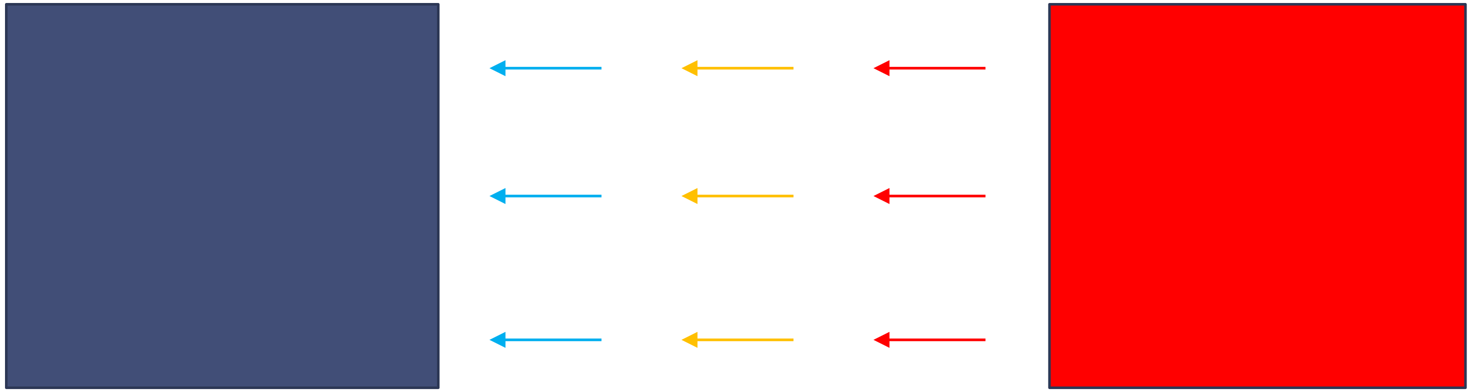
Radiation Heat Transfer
Lecture-21

Heat Transfer

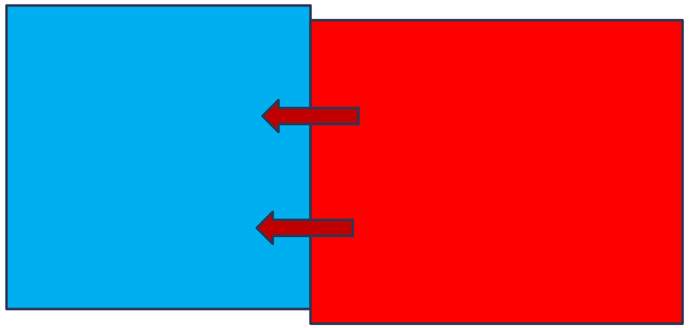
- Movement of heat energy
- Heat moves from warmer surface to cooler surface



