ME265: Thermal Engineering & Heat Transfer

Chapters
1. Energy Scenario
2. Thermodynamics
3. Mechanical Devices & Systems
4. Heat Transfer

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4.2 Conduction	
4.3 **Convection**	
4.4 Radiation	**4.4.1 Radiation Fundamentals** **4.4.2 View factors/Shape factor** **4.4.3 Radiation exchange between surfaces**
4.5 Heat Exchanger	

4.4 Radiation: Fundamentals

❑ Introduction to Radiation

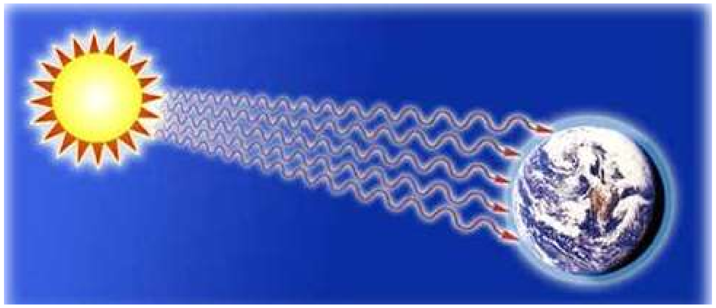

Fig. 4.4.1a Sun rays reaching earth

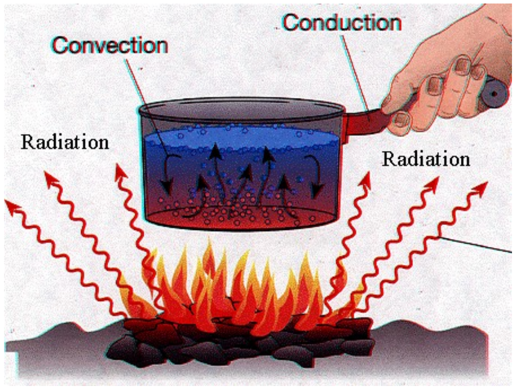

Fig. 4.4.1b Apparent heat of a fire

- Emission of internal energy of any object at a temperature T > 0 K
- Theoretical foundation [1]: **James Clerk Maxwell, 1864**
  - Energy emitted by matter as a result of changes in electrical configuration of atoms or molecules
  - Rapidly changing electrical configuration gives rise to electric and magnetic fields.
  - Rapidly changing fields are called electromagnetic waves or electromagnetic radiation

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Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

❑ Introduction to Radiation

- Theoretical foundation [1]: **Max Planck, 1900**
  - Propagation of a collection of discrete packets of energy called **photon** or **quanta**
  - Each photon of frequency $\boldsymbol{\nu}$ is considered to have an energy of:

