

# Energy & Heat Transfer

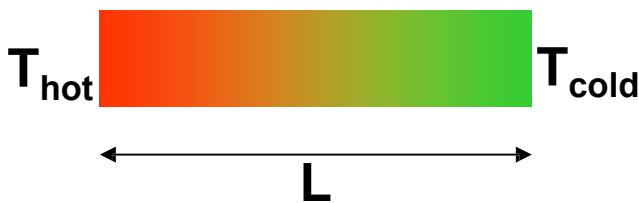
## Lecture 5

*By: Mohammad Mehrali*

# Recap of last lectures

## Heat Transfer Modes

### Heat Conduction



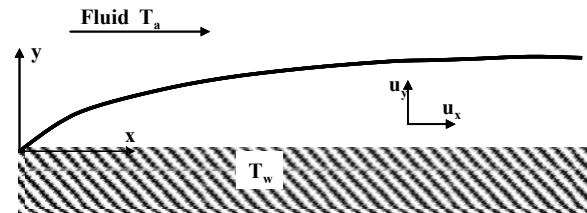
- Fourier Law

$$\dot{Q} = -kA \frac{\Delta T}{\Delta x} [W]$$

Thermal Conductivity  
[W/m.K]  
**Material properties**

Cross-  
Sectional  
Area [ $m^2$ ]

### Convection



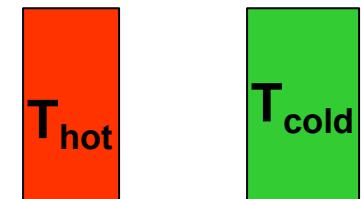
- Newton's law of cooling

$$\dot{Q} = hA(T_w - T_a) [W]$$

Convective Heat  
Transfer Coefficient  
[W/m<sup>2</sup>K]  
**Flow dependent**

- Natural Convection
- Forced Convection

### Thermal Radiation



# **LEARNING OBJECTIVES LECTURE 5**



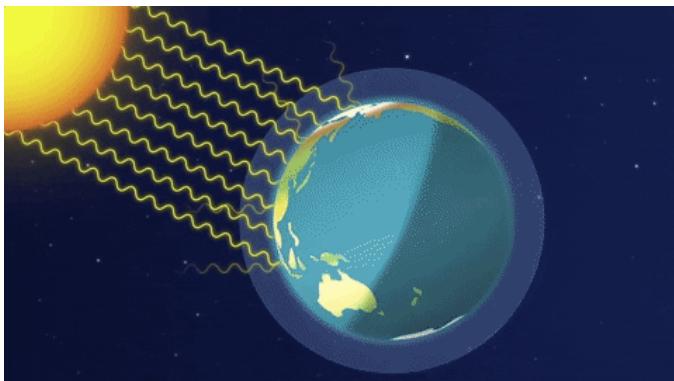
- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

# CONCEPT OF RADIATION

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## Radiation Examples

### Sun



Surface temperature : **5,778 K**

Distance from earth : **149.6 million km**

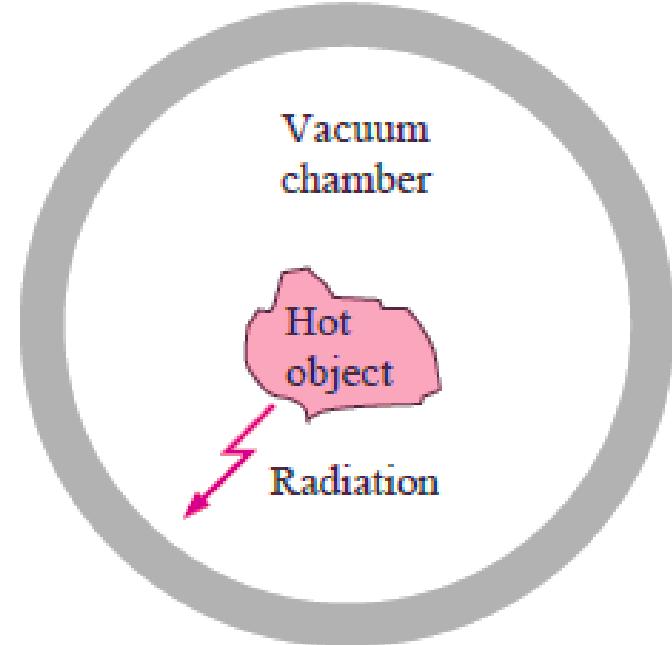
### Fire



Flame temperature  $\sim$  **750 °C**

# CONCEPT OF RADIATION

- ♣ Consider a hot object that is suspended in an evacuated chamber whose walls are at room temperature.
- ♣ The Hot object will cool down and reach equilibrium with the chamber walls due to change in **internal energy**.



**But How is this heat (internal energy) being transported without any medium ? ?**

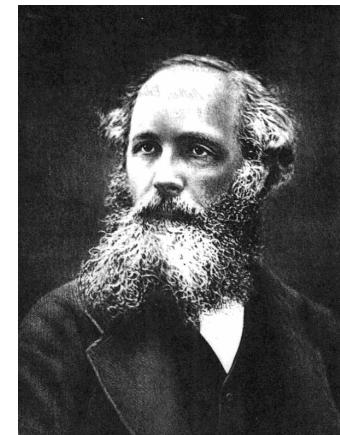
**Electromagnetic Waves or Electromagnetic Radiation  
(no medium required!)**

Heat transfer in the form of electromagnetic waves due to change in internal energy.

# Electromagnetic Waves

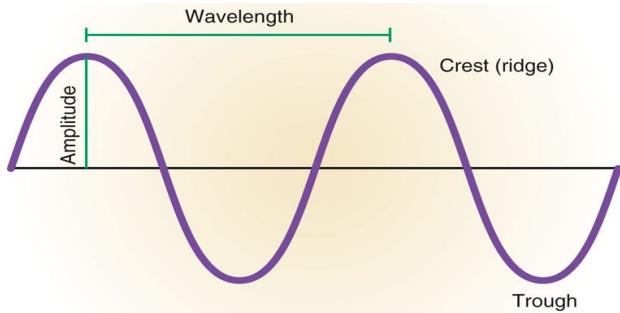
## Electromagnetic Waves :

- The theoretical foundation of radiation was established in 1864 by physicist James Clerk Maxwell.
- Accelerated charges or changing electric currents give rise to electric and magnetic fields.