Types of Heat Transfer

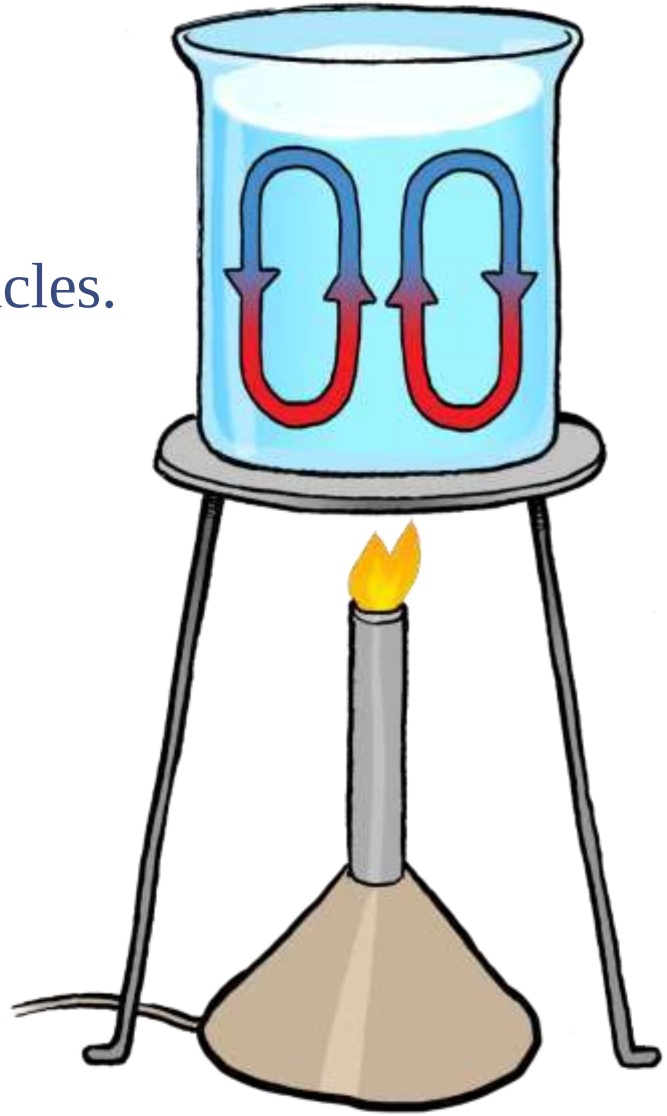
Conduction

- Heat transfer through Direct Contact
- Molecules transfer energy to the molecules next to them



Convection

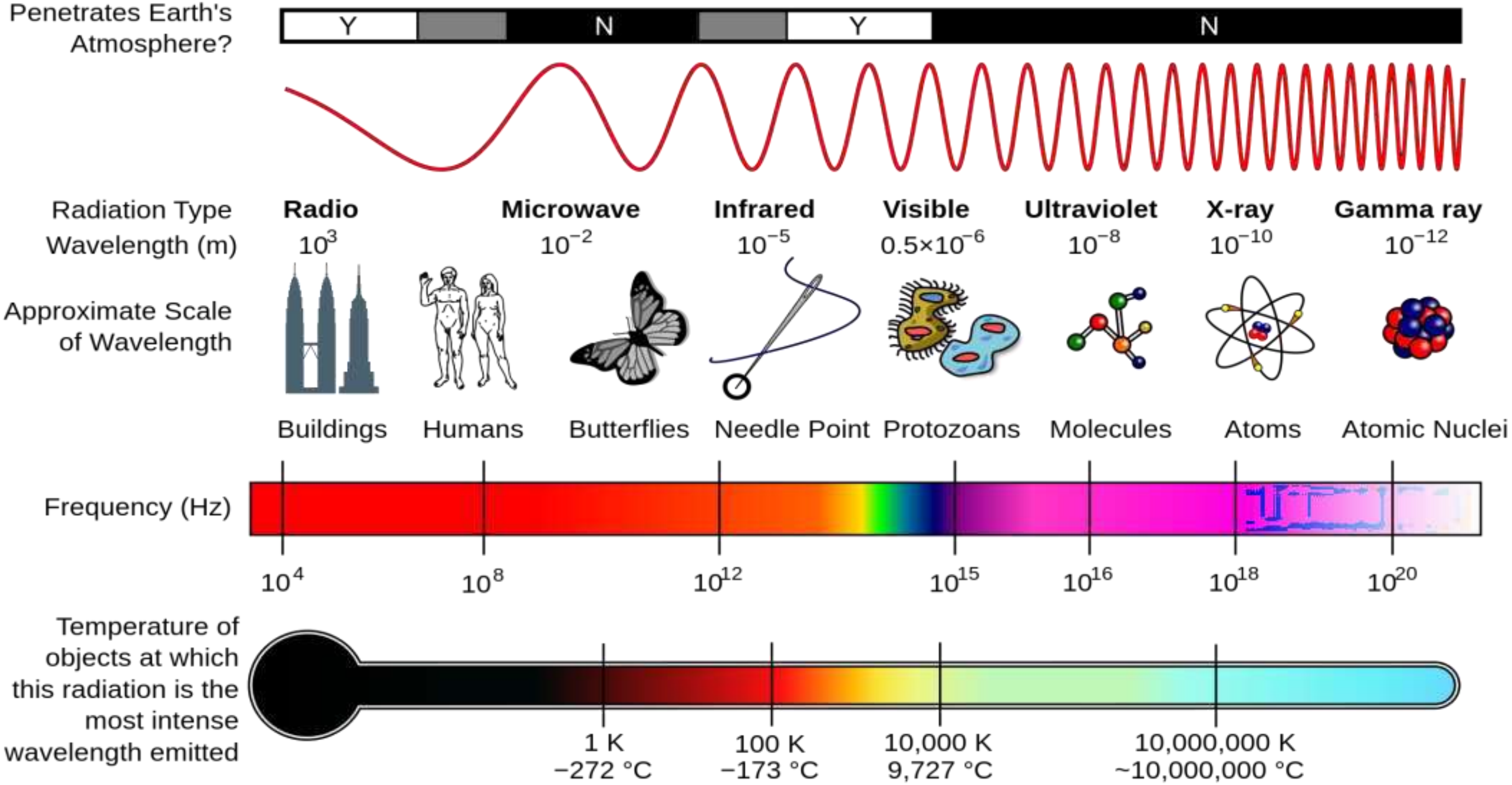
- Heat transfer by the bulk motion of fluid particles.
- Classified as two types :
  - Natural Convection (motion occurs due to density difference)
  - Forced convection (motion occurs due to external)



