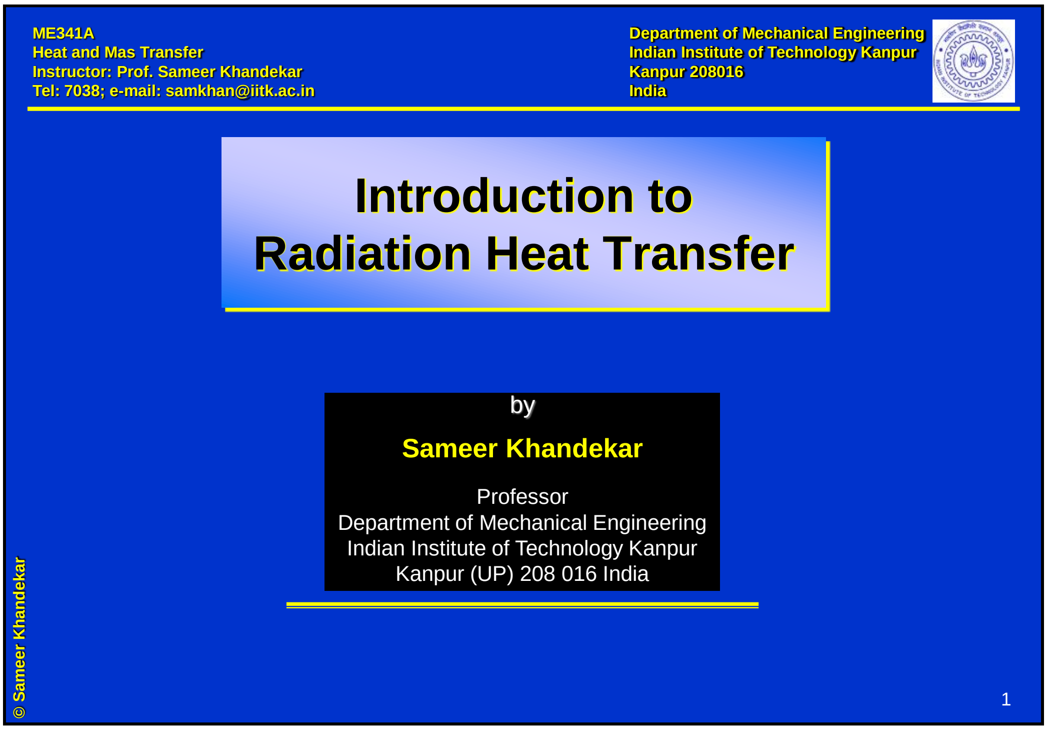

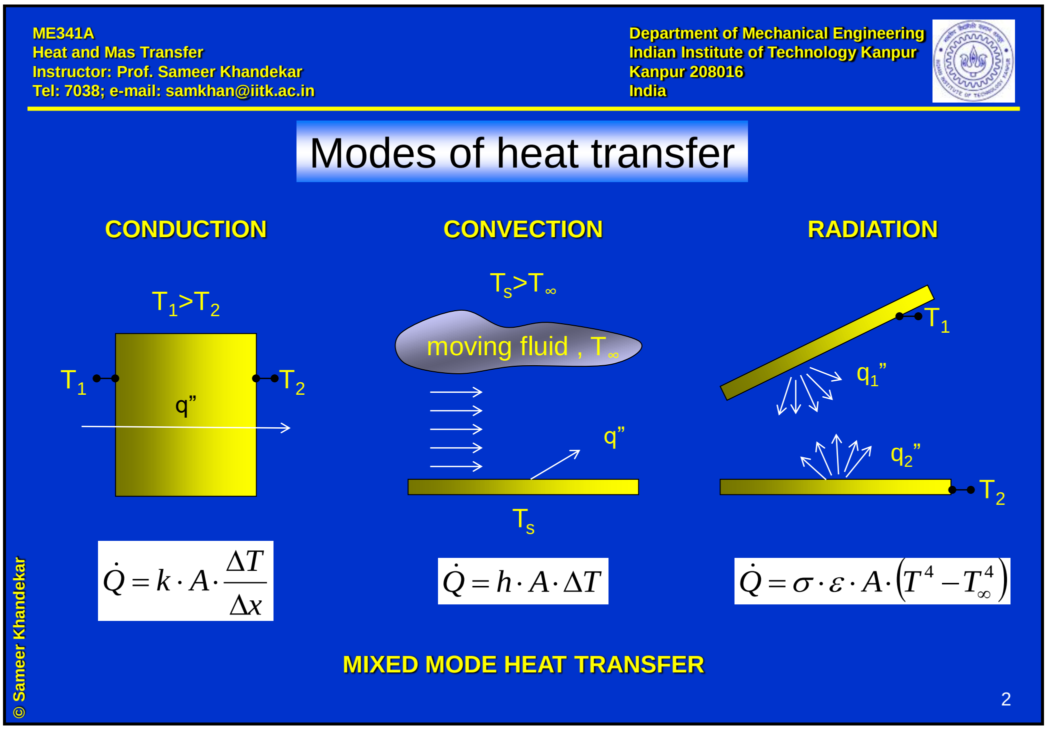

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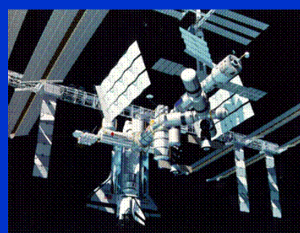
Examples: Space, Furnaces, heat treatment….