**James Clerk Maxwell**

### 1) Wavelength – the distance between wave crests

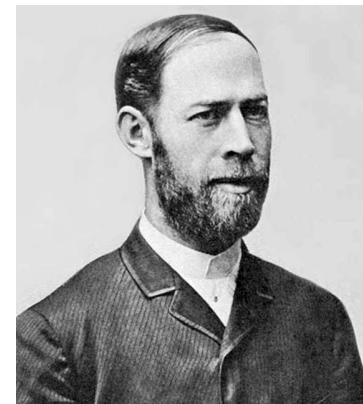


$$\lambda = \frac{c}{\nu}$$

$c$  is the speed of light in vacuum

$\lambda$  is the wavelength in meters

$\nu$  is the frequency in Hertz (Hz) or  $S^{-1}$

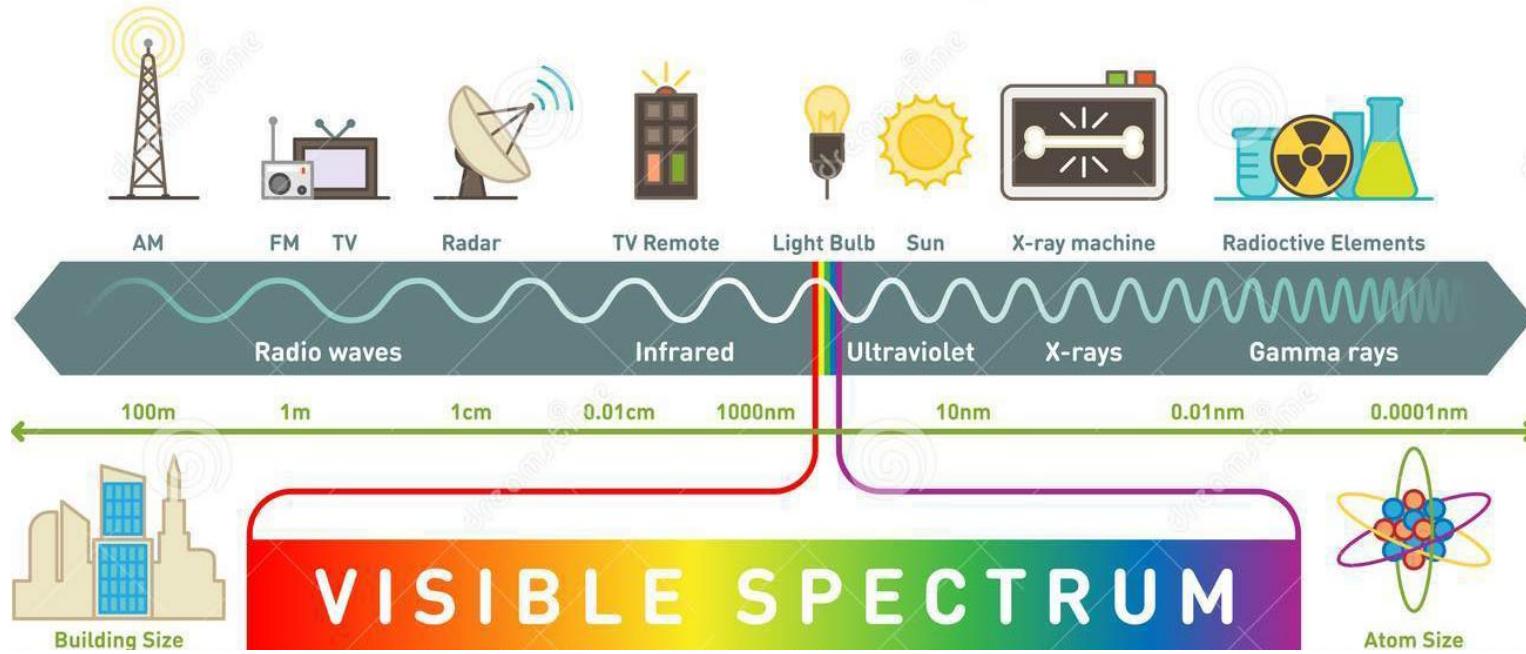


**Heinrich Rudolf Hertz**

### 2) Amplitude – the height of the wave

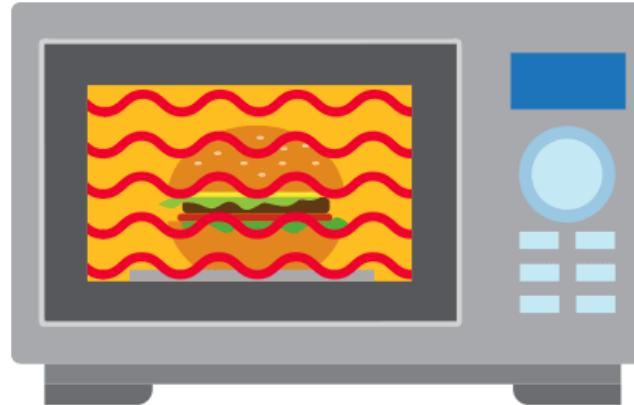
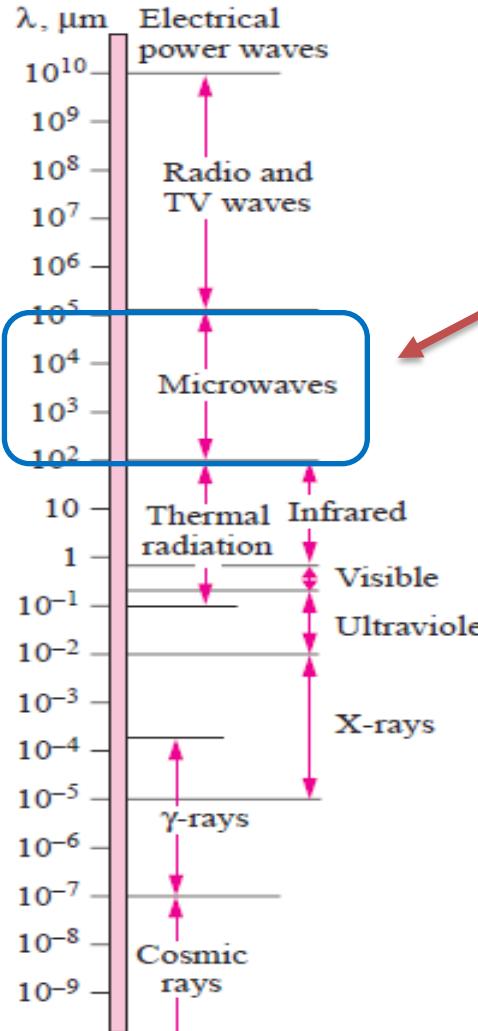
### 3) Wave speed – constant! - **speed of light (vacuum: $2.9979 \times 10^8$ m/s)**

# Electromagnetic spectrum



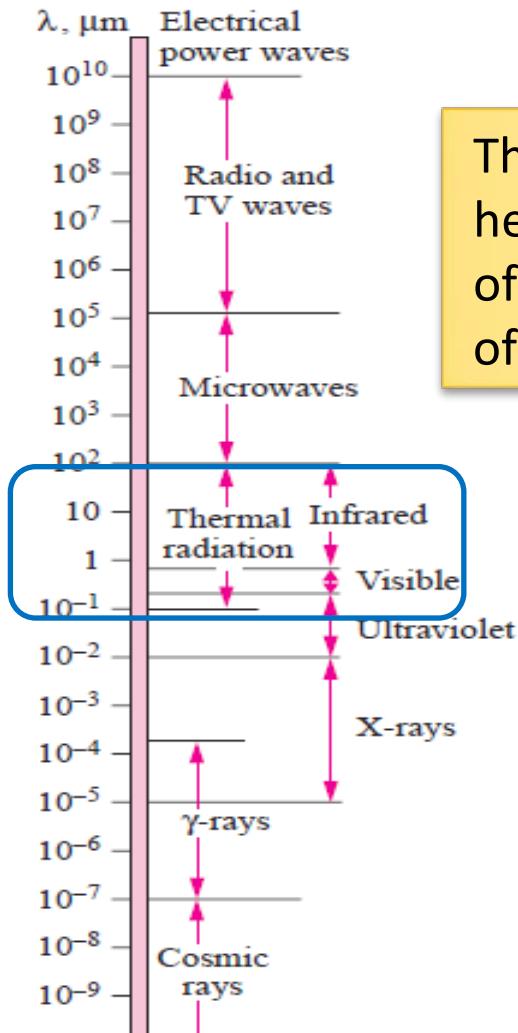
- Gamma rays are produced by nuclear reactions.
- X-rays by the bombardment of metals with high-energy electrons.
- Microwaves by special types of electron tubes such as klystrons and magnetrons.
- Radio waves by the excitation of some crystals or by the flow of alternating current through electric conductors.

# Electromagnetic spectrum



- Wavelength  $\lambda = 10^2 \dots 10^5 \mu\text{m}$
- Waves are reflected by metal (walls)
- Transmission through glass and plastics (ovendish)
- Absorption in food (mainly water molecules)
- Effective conversion: electric energy  $\rightarrow$  radiation energy  $\rightarrow$  internal (thermal) energy food

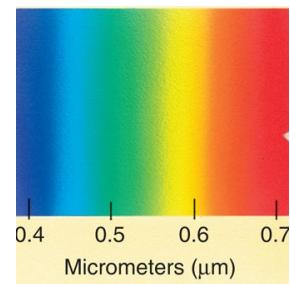
# THERMAL RADIATION



**But what is a 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.

What we call light is simply the visible portion of the electromagnetic spectrum that lies between 0.40 and 0.76  $\mu\text{m}$ .







# **ACTIVITY 1**



**Only Solids radiate thermal Energy**

- A. True**
- B. False**
- C. Not Sure**

**False: Solids, Liquids and gases emit radiation**

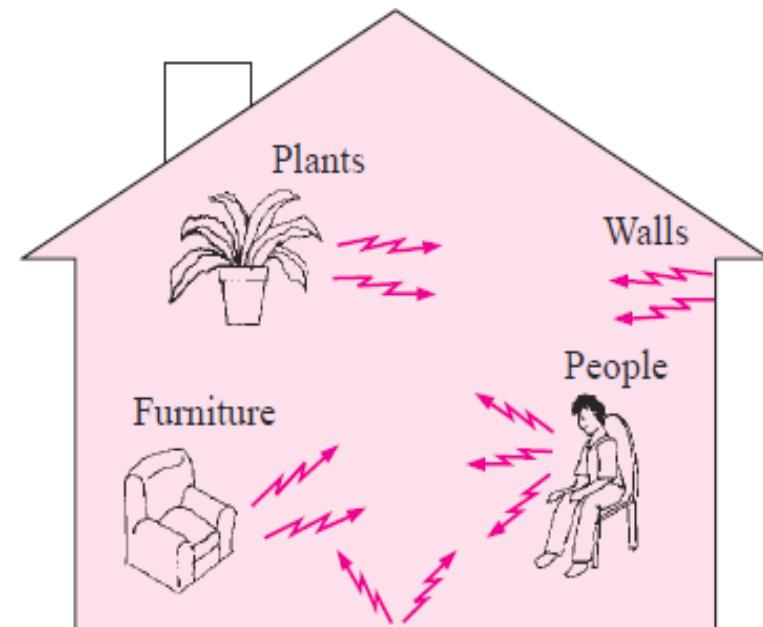


# ACTIVITY 2

What is the minimum temperature required for a body to give out thermal radiation ?

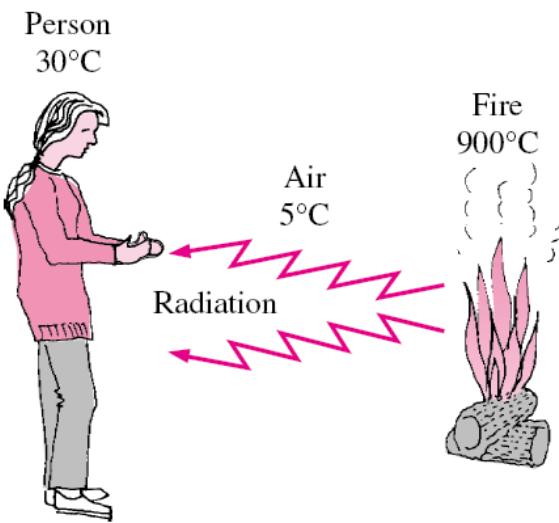
- A. 0 C
- B. 20 C
- C. 1000 C
- D. - 160 C
- E. Others

Thermal radiation is continuously emitted by all matter whose temperature is **above absolute zero (0 K or -273.15 °C)**.



This continues till equilibrium is reached with the surrounding

# CONCEPT OF RADIATION



- Radiation is independent of medium through which it travels, as opposed to conduction/convection
- Energy transport through radiation continues till equilibrium is reached, just as for conduction/convection:
- Solids, Liquids and gases emit radiation
- For non transparent materials radiation can be considered as a surface phenomenon

# **LEARNING OBJECTIVES LECTURE 5**



- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

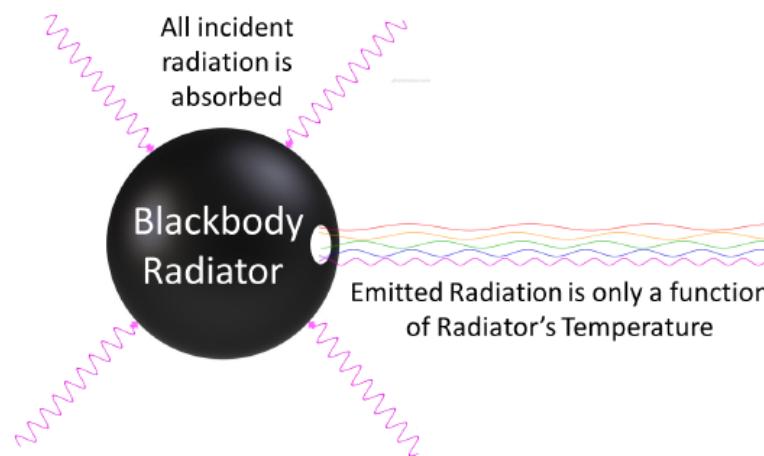
# RADIATION LAWS

## What is Blackbody ?

A perfect emitter and absorber of radiation.

