Energy & Heat Transfer

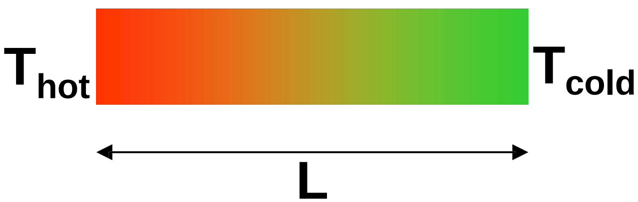
Lecture 5

By: Mohammad Mehrali

Recap of last lectures

Heat Transfer Modes

Heat Conduction



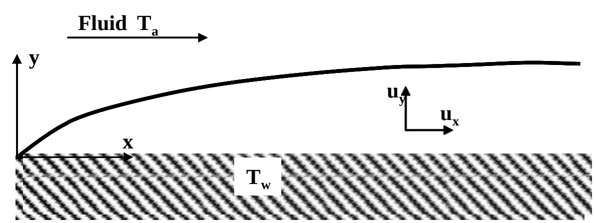
- Fourier Law

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

Thermal Conductivity [W/m.K]
Material properties

Cross-Sectional Area $[m^2]$

Convection



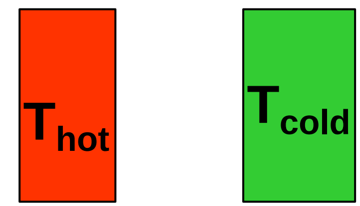
- Newton’s law of cooling

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

Convective Heat Transfer Coefficient [W/m^{2}K]
Flow dependent

- Natural Convection
- Forced Convection

Thermal Radiation

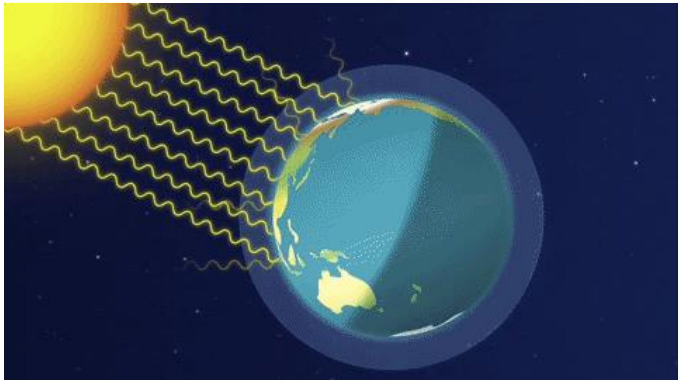


Learning objectives lecture 5

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

Radiation Examples

Sun



Surface temperature : **5,778 K**

Distance from earth : **149.6 million km**

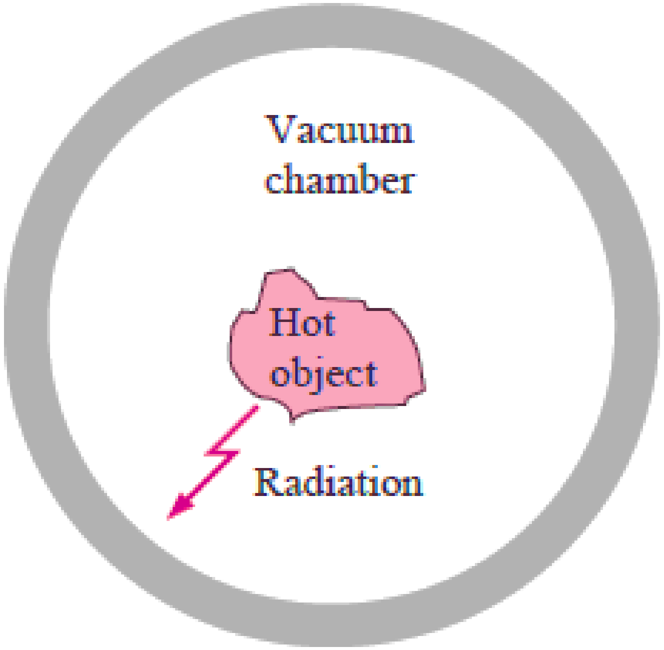
Fire

Flame temperature **~750 ℃**

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**.



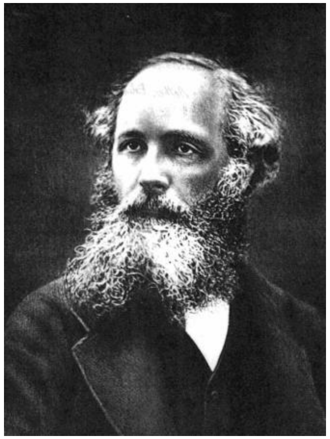
But How is this heat (internal energy) being transported without any medium ? ?

Electromagnetic Waves or Electromagnetic Radiation

(no medium required!)

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

Electromagnetic Waves :

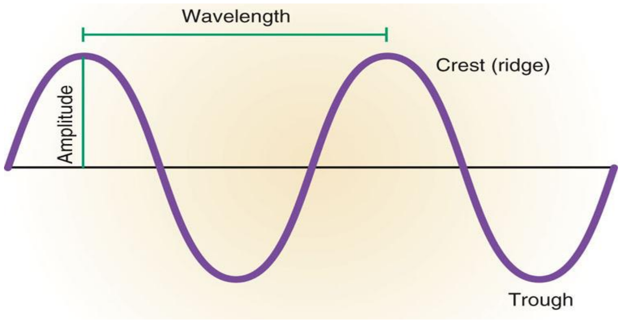


James Clerk Maxwell

- 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.

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



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

c is the speed of light in vacuum

λ is the wavelength in meters

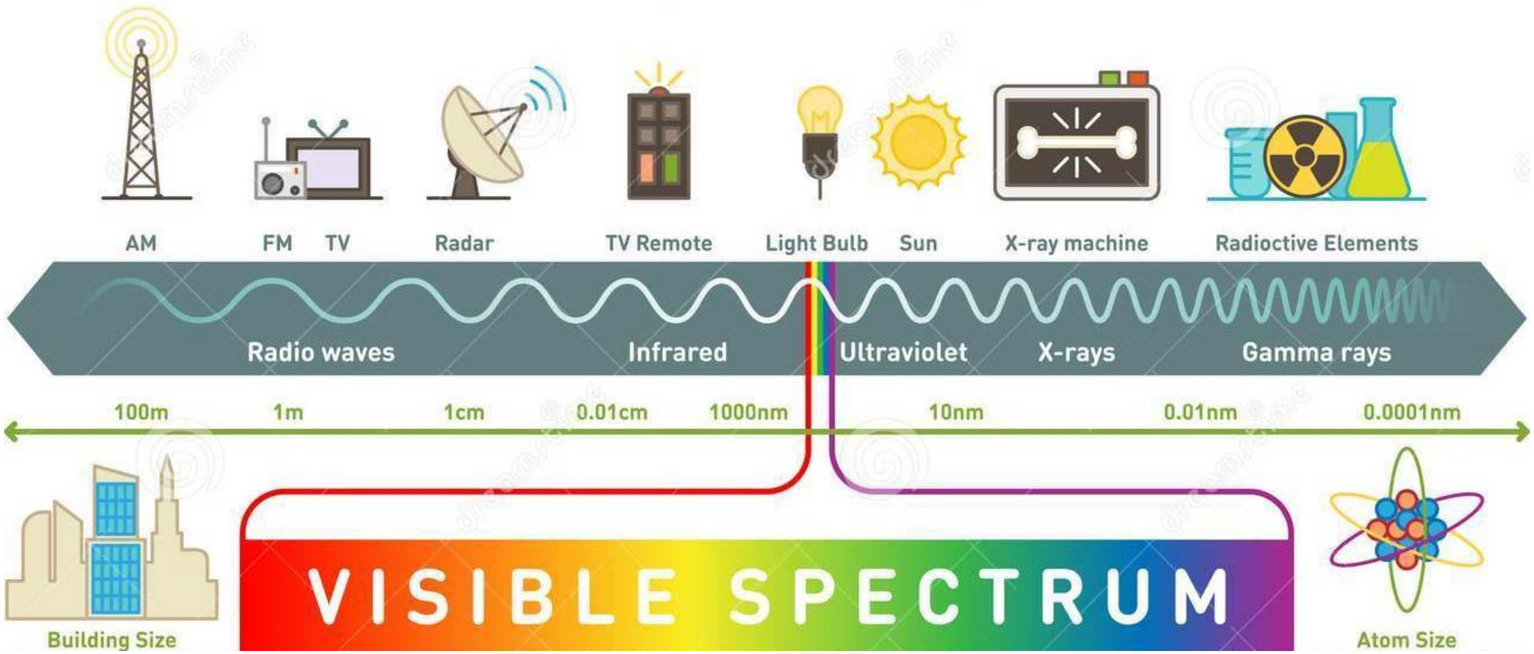
ν is the frequency in Hertz (Hz) or S^{-1}

