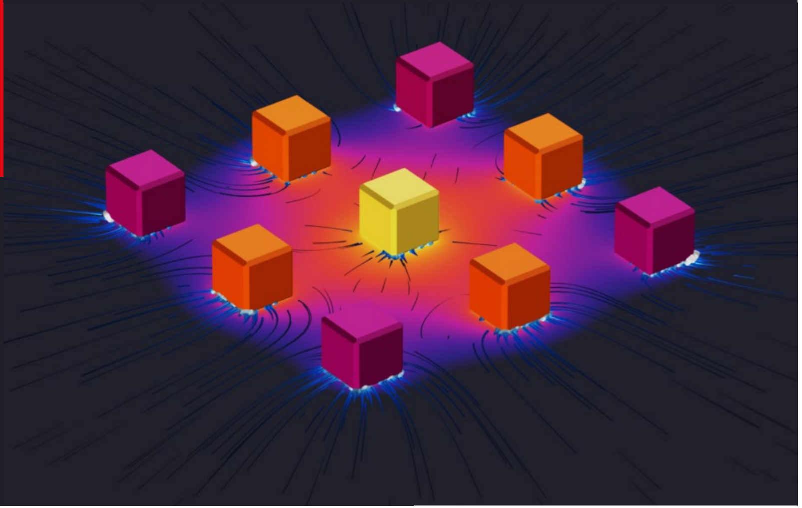
Heat and Mass Transfer
ME-341

Instructor: Giulia Tagliabue



École
polytechnique
fédérale
de Lausanne

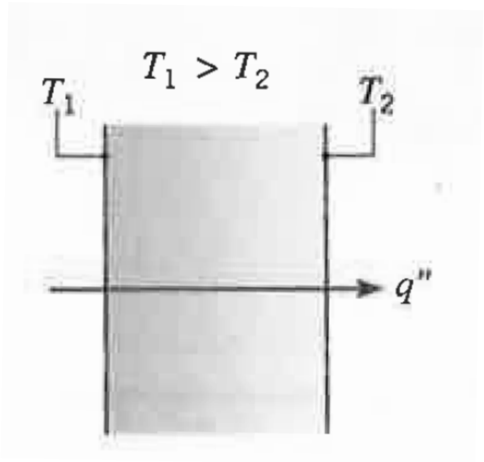
Spring Semester

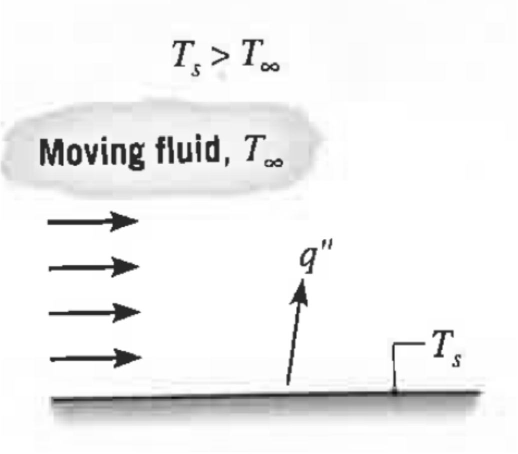
Heat Transfer Mechanisms

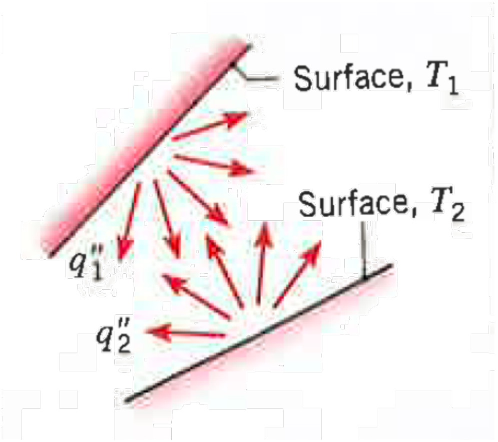
Conduction

Convection

Radiation





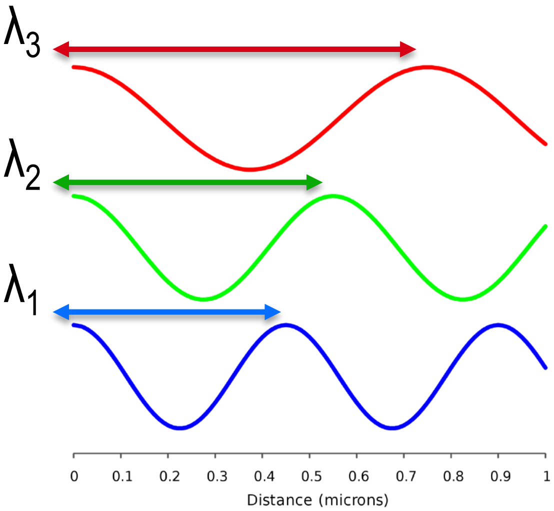


Involves mass transport

Involve physical contact

Electromagnetic Radiation

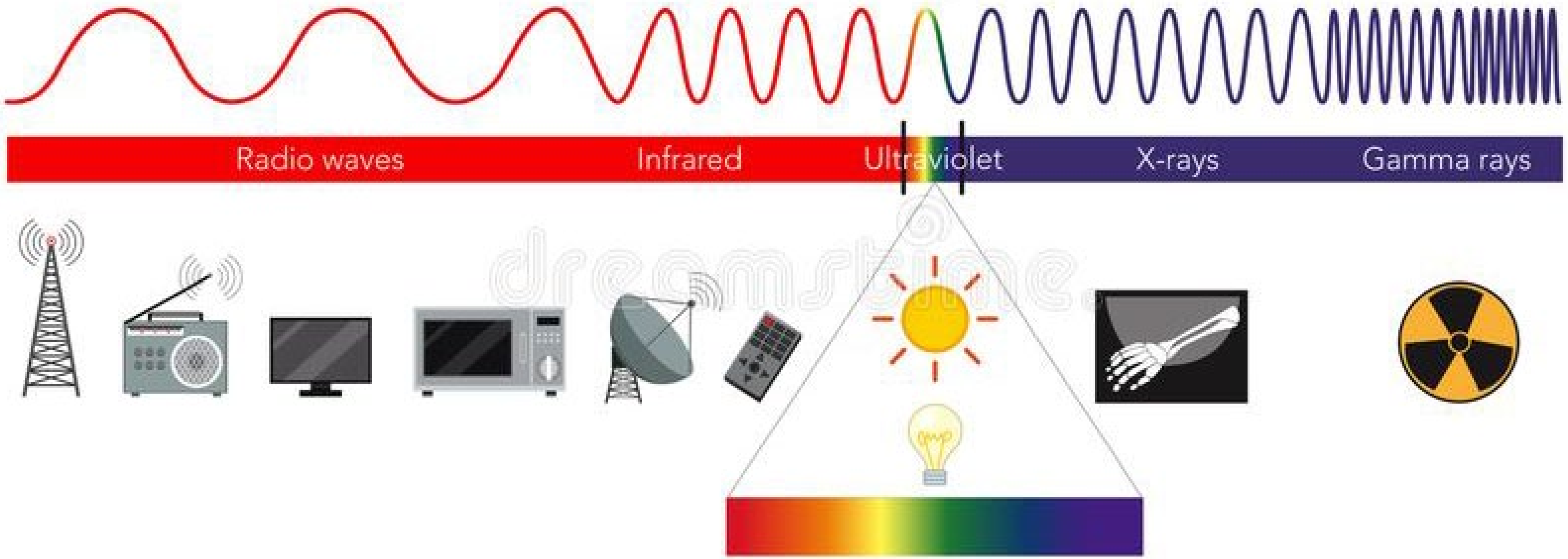
$$\lambda = wavelength$$