A blackbody absorbs all incident radiation, regardless of wavelength and direction.

A blackbody is a diffuse emitter. Diffuse means “independent of direction.”



# RADIATION LAWS

## Stefan-Boltzmann law :

- ❖ Estimates the Total power emitted by blackbody

$$\dot{Q}_b = \sigma \cdot A \cdot T^4 [W]$$



Josef Stefan

$$\sigma = 5.670 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4}$$

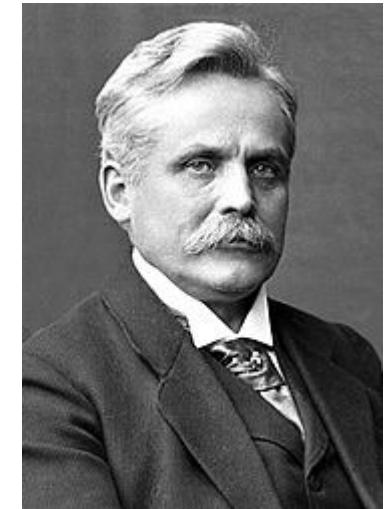
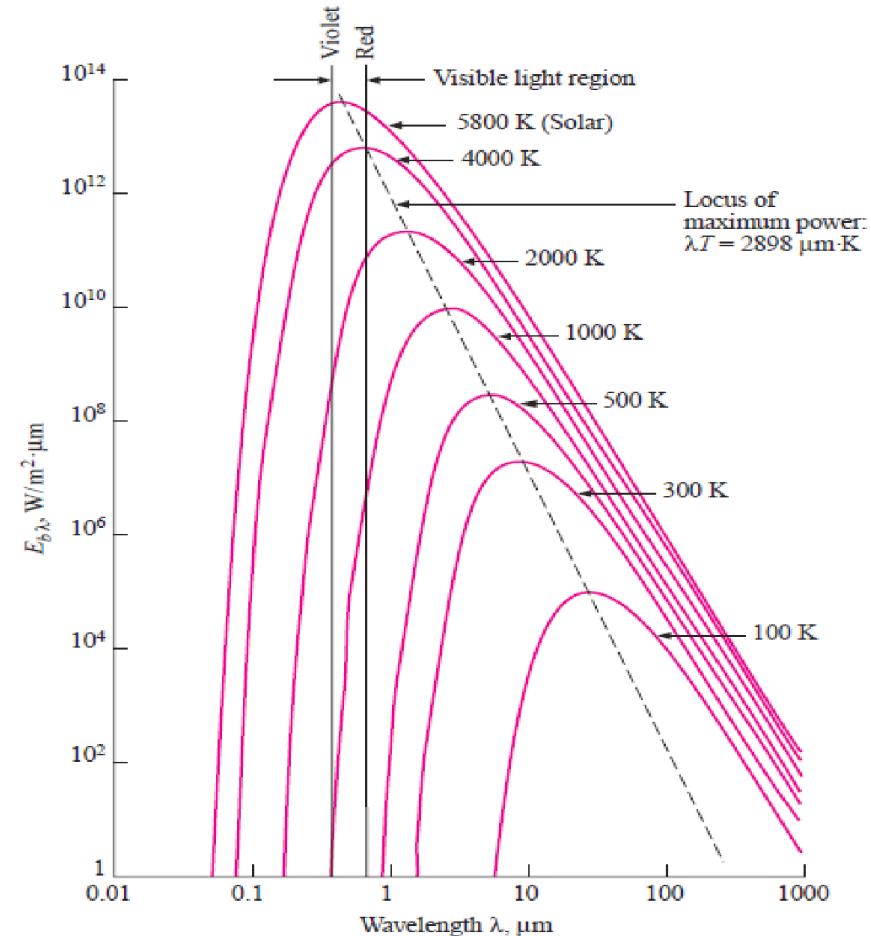
Stefan-Boltzmann  
constant



Ludwig Boltzmann

# RADIATION LAWS

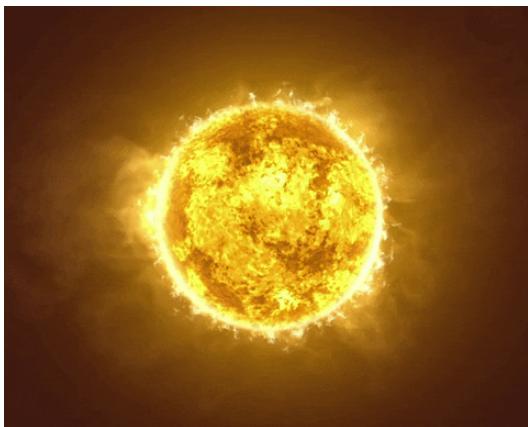
## Wien's displacement law:



Wilhelm Wien

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

# ACTIVITY 3



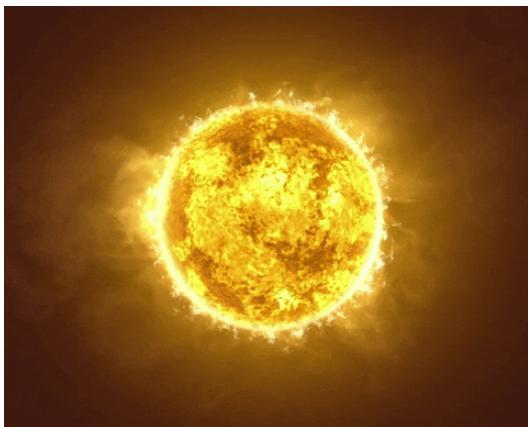
What is the  $\lambda_{\text{Max power}}$  of solar radiation ( $T=5,505^{\circ}\text{C}$ ) ?



What is the  $\lambda_{\text{Max power}}$  of human body ( $T=37^{\circ}\text{C}$ ) ?

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

# ACTIVITY 3



What is the  $\lambda_{Max\ power}$  of solar radiation( $T=5,505\ ^\circ C$ ) ?

$$\lambda_{Max\ power} = \frac{2897.8\ (\mu m \cdot K)}{(5,505 + 273.15)(K)} = 0.501\ \mu m$$

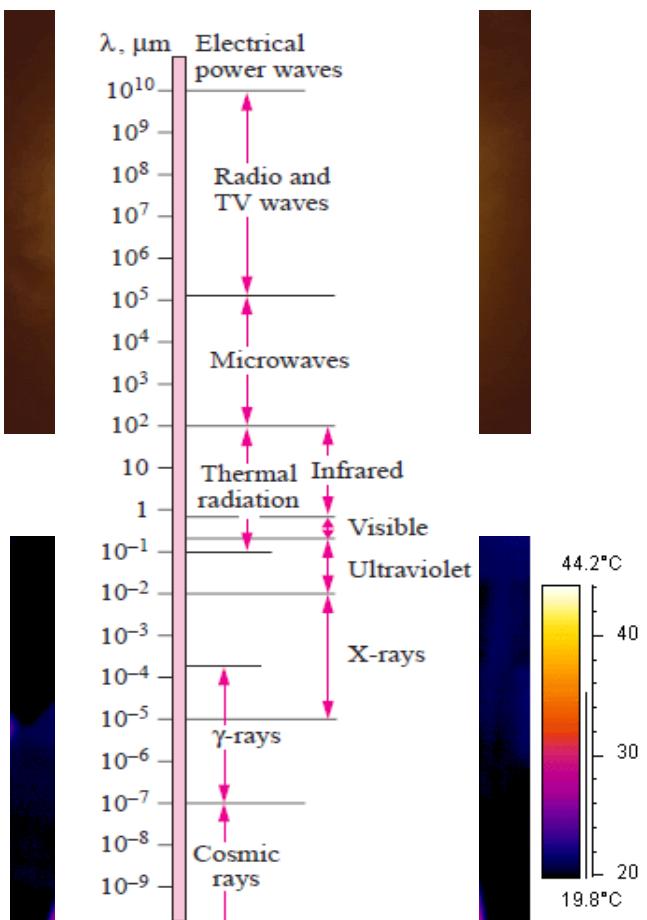


What is the  $\lambda_{Max\ power}$  of human body ( $T=37\ ^\circ C$ ) ?

$$\lambda_{Max\ power} = \frac{2897.8\ (\mu m \cdot K)}{(37 + 273.15)(K)} = 9.34\ \mu m$$

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

# ACTIVITY 3



What is the  $\lambda_{\text{Max power}}$  of solar radiation ( $T=5,505^\circ\text{C}$ ) ?