Space thermal management

Heat treatment furnaces

Bread Furnaces

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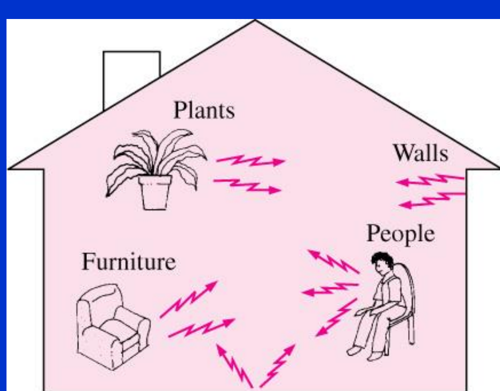
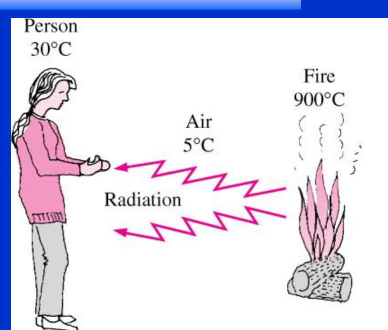
Everything around us emits radiation





Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even when they are separated by a medium colder than both.

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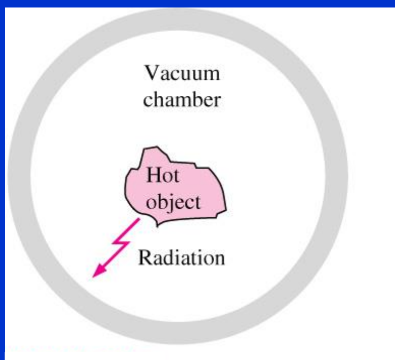
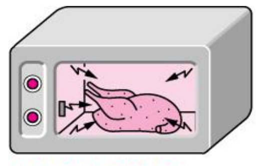
Radiation exchange: Examples



A hot object in a vacuum chamber loses heat by radiation only.



Food is heated or cooked in a microwave oven by absorbing the electromagnetic radiation energy generated by the magnetron of the oven.

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Radiation: Special characteristics

The mechanism of radiation is fundamentally different from conduction and convection.

Here:

- **Electromagnetic theory:** needed to describe the wavelike nature of radiation (Energy and 'pressure' associated with electromagnetic waves)
- **Thermodynamics:** is of course, essential to understand bulk interactions.
- **Quantum mechanics:** is necessary to describe in detail the atomic and molecular processes that occur when radiation is produced within matter and when it is absorbed by matter.
- **Statistical mechanics:** is needed to describe the way in which emery of radiation is distributed over the wavelength spectrum.

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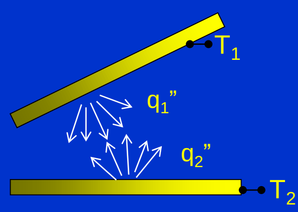
Radiation: Special characteristics

- Fundamentally different from what we have studied so far
- Conduction and Convection both depend on material medium
- Radiation is an electromagnetic phenomenon--No matter is required
- Rate of energy transfer is proportional to fourth power of temperature difference
- Radiation is long range Phenomena while conduction/convection are short range
- Mixed mode requires integro-differential equations
- Spectral and directional nature of radiation



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

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Radiation: Special characteristics

Scales are different!
Conduction and convection are
→ short range, molecular mean free path

Radiation → Long range

Partial differential equations vs integro-diferential equations
(problems involving radiation with conduction/convection)

Behavior of radiative properties is quite complex
→ Spectral and Directional
→ Difficult to measure and show ‘erratic behavior’

In contrast, behavior or properties which affect conduction/convection is rather simple/ ‘well-behaved’

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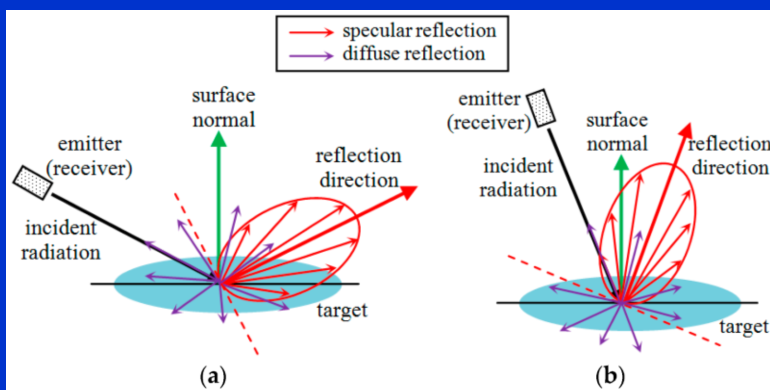
For example: Specular/Diffuse mirrors