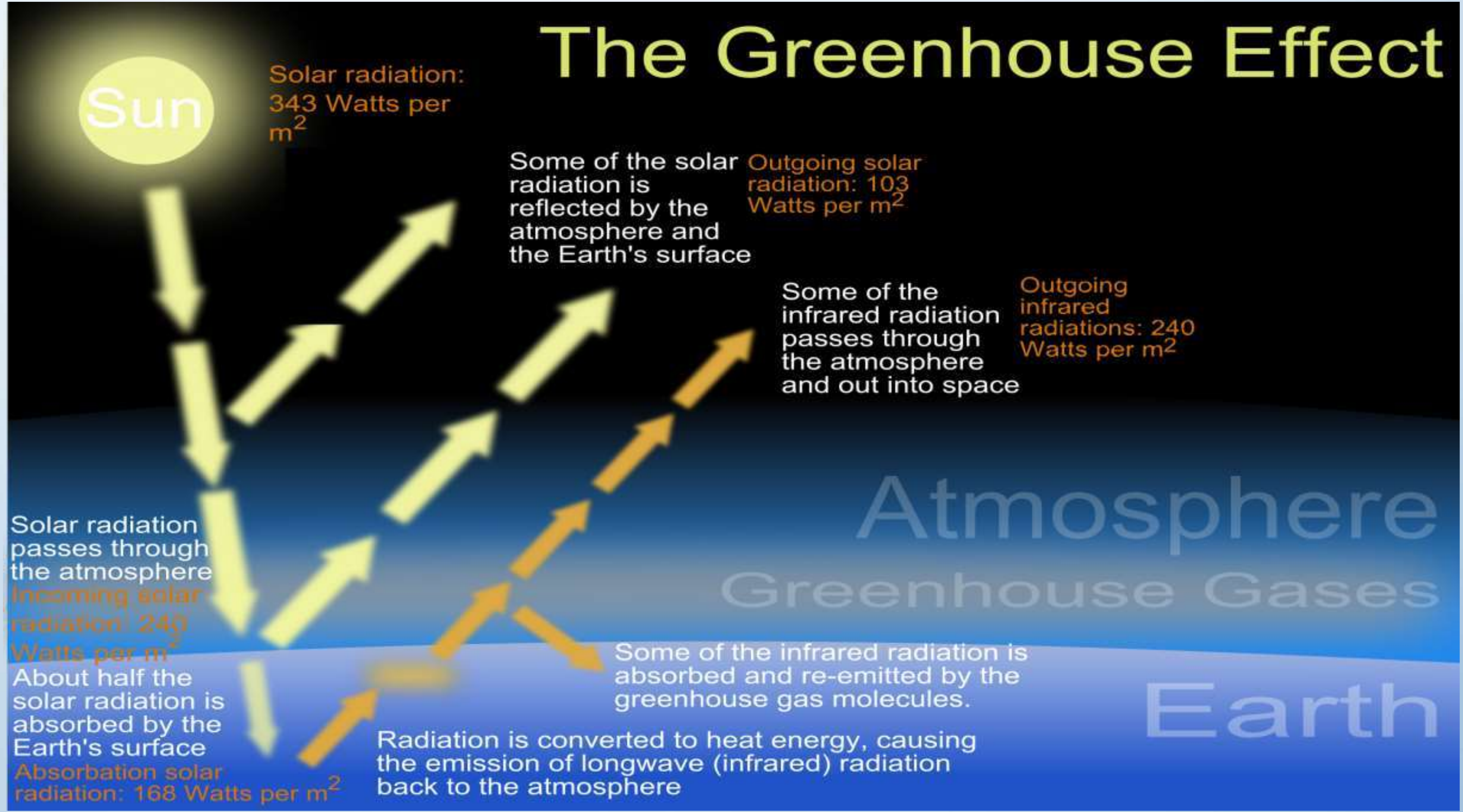
Radiation

- Heat transfer occurs in the form of electro magnetic radiation
- Only mode of heat transfer that doesn’t require any medium for transport place in vacuum (the only mode of heat transfer in vacuum

Radiation



Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Approximate Scale of Wavelength
Radio
10^3
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

