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Draft National Lighting Code of India

Part 2 Physics of Light
Section 1 General Principles

First Revision of SP 72 (Part 2/Section 1)

Illumination Engineering and Luminaries Sectional Committee, ETD 49 | Last Date for Comments: 02-03-2025

FOREWORD

(Formal clauses of the draft will be added later)

The paradoxical nature of light makes it both elusive and indispensable. While light itself is not visible, it enables vision by illuminating the world around us. Its intangible nature unable to be held like a physical object doesn't diminish its significance in our lives.

Light indeed exhibits various fascinating behaviour. It can be bent or refracted when passing through different mediums, transmitted across vast distances, and even dispersed to reveal its diverse colours. Despite its intangibility, its impact is undeniable.

Describing light as an electromagnetic wave aligns with its fundamental nature. Light comprises electric and magnetic fields oscillating perpendicular to each other, propagating through space. Understanding light as energy is crucial; it carries energy and drives numerous processes vital forlife and technology.

The study of light has seen diverse models and theories throughout the history of physics. From the particle-like behaviour proposed by Isaac Newton to the wave-like nature supported by Thomas Young's double-slit experiment, to the modern understanding of light as both particles (photons) and waves (electromagnetic radiation) in quantum physics each model contributes to comprehending the complex nature of light.

Physics, often regarded as the foundational science, indeed holds a central position in unrevealingthe mysteries of light and shaping lighting technology. Its diverse models and theories continue topave the way for innovations in lighting, optics, telecommunications, and various other fields reliant on understanding and harnessing the properties of light.

The multifaceted nature of light from its duality as waves and particles to its role as energy continues to captivate scientists and engineers, driving advancements and innovations that profoundly impact our world.

Draft National Lighting Code of India

PART 2 PHYSICS OF LIGHT
SECTION 1 GENERAL PRINCIPLES

(First Revision)

1 SCOPE

This section of the code (Part 2/ Sec 1) covers various lighting models and key characteristics of light, such as spectral power distribution, which hold significant importance for lighting professionals.

2 TERMINOLOGY

The terminology referred in this section already covered in the Part 1 of this code.

3 Propagation of Light - Physical Model

In the 1670's Christian Huygens proposed a mechanism for the propagation of light, known as Huygens' Principle. According to Huygens Principle, all points on a wavefront act as sources of new waves, and the envelope of these secondary waves constitutes the new wavefront as shown in Fig. 1.

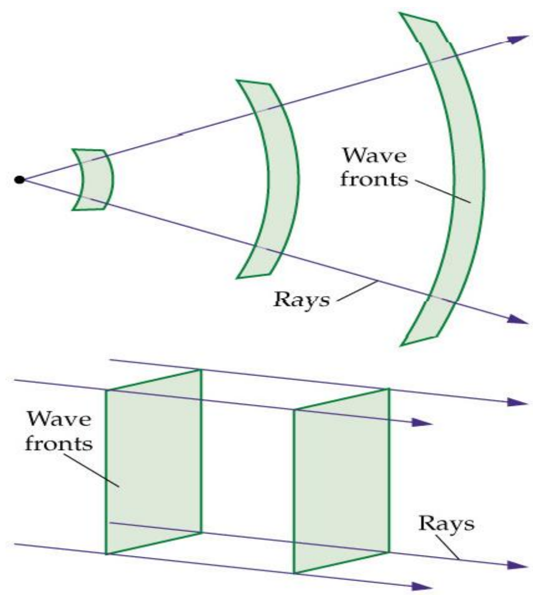


Fig. 1 Wave Fronts

In 1704 Isaac Newton published light theory discarding Greek thoughts that vision was the result of an `imago' dissociation from the object being viewed that enters the eye and the conviction that eye transmitted `visual rays', which scanned object being viewed. Newton regarded light consisting of endless stream of high-speed particles.

This theory could explain the following phenomenon:

a) Rectilinear propagation of light;
b) Reflection of light; and
c) Refraction of light.

However, this theory could not explain the phenomena of diffraction, interference, and polarization of light.

In 1873, Maxwell published his opinion that light is electromagnetic waves and that light waves are carried by an electromagnetic field. An electromagnetic wave is a transverse wave consisting of mutually perpendicular oscillating electric and magnetic fields (*see* Fig. 2). Electromagnetic waves are produced by an accelerating charge and are self-propagating waves that can travel through a vacuum or a material medium. Subsequently, Heinrich Hertz experimentally generated electromagnetic waves supporting Maxwell's theory.

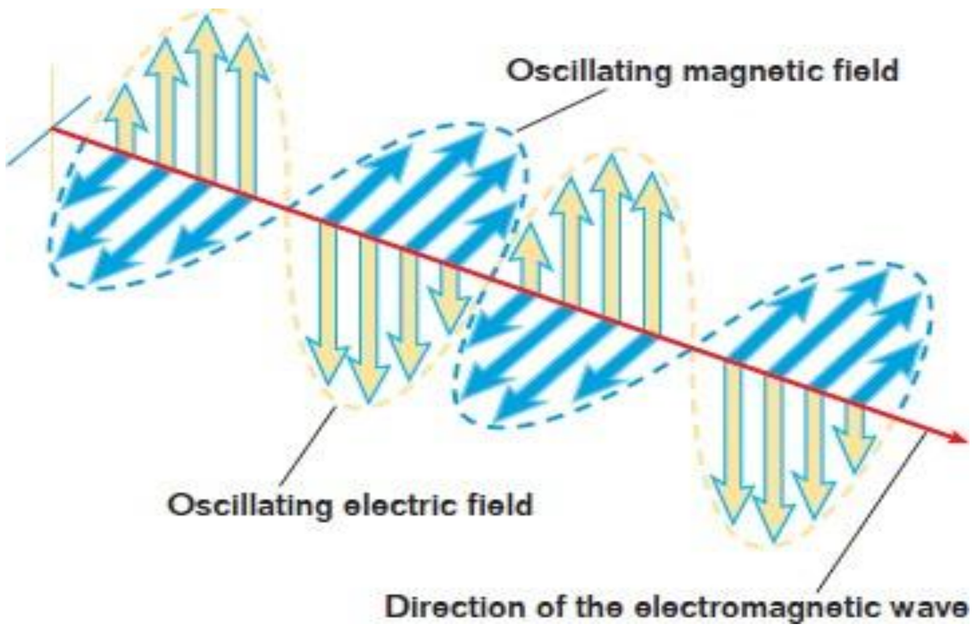


Fig. 2 An Electromagnetic Wave

All electromagnetic waves travel at the speed of light. Electromagnetic waves are distinguished from each other by their differences in wavelengths and frequencies. Wavelength is inversely related to frequency.

where,

c is the speed of light = 3.0 x 10 8 m/s in a vacuum
= 300,000 km/s
= 186,000 miles/s

This theory which deals with light as electromagnetic wave, namely, wave optics, successfully explains the optical phenomena of diffraction, interference, and polarization of light. However, is unable to explain phenomena involving the interaction of light and matter, such as the photoelectric effect.

In 1905, Einstein explained the photoelectric effect using the concept of photons. Einstein proposed that a beam of light is not a wave, but rather a collection of photons, each photon has a fixed amount of energy, which only depends on the frequency of light, thus, the quantum theory of light emerged. Quantum optics describes the wave–particle duality of light well.

4 Theories of Light: An Overview

Theories of light can currently be divided into three main branches: geometrical optics, wave optics, and quantum optics.

4.1 *Geometrical Optics*

Geometrical optics deals with light as rays that travel in straight lines in a homogeneous medium. In geometrical optics, the laws of reflection and refraction can provide very good explanations for many optical phenomena, such as specular reflection, the dispersion of light and many others. Furthermore, with the help of these two laws and the rectilinear propagation of light rays in homogeneous media, the path of a light ray can be traced throughout an optical system, revealing the main characteristics of that system. In addition, by introducing the diffraction phenomenon in terms of the laws of reflection and refraction, the diffraction of light by edges, corners, or vertices of boundary surfaces can be predicted using geometrical optics. Usually, geometrical optics can give reasonable explanations for most optical phenomena. However, because geometrical optics is determined from the approximation of wave optics as the wavelength of light approaches zero ($l \rightarrow 0$), the wave nature of light is neglected. Therefore, it is impossible to explain the physical reasons for the diffraction and interference of light using geometrical optics.

Ray optics model explain through the ray tracing principle for light distribution or redistribution of light which part and parcel for our luminaire optic design.

4.2 *Wave Optics*

Wave optics, which deals with light as waves, studies optical phenomena involved in the wave nature of light, such as diffraction, interference, and polarization. As light is a form of electromagnetic wave, all wave characteristics of light can be deduced from Maxwell’s equations. It is highly convenient to describe the propagation of light in free space with the Rayleigh Sommerfeld diffraction formula. In wave optics, the resolution of an optical imaging system is ultimately limited by the diffraction of light, which is different from the case of geometrical optics. Wave optics not only explains optical phenomena such as the diffraction and interference of light, but is also commonly used in optical system designs and optical metrology. However, as wave optics ignores the particle aspect of light, it cannot be used in scenarios involving in the interaction between light and matter, such as the photoelectric effect.

4.3 *Quantum Optics*

Optical phenomena concerning the interaction between light and matter, such as characteristic emission, the photoelectric effect, ~~etc.,~~ is in the realm of quantum optics. The concept of the photon, proposed by Einstein in 1905, is fundamental to quantum optics, and the interaction between light and matter can be considered as interactions between photons and atoms of matter. The invention of the laser is the most famous application of quantum optics. This new type of optical source provided an important experimental tool for the development of modern optics. Furthermore, commonly used photoelectric detectors, such as charge-coupled devices (CCDs), photodiodes, and photomultiplier tubes are all successful applications of quantum optics. Quantum optics describes the wave–particle duality of light well. So far, it is the most accurate theory of optics.

This optical model explains the light generation & light source spectral distribution for all kind of product be it incandescent to OLED.

5 LIGHTING PHENOMENA

5.1 Reflection of Light

Reflection of light when the waves encounter a surface or other boundary that does not absorb the energy of the radiation and bounces the waves away from the surface. The incoming light wave is referred to as an incident wave and the wave that is bounced away from the surface is called the reflected wave. The simplest example of visible light reflection is the glass-like surface of a smooth pool of water, where the light is reflected in an orderly manner to produce a clear image of the scenery surrounding the pool (*see* Fig. 3).

Percentage of reflection factor of the materials and ray tracing is very important for luminaire optical design.