$$e = h\nu = \frac{hc}{\lambda} \qquad \text{… …. … (4.1)}$$

Where

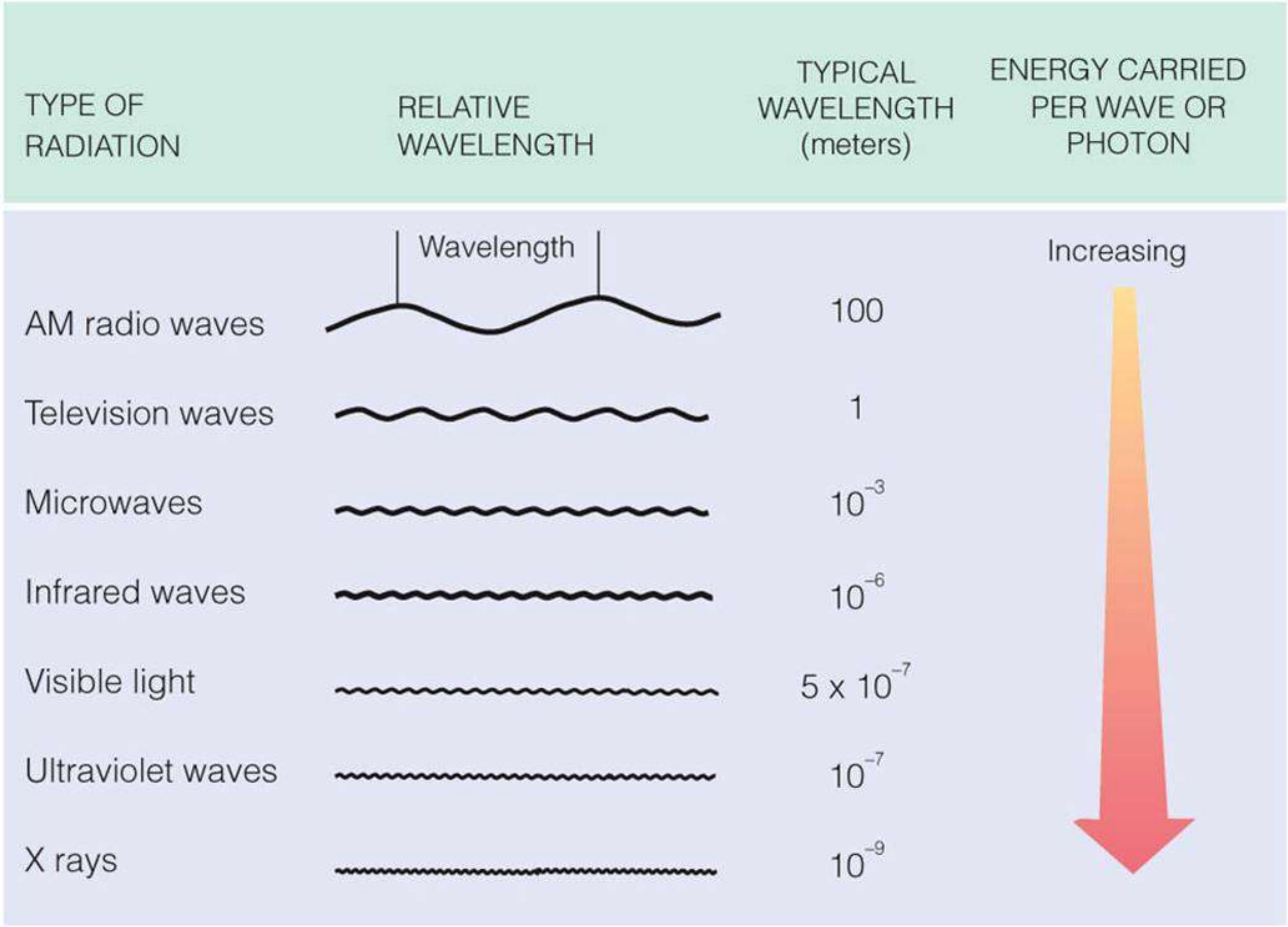
c = the speed of propagation of a wave in that medium;
it is equal to speed of light in air = $3\text{x}10^8$ m/s.
$h = 6.626069 \times 10^{-34}$ J.s is the Planck's constant, and
λ = the wavelength, m

  - Shorter-wavelength radiation possesses larger photon energy; these are destructive and we try to avoid these, e.g. X-ray, γ-ray.

Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

❑ Introduction to Radiation



TYPE OF RADIATION	RELATIVE WAVELENGTH	TYPICAL WAVELENGTH (meters)	ENERGY CARRIED PER WAVE OR PHOTON
AM radio waves	Wavelength	100	Increasing
Television waves		1	
Microwaves		10^{-3}	
Infrared waves		10^{-6}	
Visible light		5×10^{-7}	
Ultraviolet waves		10^{-7}	
X rays		10^{-9}	

