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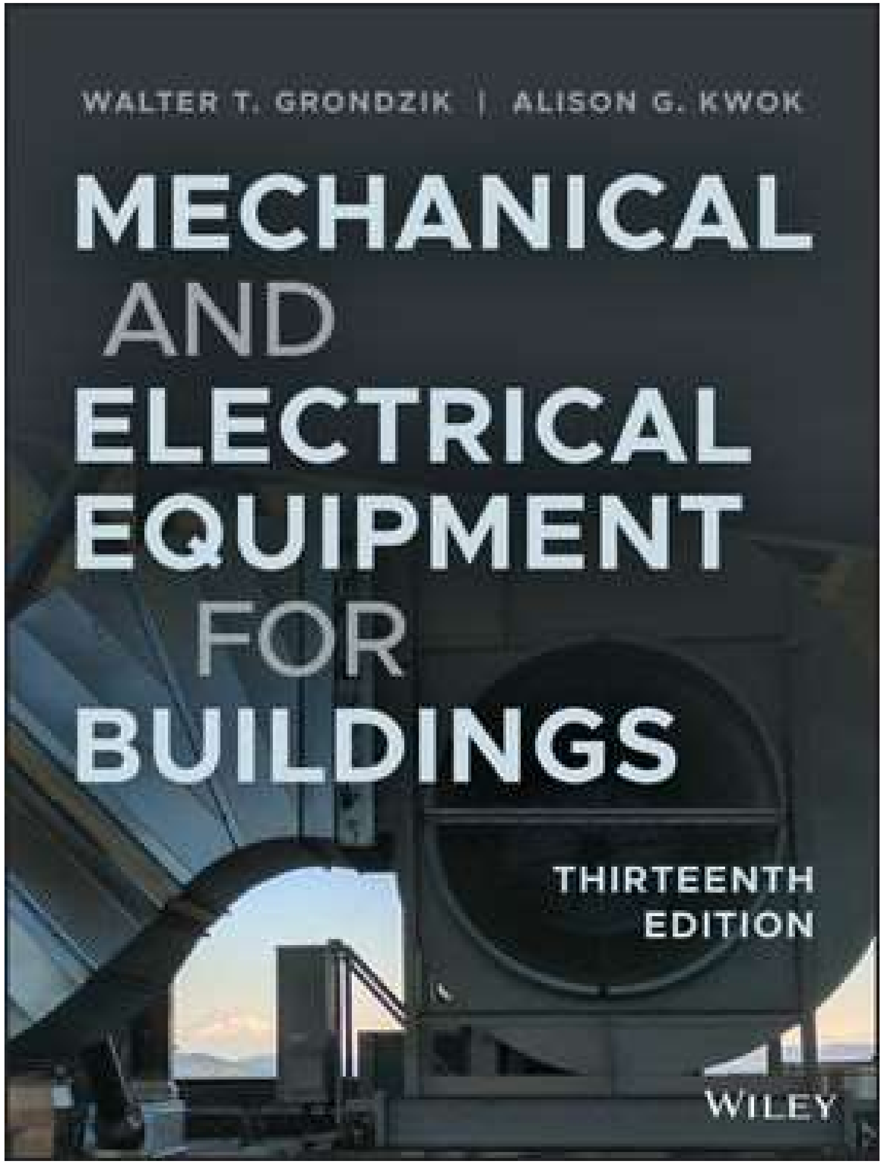
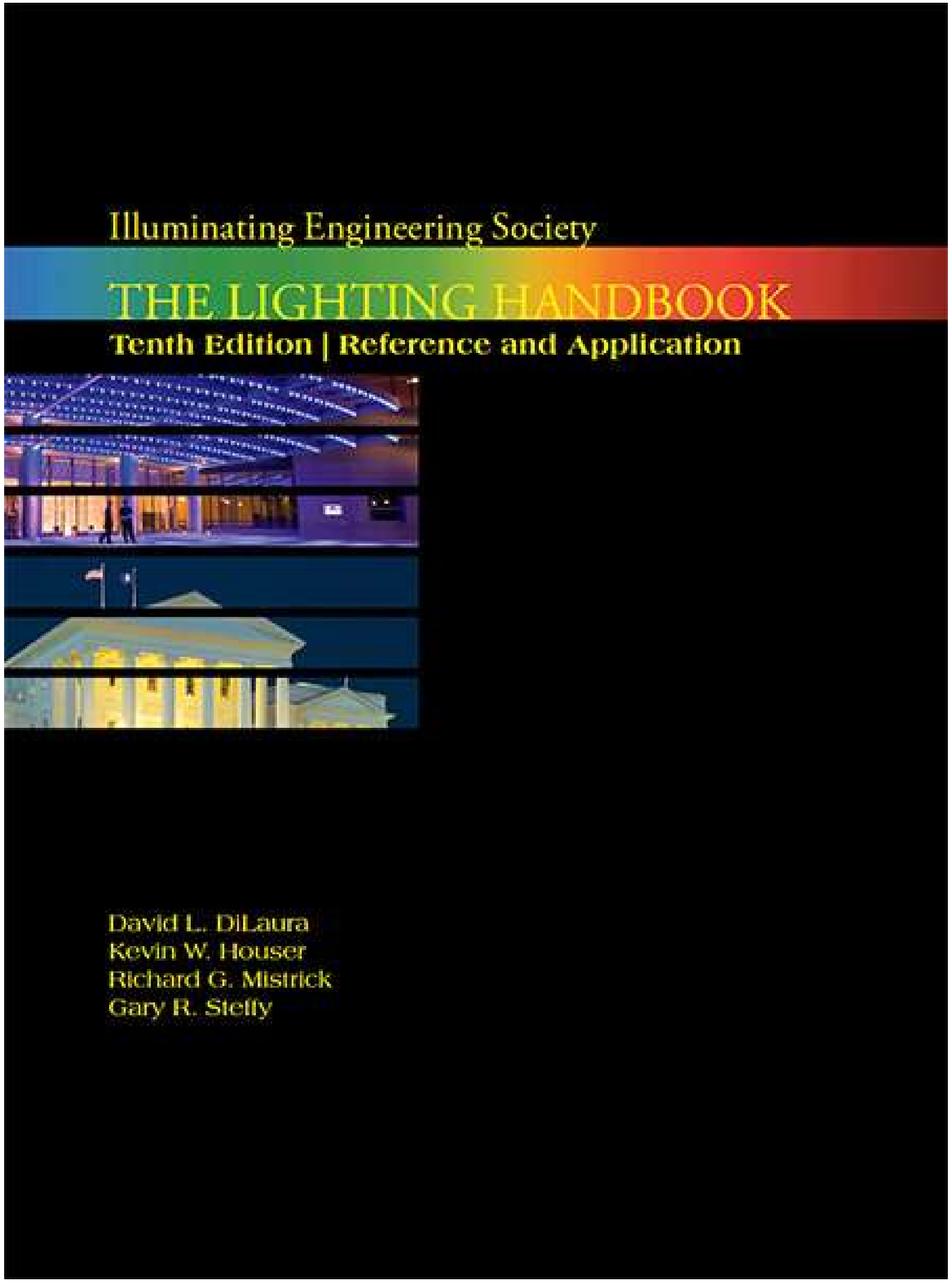