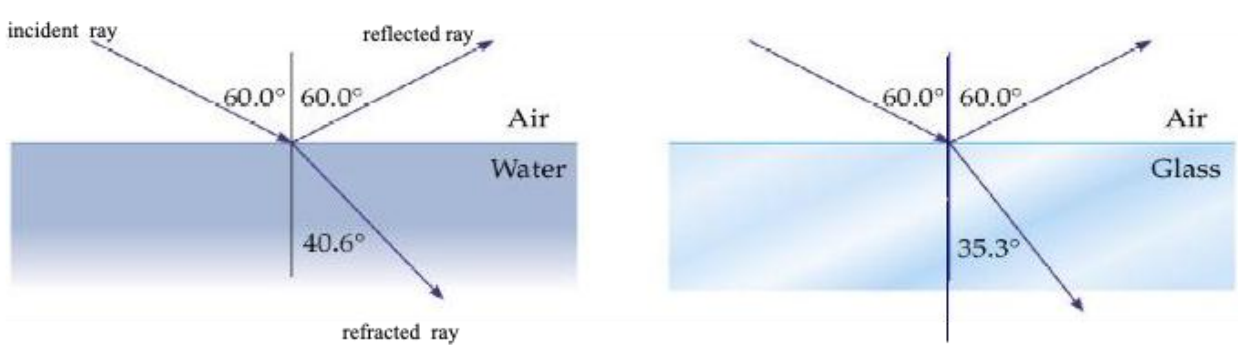


Fig. 3 Reflection of Light

If the surface of which the light is reflected is smooth, then the light undergoes specular reflection (parallel rays will all be reflected in the same directions). If, on the other hand, the surface is rough, then the light will undergo diffuse reflection (parallel rays will be reflected in a variety of directions) Below Fig. 4 a shows specular reflection and Fig. 4 b shows diffuse reflection.

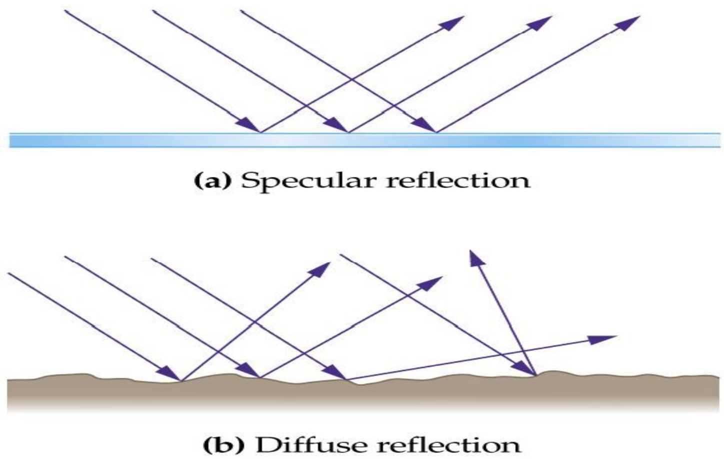


Fig. 4 (a) Specular Reflection, Fig. 4 (b) Diffuse Reflection

5.2 Refraction Light

When light propagates in a transparent material medium, its speed is in general less than the speed in vacuum c. An interesting consequence of this is that a light ray will change direction when passing from one medium to another. Since the light ray appears to be "broken", the phenomenon is known as refraction.
The speed of light is different in different materials. The index of refraction, *n*, of a material is written as, the ratio of the speed of light in vacuum to the speed of light in the material.

$$n = c/v$$

5.2.1 Snell's Law

In general, when light enters a new material its direction will change. The angle of refraction θ_2 is related to the angle of incidence θ_1 by Snell's Law. The angles θ_1 and θ_2 are measured relative to the line normal to the surface between the two materials as shown in Fig. 5.

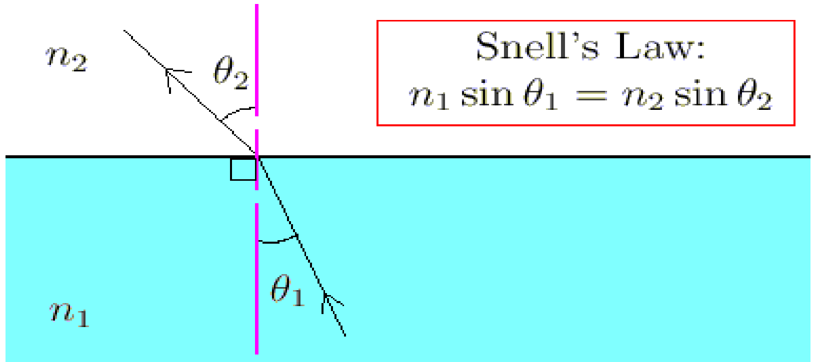


Fig. 5 Description of Snell's Law

5.2.2 Total Internal Reflection

One important consequence of Snell's law of refraction is the phenomenon of total internal reflection. If light is propagating from a dense to a less dense medium, i.e. $n_1 > n_2$, there is an angle, called the critical angle θ_c, at which all the light is reflected and none is transmitted. This process is known as total internal reflection. The critical angle occurs when $\theta_2 = 90$ degrees and is given as Fig. 6

$$\sin\theta_c = \frac{n_2}{n_1}$$

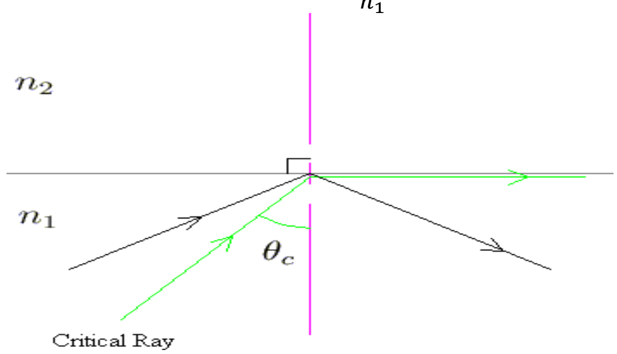


Fig. 6 Total Internal Reflection

For larger angles of incidence, the incident ray does not cross the interface, but is reflected back instead.

5.3 Dispersion

When a polychromatic light, passes through a transparent medium like a glass prism it splits into its component colours, this phenomenon is called dispersion of light, as given in Fig. 7. When a wave is refracted into a dielectric medium whose refractive index varies with wavelength then the angle of refraction also varies with wavelength. If the incident wave is not monochromatic, but is, instead, composed of a mixture of waves of different wavelengths, then each component wave is refracted through a different angle.

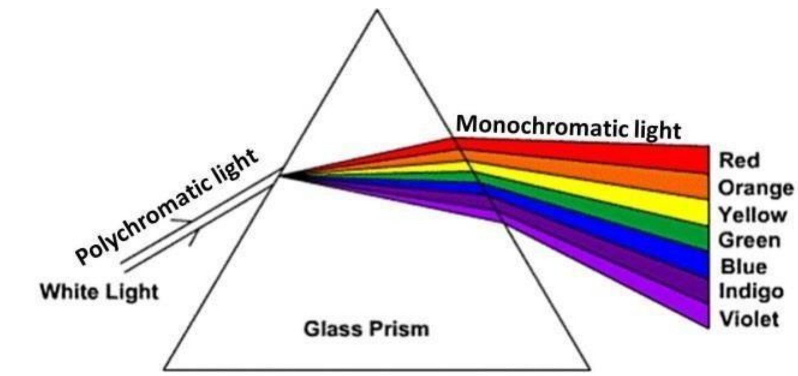


Fig. 7 Dispersion of Light by the Glass Prism

5.4 Polarization of Light

Light is a transverse electromagnetic wave and is generally unpolarized. The polarization of light can be described by specifying the orientation of the electric field at a point in the space. Light in the form of a plane wave in space is said to be linearly polarized. If light is composed of two plane waves of equal amplitude and 90° phase difference, then the light is said to be circularly polarized.

Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90° as shown in the Fig. 8.

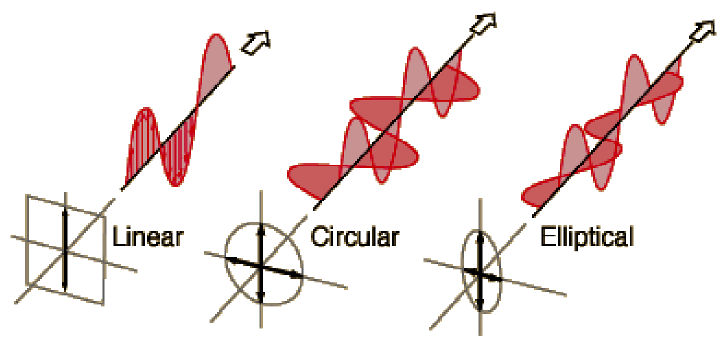


Fig. 8 Polarization of Light

The human eye does not have the ability to distinguish between randomly oriented and polarized light. The plane-polarized light can be detected through intensity and color effect.

5.5 Interference

The phenomenon of interference is of great importance. Interference occurs when two or more light beams are superimposed. If two waves are of the same frequency and phase, they vibrate at the same rate and are maximum at the same time, the wave amplitudes are added and produce constructive interference. Sametime, if the two waves are out of phase by half period, one is minimum when the other is maximum, the result is destructive interference, as given in Fig. 9.

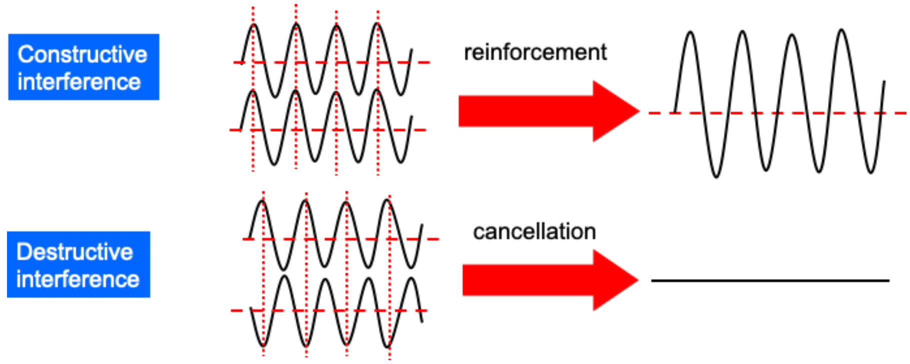


Fig. 9 Interference of Light

A classic example of interference is the light reflected from a thin film of oil floating on water.

