EEE 3352

Electromechanics & Electrical Machines

Lecture 9: Illumination

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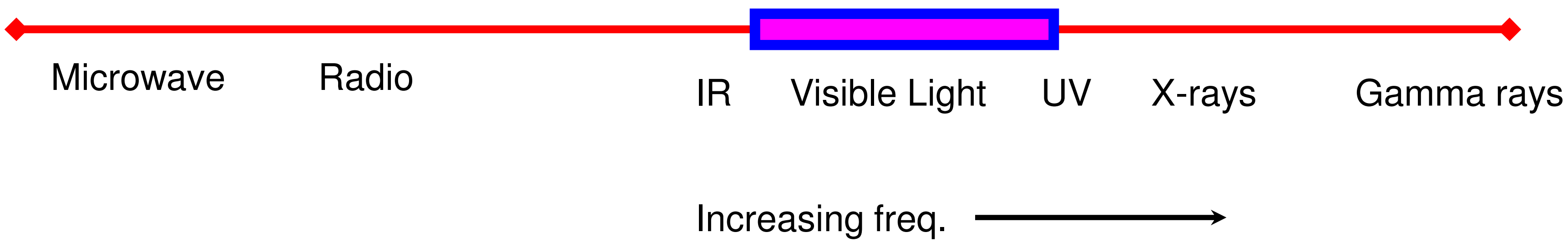
9. Illumination

1. Electromagnetic spectrum
2. Sources of artificial lighting
3. Definitions
4. Cosine law of illumination
5. Illuminance on a surface
6. Illumination factors
7. Requirements of lighting
8. Electric lighting

Objectives:

- at the end of the lecture, students should be able to
  - identify the position of visible light on the EM spectrum
  - classify sources of artificial lighting
  - define quantities of illumination
  - apply the laws and factors of illumination in lighting design
  - describe the types electric lighting

9.1 Electromagnetic spectrum



Range of visible spectrum:

From **Red**: 4×10^{14} Hz [750 nm] to **Violet**: 7×10^{14} Hz [400nm]

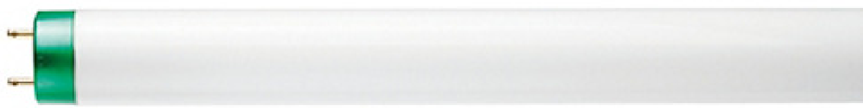
Propagation speed = c = 3×10^{8} m/s

9.2 Sources of artificial lighting

- incandescent
  - continuous spectrum
  - intensity of different colours depend on temperature of source

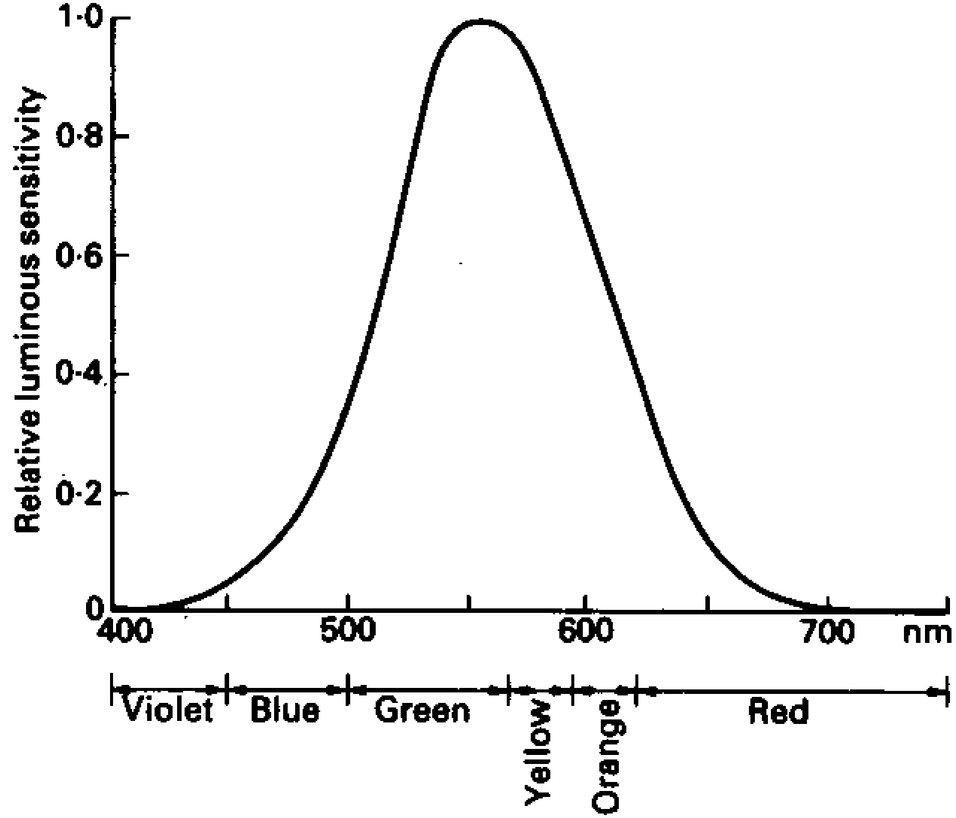
- gaseous discharge
    - discontinuous spectrum
    - e.g. sodium lamp produces 2 yellow lines at 589.0 and 598.6 nm, so close it appears monochromatic

