MSc Computer Games and Entertainment
Maths & Graphics Unit 2011/12
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Illumination Fundamentals

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Light and Electromagnetic Radiation

Light and Electromagnetic Radiation

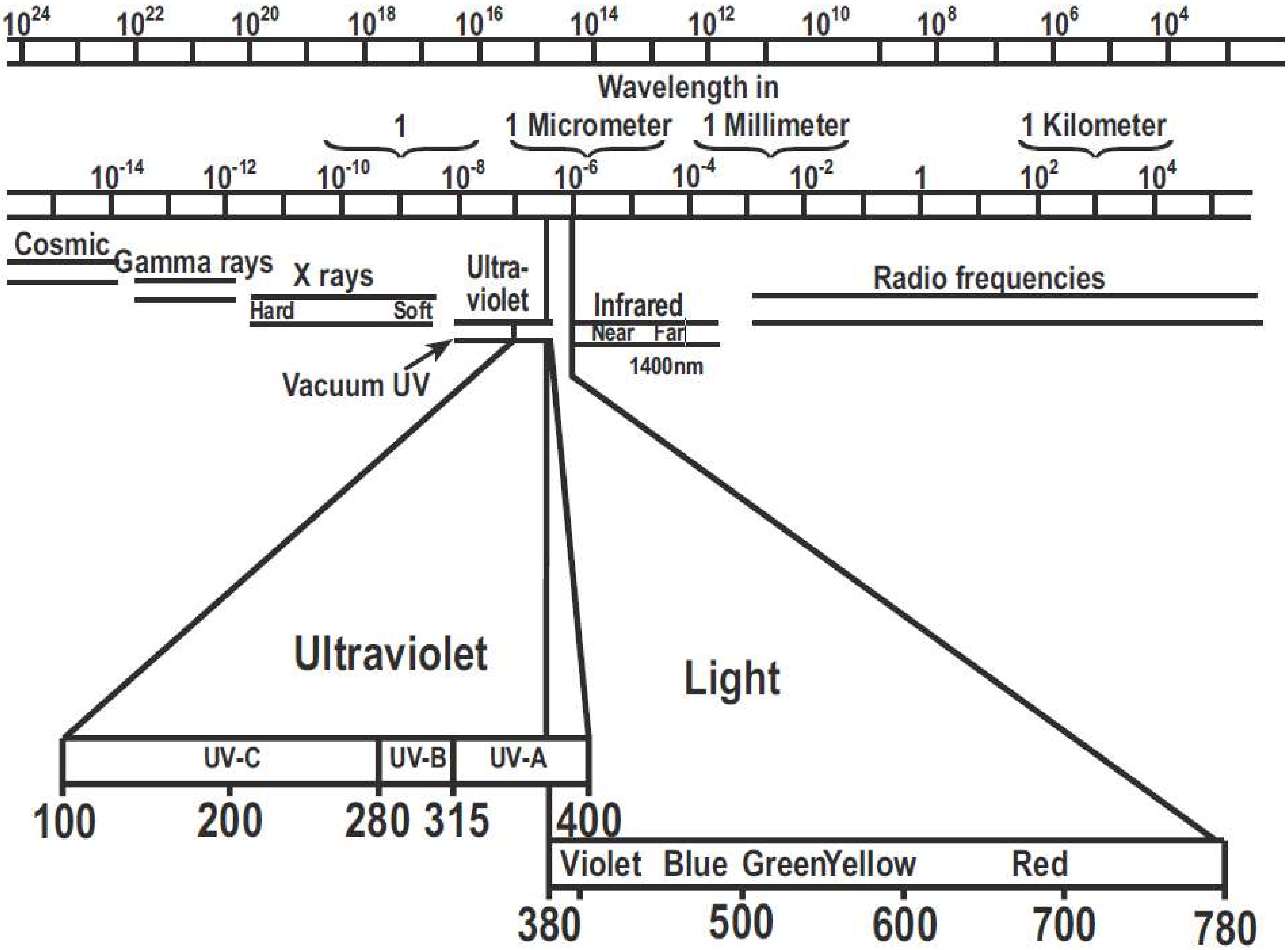
- What is Light?

- To the optical engineer, light is simply a very small part of the electromagnetic spectrum, sandwiched between ultraviolet and infrared radiation.

- The visible portion of the electromagnetic spectrum extends from about 380 to about 780 nanometres (nm), as shown on the next slide.

- What distinguishes this part of the electromagnetic spectrum from the rest is that radiation in this region is absorbed by the photoreceptors of the human visual system and thereby initiates the process of seeing.

- The Illuminating Engineering Society of North America (IESNA) defines light as “radiant energy that is capable of exciting the retina and producing a visual sensation.” Light, therefore, cannot be separately described in terms of radiant energy or of visual sensation but is a combination of the two.


10^{24} 10^{22} 10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4}
Wavelength in
1
1 Micrometer
1 Millimeter
1 Kilometer
10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4}
Cosmic
Gamma rays
X rays
Hard
Soft
Ultra-violet
Infrared
Near
Far
1400nm
Radio frequencies
Vacuum UV
Ultraviolet
Light
UV-C
UV-B
UV-A
100
200
280
315
400
Violet
Blue
Green
Yellow
Red
380
500
600
700
780

The “Visible” Spectrum

- We generally associate five basic colours with the visible portion of the electromagnetic spectrum, as indicated in previous slide.

- These colours are not distinct bands, but rather blend together.

- See later slide on “Spectrum and Colour,” for more information.

Ultraviolet Radiation

- Ultraviolet (UV) radiation, sometimes incorrectly referred as “UV light,” has shorter wavelengths than visible radiation (light).
- The Commission Internationale de l’Eclairage (CIE) divides UV radiation into three segments: UV-A (400-315 nm), UV-B (315-280 nm), and UV-C (280-100 nm).
- The UV-A segment, the most common type of UV radiation, overlaps slightly with the shortest wavelengths in the visible portion of the spectrum.
- UV-B is effectively the most destructive UV radiation from the sun, because it penetrates the atmosphere and can injure biological tissues.
- UV-C radiation from the sun would cause even more injury, but it is absorbed by air, so it almost never reaches the Earth’s surface.

Infrared Radiation

- Infrared (IR) radiation has slightly longer wavelengths than visible light.

- The CIE also divides the IR region of the electromagnetic spectrum into three segments:

    - IR-A (780–1400 nm),
    - IR-B (1400–3000 nm) and
    - IR-C (3000–106 nm).

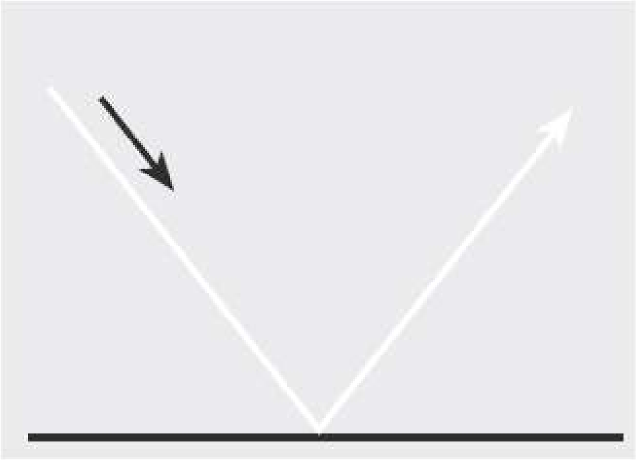
Basic Concepts in Optics

Basic Concepts in Optics

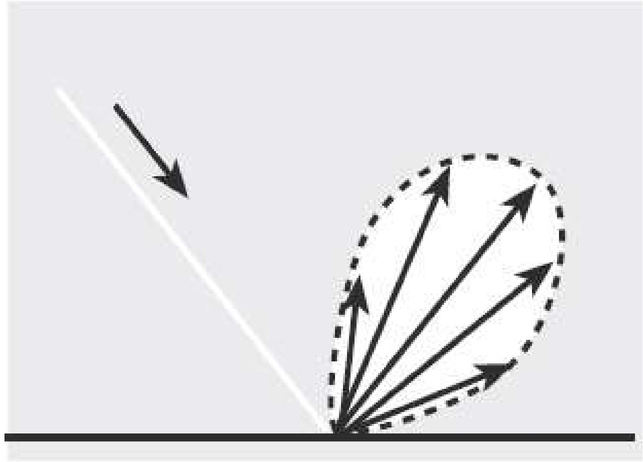
- When light encounters a surface, it can be either reflected away from the surface or refracted through the surface to the material beneath.
- Once in the material, the light can be transmitted, absorbed, or diffused (or some combination) by the material.
- Each of these properties is discussed in this section.
- Note that these properties usually apply to both light and other forms of electromagnetic radiation.
- However, to simplify this discussion, it will be limited to light.

Reflection

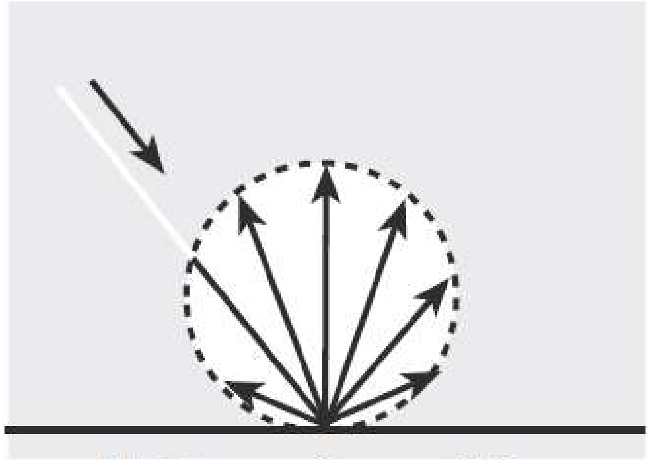
- There are three general types of reflection: specular, spread, and diffuse, as shown in the next slide.
- A specular reflection, such as what you see in a mirror or a polished surface, occurs when light is reflected away from the surface at the same angle as the incoming light’s angle.
- A spread reflection occurs when an uneven surface reflects light at more than one angle, but the reflected angles are all more or less the same as the incident angle.
- A diffuse reflection, sometimes called Lambertian scattering or diffusion, occurs when a rough or matte surface reflects the light at many different angles.
- For more information about spread and diffuse reflection, see Section 2.5, “Diffusion (Scattering).”



a. Polished surface, specular



b. Rough surface, spread



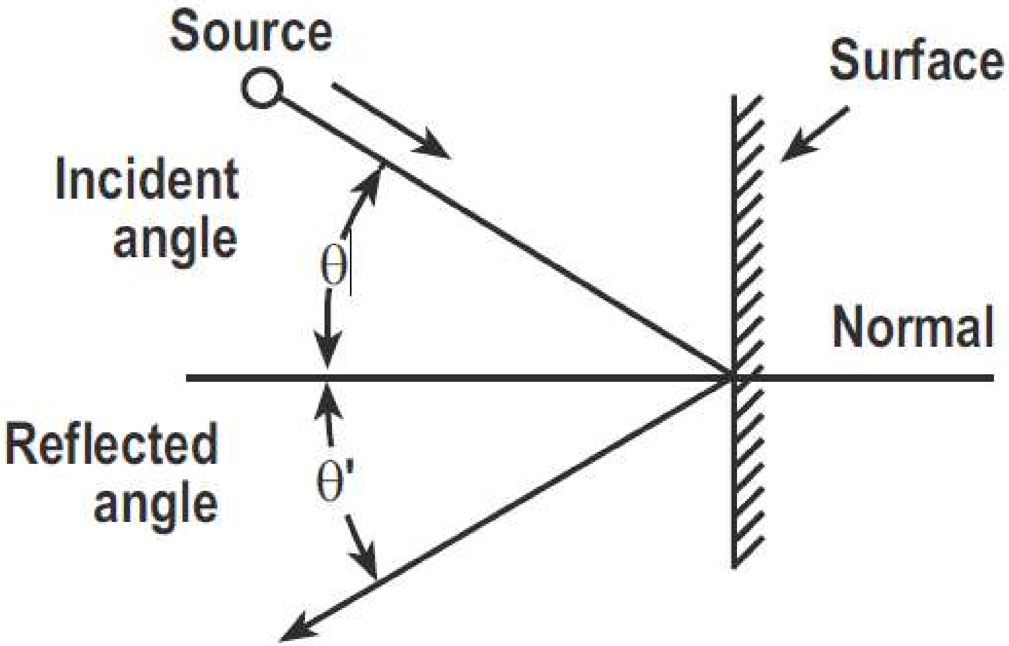
c. Matte surface, diffuse

Law of reflection

- Specular reflections demonstrate the law of reflection, which states that the angle between the incident ray and a line that is normal (perpendicular) to the surface is equal to the angle between the reflected ray and the normal.

- The angle between an incident ray and the normal is called the incident angle, denoted by the symbol θ.

- The angle between a reflected ray and the normal is called the reflected angle, denoted by the symbol θ´.



Refraction and Snell’s law

- When light travels from one material to another (such as from air to glass), it refracts — bends and changes velocity.

- Refraction depends on two factors: the incident angle (θ) and the refractive index of the material, denoted by the letter n.

- The index of refraction for a particular material is the ratio of the speed of light in a vacuum to the speed of light in that material:

  n = speed of light in vacuum/speed of light in the material = c/v

- The speed of light in air is almost identical to the speed of light in a vacuum, so the index of refraction for air is considered to be 1 (note: in air n = 1.000293).

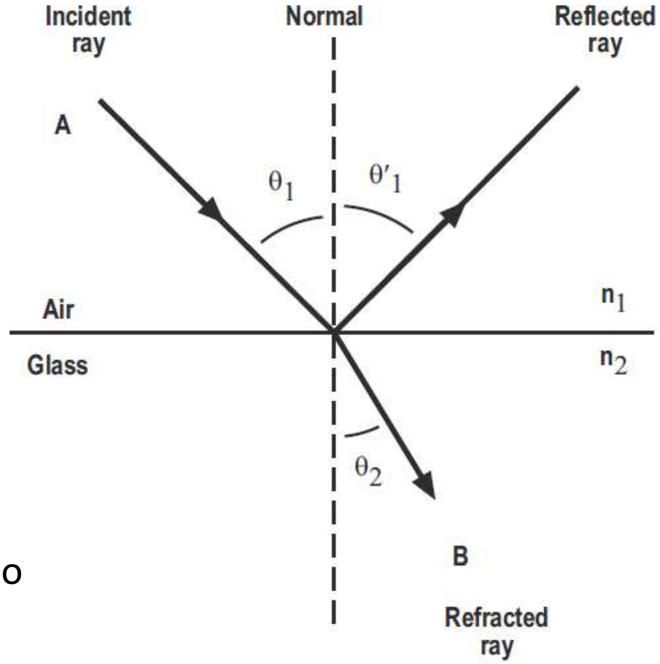
- The index of refraction for almost all other substances is greater than 1, because the speed of light is lower as it passes through them.

Refraction and Snell's law

- As shown below, Snell's law of refraction shows the relationship between the incident angle and the refractive index:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- Where:
  - n1 = the refractive index of medium 1
  - n2 = the refractive index of medium 2
  - θ1 = the incident angle of the light ray (with respect to the normal)
  - θ´1 = the reflected angle (with respect to the normal)
  - θ2 = the refracted angle (with respect to the normal)



Refraction and Snell's law

- Using this law, sin 0° = 0, which means that light with a normal incident angle does not bend at a boundary.

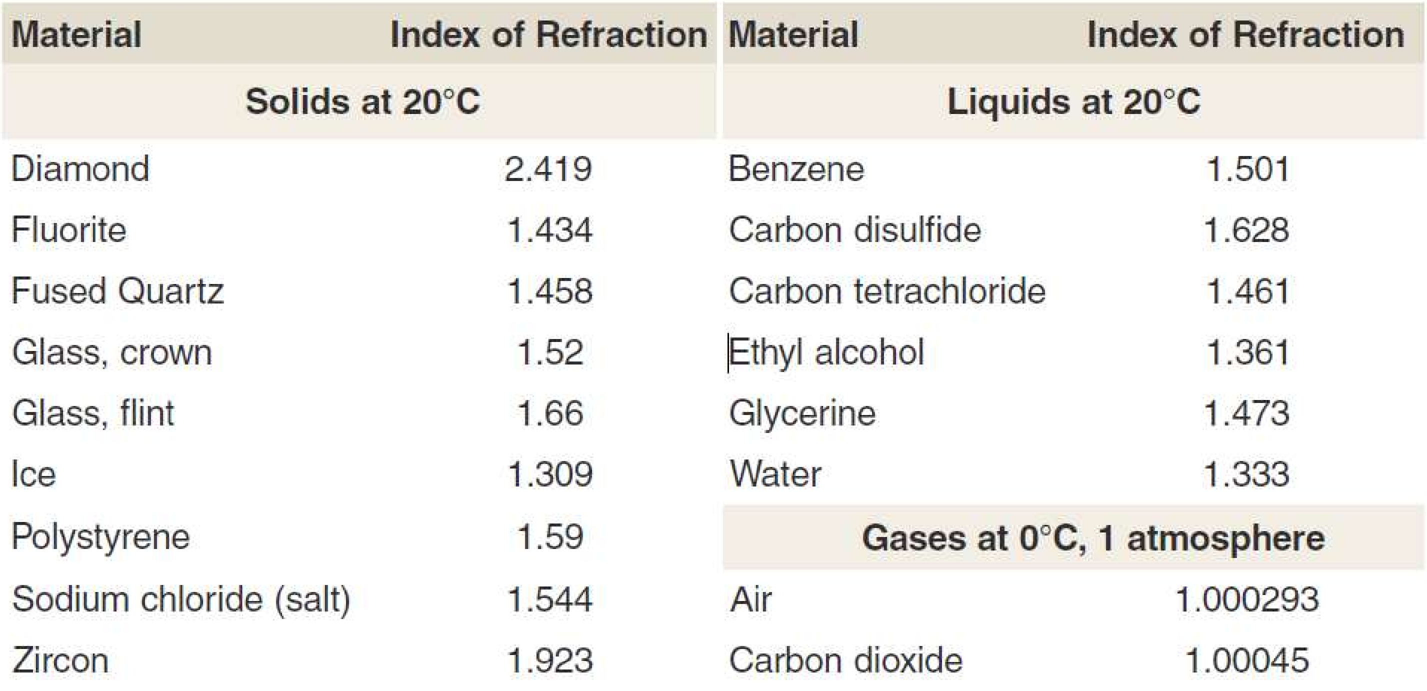
- Snell's law also shows that light travelling from a medium with a low index to one with a high index ($n1 < n2$) bends toward the normal, while light travelling from a medium with a high index to one with a low index ($n1 > n2$) bends away from the normal.

- The next slide lists the indexes of refraction for various materials.

Refraction and Snell's law

- Indexes of refraction for various materials, measured with light of wavelength 589 nm in vacuum.

- Adapted from Physics for Scientists & Engineers - 3rd edition.



