

BLDG 366

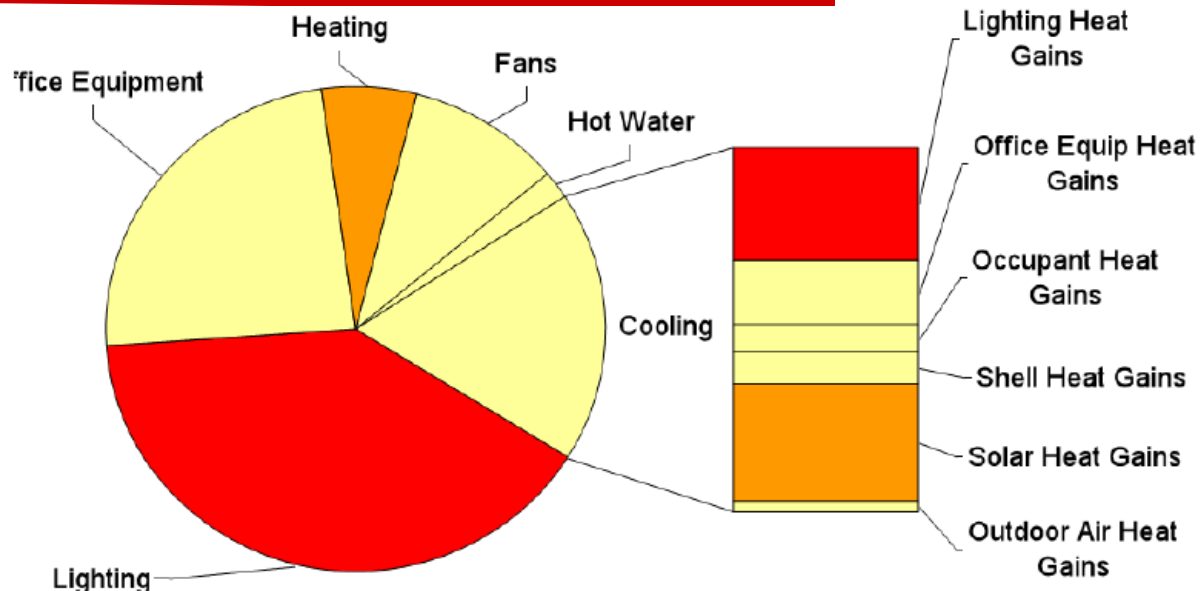
Acoustics and Lighting

Week 9: Introduction to lighting

March 4th, 2016

Instructor: Dr. Hua Ge P. Eng.

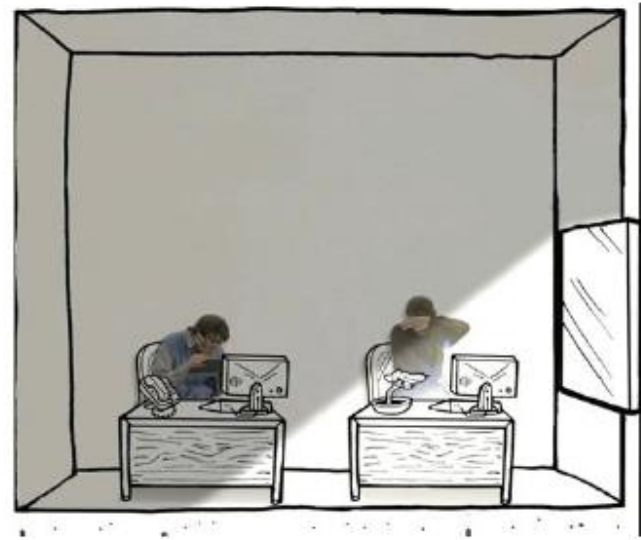
Introduction



- Electric lighting accounts for 30-50% of a building's annual energy cost
- Typically 50% or more of the total electricity consumption
- Contributes to cooling load up to 30%

Introduction

- Health & productivity
 - Daylighting
 - Visual comfort
 - Color, light level, contrast; glare
 - Color temperatures: warm & cool
 - Ultraviolet (UV) radiation disinfection

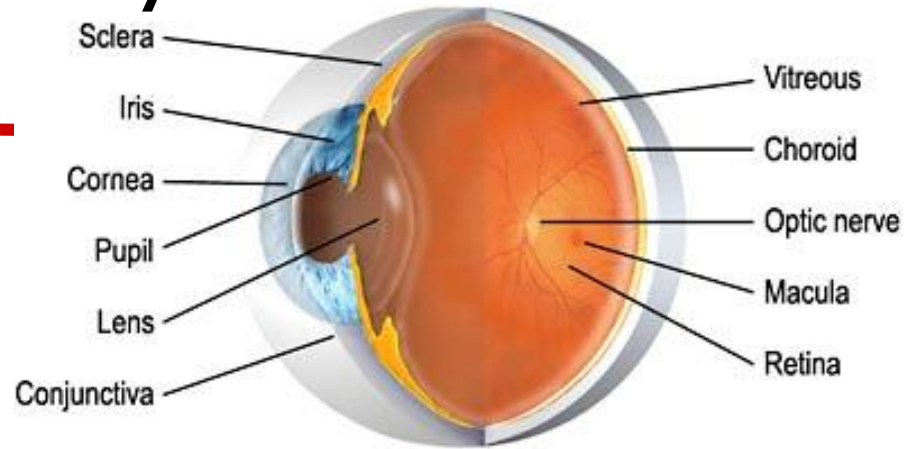


NREL RSF building

Outline

- Human eye, visual perception, color
- Physics of light
- Lighting terminology
- Main reference books:
 - J. B. Murdonch. Illuminating engineering: from Edison's lamp to the LED. TK4175M872003. Ch. 1, 8, 9 12.
 - M. David Egan, Victor W. Olgay. **Architectural Lighting.** McGraw-Hill Science Engineering, 2002. TH 7703 E3297 2002

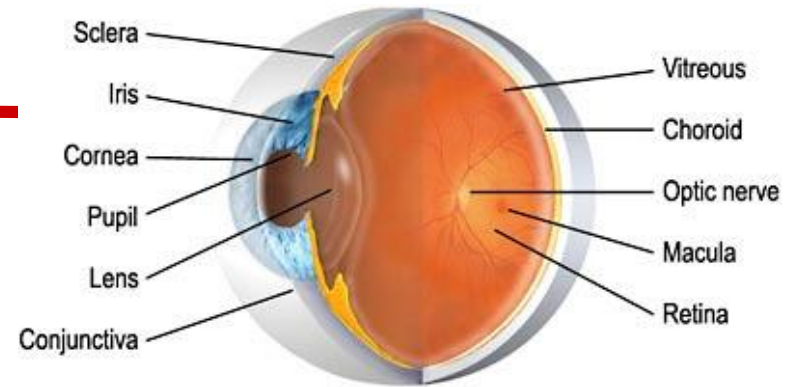
The human eye and its functions



Name	Characteristic	Function
Sclera	Outer layer, the white part of the eye	Shell that contains the component of the eye and maintain the shape of the eye
Choroid	Middle layer that contain blood vessel	
Retina	Contains rods, cones and rhodopsin, located at the back of the eye	Processes incoming images, distinguishes colour and sensitive to varying light levels
Cornea	Transparent outer membrane	Protects lens and allows light into the eye
Iris	Colored smooth muscle surrounding pupil	Dilates/contracts depending on ambient light levels
Pupil	Black circle in the centre of iris	The "hole" which light passes through

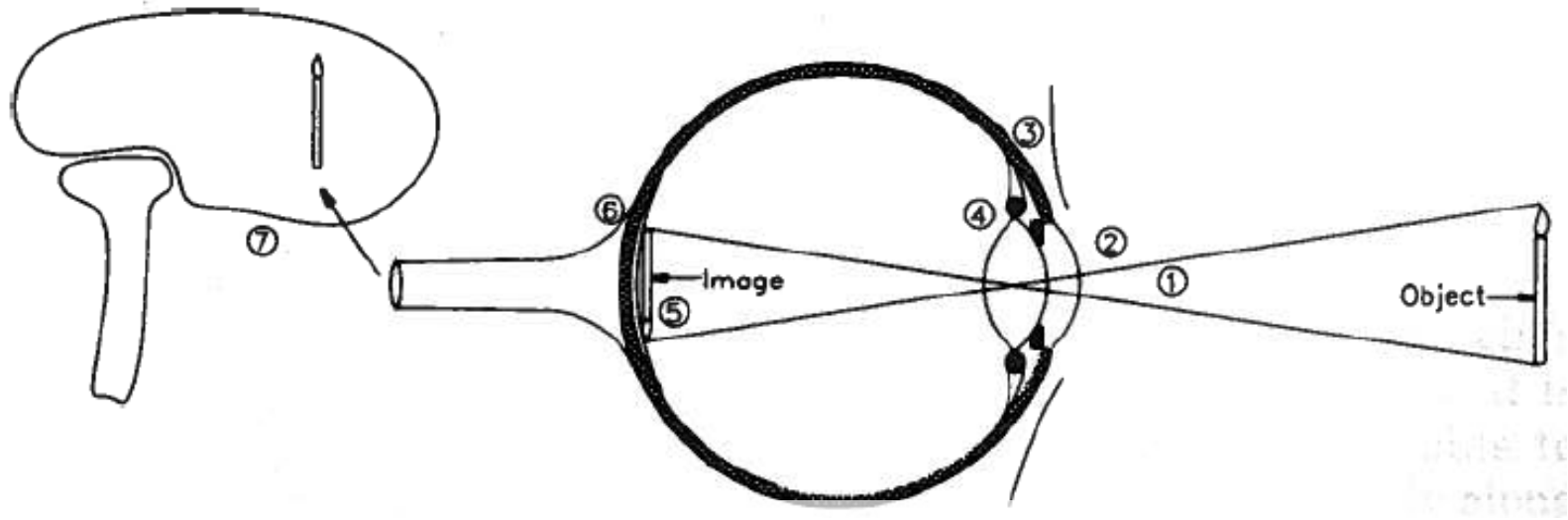
The human eye and its functions

Parts of the Eye (2)



Name	Characteristic	Function
Lens	Clear flexible tissue behind pupil	Focuses the incoming image on the retina
Ciliary Muscle	Ring-shaped muscle around the lens	Adjusts the shape of the lens focusing the image on the retina
Vitreous Humor	Clear, jelly-like substance	Maintains moisture in the eye
Optic Nerve	Nerve conveying info from eye to brain	Conduit through which data received by the eye is sent to the brain

Process of seeing (7 steps)