Heinrich Rudolf Hertz

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

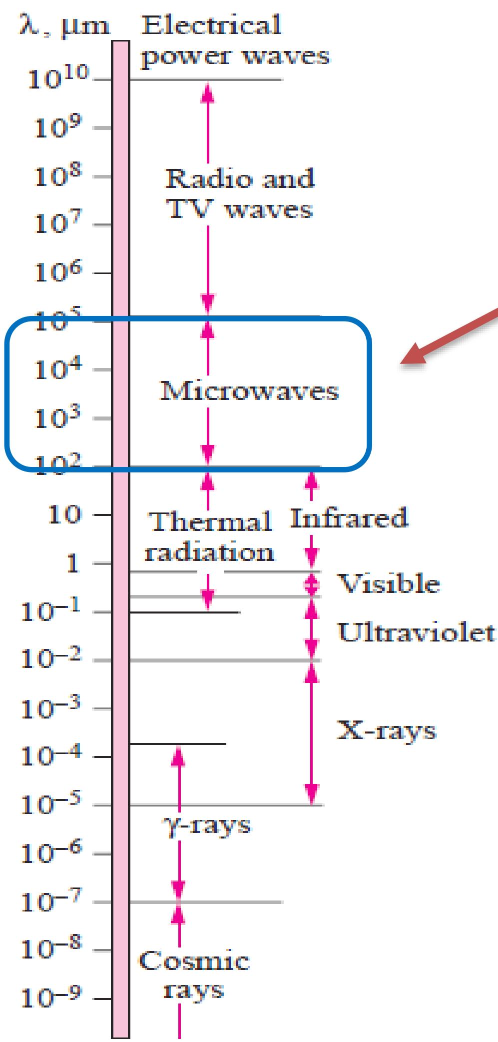
3) Wave speed – constant! - **speed of light (vacuum: 2.9979*10^8 m/s)**

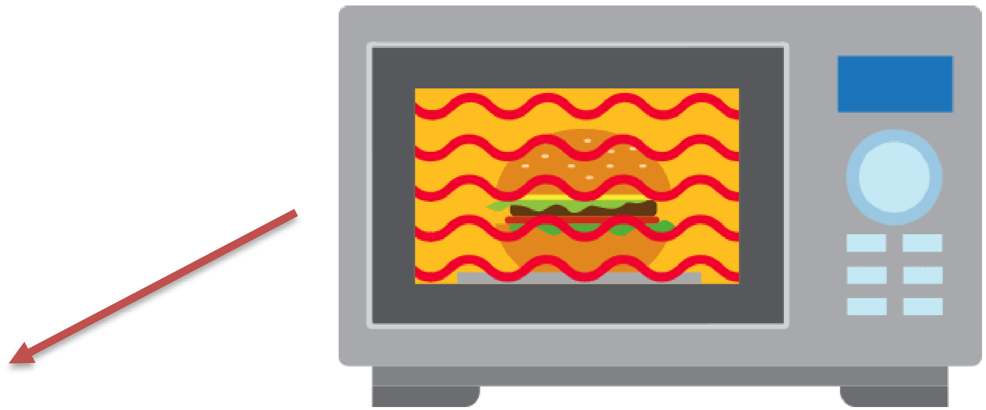
Electromagnetic spectrum



- 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.

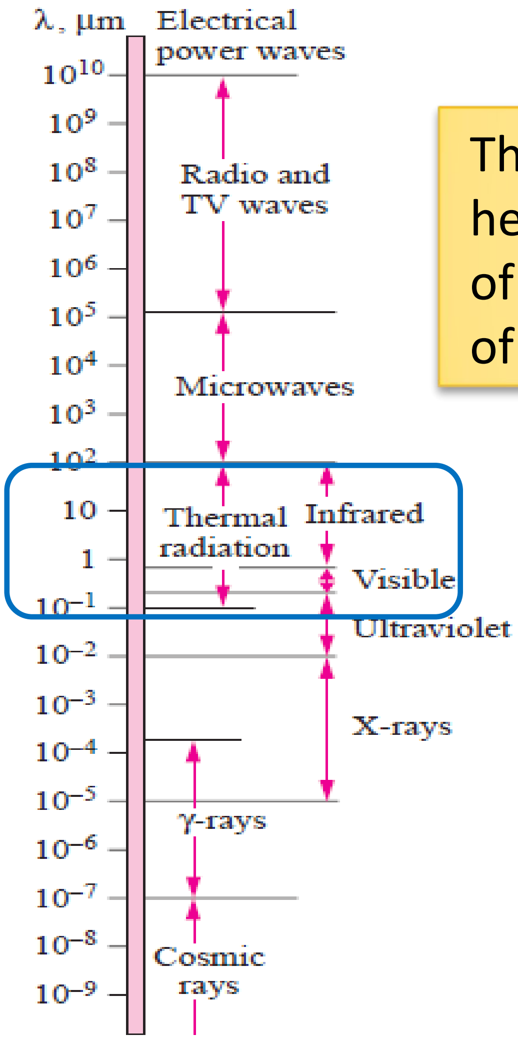
Electromagnetic spectrum





- Wavelength λ = 10^2 … 10^5 μm
- Waves are reflected by metal (walls)
- Transmission through glass and plastics (ovendish)
- Absorption in food (mainly water molecules)
- Effective conversion: electric energy → radiation energy → internal (thermal) energy food

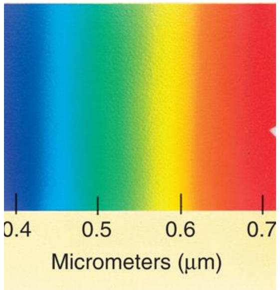
THERMAL RADIATION



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 μm.



ACTIVITY 1

Only Solids radiate thermal Energy

A. True
B. False
C. Not Sure

ACTIVITY 1

Only Solids radiate thermal Energy

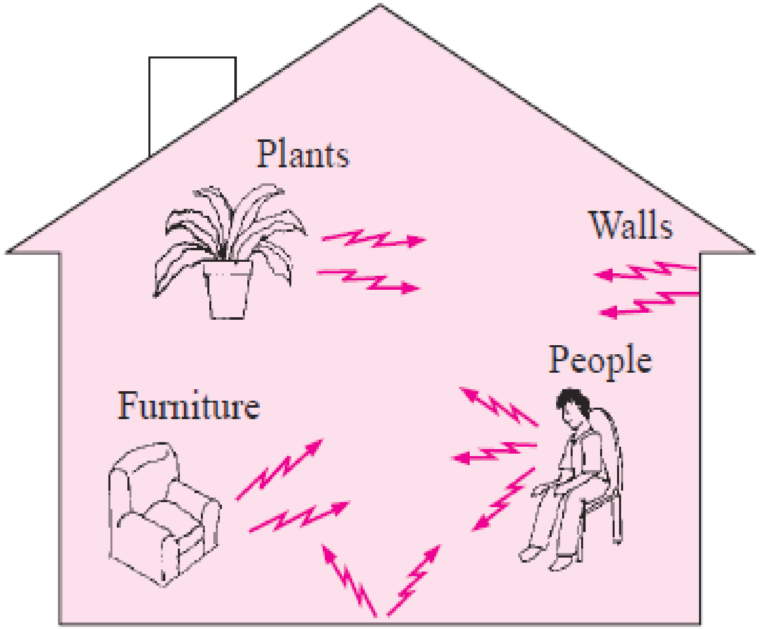
A. True
B. False
C. Not Sure

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



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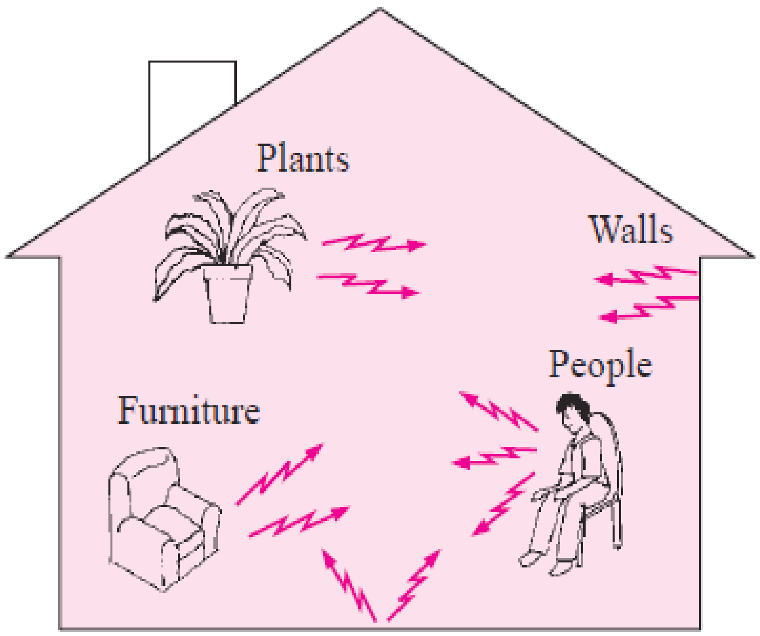
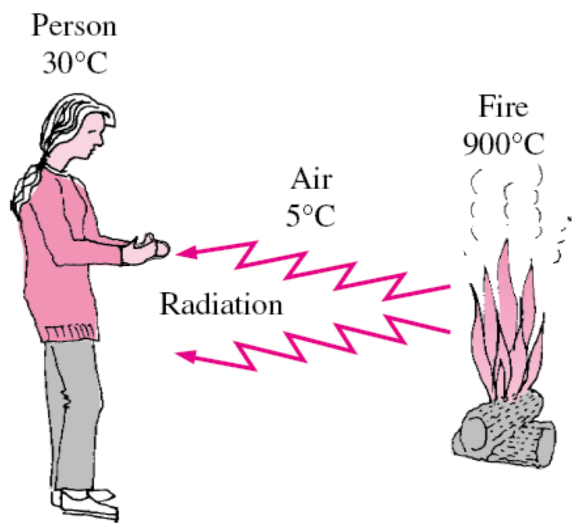


Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero (0 K or -273.15 °C).