Material	Index of Refraction	Material	Index of Refraction
Solids at 20°C		**Liquids at 20°C**	
Diamond	2.419	Benzene	1.501
Fluorite	1.434	Carbon disulfide	1.628
Fused Quartz	1.458	Carbon tetrachloride	1.461
Glass, crown	1.52	Ethyl alcohol	1.361
Glass, flint	1.66	Glycerine	1.473
Ice	1.309	Water	1.333
Polystyrene	1.59	**Gases at 0°C, 1 atmosphere**	
Sodium chloride (salt)	1.544	Air	1.000293
Zircon	1.923	Carbon dioxide	1.00045

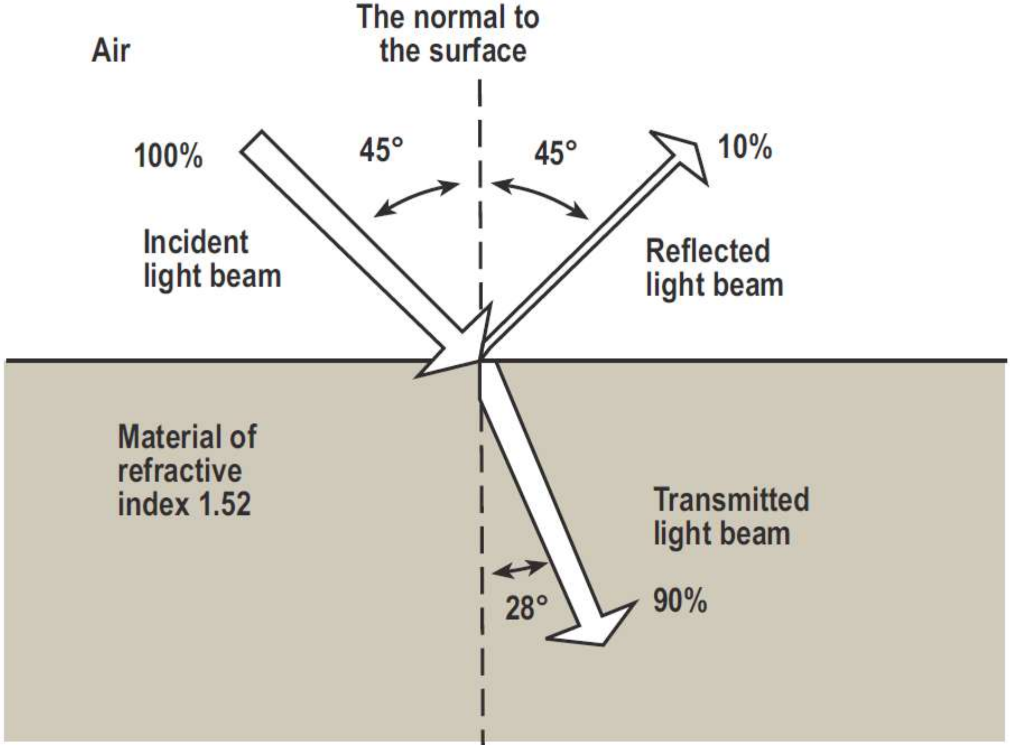
Refraction and Snell's law

- For example, a light ray entering a piece of crown glass – where n = 1.52 as per Table in previous slide - from the air (n = 1) at an incident angle of 45° bends to a refracted angle of 28°.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

$$1 \sin 45^\circ = 1.52 \sin \theta_2$$

$$\theta_2 = 28^\circ$$



Reflection and the Index of Refraction

- A transparent substance transmits almost all light, but it reflects a little bit of light from each of its two surfaces.

- This reflection occurs whenever light travels through a change in the refractive index.

- At normal incidence (incident angle = 0°), Fresnel’s law of reflection quantifies the effect:

$$r_\lambda = \frac{(n_2-n_1)^2}{(n_2+n_1)^2}$$

- Where
  - rλ = the reflection loss n1 = the refractive index of medium 1
  - n2 = the refractive index of medium 2

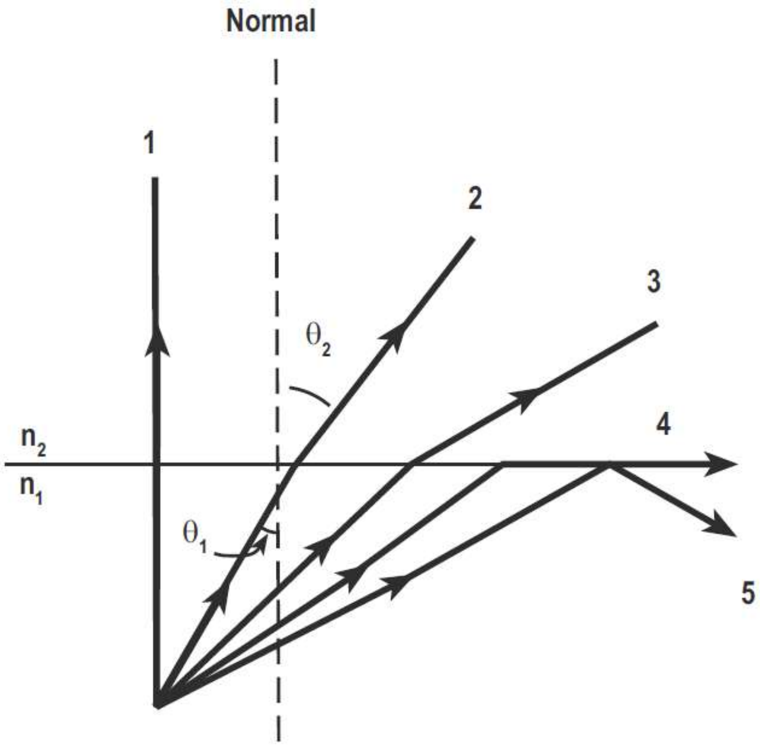
- For example, when light strikes a material that has a refractive index of 1.5 (such as glass) at a normal incident angle, each of the two boundaries with air reflects approximately 4% of the light.

- As the angle of incidence increases, so does the amount of reflected light.

Total Internal Reflection (TIR)

- As Snell's law shows for light travelling from a material with a higher index of refraction to one with a lower index of refraction (such as light moving through a piece of glass toward air), the refracted light bends away from the normal. This leads to the phenomenon called total internal reflection.

- If a beam of light's angle of incidence increases away from normal, it reaches an angle (called the critical angle, θ_c) at which the light is refracted along the boundary between the materials instead of being reflected or passing through the boundary.

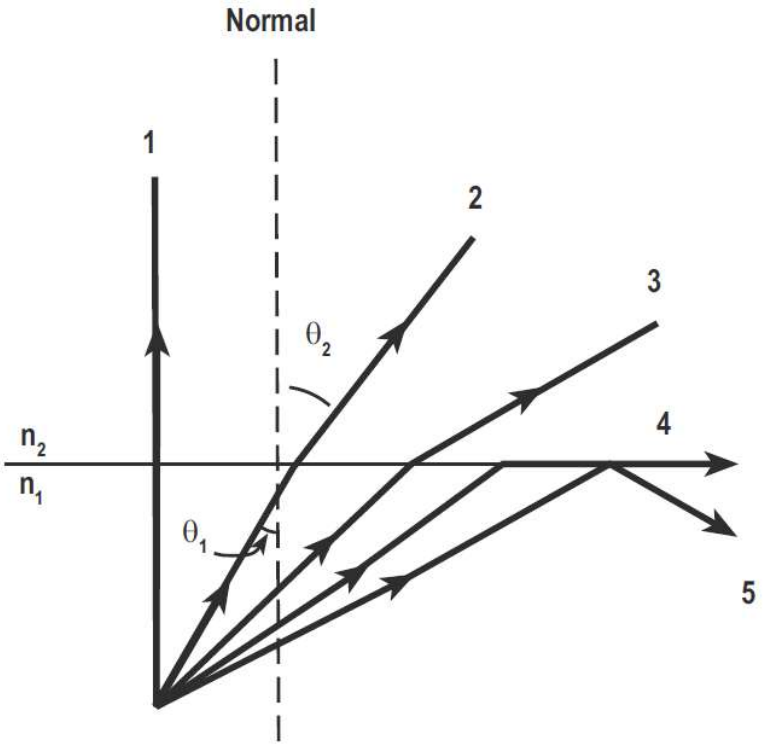


Total Internal Reflection (TIR)

- At even higher angles of incidence, all the light is reflected back into the medium, which allows fibre optics to transport light along their length with little or no loss except for absorption.

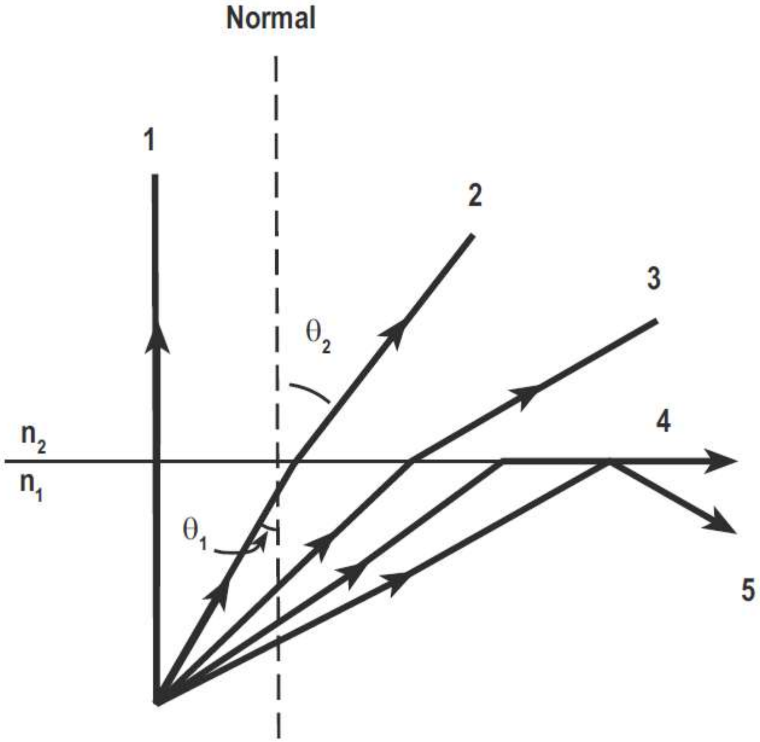
- The figure below shows several rays of light with different incident angles.

- For rays 1, 2, and 3, the incident angle is less than θ_c; ray 4's incident angle is exactly equal to θ_c; ray 5's incident angle is greater than θ_c.



Dispersion

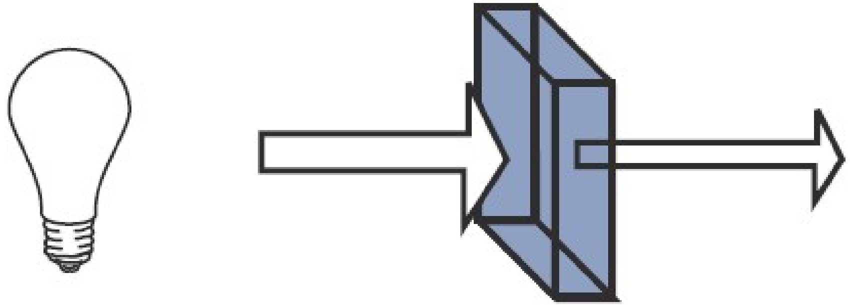
- The index of refraction depends on the wavelength of the incident light. Materials typically have a higher index of refraction for shorter wavelengths, so blue light bends more than red light.
- This phenomenon is called dispersion.
- When white light passes through the nonparallel faces of a prism, it spreads into its spectral components, thus revealing the effects of dispersion.



Transmission

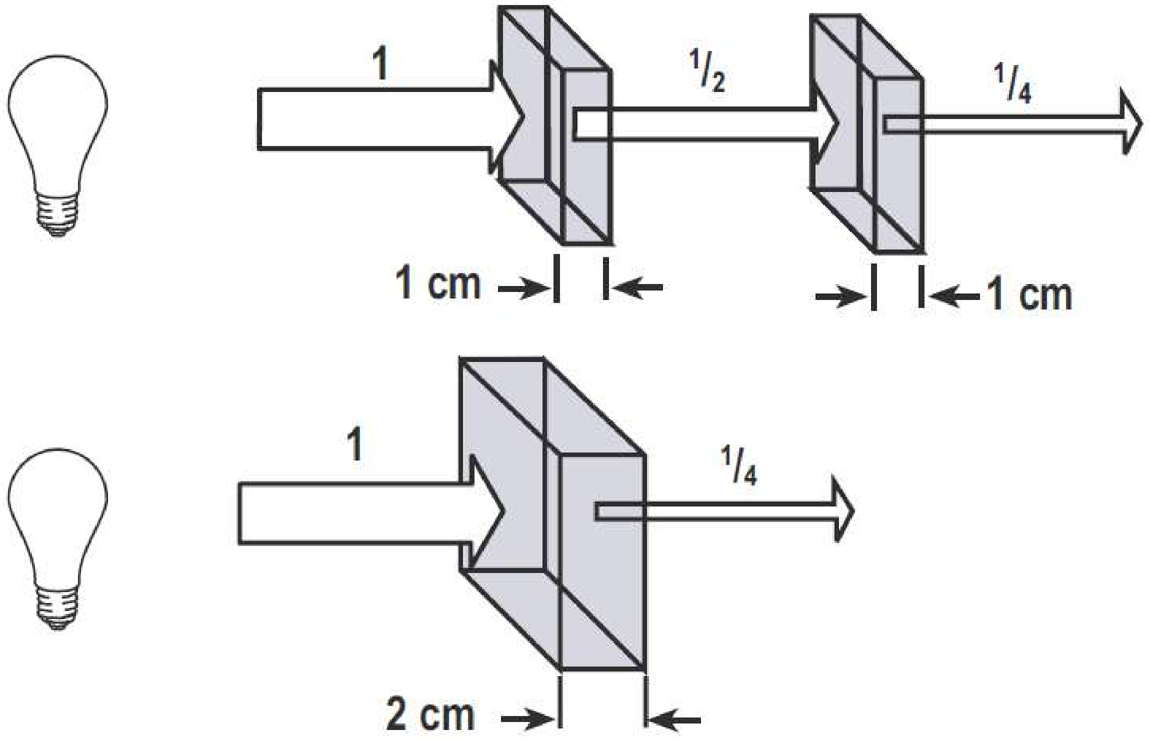
- When light passes through an object, it is called transmission. Absorption, reflection, refraction, and diffusion (explained in the following sections) all affect light transmission.

- The figure below shows an example of a transmitted light beam.



Absorption

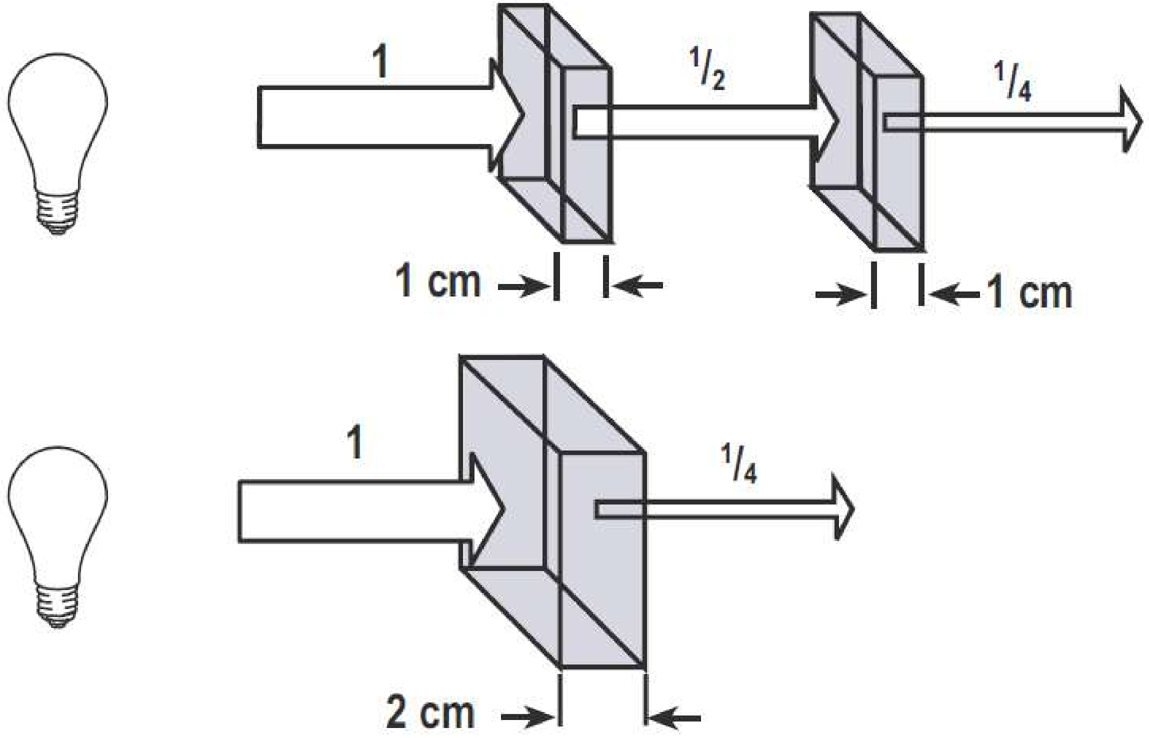
- Instead of completely transmitting light, an object can absorb part or all of the incident light, usually by converting it into heat.
- Many materials absorb some wavelengths while transmitting others, which is called selective absorption.



Absorption

- Lambert’s law of absorption states that equal thicknesses of a given homogenous material absorb the same fraction of light.

- In other words, if a 1-cm block of material absorbs half of the incoming light, a second 1-cm block of the same material would again absorb half of the beam, so that only 0.5 x 0.5, or 0.25, of the original light is transmitted through a total of 2 cm of material.



Lambert’s law of absorption

- This exponential relationship is given in the formula

$$I = I_0 e^{-\alpha x}$$

- Where:
  - I = intensity of transmitted light
  - I_0 = intensity of light entering the material (excluding surface reflection)
  - α = the absorption coefficient in inverse length units.
  - x = the thickness of the sample (measured in the same unit for thickness as α).

- Note: for complete accuracy, each wavelength must be considered separately.