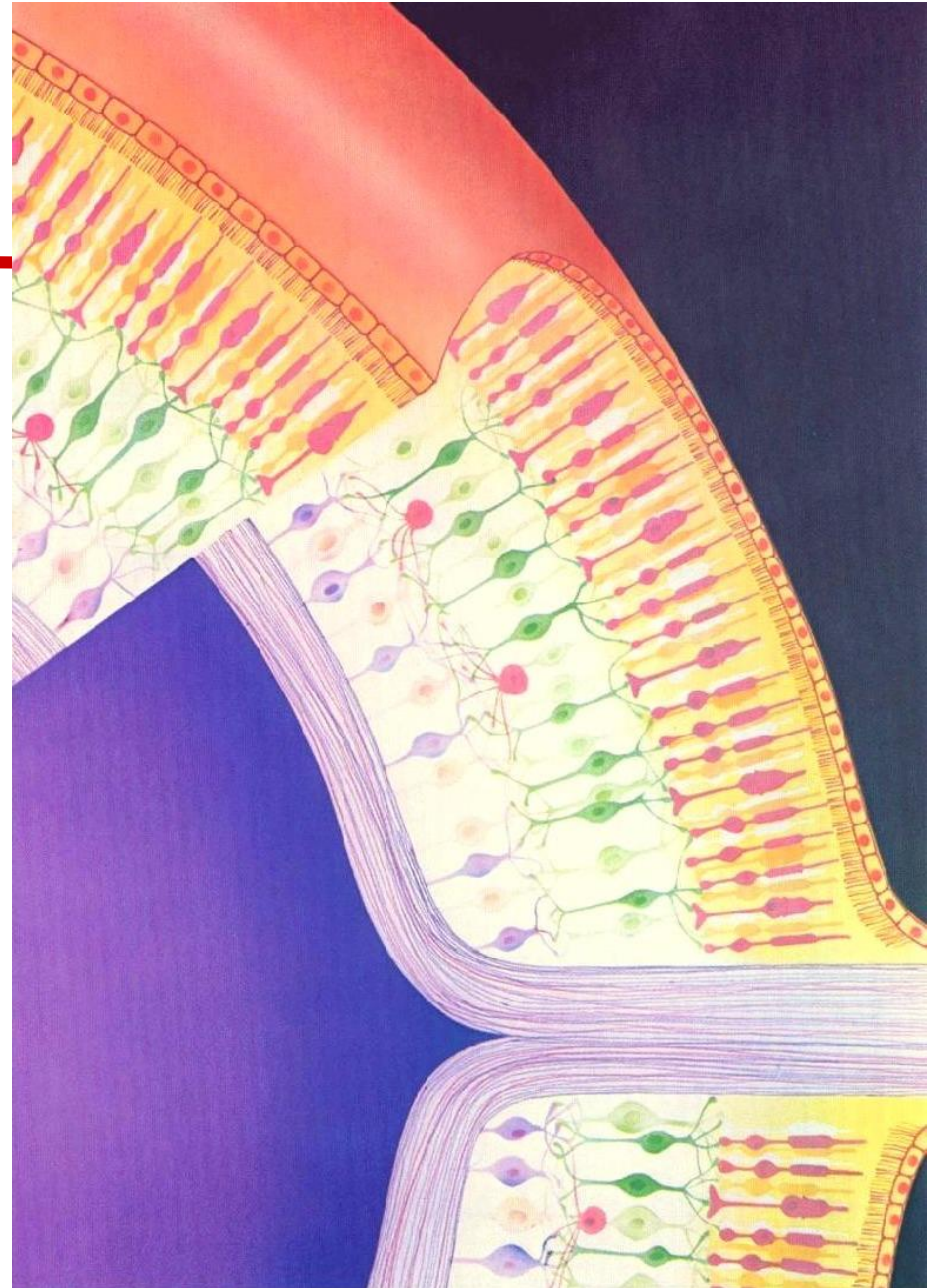


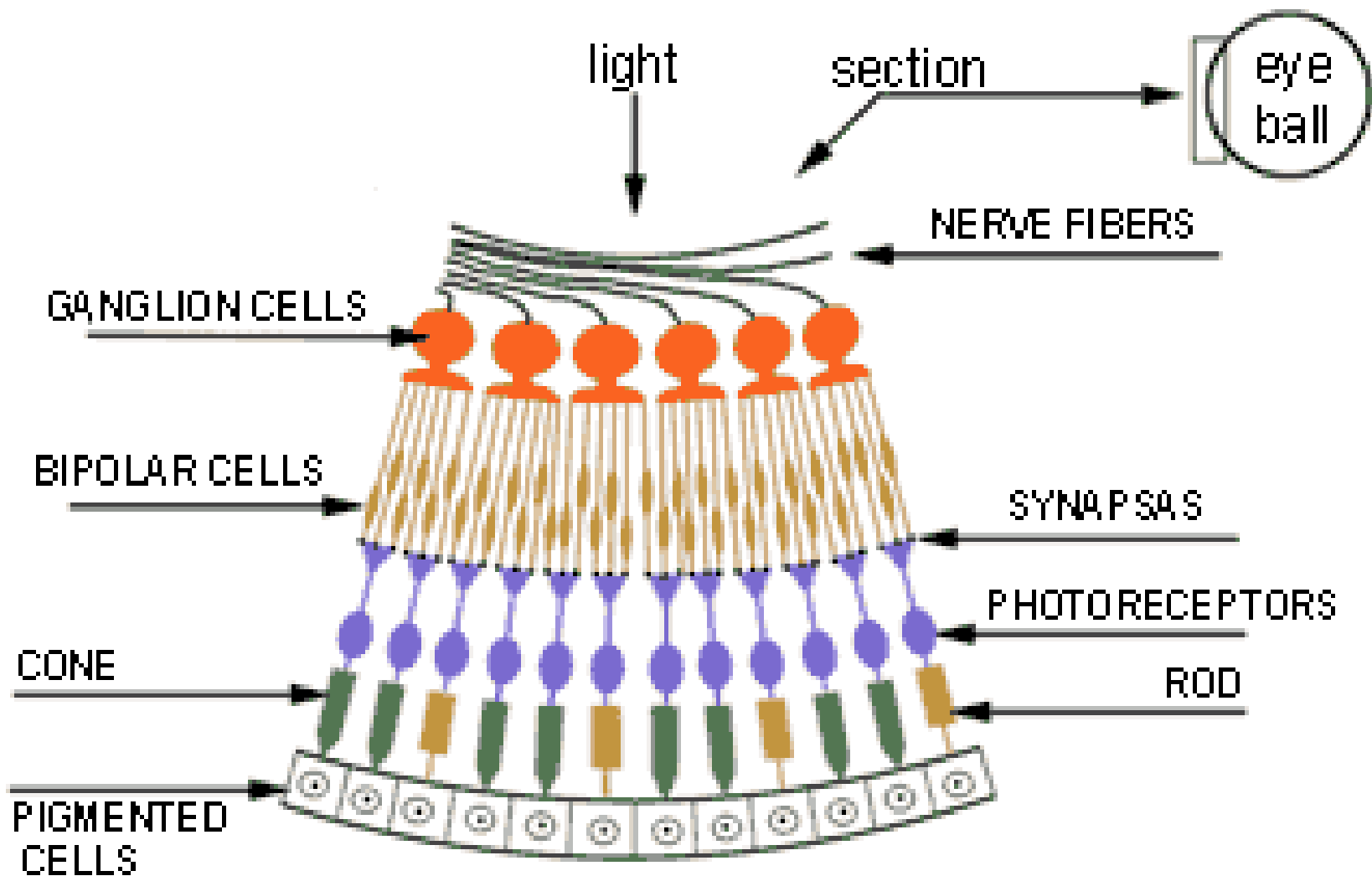
1. Reflected light approaches the eye passing through the cornea.
2. Eyelid adjusts to protect the eye.
3. Iris constricts/dilates the pupil depending on the amount of light.
4. Ciliary muscle adjusts the shape of the lens, focuses image on the retina.
5. Image appears inverted on the retina.
6. Brightness and colour is detected by rods and cones in the retina.
7. Image is converted into impulses and sent to the brain to be analyzed, interpreted and inverted.

Receivers

6 to 7 million cones, and 110 to 130 million rods, in the average human retina, but only some 800,000 fibres in the optic nerve.

The connections cannot, therefore, be simple, and the amount of information sent to the brain for interpretation is huge



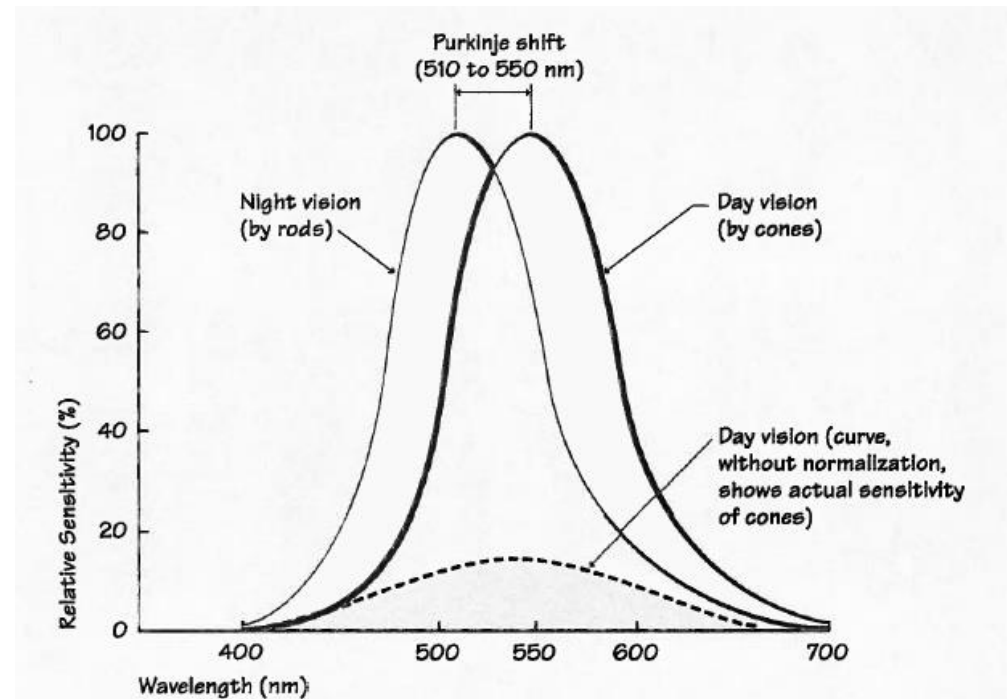


Cone: sense color and light intensity

Rod: light intensity only

Cones and rods

- Cones – used for colour identification and daytime vision, low luminance sensitivity, faster adaption time, 0.1s to 10min.
- Rods: night time vision, high luminance sensitivity, slower adaption time, several minutes to several hours



Physical characteristics of light

- Is a transverse, electromagnetic wave that can be seen by humans
- The speed of light depends upon the medium through which it travels
- The **speed of light** in a vacuum – constant 299,792,458 m/s
- The speed of light in a medium is always slower than the speed of light in a vacuum

Physical characteristics of light

- The ***amplitude*** of a light wave is related to its intensity.
- **Intensity** is the absolute measure of a light wave's power density.
- **Brightness** is the relative intensity as perceived by the average human eye.
- The wavelength of a light wave is inversely proportional to its frequency.
$$c = \lambda f$$