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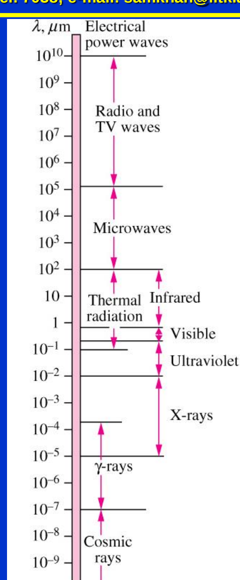
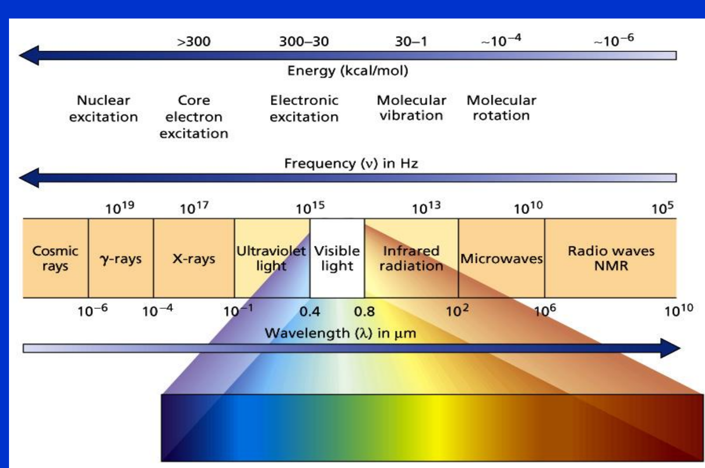
Radiation spectra





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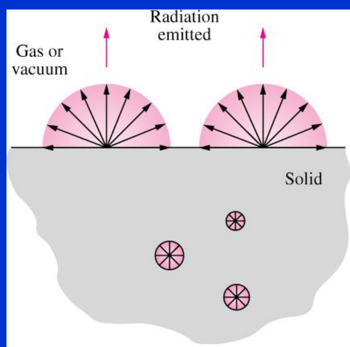
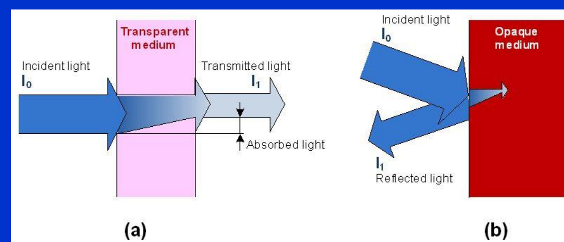
Radiation in opaque solids



Radiation in opaque solids is considered a surface phenomenon since the radiation emitted only by the molecules at the surface can escape the solid.



Transmissivity (τ)

Reflectivity (ρ)

Absorptivity (α)

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

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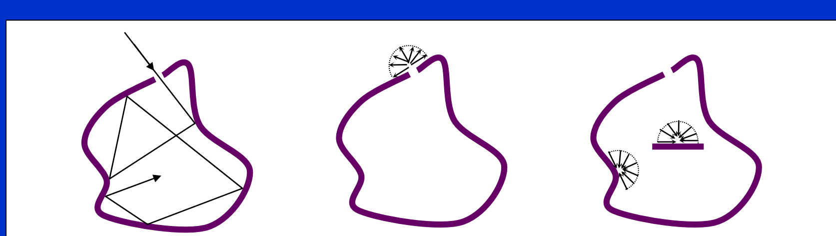
Concept of a black body

A black body is an ideal surface having the following properties

1. It absorbs all incident radiation, regardless of wavelength and direction
2. For a prescribed temperature and wavelength, no surface can emit energy more than a blackbody
3. Although the radiation emitted by a blackbody is a function of wavelength and temperature, it is independent of the direction. Hence, the blackbody is a diffuse emitter



Isothermal surface

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Black body characteristics

- A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence.
- A **white body** is one that reflects all incident rays completely and uniformly in all directions.
- A black body in thermal equilibrium (that is, at a constant temperature) emits electromagnetic radiation called black-body radiation.
- The radiation is emitted according to **Planck's law**, meaning that it has a spectrum that is determined by the temperature alone, not by the body's shape or composition.
- An ideal black body in thermal equilibrium has two notable properties:
- It is an ideal emitter: at every frequency, it emits as much or more thermal radiative energy as any other body at the same temperature.
- It is a **diffuse** emitter: the energy is radiated isotropically, independent of direction.

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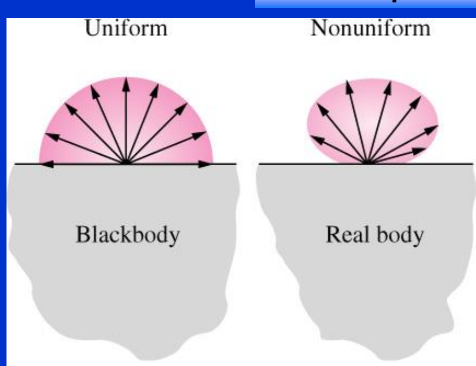
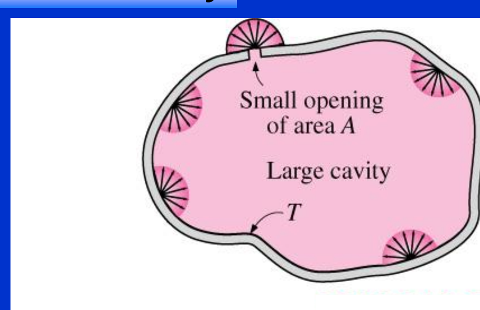
Concept of a black body



A blackbody is said to be a *diffuse* emitter since it emits radiation energy uniformly in all directions.



