Chapter 33 - Light and Illumination

A PowerPoint Presentation by

Paul E. Tippens, Professor of Physics

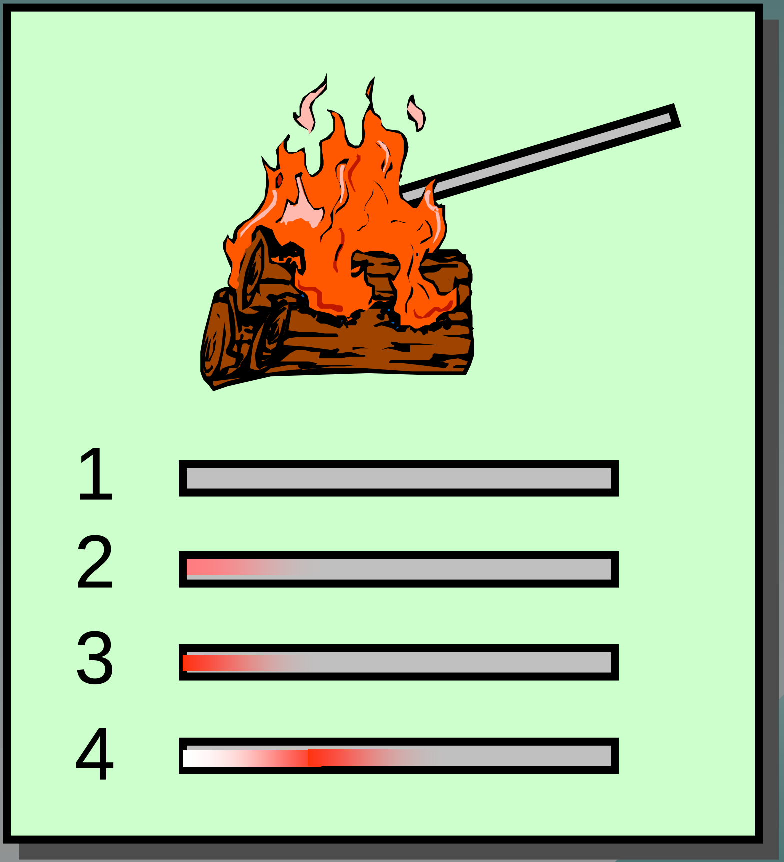
Southern Polytechnic State University

Objectives: After completing this module, you should be able to:

- Define light, discuss its properties, and give the range of wavelengths for visible spectrum.
- Apply the relationship between frequencies and wavelengths for optical waves.
- Define and apply the concepts of luminous flux, luminous intensity, and illumination.
- Solve problems similar to those presented in this module.

A Beginning Definition

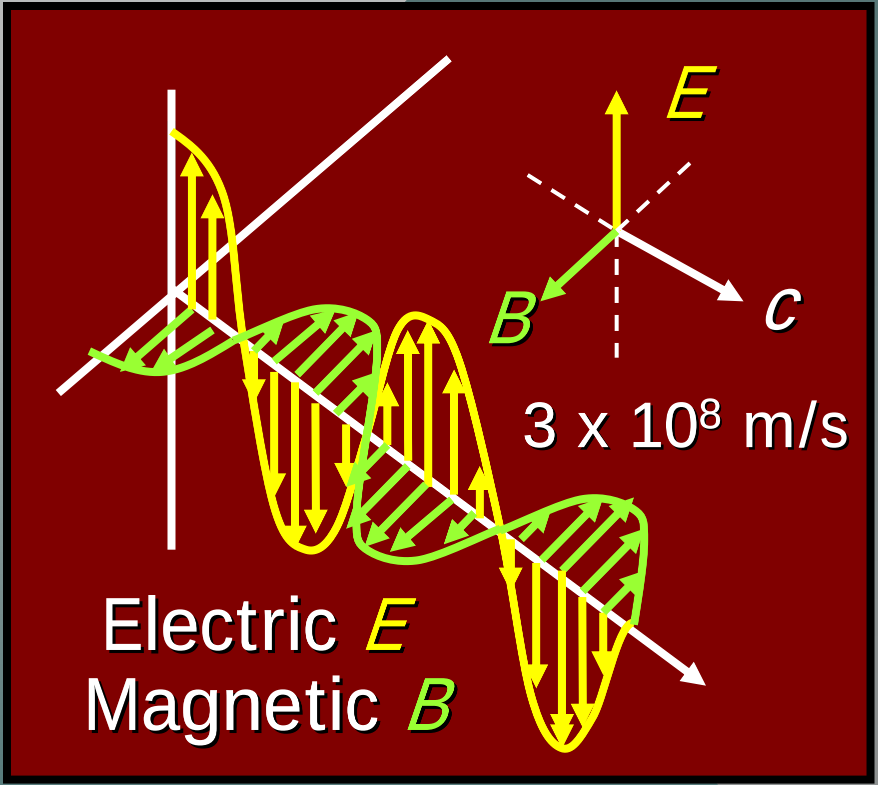
All objects are emitting and absorbing EM radiation. Consider a poker placed in a fire.