Physical characteristics of light

The *frequency* of a light wave is related to its color

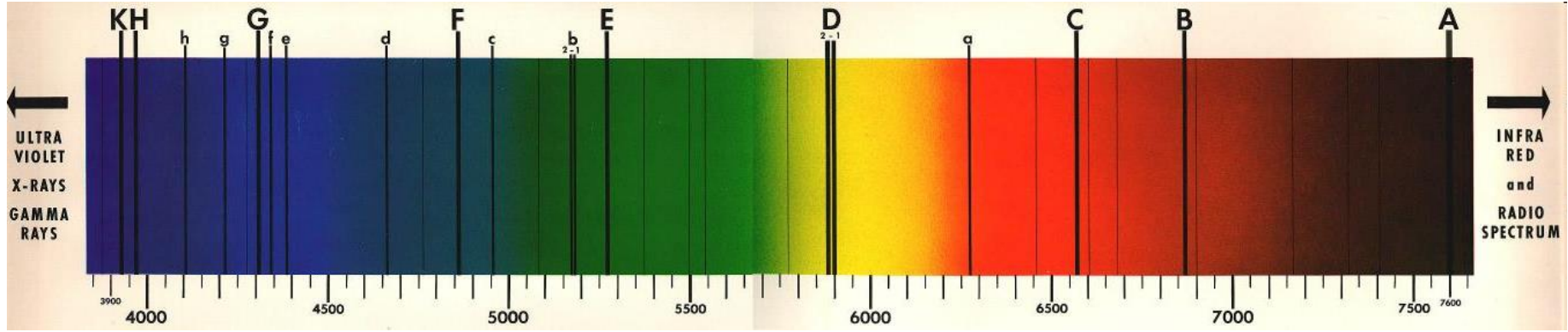
- **Monochromatic** light is described by only one frequency
- **Polychromatic** light is described by many different frequencies (Nearly every light source is polychromatic).
- A graph of relative intensity vs. frequency is called a **spectrum** (plural: **spectra**).
 - Although frequently associated with light, the term can be applied to any wave phenomena.

Physical characteristics of light

- A **continuous spectrum** is one in which every frequency is present within some range.
 - Blackbody radiators emit a continuous spectrum
- A **discrete spectrum** is one in which only a well defined set of isolated frequencies are present. (A discrete spectrum is a finite collection of monochromatic light waves.)
 - isolated atoms of chemical element only absorb or emit light at particular wavelengths
 - The excited electrons in a gas emit a discrete spectrum.

Physical characteristics of light

continuous spectrum



discrete spectrum

http://www.ess.su.nysb.edu/dpeterso/AST112/atomic spectra_web.jpg

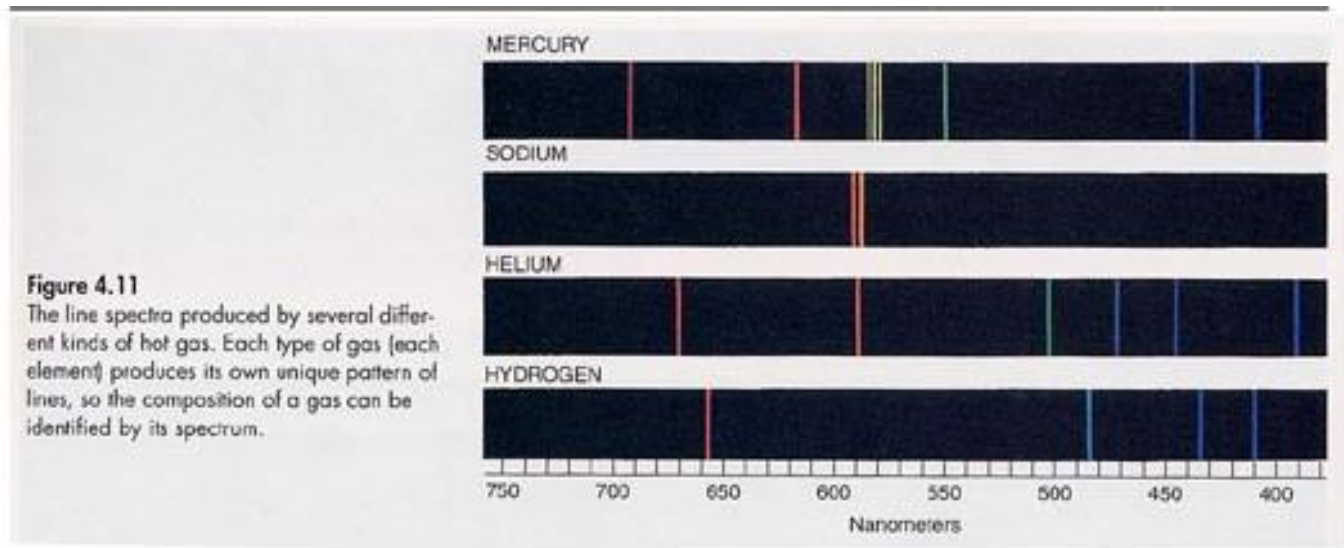
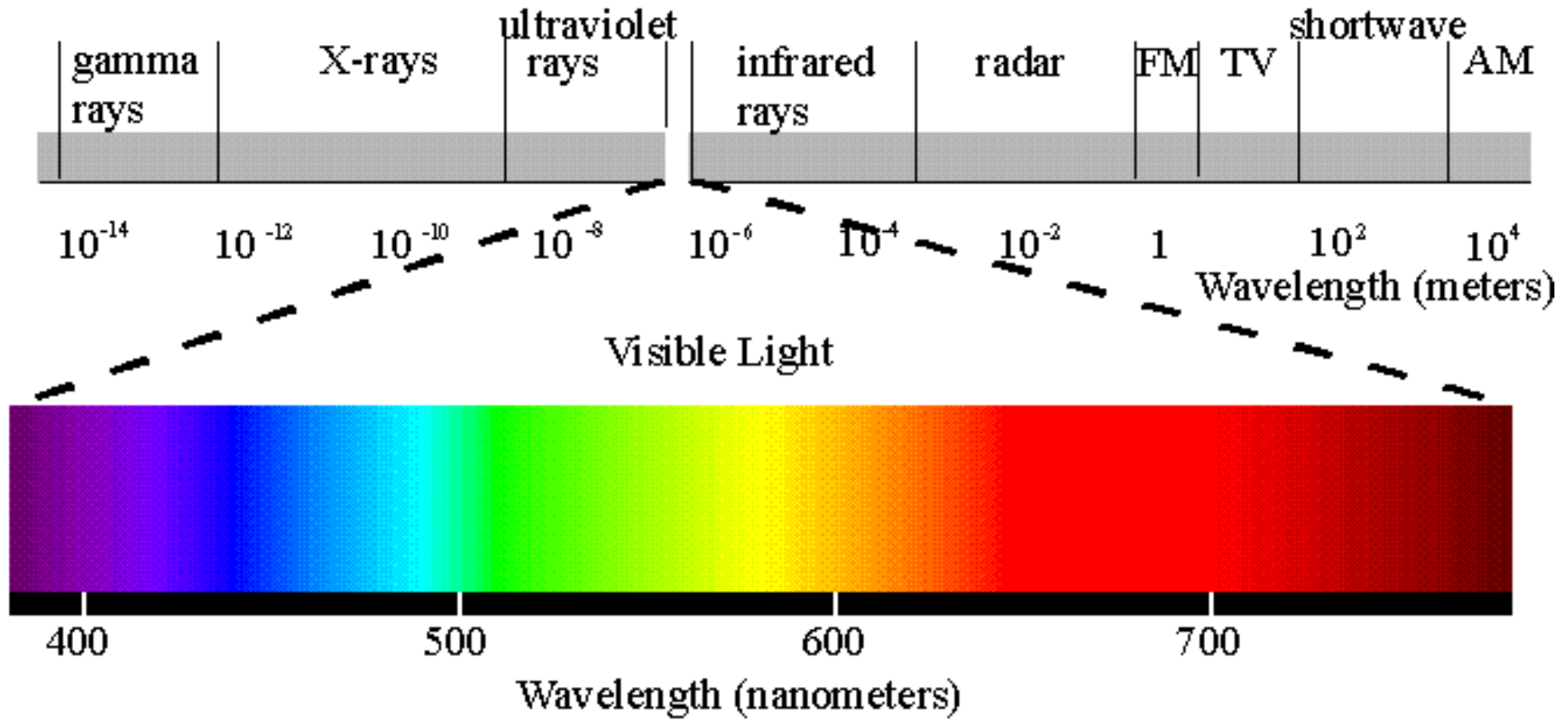


Figure 4.11
The line spectra produced by several different kinds of hot gas. Each type of gas (each element) produces its own unique pattern of lines, so the composition of a gas can be identified by its spectrum.

Physical characteristics of light (spectrum)

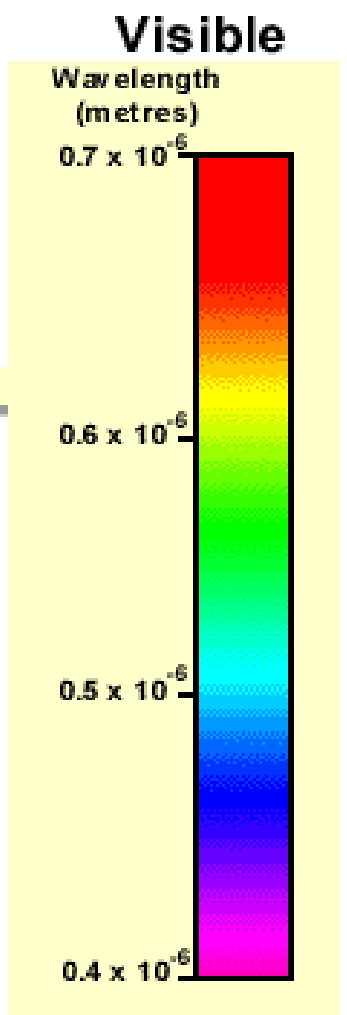
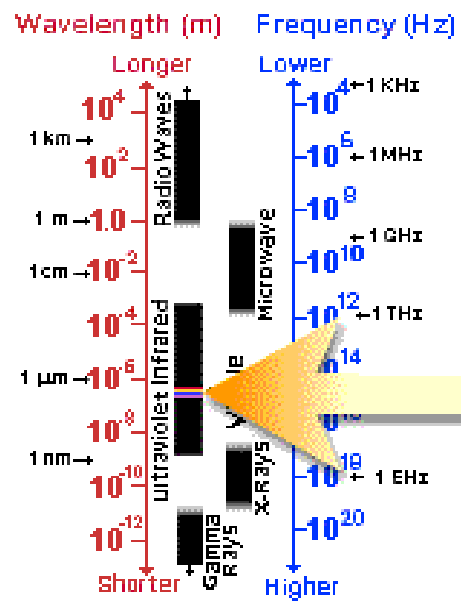
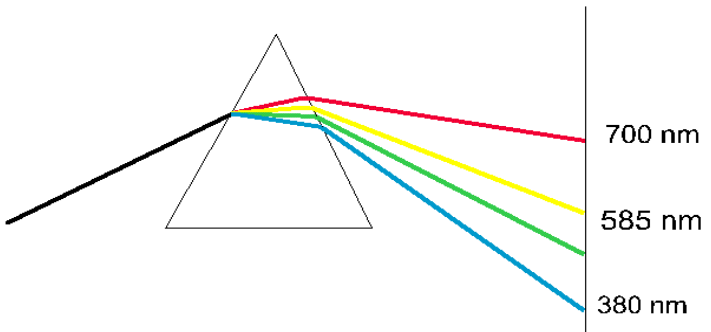


<http://hyperphysics.phy-astr.gsu.edu/hbase/sound/hearcon.html>

Physical characteristics of light (spectrum)

Visible light = 380nm – 780nm

- Below 380nm = Ultraviolet (UV)
- Above 780nm = Infrared (IR)



Color

Burnham, Haynes and Bartleson defined colour:

"Color is the attribute of visual experience that can be described as having quantitatively specifiable dimensions of hue, saturation, and brightness."