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

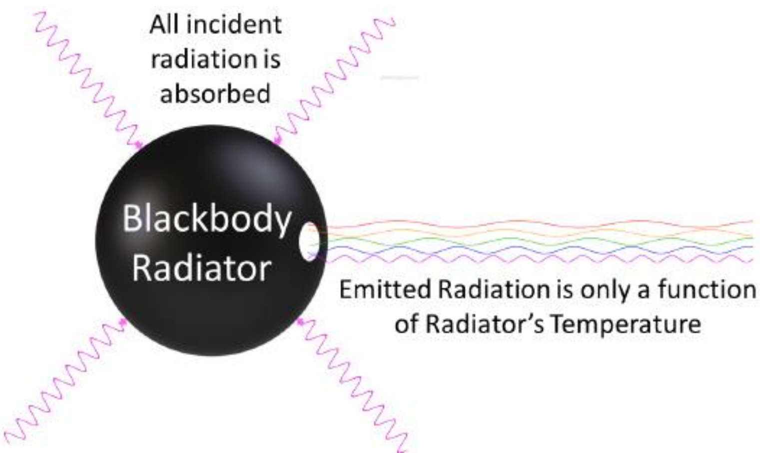
- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

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."



Stefan-Boltzmann law :

❖ Estimates the **Total power** emitted by blackbody

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

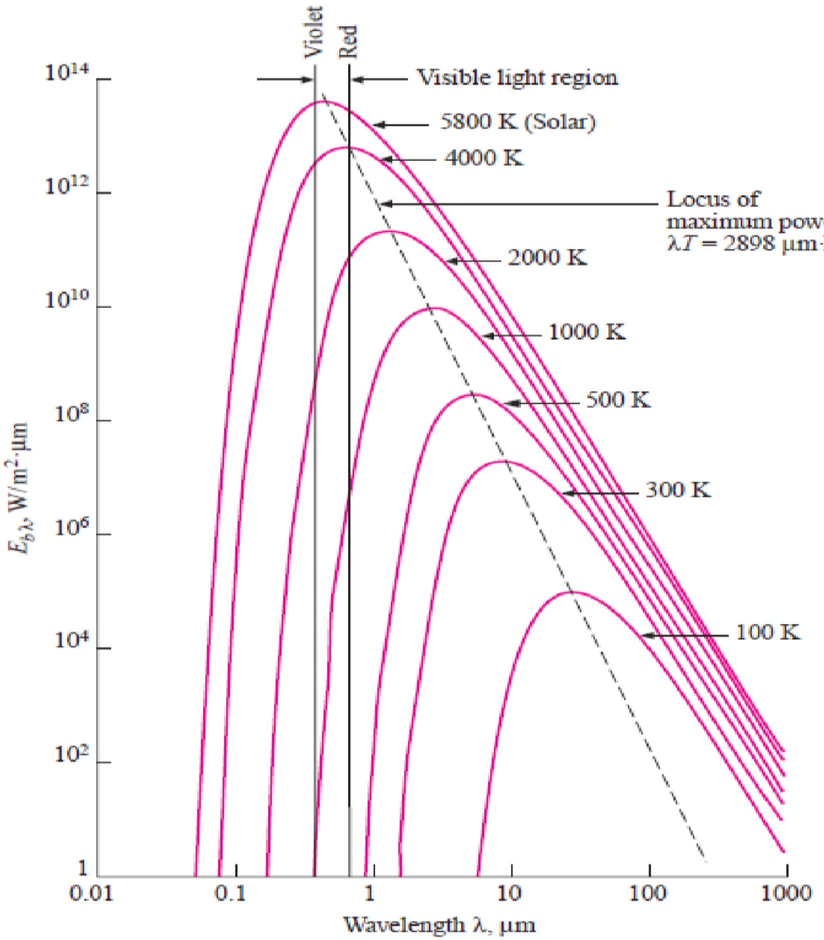
$$\sigma = 5.670 \times 10^{-8} \; \frac{\mathrm{W}}{\mathrm{m^2 K^4}}$$

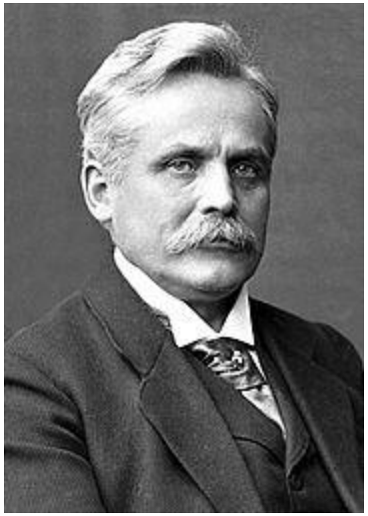
Stefan-Boltzmann constant

Josef Stefan

Ludwig Boltzmann

Wien's displacement law:

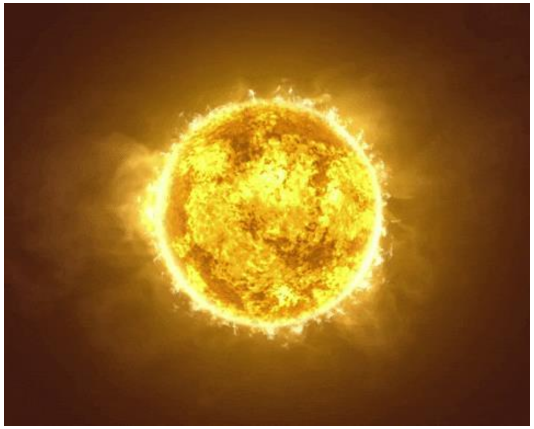




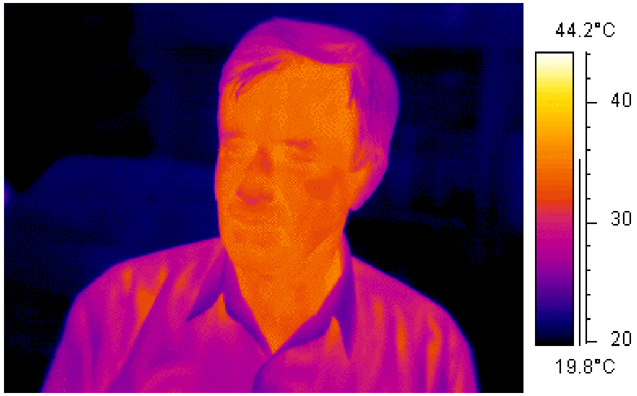
Wilhelm Wien

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

ACTIVITY 3



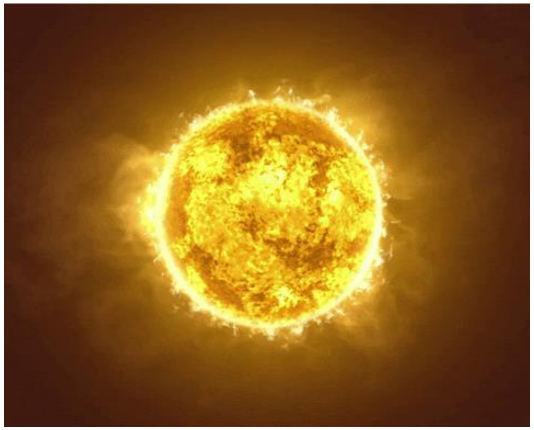
What is the $\lambda_{Max\ power}$ of solar radiation(T=5,505 ℃) ?