Reference


Illuminating Engineering Society
THE LIGHTING HANDBOOK
Tenth Edition | Reference and Application
David L. DiLaura
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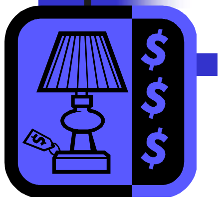
Ch.6 Light, vision, and visual comfort

Introductory remarks

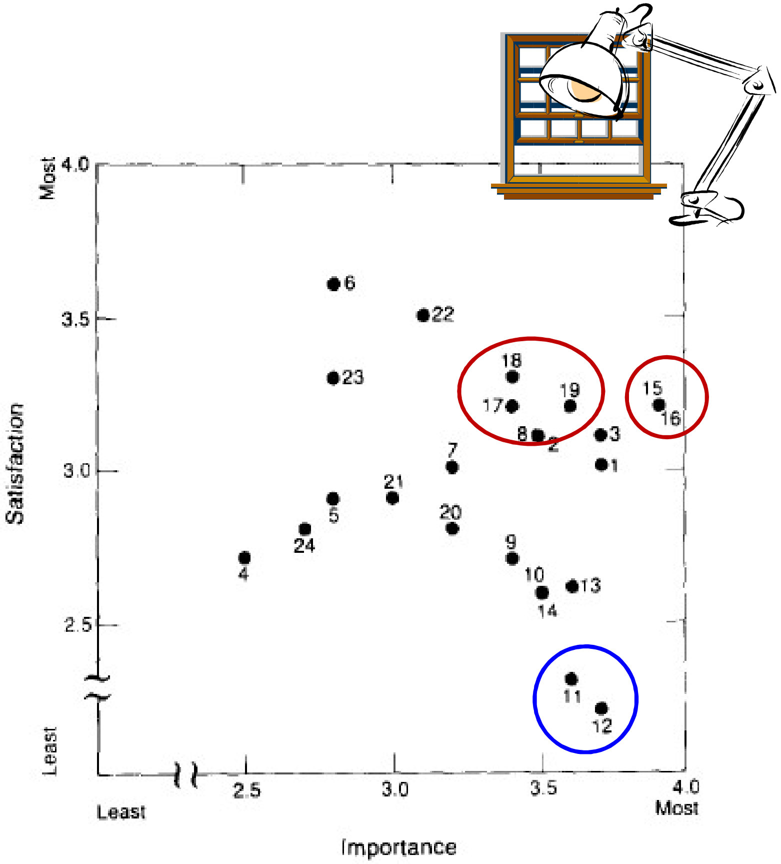
- Architectural lighting (art) vs. utilitarian design (engineering): lighting as art and science
- Artificial (electric) lighting vs. daylighting
- IESNA (Illuminating Engineering Society of North America), www.iesna.org: research, standardization, publication → lighting design on a stable scientific basis as well as with cognizance of artistic aspects
- Artificial lighting accounts for 20-35% of building energy and 30-50% of cooling energy.

