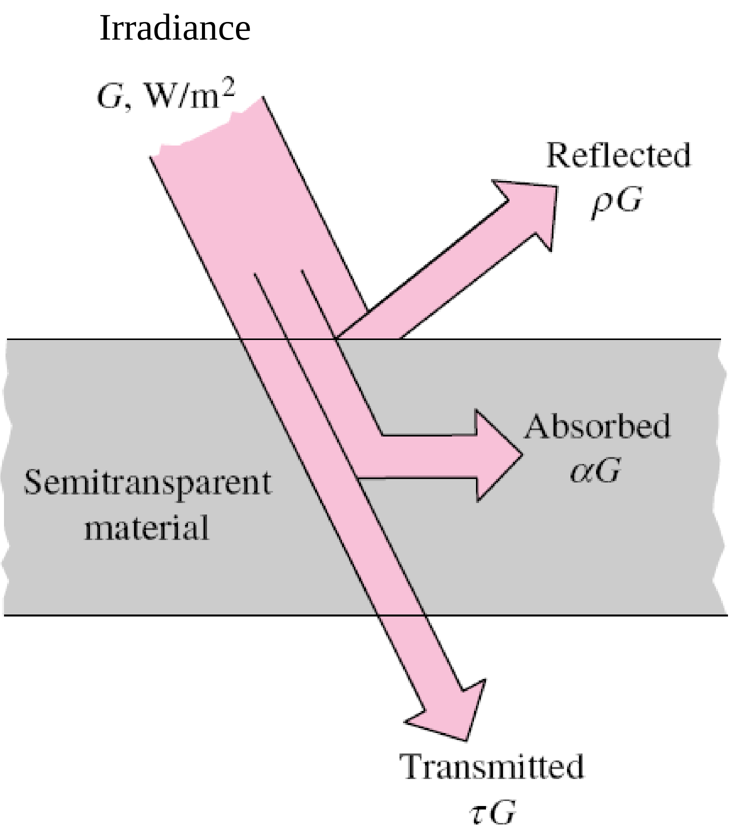
Irradiance

- ***Irradiance*** is the rate at which radiant energy is incident on a surface per unit area of that surface (W/m^2).
- Some references refer to irradiance as "incident radiation"
- It is usually denoted with (*G*).
- Irradiance can be either:
    - **Absorbed**
    - **Reflected**
    - **Transmitted (if the medium is transparent)**

Irradiance

- The ratio of absorbed irradiance to total irradiance is called ***absorptance*** (α)
- The ratio of reflected irradiance to total irradiance is called ***reflectance*** (ρ)
- The ratio of transmitted irradiance to total irradiance is called ***transmittance*** (τ)



Irradiance

- Absorptance: $\alpha = \dfrac{\text{Absorbed radiation}}{\text{Irradiance}} = \dfrac{G_{\text{abs}}}{G}, \quad 0 \le \alpha \le 1$
- Reflectance: $\rho = \dfrac{\text{Reflected radiation}}{\text{Irradiance}} = \dfrac{G_{\text{ref}}}{G}, \quad 0 \le \rho \le 1$
- Transmittance: $\tau = \dfrac{\text{Transmitted radiation}}{\text{Irradiance}} = \dfrac{G_{\text{tr}}}{G}, \quad 0 \le \tau \le 1$
- $G_{abs} + G_{ref} + G_{tr} = G$
- $\alpha + \rho + \tau = 1$
- $\alpha + \rho = 1$ (for opaque surfaces)