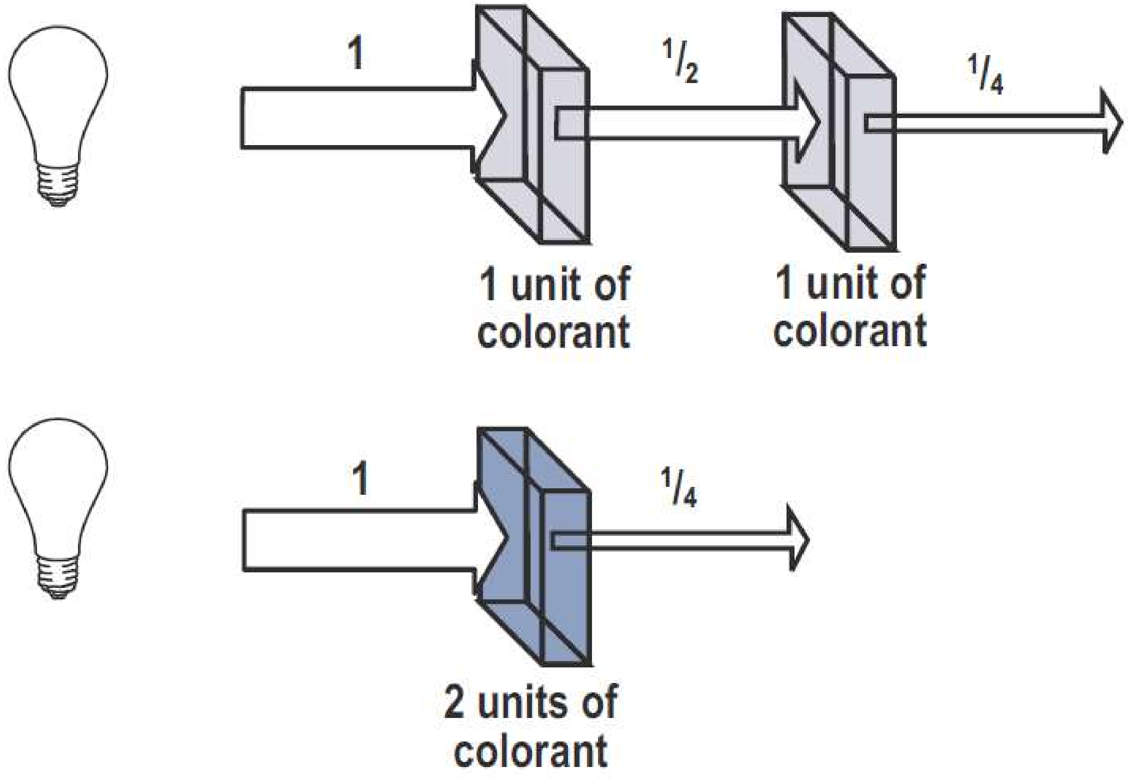
Beer’s law of absorption

- Beer’s law further breaks down the absorption coefficient α into two variables: β, an absorption per unit concentration coefficient, and c, the concentration of the material.

- Beer’s Law states that equal amounts of absorbing material (such as a dye in a liquid) absorb equal fractions of light.

Beer’s law of absorption

- For example, the figure below shows that twice as much dye in the same volume of material absorbs twice as much light.
- As with Lambert’s law of absorption, each wavelength should be considered separately for Beer’s law.



Beers Lambert law of absorption

- The two laws can be combined into a single equation that includes both the thickness and the concentration of the material.

- This equation is called the Beer-Lambert law

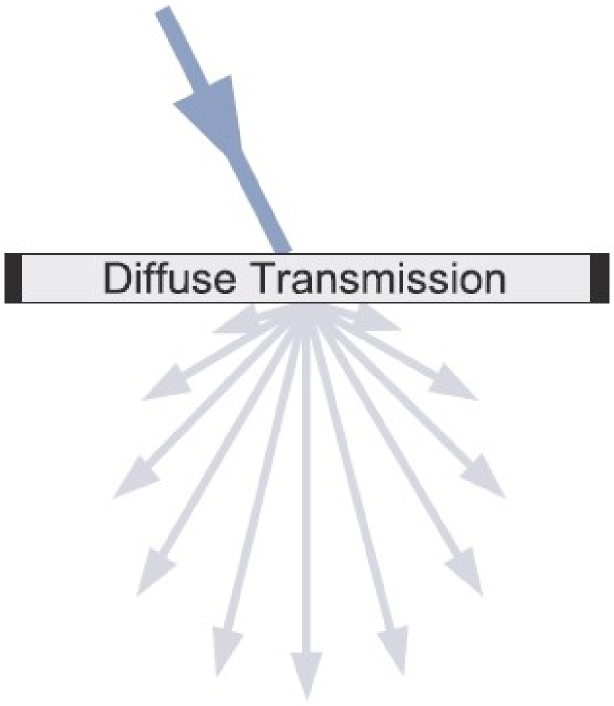
$$I = I_0 e^{-\beta c x}$$

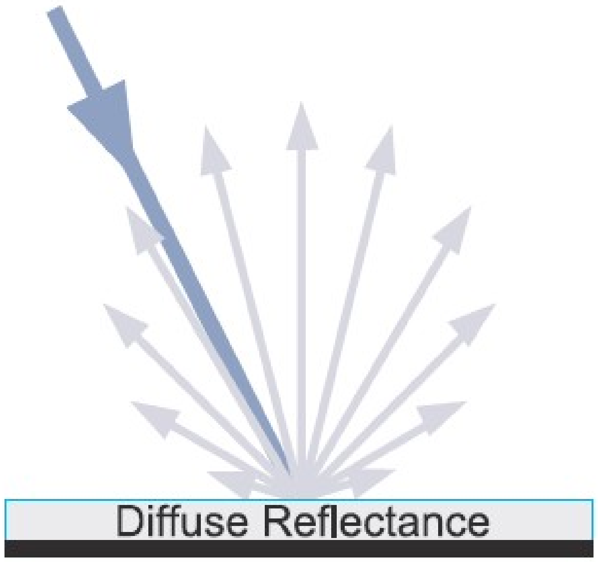
- Where:
  - I = intensity of transmitted light
  - I_0 = intensity of light entering the material (excluding surface reflection)
  - β = absorption per concentration coefficient (inverse length per inverse grams or moles per litre)
  - c = the concentration of the absorbing material
  - x = the path length (length)

Diffusion (Scattering)

- When light strikes a perfectly smooth surface, the reflection is specular, as explained in the slides on Reflection.

- When light strikes a rough surface, the light is reflected or transmitted in many different directions at once, which is called diffusion or scattering.





Diffusion (Scattering)

- The amount of diffuse transmission or reflection that occurs when light moves through one material to strike another material depends on two factors:
  - the difference in refractive index between the two materials
  - the size and shape of the particles in the diffusing material compared to the wavelength of the light
- For example, the molecules in air happen to be the right size to scatter light with shorter wavelengths, giving us blue sky.
- One method of describing diffusion is the bidirectional scatter distribution function (BSDF), which quantifies scatter and its effects.

Filtering

- A transmissive filter is a material that absorbs some wavelengths and transmits others, while a reflective filter absorbs some wavelengths and reflects others.

- For example, a red filter absorbs all but the longest wavelengths of visible light; a reflective red filter reflects the longest wavelengths, and a transmissive red filter transmits the longest wavelengths.

- The amount of light absorbed by a filter depends on the filter’s thickness.

Basic Radiometric and Photometric Principles

Basic Radiometric and Photometric Principles

- Radiometry is the study of optical radiation — light, ultraviolet radiation, and infrared radiation.
- Photometry, on the other hand, is concerned with humans' visual response to light.
- Radiometry is concerned with the total energy content of the radiation, while photometry examines only the radiation that humans can see.
- Thus, the most common unit in radiometry is the watt (W), which measures radiant flux (power), while the most common unit in photometry is the lumen (lm), which measures luminous flux.
- For monochromatic light of 555 nm, 1 watt = 683 lumens.

Basic Radiometric and Photometric Principles

- For light at other wavelengths, the conversion between watts and lumens is slightly different, because the human eye responds differently to different wavelengths.

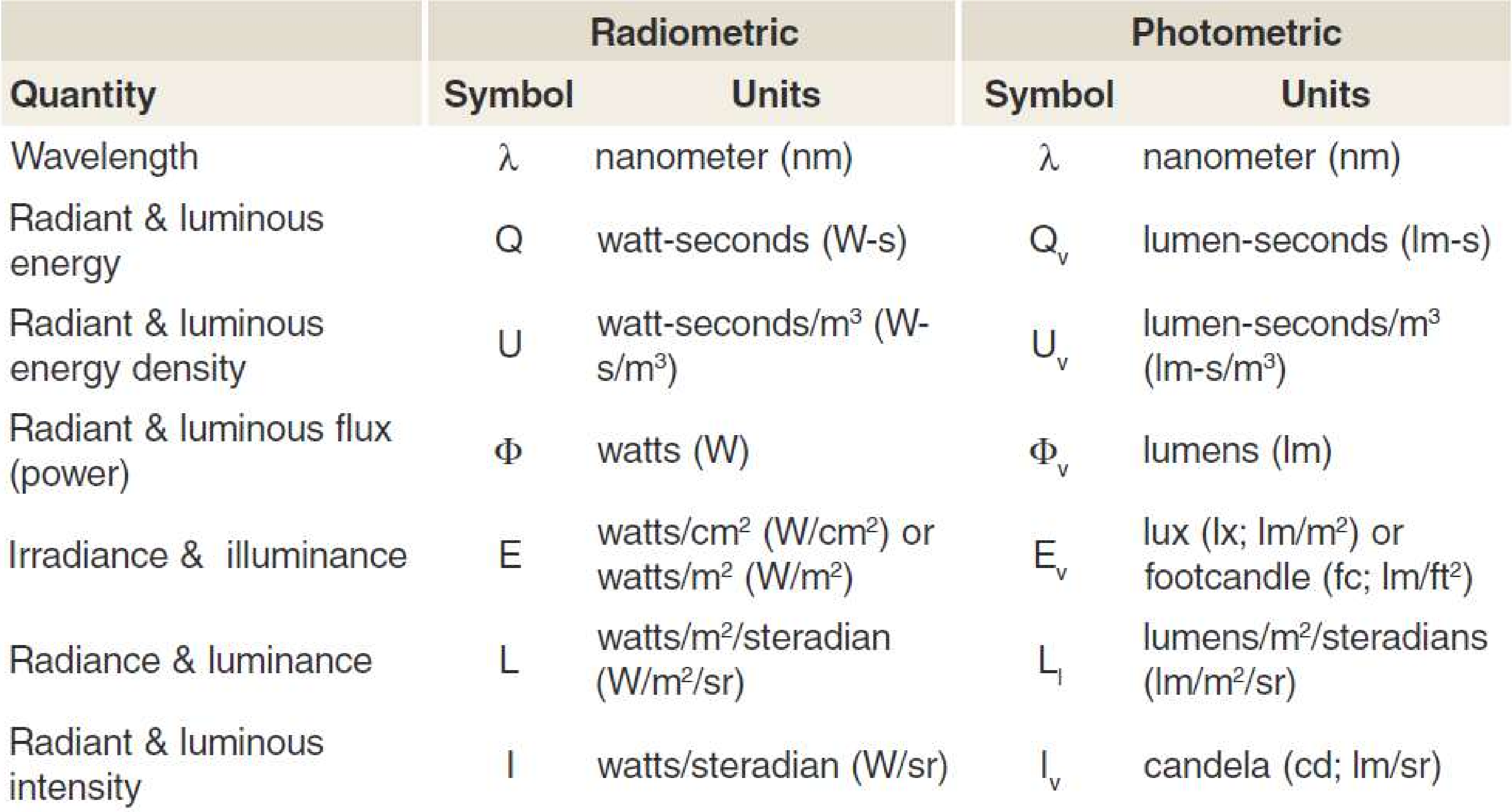
- Similarly, as explained in Section 3.8, “Radiant and Luminous Intensity,” radiant intensity is measured in watts/steradian (W/sr), while luminous intensity is measured in candelas (cd, or lm/sr).

- This booklet follows the convention of designating the photometric quantities by the same symbol used for the analogous radiometric quantity, but followed by a subscript v.

- This notation emphasizes that the theory of photometry is formally identical to that of radiometry and thus that the formal properties of radiometry apply equally well to photometry.

Radiometric and Photometric Quantities

- The following table summarizes the most common radiometric and photometric quantities, along with their symbols and units.



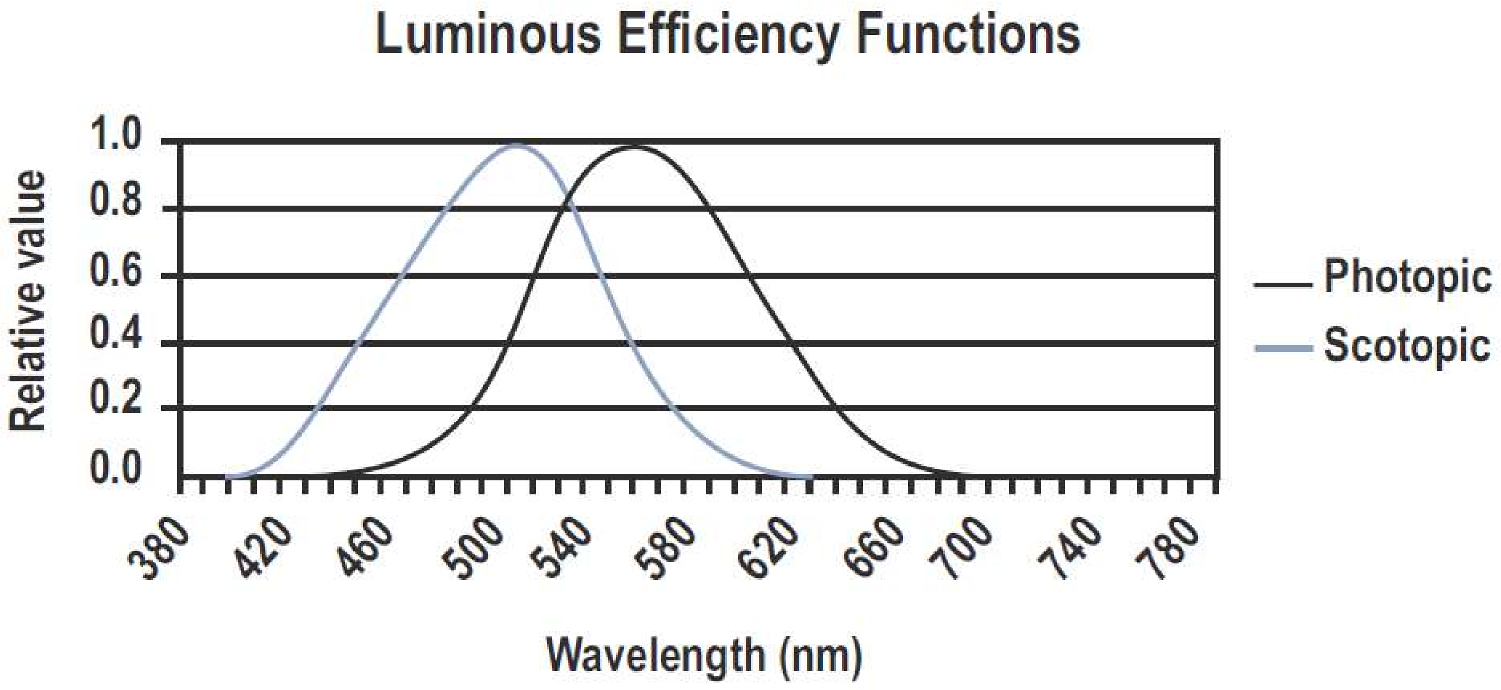
	Radiometric		Photometric	
Quantity	**Symbol**	**Units**	**Symbol**	**Units**
Wavelength	λ	nanometer (nm)	λ	nanometer (nm)
Radiant & luminous energy	Q	watt-seconds (W-s)	Q_v	lumen-seconds (lm-s)
Radiant & luminous energy density	U	watt-seconds/m^3 (W-s/m^3)	U_v	lumen-seconds/m^3 (lm-s/m^3)
Radiant & luminous flux (power)	Φ	watts (W)	Φ_v	lumens (lm)
Irradiance & illuminance	E	watts/cm^2 (W/cm^2) or watts/m^2 (W/m^2)	E_v	lux (lx; lm/m^2) or footcandle (fc; lm/ft^2)
Radiance & luminance	L	watts/m^2/steradian (W/m^2/sr)	L_l	lumens/m^2/steradians (lm/m^2/sr)
Radiant & luminous intensity	I	watts/steradian (W/sr)	I_v	candela (cd; lm/sr)

Spectral Response

- Even within the narrow spectrum of visible light, the human eye is more sensitive to some wavelengths than to others.
- This sensitivity depends on whether the eye is adapted for bright light or darkness because the human eye contains two types of photoreceptors — cones and rods.
- When the eye is adapted for bright light, called photopic vision (luminance levels generally greater than about 3.0 cd/m2), the cones dominate.
- At luminance levels below approximately 0.001 cd/m2, the rods dominate in what is called scotopic vision.

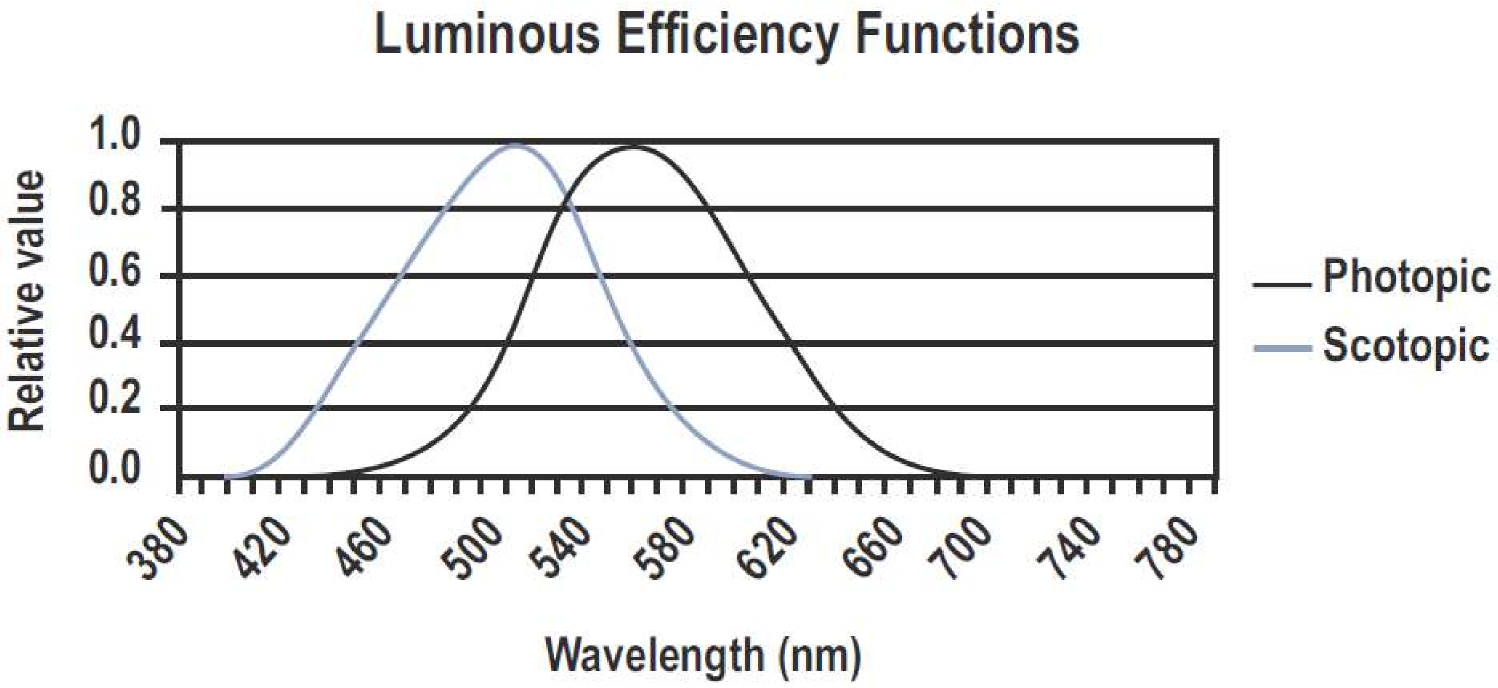
Spectral Response

- Between these two luminance levels, mesopic vision uses both rods and cones.
- The figure below shows the relative sensitivity to various wavelengths for cones (photopic) and rods (scotopic).