$$c = \lambda\nu$$

Electromagnetic Radiation

Wavelength



Red *Blue*

Distinguish sources from detectors….

Thermal Radiation

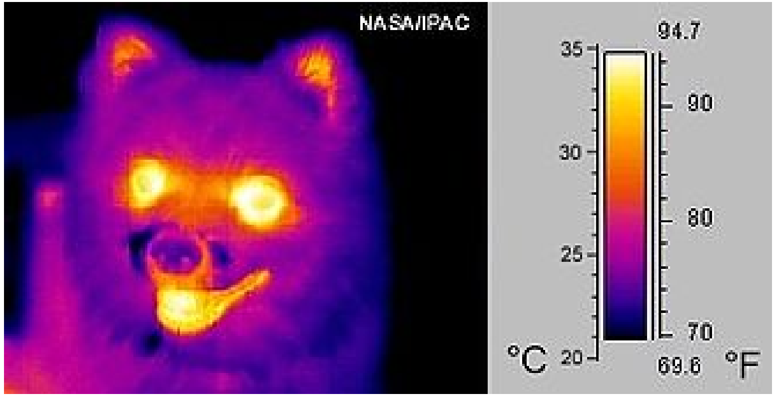
High T

Very Bright Visible Light Emission

Medium T

Visible Light Emission

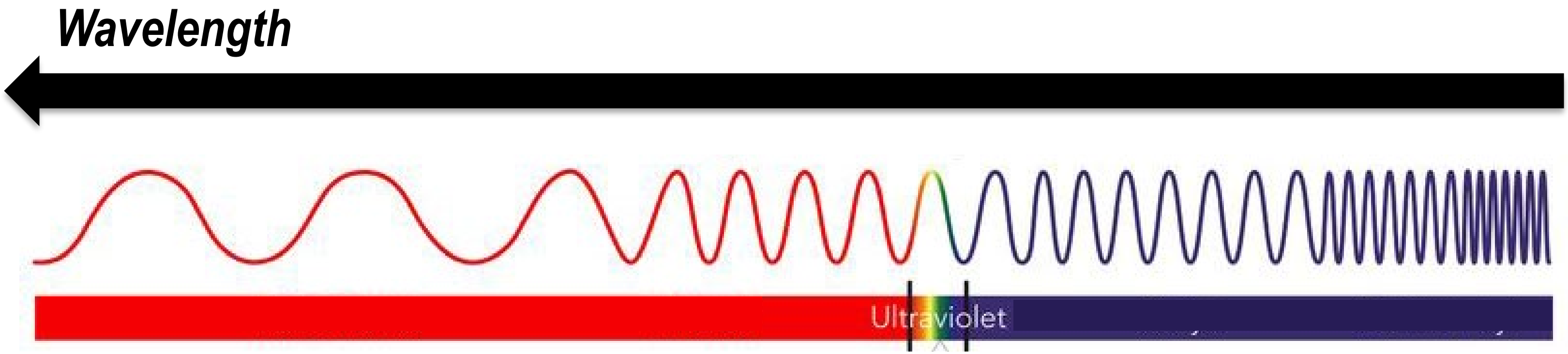
Low T

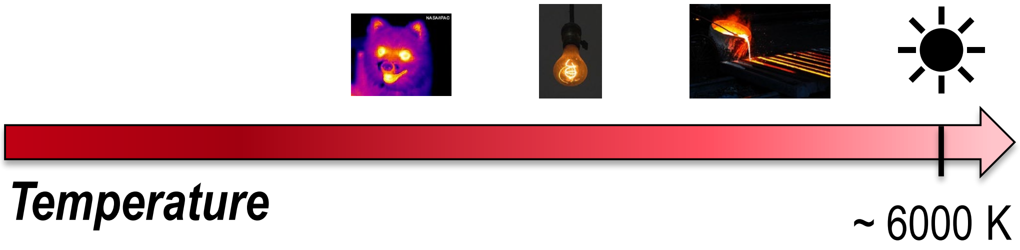


Infrared Light Emission (needs IR camera)

What is the relationship between the temperature of an object and its emission of electromagnetic waves (intensity and wavelength)?