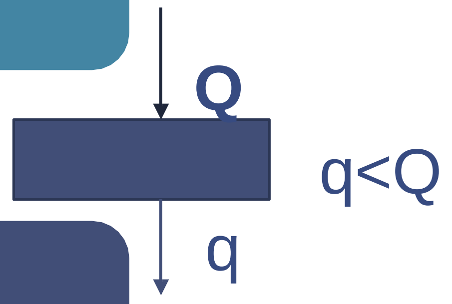


The Greenhouse Effect
Sun
Solar radiation: 343 Watts per m2
Some of the solar radiation is reflected by the atmosphere and the Earth's surface
Outgoing solar radiation: 103 Watts per m2
Some of the infrared radiation passes through the atmosphere and out into space
Outgoing infrared radiations: 240 Watts per m2
Atmosphere
Greenhouse Gases
Solar radiation passes through the atmosphere
Incoming solar radiation: 240 Watts per m2
About half the solar radiation is absorbed by the Earth's surface
Absorbation solar radiation: 168 Watts per m2
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules.
Radiation is converted to heat energy, causing the emission of longwave (infrared) radiation back to the atmosphere
Earth

Radiation : No carrier or medium required

Medium participating

- A part of the radiation gets absorbed



Medium non-participating

- The radiation passes undiminished

Radiation : Fundamental concepts

- Radiation is emitted in different wavelength and different directions

Spectral distribution

- Depends on spectra of light

Directional distribution

- Depends on direction of light

Radiative properties

Reflectivity (ρ)

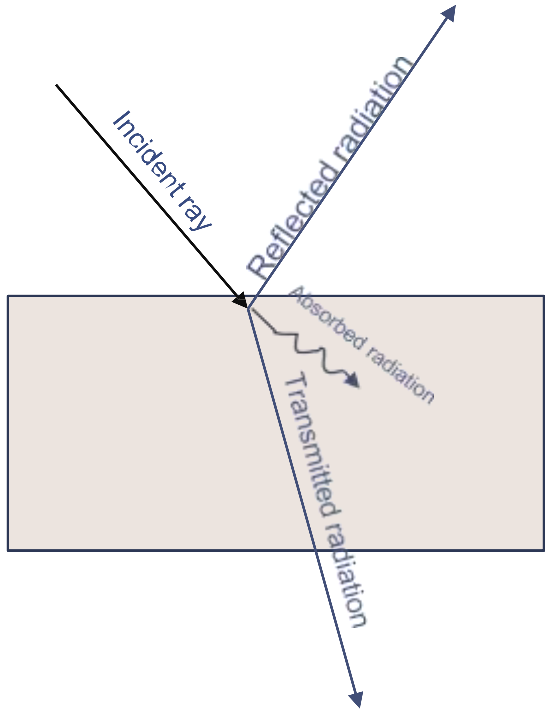
- The ratio of reflected radiation to incident radiation
- $\rho = \frac{G_{reflected}}{G_{incident}}$

Absorptivity(α)

- Fraction of incident energy that is absorbed
- $\alpha = \frac{G_{absorbed}}{G_{incident}}$

Transmitivity(τ)

- Fraction of incident energy that is transmitted through the object
- $\tau = \frac{G_{transmitted}}{G_{incident}}$



Lecture-22

Radiative Properties

- All the three radiative properties depend on wavelength and temperature. All the properties have values between 0 and 1

- $\alpha + \rho + \tau = 1$ (energy conservation)

Black body radiation

- A black body is an ideal emitter

- Energy emitted by any real surface is less than what is emitted by a black body
- Assumptions involved
    1. It is an ideal emitter: at every frequency, it emits as much energy as – or more energy than – any other body at the same temperature.
    2. It is a diffuse emitter: the energy is radiated isotropically, independent of direction
- The **monochromatic emissive power** E_λ, is defined as the rate, per unit area, at which the surface emits thermal radiation at a particular wavelength λ

- A blackbody has the highest E_λ for any given wavelength

Emissivity

- The ratio of emissive power of a body E, to the emissive power of a blackbody at the same temperature is called the hemispherical emissivity of the surface, ε

- $\varepsilon = \frac{E}{E_b}$ (emissivity depends on temperature , wavelength and surface smoothness)
- $\varepsilon_b = 1$
- In most solids and liquids , the radiation emitted from interior are absorbed by the adjacent molecules thus making it a surface phenomenon.