Why lighting?



- Energy: Lighting accounts for significant portion of building energy as well as cooling load.

- Visual comfort: Lighting is considered to be one of the most important features of the work environment that affect work satisfaction



1. Amount of space
2. Furniture arrangement
3. Chair comfort
4. Privacy of work area
5. View from window
6. Control of outside sound
7. Control of inside sound
8. Control of lighting glare
9. Private phone conversations
10. Private office conversations
11. Control of summer temperatures
12. Control of winter temperatures
13. Control of summer ventilation
14. Control of winter ventilation
15. Light for reading
16. Light for writing
17. Light for computing
18. Light for filing
19. Light for other tasks
20. Control of work surface lighting
21. Control of ceiling lighting
22. Control of venetian blinds
23. Control of drapes
24. Control of other lights

Ne'eman E, Sweitzer G, Vine E. Office worker response to lighting and daylighting issues in workspace environments: a pilot survey. Energy and Buildings 1984;6(22):159–71

To consider list (1): quantitative

- Daylight: its introduction and integration with electric light
- The interrelationship between the energy aspects of electric lighting and daylighting, heating and cooling
- The effect of lighting on interior space arrangement and vice versa
- The characteristics, means of generation, and utilization techniques of electric lighting
- Visual needs of specific occupants and of specific tasks
- The effects of brightness patterns on visual acuity (시력, acuteness or clearness of visual perception)

To consider list (2): qualitative

- The location, interrelationship, and psychological effects of light and shadow – brightness pattern
- The use of color, both of light and of surfaces, and the effect of illuminant source on object color and sometimes the reverse.
- The artistic effects possible with patterns of light and shadow including the changes inherent in daylighting, and so on
- Physiological and psychological effects of the lighting design, particularly in spaces occupied for extended periods

Renaissance hotel, Atlanta airport (2009)

Luxor hotel, Las Vegas NV (2007)

A restaurant in Vaxjo Sweden (2008)

Objectives

- To provide the principles that will help lighting designers to make their decisions correctly
- To make them proficient in the use of lighting as a design tool
- To introduce computer-based lighting theories and simulation tools

Physics of light

Light as radiant energy

- Light: wave view, particle view, duality view
- The IESNA defines light as visually evaluated radiant energy, or more simply, a form of energy that permits us to see.
- If a light is considered as a wave, it has a frequency and a wavelength ($v = f\lambda$)

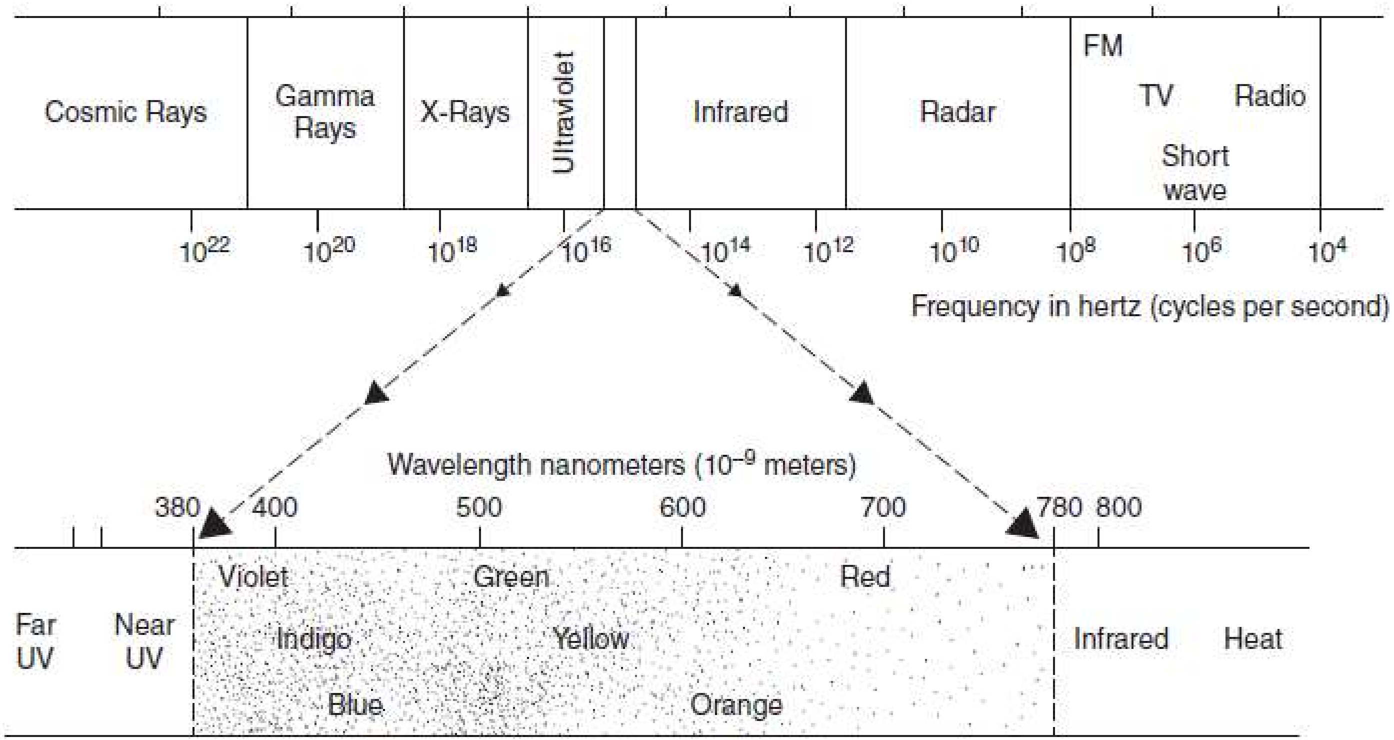
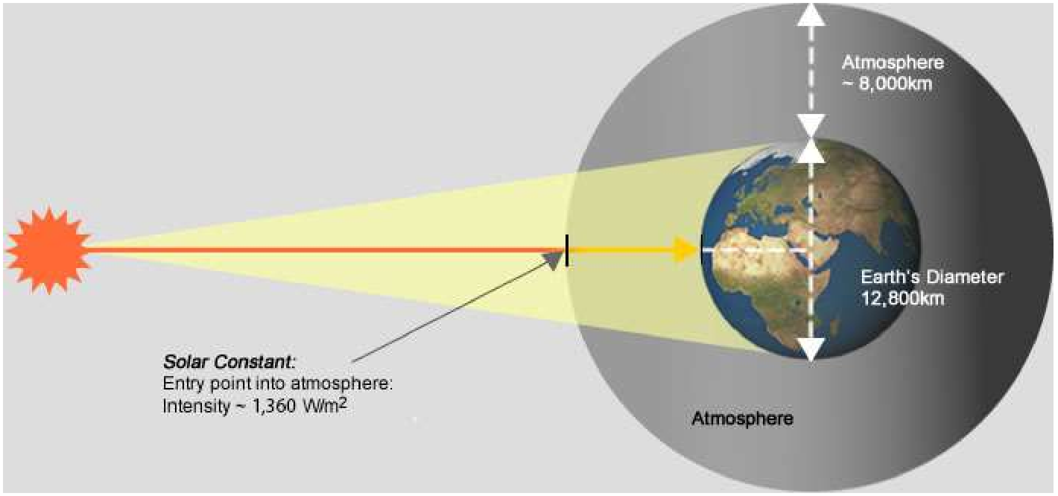