Hue:

Parameter of a colour that allows us to distinguish between colours, i.e. different wavelength bands

Saturation:

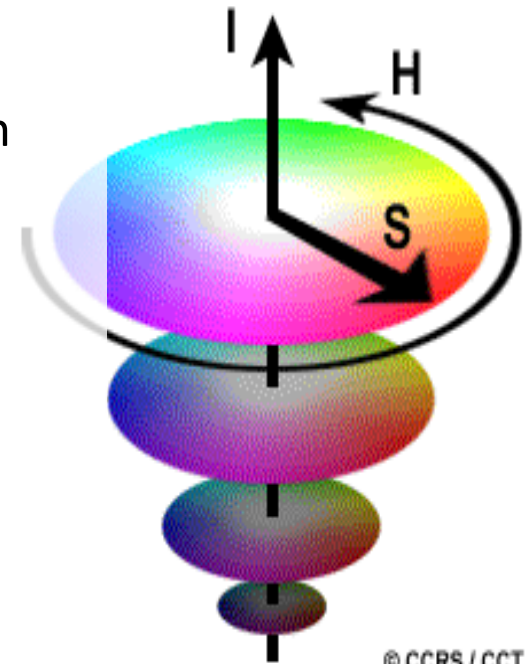
Perceived intensity or force of a certain colour.

Intensity/brightness :

Lightness or darkness of a certain colour.

At relatively low intensities ...

- monochromatic light in the red, orange, and yellow bands appear **brown**.

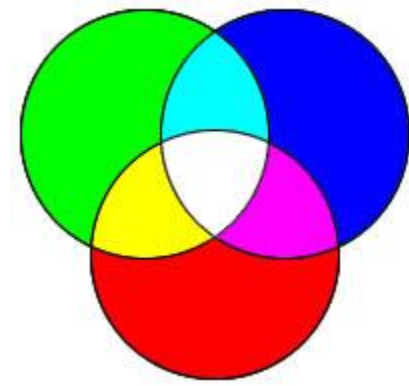


© CCRS / CCT

Color

Color	Wavelength interval	Frequency interval
Red	~ 625–740 nm	~ 480–405 THz
Orange	~ 590–625 nm	~ 510–480 THz
Yellow	~ 565–590 nm	~ 530–510 THz
Green	~ 500–565 nm	~ 600–530 THz
Cyan	~ 485–500 nm	~ 620–600 THz
Blue	~ 440–485 nm	~ 680–620 THz
Violet	~ 380–440 nm	~ 790–680 THz

Color



- **White light** is a mixture of visible frequencies which approximates that of a blackbody radiator with its peak wavelength in the middle of the visible spectrum.
- The sensation of **purple** cannot be produced using light of a single frequency, but only by combining light from the red and violet bands (or the red and blue bands) -- light from the extreme ends of the visible spectrum
- Human vision adapts to the illumination provided by the environment so that many blackbody and non-blackbody sources appear white.

Color Temperature

- Quality of white light emitted from a blackbody radiator is a function of its temperature. This quality is known as **color temperature**.

Definition:

The colour that would be emitted from a blackbody when it is heated to a particular temperature.

Units: Measured in Kelvins (K)

Color Temperature:

Red (Coolest) → Orange → Yellow → White → Blue (Hottest)



Color Temperature

- A visual region with a color temperature below 6500 K emits white light that looks reddish in comparison. For cultural reasons light of this color is called **warm white** even though it is from a "colder" source.
- A visual region with a color temperature above 6500 K emits white light that looks bluish in comparison. For cultural reasons light of this color is called **cool white** even though it is from a "hotter" source.
- A visual region looks **gray** if the light from it is similar to white light, but has an intensity somewhat lower than its surroundings.

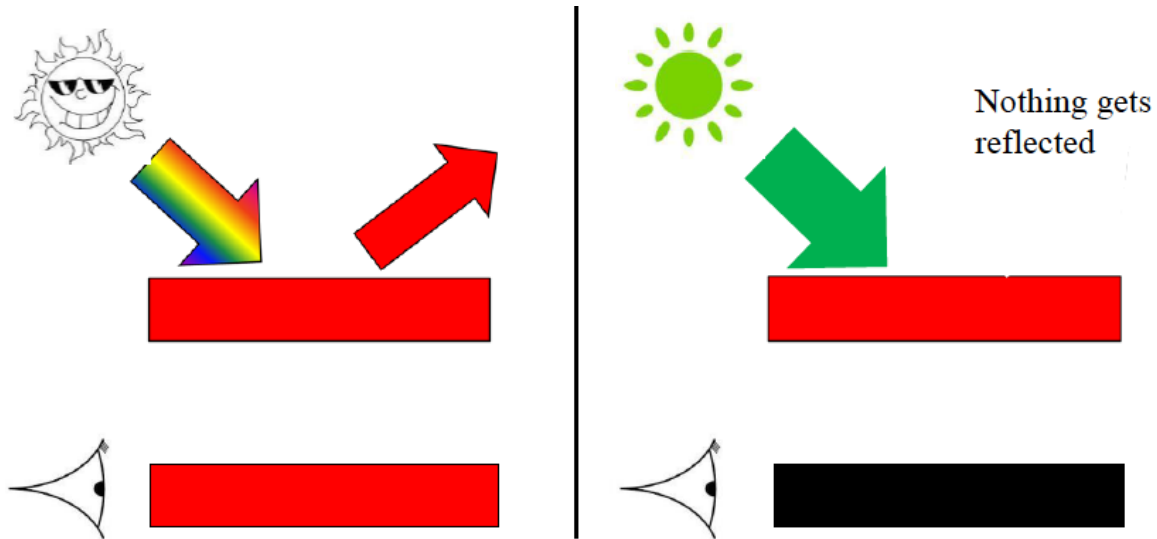
Color temperature

Example of colour temperatures:

Item	Colour Temp. (K)
Blue Sky	10,000
Cool white fluorescent lamp	4,100
Warm white fluorescent lamp	3,000
General service incandescent lamp	2,500
Candle Flame	1,800

Color

- Colour is the result of waves of radiant energy reaching our eye after they have been modified by an object.



- **Black** is the relative absence of visible light.
 - A visual region that emits, reflects, or transmits much less visible light than its surroundings looks black.
- If objects scatter all wavelengths with roughly equal strength, they appear white. If they absorb all wavelengths, they appear black.

Color

- In summarize, the color of an object is a complex result of its surface properties, its transmission properties, and its emission properties, all of which contribute to the mix of wavelengths in the light leaving the surface of the object.
- The perceived color is then further conditioned by the nature of the ambient illumination, and by the color properties of other objects nearby, and via other characteristics of the perceiving eye and brain.

Lighting terminology

Quantity	Symbol	SI Unit	Abbr.	directional	Notes (& Imperial Units)
Luminous flux	Φ	Lumen	lm	No	Also called luminous power (Lumen)
Luminous efficacy		Lumen per watt	lm/w		Ratio of luminous flux to radiant flux or power consumed by the source; max. possible is 683
Luminous intensity	I	Candela (lm/sr)	cd	Yes	An SI base unit (cd or Candela)
Illuminance	E	Lux (lm/m²)	lx	No	Used for light incident on a surface (fc or footcandels, lm/ft²)
Luminance	L	Candela per square metre	cd₂/m	Yes	Units are sometimes called nits (footlambert)
Luminous exitance	M	Lux (lm/m²)	lx	no	Used for light reflected or transmitted by a surface (Lumen per sq.ft.)

Luminous Flux (Φ)

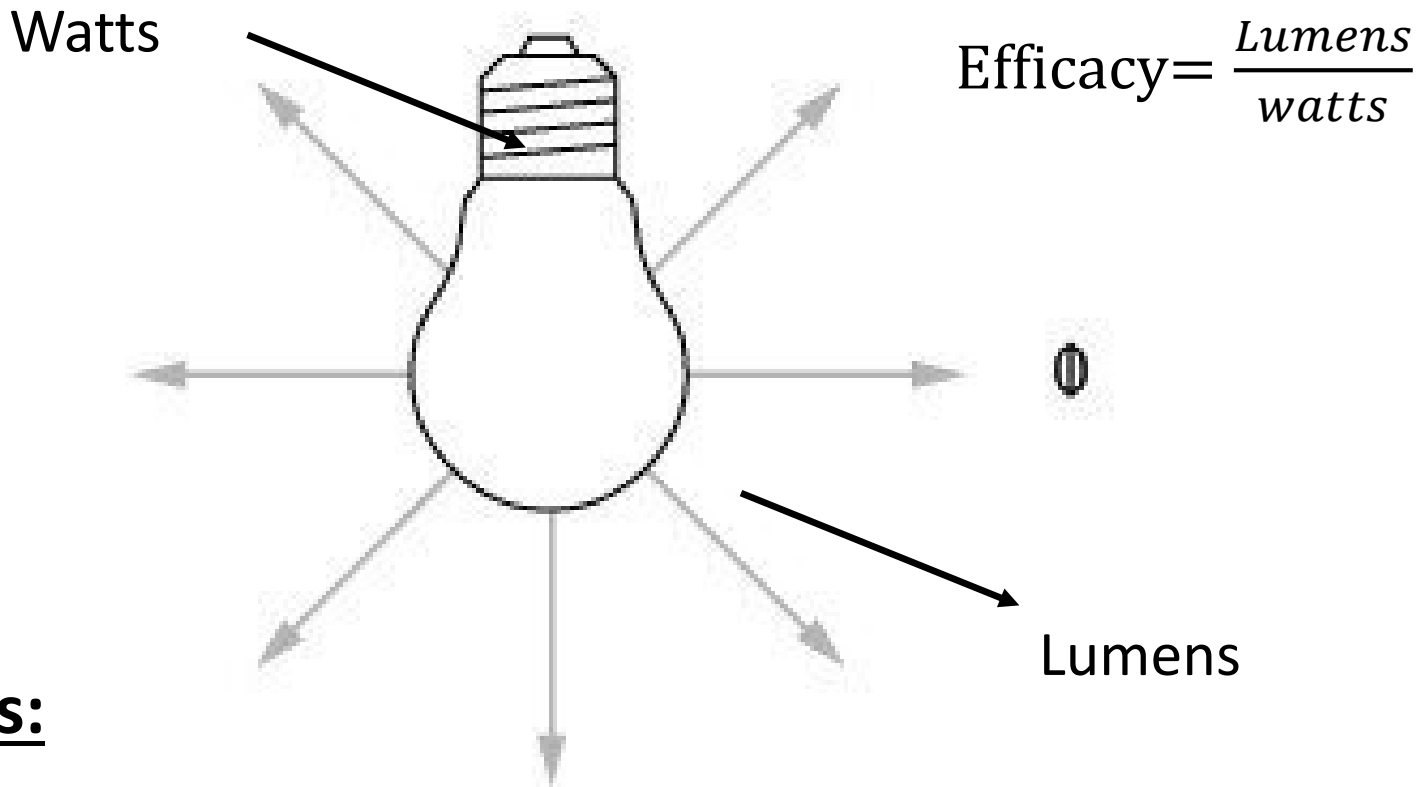
Definition:

- The rate at which light energy flows from the source. It is the quantity of the energy of the light emitted per second in all directions.
- Luminous flux differs from power (radiant flux) in that luminous flux measurements reflect the varying sensitivity of the human eye to different wavelengths of light while radiant flux measurements indicate the total power of all electromagnetic waves emitted, independent of the eye's ability to perceive it.