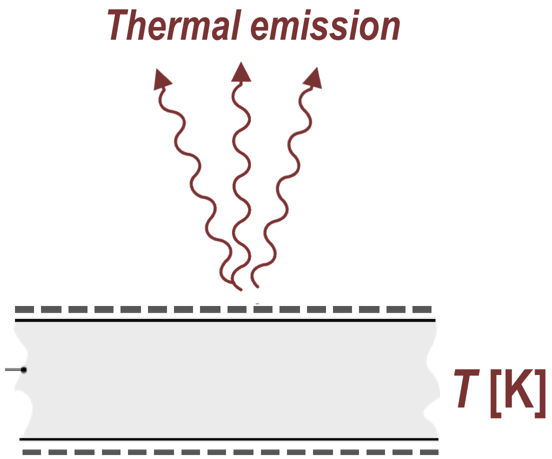
Thermal Radiation





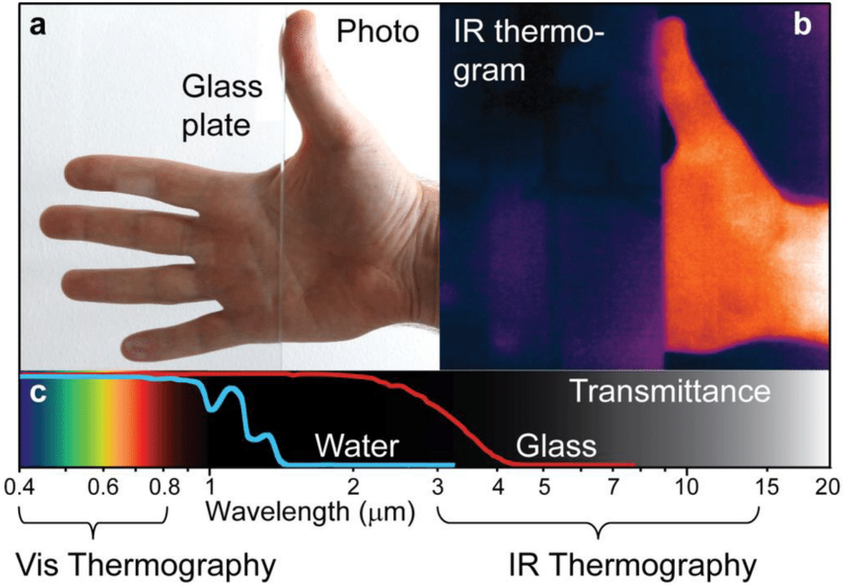
Note: the light from LEDs, from gases etc. are NOT thermal radiation !!! It originates from electronic processes in materials.

Thermal Radiation



Temperature and material properties determine how an object EMITS thermal radiation.

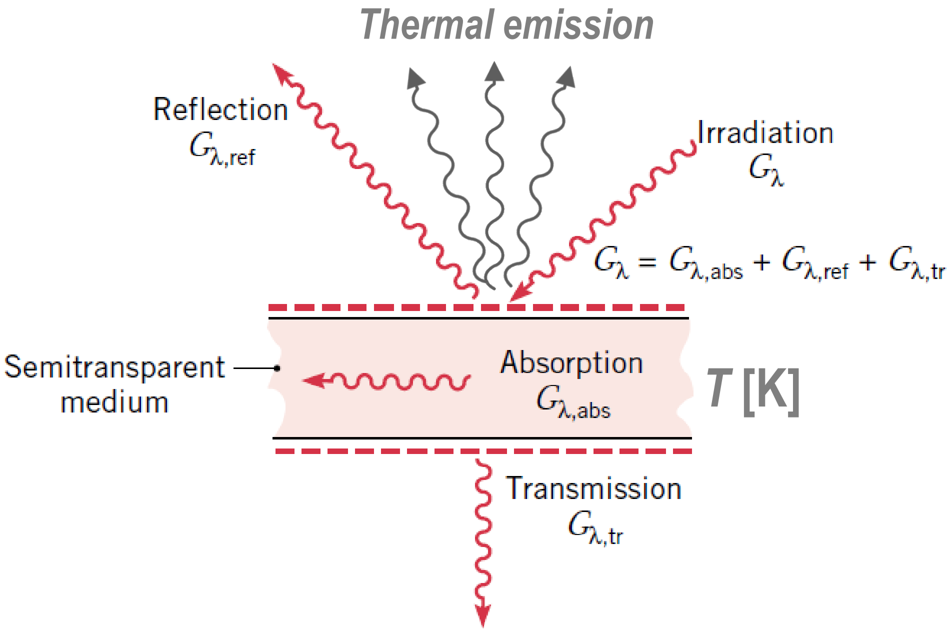
Thermal Radiation



How does thermal radiation interacts with matter?

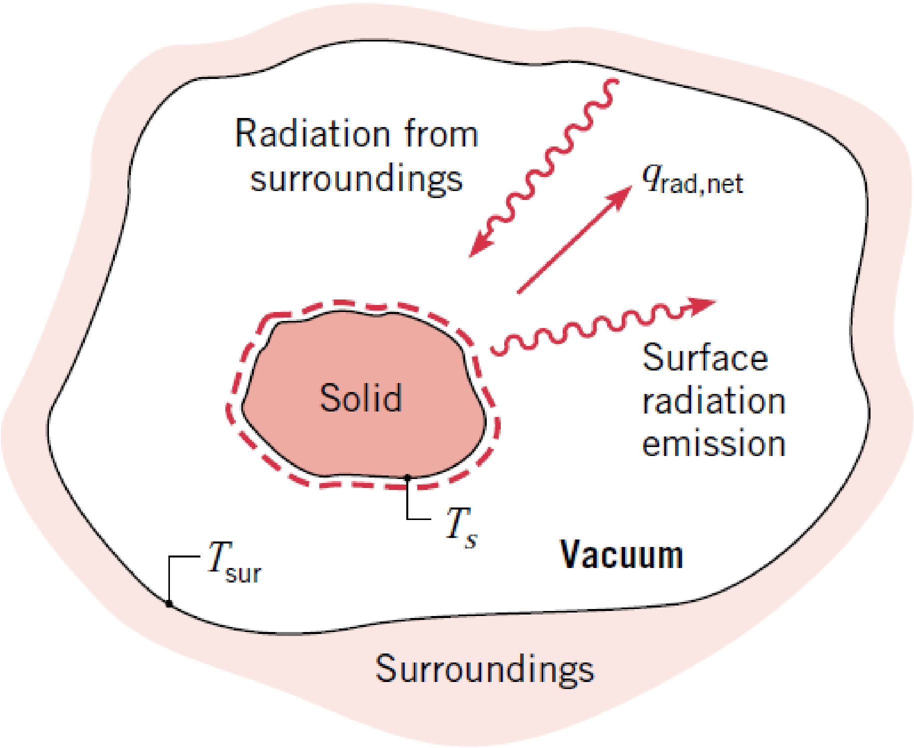
*High-resolution remote thermography using luminescent low-dimensional tin-halide perovskites