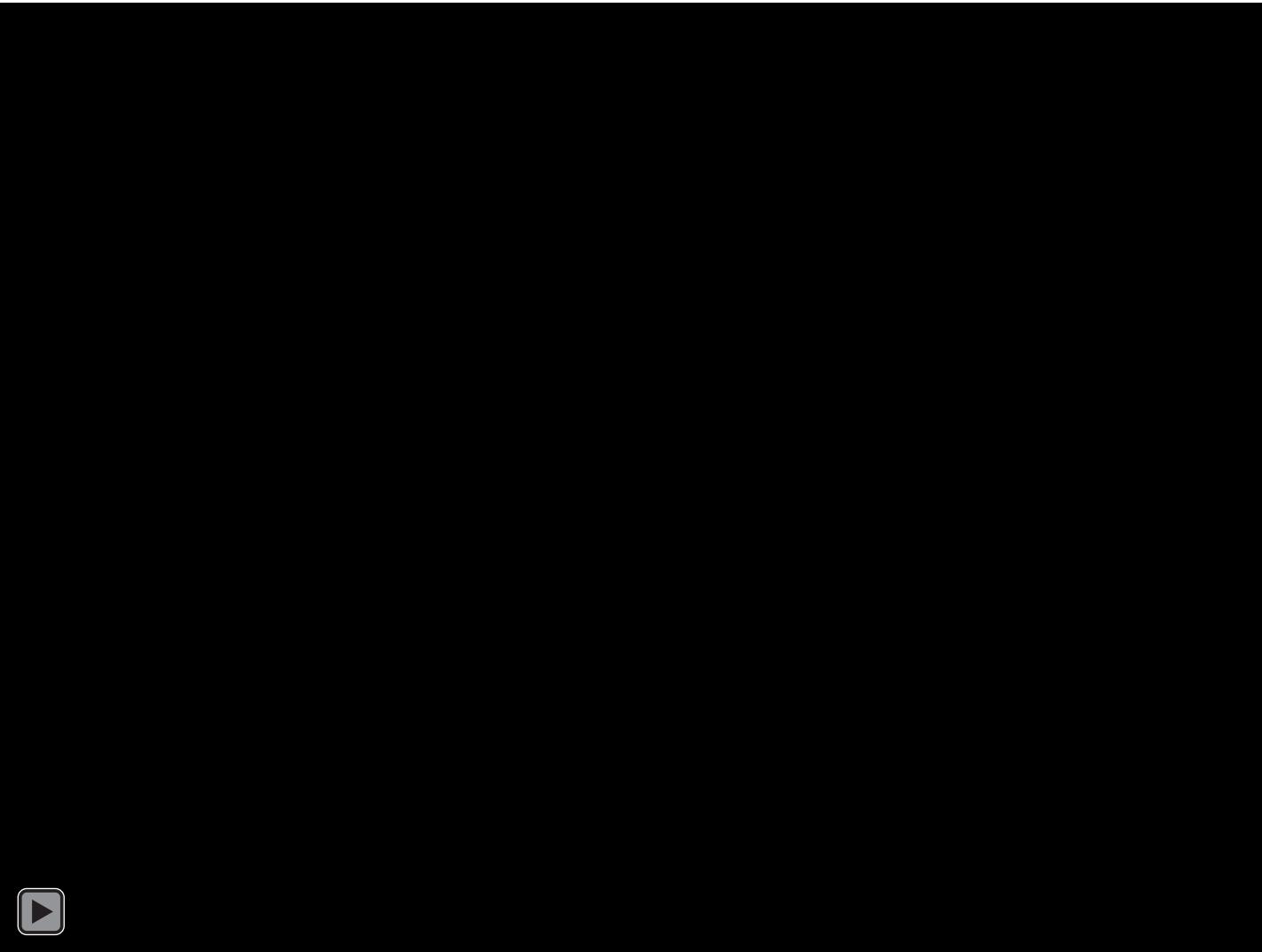
$$\lambda_{\text{Max power}} = \frac{2897.8 (\mu\text{m} \cdot \text{K})}{(5,505 + 273.15)(\text{K})} = 0.501 \mu\text{m}$$

What is the  $\lambda_{\text{Max power}}$  of human body ( $T=37^\circ\text{C}$ ) ?

$$\lambda_{\text{Max power}} = \frac{2897.8 (\mu\text{m} \cdot \text{K})}{(37 + 273.15)(\text{K})} = 9.34 \mu\text{m}$$

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

# ACTIVITY 3



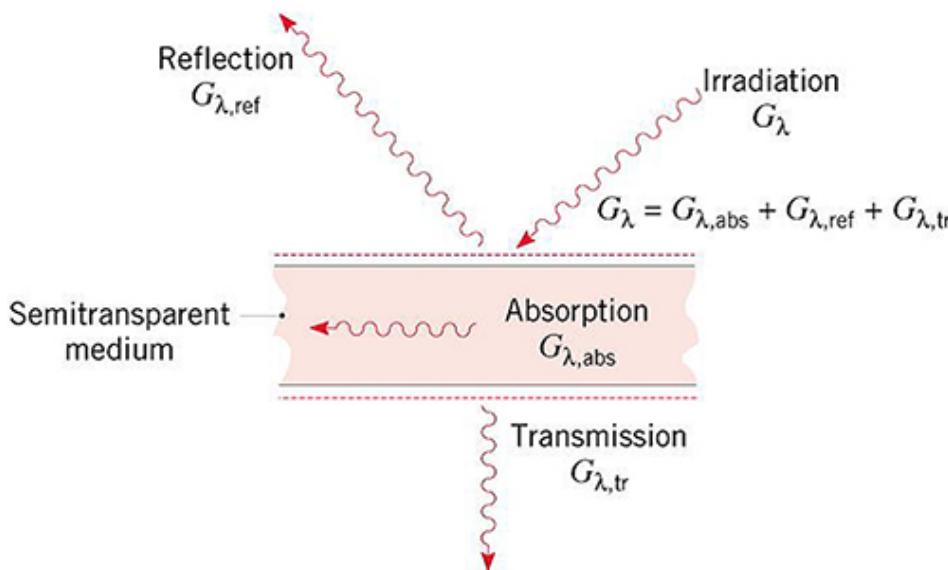
[https://www.youtube.com/watch?v=fpx7hsoYEt4&ab\\_channel=Thunderfoot](https://www.youtube.com/watch?v=fpx7hsoYEt4&ab_channel=Thunderfoot)

# **LEARNING OBJECTIVES LECTURE 5**



- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

# NON -IDEAL RADIATION



Radiation striking a solid surface has one of three fates:

1. **Absorption absorptivity ( $\alpha$ )**

2. **Transmission transmissivity ( $\tau$ )**

3. **Reflection reflectivity ( $\rho$ )**

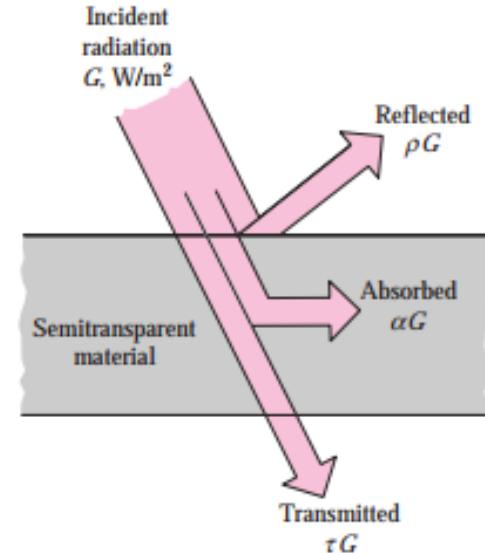
# NON -IDEAL RADIATION

**Absorptivity:**  $\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}}$

**Reflectivity:**  $\rho = \frac{\text{Reflected radiation}}{\text{Incident radiation}}$

**Transmissivity:**  $\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}}$

How are these properties related ?



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

# NON -IDEAL RADIATION



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

Two special cases require definition:

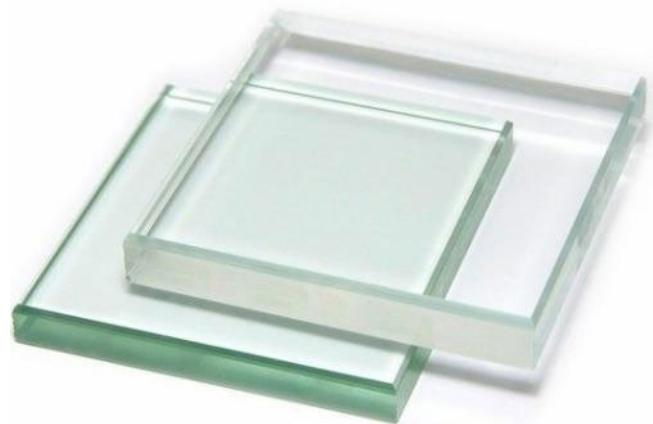
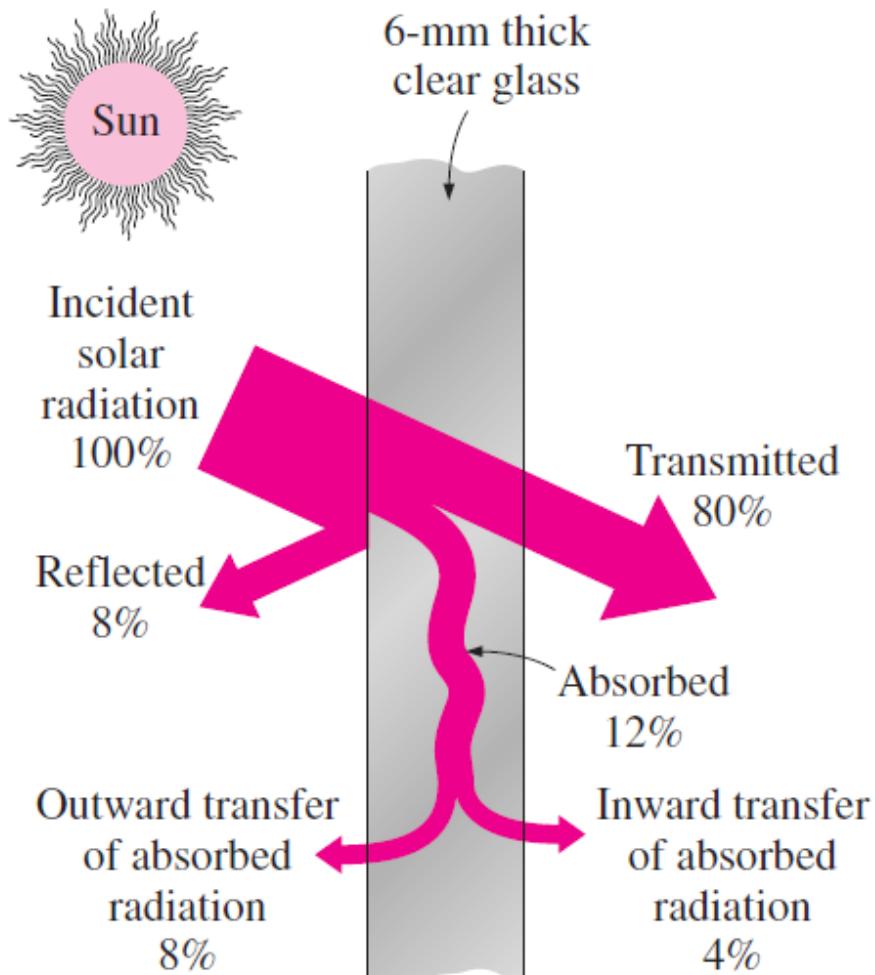
If all of the energy is either reflected or absorbed (no transmitted radiation), we define the body as

Opaque  $\alpha + \rho = 1$

If all of the energy striking a surface is absorbed, we define the body as

Black body  $\alpha = 1$

# NON -IDEAL RADIATION



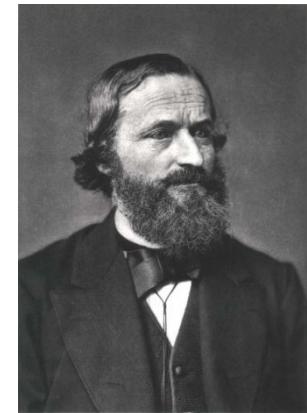
# NON -IDEAL RADIATION

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KIRCHHOFF`S LAW :

The **emissivity** of an object is **equal** to the **absorptivity** of this object at the same temperature.