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

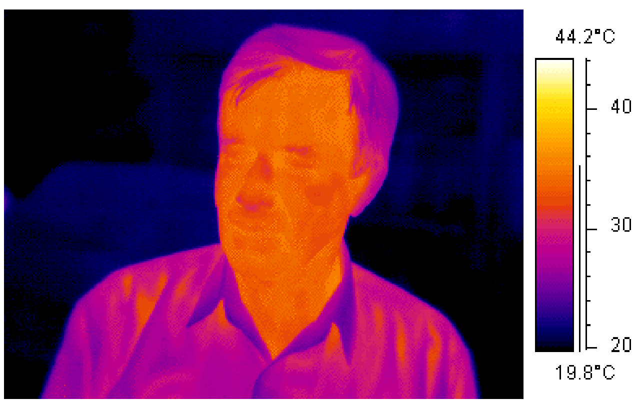
$$(\lambda T)_{\text{max power}} = 2897.8\ \mu\text{m} \cdot \text{K}$$

ACTIVITY 3



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

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

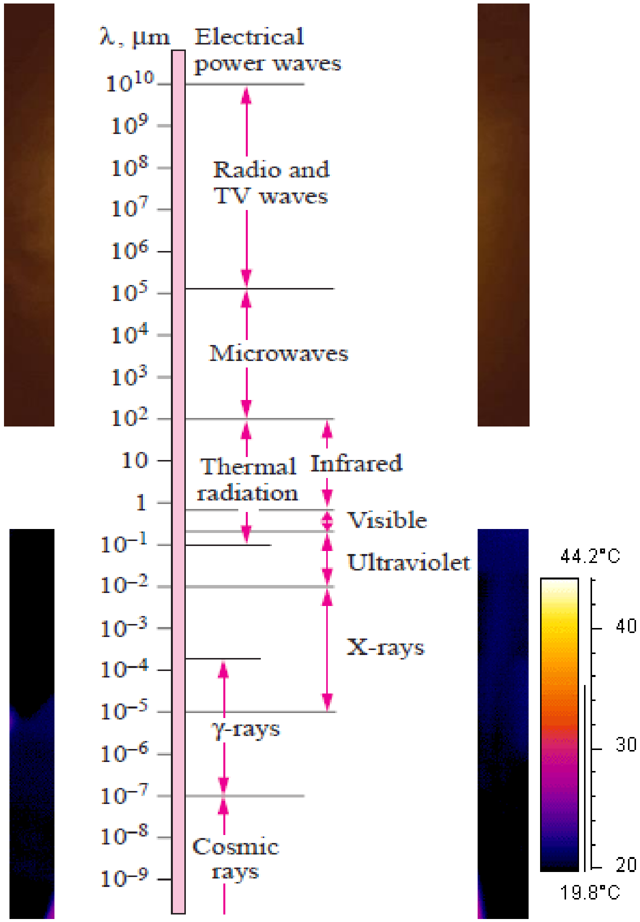


What is the $\lambda_{Max\ power}$ of human body (T=37 ℃) ?

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

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

ACTIVITY 3



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

ACTIVITY 3

https://www.youtube.com/watch?v=fpx7hsoYEt4&ab_channel=Thunderf00t

Learning objectives lecture 5

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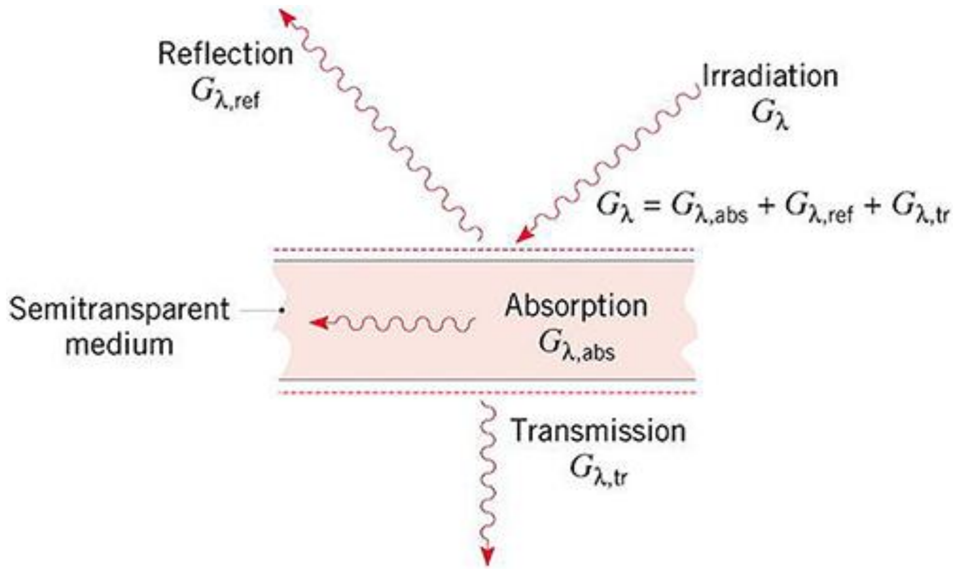
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

NON –IDEAL RADIATION



Radiation striking a solid surface has one of three fates:

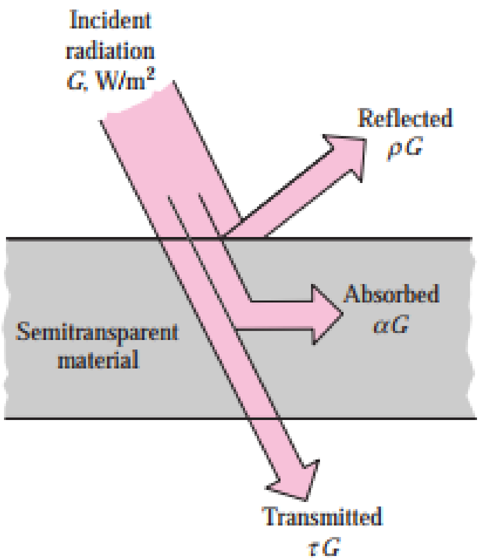
1. Absorption absorptivity (α)
2. Transmission transmissivity (τ)
3. Reflection reflectivity (ρ)

NON –IDEAL RADIATION

Absorptivity: $\alpha = \dfrac{\textbf{Absorbed radiation}}{\textbf{Incident radiation}}$

Reflectivity: $\rho = \dfrac{\textbf{Reflected radiation}}{\textbf{Incident radiation}}$

Transmissivity: $\tau = \dfrac{\textbf{Transmitted radiation}}{\textbf{Incident radiation}}$



How are these properties related ?

$$\boxed{\alpha + \tau + \rho = 1}$$

NON –IDEAL RADIATION

$$\boxed{\alpha + \rho + \tau = 1}$$

Two special cases require definition:

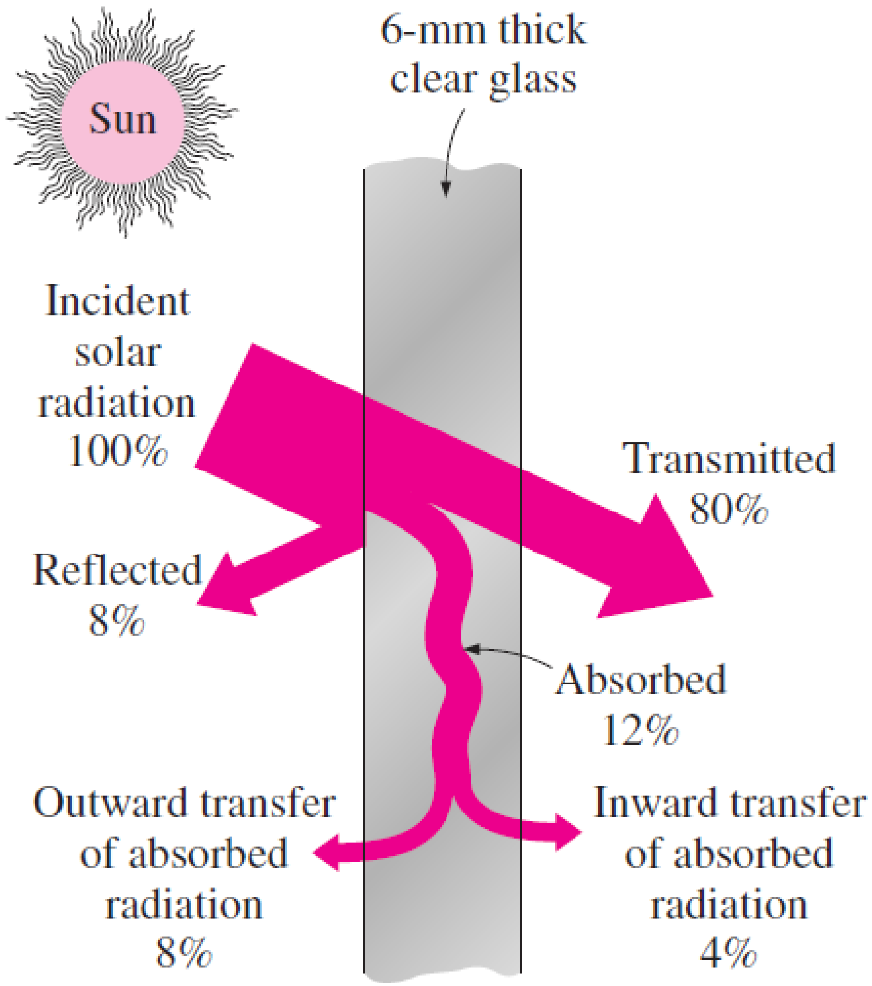
If <u>all</u> of the energy is either <u>reflected or absorbed</u> (no transmitted radiation), we define the body as

Opaque $\alpha + \rho = 1$

If <u>all</u> of the energy striking a surface is <u>absorbed</u>, we define the body as

Black body $\alpha = 1$

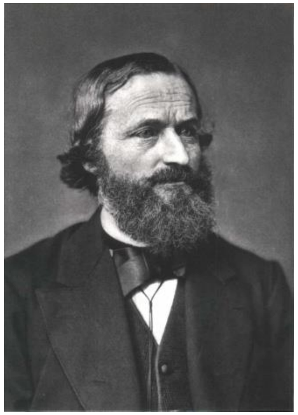
Non –Ideal radiation



KIRCHHOFF`S LAW :