- fluorescent
    - based on electric discharge of ionized gas (plasma), with UV
    - internal coating of lamp with fluorescent material, for visible light

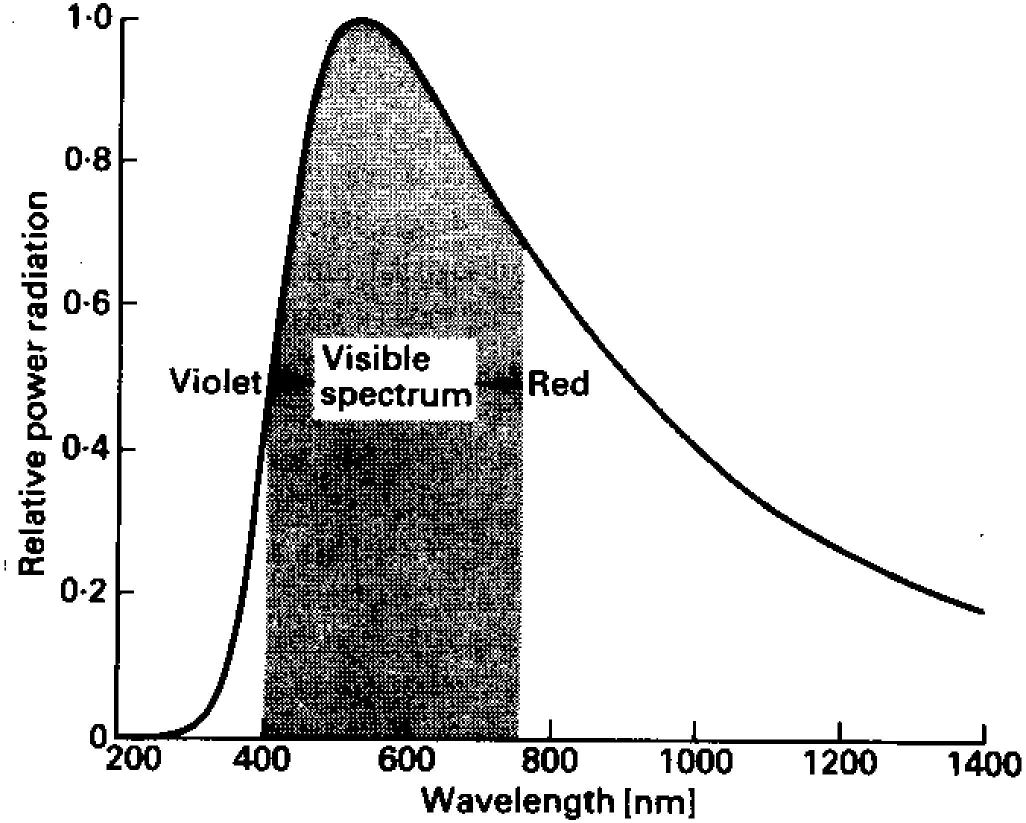


- light emitting diode
  - mechanism of electroluminescence in semiconductor materials
  - visible light, no UV ; low power activation