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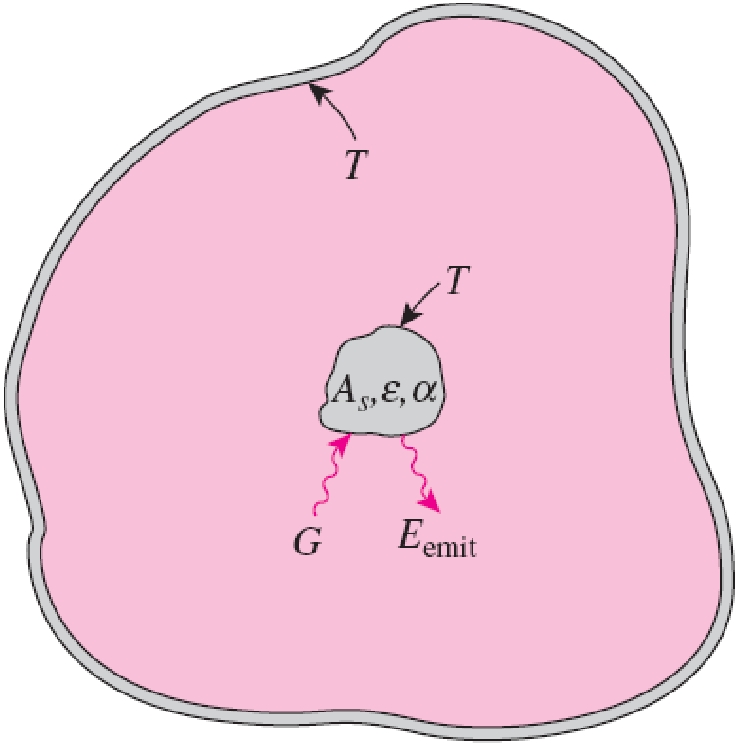
Kirchhoff's Law

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

- $\varepsilon(T) = \alpha(T)$



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Diffuse and Gray Surface

- A ***gray*** surface is a surface whose ε and α are independent of wavelength.
- If the surface is diffuse and gray:

$\varepsilon = \alpha$

- In this case, the source of irradiation does not have to be a blackbody and the source's temperature does not have to be equal to the surface temperature

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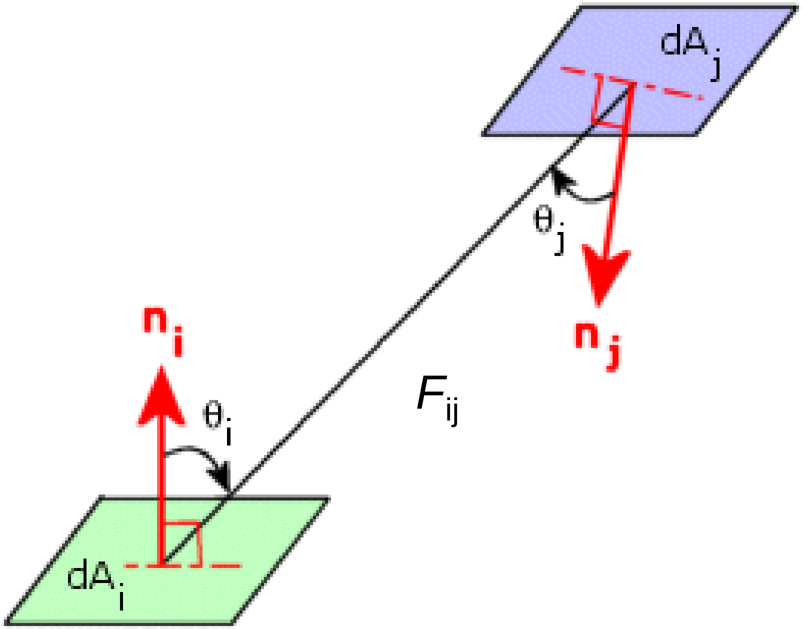
View Factor

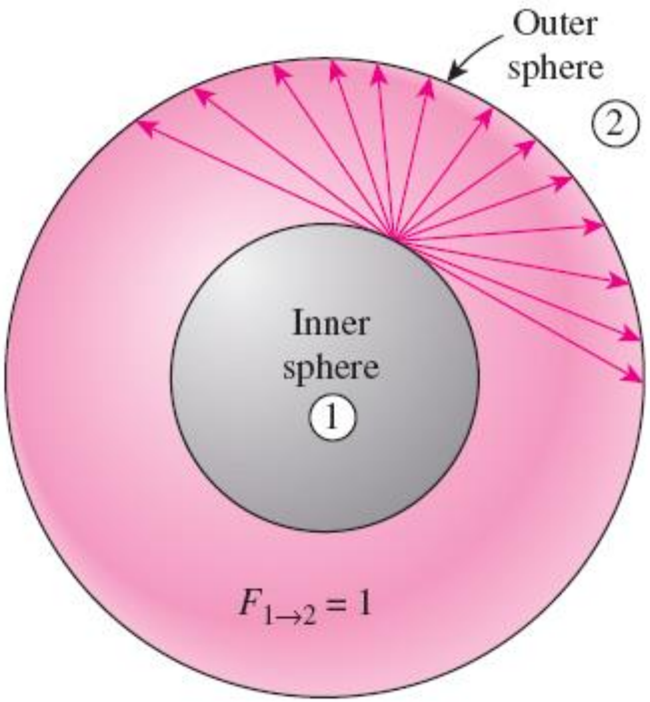
- The ***view factor*** (F_{ij}) is the fraction of the radiation leaving surface i that strikes surface j directly
- The view factor ranges between 0 and 1.