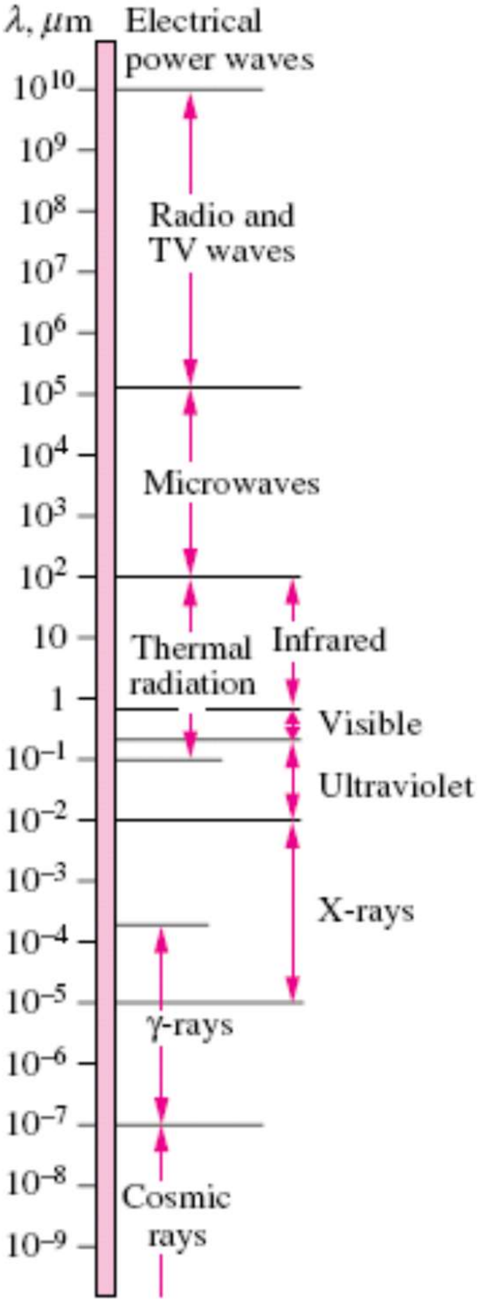
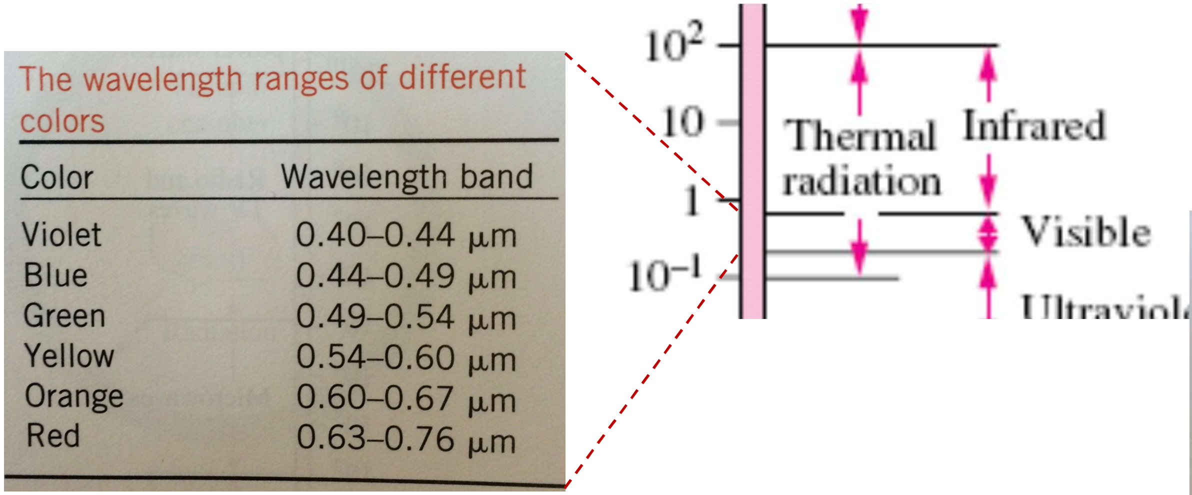


Fig. 4.4.2 Spectrum of electromagnetic wave

4.4 Radiation: Fundamentals



The wavelength ranges of different colors

Color	Wavelength band
Violet	0.40–0.44 μm
Blue	0.44–0.49 μm
Green	0.49–0.54 μm
Yellow	0.54–0.60 μm
Orange	0.60–0.67 μm
Red	0.63–0.76 μm