Human eye



Sun



- peak sensitivity of eye is at 555 nm
- maximum power radiation from the sun is at 500 nm

9.3 Definitions

1) luminous flux (ϕ)

   a. radiation ability to produce visual sensation

   b. radiant energy weighted according to its ability to cause the sensation of light

      - a matter of the wavelength of energy and the sensitivity of the eye to it

   c. the total quantity of light emitted per second by a light source

   d. unit is lumen [lm]

2) luminous intensity (I)

a. the light radiating capacity of a source

b. the luminous flux emitted per unit of solid angle in a given direction

c. unit is candela [cd]

- define 1 cd (see 1st lecture)

3) point source

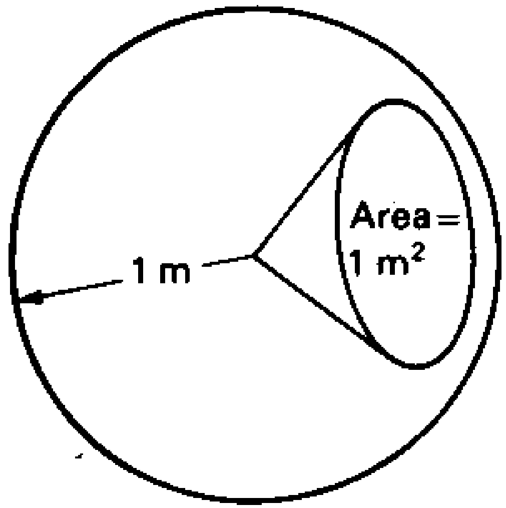
- a source that can be considered to be concentrated at a point

4) uniform point source

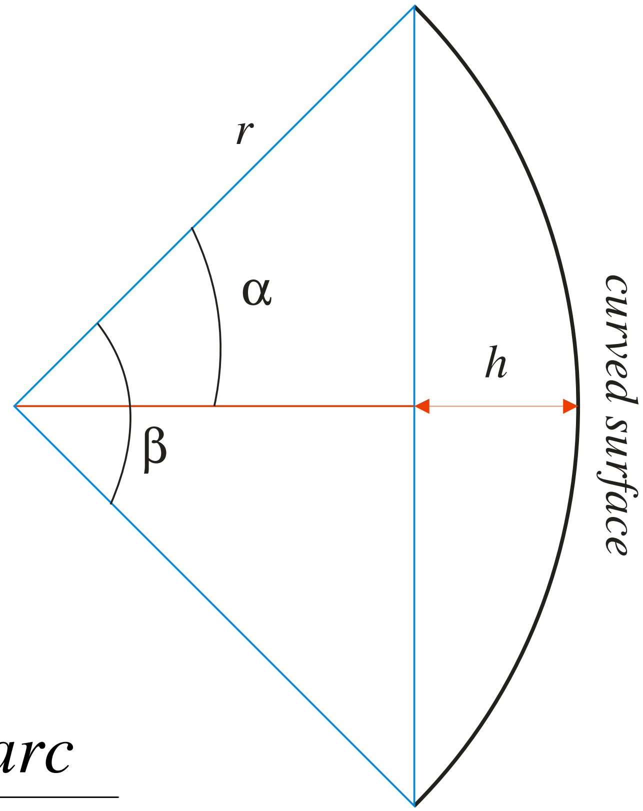
- a point source emitting light evenly in all directions

5) steradian (unit solid angle) (ω)

- solid angle subtended at the center of a sphere 1 m radius by 1 m^2 of area on the surface of the sphere