Thermal Radiation



Wavelength and material properties determine how thermal radiation interacts with objects.

Radiative Heat Transfer



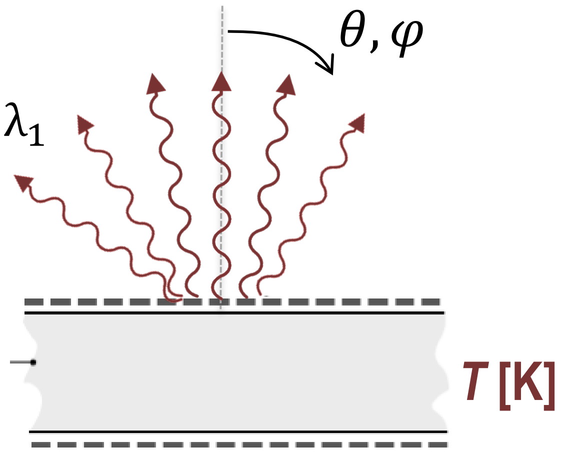
This lecture

- Emission of Thermal Radiation
  - Spatial distribution and Diffuse Emitter
  - Spectral distribution
  - Stefan-Boltzmann and Wien’s laws

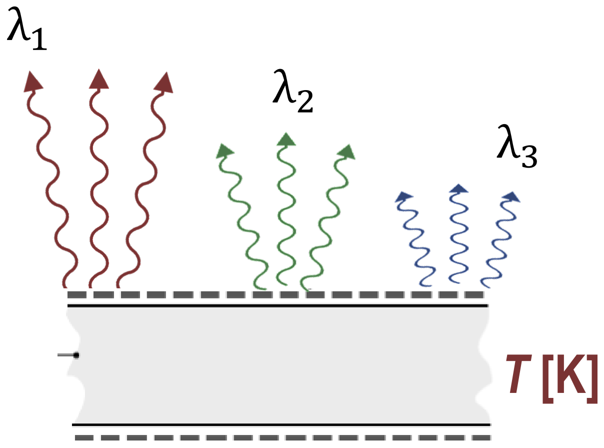
Learning Objective:

- Understand emission of thermal radiation
- Quantify the emission of thermal radiation

Emission of Thermal Radiation

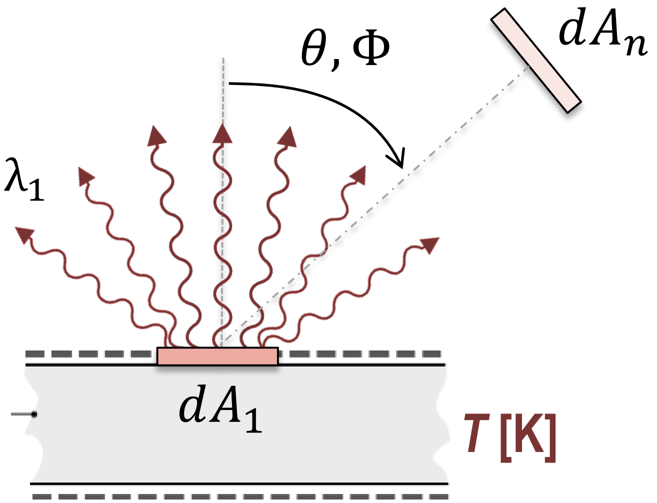


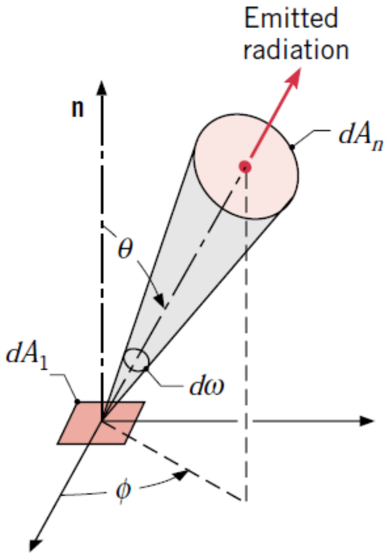
Spatial distribution



Spectral distribution

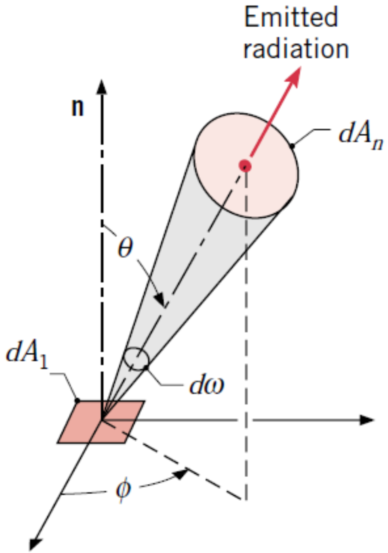
Emission of Thermal Radiation: Spatial Distribution





If the surface dA_1 emits energy at a rate $dQ\ [W]$,
how much of this radiation reaches the area dA_n
located at an angle θ, Φ with respect to the normal to dA_1?