Fig. 6.1 The electromagnetic spectrum.

Solar constant of 1367 W/m^2

		Radiation in the visible portion of the spectrum	
Wavelength range (μm)	0-0.38	0.38-0.78	0.78-∞
Fraction in range	0.064	0.480	0.456
Energy in range (W/m^2)	87	656	623



1. Duffie, J.A. and Beckman, W.A. (1991), Solar engineering of thermal process, John Wiley & Sons, Inc.
2. Image source: http://www.greenrhinoenergy.com/solar/radiation/extraterrestrial.php

Luminous intensity (I)

- = 광도 (光度)
- Unit: candlepower, cp, candela, cd, 칸델라
- 1 cd = a luminous intensity of a wax candle
- An ordinary wax candle has a horizontal luminous intensity of approximately 1 candela, hence the name.
- It represents the force that generates the light that we see.
- It is analogous to pressure in a hydraulic system and voltage in an electric system.

Luminous flux (Φ), 광속, 光束

- Unit: lumen, lm, 루멘
- Definition: If we take 1-cd(candlepower) source that radiates light equally in all directions and surround it with a transparent sphere of 1 m (ft) radius (Fig. 6.2), then *by definition* the amount of luminous energy (flux) emanating from 1 m^2 (ft^2) of surface on the sphere is 1 lm.

•1 cd produces 4 π, or 12.57 lm.
•It is analogous to flow in hydraulic systems and current in electric systems.
•A measure of luminous power (*not* radiometric [복사에너지], *but* photometric [광도 측정의] → perceived by the human eye)