Spectral Response

- Standard luminous efficiency functions have not yet been defined for the mesopic region.
- However, there is a gradual shift from a peak spectral sensitivity at 555 nm for cone vision to a peak spectral sensitivity at 507 nm for rod vision as light levels are reduced.



Spectral Response

- The CIE selected the wavelength 555 nm, the peak of the photopic luminous efficiency function, as the reference wavelength for the lumen, the standard photometric unit of light measurement.

- By definition, there are 683 lm/W at 555 nm and the lumens at all other wavelengths are scaled according to either the photopic or the scotopic luminous efficiency functions.

- For example, at 507 nm there are 1700 lm/W when the scotopic luminous efficiency function is used, but only 304 lm/W when the photopic luminous efficiency function is used.

- Nearly every light measurement uses the photopic luminous efficiency function.

Solid Angle

- A solid angle is the three-dimensional equivalent to a two-dimensional angle. In the United States, the unit of measure for an angle is the degree, but the Système Internationale (SI), or metric, unit of measure for an angle is the radian.

- According to the Cambridge Dictionary of Science and Technology, the radian is “the angle subtended at the centre of a circle by an arc equal in length to the radius.”

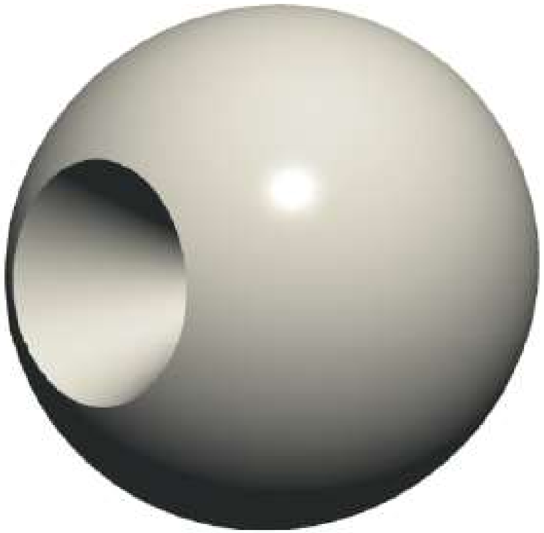
- For example, in a circle with a radius of 6 cm, a 1- radian angle intersects an arc of the circle that is exactly 6 cm long. Just as there are 360 degrees in a circle, there are exactly 2π radians in a circle.

Solid Angle

- A solid angle is measured in steradians, the three-dimensional equivalent of radians.

- A steradian (sr) is defined in the Cambridge Dictionary of Science and Technology as “the solid angle subtended at the centre of a sphere by an area on its surface numerically equal to the square of the radius.”

- The figure below shows a cutaway figure of a sphere, with a cone-shaped solid angle measuring 1 steradian removed from it.



Solid Angle

- The figure below shows a view of the removed solid angle measuring 1 steradian. For example, a one steradian section of a sphere that has a 1-meter radius subtends a surface area of one square meter.

- Note: The section of the sphere does not have to be regular.

- Regardless of its shape, its solid angle (Ω), in steradians, is equal to its surface area (A) divided by the square of the sphere's radius (r^2).

Radiant and Luminous Energy and Energy Density

- Radiant and luminous energy, denoted by the symbols Q and Qv, respectively, are the measures of all the energy received at a particular point or all the energy contained in a particular radiation field.

- Radiant energy is measured in watt-seconds, while luminous energy is measured in lumen-seconds.

- Radiant and luminous energy density, denoted as U and Uv, are the amounts of energy per unit volume, measured in either watt-seconds/m^3 or lumen-seconds/m^3

Radiant and Luminous Flux

- Radiant flux or power, denoted as F, is the flow rate of radiant energy.
- It is measured in watts (joules per second). Luminous flux, denoted as Fv, is measured in lumens.
- The CIE defines the lumen in terms of the luminous flux of monochromatic radiation at 555 nm.
- This definition of the lumen applies to both photopic and scotopic photometry.
- For other wavelengths, the luminous flux must be weighted by the appropriate photopic or scotopic luminous efficiency function, which is defined in the slide on “Spectral Response.”

Spectral Luminous Efficacy

- Spectral luminous efficacy, Kλ, is the ratio of luminous flux to radiant flux.
- In other words, spectral luminous efficacy describes the absolute eye response of the normalized efficiency function.
- The CIE defines Kλ for photopic vision as 683 lumens/watt at 555 nm.

Spectral Luminous Efficacy

- For other wavelengths, Kλ for photopic vision can be calculated using the following equation:

$$K'_{\lambda} = K'_{m} V'_{\lambda}$$

- Where:
  - Km = 683 lm/W (the maximum sensitivity for photopic vision, which occurs at 555 nm)
  - Vλ = the value of the photopic spectral luminous efficiency function for that wavelength

Spectral Luminous Efficacy

- For scotopic vision, spectral luminous efficacy is denoted by K´λ, and can be calculated using the following equation:

$$K'_{\lambda} = K'_{m} V'_{\lambda}$$

- Where:
  - K´m = 1700 lm/W (the maximum sensitivity for scotopic vision, which occurs at 510 nm)
  - V´λ = the value of the scotopic spectral luminous efficiency function for that wavelength

Radiant Exitance, Irradiance (Radiant Incidence), and Illuminance

- Radiant exitance, denoted by the letter M, is the radiant flux per unit area leaving the surface of a source of radiation.
- In other words, radiant exitance is the flux density.
- Similarly, irradiance or radiant incidence, denoted by the letter E, is the flux per unit area received by a surface. Irradiance and radiant exitance are both measured in W/cm^2 or W/m^2.
- Illuminance (Ev) is a measure of photometric flux per unit area, or visible flux density.
- Illuminance is measured in either lux (lm/m^2) or footcandles (lm/ft^2).

Radiant Exitance, Irradiance (Radiant Incidence), and Illuminance

- One steradian has a projected area of 1 square foot at a distance of 1 foot, and an area of 1 square meter at a distance of 1 meter.

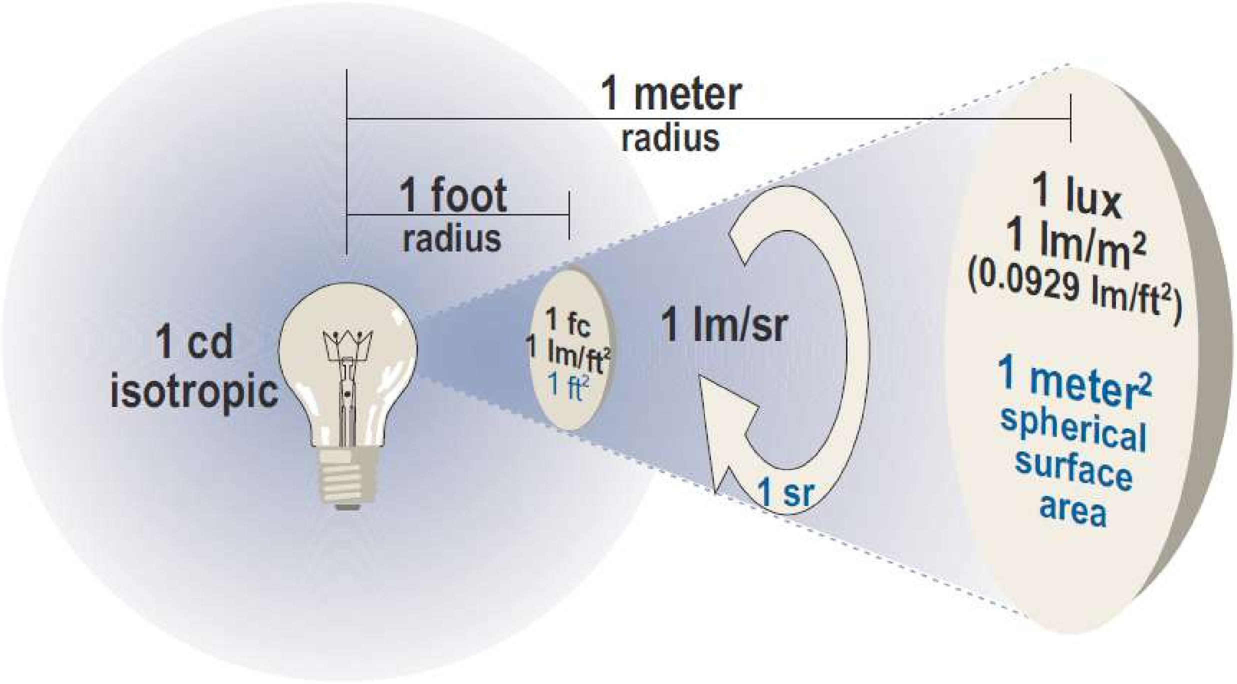
- Therefore, a 1-candela (1 lm/sr) light source produces 1 lumen per square foot at a distance of 1 foot, and 1 lumen per square meter at 1 meter.

- Note that as the luminous flux projects farther from the source, it becomes less dense.

- In the next but one slide for example, the illuminance decreases from 1 lm/ft2 at a distance of 1 foot to 0.0929 lm/ft^2 (1 lm/m^2) at a distance of 3.28 feet (1 m).

Radiant Exitance, Irradiance (Radiant Incidence), and Illuminance

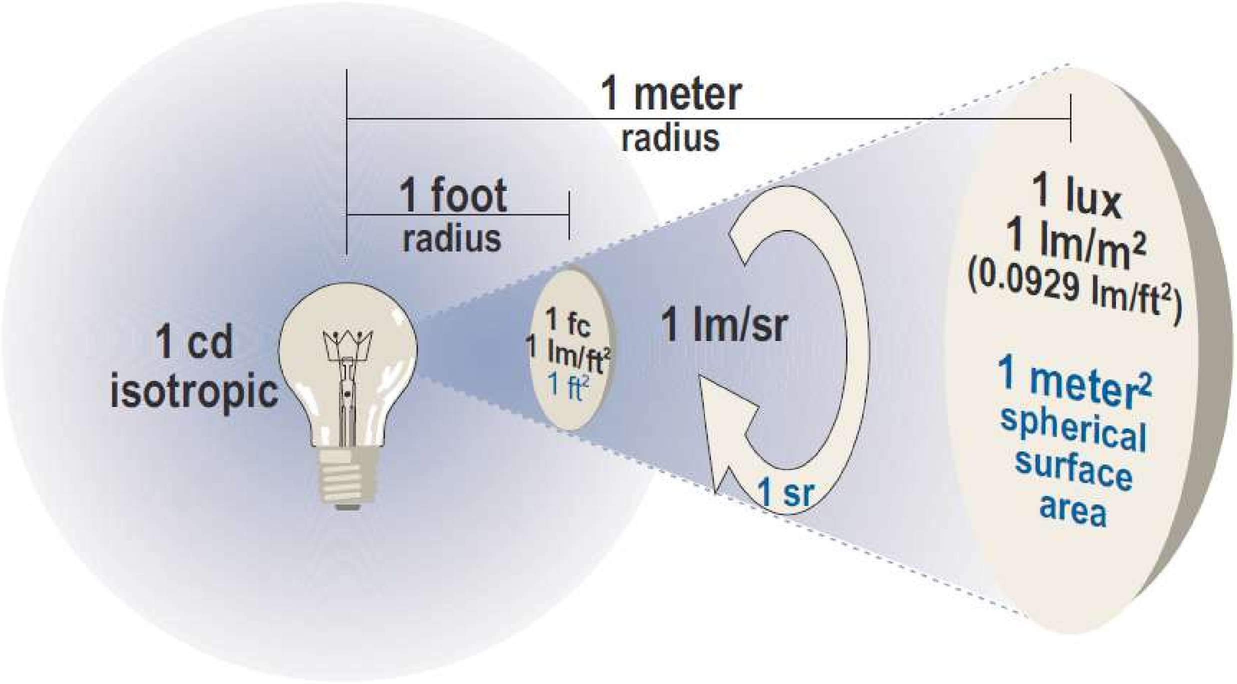
- In the figure below the lamp is producing a candela.
- A 1-cd light source emits 1 lm/sr in all directions (isotropically).



Radiant Exitance, Irradiance (Radiant Incidence), and Illuminance

- As explained in Section 3.3, “Solid Angle,” one steradian has a projected area of 1 square foot at a distance of 1 foot, and an area of 1 square meter at a distance of 1 meter.

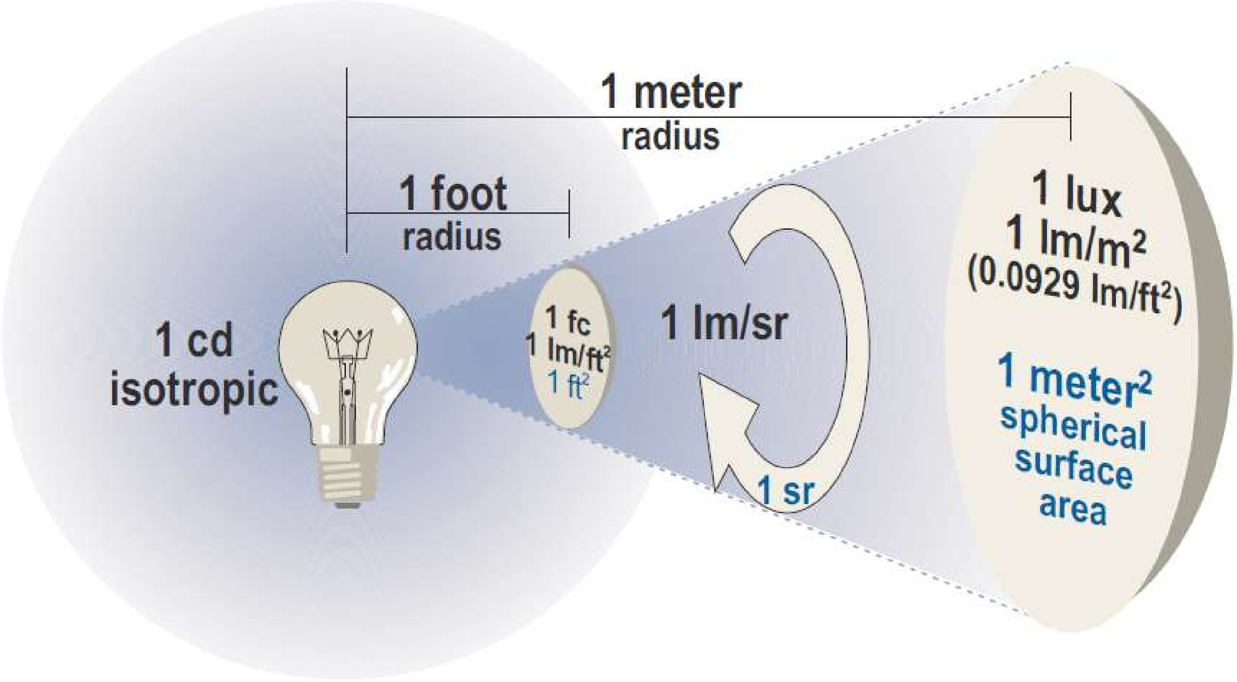
- Therefore, a 1-candela (1 lm/sr) light source produces 1 lumen per square foot at a distance of 1 foot, and 1 lumen per square meter at 1 meter.



Radiant Exitance, Irradiance (Radiant Incidence), and Illuminance

- Note that as the luminous flux projects farther from the source, it becomes less dense.

- In the example, the illuminance decreases from 1 lm/ft^2 at a distance of 1 foot to 0.0929 lm/ft^2 (1 lm/m^2) at a distance of 3.28 feet (1 m).