As heating occurs, the emitted EM waves have higher energy and eventually become visible. First red . . . then white.

Light may be defined as electromagnetic radiation that is capable of affecting the sense of sight.

Electromagnetic Waves



Wave Properties:

1. Waves travel at the speed of light *c*.
2. Perpendicular electric and magnetic fields.
3. Require no medium for propagation.

For a complete review of the electromagnetic properties, you should study module 32C.

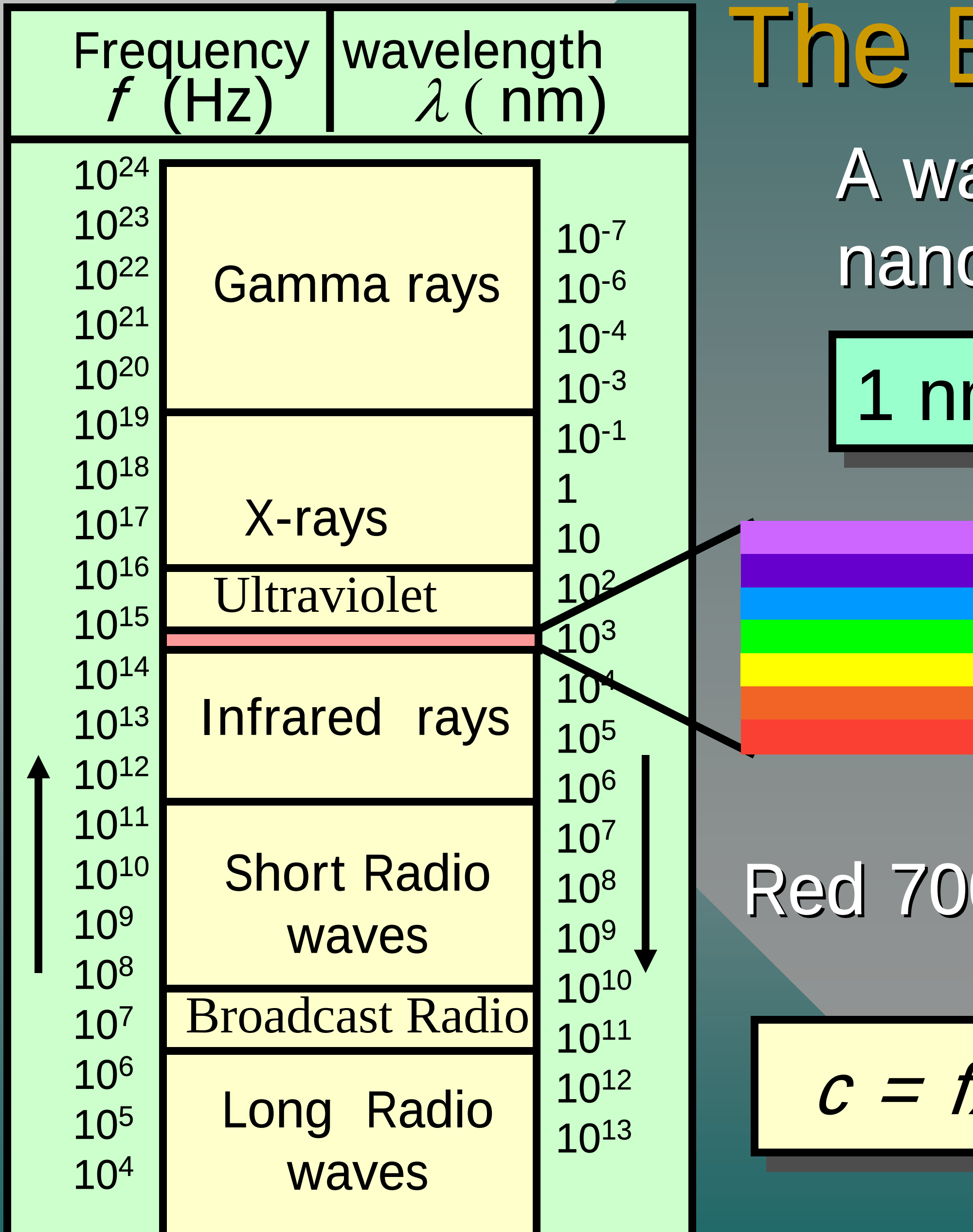
The Wavelengths of Light

The electromagnetic spectrum spreads over a tremendous range of frequencies or wavelengths. The wavelength λ is related to the frequency f:

$$c = f\lambda \qquad c = 3 \times 10^8 \text{ m/s}$$

Those EM waves that are visible (light) have wavelengths that range from 0.00004 to 0.00007 cm.

The EM Spectrum



A wavelength of one nanometer 1 nm is:

$1 \text{ nm} = 1 \times 10^{-9} \text{ m}$

Visible Spectrum