Units:

Measured in Lumens (**lm**) - *SI Units*

Luminous Flux (Φ)



Examples:

Power (Watts) input into a lamp results in an output of lumens.

Luminous Efficacy

- Efficiency of a luminaire (light fixture) is called efficacy, measured in Lumens/watt
- A source radiating a power of one watt of light in the color for which the eye is most efficient (a wavelength of 555nm, in the green region of the optical spectrum) has luminous flux of 683 lumens. One lumen represents at least 1/683 watt of visible light power depending on the spectral distribution

Source	Lumens (lm)	Luminous Efficacy (lm/W)
Candle		0.3
100 W Incandescent	1680	16.8
28 W Fluorescent Tube (T5)	2912	104
White LED		Up to 150
The Sun		80
Maximum Possible		683

Luminous Intensity (I)

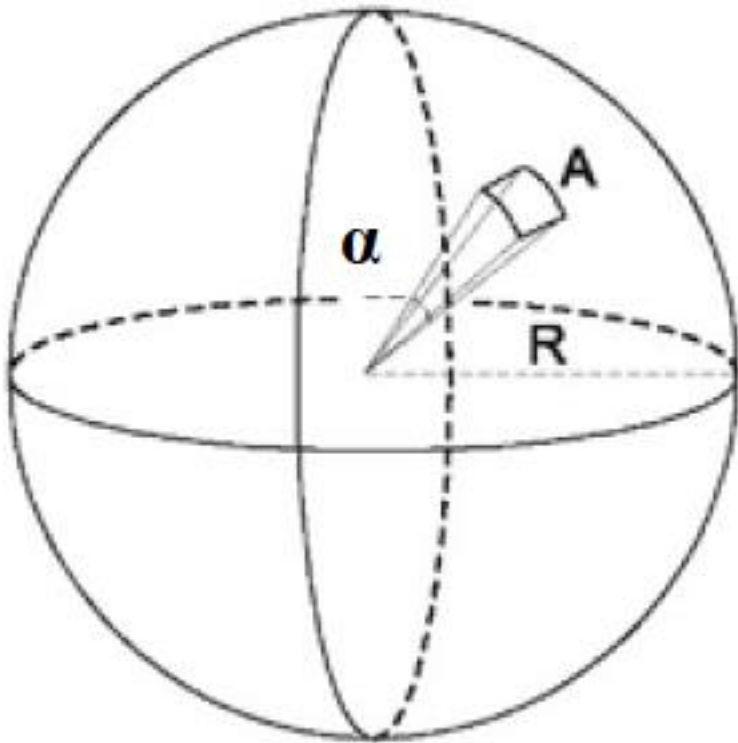
Definition:

- it is the luminous flux that is radiated by the light source in a given direction within the unit of the spatial angle.
- Measure of the wavelength-weighted power emitted by a light source in a particular direction per unit solid angle.

Units:

- Measured in Candelas (cd) – *SI Unit; lumens per steradian (sr)*
- Steradian (sr): is the SI unit of solid angle. It is used in 3D space and functions analogously to the manner in which the radian quantifies planar angles.
- A steradian can be defined as the **solid angle subtended at the centre of a unit sphere by a unit area on its surface**. For a general sphere of radius r , any portion of its surface with area $A=r^2$ subtends one steradian

Luminous Intensity (I)

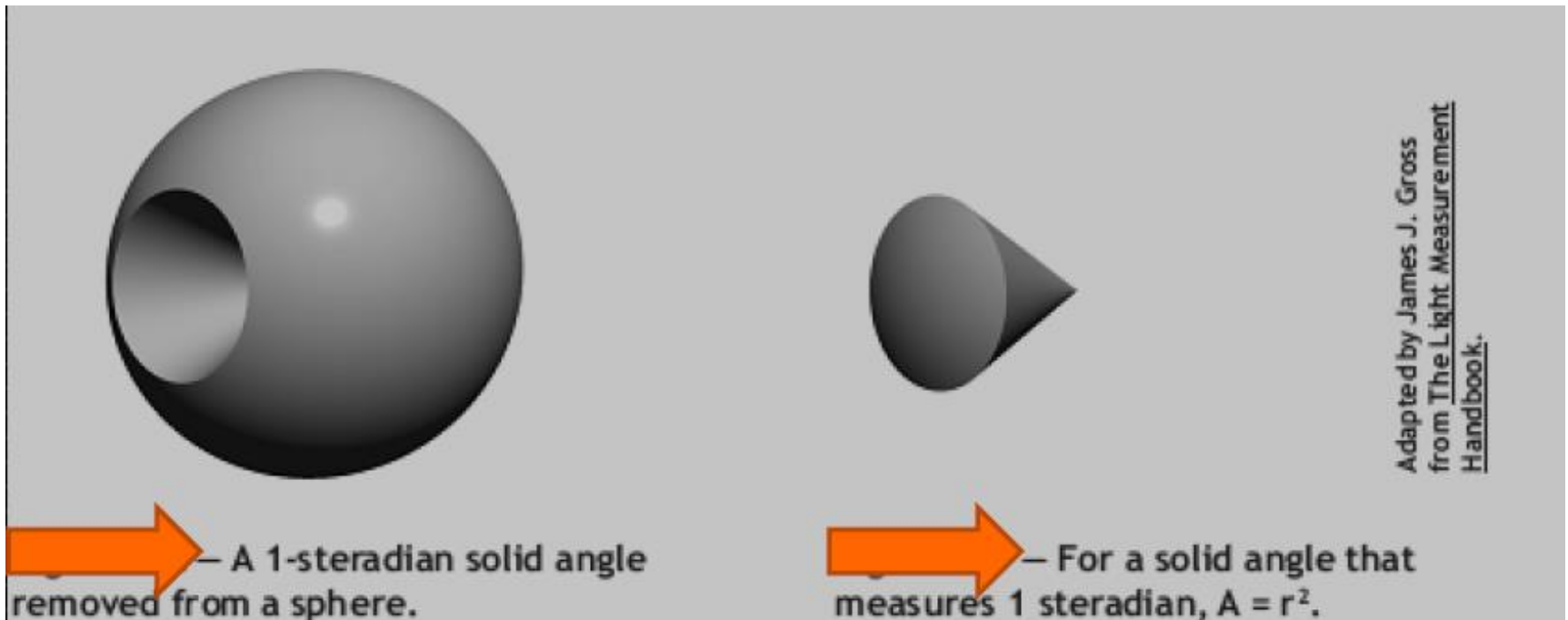


ω (solid angle)

$$= \frac{A \text{ (projected surface on a sphere)}}{R^2 \text{ (sphere radius)}}$$

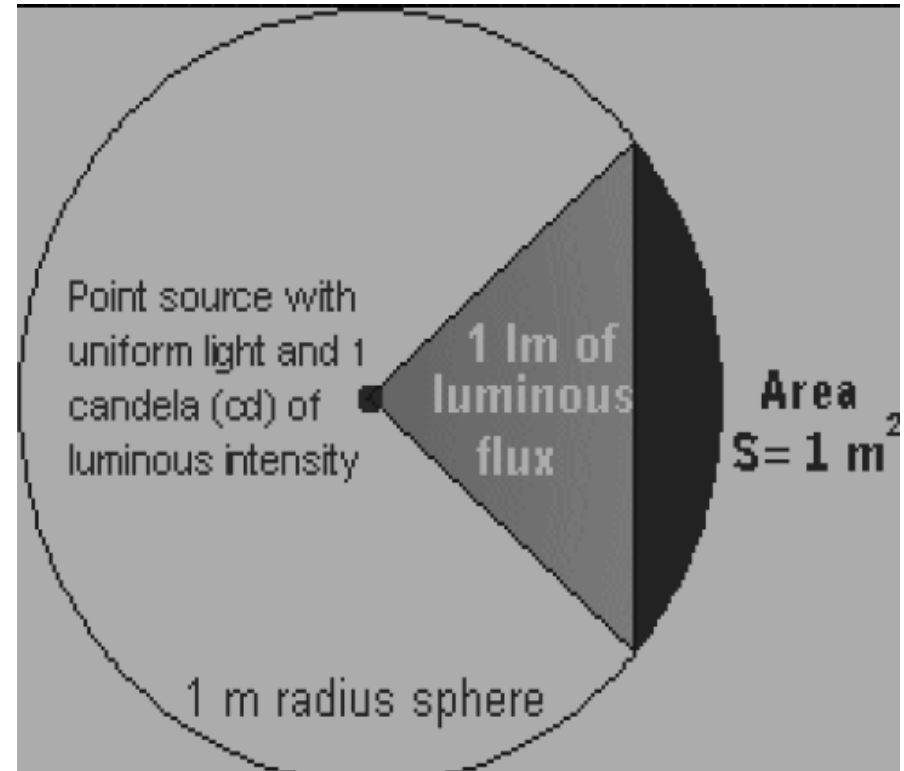
Luminous Intensity (I)

- One full sphere has a solid angle of 4π sr.
- One steradian has a projected area of 1m^2 at a distance of 1m