Relationship between solid angle ω and plane angle β



$$\beta = 2\alpha$$

- arc [radian] $\quad \beta = \dfrac{arc}{radius}$

- solid angle [steradian] $\quad \omega = \dfrac{surface\ \ area}{(radius)^2}$

- surface area *A* covered by spherical segment of height *h*

$$A = 2\pi r h$$

$$h = r - r\cos\alpha = r(1-\cos\alpha)$$

$$A = 2\pi r\left[r(1-\cos\alpha)\right] = 2\pi r^2(1-\cos\alpha)$$

$$\omega = \frac{A}{r^2} = \frac{2\pi r^2(1-\cos\alpha)}{r^2} = 2\pi(1-\cos\alpha)$$

$$\boxed{\omega = 2\pi\left(1-\cos\frac{\beta}{2}\right)}$$

6) lumen

- the luminous flux emitted in a unit solid angle by a uniform point source having a luminous intensity of 1 cd
- consider a point source of 1 cd, at centre (oo) of transparent sphere of radius $r = 1$ m
  - luminous flux through each 1 m² is 1 lm

$$S_A = 4\pi r^2 = 4\pi$$

$$\therefore \phi_{\text{total}} = 4\pi \quad [\text{lm}]$$

  - for a point source of I cd , $d\phi$ in $d\omega$ steradians is

$$d\phi = I \cdot d\omega \rightarrow I = \frac{d\phi}{d\omega}$$

7) mean spherical luminous intensity (I_{mean})

- average value of luminous intensity in all directions

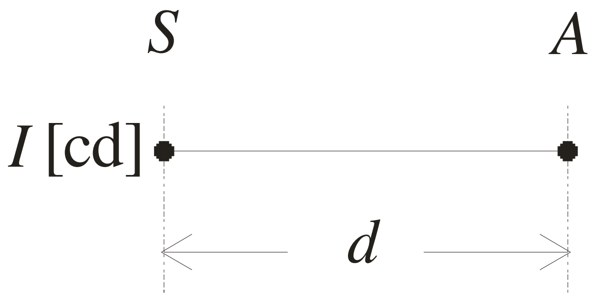
8) illuminance (E)

- luminous flux per unit area
- units [lm/m^2] or lux [lx]

- consider a sphere r = 1 m, point source of 1 cd at oo

$$\frac{E_{(\text{at } r)}}{E_{(\text{at } r=1 \text{ m})}} = \frac{\phi / 4\pi r^2}{\phi / 4\pi} = \frac{4\pi}{4\pi r^2} = \frac{1}{r^2}$$

- inverse square law of illumination



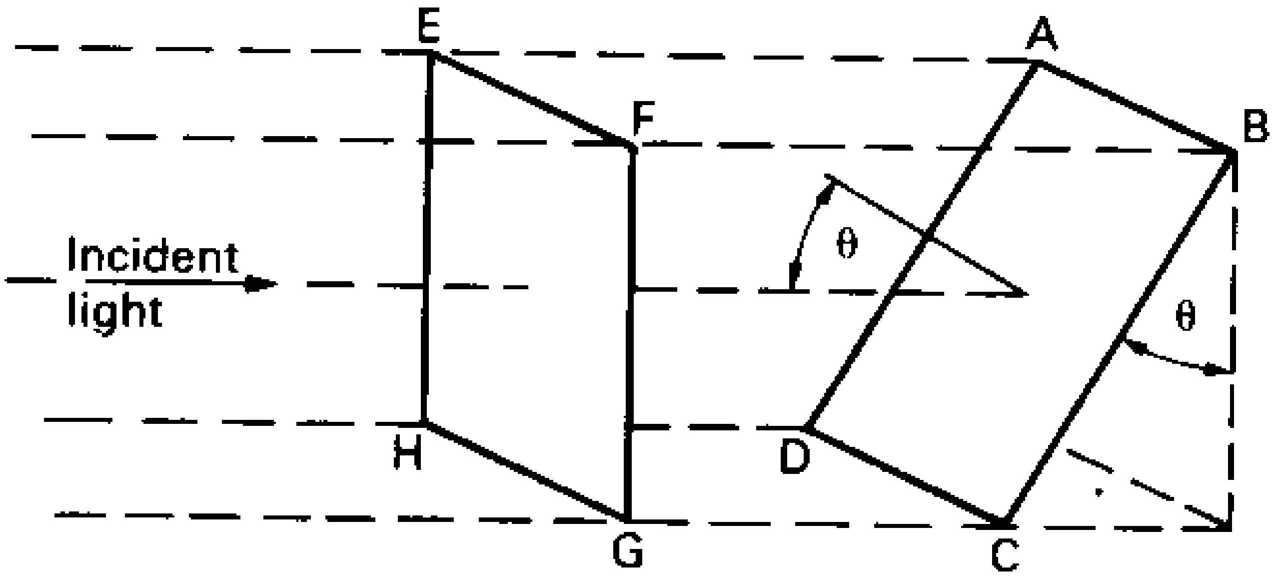
$$\boxed{E_A = \frac{I}{d^2}}$$

9) Luminance (*L*)