5.6 Photoelectric Effect

In 1905, Einstein explained the photoelectric effect (*see* Fig. 10) using the concept of photons. According to Einstein's theory, light is a collection of photons. Each photon has a fixed amount of energy, whichonly depends on the frequency of light. When photons fall on the surface of a metal, the energy ofa photon is split into two parts. One part is used for releasing an electron from the metal, and the other part transforms into the kinetic energy of the released electron. According to the law of conservation of energy, the process of energy conversion in the photo electric effect can be expressed as:

$$E = h\,n = 1/2\;m\,v^2 + w$$

where h is Planck's constant, n is the frequency of light, m is the mass of the electron, v is the speed of the photoelectron, and w is the work function of the metal, which represents the smallest energy needed for electrons to escape from the constraints of the metal. According to above equation, the release of the photoelectron from the metal by light and the speed of the photoelectron are determined by the frequency of the incoming light, irrespective of the intensity of light incident on the metal.

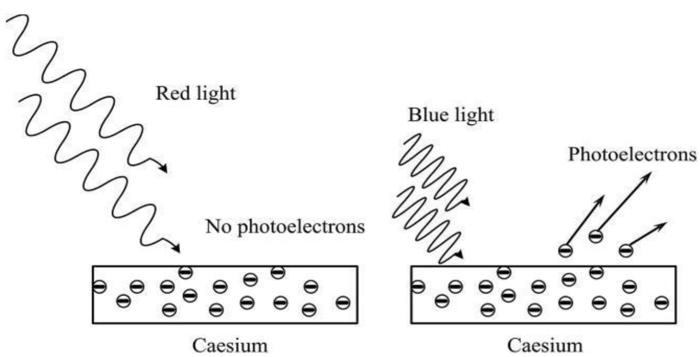


Fig. 10 Diagram of the Photoelectric Effect.

The concept of light as photons successfully explains the photoelectric effect and is confirmed by experimental results.

6 LIGHT SOURCES

The generation of light from light sources can be broadly understood through classical electromagnetic radiation theory, while it can be more precisely explained using the quantum theory of light.

6.1 Electromagnetic Wave Theory

Matter is made of atoms, and each atom is composed of a nucleus and some electrons around the nucleus. When an amount of energy is continuously infused into matter, the temperature of the matter will gradually increase, and electron movement around nuclei will be gradually accelerated. However, according to the law of conservation of energy, the temperature of matter cannot increase infinitely. Hence the accelerated electron will radiate energy in the form of electromagnetic waves. The sun, having a high temperature due to the thermonuclear reactions occurring in it, radiates electromagnetic waves across most of the electromagnetic spectrum, including gama rays, to radio waves as given in the Fig. 11.

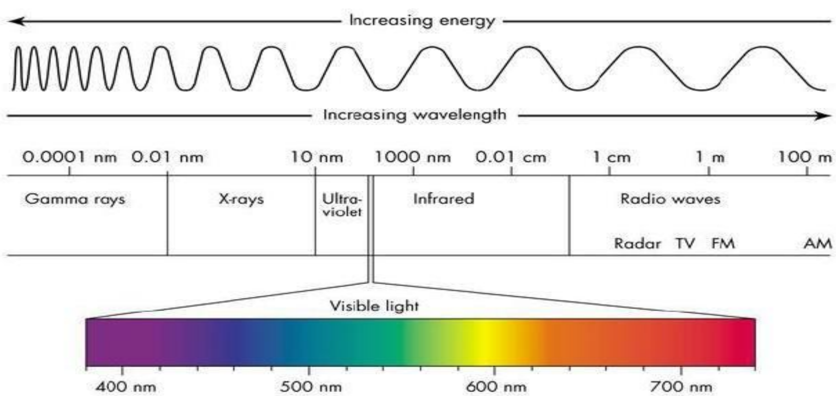


Fig. 11 Electro Magnetic Spectrum

6.2 Quantum Theory

In quantum theory, all matter particles possess the wave–particle duality. In order to understand the formation of energy levels in matter, we will suppose that a particle, e.g., an electron, is trapped inside a potential well, shown as a one-dimensional (1D) well in Fig. 12.

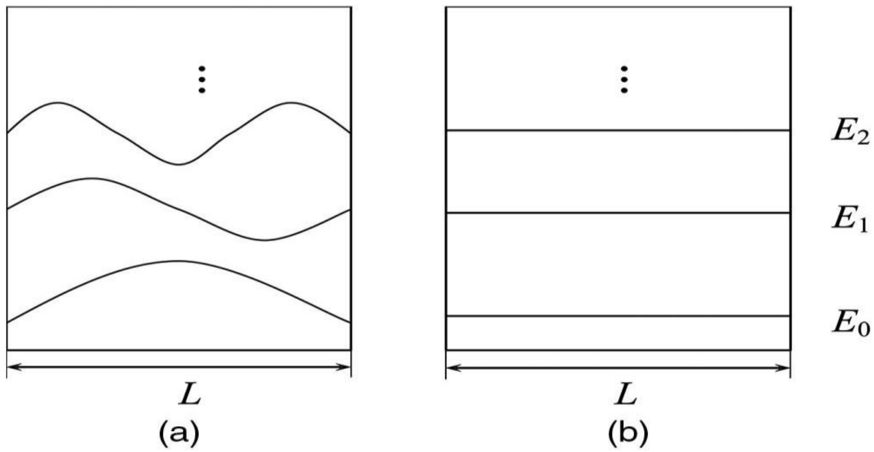


Fig. 12 Diagram of (a) Electron Waves in A 1D Potential Well and Fig. 12 (b) The Corresponding Energy Levels

This description delves into the intriguing world of quantum mechanics, specifically focusing on electron waves confined within a potential well. When electron waves encounter two parallel barriers (forming a potential well) separated by a distance L, only standing waves can exist within this space.

Standing waves are formed when the round trip distance between the barriers is an integral multiple of the corresponding wavelengths of the waves. This condition creates a wavelength selector, allowing only specific discrete wavelengths to exist within the well, represented by 2L/m where m is an integer (1, 2, 3, and so forth). Consequently, this leads to the constraint of discrete frequencies and energies for electron waves in this confined region.

The lowest energy level, depicted as E_0 in the provided figure, signifies the ground state. Electrons in the ground state are at their most stable configuration within this potential well. Any energy levels above the ground state are referred to as excited states, where electrons exist temporarily and can transition back to the ground state or to other lower energy levels.

According to Boltzmann distribution, a majority of electrons in matter tend to reside in the state with the lowest energy, i.e., the ground state. However, when external energy is introduced—such as through heating or injecting energy into the system—electrons in the ground state can absorb some of this energy and transition to excited states.

In a two-level system transition, as depicted in Fig. 13(a), electrons in excited states possess higher energy levels but have limited lifetimes. They can rapidly transition back to the ground state or other lower energy levels. During this transition process, energy is emitted in the form of light. The energy (hν) of the radiated light corresponds to the energy gap between the two energy levels. Essentially, the larger the energy gap, the greater the energy of the emitted light, resulting in shorter wavelengths of light. Below Fig. 13 shows diagram of transitions between E0 and E1 and in a two-level system.

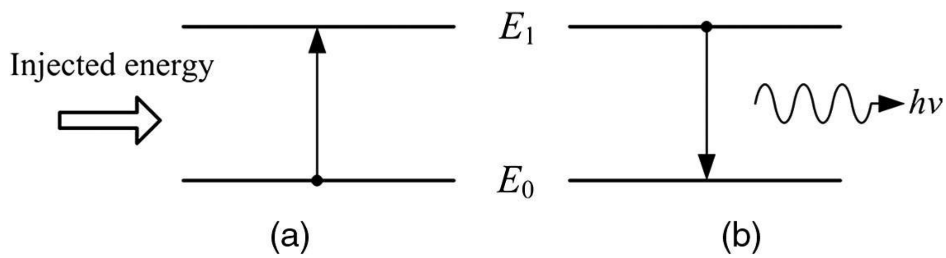


Fig. 13 Diagram of Transitions between E0 and E1 and in a Two-Level System

Furthermore, energy levels and energy gaps between those energy levels for different types of matter are completely different due to the different configurations (or different constraints to electrons) of atoms. This is the reason that each type of matter has its own characteristicabsorptions and emissions. For example, wavelengths of light emitted from any type of sodium lamp are all at 589.0 or 589.6 nm. Note that if transitions between states with many different energygaps occur simultaneously, light in multiple wavelengths or even white light can be produced. In fact, the above just explained the generation of light from incoherent sources.

7 OPTICAL SYSTEMS

Optical systems encompass various configurations of optical elements to manipulate light and achieve specific functions. These elements include lenses, mirrors, gratings, detectors, and more. The primary objective of an optical system is to control the propagation of light within it, requiring meticulous design to achieve desired outcomes.

In the realm of light, there are two fundamental types:

7.1 Ordinary Light

This type of light is emitted naturally or artificially as a result of energy changes at the atomic or molecular level, without external intervention. It encompasses the light experienced daily, from sunlight to artificial light sources.

7.2 Laser Light

Laser light differs significantly from ordinary light. It arises when an atom or molecule holds onto its excess energy until it's stimulated to emit that energy in the form of light. Lasers are specifically designed to produce and amplify this stimulated emission of light, resulting in intense and highly focused beams. The term "laser" stands for "Light Amplification by the Stimulated Emission of Radiation."

The unique characteristics of laser light have made laser technology integral in various aspects of modern life:

a) *Communications* — Laser technology plays a crucial role in optical communication systems,enabling high-speed data transmission via fibre optics;

b) *Entertainment* — Lasers are extensively used in entertainment industries, such as laser light shows in concerts, laser displays in theaters, and more, due to their ability to create vivid and controlled light patterns;

c) *Manufacturing* — Laser cutting, welding, and engraving are key applications in manufacturing industries, leveraging the precision and intensity of laser beams for variousprocesses; and

d) *Medicine* — In medicine, lasers find application in surgical procedures, diagnostics, treatments like laser therapy, and even in medical imaging technologies.

Draft National Lighting Code of India

Part 2 Physics of Light
Section 2 Vision

First Revision of SP 72 (Part 2/Section 2)

FOREWORD

Light is invisible, yet essential for sight. While the human eye plays a vital role in sensation, visual perception is a complex interplay between the eye and the brain. Despite centuries of scientific inquiry, many aspects of vision remain unresolved, driving ongoing research. Understanding the eye's intricate functionality and its role in visual processes is crucial for lighting professionals. Visual mechanisms involve intricate interplays of photo-mechanical, photo-chemical, and photo-electrical processes.

Indeed, the subject matter is both multidisciplinary and specialized, drawing upon a wide range of disciplines including biology, chronobiology, medicine, and lighting design. A basic understanding of this subject is crucial in today's context, given the continuous stream of research findings being published almost daily. As such, professionals across various fields must grasp the fundamentals of visual mechanisms to stay informed and contribute effectively to their respective fields.

Draft National Lighting Code of India

PART 2 PHYSICS OF LIGHT
SECTION 2 VISION

(First Revision)

1 SCOPE

This section of the code (Part 2/ Sec 2) covers offers an in-depth exploration of the human eye, covering its structure, function, mechanisms, and its interconnectedness with the human body.