Fig. 4.4.3 Visible Spectrum: 0.4-0.76 μm

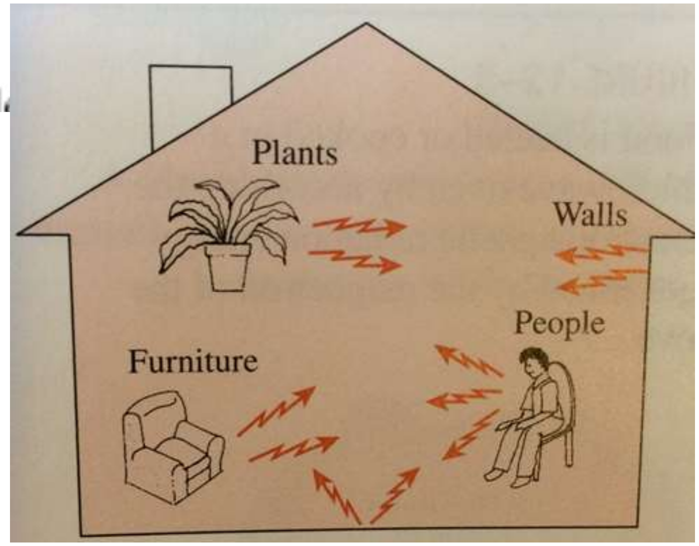


Fig. 4.4.3b Everything around us emits thermal radiation (0.1-100 μm)

- In heat transfer studies, we are interested in the energy emitted by bodies because of their temperature only.
- Therefore, we will limit your consideration to
  Thermal radiation ➔ Radiation

Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

- ☐ Radiation is generally a volumetric phenomenon
- ☐ Radiation is constantly emitted, as well as being absorbed or transmitted through out the entire volume of matters.

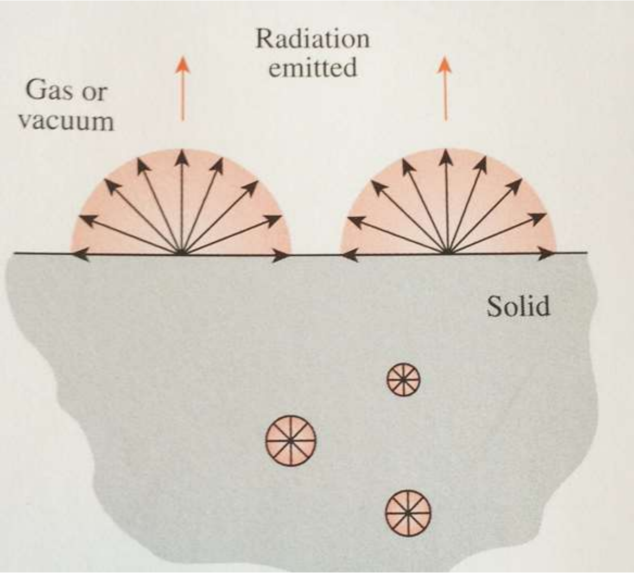


Fig. 4.4.4a Radiation in opaque solids

- ☐ For opaque (nontransparent) solids such as metals, wood and rocks, radiation is considered to be a surface phenomenon
  - ▪ Radiation incident on opaque solids is usually absorbed within a few microns from the surface

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Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

❑ Blackbody Radiation

- **Blackbody** is an **idealized body** to serve as a standard against real surfaces.
- It is defined as a **perfect emitter and absorber of radiation**.
- No real surface can emit more energy than a black body at a specified temperature and wavelength.

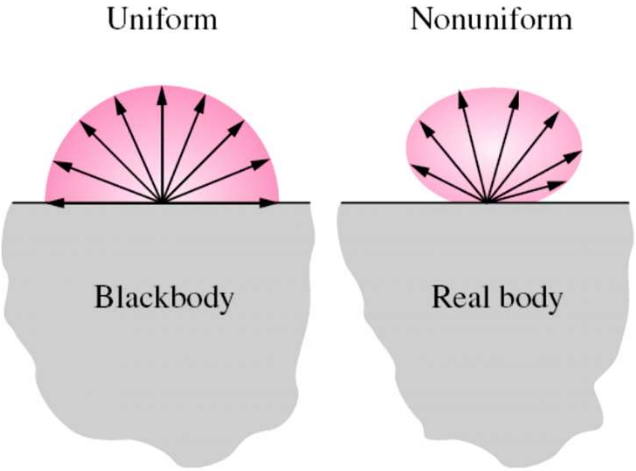

Fig. 4.4.4b Black body vs real body

- A blackbody emits radiation energy uniformly in all directions per unit area normal to the direction of emission.
- **Blackbody** is a **diffuse emitter.**
- **Emissive power of blackbody** is given by: $\boldsymbol{E_b(T) = \sigma T^4}$ **…. … (4.2)**