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



Gustav Robert Kirchhoff

# NON -IDEAL RADIATION



## EMISSIVITY

- In reality all materials: non ideal emitter
- Less power emitted than blackbody

Adjusted Stefan-Boltzmann Law for emitted radiation from object:

$$\dot{Q}_b = \sigma \cdot A \cdot T^4 \text{ (W)} \text{ so } \dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \text{ (W)}$$

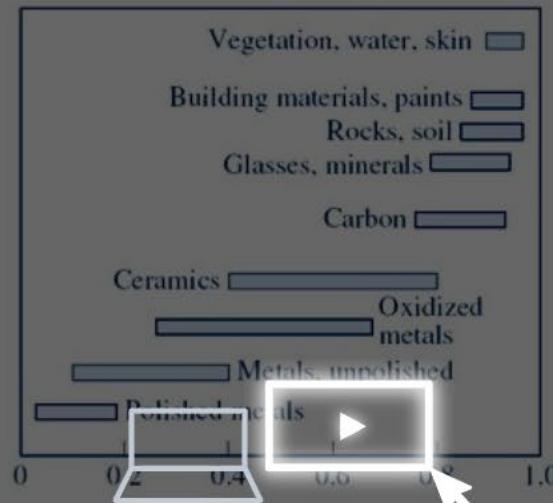
Emissivity  $\varepsilon$  ( $0 \leq \varepsilon \leq 1$ ) of a surface (material property):

Measure for emitted radiation ( $\dot{Q}$ ) in comparison to radiation ( $\dot{Q}_b$ ) emitted by a blackbody ( $\varepsilon = 1$ ) at same temperature.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_b}$$



Which of these materials have the highest Emissivity ?



Click on the projected screen to start the question

① Metal

13% 2

③ Skin

81% 13

② Polished metal

6% 1

④ Ceramics

0% 0



Can Emissivity be changed/Altered ?

① yes

94% 15

② No

6% 1

③ Not sure

0% 0

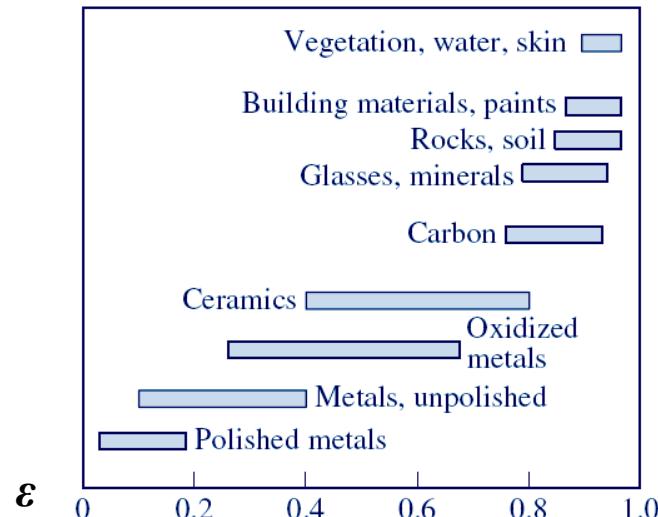


Click on the projected screen to start the question

# ACTIVITY 4

Which of these materials have the highest Emissivity ?

- A. Metal
- B. Polished metal
- C. Skin
- D. Ceramics



Can Emissivity be changed/Altered ?

- A. Yes
- B. No
- C. Not sure

Can be Changed via  
-Thermal Treatment  
- Polishing,...

Which one will cool down faster?



① Black

64% 14

② White

27% 6

③ Silver

9% 2



# **LEARNING OBJECTIVES LECTURE 5**



- Concept of Radiation
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# Radiation Heat Transfer



To calculate the heat transfer rate by radiation, we must include terms for power output and energy received from the surroundings.

power  
output:

$$\varepsilon\sigma AT_s^4$$

power  
input:

$$\sigma\alpha AT_\infty^4$$

Making the usual assumption that  $\varepsilon = \alpha$ , and multiplying by area yields:

$$\dot{Q} = \varepsilon\sigma A(T_s^4 - T_\infty^4)$$

This is the expression for an object totally enclosed by surroundings at  $T_\infty$ .

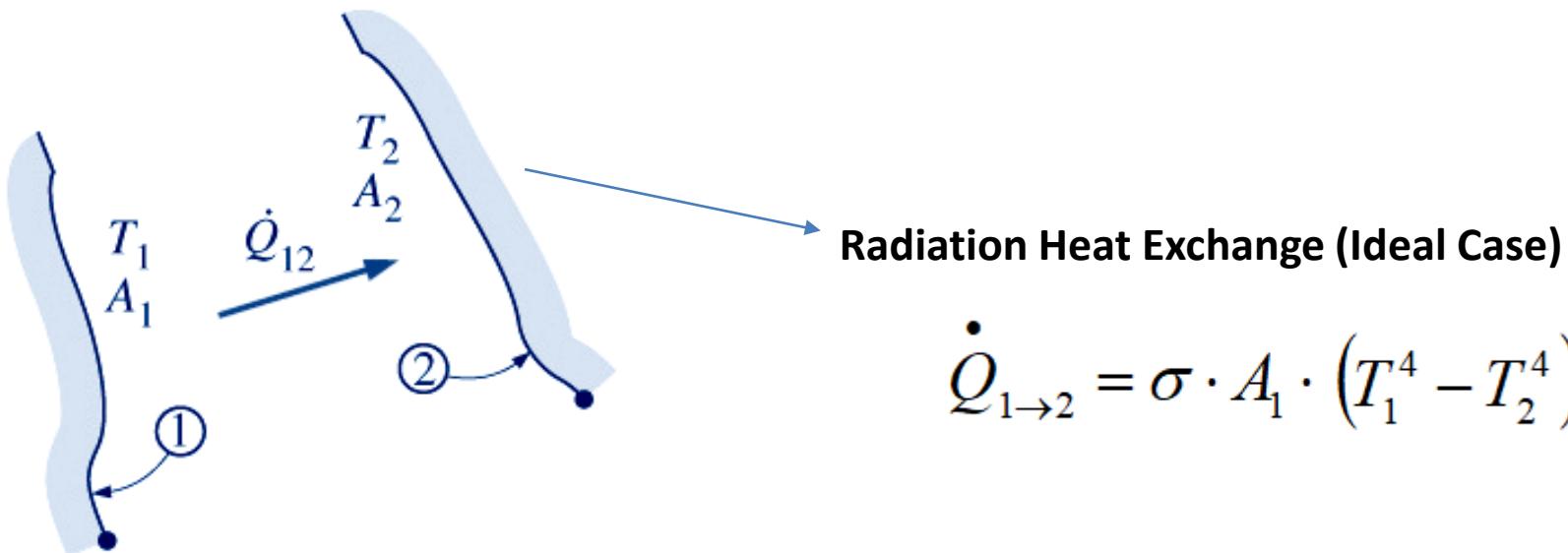
# Radiation Heat Transfer

Radiation from a single body at certain temperature T (Black Body)

$$\dot{Q} = \sigma \cdot A \cdot T^4 \quad (\text{W})$$

Radiation from a single body at certain temperature T (non ideal)

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \quad (\text{W})$$

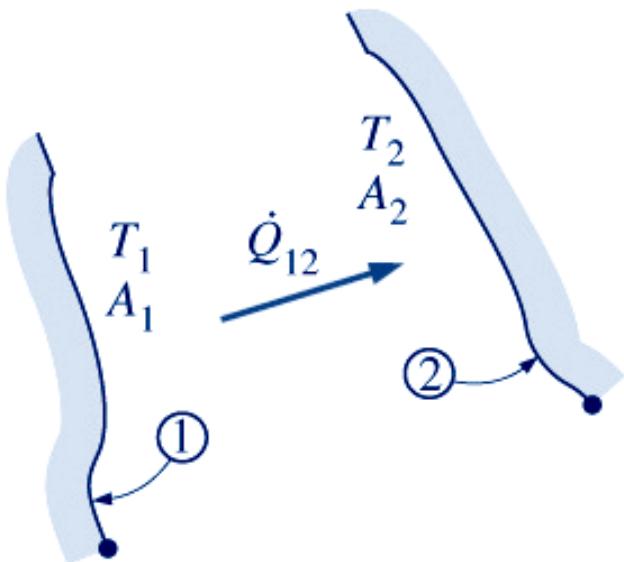


$$\dot{Q}_{1 \rightarrow 2} = \sigma \cdot A_1 \cdot (T_1^4 - T_2^4)$$

But what about the orientation and shape of the object ?