400 nm → 700 nm

Red 700 nm → Violet 400 nm

$c = f\lambda \qquad c = 3 \times 10^{8} \text{ m/s}$

Example 1. Light from a Helium-Neon laser has a wavelength of 632 nm. What is the frequency of this wave?

The Helium Neon Laser

Wavelength

λ = 632 nm

$$c = f\lambda \qquad f = \frac{c}{\lambda} = \frac{3 \text{ x } 10^{8} \text{m/s}}{632 \text{ x } 10^{-9} \text{m}}$$

f = 4.75 x 10^{14} Hz

Red light

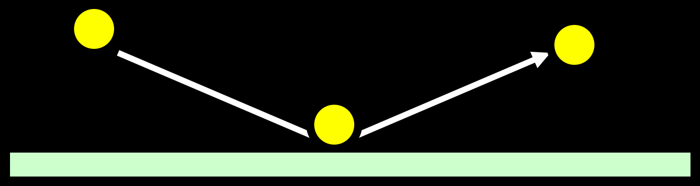
Properties of Light

Any study of the nature of light must explain the following observed properties:

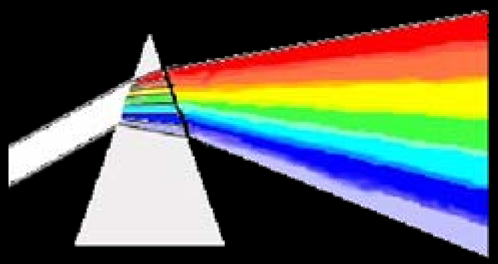
- Rectilinear propagation: Light travels in straight lines.
- Reflection: Light striking a smooth surface turns back into the original medium.
- Refraction: Light bends when entering a transparent medium.

The Nature of Light

Physicists have studied light for centuries, finding that it sometimes behaves as a particle and sometimes as a wave. Actually, both are correct!