A large isothermal cavity at temperature *T* with a small opening of area *A* closely resembles a blackbody of surface area *A* at the same temperature.

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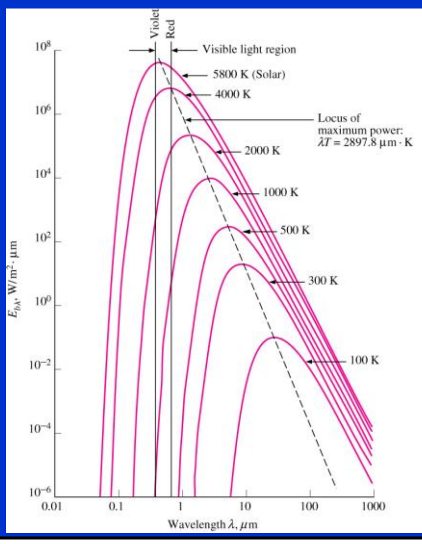
Emissive power of a black body



Emittance or **Emissive power** is the total amount of thermal energy emitted per unit area per unit time for all possible wavelengths.

Emissivity of a body at a given temperature is the ratio of the total emissive power of a body to the total emissive power of a perfectly black body at that temperature.

Spectral → fn(λ)

Directional → fn (angle of incidence)

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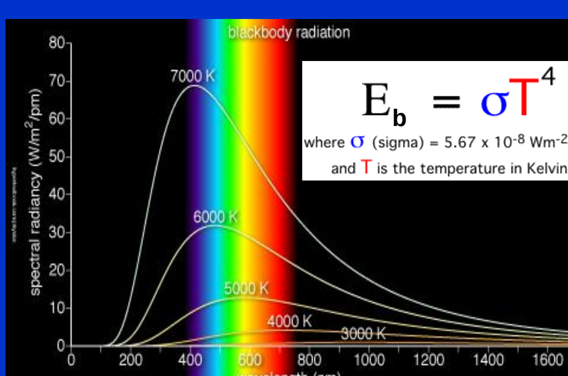
Stephan Boltzmann Law



$$E_b = \sigma T^4$$

where σ (sigma) = 5.67 x 10^{-8} Wm^{-2} K^{-4}
and T is the temperature in Kelvin

The radiation energy emitted by a black body per unit time and per unit surface area, E_b, is called as the **blackbody emissive power**.

Proportional to the fourth power of the absolute temperature

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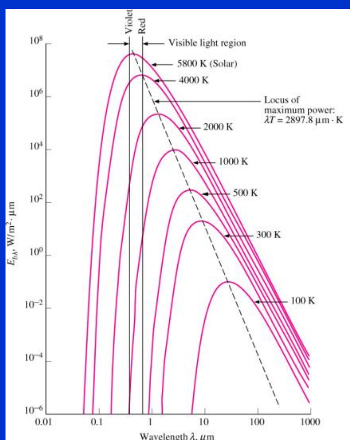
Planks Law and implications



- Emitted radiation is a continuous function of wavelength.
- At any wavelength, the amount of emitted radiation increases with temperature
- As the temperature increases, the curves shift to the left, to the shorter wavelengths. A larger fraction of the radiation is emitted at shorter wavelengths at higher temperatures.
- Solar radiation → 5800 K

$$E(\lambda, T) = \frac{2hc^2\pi}{\lambda^5} * \frac{1}{e^{\left(\frac{hc}{\lambda k T}\right)} - 1} = E_{b,\lambda}$$

h = Planck's constant = $6.626 * 10^{-34}\ J * s$
c = speed of light = $2.997925 * 10^{8}\ m / sec$
λ = wavelength (m)
k = Boltzmann's constant = $1.381 * 10^{-23}\ J/K$
T = temperature (K)

Wien's Law

$$\lambda_{max} = C/T$$

where C is a constant equal to 2897 and T is the temperature in Kelvin

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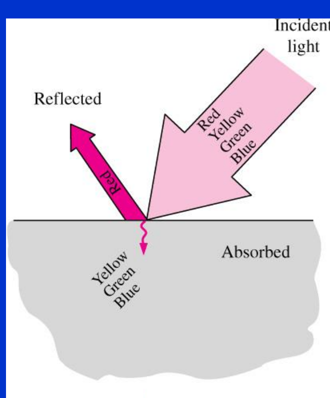
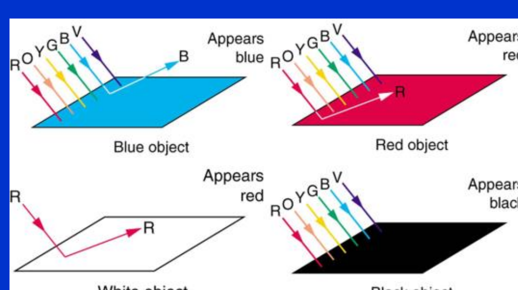
Color of an object: due to selective reflection



A surface that reflects red while absorbing the remaining parts of the incident light appears red to the eye.