# Radiation Heat Transfer

## VIEW FACTORS

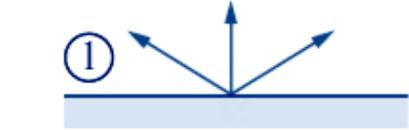


$F_{i \rightarrow j}$  is the 'view factor':

$$F_{i \rightarrow j} = \frac{\dot{Q}_{i \rightarrow j}}{\dot{Q}_i}$$

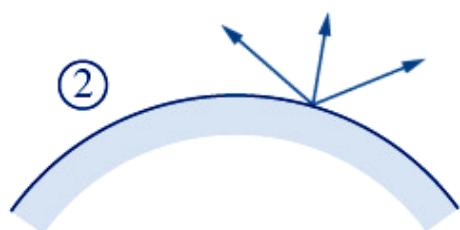
To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a **purely geometric quantity** and is independent of the surface properties and temperature. It is also called the shape factor, configuration factor, and angle factor.

# VIEW FACTORS



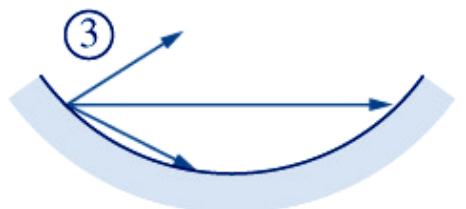
$$F_{1 \rightarrow 1} = 0$$

(a) Plane surface



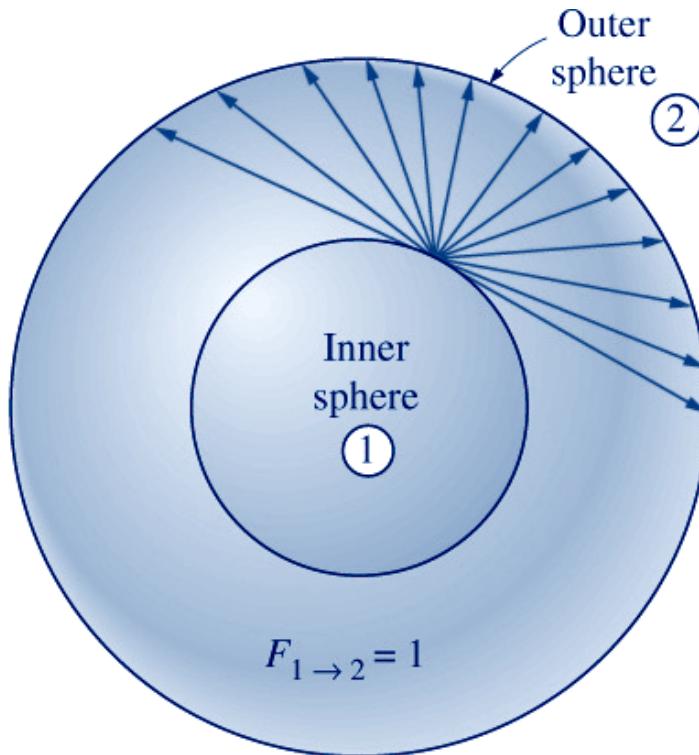
$$F_{2 \rightarrow 2} = 0$$

(b) Convex surface



$$F_{3 \rightarrow 3} \neq 0$$

(c) Concave surface



$$F_{1 \rightarrow 2} = 1$$

**Cylinder/sphere:**

- $F_{1 \rightarrow 1} = 0$
- $F_{1 \rightarrow 2} = 1$

# VIEW FACTORS

## Rules/Theorem's

### 1 The Reciprocity Relation

The view factors  $F_{i \rightarrow j}$  and  $F_{j \rightarrow i}$  are *not* equal to each other unless the areas of the two surfaces are. That is,

$$\begin{aligned} F_{j \rightarrow i} &= F_{i \rightarrow j} && \text{when } A_i = A_j \\ F_{i \rightarrow i} &\neq F_{i \rightarrow i} && \text{when } A_i \neq A_j \end{aligned}$$

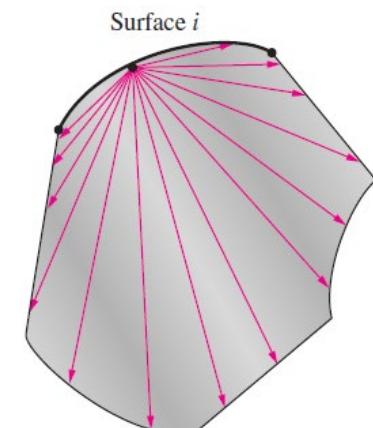
$$A_1 F_{12} = A_2 F_{21}$$

### 2 The Summation Rule

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

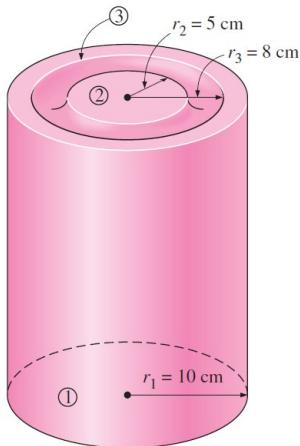
where  $N$  is the number of surfaces of the enclosure. For example, applying the summation rule to surface 1 of a three-surface enclosure yields

$$\sum_{j=1}^3 F_{1 \rightarrow j} = F_{1 \rightarrow 1} + F_{1 \rightarrow 2} + F_{1 \rightarrow 3} = 1$$



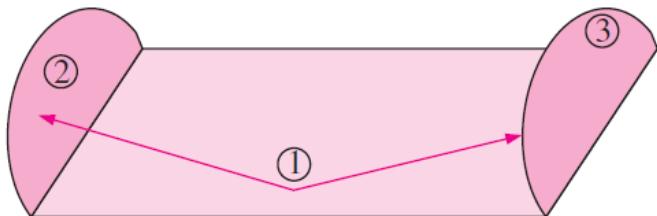
# VIEW FACTORS

## 3 The Superposition Rule



$$F_{1 \rightarrow (2, 3)} = F_{1 \rightarrow 2} + F_{1 \rightarrow 3}$$

## 4 The Symmetry Rule

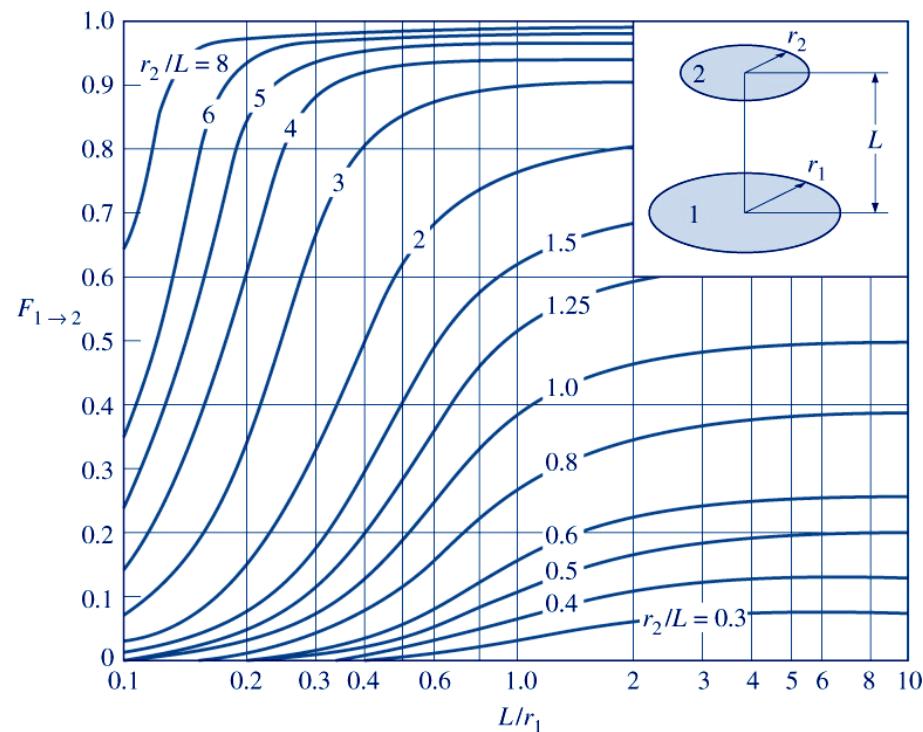
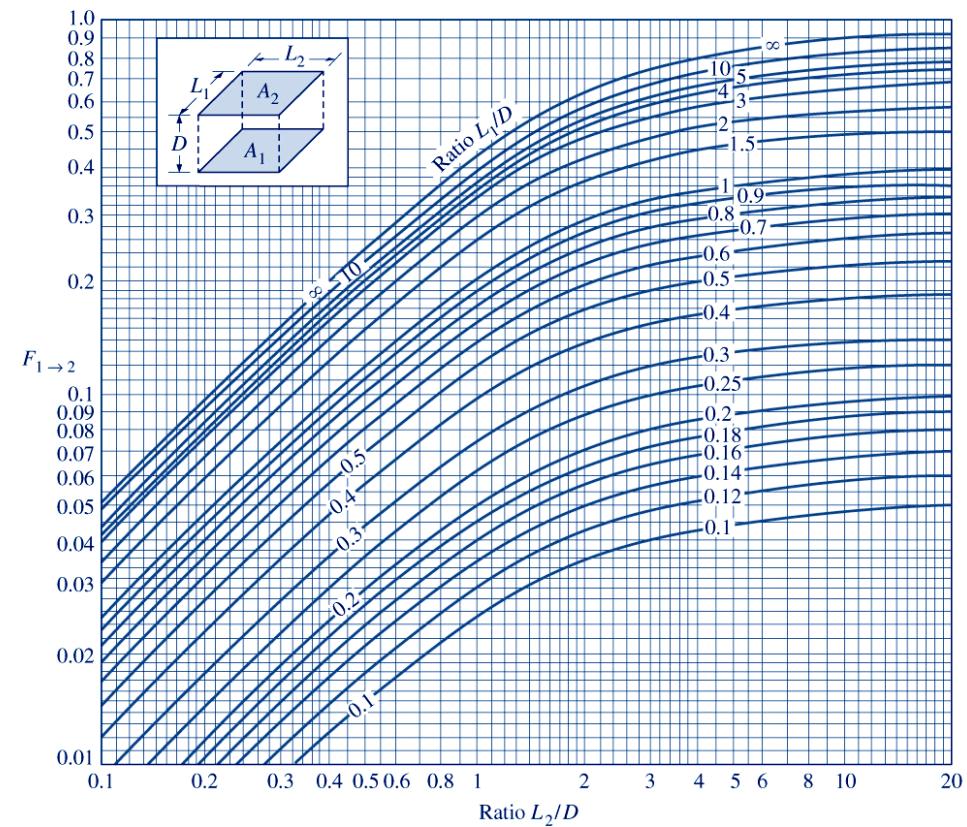


$$F_{1 \rightarrow 2} = F_{1 \rightarrow 3}$$

(Also,  $F_{2 \rightarrow 1} = F_{3 \rightarrow 1}$ )