This section also delves into the salient features and diverse components of the visual system, includingits profound impact on visual performance, as well as factors such as visual satisfaction and comfort. It emphasizes the significance of recent advancements in nonvisual mechanisms, crucially related with human behavior. Moreover, it explores the implications of lighting on performance, sleep patterns, and age-related changes in visual insight. Understanding the effects of aging on the eye is pivotal for grasping its practical implications.

2 EYE STRUCTURE

The structure of the human eye (*see* Fig. 1) is fundamentally similar to that of an optical system.

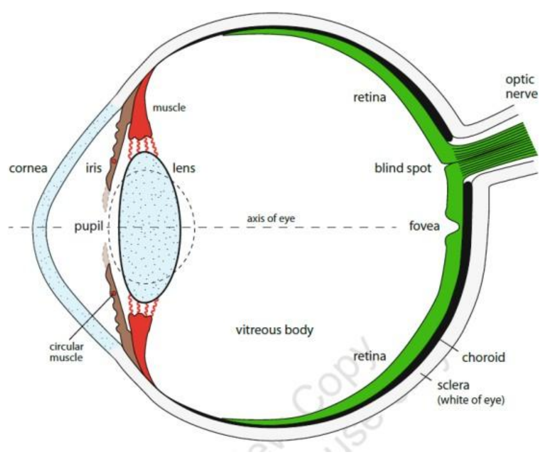


Fig. 1 Cross Section of the Eye Structure

The cross section of the optical structure has following:

a) Sclera — white of the eye is a hard transparent tissue that gives the rigidity of the eye;
b) Cornea — the bulged out portion where from light enter to the eye & then reaches to a circular diaphragm formed by Iris;

c) Iris — It determine the colour of the human eye;
d) Pupil — The pupil, which is the opening of the iris, acts like the aperture of a camera. The muscles surrounding the pupil control its size, regulating the amount of light entering the eye based on the surrounding lighting conditions. This adjustment process is known as adaptation.
e) The eye lens creates an inverted image of an object located in front of the eye. This inverted image falls onto the inner part of the eye known as the retina. The shape of the lens adjusts depending on where the eye is focused. It takes on a spherical shape for nearby objects and become flatter for distant objects. This adjustment process of the lens, based on the distance of the viewed object, is called accommodation. The eye lens is made of transparentfibers containing protein, similar to the crystalline lens
f) The fovea is positioned along the axis of the line of sight. The shape of the lens changes due to the movement of its muscle membrane; and
g) The layer behind the retina is called the Choroid. Its primary function is to prevent internalreflections of stray light within the eye, much like the dark interior of a camera. The Choroid is rich in blood vessels, which provide nourishment to the internal structures of the eye.

Below Fig. 2 shows inside structure of rods & cones and Fig. 3 shows distribution of rods & cones at retina.

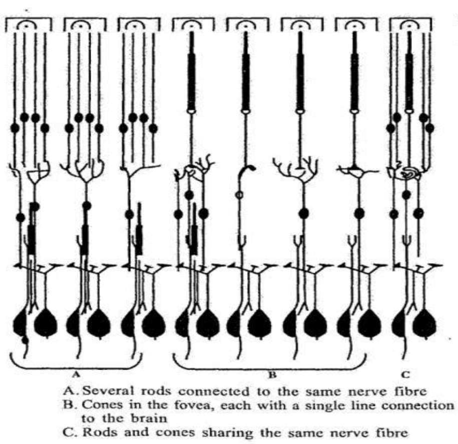


Fig. 2 Rods & Cones Structure Inside

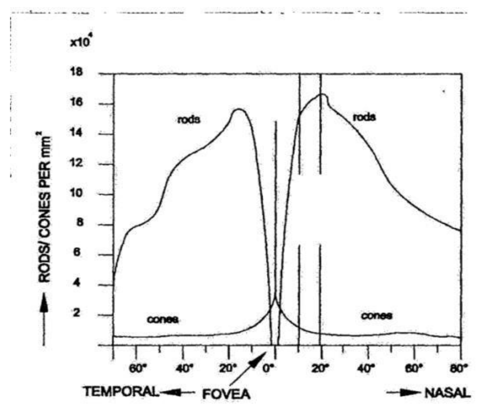


Fig. 3 Distribution of Rods & Cones at Retina.

3. THE VISUAL PROCESS AND THE BRAIN

3.1 The way the retina of both eyes are connected to the visual cortex in the two brain halves is not as straightforward as might be expected. The optic nerves of both eyes unite immediately after entering the cranial cavity, forming the so called 'optic chiasma' and then divide again into two branches, the 'optic tracts', which lead to the two halves of the visual cortex. The optic chiasma forms a cross over point, where the optic nerve from each eye splices into two strands, in such a way that each optic tract contains nerve fibres coming from both eyes. The arrangement is in fact that the left half of the visual cortex care of the right side of each retina. A person who has one of his optic tracts served will therefore be half blind in both eyes (*see* Fig. 4).

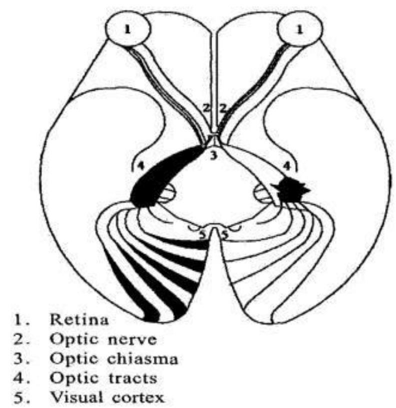


Fig. 4 Schematic Diagram of the Visual Pathway, Showing How the Retina of Both Eyes Are Connected to the Two Halves of the Visual Cortex

Each nerve fiber forms an uninterrupted link between its ending in the retina and a well-defined part of the visual cortex. It is therefore possible to 'map' the retinal area on the cortex. Remarkable, but not illogical, is the observation that the foveal area occupies a proportionally much larger region of the visual cortex than the peripheral areas of the retina.

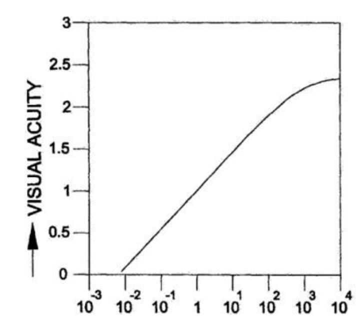
4. VISUAL ABILITY

4.1 Visual ability provides different visual information like the ability to differentiate between closely spaced visual stimuli, luminous variations in the field of view and three dimensional vision.

5. VISUAL ACUITY

5.1 Qualitatively, visual activity helps in distinguishing fine detail quantitatively it provides details on angular separation of two neighboring objects that the eye can just perceive as being separated. Visual acuity depends on the quality of the visual organ and varies with background luminance and observation time.

What is generally assessed as 'visual' in the consulting room of the ophthalmologist is not so much the pure visual acuity of the eye, but the recognition acuity. For scientific research, the study of



resolution activity is essential. Age has a marked negative effect on visual acuity. Visual acuity is expressed as the reciprocal of the minimum visual angle (in minutes of arc), being detected. Visual acuity depends on the average luminance level in the field of view to which the eye is momentarily adapted (adaptation luminance); (*see* Fig. 5)

Fig. 5 Relative Visual Acuity Plotted Against Adaptation Luminance Age Below 50 Years Under the Same Optimum Contrast

NOTE- Measurement have been taken under conditions of optimum contrast using test persons with normal eyesight and not older than 50 years.

6. CONTRAST DETECTION

6.1 Contrast can take two forms which occur together, contrast in colour and contrast in luminance. Contrast in luminance can be expressed as contrast value or contrast ratio. Contrast value has more importance under conditions of artificial lighting. The mathematical expressions are as given below:

$$C = (L_o – L_b) /L_b = \text{Contrast value}$$

$$C = L_h/L_i = \text{Contrast ratio}$$

where

C = Contrast value or Contrast ratio;

L_o =Object luminance

L_b =Background luminance

L_h = Higher luminance; and

L_i =Lower Luminance

Contrast in colour can be distinguished better, under an overall luminance level sufficient to permit full adaptation for cone vision, without excessive brightness contrasts in the field of view and under a light source having spectral energy distribution curve approximately similar to the spectral eye sensitivity curve for photopic vision. The eye will not appraise luminance values the same way under all circumstances. A white surface placed against a black background will make the white seem ‘whiter’. A dark object against a very bright background will appear darker (*see* Fig.6).

Metamerism takes place when two colour shades are observed under sources having line spectrum, separately.

Successive and simultaneous contrast takes place when looking away from a surface of strongly saturated colour and when looking at adjacent coloured surfaces respectively.

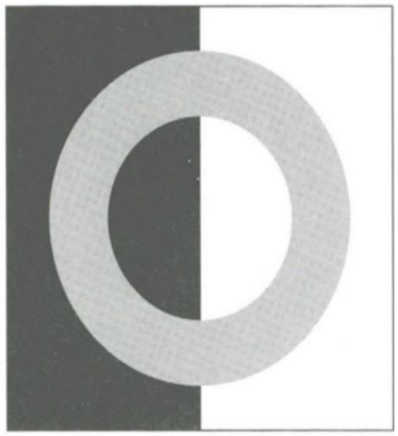


Fig. 6 Contract Effects (Simultaneous Contrast)

NOTE - The part of the grey ring seen against the background seems somewhat lighter than the part seen against the white. This effect is enhanced by placing a pencil along the black-white junction

7. THREE DIMENSIONAL VISION

7.1 Three dimensional vision is possible with the help of both eyes. Good three dimensional vision depends on coordination between two eyes and binocular vision. It is found that a difference in distance over a range of more than one kilometer is possible to judge by three dimensional vision.