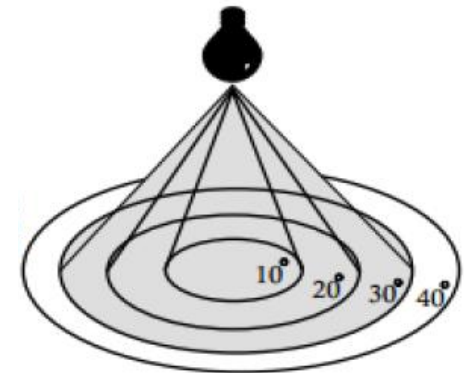
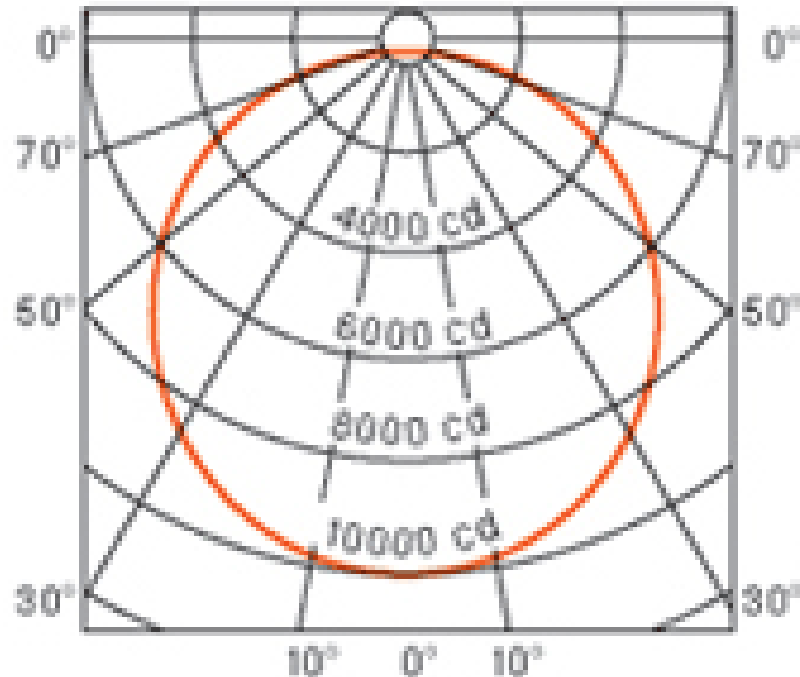
Luminous Intensity (I)

- For a uniform point light source that has luminous intensity of 1 candela, i.e. 1 lumen per steradian.
- Since the solid angle of the sphere is 4π , the luminous flux of the point light source is 4π (12.57) lumens



Luminous Intensity (I)

- The luminous intensity of a light source is commonly shown on a candle-power (cp, old term not commonly used any more) distribution curve. The polar axis graphically indicates the luminous intensity in any given direction from the source position.



Illuminance (E)

Definition:

Is the density of luminous flux incident on a surface, the luminous flux falling on a unit surface area.

Units:

Measured in Lux or Lumens per square meter (Lumens/m²)– *SI Unit*

or Lumens per square foot (Lumens/ft²), referred to footcandle; one foot candle approximately equal to 10.76 lux

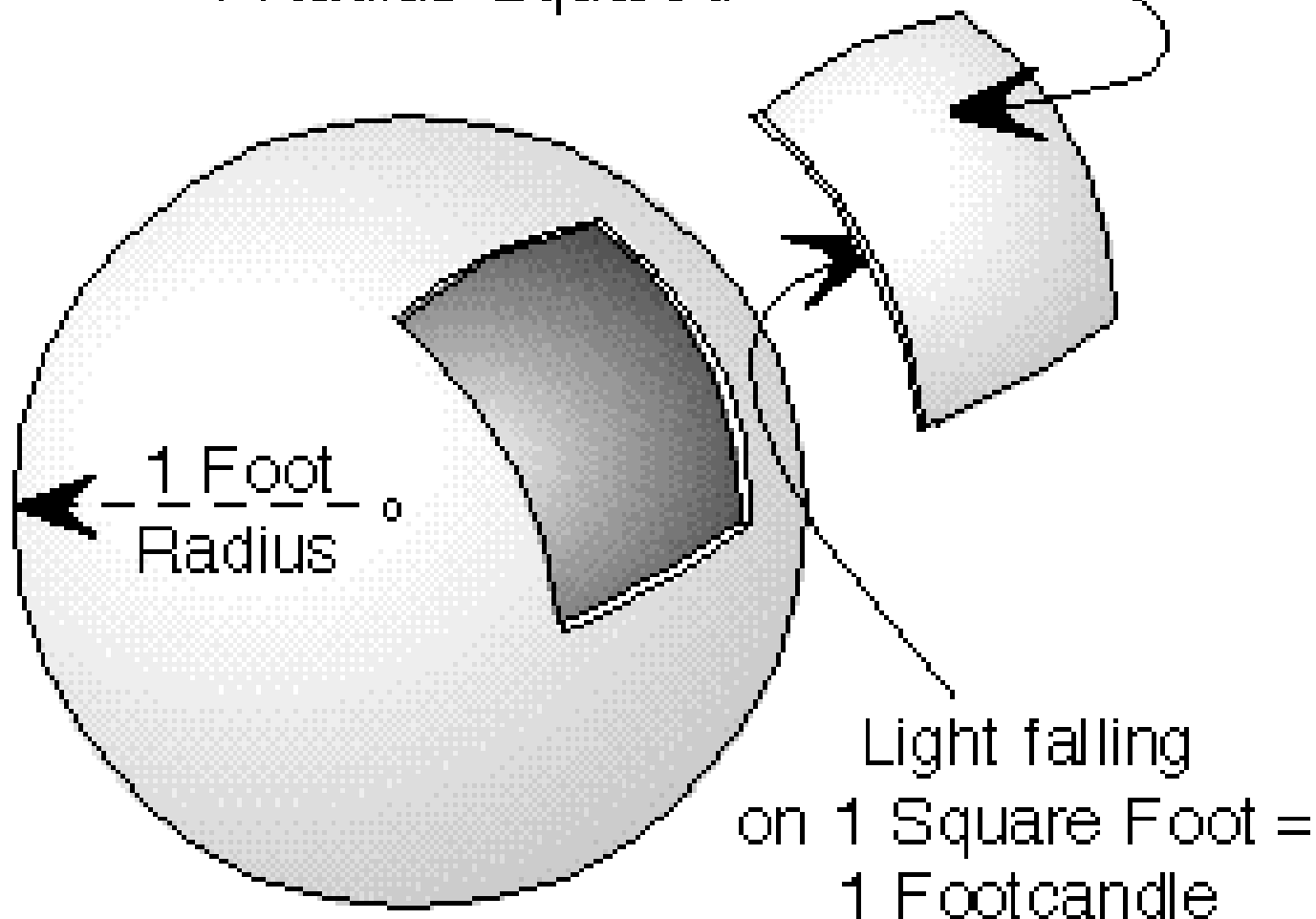
$$E = \frac{\Phi}{A}$$

Where E is Illuminance, lux

ϕ is Luminous Flux, lumen

A is the area of the surface receiving light, m²

1 Square Foot =
1 Steradian =
1 Radius Squared



Illuminance (E)

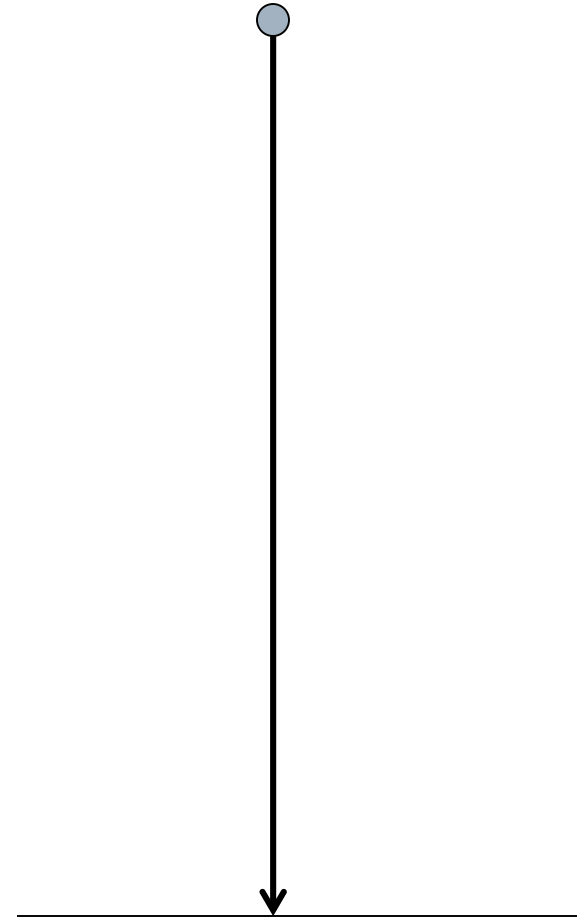
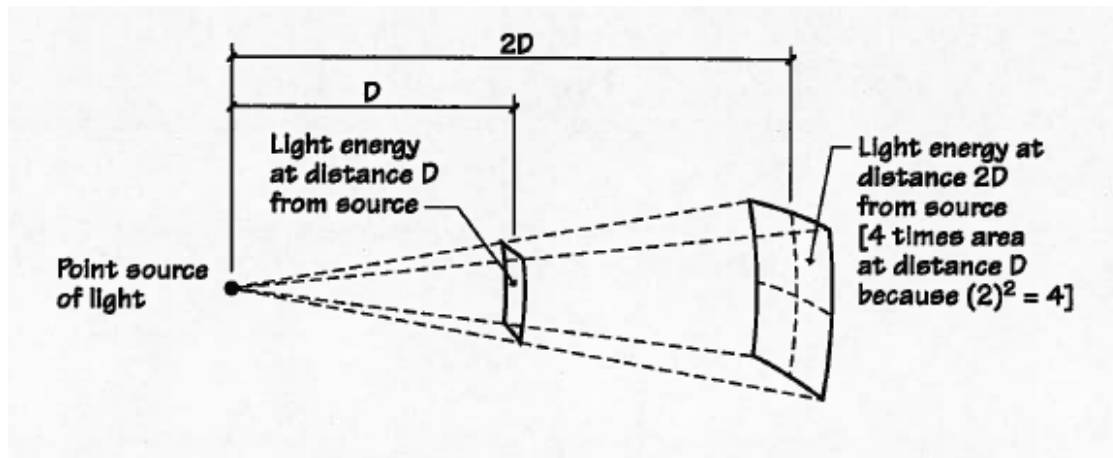
Inverse square law:

$$E = I / D^2$$

E : illuminance [lux]

I : luminous intensity [candela]

D : distance [m]

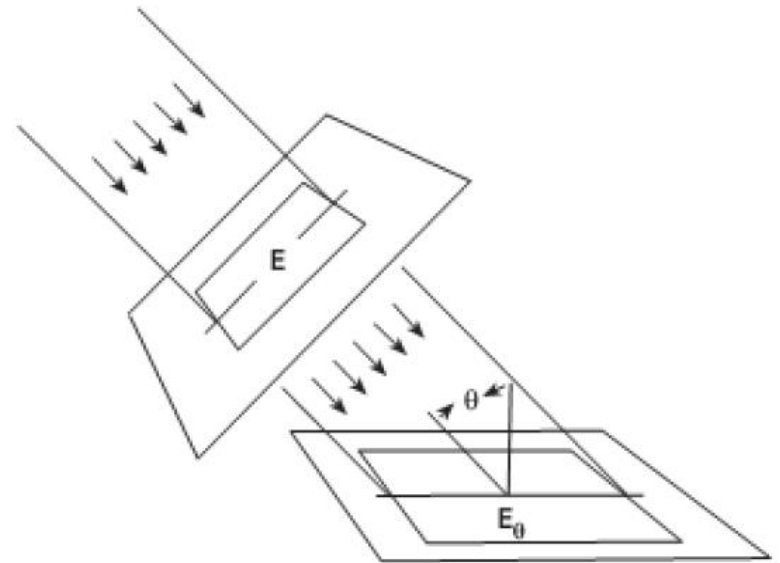


Illuminance (E)

Lambert's Cosine Law: the illuminance falling on any surface depends on the cosine of the light's angle of incidence, θ , which is measured from a line normal to the surface.