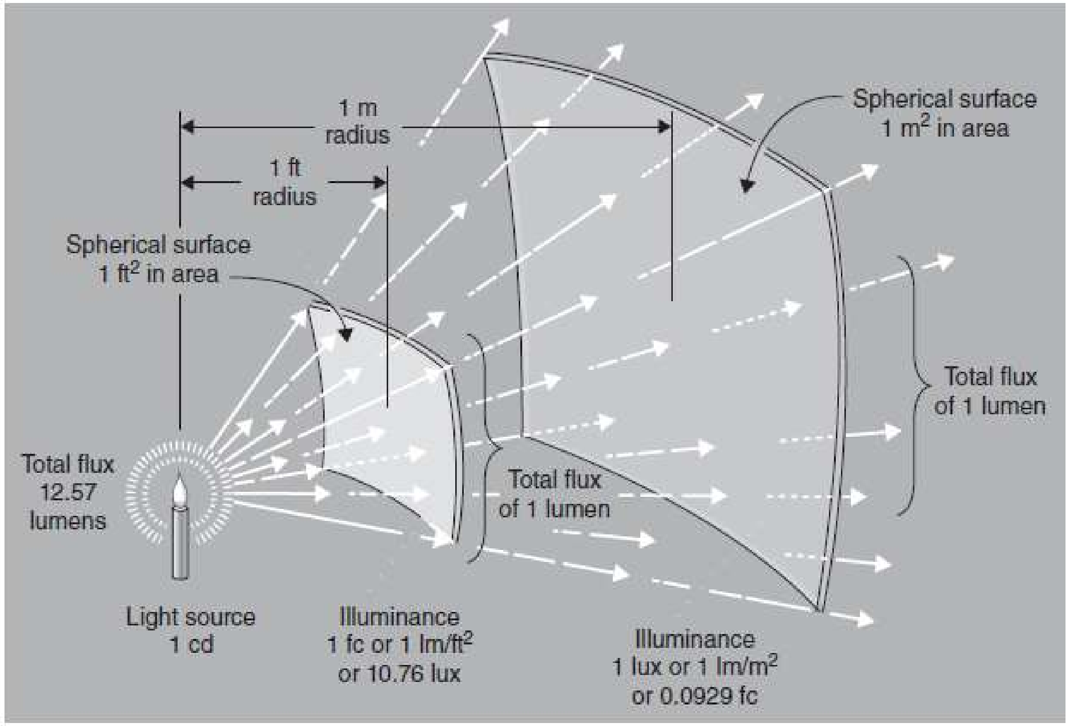


Fig. 6.2 *A source of 1-cd intensity produces 4π (12.57) lumens of light flux. Thus, each square foot (square meter) of spherical surface surrounding such a source receives 1 lumen of light flux. This quantity of light flux produces an illuminance of 1 fc (lux) on the spherical surface.*

Illuminance (E, 조도, 照度)

- meaning:
  - one lumen of luminous flux, uniformly incident on 1 m^2 (ft^2) of area, produces an illuminance of 1 lux (lx) [footcandle, fc].
  - A measure of the density of light, expressed in terms of lumens per unit area
- Unit:
  - Lux (lumens/m^2), footcandle (lumens/ft^2)
  - 10.764 lux=1 fc, 10 lx = 1 fc (8% error)
    - 1ft = 0.3048 meter, 1meter = 3.28 ft, 1m^2=10.76ft^2

Illuminance (E)

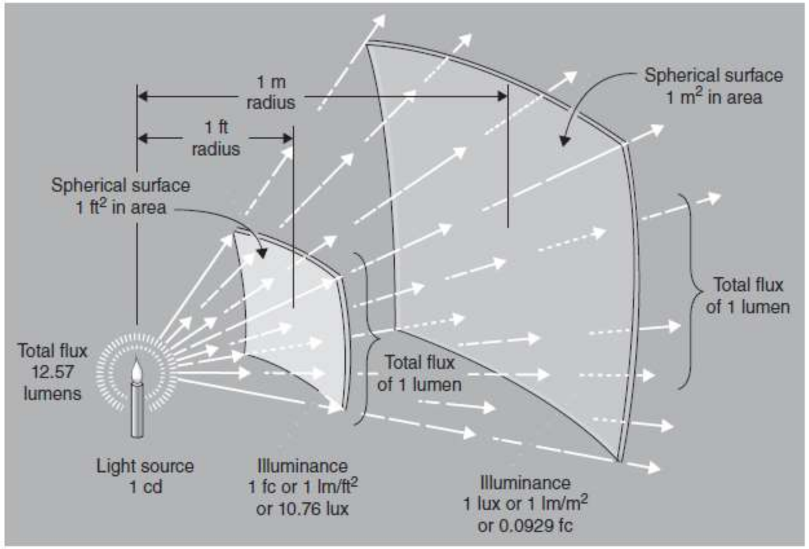
- Since the surface area of a sphere is $4\pi r^2$, the total luminous flux emitted by the source is 4π lumen, and the illuminance on the inside of the sphere (Fig. 6.5) is

$$E = \frac{4\pi \text{ lumen}}{4\pi\ m^2} = 1 \text{ lux}$$

- This can be generalized to the inverse square law of illumination (ISL). 'r' (radius) can be understood as 'distance' from the source.

$$E = \frac{I}{r^2}$$

→ operational definition
(E is lumens/area, but this is cd/distance^2)



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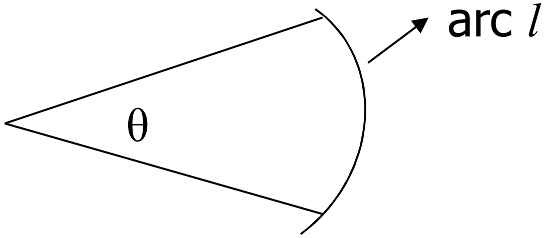
Example 6.1

- A 34W, 425 mA (milliampere), 48 in (122cm) fluorescent tube produces 3200 lm. What is the illuminance on the floor of 3m by 3m square room assuming 60% overall efficiency and uniform illumination?
  - Useful lumens: 3200*0.6 = 1920 lm
  - E (Lx) = 3200*0.6/(3*3) = 213.3 lx
  - 3m=9.84 ft, E (Fc) = 1920/(9.84*9.84) = 19.8fc
    - By approximation: 21.3 fc