View Factor

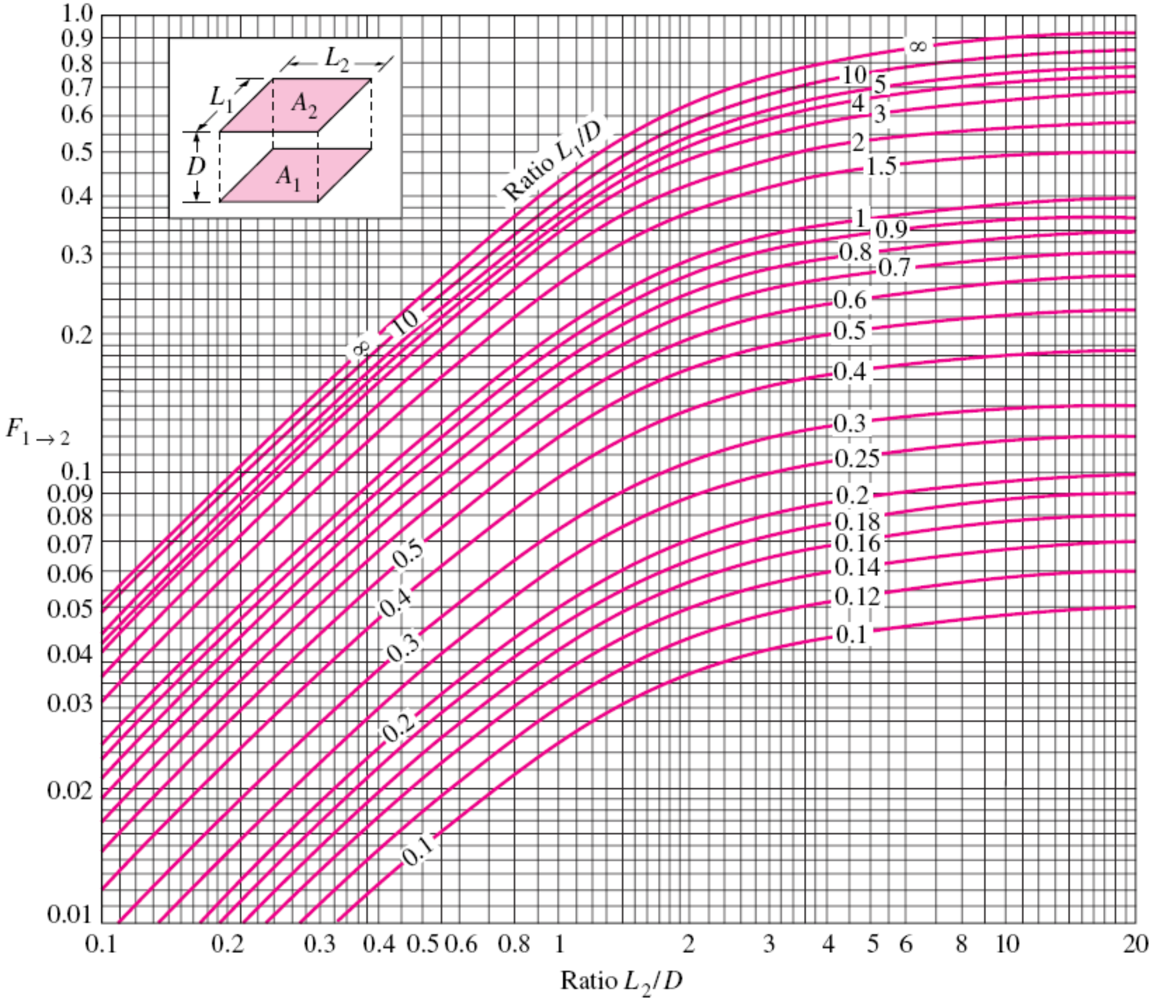
EXAMPLE

- The view factor $F_{12} = 1$ since all the radiation leaving Surface 1 hits Surface 2.
- $F_{21} < 1$, since not all the radiation leaving Surface 2 will hit Surface 1.
- Some of the radiation leaving one part of Surface 2 will hit another part on Surface 2 itself.