- of a source in a given direction
- is the luminous intensity in that direction per unit of projected area
- unit [cd/m^2]
- e.g.

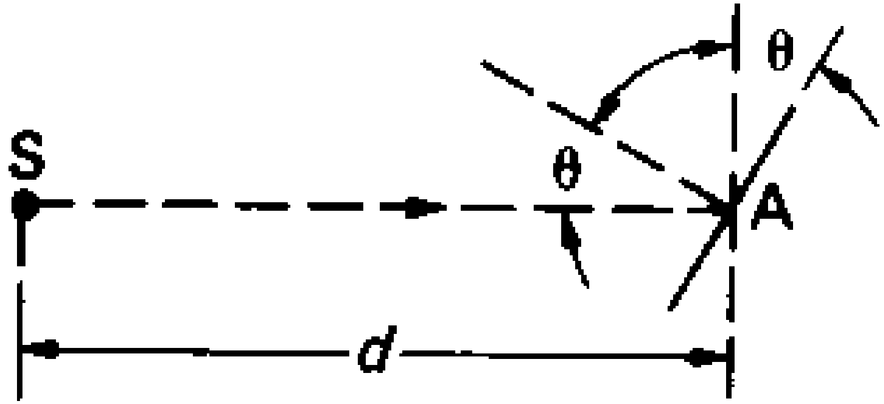
Source	*L* [cd/m^2]
Zenith sun	6×10^8
Tungsten bulb, gas-filled, clear (100 W)	6.5×10^6
Mercury low-pressure, fluorescent (80 W)	0.9×10^4
Clear blue sky	0.4×10^4

9.4 Cosine law of illuminance



$$\frac{E_{\text{ABCD}}}{E_{\text{EFGH}}}=\frac{\phi/S_{ABCD}}{\phi/S_{EFGH}}=\frac{S_{EFGH}}{S_{ABCD}}=\cos\theta$$

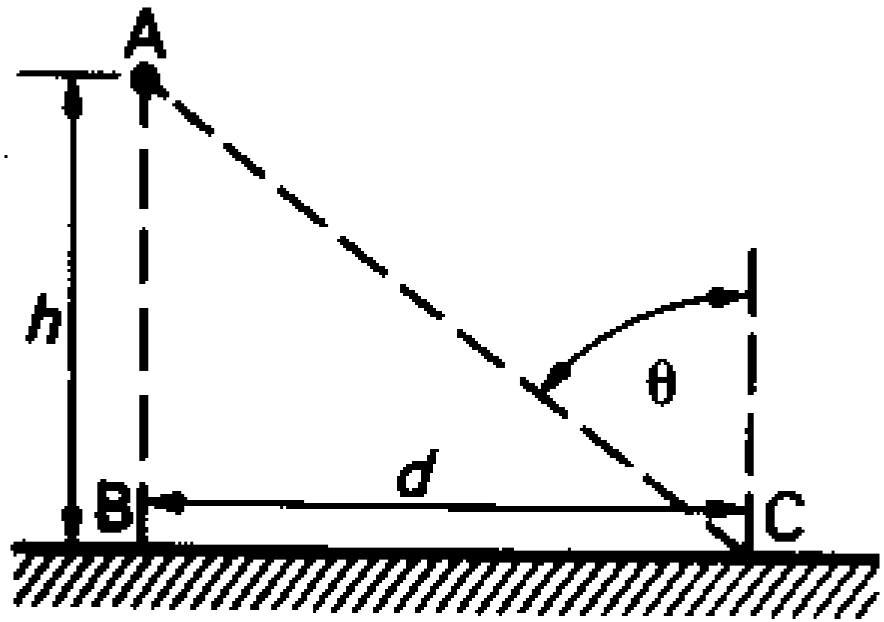
- if the surface at *A*, illuminated from a point source *S*
  - is tilted so that the angle of incidence of light is θ