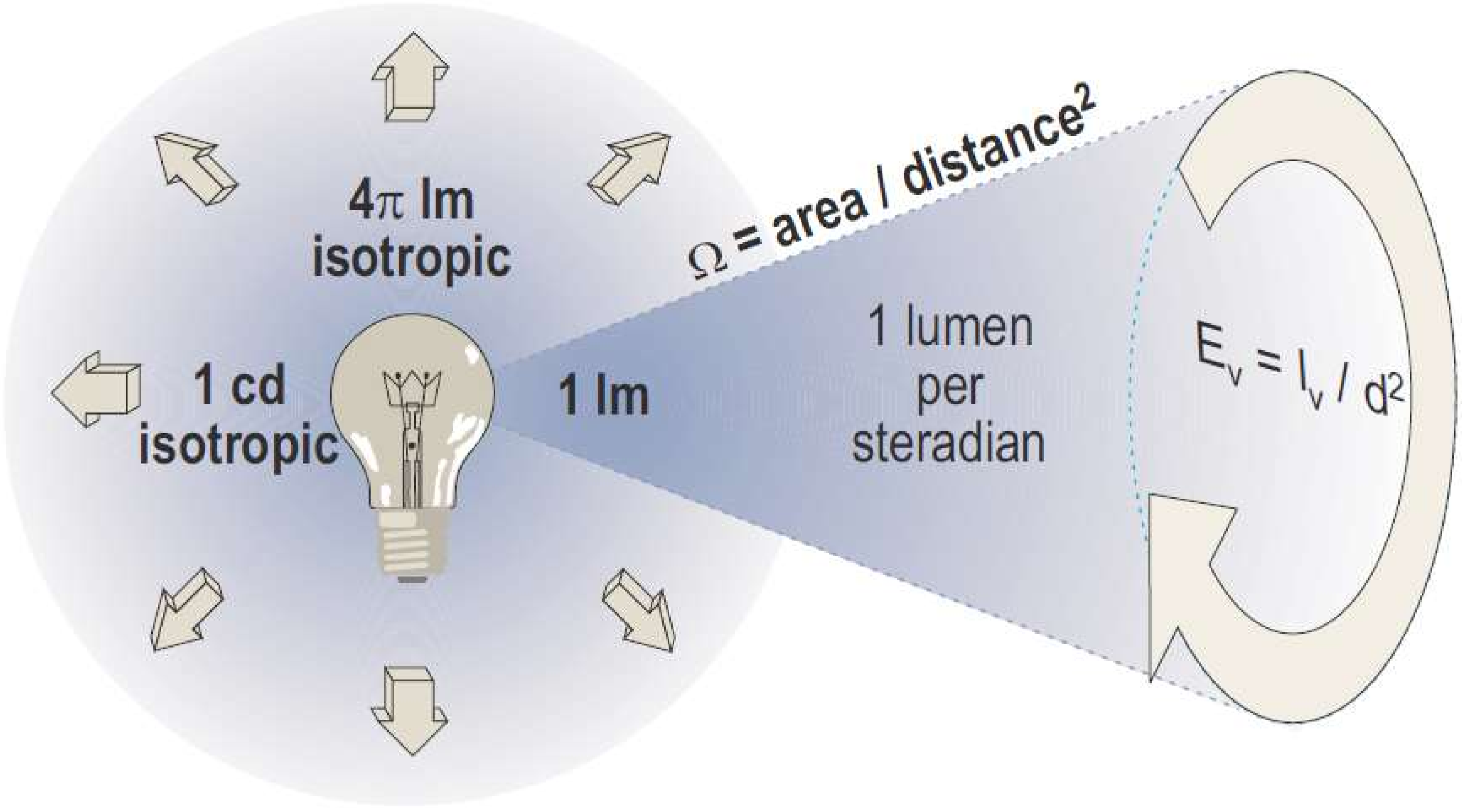
Radiance and Luminance

- Radiance, denoted by the letter L, is the irradiance per unit solid angle.
- It is measured in W/m^2/sr.
- Luminance (Lv) is the illuminance per unit solid angle, measured in lm/m^2/sr.
- In other words, luminance is the density of visible radiation (photopic or scotopic) in a given direction.
- Luminance is the measurable quantity that most resembles a person’s perception of brightness, although they are not quite the same.
- For ambertian surfaces you can convert between luminance and illuminance with the following equation:

$$L_v = E_v / \pi$$

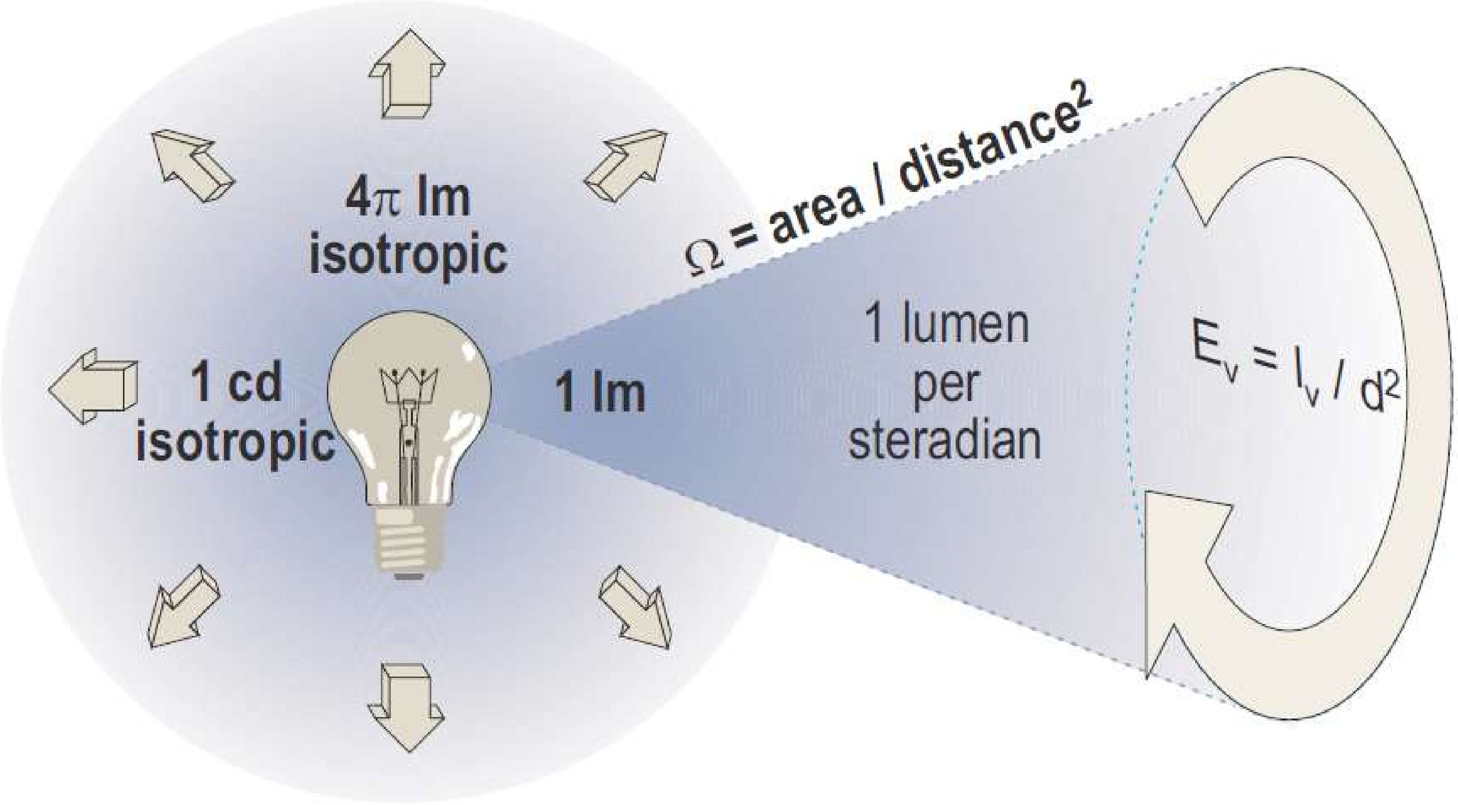
Radiant and Luminous Intensity

- Radiant intensity, denoted by the letter I, is the amount of power radiated per unit solid angle, measured in W/sr.
- Luminous intensity is the amount of visible power per unit solid angle, measured in candelas (cd, or lm/sr).



Radiant and Luminous Intensity

- For example, in the figure below a 1-cd light source is emitting 1 lm/sr in all directions (isotropically).
- Luminous intensity (Iv) is the fundamental SI quantity for photometry.
- The candela is the fundamental unit from which all other photometric units are derived.



Basic Radiometric and Photometric Measurement

Basic Radiometric and Photometric Measurement

The Inverse Square Law

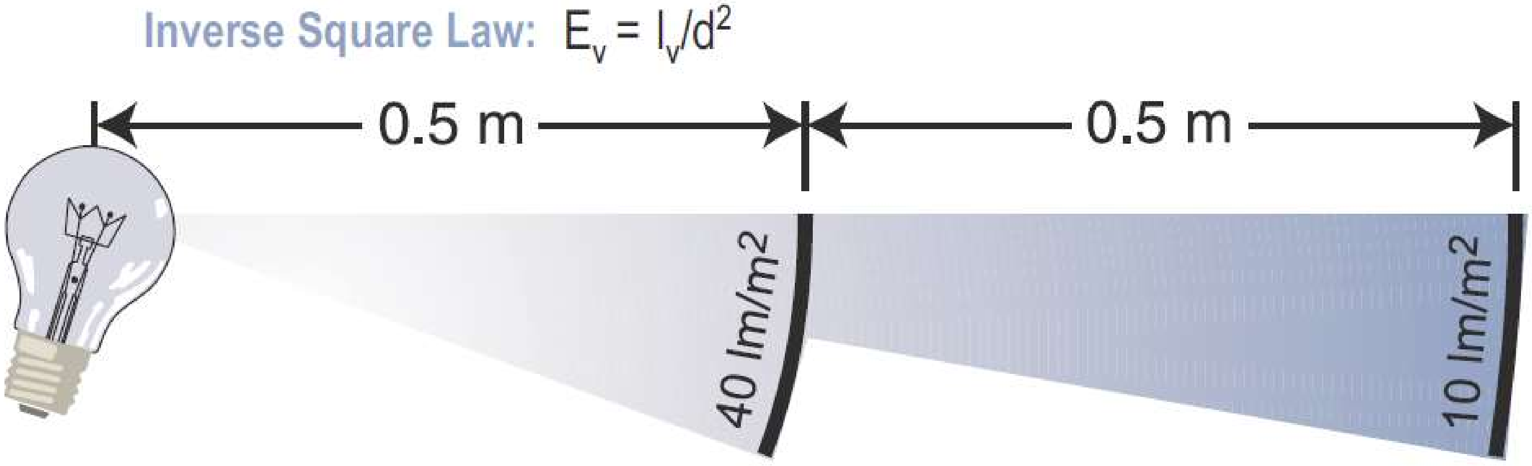
- As a surface that is illuminated by a light source moves away from the light source, the surface appears dimmer.
- In fact, it becomes dimmer much faster than it moves away from the source.
- The inverse square law, which quantifies this effect, relates illuminance (Ev) and intensity (Iv) as follows:

$$E_v = I_v / d^2$$

- Where d = the distance from the light source.

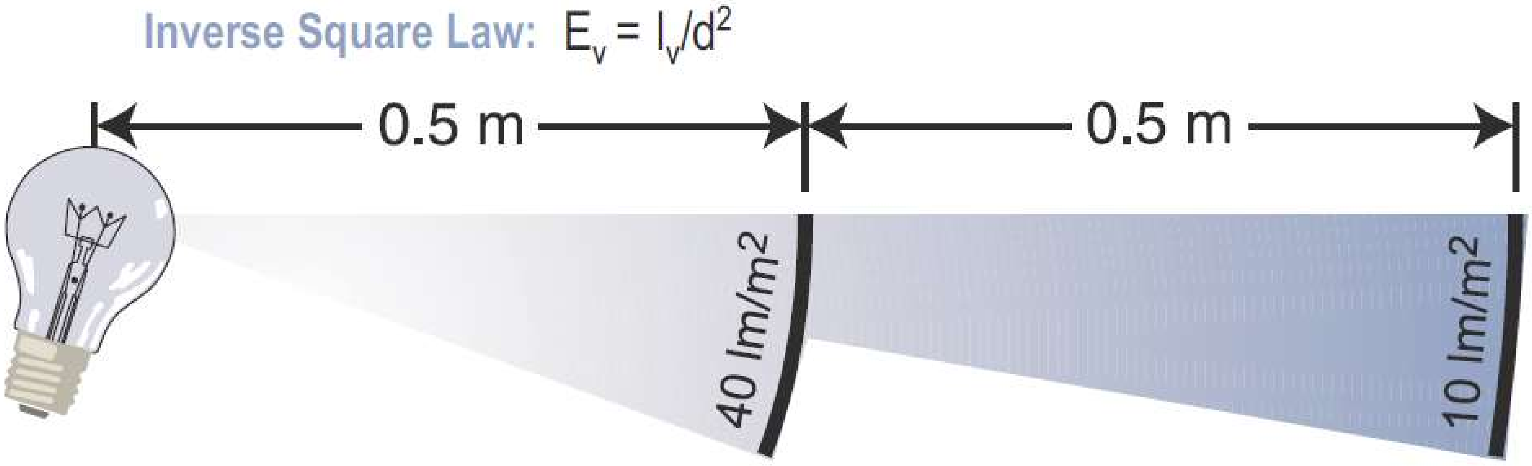
Basic Radiometric and Photometric Measurement

- For example, if the illuminance on a surface is 40 lux (lm/m2) at a distance of 0.5 meters from the light source, the illuminance decreases to 10 lux at a distance of 1 meter, as shown in the following figure below.



Basic Radiometric and Photometric Measurement

- Note: The inverse square law can only be used in cases where the light source approximates a point source.



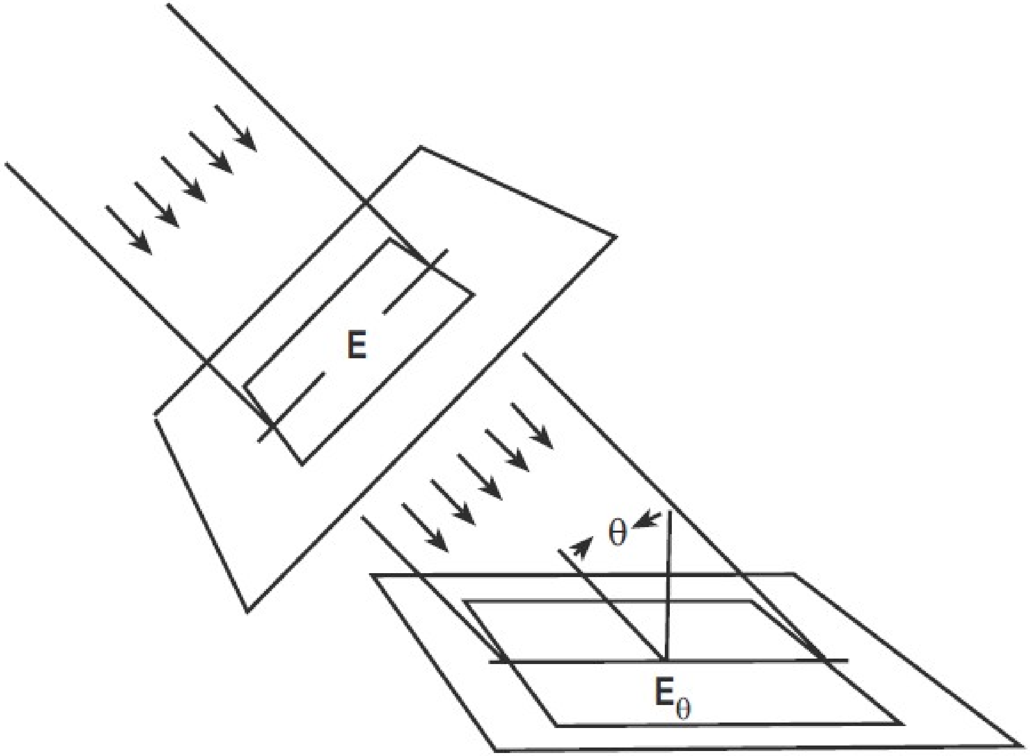
- For Lambertian light sources a useful guideline to use for illuminance measurements is the “five times rule”: the distance from the measurement point to the light source should be greater than five times the largest dimension of the source for an accurate measurement.

- However, the five times rule does not work for a strongly directional light source

Lambert’s Cosine Law

- Lambert’s cosine law states that the illuminance falling on any surface depends on the cosine of the light’s angle of incidence, θ.
- Remember from that the angle of incidence is measured from a line normal to the surface.

$$E_\theta = E\cos\theta$$

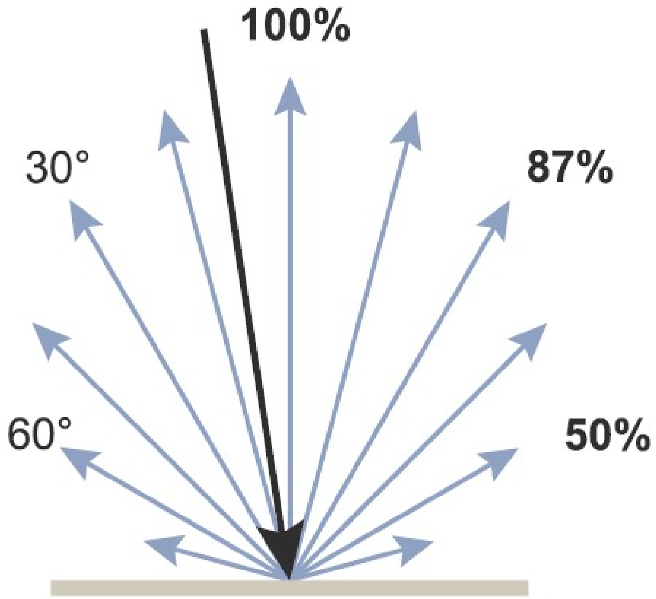


Lambertian Emission and Reflection

- The figure below shows a Lambertian reflection from a surface. Notice that the reflection follows the cosine law — the amount of reflected energy in a particular direction (the intensity) is proportional to the cosine of the reflected angle.

- Remember that luminance is intensity per unit area. Because both intensity and apparent area follow the cosine law, they remain in proportion to each other as the viewing angle changes.

- Therefore, luminance remains constant while luminous intensity does not.



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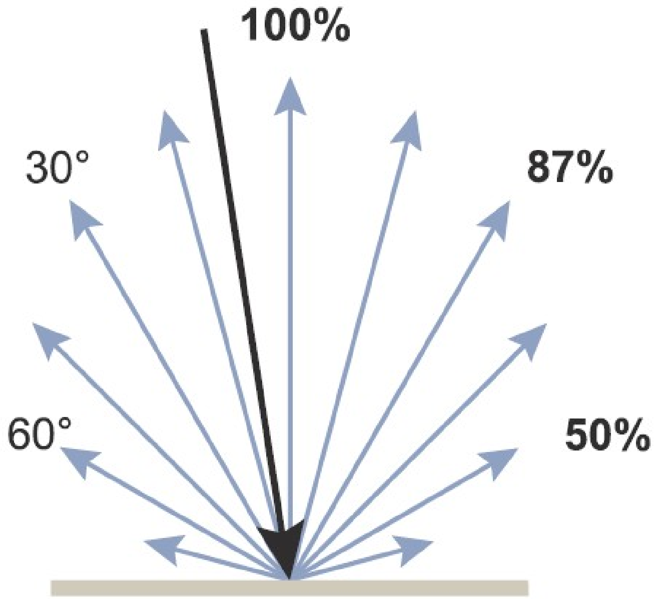


Light Sources

Light Sources

- The lighting industry makes millions of electric light sources, called lamps.

- Those used for providing illumination can be divided into three general classes: incandescent, discharge, and solid-state lamps. Incandescent lamps produce light by heating a filament until it glows.

- Discharge lamps produce light by ionizing a gas through electric discharge inside the lamp.

- Solid-state lamps use a phenomenon called electroluminescence to convert electrical energy directly to light.

Light Sources

- In addition to manufactured light sources, daylight — sunlight received on the Earth, either directly from the sun, scattered and reflected by the atmosphere, or reflected by the moon — provides illumination.

- The prime characteristic of daylight is its variability.

- Daylight varies in magnitude, spectral content, and distribution with different meteorological conditions, at different times of the day and year, and at different latitudes.

- The illuminances on the Earth’s surface produced by daylight can cover a large range, from 150,000 lx on a sunny summer’s day to 1000 lx on a heavily overcast day in winter.

- The spectral composition of daylight also varies with the nature of the atmosphere and the path length through it.

Incandescent Lamps

- Incandescent lamp technology uses electric current to heat a coiled tungsten filament to incandescence.