# VIEW FACTORS

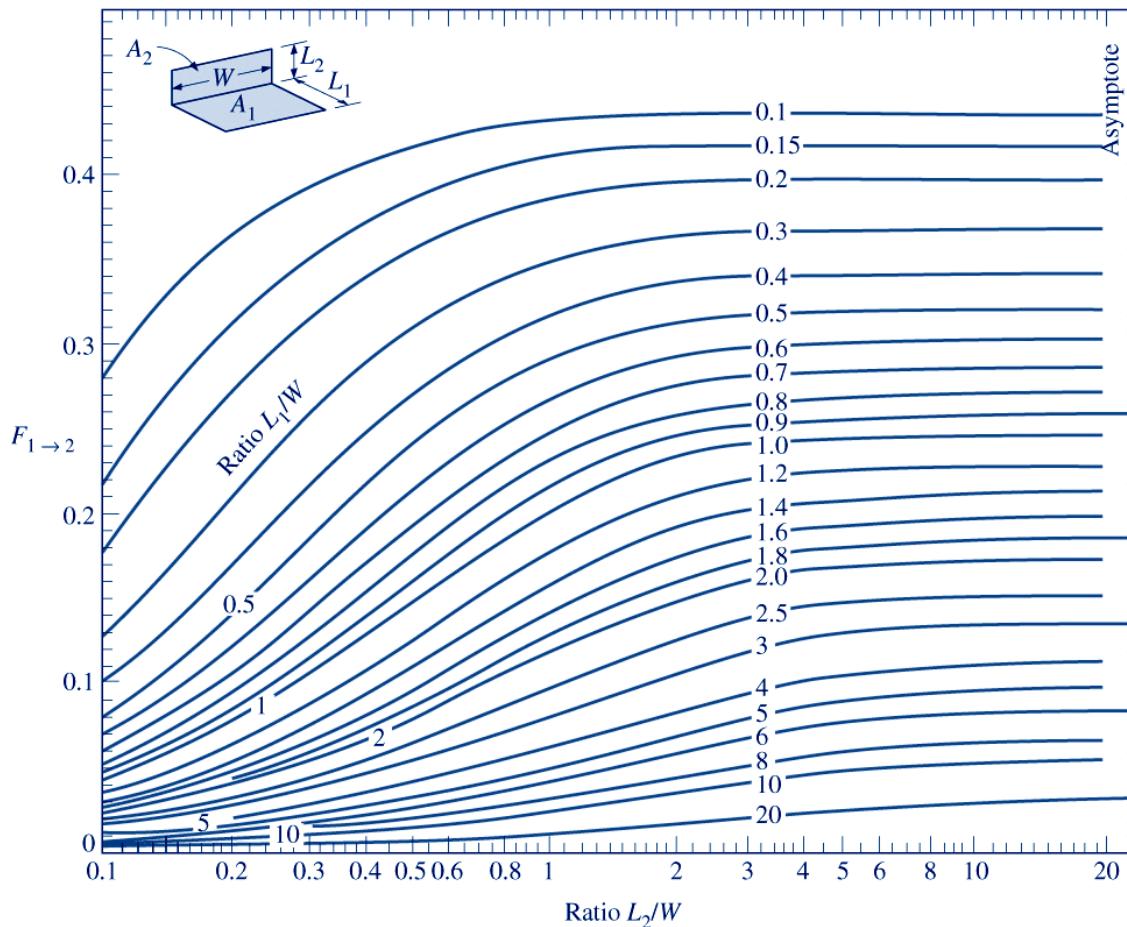
## PARALEL PLANES



Beware: not valid if the surfaces are shifted in their plane (surfaces have to be aligned or coaxial)

# VIEW FACTORS

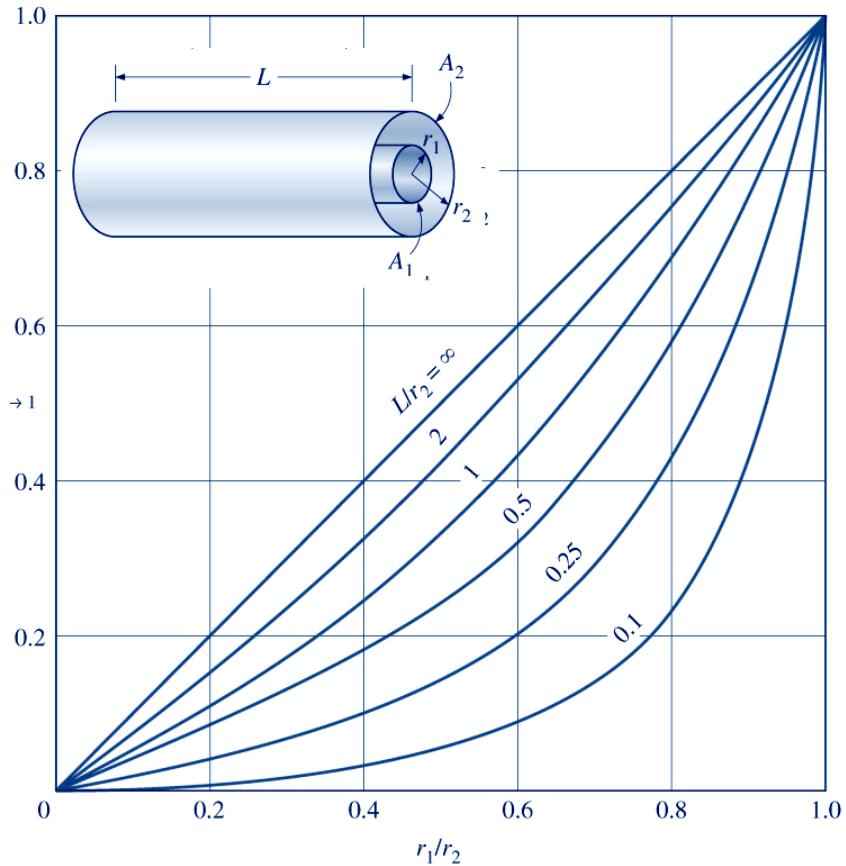
## PERPENDICULAR, ATTACHED RECTANGLES



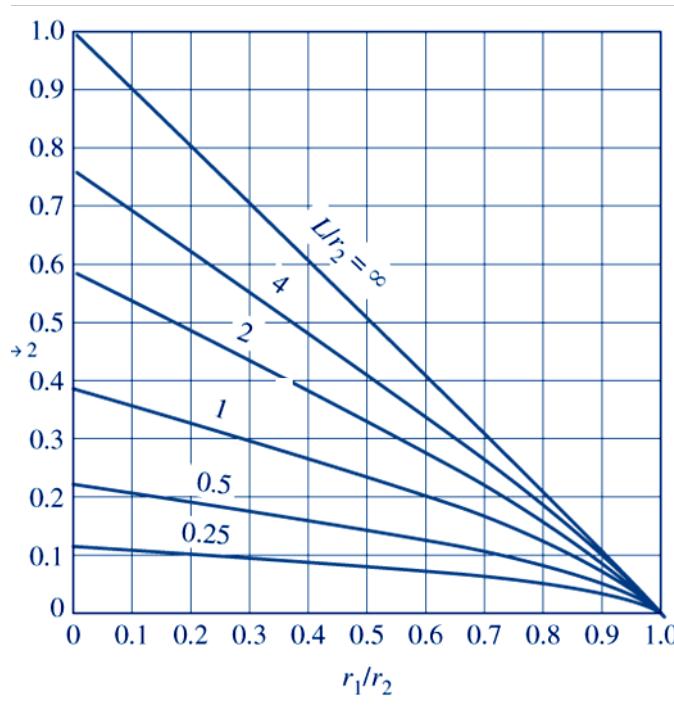
# VIEW FACTORS

## CONCENTRIC CYLINDERS

$F_{2 \rightarrow 1}$



$F_{2 \rightarrow 2}$



Established earlier:

- $F_{1 \rightarrow 1} = 0$
- $F_{1 \rightarrow 2} = 1$

# Heat Quiz



## Practise path: View Factors

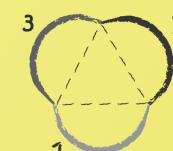
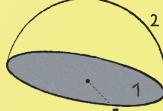
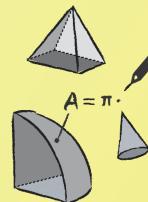
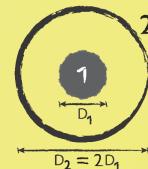
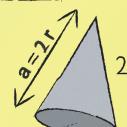
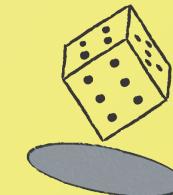
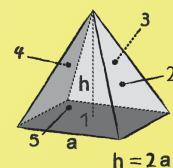
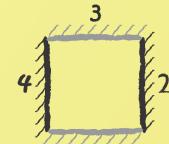
### Hints