Emission of Thermal Radiation: Spatial Distribution



$$I_{\lambda,e}(\lambda, \theta, \Phi, T) = spectral\ intensity$$

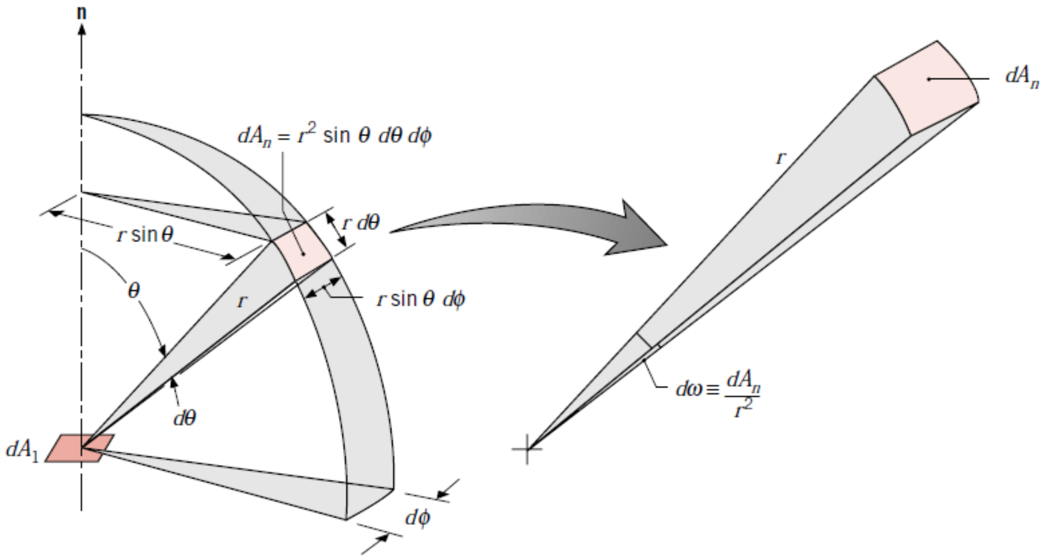
rate at which energy is emitted at wavelength λ and along the direction (Φ,θ)

- *per unit area of the emitting surface* ***normal to this direction*** $= dA_1 cos\theta$
- per unit solid angle about this direction $= d\omega$
- per unit wavelength interval about λ $= d\lambda$

$$I_{\lambda,e}(\lambda, \theta, \Phi) = \frac{dQ}{dA_1 cos\theta\, d\omega\, d\lambda}$$

Note: for convenience, we avoid to explicitly indicate the T dependence

Emission of Thermal Radiation: Spatial Distribution



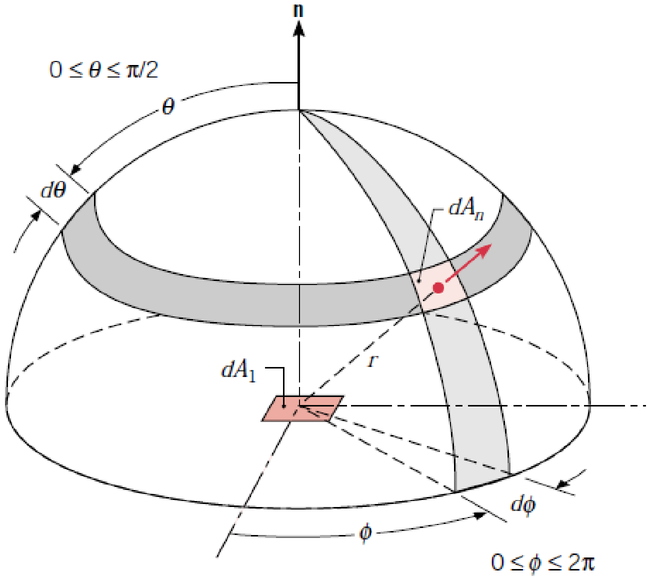
$$I_{\lambda,e}(\lambda,\theta,\Phi) = \frac{dQ}{dA_1 cos\theta d\omega d\lambda}$$

$$dA_n = r^2 sin\theta d\theta d\Phi$$

$$d\omega \equiv \frac{dA_n}{r^2} = sin\theta d\theta d\Phi$$

$$I_{\lambda,e}(\lambda,\theta,\Phi) = \frac{dQ/d\lambda}{dA_1 cos\theta(sin\theta d\Phi d\theta)} = \frac{dQ_\lambda/dA_1}{cos\theta sin\theta d\Phi d\theta} = \frac{dq_\lambda^{''}}{cos\theta sin\theta d\Phi d\theta}$$

Emission of Thermal Radiation: Spatial Distribution



$$dq''_{\lambda} = I_{\lambda,e}(\lambda, \theta, \Phi) cos\theta sin\theta d\Phi d\theta$$

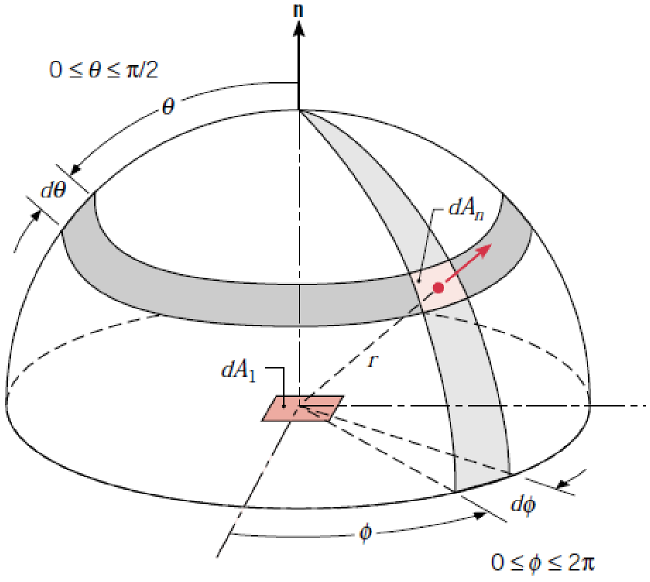
Spectral (hemispherical) emissive power $\left[\frac{W}{m^2 \mu m}\right]$:

$$E_{\lambda}(\lambda) = q''_{\lambda}(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e}(\lambda, \theta, \Phi) cos\theta sin\theta d\Phi d\theta$$