Where, $\sigma = 5.67 \times 10^{-8}$ W/m^2.K^4, Stefan-Boltzmann constant. Stefan (1879) determined experimentally and later Boltzmann (1884) verified theoretically. **Stefan-Boltzmann Law**

4.4 Radiation: Fundamentals

❑ Spectral Emissive Power of Blackbody, $E_{b\lambda}$

Max Planck in 1901 developed a law on spectral emissive power of blackbody (**Planck's Law**)

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5[exp(C_2/\lambda T) - 1]} \quad \text{.... ... (4.3)}$$

$$C_1 = 2\pi h c_0^2 = 3.74177\times10^8 \qquad \left(\mathrm{W}\cdot\mu\mathrm{m}^4/\mathrm{m}^2\right)$$

$$C_2 = hc_0/k = 1.43878\times10^4 \qquad \left(\mu\mathrm{m}\cdot\mathrm{K}\right)$$

h : Planck's constant: 6.626×10^{-34} J s
k : Boltzmann constant: 1.80×10^{-23} J/K
c_0 : Speed of light: 3×10^{8} m/s

Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

❑ SEP of Blackbody, $E_{b\lambda}$

Planck's Law

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5[exp(C_2/\lambda T) - 1]} \quad \text{…. … (4.3)}$$

Observations:

- at any specified temperature a maximum exists.
- at any wavelength, the amount of emitted radiation *increases* with increasing temperature,
- as temperature increases, the curves shift to the shorter wavelength,
- the maximum radiation emitted by the *sun* (5780 K) is in the visible spectrum.
- Surfaces at T<800K emit radiation entirely in the infrared region.