- In gases and semitransparent solids , radiation is a volumetric phenomenon

Lecture-23

Radiation laws

Planck Radiation Law

- Governs the intensity of radiation emitted by unit surface area into a fixed direction (solid angle) from the blackbody as a function of wavelength for a fixed temperature

$$E_{b\lambda}(\lambda, T) = \frac{c_1}{\lambda^5} \frac{1}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}$$

$c_1 = 2\pi hc^2$

$c_2 = hc/k_B$

Stefan Boltzmann Law

- The total energy radiated per unit surface area of a black body across all wavelengths per unit time (also known as the black-body radiant exitance or emissive power), E_b, is directly proportional to the fourth power of the black body's thermodynamic temperature T

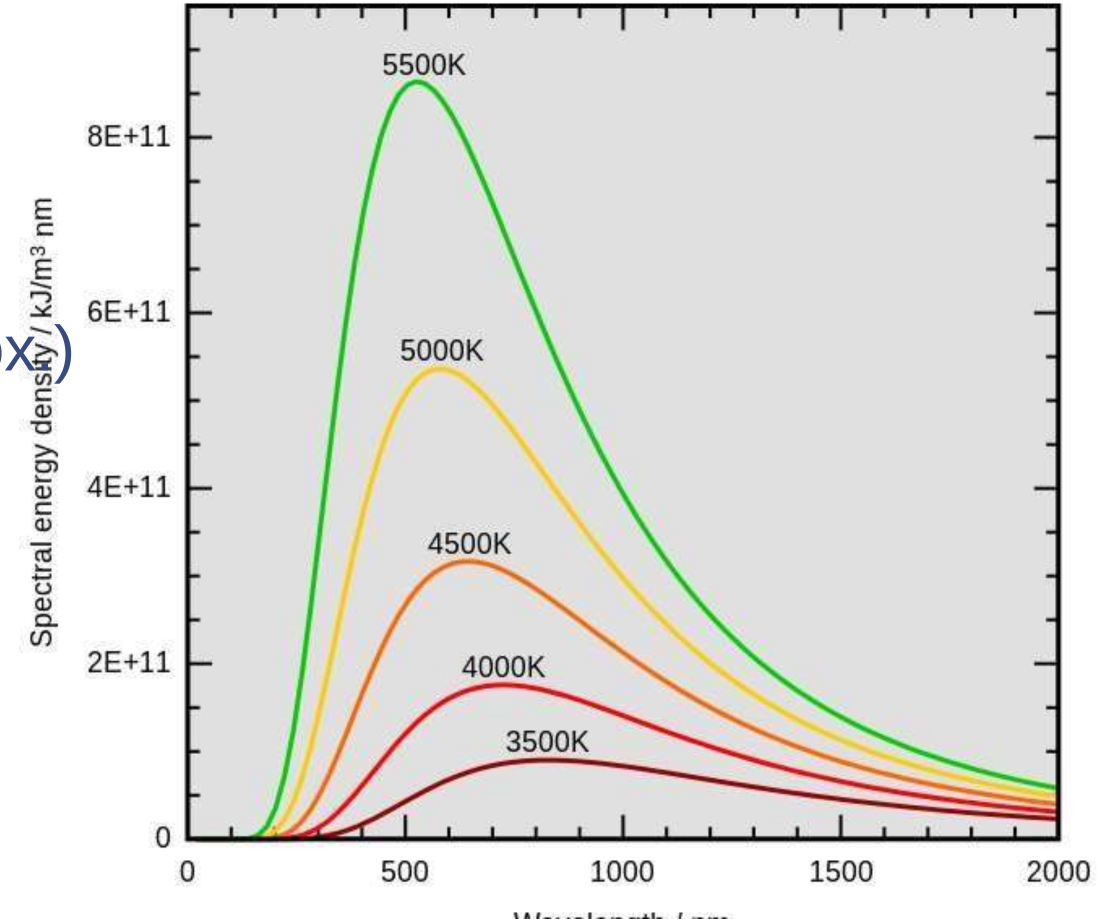
  - $E_b = \sigma T^4$

  - $\sigma = 5.67E-8$

- For a real body $\varepsilon = \frac{E}{E_b}$ => $E_{real\ body} = \varepsilon \sigma T^4$

Wien’s displacement law

- The black body radiation curve for different temperatures peaks at a wavelength inversely proportional to the temperature
  - λ_{max} x T = c
  - T - absolute temperature in Kelvin
  - c = 2.898E-3 (Rayleigh-Jeans approx.)