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

$$\boxed{\varepsilon(T) = \alpha(T)}$$



Gustav Robert Kirchhoff

EMISSIVITY

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

Adjusted Stefan-Boltzmann Law for emitted radiation from object:

$$\dot{Q}_{\boldsymbol{b}} = \sigma \cdot A \cdot T^4 \ (W) \ \textbf{so} \ \dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 (\mathrm{W})$$

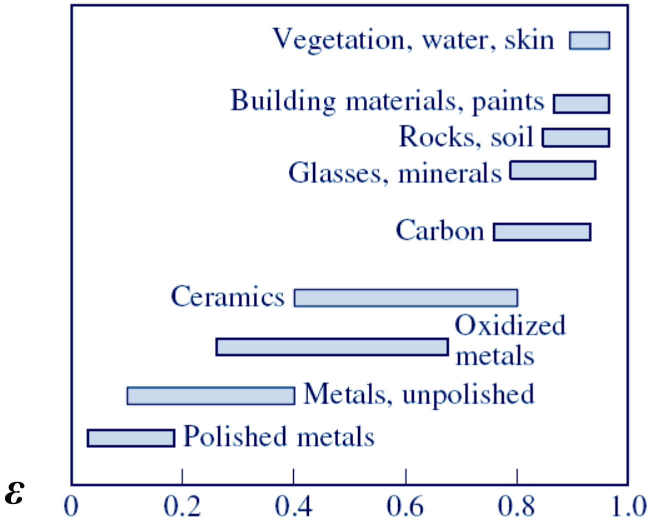
Emissivity *ε* (0 ≤ *ε* ≤ 1) of a surface (material property):
Measure for emitted radiation ($\dot{Q}$) in comparison to radiation ($\dot{Q}_b$) emitted by a blackbody (ε = 1) at same temperature.

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

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,…

Demonstration

https://www.youtube.com/watch?v=ClRrU6JuBOc&ab_channel=QuantumBoffin

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: $\boxed{\varepsilon\sigma A T_s^4}$

power input: $\boxed{\sigma\alpha A T_\infty^4}$

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

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

This is the expression for an object totally enclosed by surroundings at T_∞.

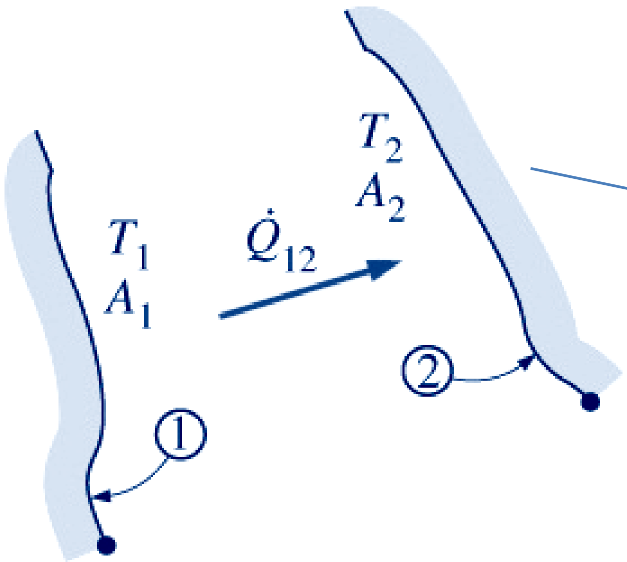
Radiation Heat Transfer

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

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

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

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

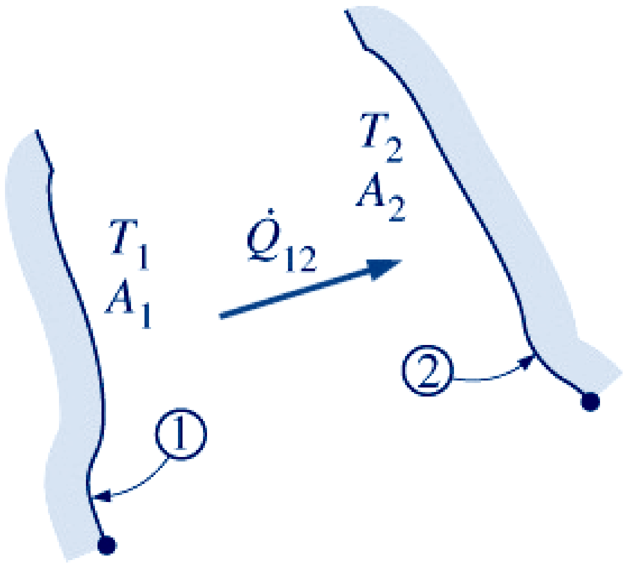


Radiation Heat Exchange (Ideal Case)

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

But what about the orientation and shape of the object ?

VIEW FACTORS

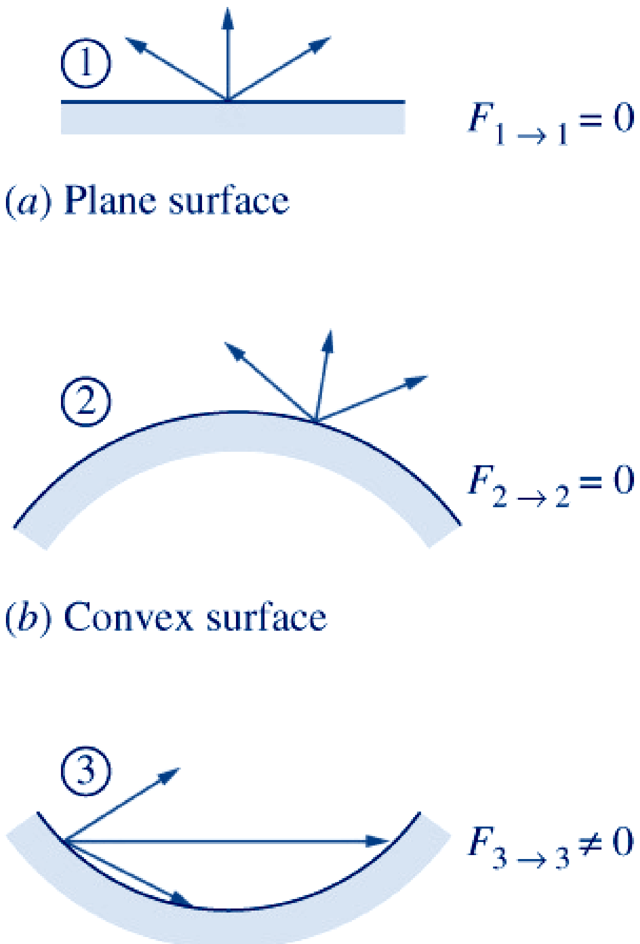


$F_{i\to j}$ is the 'view factor':

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

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.

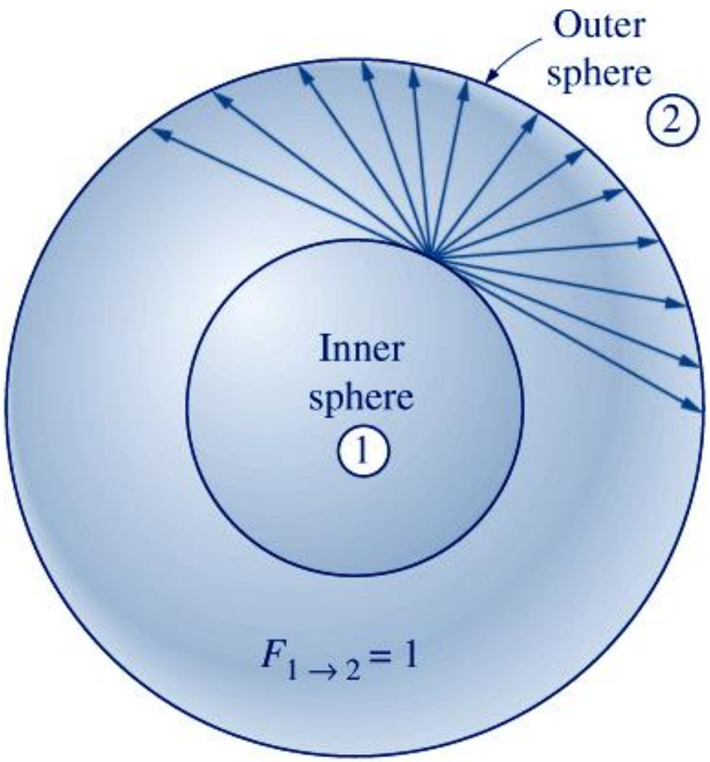
VIEW FACTORS



(a) Plane surface

(b) Convex surface

(c) Concave surface



Cylinder/sphere:

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

Rules/Theorem's

1 The Reciprocity Relation

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

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

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

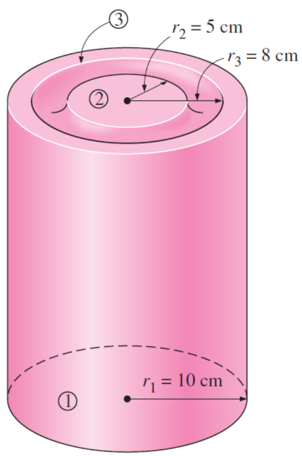
2 The Summation Rule

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

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

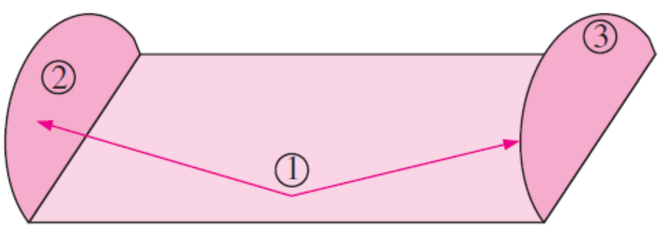
$$\sum_{j=1}^{3} F_{1 \to j} = F_{1 \to 1} + F_{1 \to 2} + F_{1 \to 3} = 1$$

3 The Superposition Rule



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

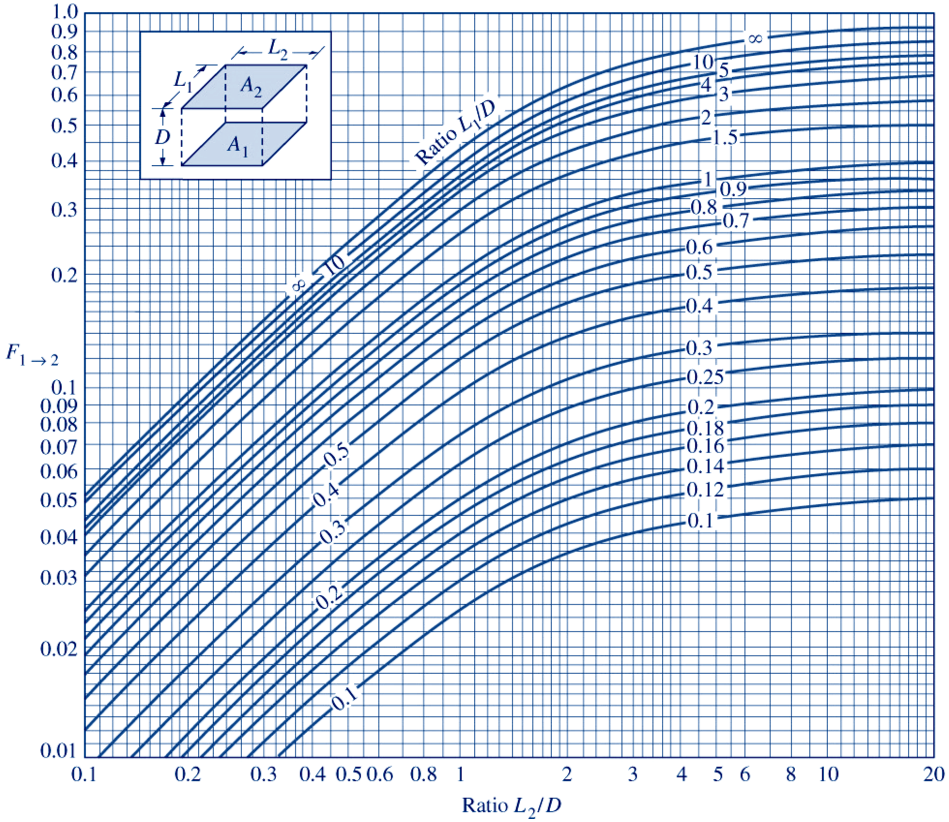
4 The Symmetry Rule

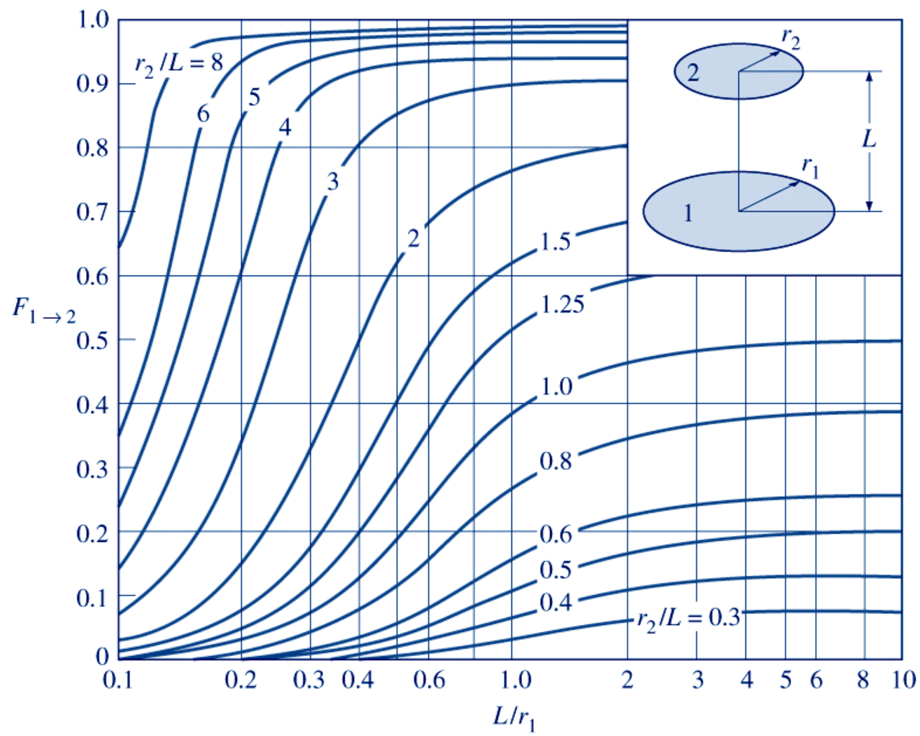


$F_{1 \to 2} = F_{1 \to 3}$

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

PARALEL PLANES

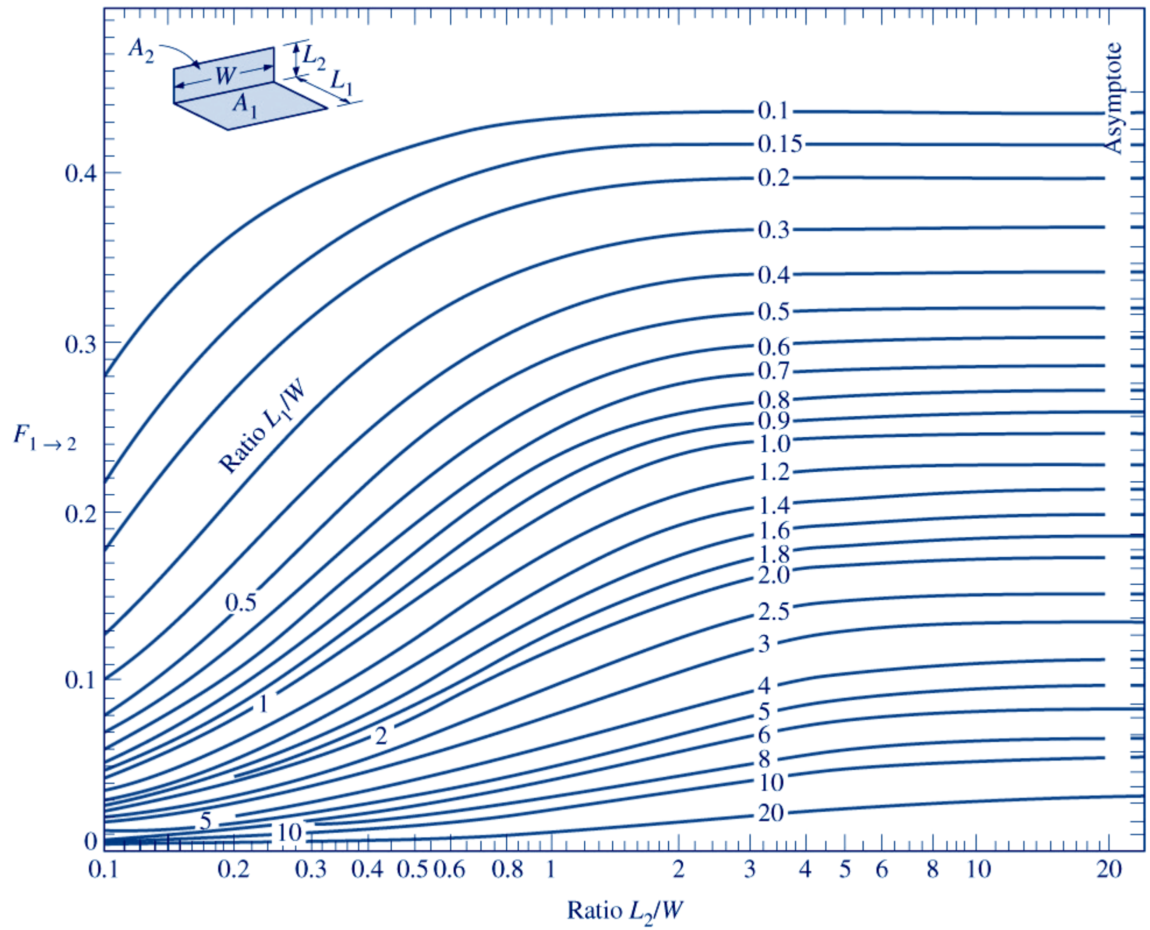




Beware: not valid if the surfaces are shifted in their plane (surfaces have to be alligned or coaxial)