Solid angle

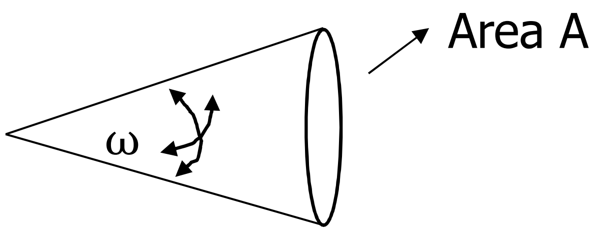
- Plane angle specifies the extent of separation between two intersecting lines of indeterminate length.
- Solid angle specifies the extent of a cone of indeterminate length.
- Solid angle is used to define spatial extent for establishing spatial luminous flux densities.
- Measured in steradian.



$$l = r\theta$$

$$\theta = \frac{l}{r}$$

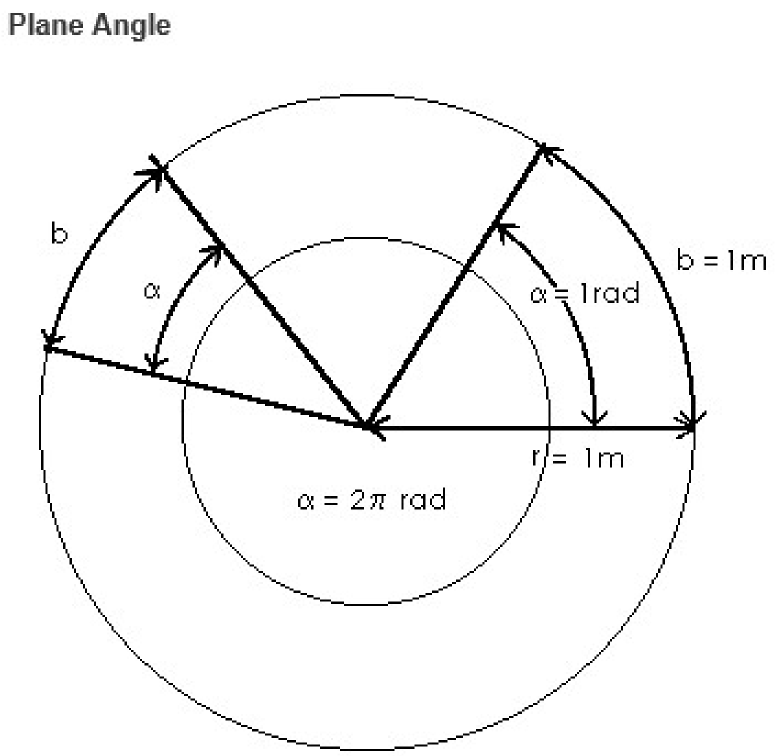
l = arc of circle
Angle for a full circle → 2π radian

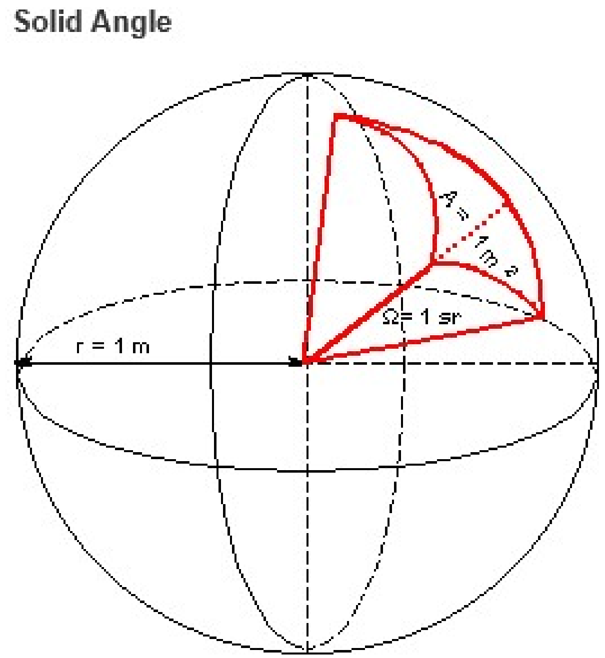


$$A = \omega r^2$$

$$\omega = \frac{A}{r^2}$$

A = cap of sphere
Solid angle for an entire sphere → 4π steradian





- The biggest plane angle for a full circle ($2\pi r$) is 2π (radian).
- The biggest solid angle for a spherical surface ($4\pi r^2$) is 4π (steradian, sr).

Image source: https://dialux4.support-en.dial.de/support/solutions/articles/9000078326-solid-angle-

Example of solid angle

- Though three discs have different sizes and orientations, they have same spatial extent (solid angle) with respect to the apex of the cone.