Kirchhoff's law of heat radiation

- For a body of any arbitrary material, emitting and absorbing thermal electromagnetic radiation at every wavelength in thermodynamic equilibrium, the ratio of its emissive power to its absorptive power is equal to a universal function only of radiative wavelength and temperature. That universal function describes the perfect black-body emissive power
- An arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity

$$\varepsilon_\lambda=\alpha_\lambda$$

- Such bodies do not occur in physical reality

Kirchhoff's law

- Sets up a correlation between spectral emissivity and spectral absorptivity
- This also means that

$$\int_0^\infty \varepsilon_\lambda \, d\lambda = \int_0^\infty \alpha_\lambda \, d\lambda$$

$$\varepsilon = \alpha$$

- All calorimetry based total hemispherical emissivity calculations are based on this law

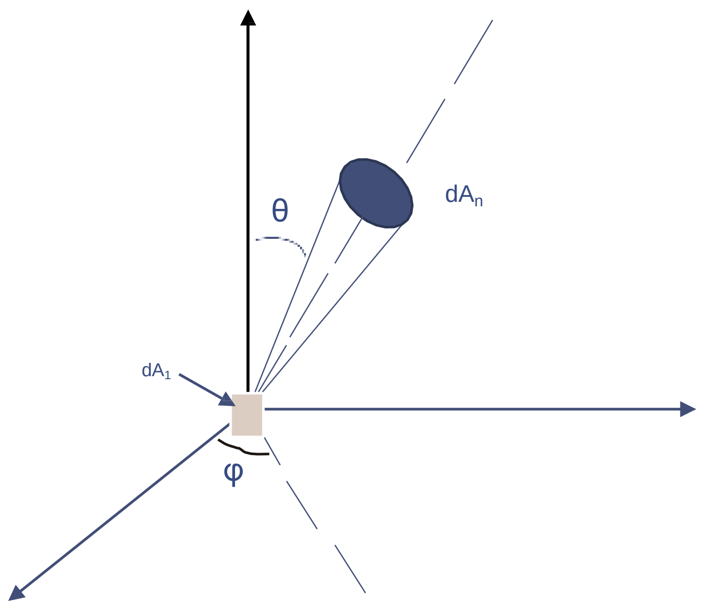
Lecture-24

Gray and Diffuse bodies

- A source with low emissivity (ε<1) independent of wavelength of light often is referred to as a **gray body**
- **Gray bodies** will have emissive and absorptive power less than that of a blackbody
- **Diffuse emitter** is a surface for which the intensity of emitted radiation is independent of direction.
- The Diffuse- gray body approximation of real bodies make their otherwise complex study and analysis simple

Radiation Intensity

- Intensity I of radiation at any λ is defined as the rate at which radiant energy is emitted in (θ,φ) direction per unit dA_n per unit Solid angle , per unit wavelength $W/(m^2.sr.\mu m)$