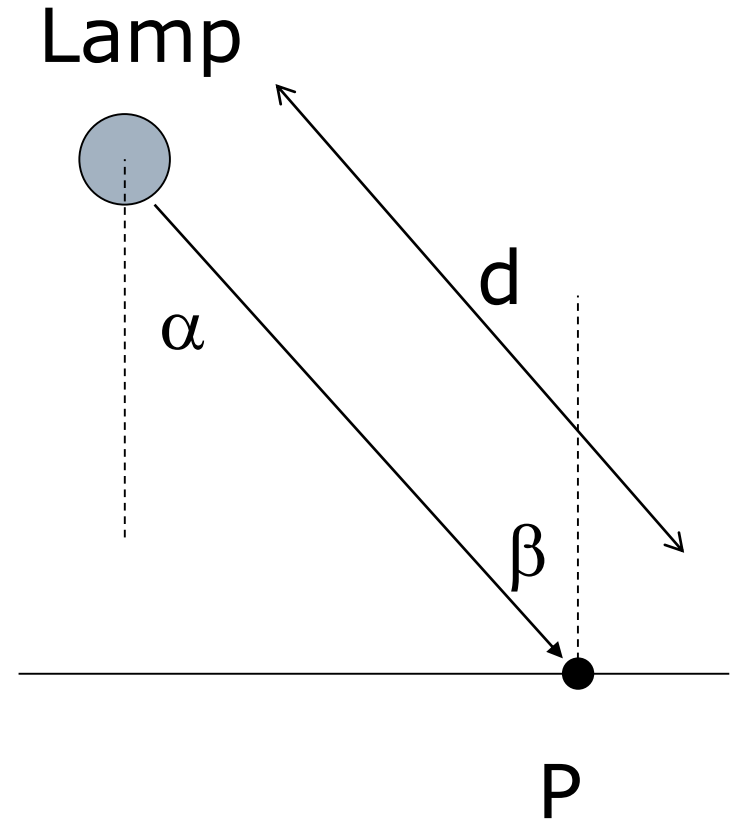
$$E_{\theta} = E \cos \theta$$

Adapted from the IESNA Lighting Handbook - 9th Edition.



Illuminance (E)

$$E = \frac{I \cos \beta}{d^2}$$



Illuminance category	Ranges of illuminance maintained in service, lux (fc)	Type of activity
General illuminance throughout room:		
A	20–30–50 (2–3–5)	Public spaces with dark surroundings
B	50–75–100 (5–7.5–10)	Simple orientation for short temporary visits
C	100–150–200 (10–15–20)	Working spaces where visual tasks are only occasionally performed
Illuminance on task:		
D	200–300–500 (20–30–50)	Performance of visual tasks of high contrast or large size: reading printed material, typed originals, handwriting in ink, and good xerography; rough bench and machine work; ordinary inspection; rough assembly
E	500–750–1000 (50–75–100)	Performance of visual tasks of medium contrast or small size: reading medium pencil handwriting, poorly printed or reproduced material; medium bench and machine work; difficult inspection; medium assembly
F	1000–1500–2000 (100–150–200)	Performance of visual tasks of low contrast or very small size: reading handwriting in hard pencil on poor-quality paper and very poorly reproduced material; highly difficult inspection
Illuminance on task, obtained by a combination of general and local (supplementary) lighting:		
G	2000–3000–5000 (200–300–500)	Performance of visual tasks of low contrast and very small size over a prolonged period: fine assembly; very difficult inspection; fine bench and machine work
H	5000–7500–10,000 (500–750–1000)	Performance of very prolonged and exacting visual tasks: the most difficult inspection; extra-fine bench and machine work; extra-fine assembly
I	10,000–15,000–20,000 (1000–1500–2000)	Performance of very special visual tasks of extremely low contrast and small size: for example, surgical procedures

Luminance (L)

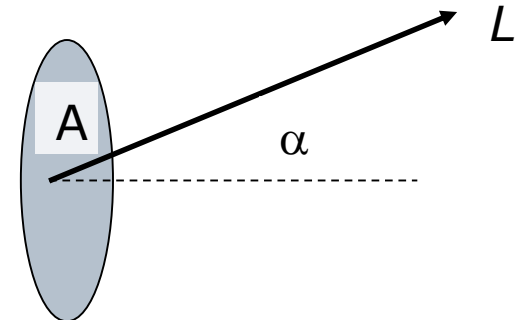
Definition:

- Luminance is defined as the intensity of a source or surface in the direction of the observer, divided by the projected area of the source or surface seen by the observer.
- L is the luminous intensity emitted by the surface area of 1 m² of the light source.
- Luminance is measured brightness and it is also a directional quantity

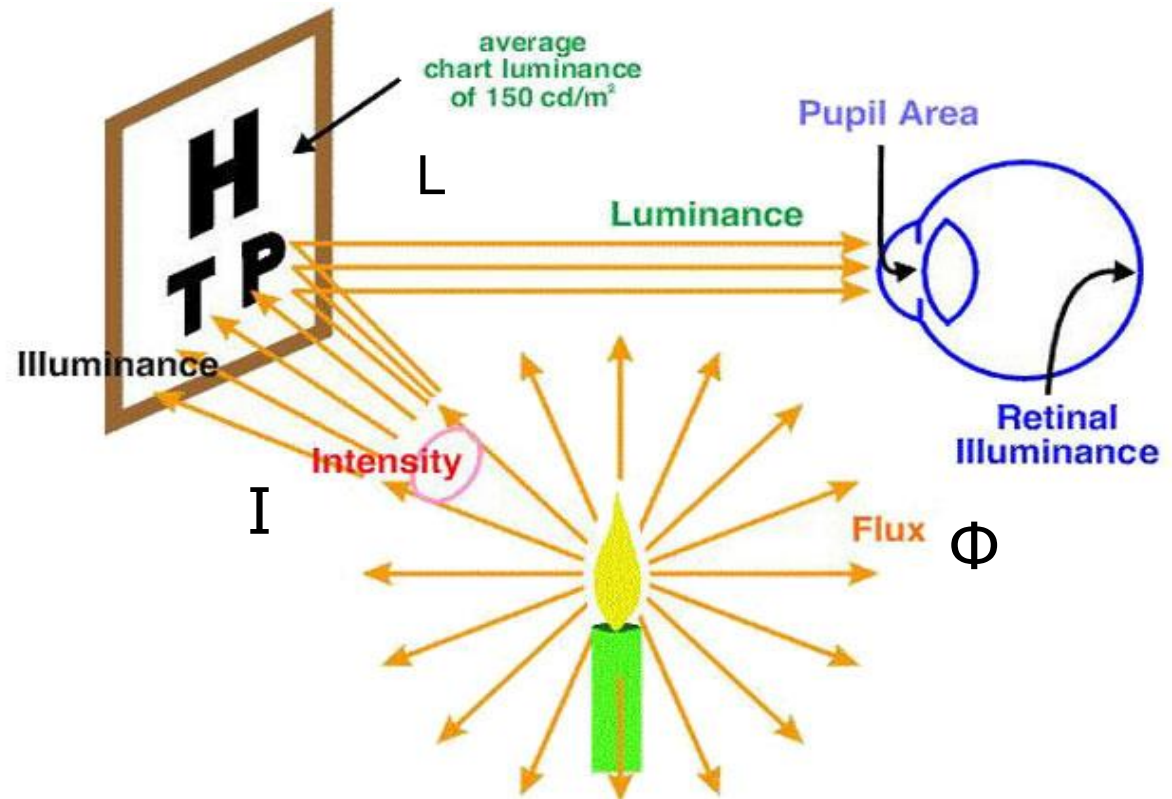
Units:

Measured in Candela per square metre (cd/m²). Previously known as footlamberts, **which equals 1/π cd per square foot**

$$L = \frac{I}{A \cos \alpha}$$



Luminance (L)



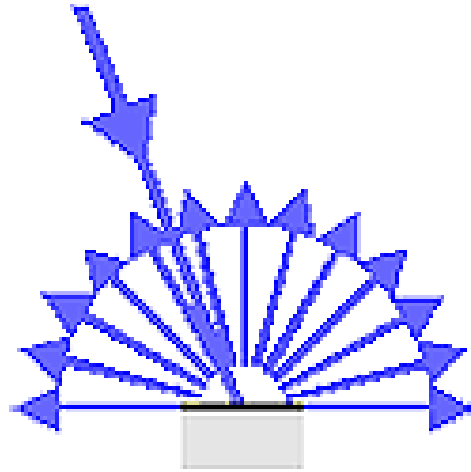
- The luminance value indicates glare and discomfort when we look at the lighting source. These values are very high for the sun or a small lamp and are low for large lighting fixtures.