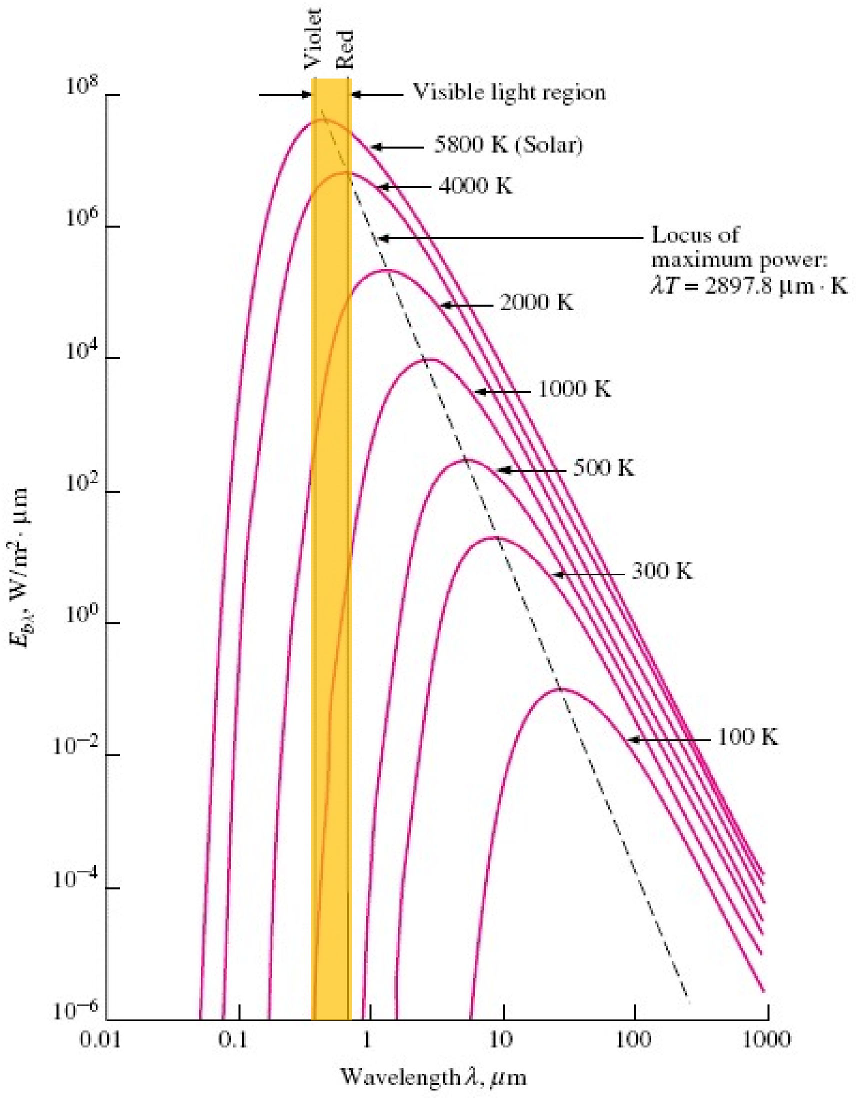

Fig. 4.4.5 Variation of SEP with wavelength for several temperatures

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Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

- ❑ **SEP of Blackbody, $E_{b\lambda}$**

Planck's Law

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5[exp(C_2/\lambda T) - 1]} \;\ldots\;\ldots\; \mathbf{(4.3)}$$

$$E_b(T) = \int_0^{\infty} E_{b\lambda}(\lambda, T)\, d\lambda = \sigma T^4 \;\ldots\;\ldots\; \mathbf{(4.4)}$$

For maximum SEP: $\dfrac{\partial E_{b\lambda}}{\partial \lambda} = 0$

$$\Rightarrow \lambda T = 2897.8 \;\ldots\;\ldots\; \mathbf{(4.5)}$$

This is called **Wien's Displacement Law**

Max SEP

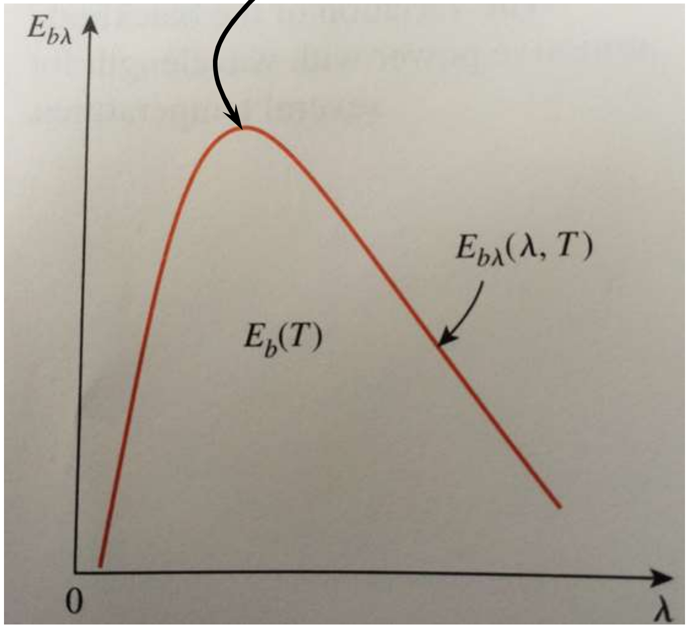


Fig. 4.4.6a Variation of SEP with wavelength at a temperature, T

4.4 Radiation: Fundamentals

❑ SEP of Blackbody, $E_{b\lambda}$

- We are often interested in the amount of radiation emitted over some wavelength band.
- The radiation energy emitted by a blackbody per unit area over a wavelength band from $\lambda = 0 - \lambda$ is determined from

$$E_{b,0-\lambda}(T) = \int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda$$