Radiosity

- Total radiation leaving a surface due to reflection and emission

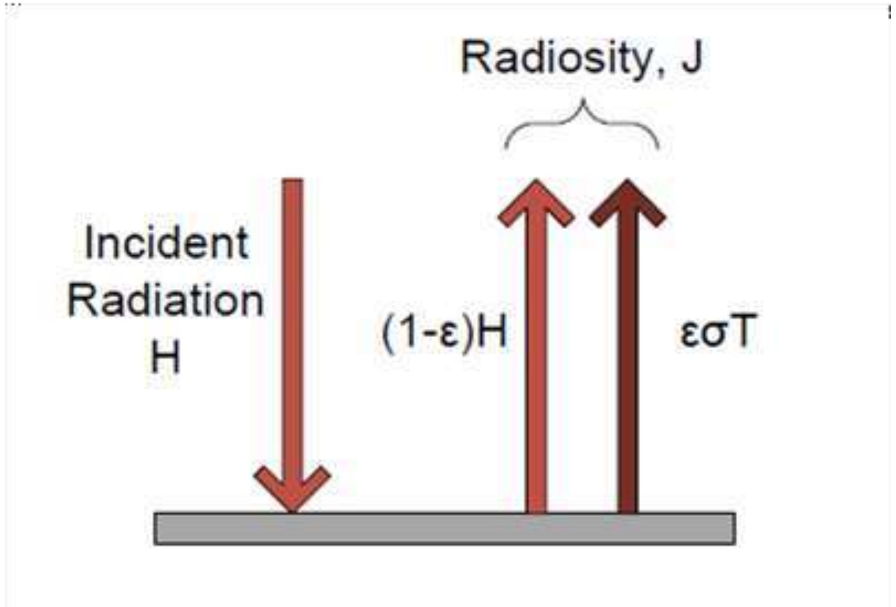
$$J=\varepsilon E_b + \rho G$$

- For an opaque object

$$J= \varepsilon E_b + (1-\alpha)G$$

- According to Kirchhoff's law $\alpha=\varepsilon$

$$J= \varepsilon E_b + (1-\varepsilon)G$$

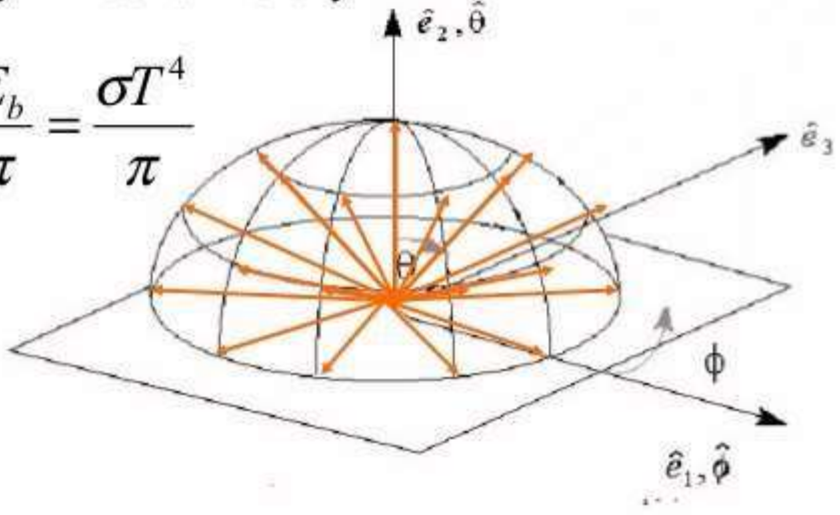


Hemispherical Black surface emission

Hemispherical Black Surface Emission

Black body Emissive Intensity

$$I_b = \frac{E_b}{\pi} = \frac{\sigma T^4}{\pi}$$



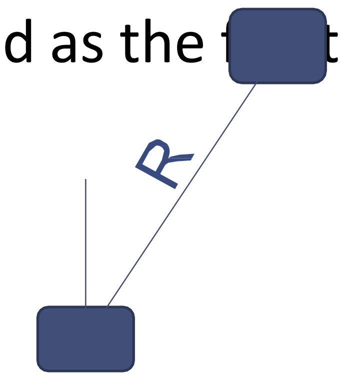
Radiation exchange between surfaces

- Assumptions:
- Surfaces are separated by non-participating medium which neither emits, absorb or scatter radiation
- **View Factor:** The view factor F_{ij} is defined as the f tion of the radiation leaving surface i, which is intercepted by surface j

$$F_{ij} A_i = F_{ji} A_j$$

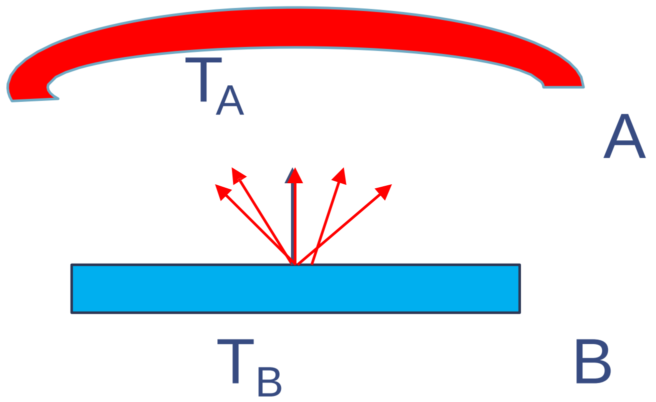
Summation rule :

$$F_{ij} = 1$$



Radiative Heat Exchange between surfaces

- Rate of heat transfer into surface B



$$Q_{A\,emitted} = \varepsilon_A \sigma_A A_A T_A^4$$

$$Q_{B\,absorbed} = \alpha_B \varepsilon_B F_{A \rightarrow B} \sigma A_A T_A^4$$

