Chapter 1 Nature of Light

1.1 A brief History

From the 17th century:

- Willebrord Snell (1591 – 1626) discovered "Law of Refraction"
- Johannes Kepler (1571 – 1630) discovered "Total Internal Reflection"
- Pierre de Fermat (1601 – 1665) rederived "Law of Refraction" from his "Principle of Least time"
- Christiaan Huygens (1629 – 1695) proposed Wave Theory and discovered the phenomenon of polarization
- Isaac Newton (1642 – 1727): he described light as a stream of particles or corpuscles; concluded that white light was composed a mixture of a whole range of independent colors; he had difficulty to explain Newton' ring

What is light? Was it stream of particles, or a wave ?

1.1 Brief History

The 19th century:

- Thomas Young (1773 – 1829): Young' double-slit experiment → "Principle of Interference"
- Augustin Jean Fresnel (1788 – 1827): synthesized the concepts of Huygens' s wave description and interference principle; wave is a transverse wave; "Fresnel' equation" for partial reflection and transmission.
- James Clerk Maxwell (1831 – 1879): Final vindication of wave theory – Maxwell's equations; he synthesized the basic physics of E & M into 4 Maxwell's equations. He concluded that *Light was an electromagnetic disturbance in the form of waves propagated through the aether*.

$$\boxed{c = 1/\sqrt{\mu_o \varepsilon_o}}$$

1-1 Brief History

20th-century Optics:

- Max Planck (1858 – 1947): showed that the form of the black-body spectrum could be explained by postulating that the walls of the body consisted of harmonic oscillators with a range of frequency, and that the energies of those with frequency ν were restricted to integral multiple of the quantity $h\nu$ (1900, NP1918)

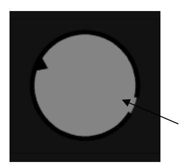
$$\boxed{E = h\nu}$$

h : Planck constant (6.626×10^{-34} J-s)

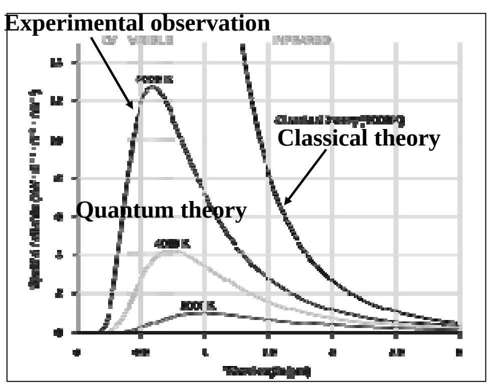
- Albert Einstein (1879 – 1955): Explained the *Photoelectric Effect*; Central to his explanation was the conception of light as a stream of light quanta (*Photon*) whose energy is related by above Equation (1905, NP1921)

- Niels Bohr (1885 – 1962): explained the emission and absorption processes of the Hydrogen atom; made fundamental contributions to understanding atomic structure and quantum mechanics (1913, NP1922)

Introduction to Blackbody radiation spectrum



- A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence.
- It is also a full radiator, with a *spectral* energy distribution dependent on its absolute temperature.
- Great difference between the classical theory and experimental evidence led to significant quantum mechanical developments from Plank and Einstein



1-1 Brief History

20th-century Optics:

- Arthur Compton (1892 – 1962): explained the scattering of X-rays from electrons as particle-like collisions between light quanta and electrons in which both energy and momentum were conserved (1922, NP1927)

- Louis de Broglie (1892 – 1987): best known for his research on quantum theory and for his discovery of wave nature of electron (1924, NP1929)

$$\boxed{\lambda = \frac{h}{p}}$$

What is light? Was it stream of particles, or a wave ?

- Light behaves like waves in its propagation and in the phenomena of interference and diffraction; however, it exhibits particle-like behavior when exchanging energy with matter, as in the Compton and photoelectric effects

1-2 Particles and Photons

$$p = \frac{\sqrt{E^2 - m^2c^4}}{c}$$

$$\lambda = \frac{h}{p}$$

$$\mathrm{v} = \frac{pc^2}{E} = c\sqrt{1 - \frac{m^2c^4}{E^2}}$$

- Quantum mechanics describes both light and matter and, together with special relativity, predicts the momentum p, wavelength λ, and speed v for both *material particles* and *photons* are given by the same general equations:

  Total energy: $\boxed{E = mc^2 + E_k}$

- Photon has zero rest mass, but each photon has energy $h\nu$

- Energy unit eV: $\boxed{1eV = 1.6 \times 10^{-19}\,J}$

$$p = \frac{E}{c}$$

$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

$$\mathrm{v} = c$$

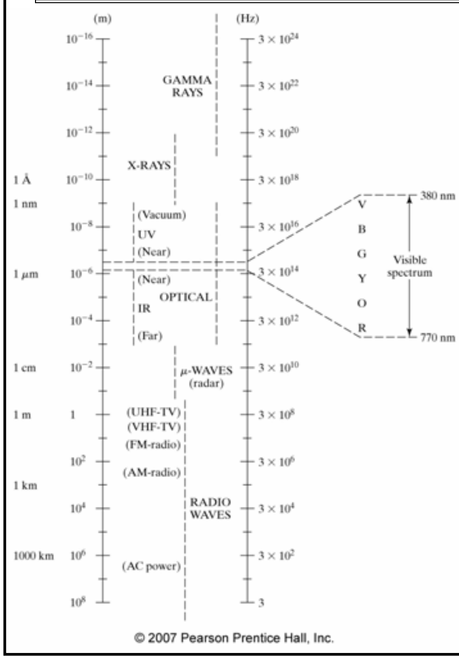
Example 1.1

An electron is accelerated to a kinetic energy E_k of 2.5 MeV.