For objects below about 800 K, the colour of the object is not due to emission (emission is dominated by infra-red), it is due to due to selective reflection of a particular wavelength

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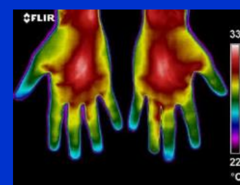
Color of an object: due to emission

Temperature (°C)
550
630
680
740
770
800
850
900
950
1000
1100
1200
1300



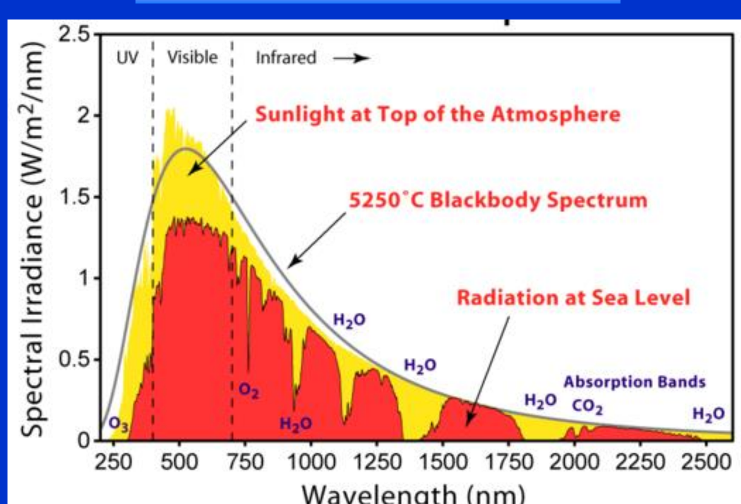
Infra-red camera
> 0.8 micrometer

Hot steel ingot

Electric heater

Objects beyond 1000K emit visible radiation

Solar radiation spectrum



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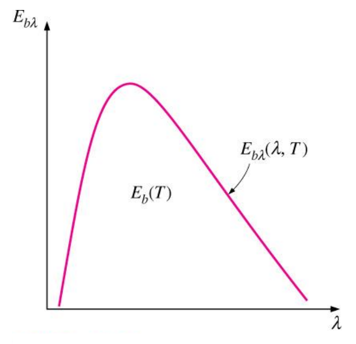
Relation between laws of radiation



On an $E_{b\lambda}$–λ chart, the area under a curve for a given temperature represents the total radiation energy emitted by a blackbody at that temperature.

- Stephan-Boltzmann Law is obtained by integrating the Planks Law over the entire range of wavelengths
- That is: the integration of the spectral black body emissive power $E_{b,\lambda}$ over the entire wavelength spectrum gives the total black body emissive power E_b

$$\int_0^\infty E(\lambda,T)d\lambda = \int_0^\infty \left\{ \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \right\} d\lambda$$

$$E_b(T) = \frac{2hc^2\pi^4}{15\left[\frac{hc}{k}\right]^4} T^4 = \sigma T^4$$

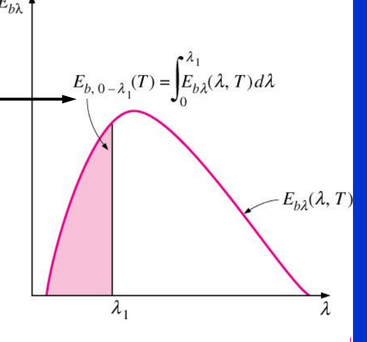
Band emissive power

The radiation energy emitted by a blackbody per unit area over a wavelength band $\lambda = 0$ to λ_1 is determined by this integral

However, a closed form solution is not possible with the limits 0 to any arbitrary λ_1

(Only $\lambda_1 = \infty$ is possible, as we did earlier)

Only numerical integration is possible which is rather tedious to perform every time



On an $E_{b\lambda}$–λ chart, the area under the curve to the left of the $\lambda = \lambda_1$ line represents the radiation energy emitted by a blackbody in the wavelength range 0–λ_1 for the given temperature.

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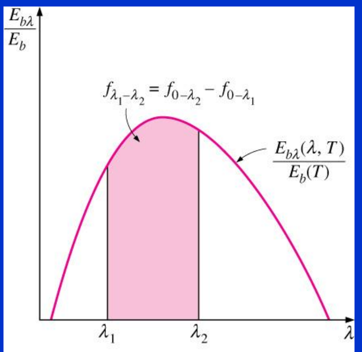
Black body radiation function



Graphical representation of the fraction of radiation emitted in the wavelength band from λ_1 to λ_2.

λT (μm·K)	$f_{0\text{-}\lambda}$
200	0.000000
400	0.000000
600	0.000000
800	0.000016
1,000	0.000321
1,200	0.002134
1,400	0.007790
1,600	0.019718
1,800	0.039341
2,000	0.066728
2,200	0.100888
2,400	0.140256
2,600	0.183120
2,800	0.227897
2,898	0.250108

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

The above function represents the fraction of the radiation emitted from a blackbody at temperature *T* in the wavelength band *0 - λ*

The fraction of the radiation energy emitted by a black body at temperature *T* over a finite wavelength band is:

$$f_{\lambda 1-\lambda 2}(T) = f_{\lambda 2}(T) - f_{\lambda 1}(T)$$

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Why an incandescent bulb is inefficient

HIGHLY INEFFICIENT

- White filament ≈ 2500 K
- Visible spectrum 0.4 μm to 0.76 μm
- λ_1 T = 0.4 x 2500 = 1000 μmK → hence, $f_{\lambda 1}$ = 0.000321
- λ_2T = 0.76 x 2500 = 1900 μmK→ hence, $f_{\lambda 2}$ = 0.053035
- 0.03 percent of radiation is emitted at wavelengths less than 0.4 μm and 5.3 percent at wavelengths less than 0.76 μm
- Hene, the fraction of the radiation emitted between these two wavelengths is:
- $f_{\lambda 1 - \lambda 2} = f_{\lambda 2} - f_{\lambda 1}$ = 0.053035 – 0.000321 = 0.0527135

Only about 5% of the total emission radiated by the filament is in the visible spectrum. The rest 95% is all primarily infrared.