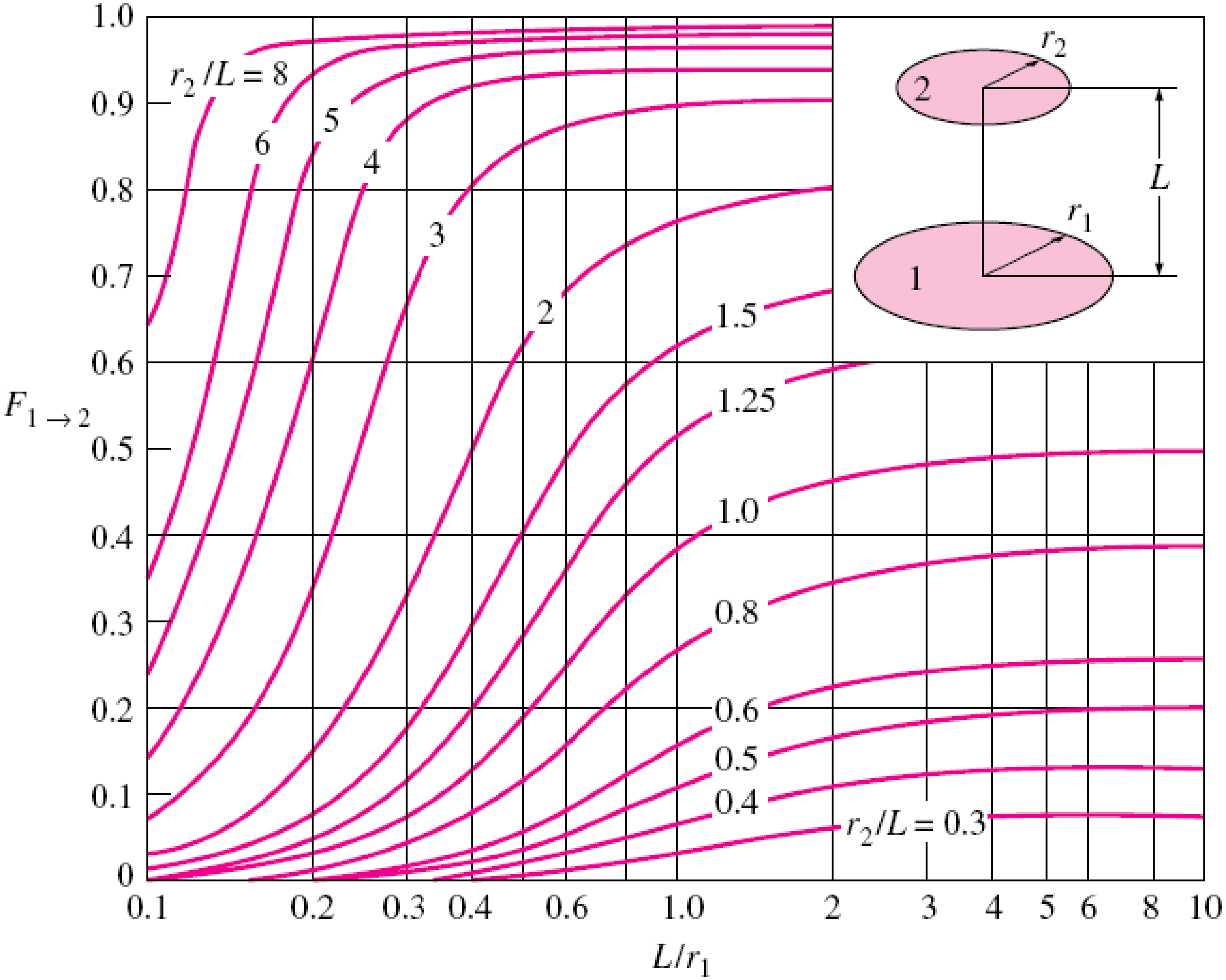
View Factor

View factor between two aligned parallel rectangles of equal size



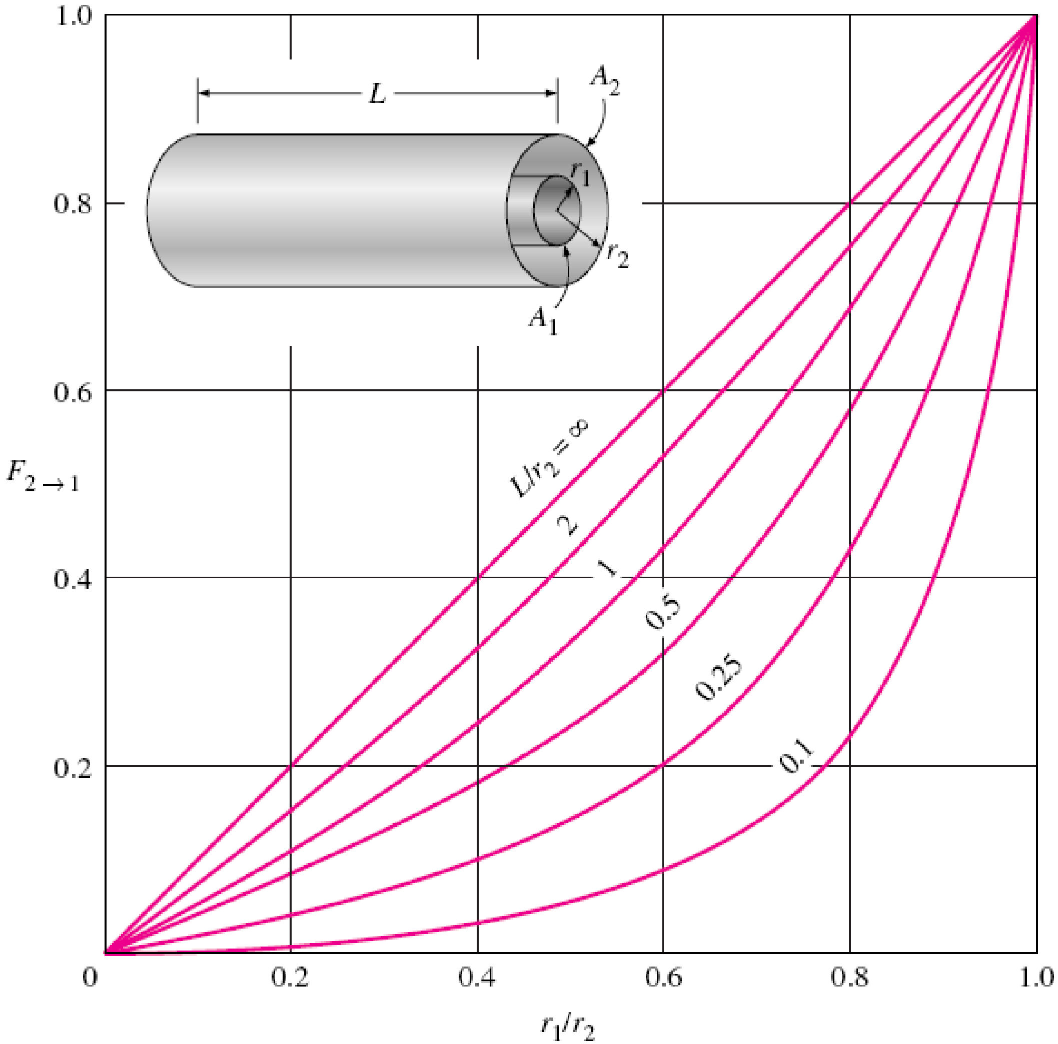
View Factor

View factor between two coaxial parallel disks



View Factor

View factors for two concentric cylinders of finite length



The Reciprocity Relation

$$F_{j \to i} = F_{i \to j} \qquad \text{when} \qquad A_i = A_j$$

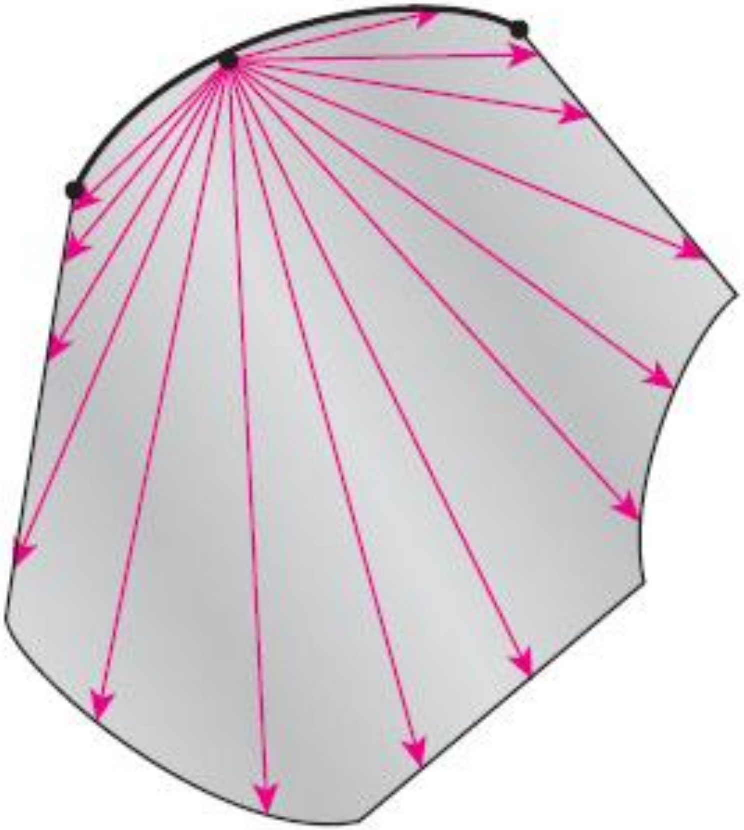