Total (hemispherical) emissive power E $\left[\frac{W}{m^2}\right]$:

$$E = \int_0^{\infty} E_{\lambda}(\lambda) d\lambda = \int_0^{\infty} \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e}(\lambda, \theta, \Phi) cos\theta sin\theta d\Phi d\theta d\lambda$$

Emission of Thermal Radiation: Diffuse Emitter



We define a **diffuse emitter** as a surface that emits radiation at the same rate irrespective of the emission direction (θ, Φ):

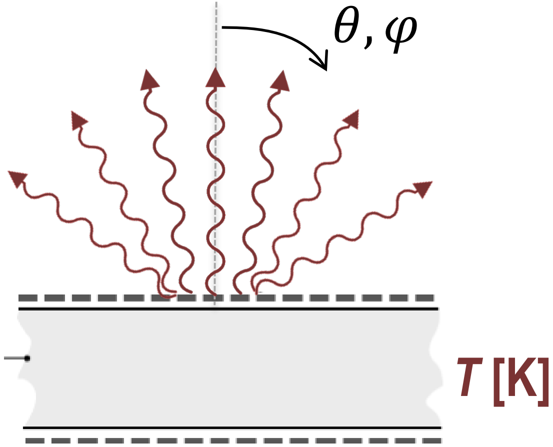
$$I_{\lambda,e}(\lambda, \theta, \Phi) = I_{\lambda,e}(\lambda)$$

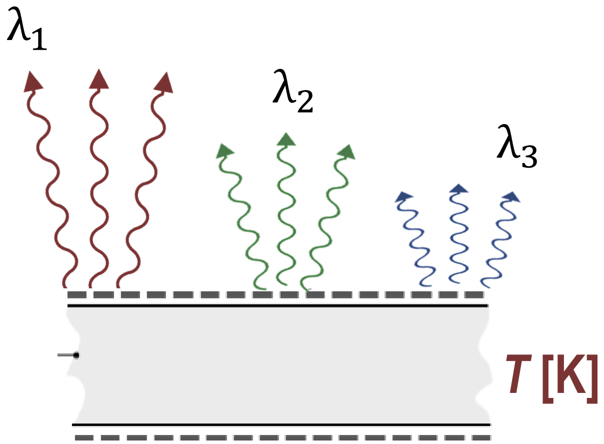
$$E_\lambda(\lambda) = I_{\lambda,e}(\lambda) \int_0^{2\pi} \int_0^{\pi/2} cos\theta sin\theta d\Phi d\theta = \pi I_{\lambda,e}(\lambda)$$

$$E = \pi \int_0^{\infty} I_{\lambda,e}(\lambda) d\lambda = \pi I_e$$

$I_e = \int_0^{\infty} I_{\lambda,e}(\lambda) d\lambda = total\ intensity$ of emitted radiation

Emission of Thermal Radiation





$$E(T) = \int_0^{\infty}\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\Phi,T)cos\theta sin\theta d\Phi d\theta d\lambda$$

Spectral distribution

$$E(T) = \pi\int_0^{\infty} \boldsymbol{I_{\lambda,e}(\lambda,T)}d\lambda$$ (*diffuse emitter*)

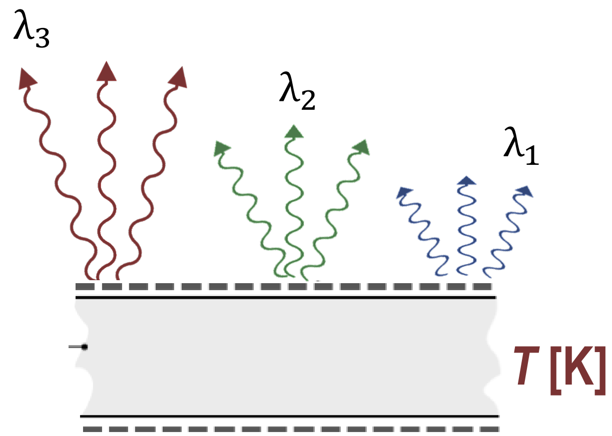
This lecture

- ❑ Emission of Thermal Radiation
  - ☑ Spatial distribution and Diffuse Emitter
  - ❑ Spectral distribution
  - ❑ Stefan-Boltzmann and Wien's laws

Learning Objective:

- ☑ Understand emission of thermal radiation
- ❑ Quantify the emission of thermal radiation

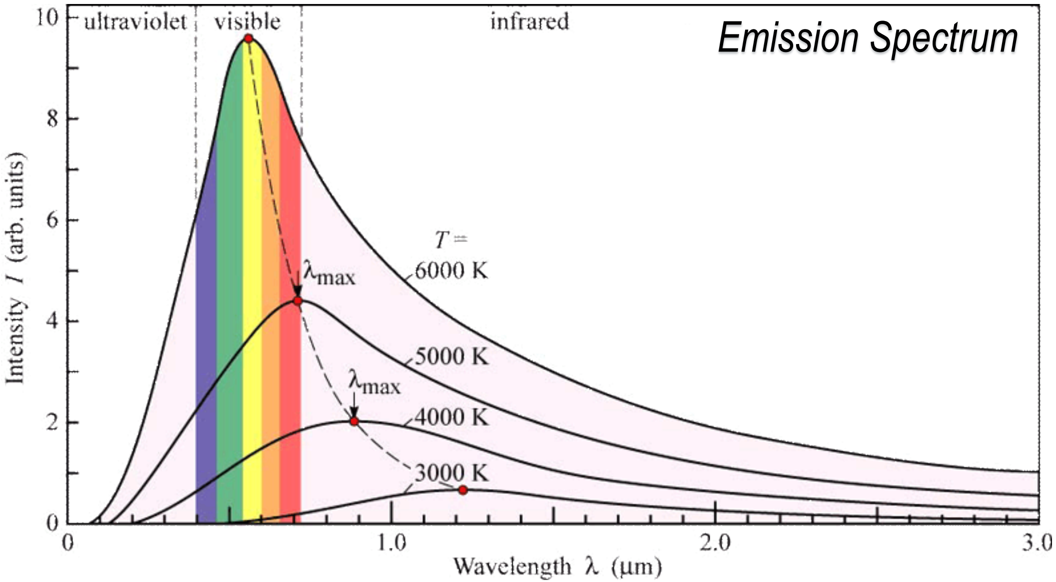
Emission of Thermal Radiation: Spectral Distribution



Thermal radiation consists of electromagnetic waves with many different wavelengths.