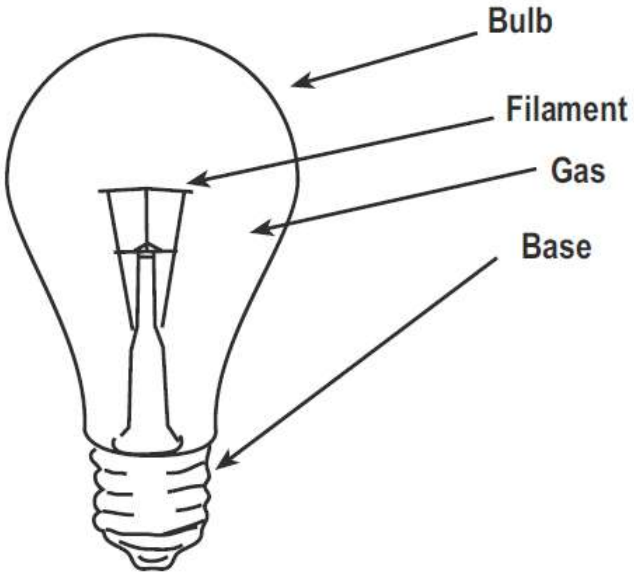
- The glass envelope contains a mixture of nitrogen and a small amount of other inert gases such as argon.

- Some incandescent lamps, such as some flashlight lamps, also contain xenon.

- Some of these incandescent lamps are called xenon lamps, but are not the same as the high-pressure xenon lamps discussed in later slides.

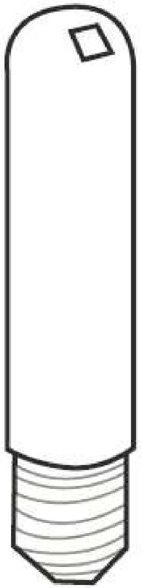
Incandescent Lamps

- Incandescent lamps have come a long way since Thomas Edison’s first carbon filament lamp, which, when introduced in 1879, had a life of about 40 hours.
- Today, commonly available incandescent lamps have average lives of between 750 and 2000 hours.
- The figure below shows the construction of a typical incandescent lamp.

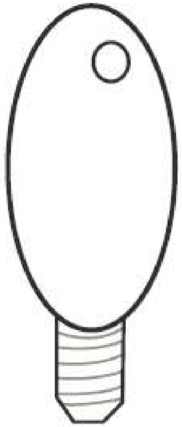


Incandescent Lamps

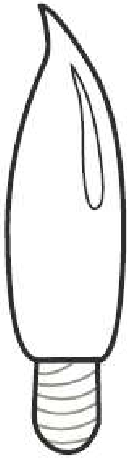
- Other commonly used bulb shapes are shown below.



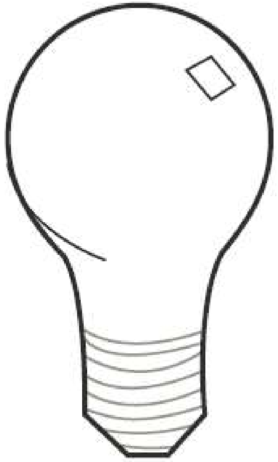
Tubular



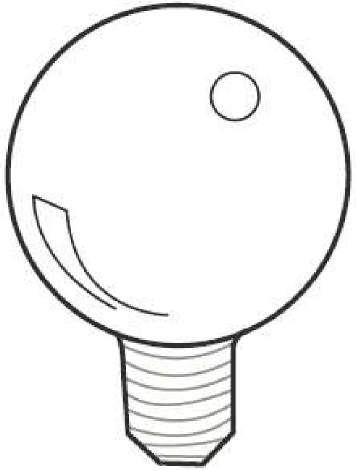
Candle



Flame



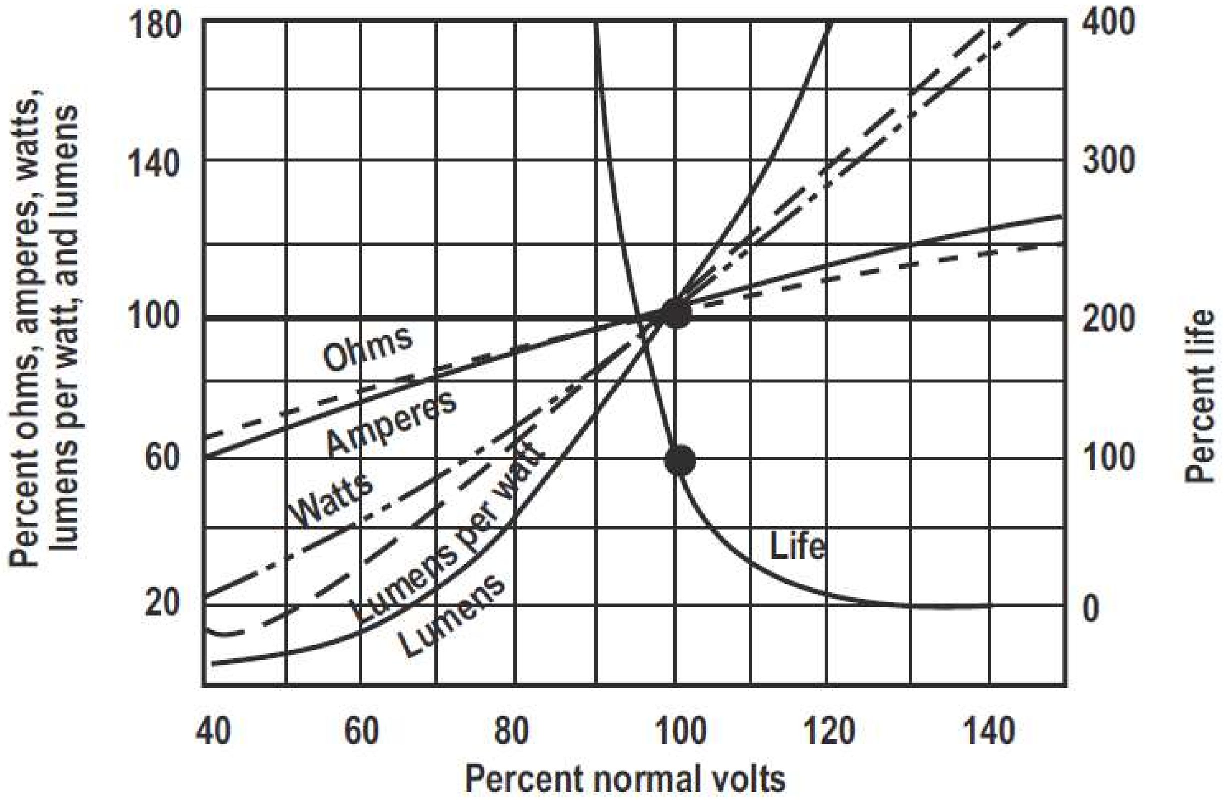
A-lamp



Globe
(G-lamp)

Incandescent Lamps

- Incandescent lamps are strongly affected by input voltage. For example, reducing input voltage from the normal 110 volts (V) to 104.5 V (95%) can double the life of a standard incandescent lamp, while increasing voltage to just 115.5 V (105% of normal) can halve its life. Voltage variations also affect light output (lumens), power (watts), and efficacy (lumens per watt), as shown below.



Halogen Lamps

- Unlike incandescent lamps, halogen lamps use a halogen gas fill (typically iodine or bromine), to produce what is called a “halogen cycle” inside the lamp.

- In the halogen cycle, halogen gas combines with the tungsten that evaporates from the lamp filament, eventually re-depositing the tungsten on the filament instead of allowing it to accumulate on the bulb wall as it does in standard incandescent lamps.

Halogen Lamps

- The tungsten- halogen lamp has several differences from incandescent lamps:
  - The lamps have a longer life (2000-3500 hours).
  - The bulb wall remains cleaner, because the evaporated tungsten is constantly re-deposited on the filament by the halogen cycle. This allows the lamp to maintain lumen output throughout its life.
  - The higher operating temperature of the filament improves luminous efficacy.
  - The lamp produces a “whiter” or “cooler” light, which has a higher correlated colour temperature (CCT) than standard incandescent lamps.
  - The bulbs are more compact, offering opportunities for better optical control. Halogen lamps are sometimes called “quartz” lamps because their higher temperature requires quartz envelopes instead of the softer glass used for other incandescent lamps.

Discharge Lamps

- Discharge lamps produce light by passing an electric current through a gas that emits light when ionized by the current.

- An auxiliary device known as a ballast supplies voltage to the lamp’s electrodes, which have been coated with a mixture of alkaline earth oxides to enhance electron emission.

- Two general categories of discharge lamps are used to provide illumination: high-intensity discharge and fluorescent lamps.

HID Lamps

- Four types of high-intensity discharge (HID) lamps are most widely available on today’s market: high-pressure mercury vapour lamps, metal-halide lamps, high-pressure sodium lamps, and xenon lamps.

High-Pressure Mercury Vapour Lamps

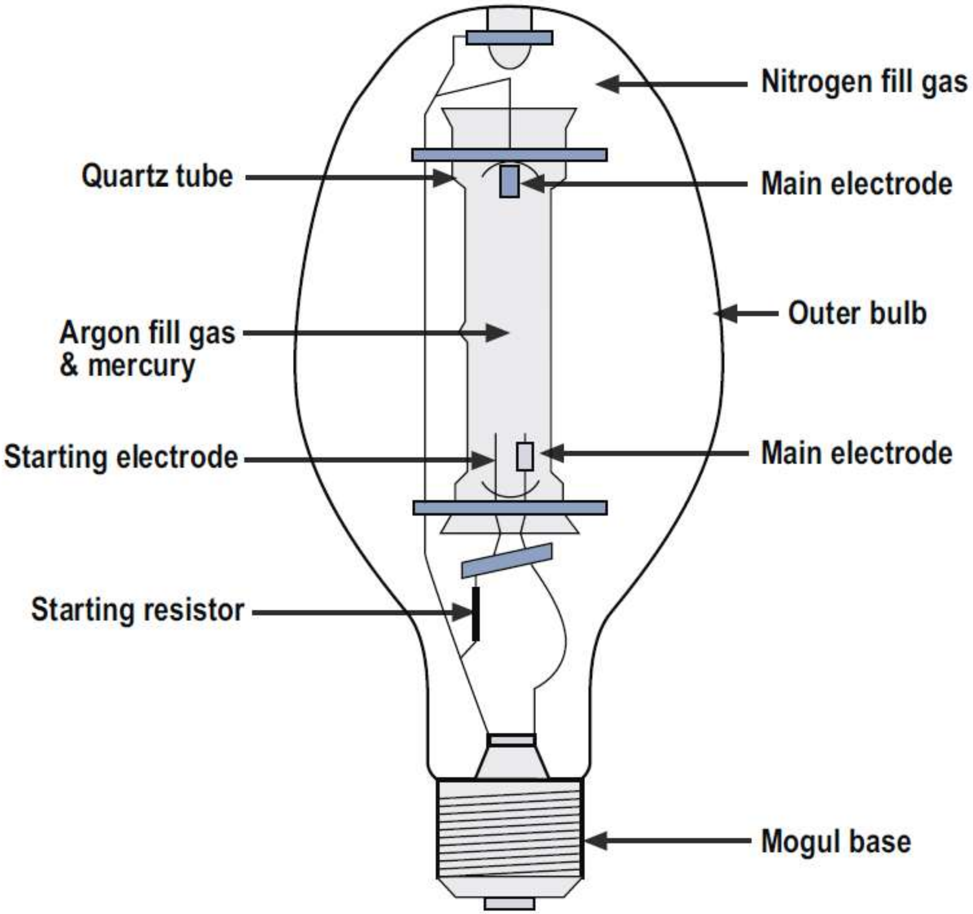
- In a high-pressure mercury vapour lamp, light is produced by an electric discharge through gaseous mercury.

- The mercury, typically along with argon gas, is contained within a quartz arc tube, which is surrounded by an outer bulb of borosilicate glass.

- The figure in the next slide shows the construction of a typical high-pressure mercury vapour lamp.

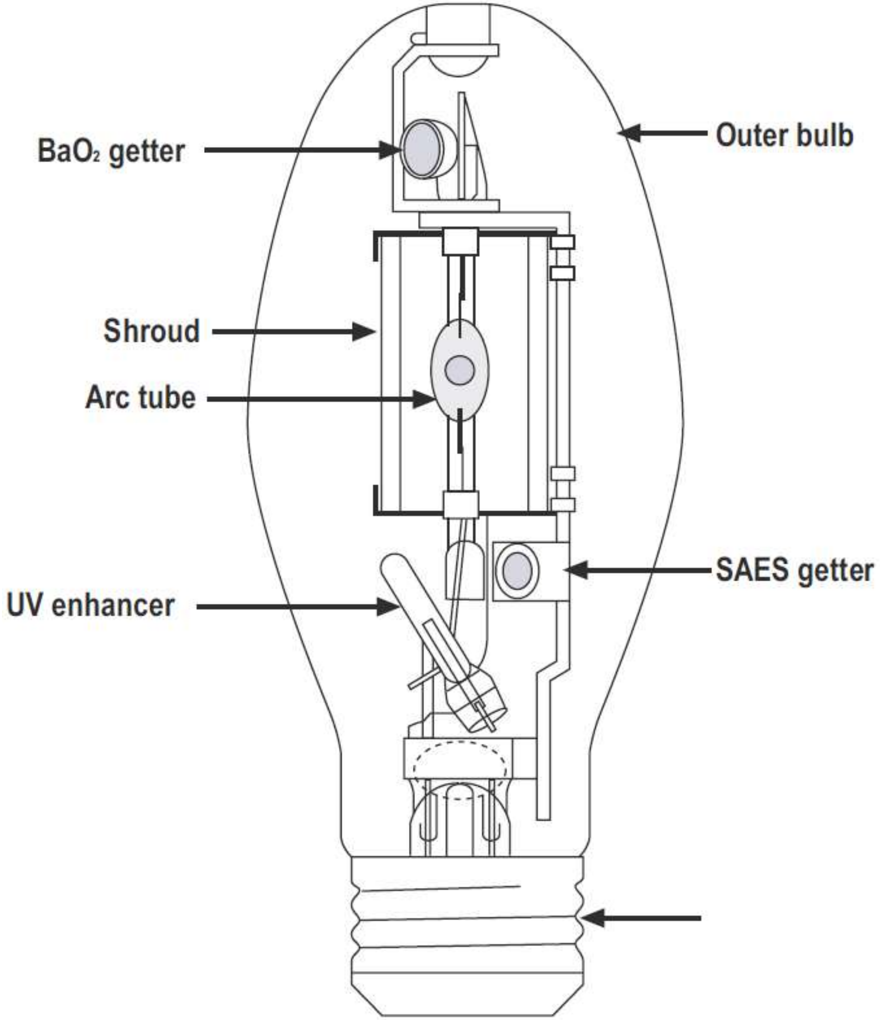
- Xenon may also be used in high-pressure mercury vapour lamps to aid starting time, and does not significantly change the visible spectrum of the lamp.

High-Pressure Mercury Vapour Lamps



Metal-Halide Lamps

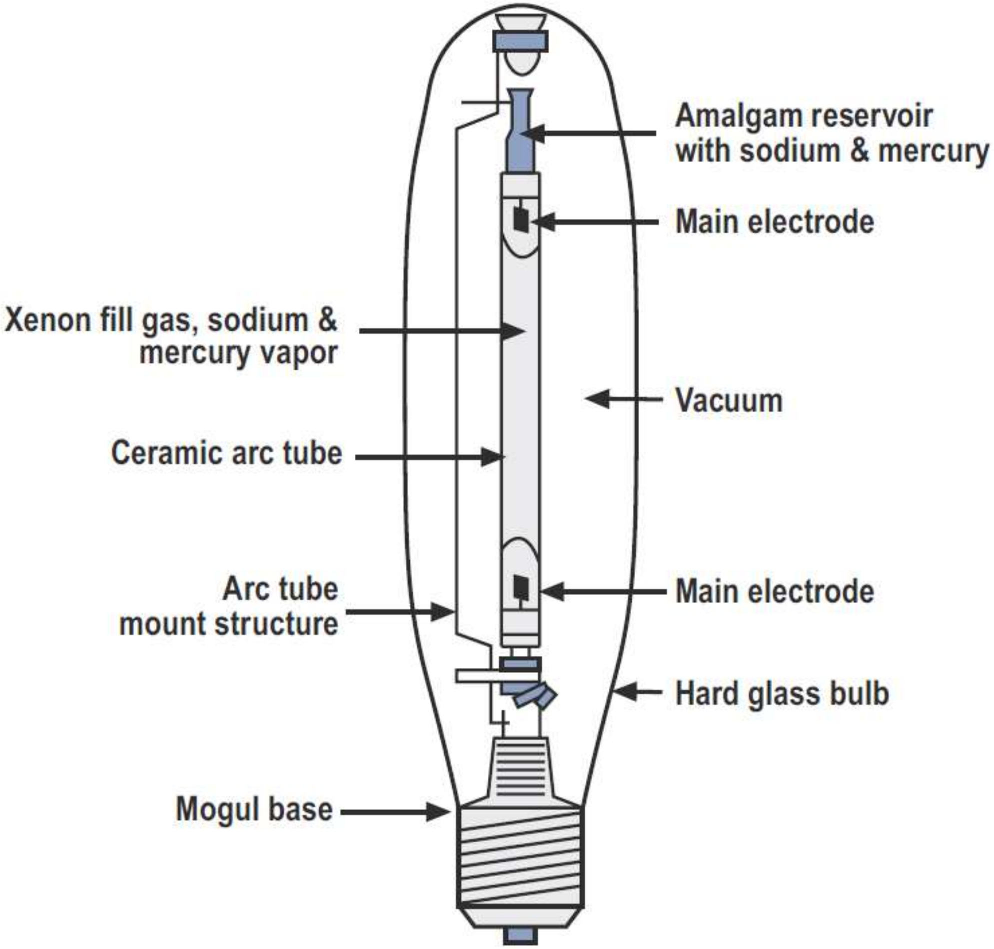
- A metal-halide lamp is a mercury vapour lamp with other metal compounds (known as halides) added to the arc tube to improve both colour and luminous efficacy.



High-Pressure Sodium Lamps

- Light is produced in a high-pressure sodium (HPS) lamp by an electric discharge through combined vapours of mercury and sodium, with the sodium radiation dominating the spectral emission.

- The hard glass outer bulb may be clear, or its inner surface may be coated with a diffuse powder to reduce the brightness of the arc tube.