- the illuminance E_A is

$$E_A = \frac{I}{d^2}\cos\theta$$

9.5 Illuminance on a surface



$$AC = \left(h^2 + d^2\right)^{\frac{1}{2}}$$

$$\cos\theta = \frac{h}{\left(h^2 + d^2\right)^{\frac{1}{2}}}$$

Inverse square law + cosine law of *E*

$$E_B = \frac{I_{AB}}{h^2}$$

$$E_C = \frac{I_{AC}\cos\theta}{AC^2} = I_{AC} \cdot \frac{h}{\left(h^2 + d^2\right)^{\frac{3}{2}}}$$

- Assume the luminous intensity is uniform in the lower hemisphere

$$I_{AB} = I_{AC} = I$$

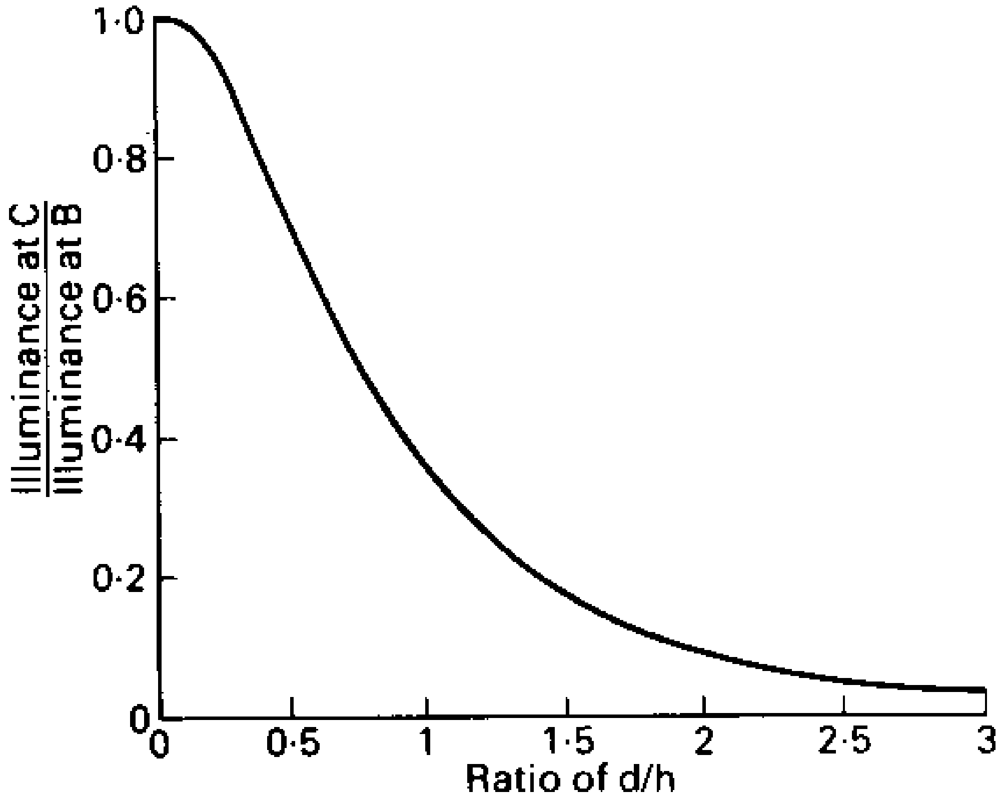
$$I = E_B \cdot h^2$$

$$I = E_C \cdot \frac{\left(h^2 + d^2\right)^{\frac{3}{2}}}{h}$$

$$E_C = E_B \cdot \frac{h^3}{\left(h^2 + d^2\right)^{\frac{3}{2}}} = E_B \left[\frac{h}{\left(h^2 + d^2\right)^{\frac{1}{2}}} \right]^3 = E_B \cos^3 \theta$$

$$E_C = E_B \cos^3 \theta$$

$$E_C = E_B \cdot \frac{h^3}{\left(h^2\left[1+\left\{\frac{d}{h}\right\}^2\right]\right)^{\frac{3}{2}}} = \frac{E_B}{\left[1+\left\{\frac{d}{h}\right\}^2\right]^{\frac{3}{2}}}$$



- *E* falls dramatically away from points directly over the source
- improvement:
  - distribute light at angle of 60-75° to vertical using a luminaire

9.6 Factors of illumination

Utilisation factor (U.F.)