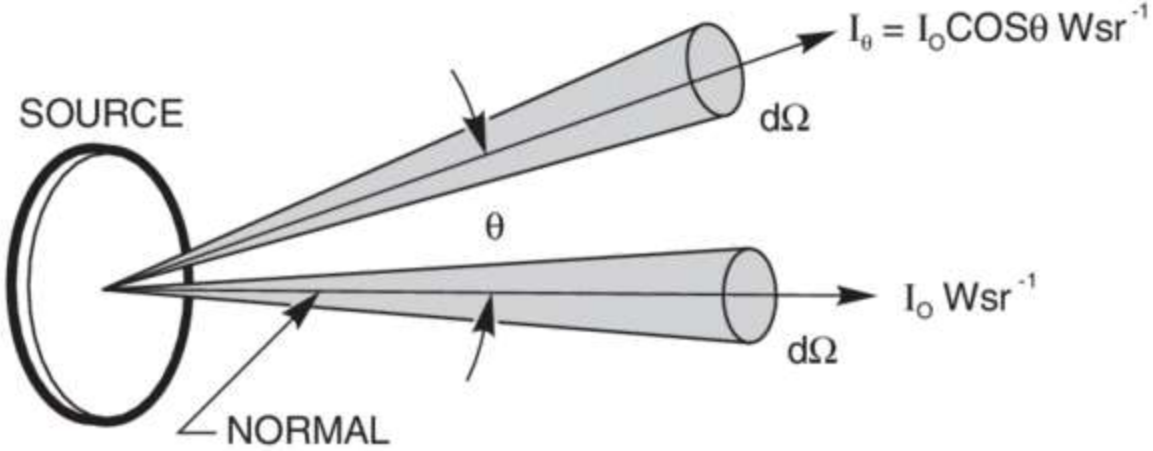
$$Q_{B\,emitted} = \varepsilon_B \sigma A_B T_B^4$$

$$Q_B = Q_{B\,absorbed} - Q_{B\,emitted}$$

$$Q_B = \alpha_B \varepsilon_B F_{A \rightarrow B} \sigma A_A T_A^4 - \varepsilon_A \sigma_A A_A T_A^4$$

Lecture-25

Lamberts law



Relationship Between Emissive Power and Intensity

By definition of the two terms, emissive power for an ideal surface, E_b, and intensity for an ideal surface, I_b.

$$E_b = \int_{hemisphere} I_b \cdot \cos\theta \cdot d\Omega$$

Replacing the solid angle by its equivalent in spherical angles:

$$E_b = \int_0^{2\cdot\pi} \int_0^{\pi/2} I_b \cdot \cos\theta \cdot \sin\theta \cdot d\theta \cdot d\varphi$$

Integrate once, holding I_b constant:

$$E_b = 2\cdot\pi\cdot I_b \cdot \int_0^{\pi/2} \cos\theta \cdot \sin\theta \cdot d\theta$$

Integrate once, holding I_b constant:

$$E_b = 2 \cdot \pi \cdot I_b \cdot \int_0^{\pi/2} \cos\theta \cdot \sin\theta \cdot d\theta$$

Integrate a second time. (Note that the derivative of sin θ is cos θ·dθ.)

$$E_b = 2 \cdot \pi \cdot I_b \cdot \left. \frac{\sin^2\theta}{2} \right|_0^{\pi/2} = \pi \cdot I_b$$

$$\boxed{E_b = \pi \cdot I_b}$$

Reciprocity

Reciprocity

We may write the view factor from surface i to surface j as:

$$A_i \cdot F_{i \to j} = \int_{A_j} \int_{A_i} \frac{\cos\theta_i \cdot \cos\theta_j \cdot dA_i \cdot dA_j}{\pi \cdot R^2}$$

Similarly, between surfaces j and i:

$$A_j \cdot F_{j \to i} = \int_{A_j} \int_{A_i} \frac{\cos\theta_j \cdot \cos\theta_i \cdot dA_j \cdot dA_i}{\pi \cdot R^2}$$

Comparing the integrals we see that they are identical so that:

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

This relationship is known as "Reciprocity".

Quiz

- Two black plates at 800 C and 300 C exchange heat by radiation.calculate the heat transfer per unit area?
- **OPTION A**
- 0
- **OPTION B**
- 69 kW/m2
- **OPTION C**
- 80 kW/m2
- **OPTION D**
- 90 kW/m2

- Emissivity of black body is equal to one
- **True**
- **False**

- Calculate the radiant flux emitted by a black body at 1000 C temperature
- **OPTION A**
- 56.7 kW/m2
- **OPTION B**
- 149 kW/m^2
- **OPTION C**
- 250 kW
- **OPTION D**
- 5.67 W/m2

- Which of the following statement is false about emissivity?
- **OPTION A**
- The value of emissivity is between zero to one for any real surface
- **OPTION B**
- Emissivity is the ratio of radiant flux emitted from a surface to the radiant flux emitted from a black body.
- **OPTION C**
- Monochromatic Emissivity is constant for different wavelengths in case of real surface
- **OPTION D**
- Monochromatic Emissivity is different for different wavelengths in case of real surface