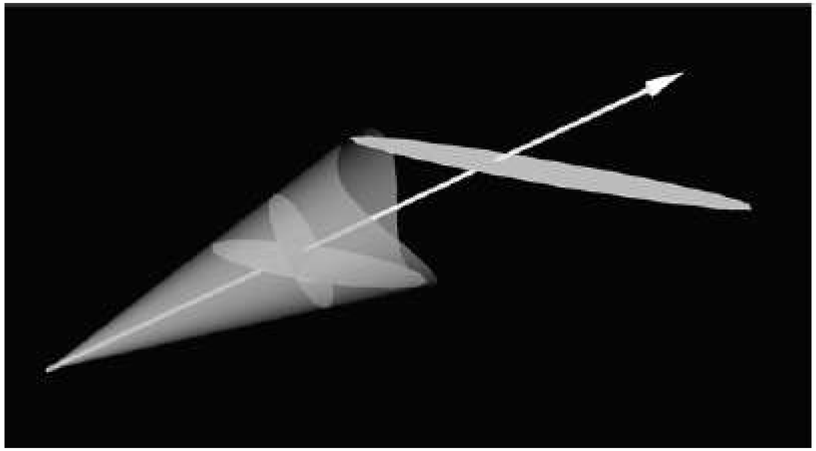


Image source: IESNA handbook 10th Ed.

Luminous intensity and solid angle

- Luminous intensity specifies the light emitting power of a point source in a particular direction.
- Defined as the density of luminous flux in space in that direction.
- Unit: candela, cd
- $\mathrm{I} = \frac{\Phi}{\omega}$ (lumen/steradian)
- Luminous intensity is invariant with distance from the source.

Operational definition (조작적 정의)

- articulation of operationalization to characterize a phenomenon of interest.
  - 물리량이 서로 일치하지 않는 경우
  - 다루고자 하는 개념을 경험적으로 측정할 수 장점
- $\mathrm{I} = \frac{\Phi}{\omega}$ (lumen/steradian)
- 'Operational' definition of luminous intensity (IESNA handbook) can be used as follows:
  - $E = \frac{I}{r^2}$
  - E: lumen/area, intensity/(distance)^2
  - I: lumen/steradian

Source: https://ko.wikipedia.org/wiki/%EC%A1%B0%EC%9E%91%EC%A0%81_%EC%A0%95%EC%9D%98
IESNA handbook 10th Ed.

Luminance (L)

- Brightness: subjective impression or apparent brightness and dependent on luminance and the state of adaptation of the eye, the physiological sensation
  - Brightness vs. lightness
    - Brightness: self-luminous surfaces (Sun)
    - Lightness: objects deriving their luminance from reflection (Moon)

- Luminance:
  - The measurable, reproducible state of object luminosity
  - Defined as luminous intensity (cd) per unit of apparent (projected) area (m^2) of a primary (emitting) or secondary (reflecting) light source.
  - Note that the projected area is the actual area of the lamp face (light source's face).
  - A measure of the light emitting power of a surface, in a particular direction, per unit apparent area.
  - It does not depend on source-to-receiver distance.
  - Unit: cd/m^2, 스틸브(Stilb, sb), 니트(nit, nt), footlambert(I-P)
    - $1(sb) = 1cd/cm^2$, $1(nt) = 1cd/m^2$

$$L = \frac{I}{A} \quad \begin{array}{l}\text{(Intensity)} \\ \text{(projected area)}\end{array} \qquad \text{vs.} \qquad E = \frac{I}{r^2}$$

Exitance

- 광속발산도
- Total luminous flux density leaving (exiting) a surface, irrespective of directivity or viewer position
- Unit: lm/m^2
- If a surface 1 meter square emits 1 lumen, its luminous exitance is 1 lm/m^2
- For a reflecting surface: $\mathrm{M} = \rho E$
- For a transmitting surface: $\mathrm{M} = \tau E$

Relationship and meaning

- Intensity (I): cd, lumen/sr
- Flux (Φ): lumen (lm)
- Luminance (L): cd/m^2, lumen/(sr.m^2)
- Illuminance (E): what comes to a surface, lm/m^2
- Exitance (M): what leaves a surface, lm/m^2
  - Illuminance: 면(面)에 도달하는 광속의 밀도
  - Exitance: 면(面)을 떠나는 광속의 밀도

- Illuminance is with regard to the flux incident on the surface.
- It is luminance that we see, not illuminance.

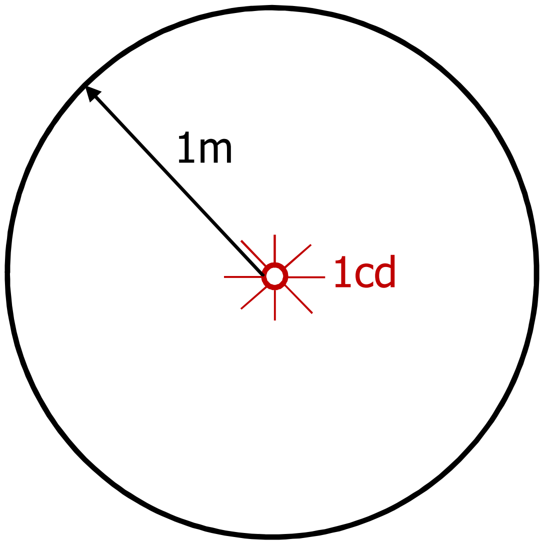
Lambertian surface

- Lambertian surface: a perfect diffuse surface, whether by emitting light diffusely or reflecting light diffusely.
- Although very few surfaces are truly Lambertian, but many are approximately so.
- $L=M/\pi = \rho E/\pi$ 적용 (luminance ← exitance approximation)