Summation rule:  $\sum_j \phi_{ij} = 1$

Reciprocity rule:  $A_i \phi_{ij} = A_j \phi_{ji}$

Make use of symmetries

Think of auxiliary planes

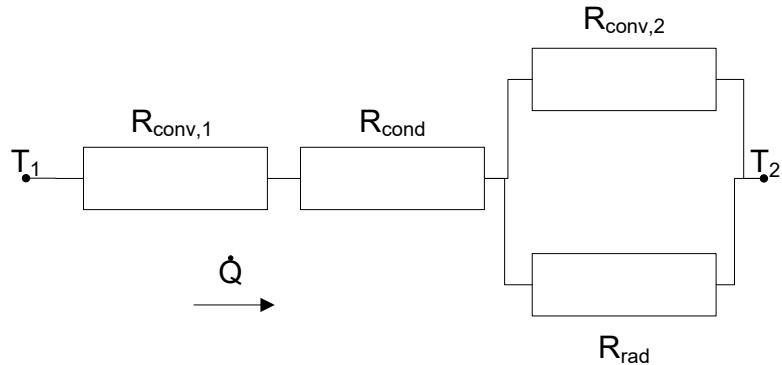


# **LEARNING OBJECTIVES LECTURE 5**

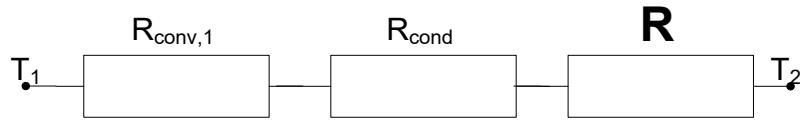


- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Exchange
- Resistance Networks – (Radiation and Convection)

# Overall resistance Network

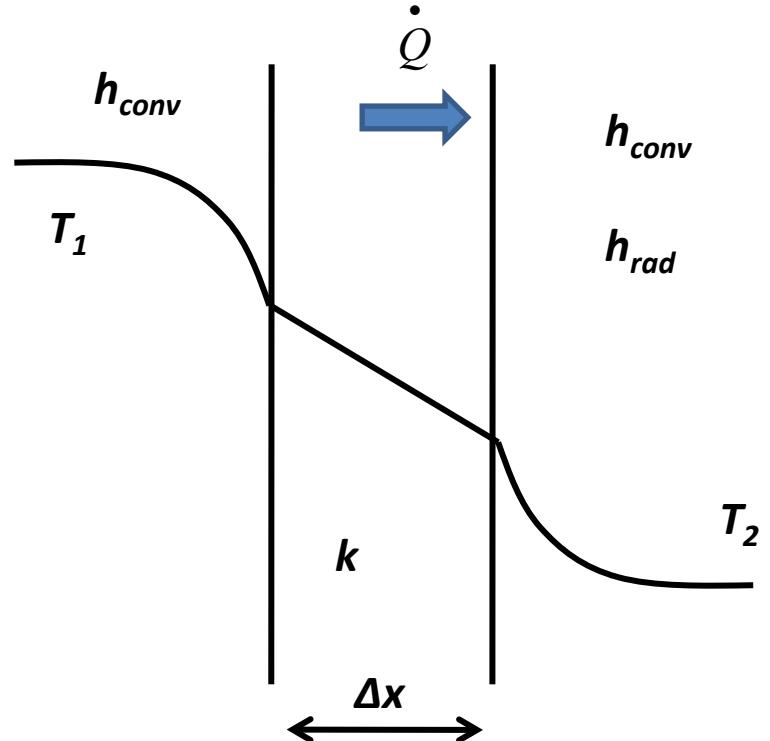


$$\frac{1}{R} = \frac{1}{R_{conv,2}} + \frac{1}{R_{rad}}$$

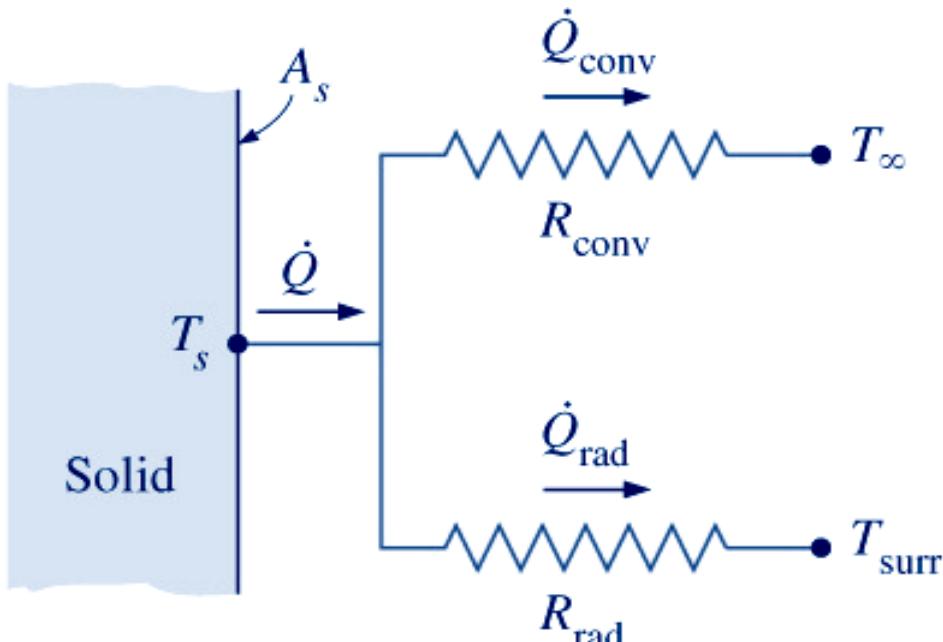


$$R_{tot} = R_{conv,1} + R_{cond} + R$$

$$\dot{Q} = \frac{T_1 - T_2}{R_{tot}}$$

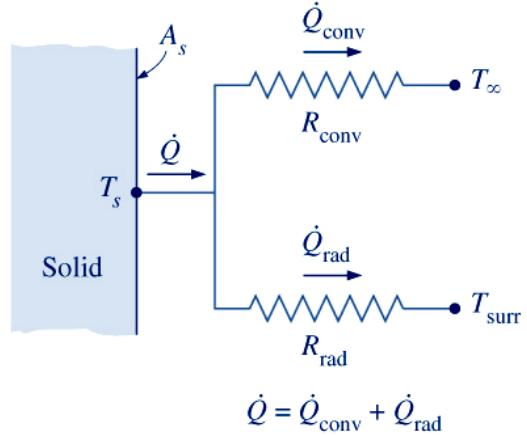


# Radiation and convection



$$\dot{Q} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}}$$

# Radiation and convection



$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_\infty^4)$$

$$Let, h_{rad} = \varepsilon \cdot \sigma \cdot (T_s^2 + T_\infty^2) \cdot (T_s + T_\infty)$$

$$Therefore, \dot{Q}_{rad} = h_{rad} \cdot A \cdot (T_s - T_\infty)$$

$$\dot{Q}_{rad} = \frac{T_s - T_\infty}{R_{rad}} \quad \text{with} \quad R_{rad} = \frac{1}{h_{rad} A}$$

$$\frac{1}{R_{tot}} = \frac{1}{R_{conv}} + \frac{1}{R_{rad}}$$

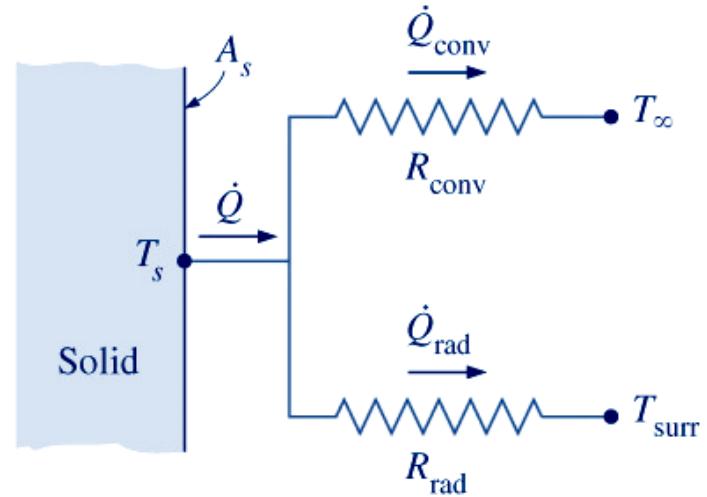
# Radiation and convection

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

$$= h_{conv} A \Delta T + h_{rad} A \Delta T$$

$$= (h_{conv} + h_{rad}) A \Delta T$$

$$\Rightarrow \dot{Q} = h_{tot} A \Delta T \quad \text{with } h_{tot} = h_{conv} + h_{rad}$$



$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

# SUMMARY LECTURE 5 (1/2)



- Radiation
  - Does not need a transport medium
  - Thermal:  $0,1 \mu\text{m} < \lambda < 100 \mu\text{m}$
- Blackbody:
- Non ideal emitters
  - Emissivity  $\varepsilon$
  - Absorptivity  $\alpha$
  - Reflectivity  $\rho$
  - Transmissivity  $\tau$

# SUMMARY LECTURE 5 (2/2)

- Stefan-Boltzmann's Law for radiation coming **from** all emitters (blackbody:  $\varepsilon = 1$ )

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \quad (\text{W})$$

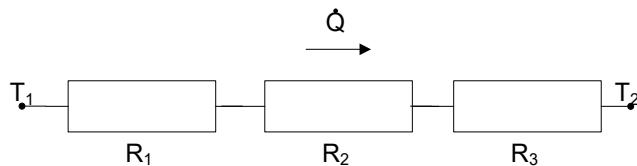
- **Net** radiation from non ideal emitter towards environment (with  $\varepsilon < 1$ )

$$\boxed{\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot (T^4 - T_\infty^4)}$$

- View factor: fraction of radiation from surface i that directly hits surface j ( $F_{i \rightarrow j}$ )

- Radiation and convection:  $h_{tot} = h_{conv} + h_{rad}$

- Series resistors:  
**(add resistors)**



- Parallel resistors:  
**(add heat flows)**

$$\frac{1}{R_{tot}} = \sum_i \frac{1}{R_i}$$