Eyesight deteriorates first slowly, but then at a rapidly increasing rate with age. From about 45 years of age nearby seeing, (reading for example) becomes increasingly difficult, whereas distant objects give no problems that is known as 'presbyopia'. From about 50 years of age human being will suffer from overall eye sensitivity, visual acuity, contrast sensitivity and colour sensitivity. Old people need as much as 15 times more light for a specific task than do the young [*see* Fig. 7 a) and Fig. 7 b)]

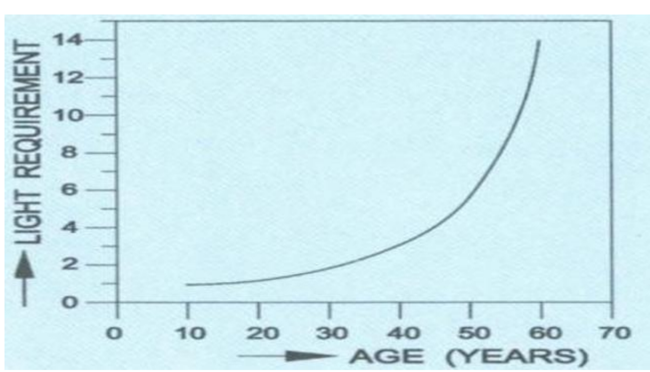


Fig. 7 a Light Requirement for a Specific Reading Task Plotted Against Age

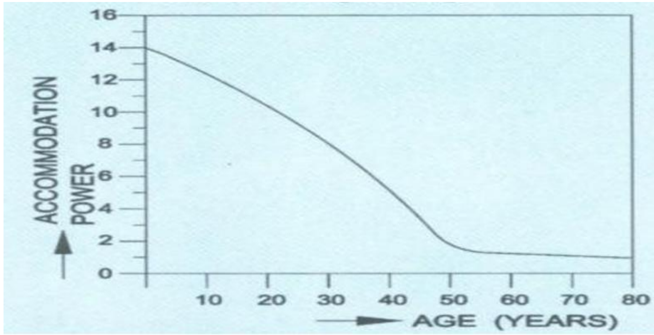


Fig. 7 b Accommodation Powers, in Diopters Plotted against Age

Fig. 7 Eye Visibility Factors with Age

8 SPECTRAL SENSITIVITY OF VISION

8.1 Rods & Cones

Vision is primarily dependent on the function of rods and cones. Rods are highly sensitive to light and are mainly responsible for detecting shape and movement, though they cannot distinguish colors. Cones, on the other hand, are less sensitive to light but are essential for color discrimination and for perceiving finer details.

In the case of rods, around one hundred rods are typically connected to a single nerve fiber. This clustering enhances light sensitivity, as the stimulation from multiple rods is combined. However, it also results in a lack of definition, as the brain cannot differentiate between individual rods within a cluster. As a result, when vision relies primarily on rods, the image tends to be blurred.

Rods are not capable of distinguishing colors, but their sensitivity to light varies across different wavelengths. At higher light levels, the photopigments in rods, such as rhodopsin (or rod-opsin), become bleached or exhausted, and their sensitivity decreases significantly at light levels exceeding 5 cd/m². Therefore, rods are more sensitive to light than cones, and as lighting conditions improve, rods become less active, allowing cones to take over vision.

The transition from high light to low light or darkness takes only a few minutes, as rods become less active and cones become more functional. However, adapting from darkness or low light to bright light takes more than 30 minutes for full adjustment.

Rods exhibit peak sensitivity at a wavelength of 507 nm, which falls within the green-blue spectrum. Sensitivity sharply decreases toward both ends of the light spectrum. Rod vision is characterized by low acuity and monochromatic perception. While rods are sparsely distributed across the retina, cones are present throughout, with a dense concentration in the fovea (*see* Fig. 2). Unlike rods, which are less abundant in the foveal region, each cone is individually connected to the brain, resulting in high resolving power and color perception. However, cones are much less sensitive to light compared to rods. As a result, at luminance levels of 3.5 cd/m² or lower, cone function diminishes. The spectral sensitivity curve for cones differs from that of rods, with peak sensitivity occurring at 555 nm (bright yellow). The decline in sensitivity toward the red end of the spectrum is less pronounced in cones. As lighting decreases, and cones cease to function while rods take over, blue colors appear brighter than red ones (*see* Fig. 8a).

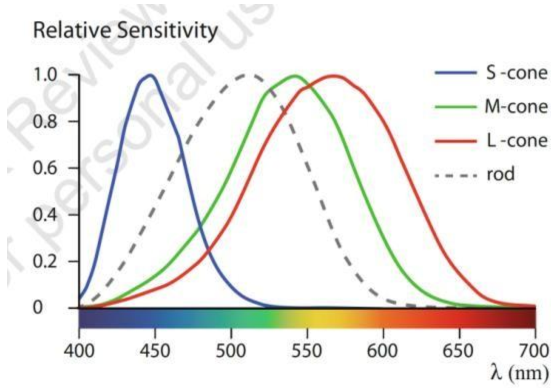


Fig. 8 (a) Relative Spectral Sensitivity Curve for Different Opsin of Cones & Rod

Cones are responsible for color vision, a process that was not fully understood until relatively recently. Previously referred to as photopsins, Now there are three types of cone photoreceptors based on their wavelength sensitivity: S-CONE opsin pigment (for short wavelengths, blue light), M-CONE opsin pigment (for medium wavelengths, green light), and L-CONE opsin pigment (for long wavelengths, red light) (*see* Fig. 4). Cones are not distributed evenly across the retina; the S-cones, which are sensitive to blue light, are concentrated more at the outer edges of the fovea. Additionally, the distribution of these cones varies—S-cones make up only about 5 to 7% of the total cone population.

Each cone type is sensitive to a specific part of the light spectrum: red, green, or blue. If an individual is missing one type of cone, they are colorblind. Furthermore, individuals who only have rods, with no cones, experience not only color blindness but also other significant visual deficiencies.

At very low luminance levels (below 0.005 cd/m²), cones cease to function, and vision is entirely reliant on rods. This results in a low-definition image with no color perception. Although focusing on specific objects becomes impossible, movement detection remains relatively easy. Due to the Purkinje shift, blue objects are visible for longer than red ones as the luminance decreases. This type of vision is called scotopic vision, which occurs under very low to dim lighting, such as at night without artificial light (*see* Fig. 8 b).

Between the ranges of photopic and scotopic vision (from 5 to 0.005 cd/m²), both rods and cones are active. This condition is referred to as mesopic vision and typically occurs under conditions where there is low to moderate lighting, like streetlights or dim ambient lighting. Most roadways, public spaces, and outdoor environments fall into this range.

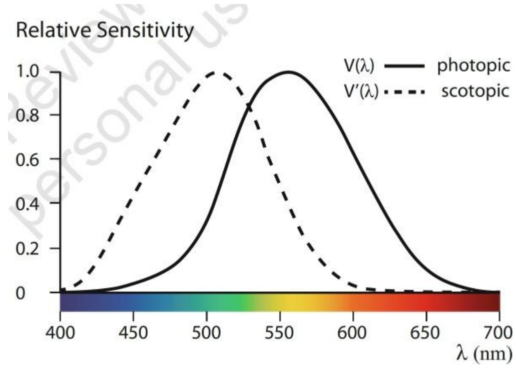


Fig. 8 (b) Peak of Photophic at 550nm, Peak of Scotopic At 507nm.

With the understanding of mesopic vision, a new area of research and measurement has emerged in lighting parameters. Traditionally, photometric units have been based on photopic conditions, where the photopic spectral sensitivity function is used to convert radiometric units (such as radiant power in watts) into photometric units like luminous flux, expressed in lumens. However, in mesopic conditions, where both rods and cones are active, using traditional photopic measurement techniques can lead to inaccurate results. This is because the efficacy of light sources changes, and lux levels also vary in mesopic lighting, making the photopic-based approach unsuitable for such scenarios. As shown in Fig. 9, a more refined measurement approach is needed to properly assess lighting in the mesopic range.

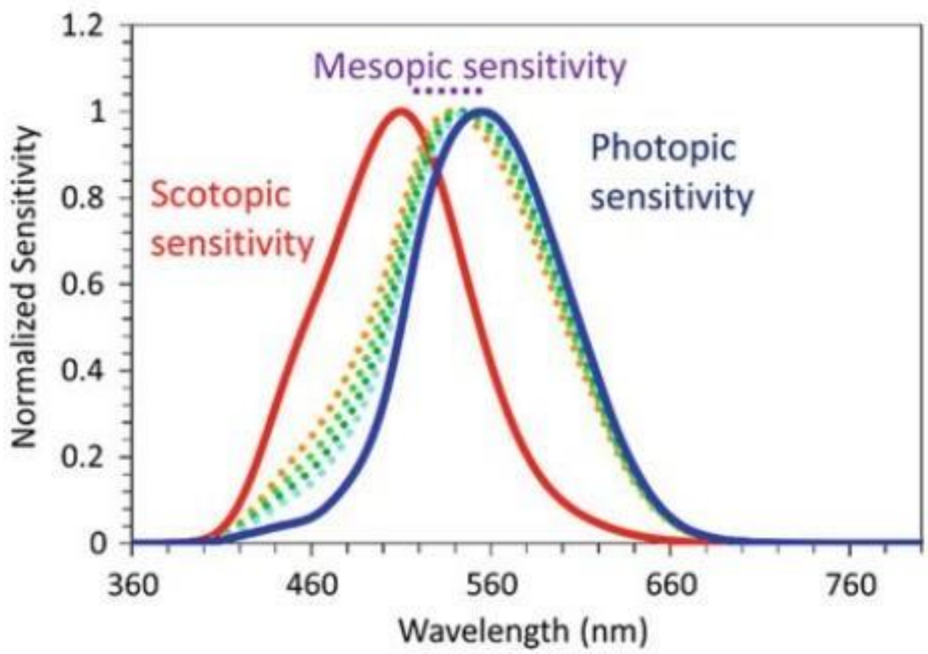


Fig. 9 Mesopic Vision

The mesopic photometry system defines a mesopic luminous efficiency function, V_mes(λ)**,** as a linear combination of the photopic luminous efficiency function, **V(λ)**, and the scotopic luminous efficiency function, V'(λ)**.** The spectral efficiency of this function varies depending on the luminance, which is referred to as the adaptation luminance—the level of luminance to which the eyes are adapted.

Table 1 has been given for real value effective calculations.

Table 1 Photopic and Scotopic Value of Different Type of Lamps
(*Clause* 8.1)

Sl. No (1)	**Source** (2)	**Photopic** lm/W (3)	**Scotopic** lm/W (4)
i)	Incandescent	12	12
ii)	CFL 2700K	55	43
iii)	T8 Fluor 3000 K	100	79
iv)	T8 Fluor 4100 K	100	114
v)	T8 Fluor 6500 K	90	139
vi)	T12 Fluor 7500 K	55	91
vii)	Metal halide	95	114
viii)	White LED	62	108

Draft National Lighting Code of India

Part 2 Physics of Light
Section 3 Colour

First Revision of SP 72 (Part 2/Section 3)

FOREWORD

Indeed, color is a fascinating and important aspect of our visual perception. It is true that color is a subjective experience that is perceived and interpreted by the human eye and brain working together. Our visual system responds to electromagnetic waves generated by light sources, and the brain processes this information to create the experience of color.

The association of color with the objects and things around us is a result of our learned experiences and cultural influences. Different individuals may perceive and interpret colours slightly differently due to variations in their visual systems and personal factors. This subjectivity has led to the development of various methods of color assessment and standardization to ensure consistency and accuracy in color representation.