$$F_{j \to i} \neq F_{i \to j} \qquad \text{when} \qquad A_i \neq A_j$$

$$A_i F_{i \to j} = A_j F_{j \to i}$$

View Factor Relations

The Summation Rule

$$\sum_{j=1}^{N} F_{i \to j} = 1$$



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Radiation Exchange Between Two Black Bodies

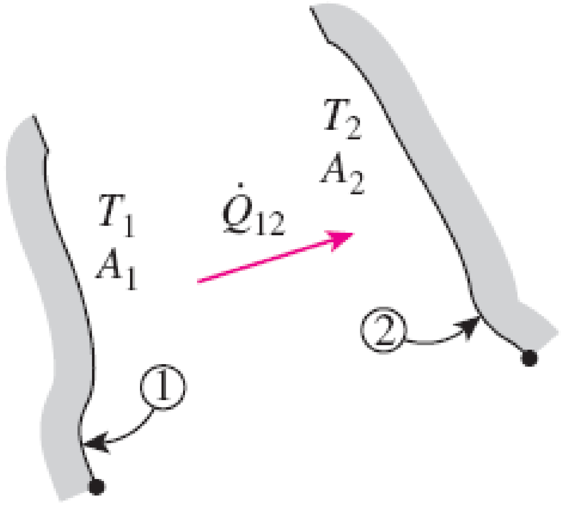
- If Surface 1 and Surface 2 are blackbodies, the net radiation heat transfer from Surface 1 to Surface 2 is:

$$\dot{Q}_{1\rightarrow 2} = \begin{pmatrix} \text{Radiation leaving} \\ \text{the entire surface 1} \\ \text{that strikes surface 2} \end{pmatrix} - \begin{pmatrix} \text{Radiation leaving} \\ \text{the entire surface 2} \\ \text{that strikes surface 1} \end{pmatrix}$$

$$= A_1 E_{b1} F_{1\rightarrow 2} - A_2 E_{b2} F_{2\rightarrow 1}$$

- The reciprocity relation asserts that: $A_1 F_{1\rightarrow 2} = A_2 F_{2\rightarrow 1}$
- Also: $E_b = \sigma T^4$
- Therefore,