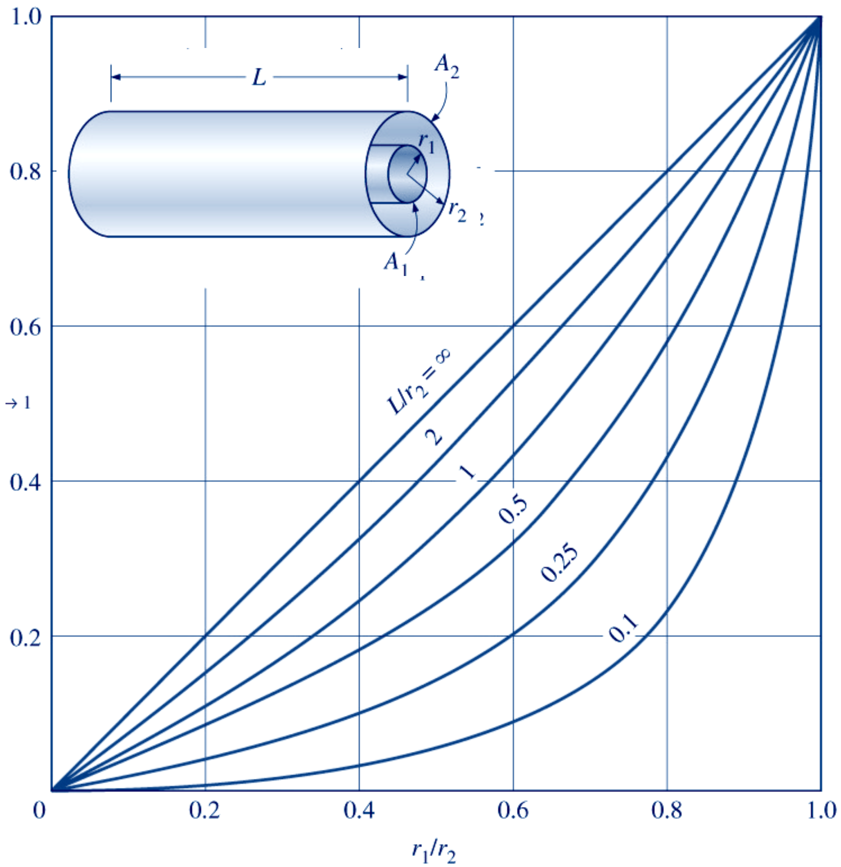
VIEW FACTORS

PERPENDICULAR, ATTACHED RECTANGLES

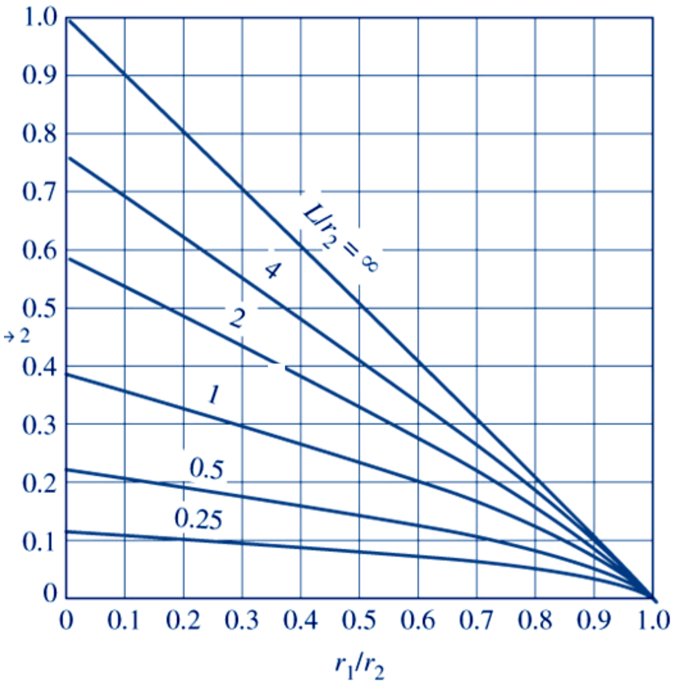


CONCENTRIC CYLINDERS

$F_{2\rightarrow 1}$

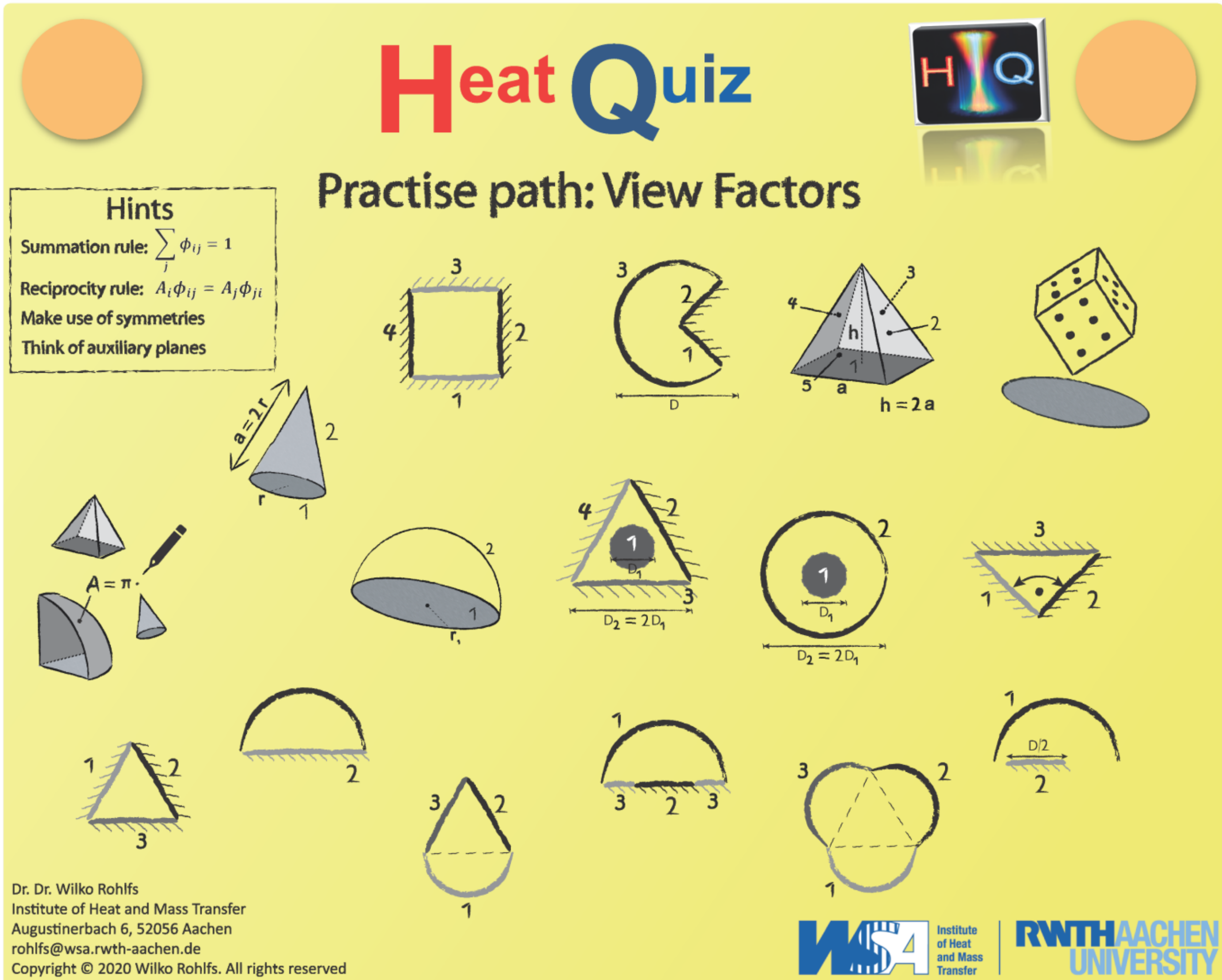


$F_{2\rightarrow 2}$



Established earlier:

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


Heat Quiz
HIQ
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
h = 2 a
a = 2 r
$A = \pi \cdot$
$D_2 = 2D_1$
$D_2 = 2D_1$
D/2
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LEARNING OBJECTIVES LECTURE 5

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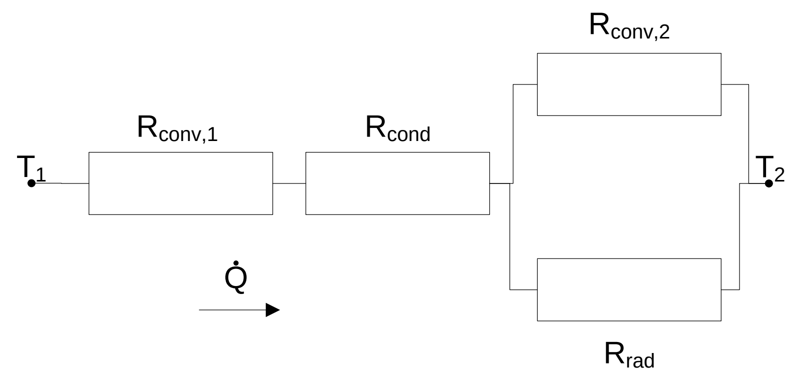
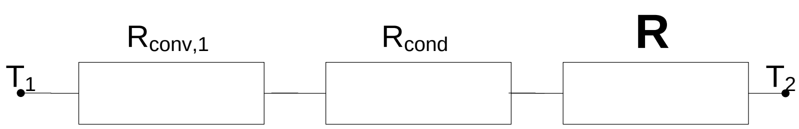
- Non- Ideal Radiation
- Radiation Heat Exchange
- Resistance Networks – (Radiation and Convection)