From Wiens law, the peak emission occurs at a wavelength of 1.16 μm [$(\lambda T)_{max\ power}$ = 2897.7]

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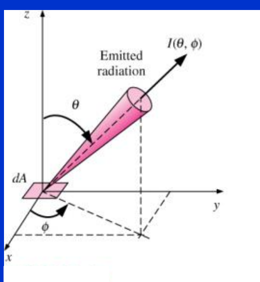
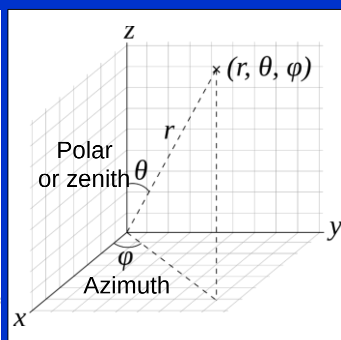
Radiation intensity in spherical coordinate system



Radiation intensity is used to describe the variation of radiation energy with direction.



- Radiation is emitted by all parts of a plane surface into the hemisphere above the surface.
- The directional distribution of the 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 called as Radiation Intensity, denoted by *I*

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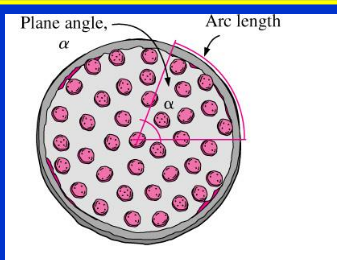
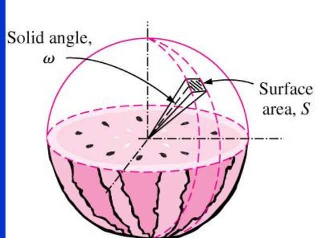


A slice of pizza of plane angle α



A slice of watermelon of solid angle ω

Plane angle vs Solid Angle

$$Plane\ Angle = \frac{Arc}{Radius}$$ **radians**

- For a circle of unit radius, the length of the arc is equivalent to the plane angle which it subtends; both are 2π for a complete circle of radius r = 1)

$$Solid\ Angle = \frac{Surface\ Area}{(Radius)^2}$$ **steradians**

- For a sphere of unit radius, the area on the surface of a sphere is equivalent to the solid angle which it subtends; both are 4π for a complete circle of radius r = 1)

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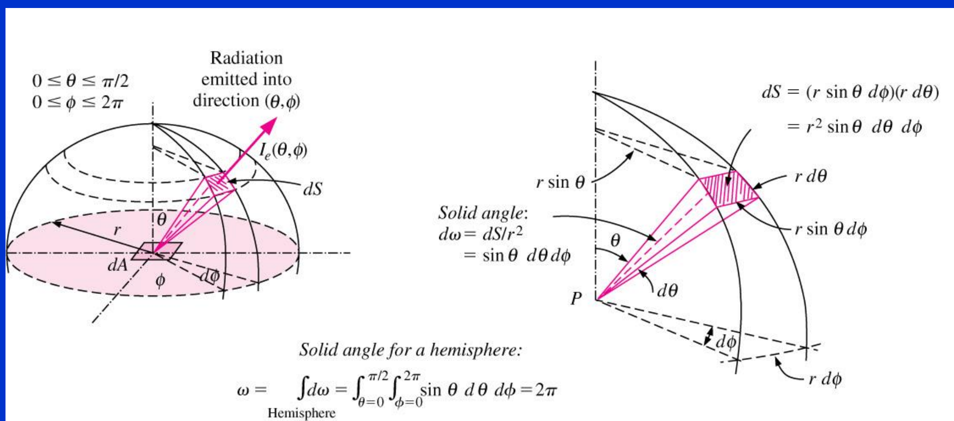
Solid angle for a hemisphere

The emission of radiation from a differential surface element into the surrounding hemispherical space through a differential solid angle



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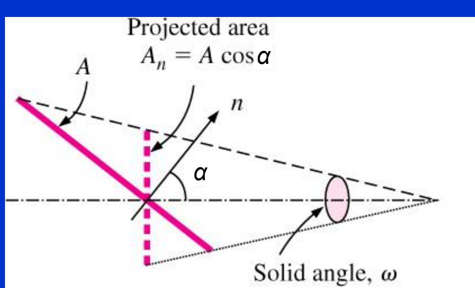
Generalized viewing angle



Radiation intensity is based on the projected area, and thus the calculation of radiation emission from a surface involves the projection of the surface

HENCE

In general, the differential solid angle $d\omega$ subtended by a differential surface area dA when viewed from a point at a distance r from dA is expressed as

α is the angle between the normal of the surface and the direction of viewing

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

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Intensity of emitted radiation

- The radiation intensity of the emitted radiation $I_e(\theta,\varphi)$ is defined as the rate at which radiation energy dQ_e is emitted in the (θ,φ) direction per unit area normal to this direction and per unit solid angle about this direction.