$$\dot{Q}_{1\rightarrow 2} = A_1 F_{1\rightarrow 2}\,\sigma (T_1^4 - T_2^4)$$



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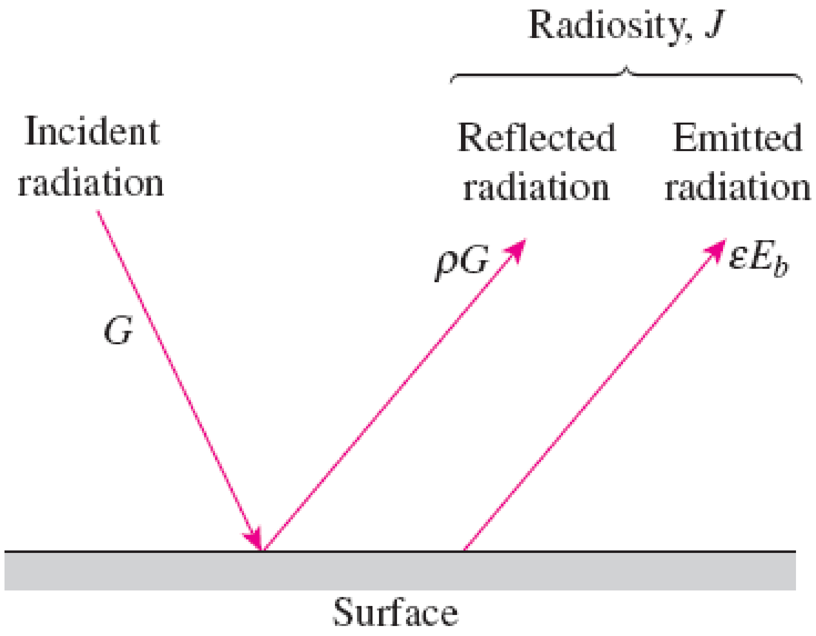
Radiosity

- Radiation from a diffuse gray surface differs from radiation from a black body in two ways:
  - **The radiation emitted is εE_b (instead of E_b)**
  - **The reflected radiation is ρG (instead of 0)**
- The total radiation energy leaving a surface per unit time and per unit area is called **radiosity** (J).



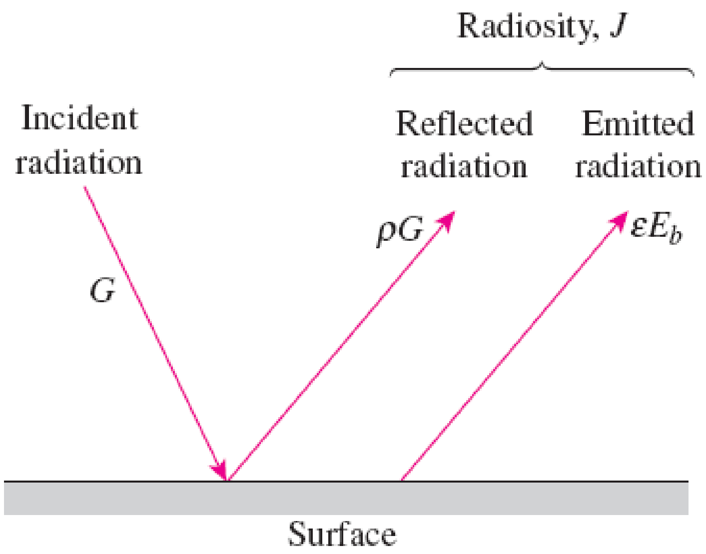
Radiosity

$$J_i = \begin{pmatrix}\text{Radiation emitted} \\ \text{by surface } i\end{pmatrix} + \begin{pmatrix}\text{Radiation reflected} \\ \text{by surface } i\end{pmatrix}$$

$$J_i = \varepsilon_i \, E_b + \rho_i \, G_i$$

- But $\rho_i + \alpha_i = 1$
- For a diffuse gray surface, $\alpha_i = \varepsilon_i$
- Therefore: $\rho_i + \varepsilon_i = 1$