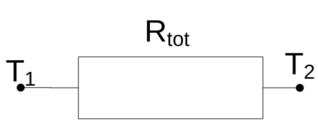
Overall resistance Network



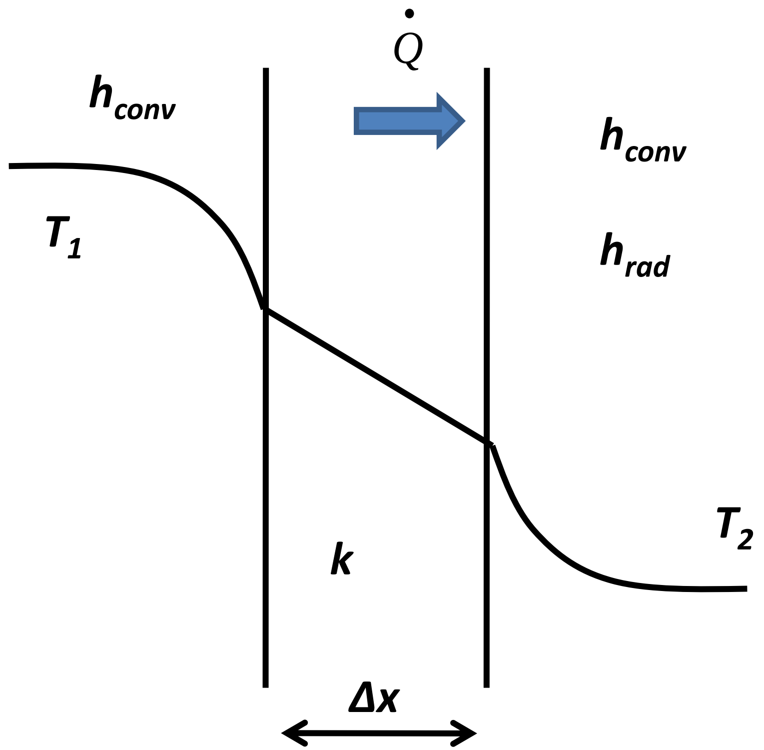
$$\frac{1}{R}=\frac{1}{R_{conv,2}}+\frac{1}{R_{rad}}$$



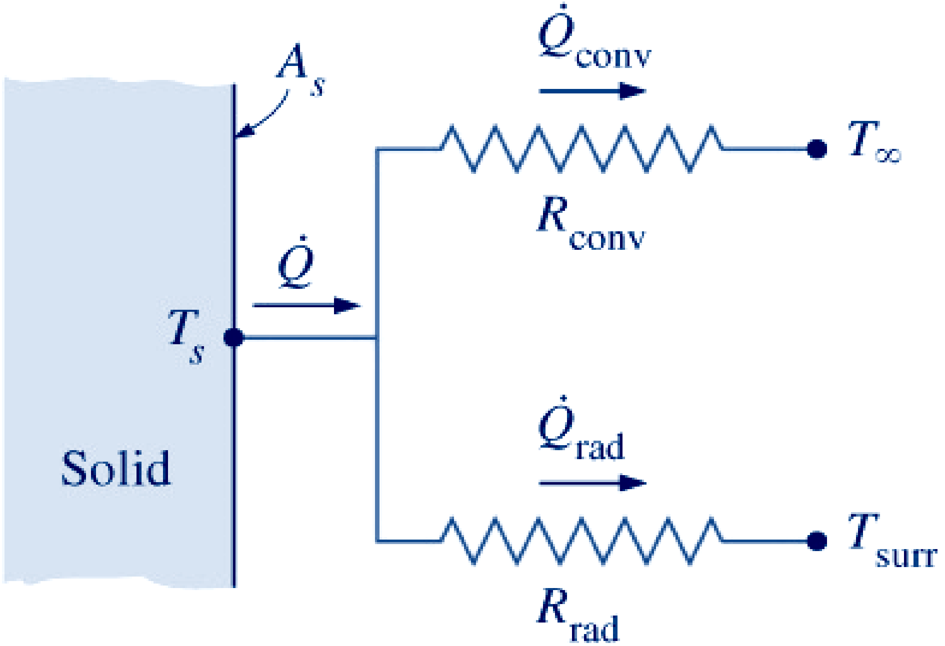
$$R_{tot}=R_{conv,1}+R_{cond}+R$$



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

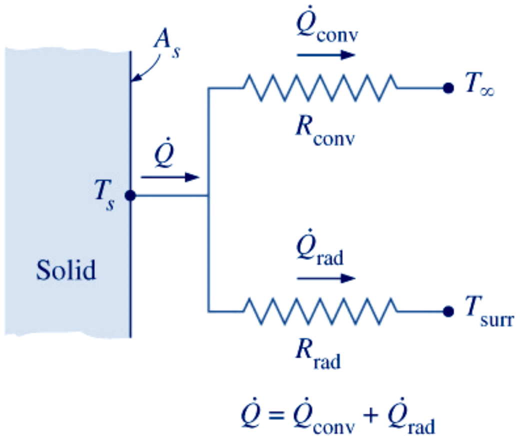


Radiation and convection



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

Radiation and convection



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

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

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

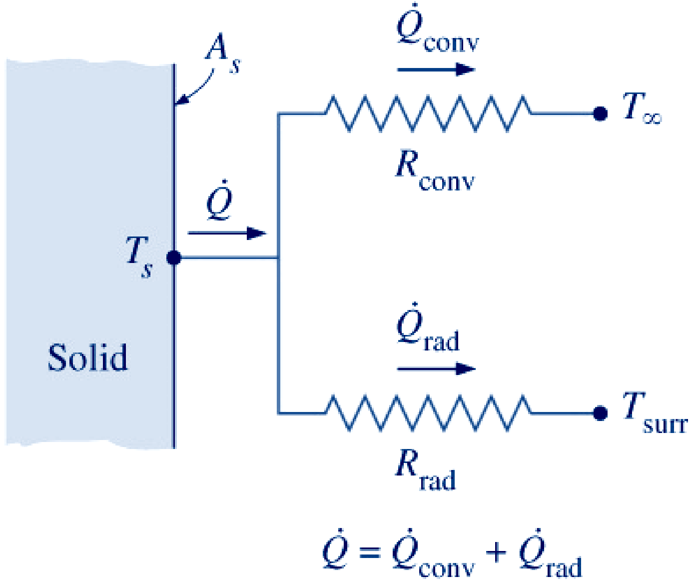
$$\dot{\boldsymbol{Q}}_{\boldsymbol{rad}} = \frac{T_s - T_\infty}{R_{rad}} \quad \text{with} \quad R_{rad} = \frac{1}{h_{rad} A}$$

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

Radiation and convection

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

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



Summary lecture 5 (1/2)

- Radiation
  - Does not need a transport medium
  - Thermal: 0,1 µm < λ < 100 µm
- Blackbody:
- Non ideal emitters
  - Emissivity ε
  - Absorptivity α
  - Reflectivity ρ
  - Transmissivity τ

Summary Lecture 5 (2/2)

- Stefan-Boltzmann's Law for radiation coming **from** all emittors (blackbody: ε = 1)

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

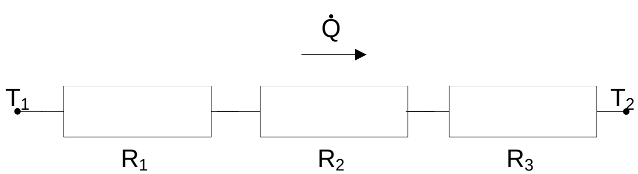
- **Net** radiation from non ideal emitter towards environment (with ε <1)

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

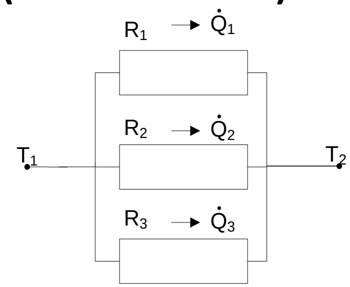
- View factor: fraction of radiation from surface i that directly hits surface j ($F_{i \to j}$)

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

- Series resistors: $R_{tot} = \sum_i R_i$
  (add resistors)



Parallel resistors: $\frac{1}{R_{tot}} = \sum_i \frac{1}{R_i}$
(add heat flows)



Lectorial 2

⇒ Lecture 6- Preparation (Activities & Slides)

⇒On campus Lectorial : 29 Sept: 08:45 – 10:30

⇒ Assignments: bundle on HeatQuiz

⇒ Deadlines: schedule on Canvas

Ready, set,

GO!...