The **temperature** of the object determines the *spectrum* of emitted thermal radiation.

Emission of Thermal Radiation: Spectral Distribution



Spectral intensity of a *black-body** $\left[\frac{W}{m^2 sr\ \mu m}\right]$:

$$I_{\lambda,b}(\lambda, T) = \frac{2hc_0^2}{\lambda^5[\exp(hc_0/\lambda kT) - 1]}$$

$h = 6.626 \times 10^{-34}$ J · s *Planck constant*

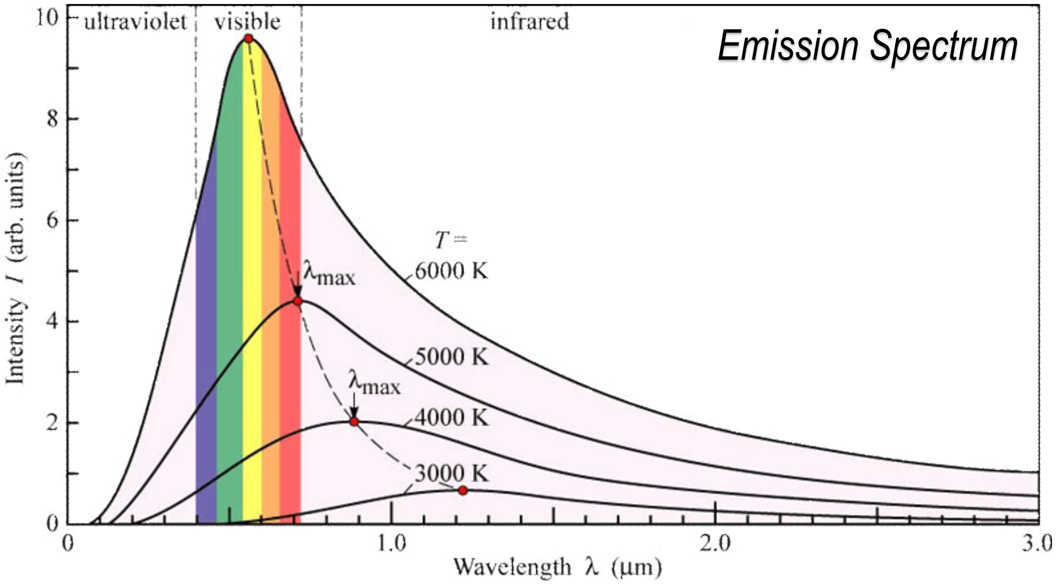
$k = 1.381 \times 10^{-23}$ J/K *Boltzmann constant*

$c_o = 2.998 \times 10^{8}$ m/s *Speed of light*

Temperatures MUST BE in Kelvin: T[K]

a black-body is a **diffuse emitter that absorbs all energy that impinges on it. We discuss this in detail later*

Emission of Thermal Radiation: Spectral Distribution



Stefan-Boltzman Law *(total emissive power)*

$$\boldsymbol{E_b(T)} = \pi \int_0^\infty I_{\lambda,b}(\lambda, T)\, d\lambda = \boldsymbol{\sigma T^4}$$

T = absolute temperature [K]

σ = 5.670367 10^{-8} W/m^2K^4

Total intensity of thermal emission

$$I_b = \frac{E_b}{\pi}$$

Temperatures MUST BE in Kelvin: T[K]

Emission of Thermal Radiation: Spectral Distribution

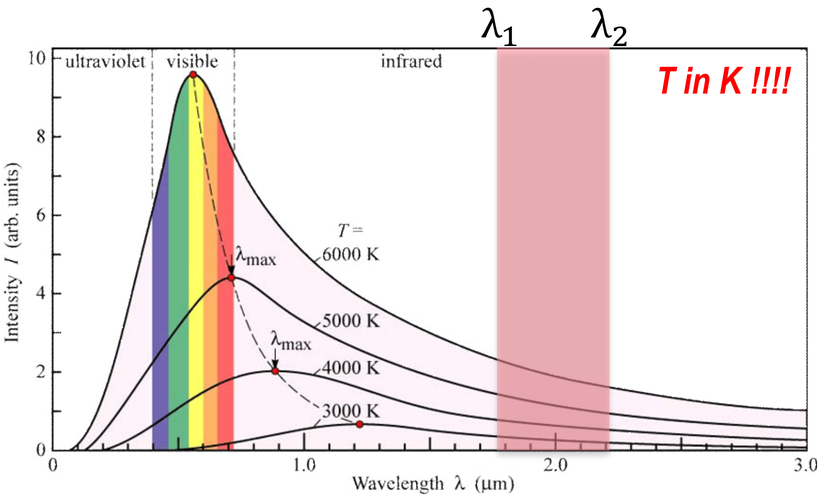


Table 12.1 Blackbody Radiation Functions

λT (μm · K)	$F_{(0\to\lambda)}$	$I_{\lambda,b}(\lambda,T)/\sigma T^5$ (μm · K · sr)$^{-1}$	$\frac{I_{\lambda,b}(\lambda,T)}{I_{\lambda,b}(\lambda_{max},T)}$
200	0.000000	0.375034×10^{-27}	0.000000
400	0.000000	0.490335×10^{-13}	0.000000
600	0.000000	0.104046×10^{-8}	0.000014
800	0.000016	0.991126×10^{-7}	0.001372
1,000	0.000321	0.118505×10^{-5}	0.016406
1,200	0.002134	0.523927×10^{-5}	0.072534
1,400	0.007790	0.134411×10^{-4}	0.186082
1,600	0.019718	0.249130	0.344904
1,800	0.039341	0.375568	0.519949