Color is a complex phenomenon influenced by factors such as light source properties, surface reflectance, and human perception. As a result, organizations and researchers continue to explore and refine our understanding of color to improve its measurement, reproduction, and control.

Color also plays a vital role in lighting. Lighting designers use color to create visually appealing scenes and enhance the overall experience. With the advancements in solid-state lighting (SSL) and intelligent lighting electronics, a comprehensive knowledge of color and its properties has become crucial for lighting professionals. Understanding color temperature, color rendering, chromaticity, and other color-related concepts helps them design lighting solutions that meet specific aesthetic and functional requirements.

In summary, color is a psychological experience perceived by the human eye and interpreted by the brain. Sir Isaac Newton's foundational work in color science still holds true today, but ongoing research and standardization efforts continue to deepen our understanding of color and its complex characteristics. In the realm of lighting, color is a powerful tool used by designers to create visually appealing and impactful environments.

Draft National Lighting Code of India

PART 2 PHYSICS OF LIGHT
SECTION 3 COLOUR

(First Revision)

1 SCOPE

This section of the code (Part 2/ Sec 3) covers the importance of colour in lighting, its concept, basic phenomenon and general information about colour theories.

2 REFERENCES

a) CIE 1931 Color Sapce;
b) CIE 224: 2017 Colour Rendition Metrics ;
c) IES TM30 -15 Method for Measuring Color Rendition ; and
d) IES TM 30-18 Color Rendition Guidelines & Reports.

3 TERMINOLOGY

The definition given in the Part 1 of this code shall apply.

4 COLOUR FUNDAMENTAL

The existence of color requires three components: a viewer (such as a human eye), an object that reflects or emits light, and the presence of light itself. When these three elements come together, we perceive color.

By observing the dispersion of light, Newton discoveredthat white light is actually composed of a continuous spectrum of colours. He identified and namedseven colours in the spectrum: violet, indigo, blue, green, yellow, orange, and red.

However, it's important to note that Newton's classification of these seven colours as primary colours was specific to his work and not the same as the primary colours used in modern color systems. In modern color theory, the primary colours are typically considered to be red, blue, and green, which are used in additive color mixing systems (such as those used in displays and electronics) to create a wide range of colours. This is different from the subtractive color mixing system (used in physical pigments and dyes) where the primary colours are cyan, magenta, and yellow.

Nevertheless, Newton's experiments and his identification of the spectral colours laid the foundation for our understanding of light and color. His work was instrumental in advancing the field of color science and color theory. Wave length of seven colours has shown in the Table 1.

Table 1 Wavelength of Seven Colours
(*Clause* 4)

Sl. No.	**Colour**	**Wave Length Range** (nm)
(1)	(2)	(3)
i)	Violet	380-420
ii)	Indigo	420-440
iii)	Blue	440-490
iv)	Green	490-560
v)	Yellow	560-590
vi)	Orange	590-630
vii)	Red	630-780

Colour is perceived through the interaction of light, objects, and the human visual system. When white light is emitted or transmitted, it contains all the colours in the visible spectrum. However, light emitted or transmitted by specific sources or mediums may only contain certain colours or be close to monochrome.

When white light strikes an object, the object absorbs certain colors and reflects others. The reflected light is what we perceive as the object's color. The colors we see result from the combination of different wavelengths of light entering our eyes.

The colour appearance of surfaces can be affected by the choice of light source. For example, a white paper appears white under white light because it reflects all the colours of the light spectrum to our eyes. However, if the same white paper is observed under red light, it will appear red because there are no other wavelengths present except for red to be reflected to our eyes.

It is important to note that not all spectral colours occur in all light sources, and even if they do, they may be present in varying proportions. Various light sources emit different combinations of colours, which can influence the perceived color of objects illuminated by those sources.

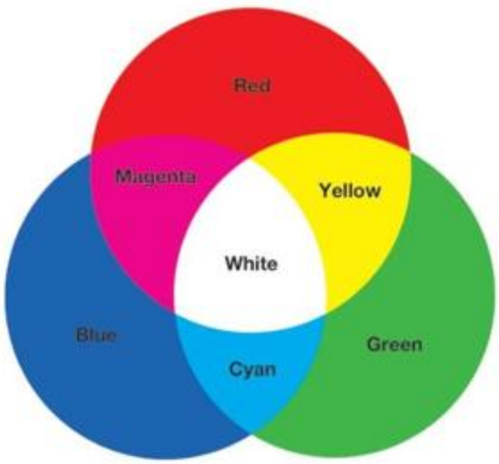
The color matching principle established by James Clerk Maxwell. This principle involves matching colours of different wavelengths using the primary colours of red, green, and blue lights (often abbreviated as RGB). By varying the proportions of these primary colors, a broad spectrum of colors can be created.

5 COLOUR MIXING

There are two fundamentally different methods of color mixing: additive color mixing and subtractive color mixing.

5.1 Additive Colour Mixing

The mixing of coloured lights is called additive colour mixing (*see* Fig. 1) process. This can be explained by considering three basic colours, termed as Primaries. These are Red (R), Green (G) and Blue (B). By mixing two primary colours secondary colours or complementary colours are produced. If three primary colours are mixed in the right intensities a white light will be produced.



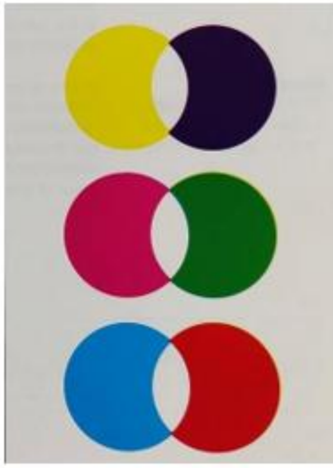


Fig. 1 Additive Colour Mixing

5.2 Subtractive Colour Mixing

There is a fundamental difference between mixing of coloured lights and mixing of dyes and paints. If the coloured paints are mixed the result will be always darker than any of the paints mixed. If the right colours of dyes and paints are mixed in the right proportions the effect will be black. This form of mixing dyes and pigments is known as subtractive colour mixing (*see* Fig. 2).

The colour of an object is due to selective reflection and/or transmission. Due to this property, therefore, a coloured object subtracts out certain spectrum of incident light.

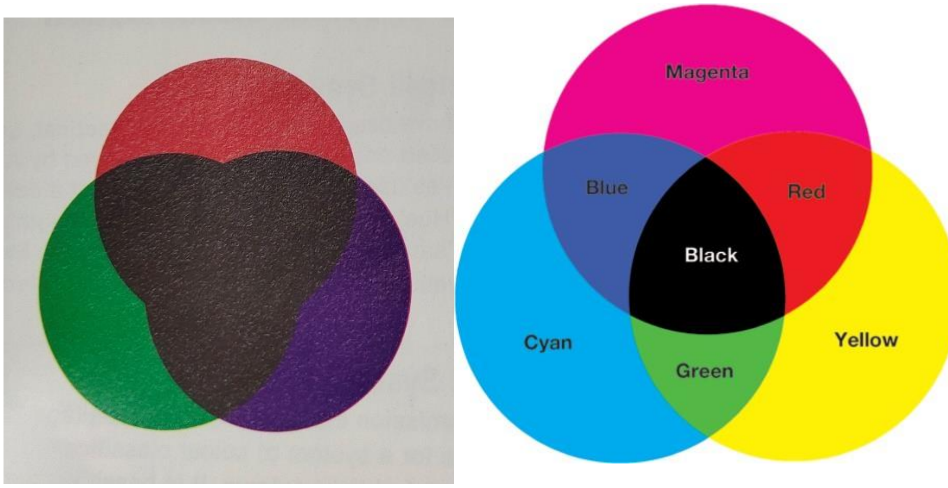


Fig. 2 Subtractive Colour Mixing

6 COLOUR THEORIES

The foundation of color theory began with the tri-color colorimetry theory proposed by Young and Helmholtz. According to this theory, the human eye contains three types of receptors that selectively respond to different wavelengths of light in proportion to their intensity. This theory focuses on the stimulus aspect and assumes that color perception is based on the response of these receptors.

Another color theory, known as the opponent color theory, was introduced by Hering. It emphasizes the basic response of the eye rather than the stimulus. Hering's theory suggests that there are six basic colors: red, yellow, green, blue, black, and white. These colors are organized into three pairs of opposing processes. For example, there is a blue-yellow opponent pair, which means that a color cannot simultaneously appear both bluish and yellowish. Blue cancels out yellow, and vice versa. The same principle applies to the red-green opponent pair. In the black-white pair, a color can shift towards black or white from gray, but not towards both at the same time. White does not cancel out black; instead, they blend to produce shades of gray.

Both the tri-color colorimetry theory and the opponent color theory are needed to explain color perception comprehensively. Each theory provides a different perspective on color and its perception.

7 COLORIMETRY & MATHEMATICAL FORMULATION

Colorimetry is a scientific discipline that involves the measurement and systematic design of color. One of the fundamental aspects of colorimetry is color mixing and color matching.

However, the data obtained from the initial experiments lacked the necessary accuracy for precise color specification. These measurements were also influenced by individual observers, as well as the combined effects of luminance and color.

To address these limitations, two alternative approaches to color specification were developed. The first approach involves using tristimulus value curves, which are calibrated with respect to a reference white point. Through complex mathematical calculations and manipulations, tristimulus value curves were derived. However, this process was laborious and relative values introduced some drawbacks.

In the search for improved color specification, scientists explored and published alternative methods based on tristimulus values and color matching. These efforts aimed to overcome the limitations of the previous approaches and provide more accurate and reliable color specifications. Additive mixing of colour (*see* Fig. 1) can be being mathematically represent as:

R +G = Yellow
G+B = Cyan
B+R = Magenta
R+G+B = White

Here, symbol "=" is used to represent matched equivalent. This trichromatic mixing however, follows algebraic law, i.e., any colour stimuli 'C' can be matched by adding R, G, and B and expressed as,

C(C) =R(R) +G (G) +B (B) ....(1)

The symbols within brackets represent corresponding stimuli including the colour C to be matched. R, G, B and C are quantities or amounts of the stimuli. Now, as the stimuli is due tovarious quantities of reference lights only, we must have

C=R + G + B… ....(2)

Instead of using actual values of the quantities, a ratio of the matching stimuli can be used. Thus, dividing both sides of the equation (1) above by (R + G + B), we may write

l = r + g + b…... ....(3)

where,

r = R/(R + G + B);
g = G/(R + G + B);
b = B/ (R + G + B)

Thus, the equation (1) can be written as

1.0 (C) = r (R) + g (G) + b (B)… ....(4)

The r, g and b are uniform. A white light is matched by equal amount of R (700 nm), G(546.1nm) and B (435.8nm).