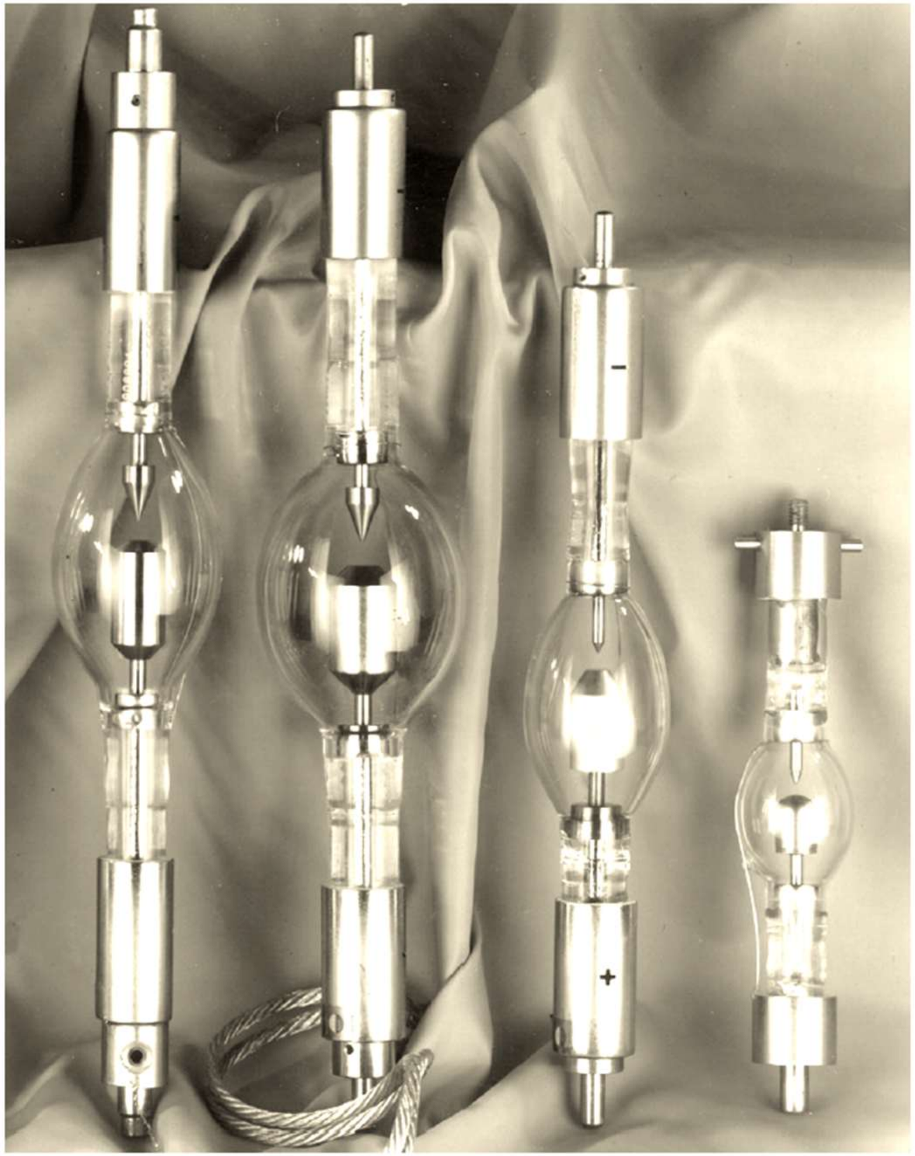


Xenon Lamps

- Unlike the other three HID lamps described here, xenon lamps do not contain mercury vapour.
- They contain xenon gas, kept at a pressure of several atmospheres. Xenon lamps are available in wattages from 5 to 32,000 watts.
- Some incandescent lamps, such as some flashlight lamps, also contain xenon.
- These incandescent lamps are sometimes called xenon lamps, but are not the same as high-pressure xenon lamps.

Xenon Lamps

- The figure to the right some examples of xenon lamps.

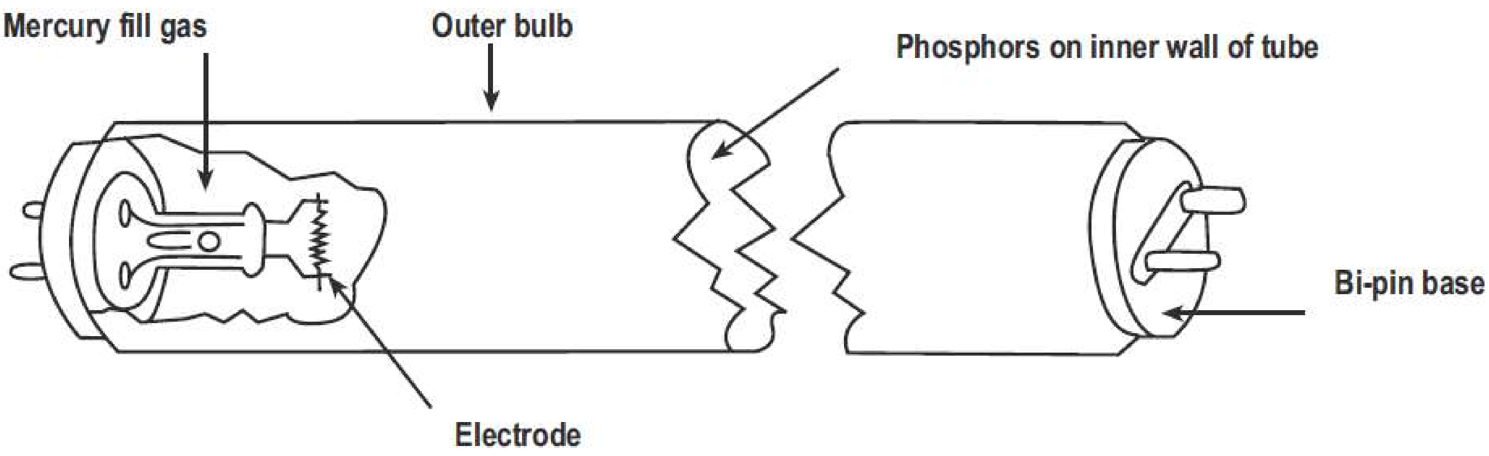


Fluorescent Lamps

- Fluorescent lighting accounts for two-thirds of all electric light in the United States.
- The fluorescent lamp is a gas discharge source that contains mercury vapour at low pressure, with a small amount of inert gas for starting.
- Once an arc is established, the mercury vapour emits ultraviolet radiation.
- Fluorescent powders (phosphors) coating the inner walls of the glass bulb respond to this ultraviolet radiation by emitting wavelengths in the visible region of the spectrum.
- Fluorescent lamps are often described in terms of the diameter of the lamp tube. For this designation, the diameter is given in eighths of an inch. For example, a T8 lamp has a diameter of one inch (eight eighths), while a T5 lamp has a diameter of 5/8 inch.

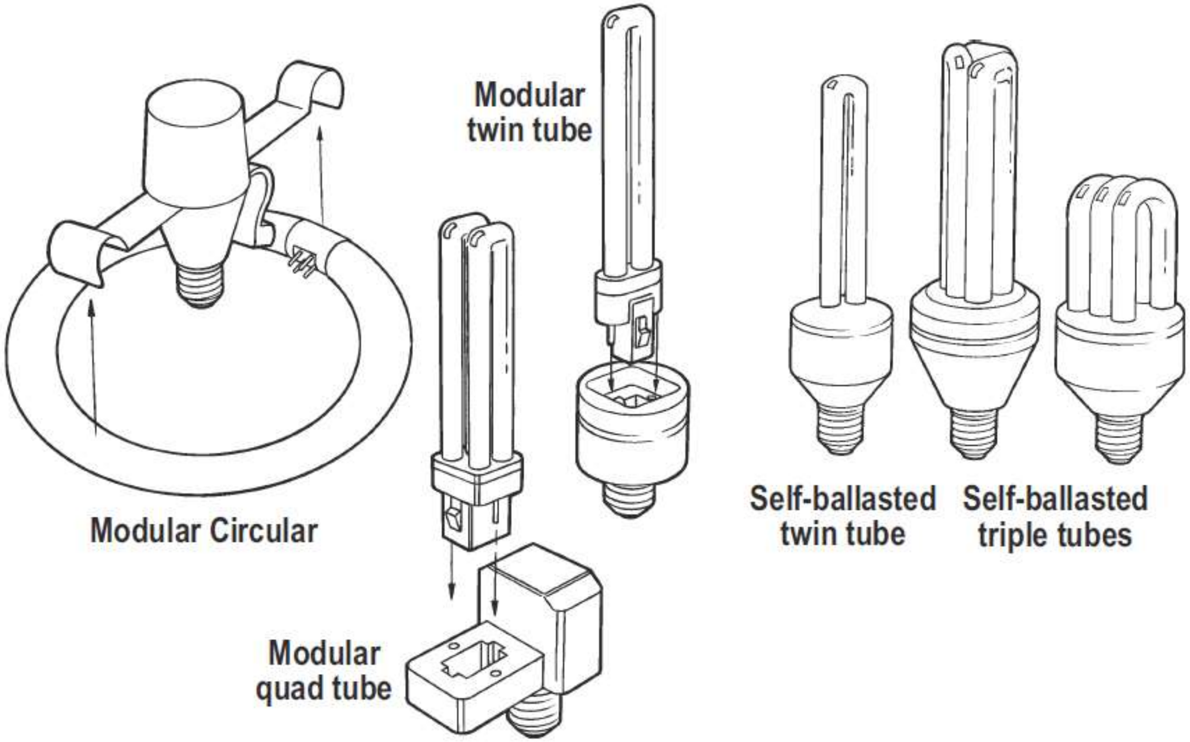
Linear Fluorescent Lamps

- Linear fluorescent lamps range in length from six inches to eight feet, and in diameter from 2/8 inch (T2) to 2-1/8 inches (T17). Their power ranges from 14 to 215 watts.



Compact Fluorescent Lamps (CFLs)

- CFLs produce light in the same manner as linear fluorescent lamps.
- Their tube diameter is usually 5/8 inch (T5) or smaller. CFL power ranges from 5 to 55 watts.



LEDs (Light-Emitting Diodes)

- LEDs are solid-state semiconductor devices that convert electrical energy directly into light.

- LEDs can be extremely small and durable; some LEDs can provide much longer lamp life than other sources.

- The plastic encapsulate and the lead frame occupy most of the volume. The light-generating chip is quite small (typically a cuboid with one side equal to 0.25 mm).

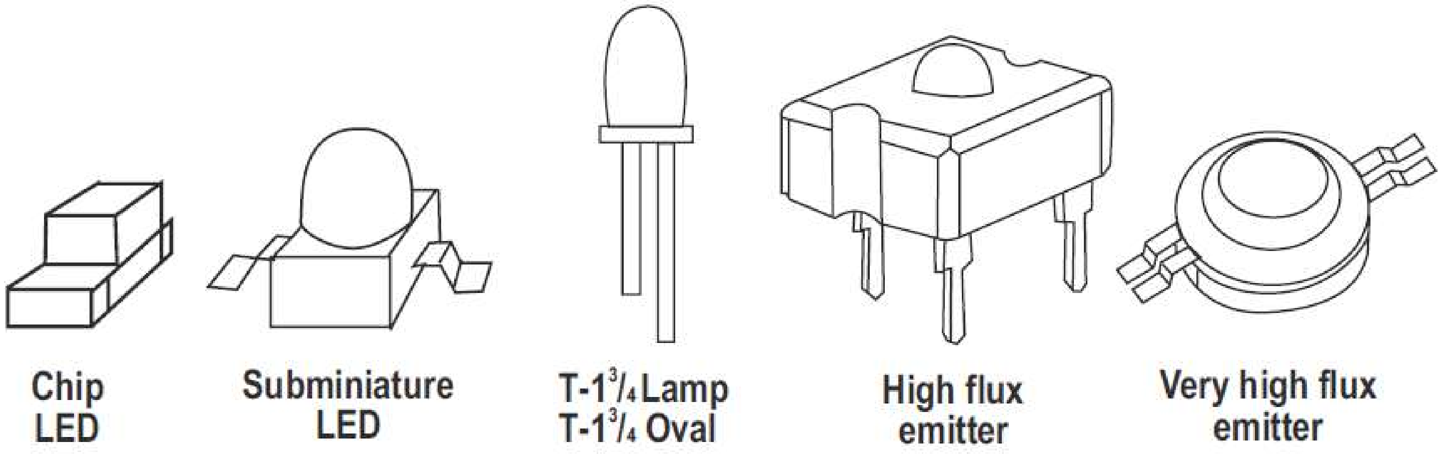
- Light is generated inside the chip, a solid crystal material, when current flows across the junctions of different materials.

- The composition of the materials determines the wavelength and therefore the colour of light.

LEDs (Light-Emitting Diodes)

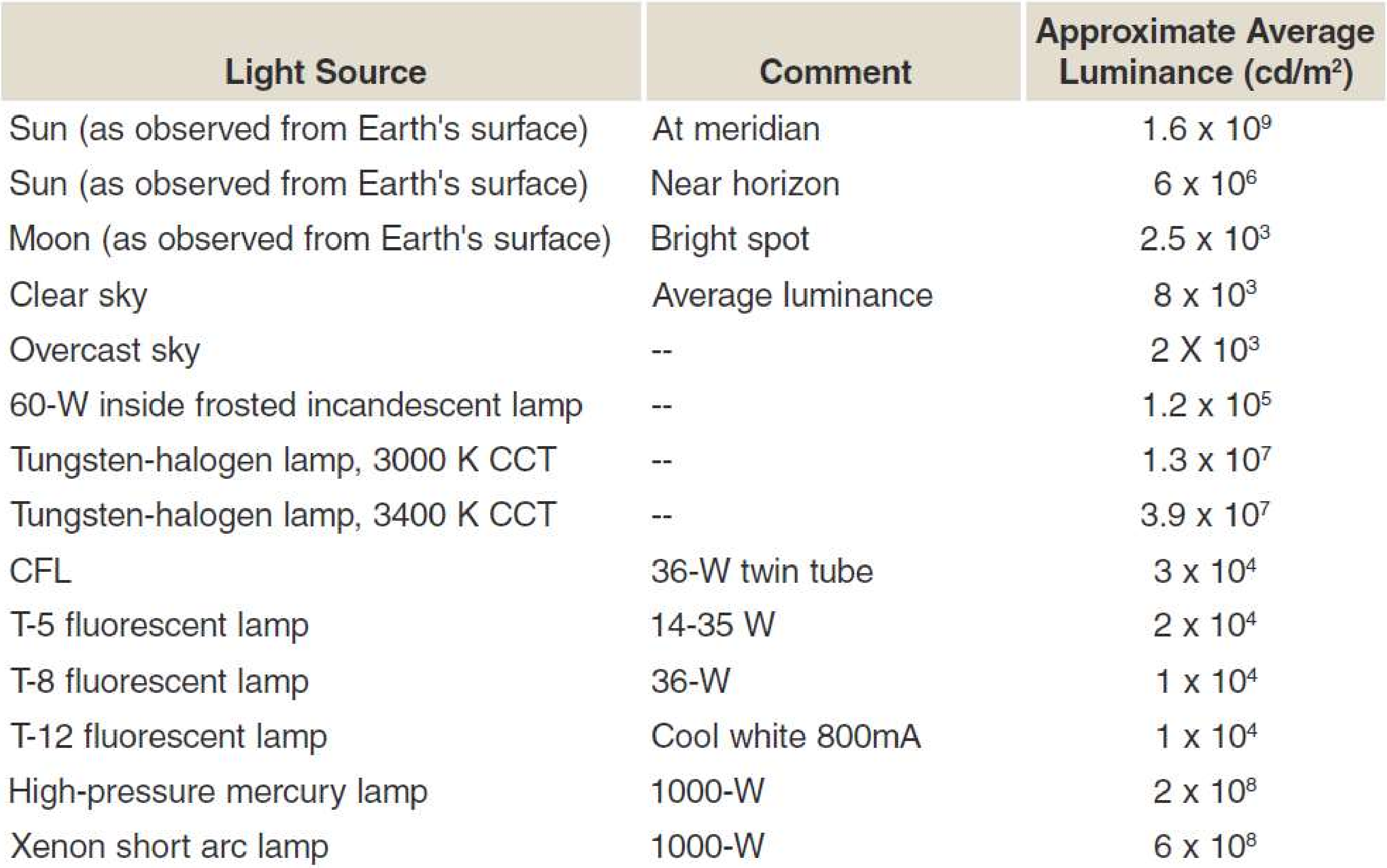
- LEDs can generate red, yellow, green, blue or white light, have a life up to 100,000 hours, and are widely used in traffic signals and for decorative purposes.

- White light LEDs are a recent advance and may have a great potential market for some general lighting applications.



Common Lamp Luminance's

- Different light sources generate a wide range of luminance's.
- The following table shows the approximate luminance's of several common light sources.



Light Source	Comment	Approximate Average Luminance (cd/m^2)
Sun (as observed from Earth's surface)	At meridian	1.6 x 10^9
Sun (as observed from Earth's surface)	Near horizon	6 x 10^6
Moon (as observed from Earth's surface)	Bright spot	2.5 x 10^3
Clear sky	Average luminance	8 x 10^3
Overcast sky	--	2 X 10^3
60-W inside frosted incandescent lamp	--	1.2 x 10^5
Tungsten-halogen lamp, 3000 K CCT	--	1.3 x 10^7
Tungsten-halogen lamp, 3400 K CCT	--	3.9 x 10^7
CFL	36-W twin tube	3 x 10^4
T-5 fluorescent lamp	14-35 W	2 x 10^4
T-8 fluorescent lamp	36-W	1 x 10^4
T-12 fluorescent lamp	Cool white 800mA	1 x 10^4
High-pressure mercury lamp	1000-W	2 x 10^8
Xenon short arc lamp	1000-W	6 x 10^8

Common Lamp Efficacies

- The Illuminating Engineering Society of North America (IESNA) defines lamp efficacy as “the quotient of the total luminous flux emitted divided by the total lamp power input.” It is expressed in lumens per watt (lm/W).