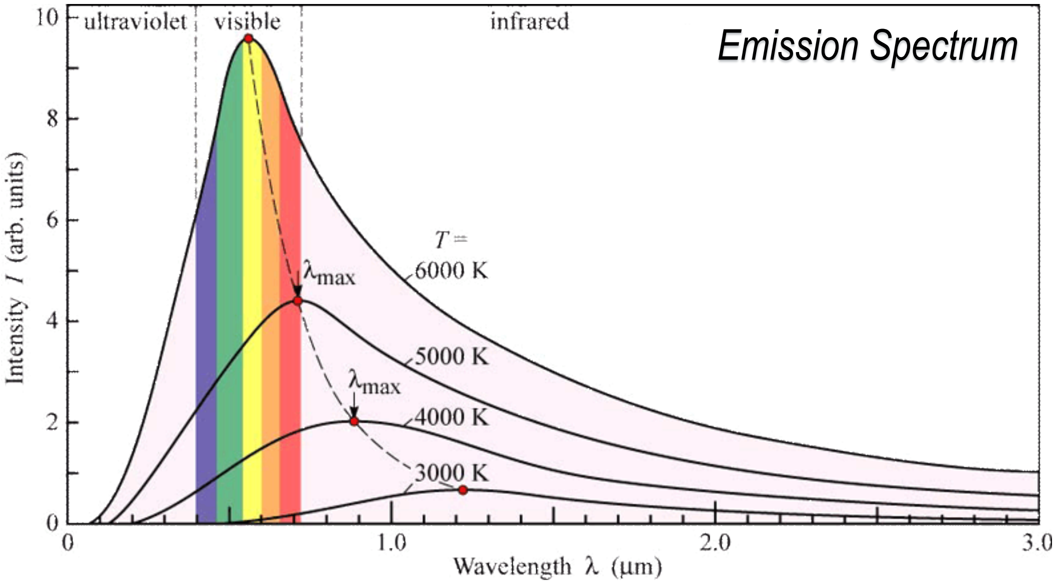
Often we want to know what is the emissive power within a limited wavelength range $[\lambda_1, \lambda_2]$. Therefore we define:

$$F_{(0\to\lambda)} \equiv \frac{\int_0^{\lambda} E_{\lambda,b}\, d\lambda}{\int_0^{\infty} E_{\lambda,b}\, d\lambda} = \frac{\int_0^{\lambda} E_{\lambda,b}\, d\lambda}{\sigma T^4} = \int_0^{\lambda T} \frac{E_{\lambda,b}}{\sigma T^5}\, d(\lambda T) = f(\lambda T)$$

The values of *F* are tabulated. Hence within a given wavelength range we have:

$$F_{(\lambda_1\to\lambda_2)} = \frac{\int_0^{\lambda_2} E_{\lambda,b}\, d\lambda - \int_0^{\lambda_1} E_{\lambda,b}\, d\lambda}{\sigma T^4} = F_{(0\to\lambda_2)} - F_{(0\to\lambda_1)}$$

Emission of Thermal Radiation: Spectral Distribution

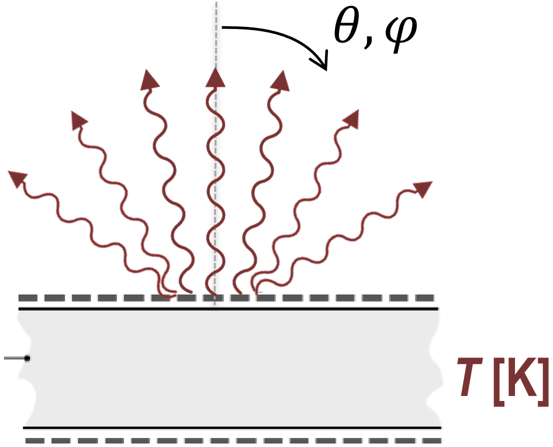


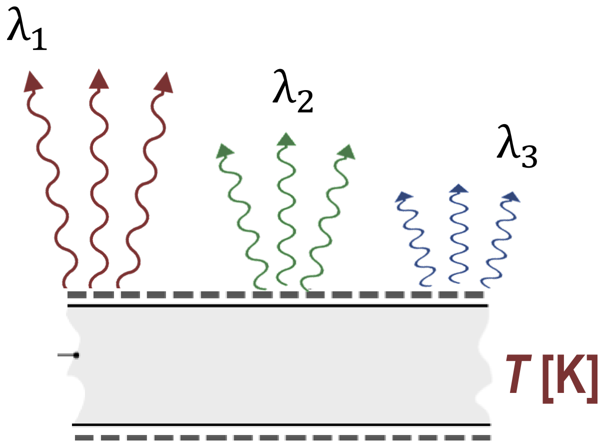
Wien's Law (peak emission)

$$(\lambda T)_{e_{\lambda=max}} = 2898\ \mu m \cdot K$$

Temperatures MUST BE in Kelvin: T[K]

Emission of Thermal Radiation (Black-body)





$$I_{\lambda,e}(\lambda, \theta, \Phi, T) = I_{\lambda,b}(\lambda, T)$$

$$I_{\lambda,b}(\lambda, T) = \frac{2hc_0^2}{\lambda^5[\exp(hc_0/\lambda kT) - 1]}$$

$$E_b(T) = \sigma T^4$$

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Next Lecture

- Interaction of Thermal Radiation with Matter
  - Absorptivity, Reflectivity and Transmissivity
  - Irradiation and Radiosity
- Black-body
- Real surfaces: Emissivity, Diffuse & Gray Surfaces, Kirchoff’s Laws