It can be seen that it is possible to match all colours of the spectrum by means of additive mixture of three stimuli. This can be represented by curves as shown in Fig. 3 and are known as colour matching functions. It is important to note that all three curves (for red, green, and blue) may have negative portions, these negative values are very small for blue and green.

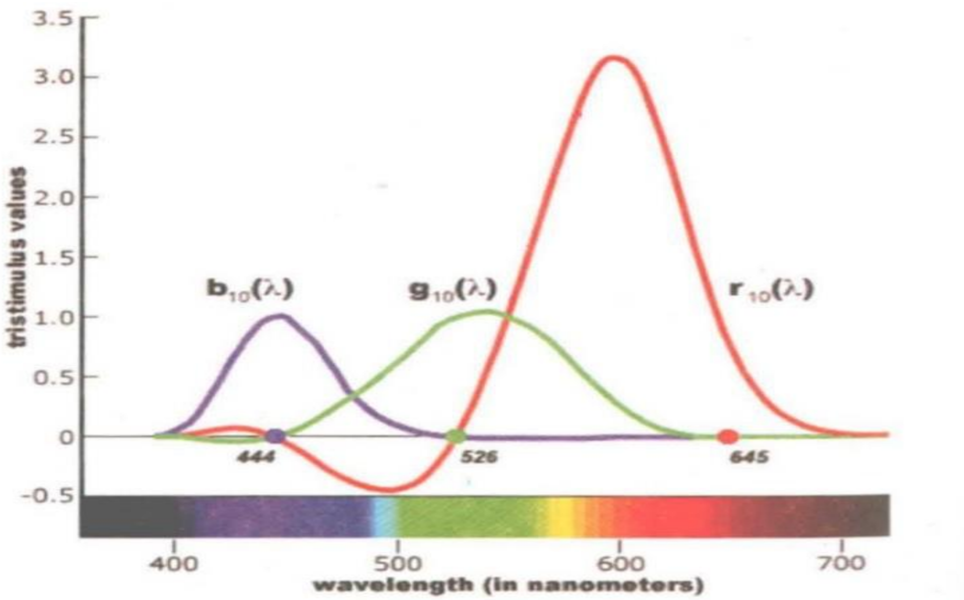


Fig. 3 Tristimulus Value Curves for r(λ), g(λ), b(λ)

In order to prevent the color matching functions from yielding negative values, a decision was made to transform the color axes. This transformation ensures that the functions remain non-negative at all times. To achieve this, the R, G, and B functions are converted into three imaginary primaries.

Additionally, one of the functions is aligned with the V (λ) standard observer curve, while another function is adjusted to be nearly equal to zero. This transformation helps ensure that theresulting values of the color matching functions are always positive or zero.

The International Commission on Illumination (CIE) has defined new stimuli denoted as X, Y, and Z. These values can be derived from the proportions of R, G, and B required for a color match using the transformation method. This approach allows for a more consistent and reliable representation of colors without the occurrence of negative values.

So, we have:

$$C(C) = X(X) + Y(Y) + Z\,(Z) \qquad \ldots (5)$$

Following the arguments given in 3.1, we can have,

$$1.0\ (C) = x(X) + y(Y) + z\ (Z) \quad \ldots\ldots\ (6)$$

where,

$x = X/(X + Y + Z)$;
$y = Y/(X + Y + Z)$;
$z = Z/(X + Y + Z)$ and
$x + y + z = 1 \quad \ldots\ldots\ (7)$

Like additive primaries, three colours are chosen as subtractive primaries, which will absorb only red, green and blue light respectively. For example, a colourant absorbing Red will not absorb the Blue and Green spectra of the incident light. The object, therefore, will appear as bluish green, that is, Cyan (C) and Cyan will be one of the subtractive primaries. Similarly, Magenta(M) and Yellow (Y) will be other two subtractive primaries, like additive mixing.

We may write

Y+C = Green

C+ M = Blue

M+ Y = Red; and

Y+C+M = Black (*see* Fig. 2)

9 THE CIE SYSTEM

All colours that can be produced by three primary colours can only be presented by in a three-dimensional space. However, by neglecting the effect of differences in brightness of the colour stimulus and concentrating on hue and saturation of the colour sensation only, a two-dimensional plane presentation is done here. In fact, one cross section of the three-dimensional space.

Below Fig. 4 shows CIE 1931 standard observer and Fig. 5 shows CIE 1964 colour matching & tristimulus function.

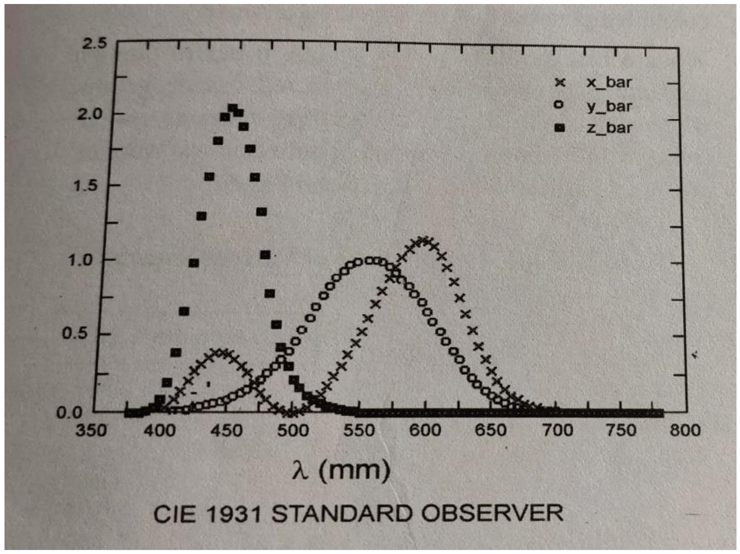


Fig. 4 CIE 1931 Standard Observer

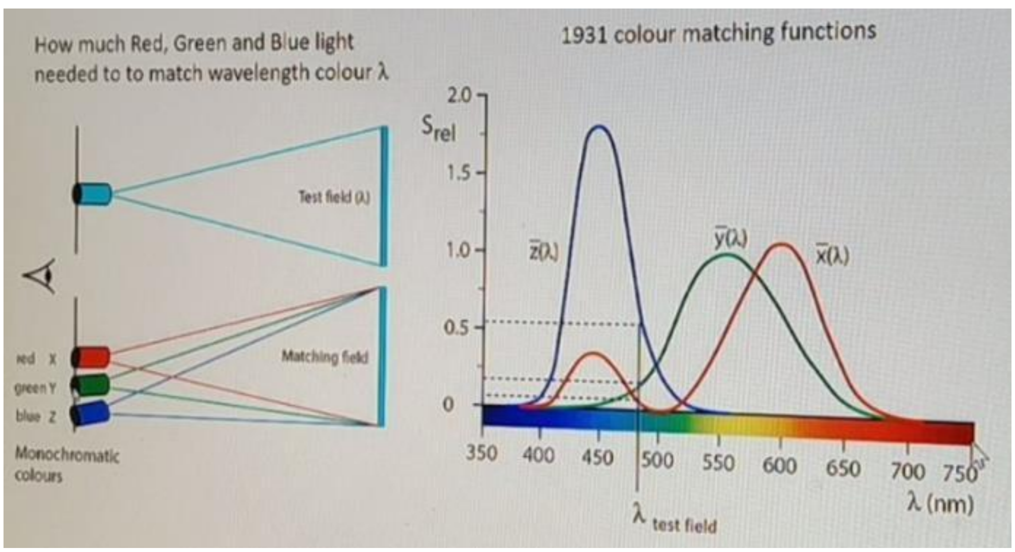


Fig. 5 CIE 1964 Colour Matching & Tristimulus Function

For defining colours in the two-dimensional plane, it needs to have its own coordinates that relate to the primary colours X, Y and Z of the three-dimensional space. These coordinates are defined by the relative amount of tristimulus values X, Y, and Z as shown in equation 6.

$$x = X/(X + Y + Z);$$
$$y = Y/(X + Y + Z);$$

These two coordinates used in a rectangular coordinating system.

International Commission on Illumination (CIE) developed three color matching functions that approximate the sensitivities of the three types of cones in the human eye: red, green, and blue. The CIE 1931 color system is based on additive color principles but addresses its limitations through mathematical transformations. By applying these functions to the light source spectrum, a 3-coordinate system (X, Y, Z) and chromaticity coordinates (x, y, z) are generated, with the condition that $x + y + z = 1$. This allows color representation using just the x and y values.

To improve the system, two key changes were made: First, the color triangle was adjusted to better represent highly saturated spectral colors, especially in the green and blue regions where color differences are more noticeable. This modification created the characteristic CIE color triangle, bounded by the spectrum locus curve.

Second, numerical color values were plotted along the axes of a right-angled triangle, where each color is defined by its x and y chromaticity coordinates. In the CIE 1931 diagram (*see* Fig. 6), spectral colors are along the triangle's edges, with primary colors (red, green, violet-blue) at the corners. The most saturated colors are found at the perimeter, becoming lighter and less saturated towards the center, where white is located, following additive color mixing principles.

Compared to the Munsell system (which defines hue, value, and chroma), the CIE system defines hue based on the spectrum locus and chroma by the distance to that point. For surface colors, reflectance replaces the value component. A color is defined by its chromaticity coordinates (x, y) and reflectance (0–199), such as x = 0.545, y = 0.389, and reflectance = 28.8, representing a shade of orange.

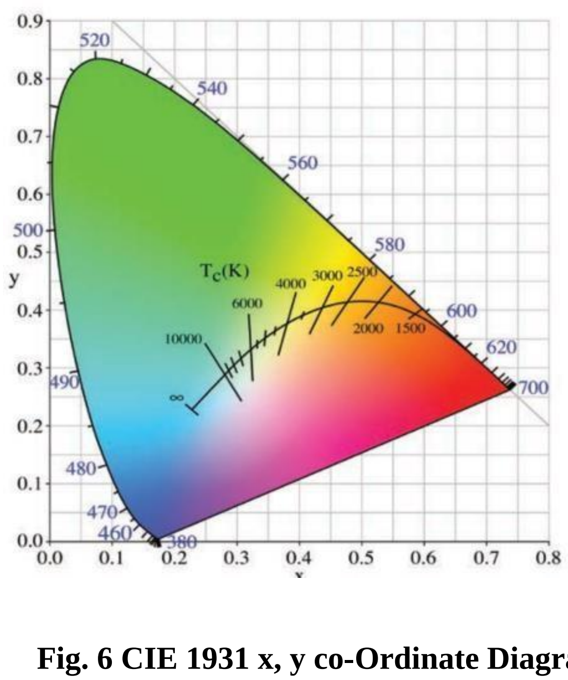


Fig. 6 CIE 1931 x, y co-Ordinate Diagram

10 THE BLACK BODY LOCUS IN THE CIE COLOUR TRIANGLE, COLOUR APPEARANCE (CCT)

Color appearance refers to the perception of color resulting from the combination of different wavelengths entering our eyes. It is not an inherent characteristic of any surface. When determining how a color will appear under a specific light source, practical experience is often relied upon. When heated, such a body emits visible radiation with a colorthat is specific to its temperature. This color of light is referred to as "color temperature." A colortemperature scale can be plotted within the CIE color triangle, forming a curve known as the "Black Body Locus" or the Planckian locus.