- Let
  - A = area of surface to be illuminated
  - E = average illuminance on surface

- $\therefore$ useful luminous flux = EA

$$U.F. = \frac{\text{useful} \quad \text{lumens}}{\text{total} \quad \text{lumens} \quad \text{emitted} \quad \text{by} \quad \text{lamps}}$$

$$U.F = \frac{EA}{\text{total} \quad \text{lumens} \quad \text{from} \quad \text{lamps}}$$

- influence on U.F.
  - reflection factor (r_{ceilng}, r_{wall})
  - room index
- tables of U.F.s for various
  - {shapes, luminaires, spacing/height ratio, ceiling colour}
    - are available, e.g.
      - open reflectors, U.F. = 0.4 - 0.8
      - pendant fittings, U.F. $\approx$ 0.1

Maintenance factor (M.F.)

$$M.F. = \frac{\text{Illuminance at given time}}{\text{Illuminance with lamps NEW and fittings CLEAN}}$$

- takes account of depreciation in useful luminous flux resulting from
    - accumulation of dust on bulbs and luminaires
    - fall in output of lamp with time

$$total \quad lumens \quad from \quad lamps \quad when \quad new = \frac{EA}{U.F. \times M.F.}$$

9.7 Requirements of lighting

Minimum illuminance at working plane

- E_{min} at any working plane ≥ 70% E_{max}
- guidance for spacing of luminaires
    - 1 - 1.5 times their height above working plane, e.g.
        - factory E_{min} ≥ 400 lx
        - fine working assembly E_{min} = 1 – 2 klx

Provision of shadow (or shading)

- to give objects their 3-dimensional characteristics
- to make shapes recognisable

Task / Background / Surrounding ratio

- principal object: brightest
- background : less bright
- surrounding: least bright
- recommended illumination ratio:
  - 10 : 3 : 1

9.8 Electric lighting

- luminous efficacy
  - the amount of luminous flux produced per unit input power to the lighting apparatus

$$= \frac{\text{total luminous flux produced}}{\text{input power}} \quad [\text{lm/W}]$$

  - e.g.
    - 100-W gas-filled incandescent lamp: 12-20 lm/W
    - 400-W mercury lamp with yttrium coating: 50 lm/W
    - 1-kW mercury iodide lamp: 85 lm/W
    - 400-W sodium lamp: 100 lm/W
    - warm white fluorescent lamp; 60 lm/W

Types of electric lighting

- Incandescent lamps
  - vacuum
  - gas-filled

Banned: EU 2012; Zambia 2015

- Discharge / fluorescent lamps
  - low-pressure and high-pressure sodium vapour
  - low-pressure fluorescent mercury vapour
  - linear tube / bent tube / circline tube / CFL fluorescent
- LED lamps
  - bulb / tube

Examples

1) A 500-cd lamp emits light uniformly in all directions and is suspended 5 m above the centre of a working plane which is 7 m square. Find the illuminance below the lamp and also at each corner of the square.

2) A lamp having a luminous intensity of 500 lumens per steradian is hung 4 m above a circular area of 6 m diameter. Calculate the illuminance at
   a. centre of area
   b. periphery of the area
   c. average illuminance on the area

3) A drawing hall 30 m x 15 m with a ceiling height of 5 m is provided with general illumination of 120 lx. Taking U.F. = 0.5, M.F. = 0.71, determine the number of fluorescent tubes required, their spacing, mounting height and total wattage. The luminous efficacy of a fluorescent tube is 40 lm/W for an 80-W tube.

- End of Lecture 9 -