Light Source	Power (watts)	Lamp Efficacy (lumens/watt)
Standard incandescent filament	100	17
Linear tungsten-halogen	300	20
Fluorescent T-5, 4 ft	28	100
Fluorescent T-8, 4 ft	32	90
CFL	26	70
Mercury vapor	175	45
Metal-halide, low wattage	100	80
Metal-halide, high wattage	400	90
High-pressure mercury lamp	1000	50
Xenon short arc lamp	1000	30
High-pressure sodium, low wattage	70	90
High-pressure sodium, high wattage (diffuse)	250	100
Low-pressure sodium, U-type	180	180

Spectrum and Colour

Spectrum and Colour

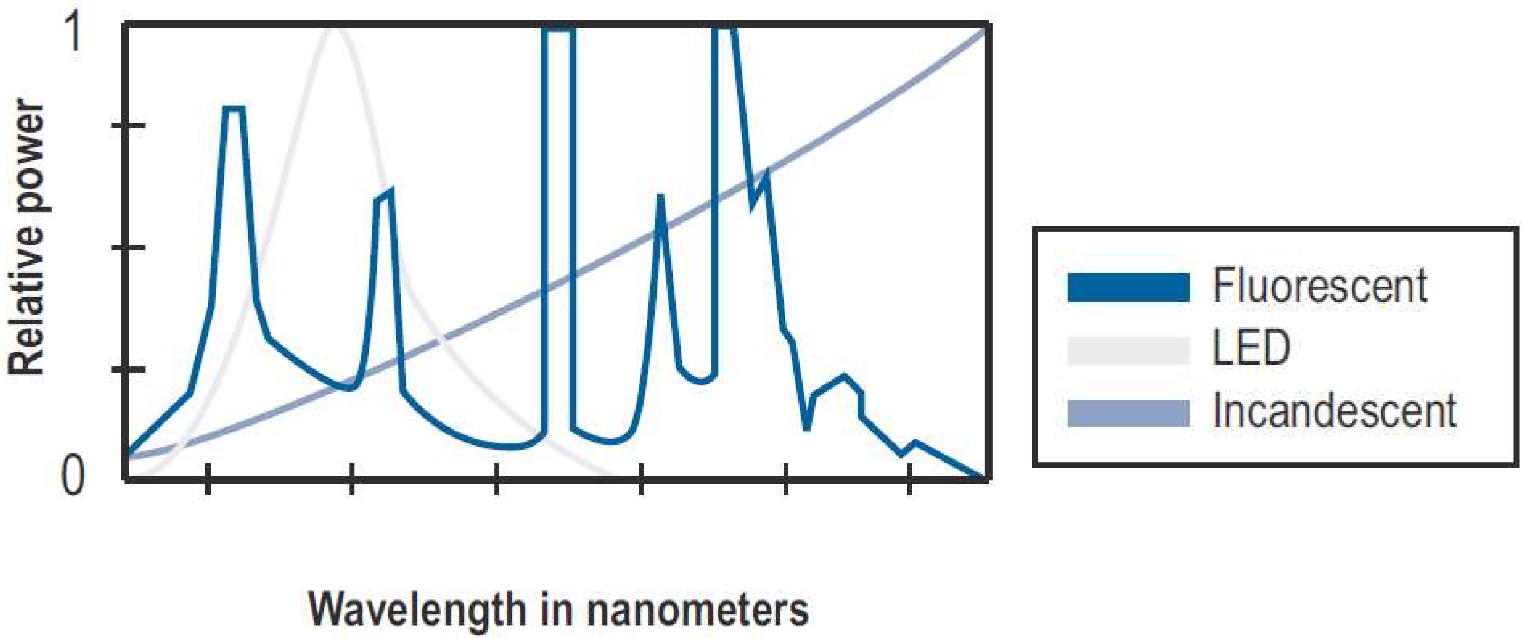
- Light is the small portion of the electromagnetic spectrum between 380 and 780 nm that is visible to the human eye.
- Two types of photoreceptors within the eye, rods and cones, convert radiation within this range into signals to the brain.
- In this wavelength range the cone photoreceptors also translate light into colour, dependent on the light's wavelength.
- In fact, colour is not an inherent attribute of light but rather the brain's interpretation of the signals from the cones.
- When a human sees light made up exclusively of shorter wavelengths (around 400 to 480 nm), the brain interprets it as "blue."
- As wavelength increases, the associated colour changes continuously through the visible spectrum, from "cyan" to "green" to "yellow" to "orange," ending with "red" at the longest visible wavelengths (around 710 to 780nm).

Spectrum and Colour

- The term colour can be used in two ways in describing light.
- The colour appearance of generated or reflected light is a perceptual concept that, even after extensive investigation, still eludes precise quantification.
- This is because colour appearance depends on other factors such as brightness and surrounding apparent colour.
- Colour matching, however, can be used very precisely to quantify colour.
- Using a colour matching system to quantify colours is known as coulorimetry.
- It is based on the principle that light can be matched in appearance with the right combination of three idealized lights, typically red, green, and blue lights.

Spectrum and Colour

- In order to quantify colour, the spectrum or wavelength composition of light must be known.
- A spectral power distribution (SPD), defined as the radiant power at each wavelength or band of wavelengths in the visible region, is typically used to characterize light.
- Depending on how light is generated by the source, the SPD of light can vary from continuous across the visible spectrum to discrete across the spectrum to a narrow band at a particular wavelength.



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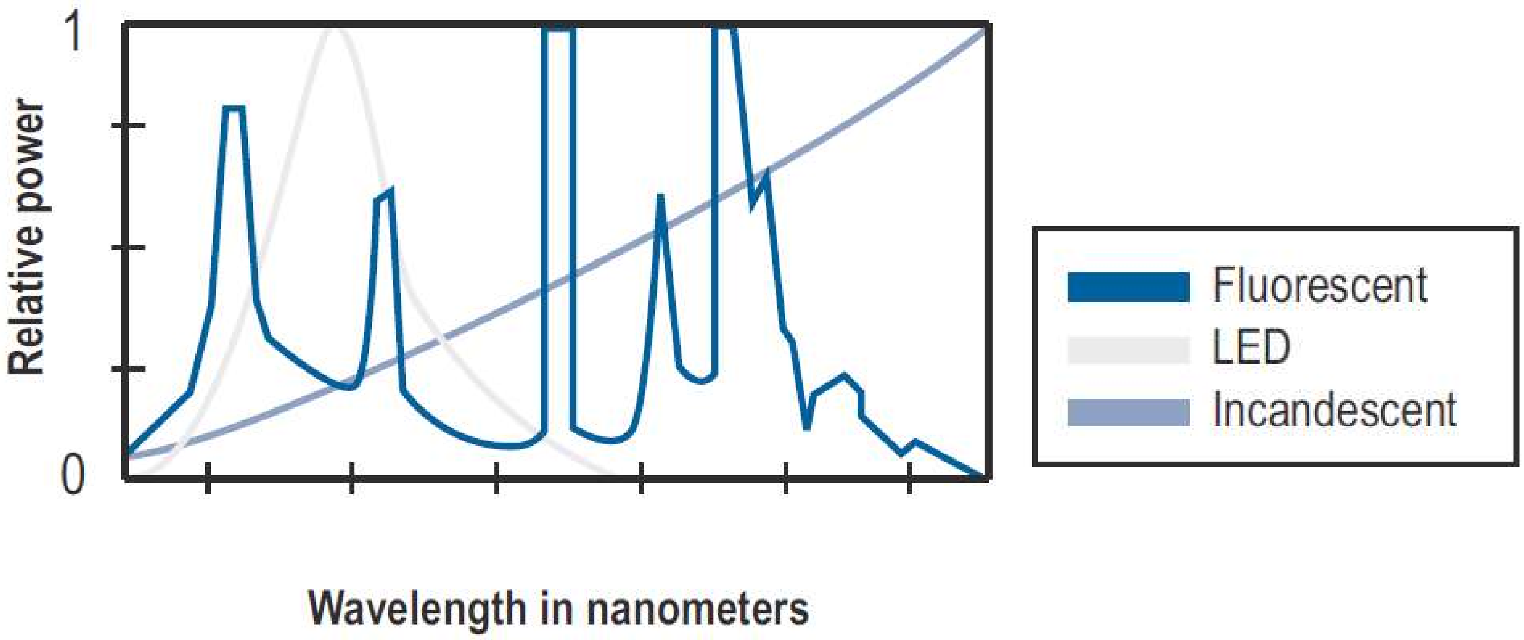

Spectrum and Colour

- Identical colours are produced not only by identical SPDs but also by many different SPDs that produce the same visual response.

- Physically different SPDs that appear to have the same colour are called metamers.

- Other useful colour measures can be derived from coulorimetry.

- Two of the most commonly used are colour rendering index (CRI) and correlated colour temperature (CCT).

- Although these measures are based on colour matching, not colour appearance, they are also useful to designers and specifiers for colour appearance.

- Colour rendering index is a measure of how colours of surfaces will appear when illuminated by a light source. Light that has an even SPD across the visible spectrum, such as daylight or incandescent light, has a high CRI (the maximum is 100). Light that has gaps in its SPD has a lower CRI.

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Spectrum and Colour

- Correlated colour temperature, measured in Kelvin's (K), describes the appearance of light generated by a hot object, such as an incandescent filament.
- As a body is heated it produces light.
- The light that is produced is correlated to the black body curve.
- At lower temperatures reddish light is generated; consider a heating element from an electric oven.
- As the temperature increases the light appears to shift from red to reddish-yellow to yellowish-white to white to bluish-white at high temperatures.
- Confusingly, light with a CCT between 2700 K and 3200 K is a yellowish-white light and is described as “warm” while light with a CCT between 4000 K and 7500 K is a bluish-white light and is described as “cool”.

Optical Modelling

Optical Modelling

- Optical engineers apply the science of optics to design practical systems that control light or other forms of radiation, such as UV or IR.

- Systems that an optical designer might consider include camera lenses, binoculars, telescopes, laser systems, fibre optic communication systems, instrument display systems, luminaries, automotive headlamps, and many others.

- Computer modelling is a very useful tool in optical engineering.

- While there is no closed algorithm or computer program that will create an optical system without the guidance and experience of an optical engineer, computer modelling greatly simplifies and accelerates the design process.

- Increasing the speed of system calculations (many orders of magnitude faster than calculating by hand) enables the designer to examine more aspects of system performance and to explore a larger number of solutions.

Ray Tracing

- If we consider light as an electromagnetic wave travelling through space (although it can also be considered a particle), then we can define a light ray as a line normal to the direction of wave propagation.

- A light ray, or ray, obeys the laws of geometrical optics and can be transmitted, reflected, and refracted through an optical system by relatively simple formulae to determine light paths.

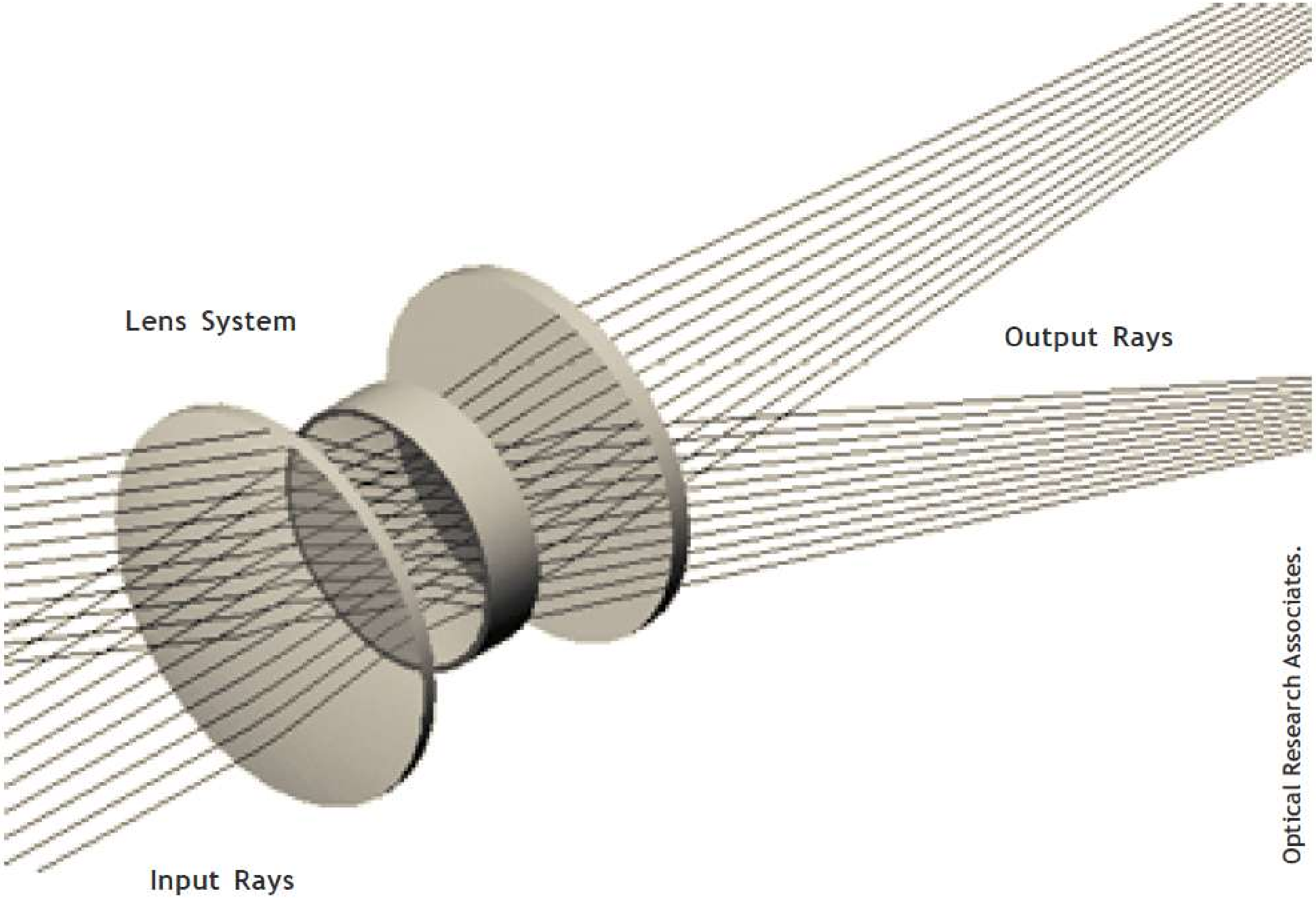
- Ray tracing for optical design is based on a calculation of how rays travel through the system, and can be broken into two major types, sequential and non-sequential.

Sequential Ray Tracing

- Image-forming systems, such as cameras, binoculars, and the human eye, typically use sequential ray tracing.
- Systems are called sequential when the exact order in which rays strike each surface in the system is exactly known.

Sequential Ray Tracing

- In the system shown below, light cannot strike the image plane without first encountering the first lens front surface, then the first lens rear surface, and so on.



Optical Research Associates.

Sequential imaging optical system

- Ray tracing for sequential systems is relatively straightforward. Because the order of intersection is known for each surface, ray propagation can be calculated systematically.

- Also, because sequential systems are concerned with imaging they are constrained to point-to-point mapping.

- Any deviation from an object point mapping to an image point is termed an aberration.

- A large portion of an optical engineer's job in designing an imaging system is to reduce or eliminate the effects of aberrations.

- Because imaging system rays act in such a well-described manner, only a few of them need to be traced to accurately describe the properties of the entire system.

- Tracing only two well-chosen rays (the marginal and chief rays) can tell you much about an imaging system; tracing several hundred rays can almost completely define the optical characteristics of the system

Non-sequential Ray Tracing

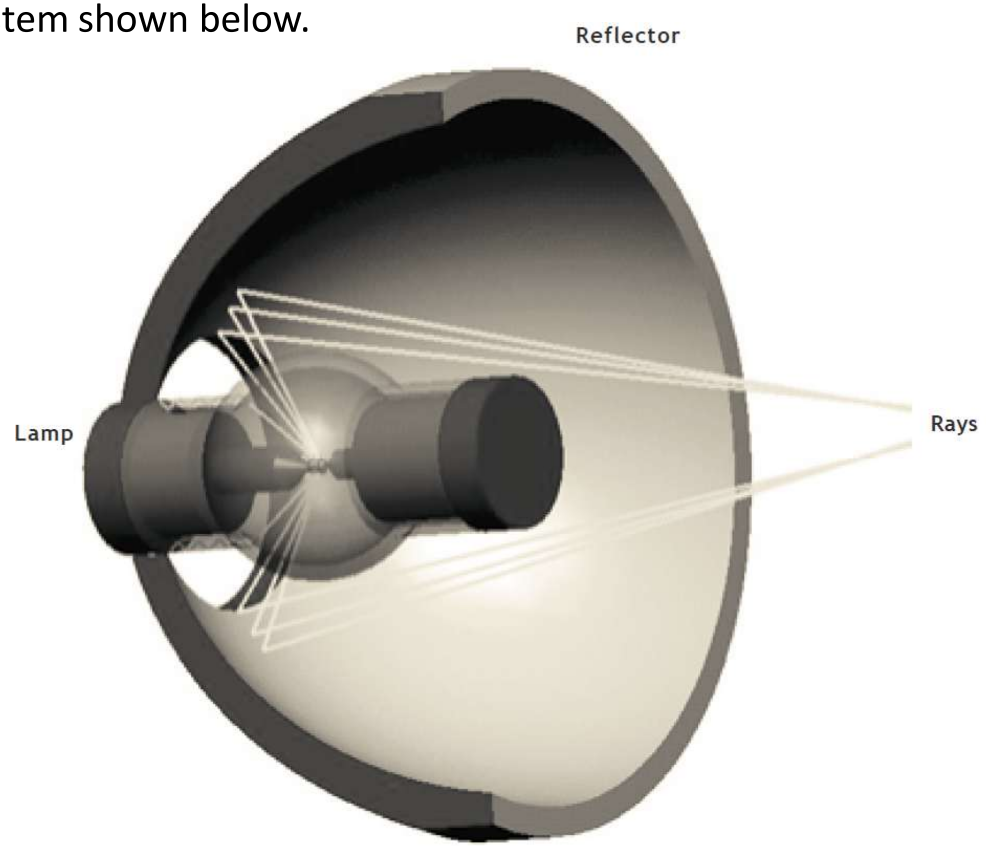
- In a non-sequential system the order of ray surface intersection is not known, and these systems are typically not concerned with image formation.

- Non-imaging systems include fibre optics, light pipes, solar concentrators, luminaries, and headlamps.

Non-sequential Ray Tracing

- A light ray starts from the plasma of the discharge lamp. What surface does it encounter before it exits the system? It may intersect the glass envelope of the lamp, the lamp electrodes, or the reflector, or it may exit through the front aperture of the reflector. The order of, or even which, surfaces are encountered is not known in advance for each ray.

- Consider the illumination system shown below.



Non-sequential illumination system

- Since in non-imaging systems rays do not act in a well-prescribed manner, and there is no imaging constraint (points don’t have to map to points), many rays need to be traced in order to analyze system performance.

- This can be on the order of millions or tens of millions of rays. In fact, before the advent of computerized ray tracing, non-imaging illumination system analysis was practical for only a limited number of special cases.

- Instead of tracing a few well-chosen rays, non-sequential analysis requires many rays to be started randomly from an extended source (such as an incandescent filament) and traced through the system.

- Typically the random location and direction of rays from a source are determined through Monte Carlo simulation. A detector is placed at the area of interest and rays are collected, binned, and analyzed. From this analysis intensity, luminance, and illuminance can be determined.

Non-sequential illumination system

- major source of statistical error, due to finite sampling, arises when simulating incoherent extended sources.
- The amount of error based solely on finite sampling can be calculated.
- Using statistical analysis one can show that error, or signal-to-noise ratio, at the detector for a system where each ray carries equal energy is:

$$\frac{Signal}{Noise} = \sqrt{N_{\text{det}}}$$

- Where
  - N_{det} is the total number of rays that hits the detector.
- Since the signal-to- noise ratio increases only as the square root of the number of rays hitting the detector, a large number of rays must be traced to achieve acceptable error.
- Using the appropriate number of source rays ensures statistical accuracy while minimizing the computational time.

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