To compare the light characteristics of different light sources with those of thermal radiators in terms of color temperature, the concept of correlated color temperature (CCT) was introduced. It is important to note that these classifications are represented by lines perpendicular to the black body locus, rather than points. This means that two sources with the same CCT can actually have different colors. In the diagram below, the CCT lines for various temperatures such as 1500K, 2000K, 2500K, 3000K, 4000K, 6000K, and 10000K are labeled. The "K" stands for degrees on the Kelvin temperature scale, where 0 degrees Celsius is equivalent to 273 Kelvin. Below Table 2 describes colour CCT tolerance and deviation.

Table 2 Colour CCT Tolerance and Deviation
(*Clause* 10)

Sl. No	**Nominal CCT[1)]**	**Target CCT and Tolerance (K)**	**Target Duv and Tolerance**
(1)	(2)	(3)	(4)
i)	2700 K	2725 ± 145	0.000 ± 0.006
ii)	3000 K	3045 ± 175	0.000 ± 0.006
iii)	3500 K	3465 ± 245	0.000 ± 0.006
iv)	4000 K	3985 ± 275	0.001 ± 0.006
v)	4500 K	4503 ± 243	0.001 ± 0.006
vi)	5000 K	5028 ± 283	0.002 ± 0.006
vii)	5700 K	5665 ± 355	0.002 ± 0.006
viii)	6500 K	6530 ± 510	0.003 ± 0.006
ix)	Flexible CCT (2700 K – 6500 K)	T[2)] ± ΔT[3)]	D_{uv}[4)] ± 0.006

12 COLOUR RENDERING

Color rendering measures how accurately a light source replicates colors compared to a reference light source, typically a blackbody radiator suited to the application (for example, 4100K for office lighting).

Even if light sources have the same color temperature, their effect on surface colors may differ because surfaces reflect specific wavelengths from the light. For example, although yellow light from both low-pressure sodium lamps and incandescent lamps may appear the same, object colors are more distinguishable under incandescent light. This is because incandescent lamps emit a continuous spectrum, unlike selective discharge lamps or LEDs, which emit specific spectral lines, affecting color rendering.

A light source's color rendering ability depends on the number, arrangement, and intensity of spectral lines in its spectrum. The CIE evaluates this using a Color Rendering Index (Ra), calculated based on how eight test colors (R1 to R8) appear compared to a blackbody radiator. Ra ranges from 0 (monochromatic) to 100 (blackbody radiation). Values below 25 are generally not meaningful, and additional samples (R9 to R14) assess mixed color recognition. Below Fig. 7 shows CIE Colour Chart.

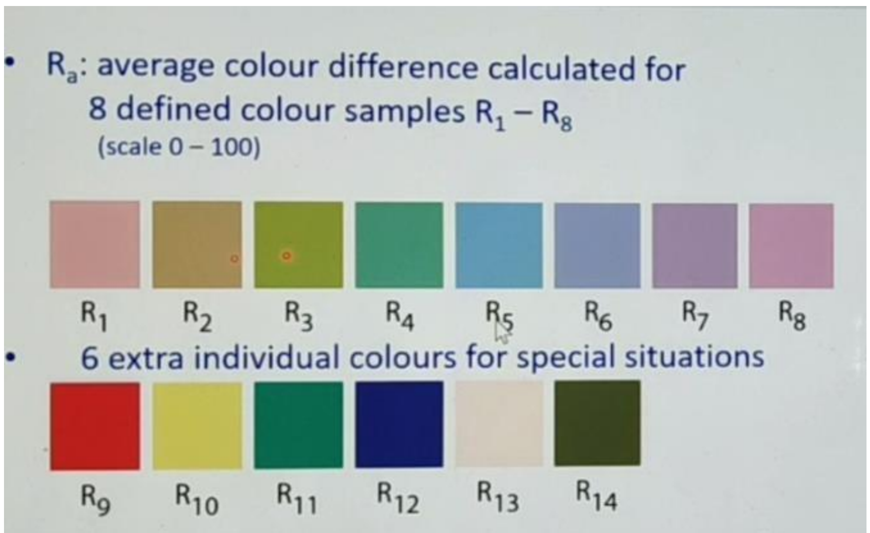


Fig. 7 CIE Colour Chart

For lighting applications, the color rendering index (Ra) is classified as follows:

a) 100: Perfect match with blackbody radiation
b) 90: Excellent
c) 80 to 89: Very good
d) 70 to 79: Good
e) 60 to 69: Fair
f) 50 to 59: Poor

12.1 IES TM 30, CIE 2017 NEW METHOD OF COLOUR RENDITION

The IES TM-30-2018 method, updated from the CIE 1965 method, was developed to better evaluate color rendering in modern lighting, especially with LEDs, which require more precise quantification. The original CIE method worked well for discharge lamps but lacked accuracy for newer lighting technologies. The IES TM-30 was first published in 2015 and revised in 2018, and is now widely accepted.

IES TM-30 evaluates color rendition through three components:

a) FIDELITY Index R_f;
b) Gamut Index R_g: and
c) Colour Graphics/ Picture

12.1.1 *The Fidelity Index*

The Fidelity Index is a new index for color rendering, and it shares the same scale asthe CIE system, ranging from 0 to 100. The calculation procedure for the Fidelity Index in the IES system has been improved by considering a three-dimensional color space, whereas the CIE system only considers two dimensions. The Fidelity Index incorporates 99 evenly distributed color samples within the color space, excluding extremes in saturation or darkness. The color fidelity index for each of these samples is obtained by calculating the color deviation. The overall color fidelity index is determined by averaging the results of the 99 individual test colors (*see* Fig. 8), referring to the CIECAM02-UCS model for guidance.

Fig. 8 99 TM -30 Colours

All colour spaces and chromaticity diagrams are designed so that so that more saturated colours are located outwards and unsaturated colours inwards. The saturation aspects of colour rendering of a specific light source is thus directly dependent on the direction of the colour shift of colour sample: shift outwards increases saturation and shift outwards decreases the saturation. The area obtained by connecting the chromaticity points of the colour samples when illuminated with a specific light source is called the gamut area. Larger the gamut area larger the saturation of colour obtained with that light source relative to reference light source.

12.1.2 *Garmut Index*

In TM30, The Gamut Index, R_g is the percentage of the gamut area of the test source relative to the area of the reference source. This is basically based on comparisons of a light source with that of a reference source, the same light source used for Rf value. TM30 gamut area based on chromatically coordinates of 16 colours (based on practical possibility) groups or colour bins and deviation is taken into account for calculations of CIECAM02-USC colour space. When there is no shift the R_g value is 100. R_g value > 100 means increased saturation, R_g <100 means decreased saturation. Practically R_g scale is 60 to 140 for all lamps with R_f > 60.

12.1.3 IES *Colour Graphics*

Below Fig. 9 is termed as colour graphics or colour vector graphics. Here both test lamps have same R_f of 70 but one test samples colour vector graphics gone outside which is more saturated and other test lamp inside the reference lamp graphics hence have lower saturation.

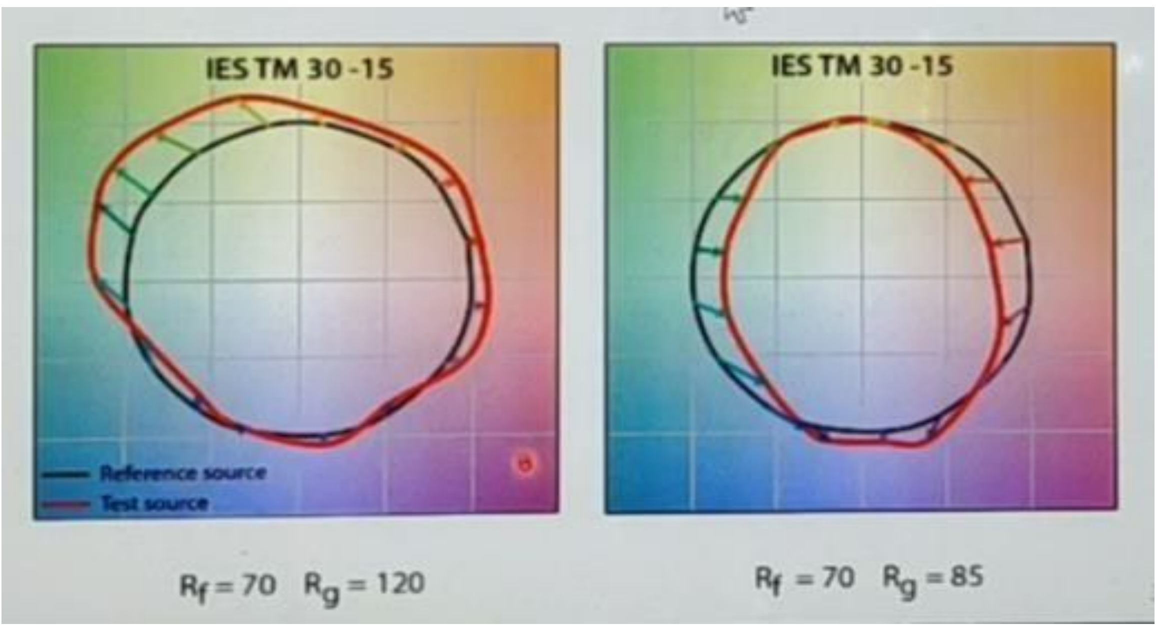


Fig. 9 Colour Vector Graphs Visualizing the Colour Shift

Fidelity Index is suitable and mostly used in specification, regulation and standard but the gamut index is not used that way. This R_g tool is very important for the lighting designer. The concept of these two helps them to blend best with colours of the object of the spaceto be illuminated.

NOTE — So at the end in colour rendition both CIE & IESNA designation exist. Therefore, while defining the colour rendering index, one has to clarify which CRI is specifying. Is it CRI of CIE or CRI of IES system.