$\rightarrow \rho_i = 1 - \varepsilon_i$



$$\Rightarrow \quad J_i = \varepsilon_i \, E_b + (1 - \varepsilon_i) \, G_i$$

$$\Rightarrow \quad G_i = \frac{J_i - \varepsilon_i \, E_b}{(1 - \varepsilon_i)}$$

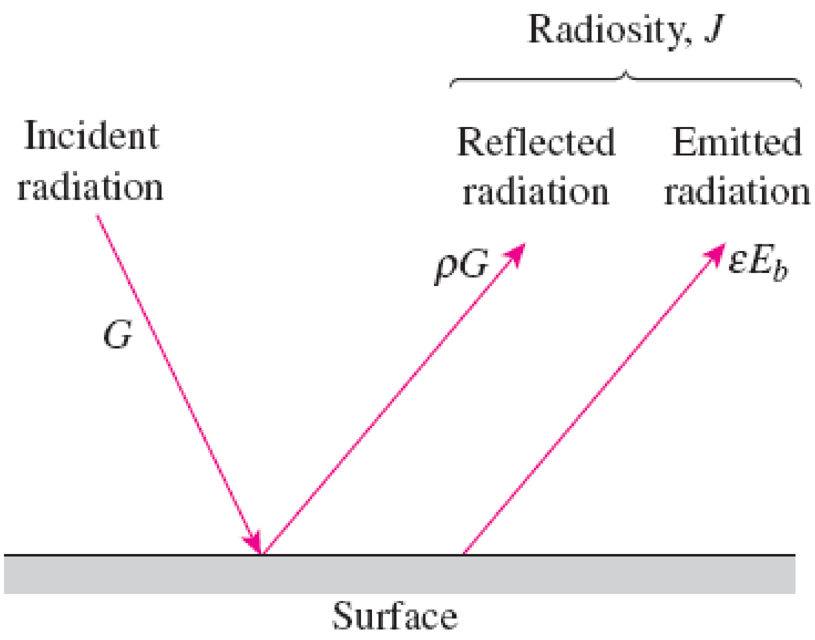
Net Rate of Radiation Heat Transfer from a Diffuse Gray Surface

$$\dot{Q}_i = \begin{pmatrix}\text{Radiation leaving} \\ \text{entire surface } i\end{pmatrix} - \begin{pmatrix}\text{Radiation incident} \\ \text{on entire surface } i\end{pmatrix}$$

$$= A_i(J_i - G_i)$$

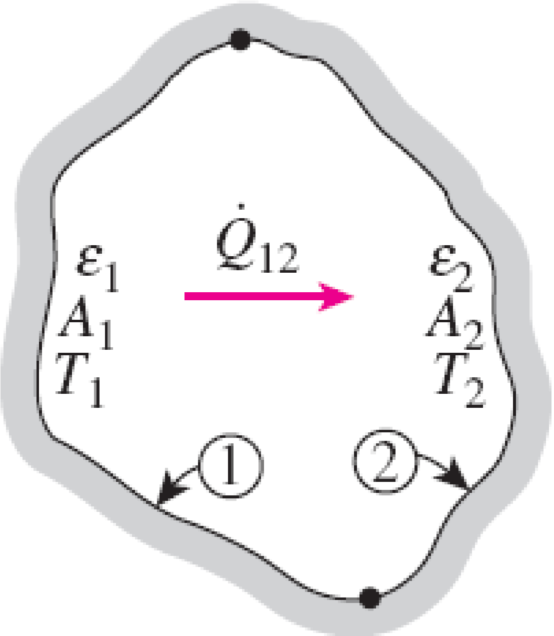
$$= A_i\left(J_i - \frac{J_i - \varepsilon_i E_b}{1 - \varepsilon_i}\right)$$

$$= \frac{A_i\,\varepsilon_i}{1 - \varepsilon_i}(E_{bi} - J_i)$$



Radiation Heat Transfer in Two-Surface Enclosures

$$\dot{Q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1F_{12}} + \dfrac{1-\varepsilon_2}{A_2\varepsilon_2}} \quad \text{(W)}$$



- This is true for any two diffuse gray surfaces.

Example: Radiation from a horizontal solar collector to the sky at night

- The sky can be considered a blackbody at a temperature below ambient