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

- The radiation flux for emitted radiation is the emissive power E, which can be expressed in the differential form as:

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

- The emissive power from the surface into the hemisphere surrounding it can be determined by integration:

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

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Averaging of quantities

Naming	Depends on		For example
	Wavelength	**Angle (θ, φ)**	**Intensity**
Spectral-Directional	Yes	Yes	$I_{\lambda,e}$ *(λ, θ, φ, T)*
Total-Directional	No (Averaged)	Yes	I_e *(θ, φ, T)*
Spectral-Hemispherical	Yes	No (Averaged)	$I_{\lambda,e}$ *(λ, T)*
Total-Hemispherical	No (Averaged)	No (Averaged)	I_e *(T)*

Diffused Systems (no dependency on the angle)

$$E = \int_{hemisphere} dE = \int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi/2} I_e(\theta,\varphi)\cdot cos(\theta)\cdot \sin(\theta)\, d\theta d\varphi = \pi I_e$$

Since a black body is a diffused emitter $\quad E_b = \pi I_b = \sigma T^4$

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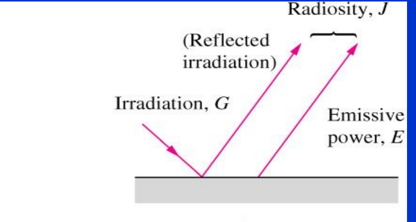
Radiation fluxes

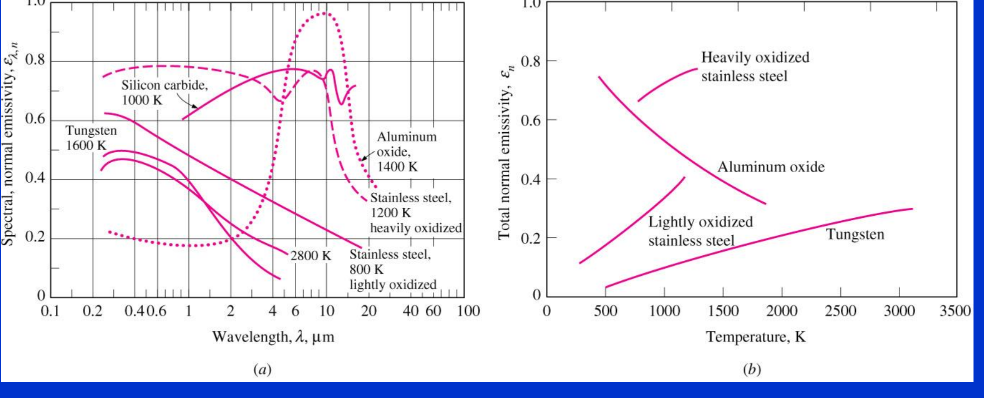


The three kinds of radiation flux (in W/m^2): emissive power, irradiation, and radiosity.

Corresponding intensities are defined as:

- E → I_e
- G → I_i
- R → I_r
- J =(E+R) → I_{e+r}
- Again there are four possibilities depending on whether the intensities are dependent on frequency (specular) and direction.
- If the intensities are diffuse I = constant, then:
- $E = \pi I_e$
- $G = \pi I_i$
- $R = \pi I_r$
- $J = \pi I_{e+r}$

Spectral and directional nature of emissivity



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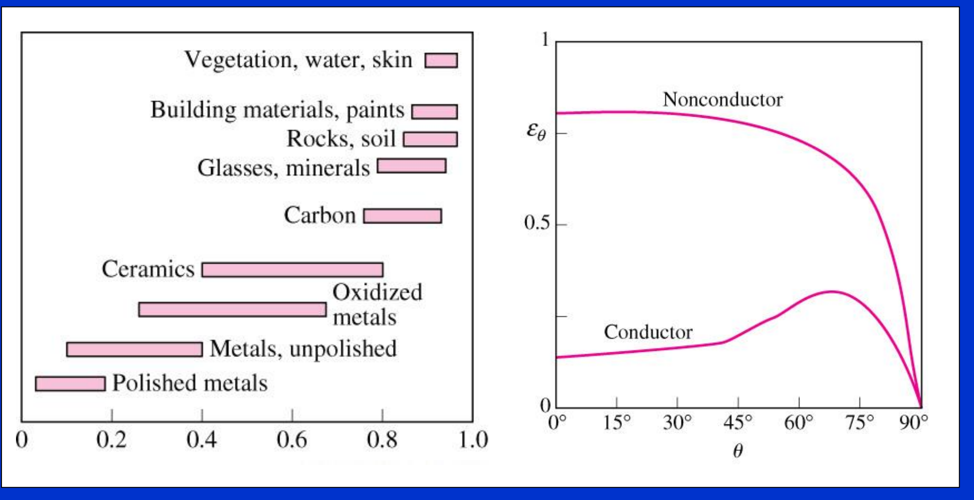
Spectral and directional nature of emissivity