Luminous Exitance (M)

- Is the **total amount** of luminous flux reflected or transmitted by a source or surface per unit area of the surface, i.e. the density of luminous flux leaving a surface.
- It is similar to luminance in that it describes luminous flux leaving a surface, however, independent of direction.
- Measured in the same units as illuminance, lumens/m² or lumens/ft²
- For perfectly diffusing surfaces:

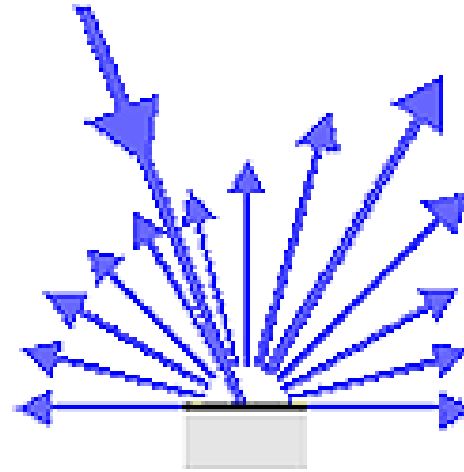
$$M = \pi L \quad \text{L is luminance (cd/m}^2\text{)}$$

Luminous Exitance (M)



Perfectly Diffusing
Surface (Lambertian
surface)

Example, mat finishes,
ceiling tiles, painted
walls



Diffuse reflection with a
directional component

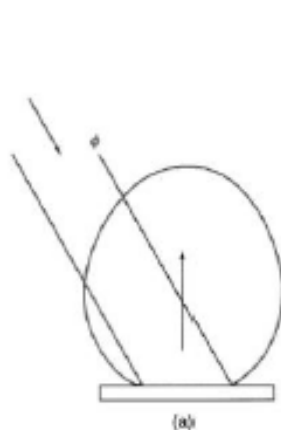
Examples: Glossy
surfaces, magazine-
quality print, mirror

Luminous Exitance (M)

- To determine the luminous exitance of an illuminated surface, we use:
 - Reflectivity (ρ) for reflected light
 - Transmittance (τ) for transmitted lightsurface

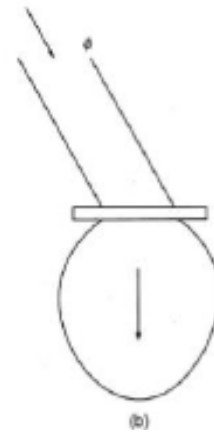
Reflection
with a
reflectance of

ρ



Transmission
with a
transmittance of

τ



$$M_{\rho} = \frac{\Phi (\text{departing luminous flux})}{A (\text{area})} = \frac{\rho \Phi (\text{incident})}{A} = \rho E (\text{illuminance})$$

$$M_{\tau} = \frac{\Phi (\text{departing luminous flux})}{A (\text{area})} = \frac{\tau \Phi (\text{incident})}{A} = \tau E$$

Example:

1. Find luminance of a diffusing surface that reflects 70% of incident light if the illuminance is 25 lux.

Illuminance = $E = 25$ lux;

Luminous exitance = $M = 25 * .7 = 17.5$ lumens/sq.m

Therefore, $L = M/\pi = 17.5 / 3.14 = 5.6$ nits (cd/m^2)

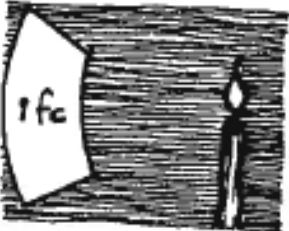
2. Find luminance of a diffusing surface that reflects 70% of incident light if the illuminance is 25 fc.

Illuminance = $E = 25$ fc = 25 lumens/sq.ft.;

Luminous exitance = $M = 25 * .7 = 17.5$ lumens/sq.ft
 $= 17.5 * 10.76 = 188.3$ lumens/sq.m

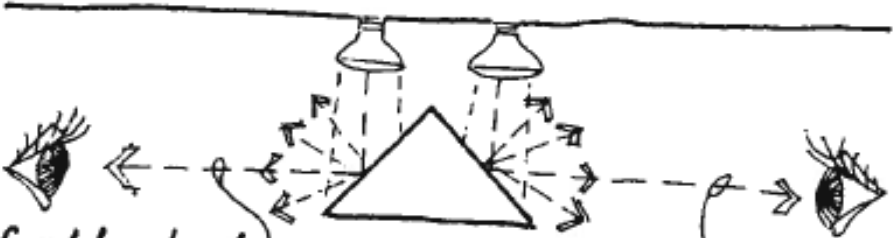
Therefore, $L = M/\pi = 188.3 / \pi = 59.9$ nits (cd/m^2)

Lighting metrics



1 candle power = 12.57 lumens
 illuminance 1 foot away ~ 1fc
 1 footcandle = 1 lumen per sqft.
 if the surface facing the candle
 reflects 1 lumen per square foot
 its luminance is 1 footlambert

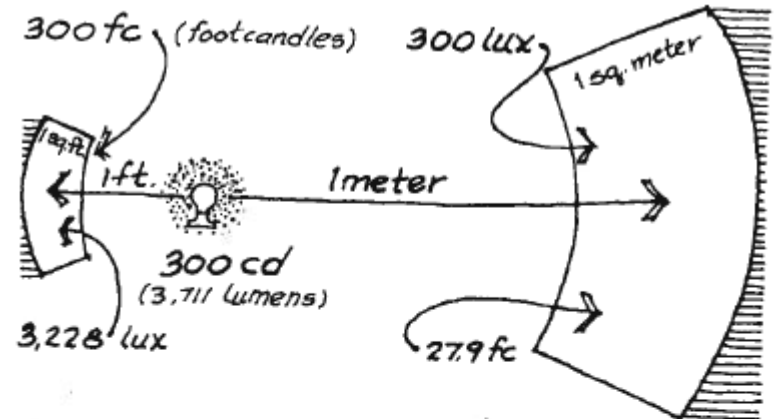
standard candle



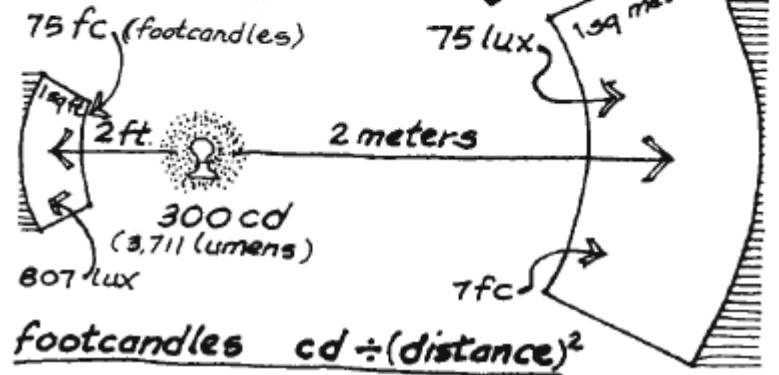
footlambert
 1 lumen / square foot
 not acceptable since 1967

cd/m²
 1 lumen / square meter

luminance numbers



illuminance numbers



footcandles $cd \div (\text{distance})^2$

Lighting metrics

<i>Intensity Values</i>	<i>cd</i>
Sun (clear day)	670,000,000
75 watt spot lamp (average)	4,500
75 watt flood lamp (average)	1,800
Candle flame (1 foot distant)	1

<i>Luminance of Light Sources</i>	<i>cd/m²</i>
Sun	+/- 2,000,000,000
Incandescent lamps	
500 watt (clear)	12,000,000
100 watt (frosted)	170,000
Fluorescent lamp (40 watt cw)	7,000
Moon	5,000
Candle flame	5,000

Values are for brightest spot on each source.

<i>Illuminance Values</i>	<i>fc</i>
Sunlight + skylight (clear day)	10,000
Foggy day (dense fog)	1,000
Commercial offices	10–100
Residence interior (at night)	10
Candle flame (1 foot distant)	1
Moonlight (clear, full moon)	0.01

<i>Surface Luminance (estimated)</i>	<i>cd/m²</i>
Snow in sunlight	20,000–30,000
Grass in sunlight	2,000
Grass in shade	100
This page in sunlight	13,000
This page in shade	1,000
This page in library at night	150
This page in home at night	20

Unit conversion

Converting Photometric Units

<i>Multiply</i>	<i>By</i>	<i>To Get</i>
Candela	1	Candlepower
Candela	12.57	Lumens
Footcandle	10.76	Lux
Lux	0.09	Footcandles
cd/m ²	0.29	Footlamberts
footlambert	3.42	cd/m ²

Lighting terminology

Quantity	Symbol	SI Unit	Abbr.	directional	Notes (& Imperial Units)
Luminous flux	Φ	Lumen	lm	No	Also called luminous power (Lumen)
Luminous efficacy		Lumen per watt	lm/w		Ratio of luminous flux to radiant flux or power consumed by the source; max. possible is 683
Luminous intensity	I	Candela (lm/sr)	cd	Yes	An SI base unit (cd or Candela)
Illuminance	E	Lux (lm/m ²)	lx	No	Used for light incident on a surface (fc or footcandels, lm/ft ²)
Luminance	L	Candela per square metre	cd/m ²	Yes	Units are sometimes called nits (footlambert)
Luminous exitance	M	Lux (lm/m ²)	lx	no	Used for light reflected or transmitted by a surface (Lumen per sq.ft.)

Equations

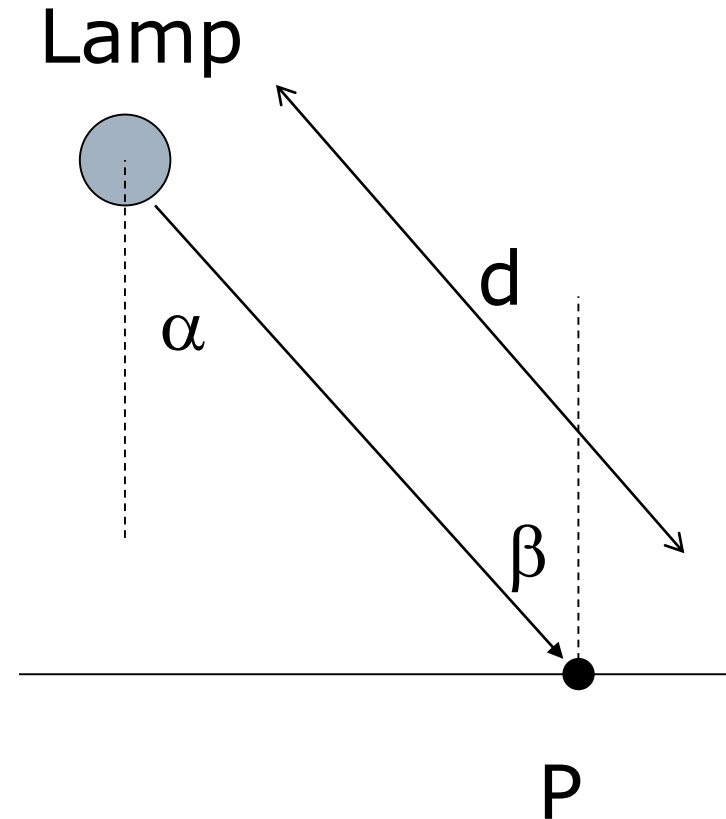
Luminous Flux (Φ)

$$E = \frac{\Phi}{A} \qquad I = \frac{\Phi}{4\pi}$$

$$E = I / D^2$$

$$E = \frac{I \cos \beta}{d^2}$$

$$L = \frac{I}{A \cos \alpha} \qquad M = \pi L$$



Exercises

1. Find the total luminous flux emitted by a lamp rated at 100 candelas;
2. Find the illuminance (lux) @ 1 metre distance from a point light source rated at 100 candelas;
3. Find the illuminance (lux) @ 2 metres distance from a point light source rated at 100 candelas;
4. Find the illuminance (fc) @ 1 foot distance from a point light source rated at 100 candelas;
5. Find the illuminance (fc) @ 6.56 feet distance from a point light source rated at 100 candelas;

References

- M. David Egan and V. Olgyay. Architectural Lighting. McGraw Hill, 2002
- P. C. Sorcar, 1987. Architectural Lighting for commercial interiors. John Wiley & Sons. TH7900S67
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