TABLE 6.1 Common Lighting Units and Conversion Factors

Unit	Multiply	By	To Obtain
Illuminance (*E*)	Lux	0.0929	Footcandle
	Footcandle	10.764	Lux
Luminance (*L*)	cd/m^2	0.2919	Footlambert
	cd/cm^2	10,000	cd/m^2
	$cd/in.^2$	1,550	cd/m^2
	cd/ft^2	10.76	cd/m^2
	millilambert	3.183	cd/m^2
	Footlambert	3.4263	cd/m^2
Intensity (*I*)	Candela	1.0	Candlepower

Example of perfect diffusion



- The sphere (right) is made of translucent glass or plastic and that it transmits 80% of the luminous flux it receives (reflecting none back to the inside surface and absorbing the remaining 20%).
- $0.8 \times 4\pi = 3.2\pi$ (lm) leave the sphere.
  - The sphere's surface area is 4π (m^2)
- The density of the luminous flux leaving the surface (M) is (3.2π lm)/(4π m^2) = 0.8 (lm/m^2)
- What is the sphere luminance?
  - What is seen is no longer a luminous sphere, but a luminous circular plane, much as the full moon seen as a flat luminous disc as though it has an intensity of 0.8 cd.
  - Its projected area is π m^2
  - Luminance = $0.8/\pi$ (cd/m^2)
- $L=M/\pi$ because the sphere is perfectly diffusing.

Find the luminance of a reflected inner surface with ρ=0.5?

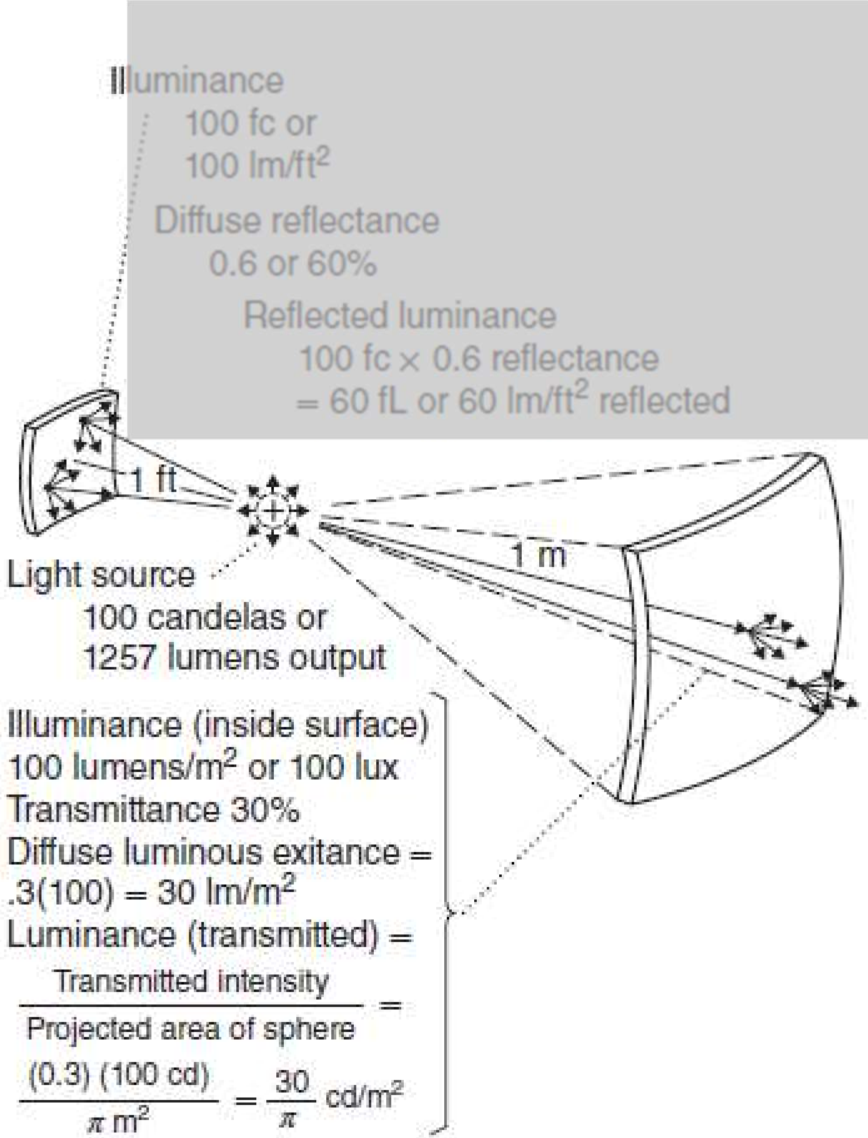


Fig. 6.4 Luminance may be the result of light that is either reflected or transmitted. In the former case, it is calculated as the product of the incident lumens and the reflectance; in the latter case, it is calculated as the transmitted intensity divided by the projected area.