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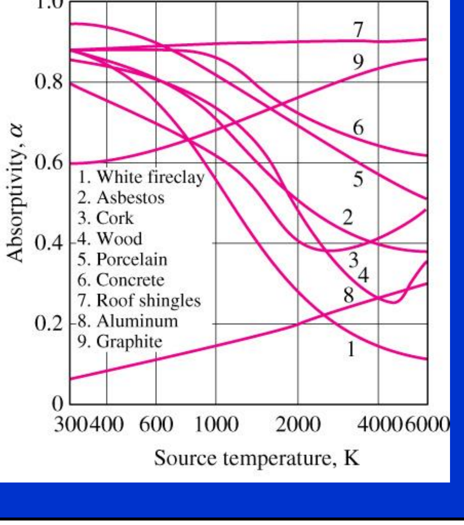
Absorptivity w.r.t. temperature of the source

At room temperature



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Real surfaces: Diffuse and Grey approximations

Real surface:

$\varepsilon_\theta \neq \text{constant}$

$\varepsilon_\lambda \neq \text{constant}$

Diffuse surface:

$\varepsilon_\theta = \text{constant}$

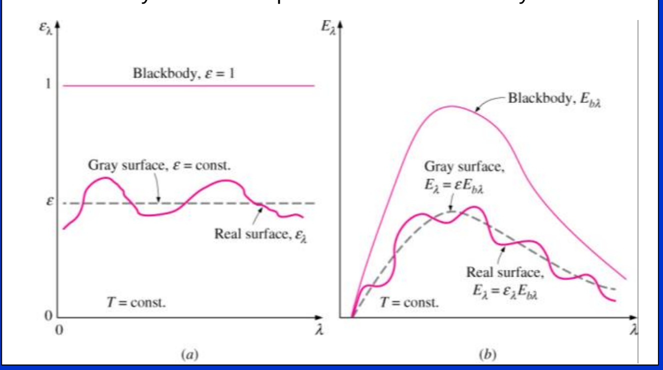
Gray surface:

$\varepsilon_\lambda = \text{constant}$

Diffuse, gray surface:

$\varepsilon = \varepsilon_\lambda = \varepsilon_\theta = \text{constant}$

Real materials emit energy at a fraction of black-body energy levels. A black body in thermal equilibrium has an emissivity of ε = 1.0.



Most first order engineering calculations for radiation are done with this assumption

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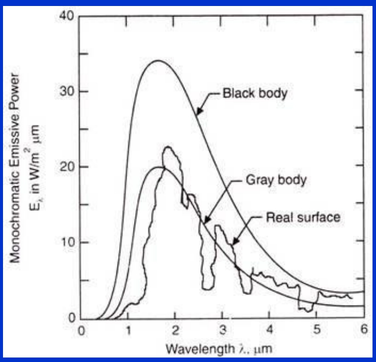
Real or Gray Bodies/surfaces

- Real materials emit energy at a fraction of black-body energy levels.
- By definition, a black body in thermal equilibrium has an emissivity of ε = 1.0.
- A source with lower emissivity independent of frequency is often referred to as a **gray body**



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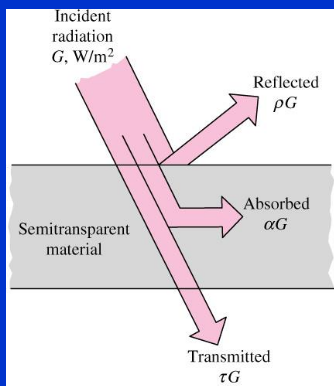
Absorptivity, Reflectivity and Transmissivity



Semi-Transparent Material

$$\alpha = \frac{Absorbed\ radiation}{Incident\ radiation} = \frac{G_{abs}}{G} \mid (0 \le \alpha \le 1)$$

$$\rho = \frac{Reflected\ radiation}{Incident\ radiation} = \frac{G_{ref}}{G} \mid (0 \le \rho \le 1)$$

$$\tau = \frac{Transmitted\ radiation}{Incident\ radiation} = \frac{G_{tran}}{G} \mid (0 \le \tau \le 1)$$

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

Hence

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

For opaque surfaces:

$$\alpha + \rho = 1$$

Here too, we can define spectral, directional, total, hemispherical (four types) of quantities

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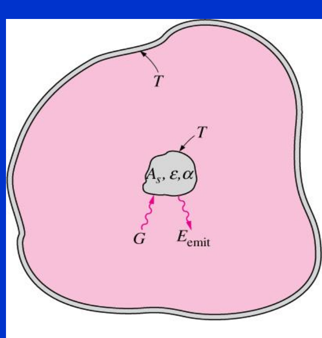
Kirchhoff's law



The small body contained in a large isothermal enclosure used in the development of 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 black body at the same temperature.

- The radiation incident on any part of the surface of the small body is equal to the radiation emitted by a black body at temperature *T*.
- Hence, $G = E_b(T) = \sigma T^4$
- $G_{abs} = \alpha G = \alpha \cdot \sigma T^4$
- The radiation emitted by the small body is $E_{emit} = \varepsilon \cdot \sigma T^4$

Considering that the small body is in thermal equilibrium with the enclosure, applying energy equation, we get $\varepsilon(T) = \alpha(T)$.

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End of Lecture

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