(a) Determine its relativistic momentum, de Broglie wavelength, and speed.

(b) Determine the same properties for a photon having the same total energy as the electron.

1-3 The Electromagnetic Spectrum



- "Light" is identified as an electromagnetic wave having a frequency in the range that human eyes can detect and interpret

  380 nm – 770 nm

- Relations:

  $$\boxed{c = \lambda \nu \quad \text{or} \quad \lambda = c/\nu}$$

- Common unit for λ:

  Angstrom: $1\mathring{A} = 10^{-10} m$

  Nanometer: $1nm = 10^{-9} m$

1-3 The Electromagnetic Spectrum

Example 1.2

A certain sensitive radar receiver detects an electromagnetic signal of frequency 100 MHz and power (energy/time) $6.63\text{x}10^{-16}$ J/s.

(a) What is the wavelength of a photon with this frequency?

(b) What is the energy of a photon in this signal? Express this energy in J and in eV

(c) How many photons/s would arrive at the receiver in this signal?

(d) What is the energy (in J and in eV) of a visible photon of wavelength 555 nm?

(e) How many visible (λ = 555 nm) photons/s would correspond to a detected power of $6.63\text{x}10^{-16}$ J/s?

(f) What is the energy (in J and in eV) of an X-ray of wavelength 0.1 nm?

(g) How many X-ray (λ = 0.1 nm) photons/s would correspond to a detected power of $6.63\text{x}10^{-16}$ J/s?

1-4 Radiometry

- Radiometry is the science of measurement of electromagnetic radiation

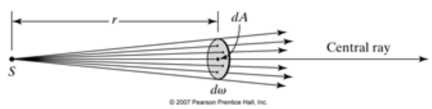
TABLE 1-1 RADIOMETRIC TERMS

Term	Symbol (units)	Defining equation
Radiant energy	$Q_e(\mathrm{J} = \mathrm{W} \cdot \mathrm{s})$	—
Radiant energy density	$w_e(\mathrm{J/m^3})$	$w_e = dQ_e/dV$
Radiant flux, Radiant power	$\Phi_e(\mathrm{W})$	$\Phi_e = dQ_e/dt$
Scattered, reflected → Radiant exitance	$M_e(\mathrm{W/m^2})$	$M_e = d\Phi_e/dA$
Irradiance	$E_e(\mathrm{W/m^2})$	$E_e = d\Phi_e/dA$
Radiant intensity	$I_e(\mathrm{W/sr})$	$I_e = d\Phi_e/d\omega$
Radiance	$L_e\left(\frac{\mathrm{W}}{\mathrm{sr} \cdot \mathrm{m^2}}\right)$	$Le = dI_e/dA \cos\theta$

Abbreviations: J, joule; W, watt; m, meter; sr, steradian.

- The steradian (symbol: **sr**) is the SI unit of solid angle. It is used to describe 2-D angular spans in 3-D space, analogous to the way in which the radian describes angles in a plane.

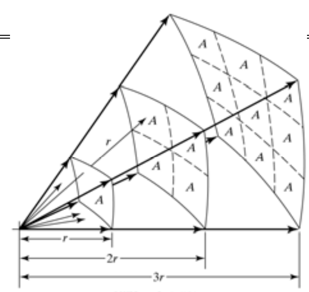
$$\boxed{d\omega = \frac{dA}{r^2}}$$



1-4 Radiometry

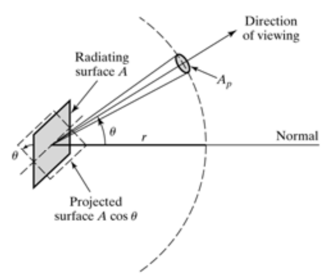
- Inverse square law: The flux leaving a point source within any solid angle is distributed over increasingly larger areas, producing an irradiance that decreases inversely with the square of the distance

$$\boxed{E_e = \frac{d\Phi_e}{dA} = \frac{\Phi_e}{A} = \frac{4\pi I_e}{4\pi r^2} = \frac{I_e}{r^2}}$$



- The radiance, L_e, describes the radiant intensity per unit of projected area, perpendicular to the specified direction:

$$\boxed{L_e = \frac{dI_e}{dA\cos\theta}}$$



1-4 Radiometry

➢ Suggested problems: 2, 3, 10, 11, 12, 14, 16

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Problems: 1-17

A 1.5-mW helium-neon laser beam delivers a spot of light 5 mm in diameter across a room 15 m wide. The beam radiates from a small circular area of diameter 0.5 mm at the output mirror of the laser. Assume that the beam irradiance is constant across the diverging beam.

(a) What is the beam divergence angle of this lasers?
(b) Into what solid angle is the laser sending its beam?
(c) What is the irradiance at the spot on the wall 15 m from the laser?
(d) What is the radiance of the laser?