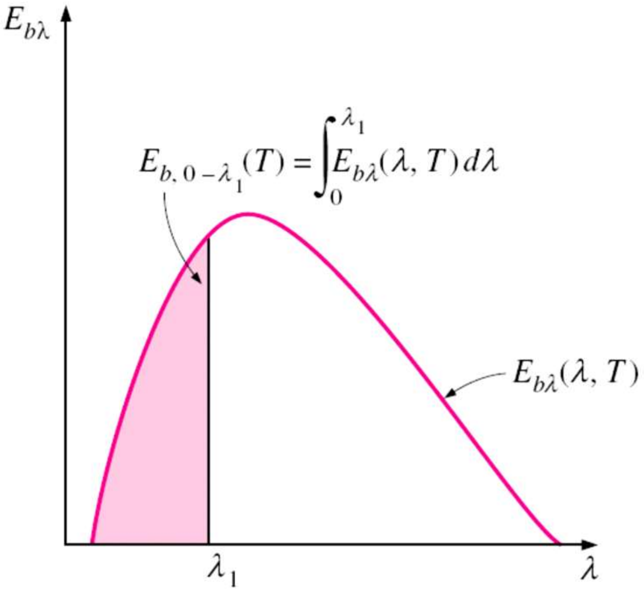


Fig. 4.4.6b $E_{b\lambda} - \lambda$ chart

- Blackbody radiation function f_λ is used for convenience, which is defined by:

$$f_\lambda = \frac{E_{b,0-\lambda}}{E_b} = \frac{\int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4} \quad \text{…. … (4.6)}$$

4.4 Radiation: Fundamentals

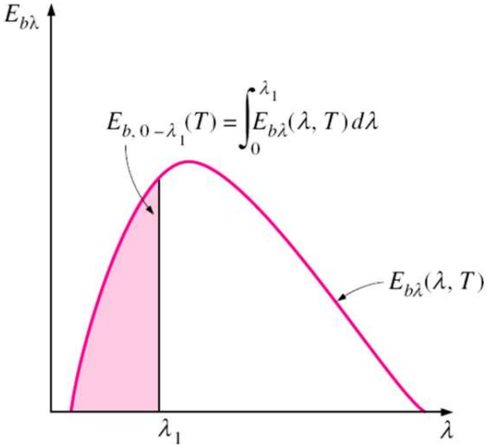
❑ Blackbody radiation function f_λ

TABLE 12–2

Blackbody radiation functions f_λ

λT, μm · K	f_λ	λT, μm · K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905

$$f_{\lambda_1}(T) = \frac{\int_0^{\lambda_1} E_{b\lambda}(\lambda, T)\,d\lambda}{\sigma T^4}$$



$$f_{\lambda_1-\lambda_2}(T) = f_{\lambda_2}(T) - f_{\lambda_1}(T)$$

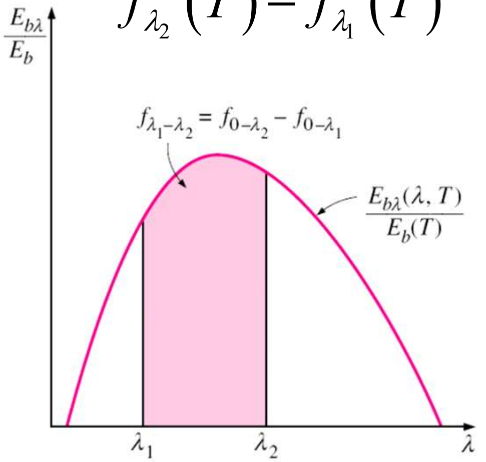


Fig. 4.6c $E_{b\lambda} - \lambda$ charts

4.4 Radiation: Fundamentals

EP#4.1 **(Cengel et. al. Example 12-7)**

Charged-coupled device (CCD) image sensors, that are common in modern digital cameras, respond differently to light sources with different spectral distributions. Daylight and incandescent light are emitted, respectively, from the sun and lightbulb having effective surface temperatures of 5800 K and 2800 K. If these light sources are approximated as blackbodies, determine the fraction of radiation emitted within visible spectrum. Also find calculate the **wavelength of maximum radiation** emitted from the bulb.