Reflection and rectilinear propagation (straight line path)

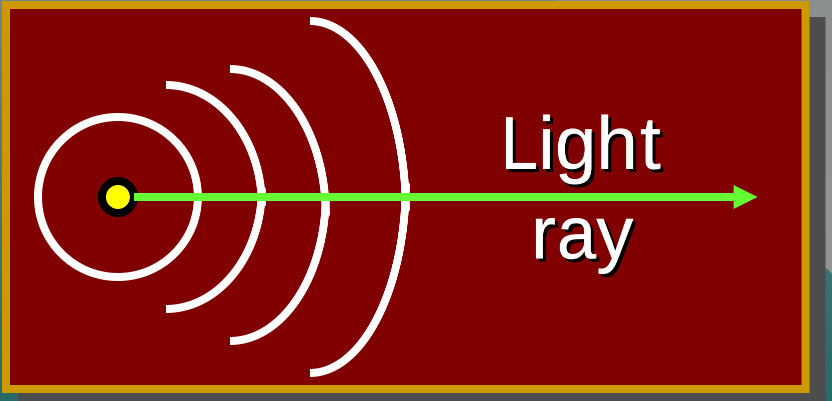


Dispersion of white light into colors.

Photons and Light Rays

Light may be thought of as little bundles of waves emitted in discrete packets called photons.

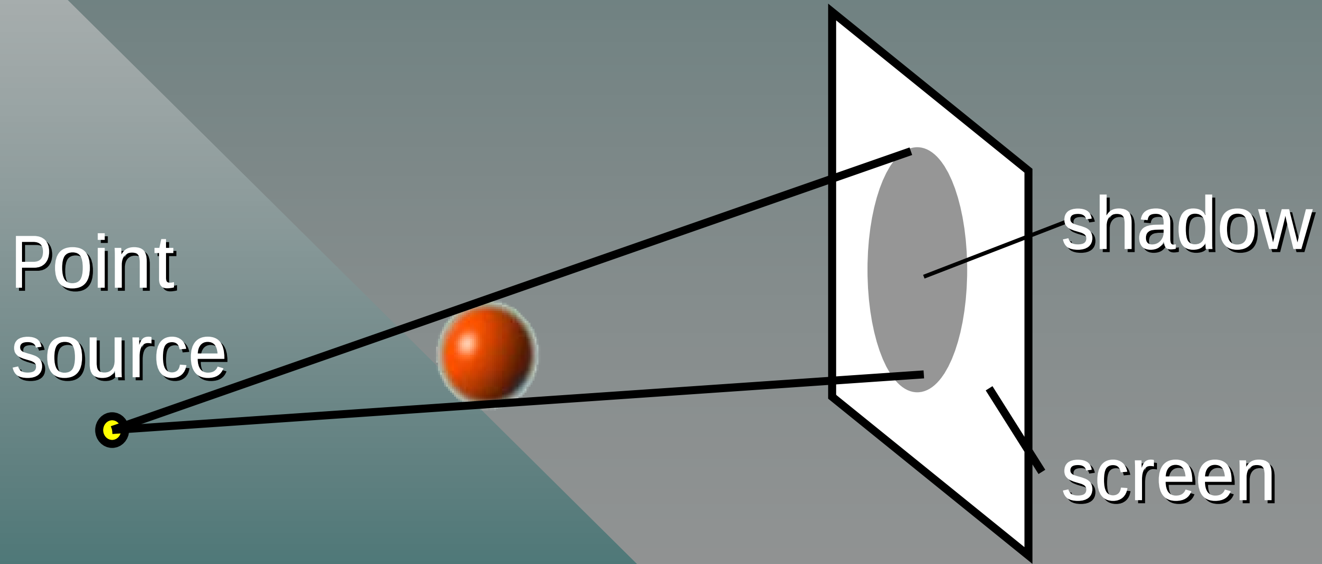
The wave treatment uses rays to show the direction of advancing wave fronts.



Light rays are convenient for describing how light behaves.

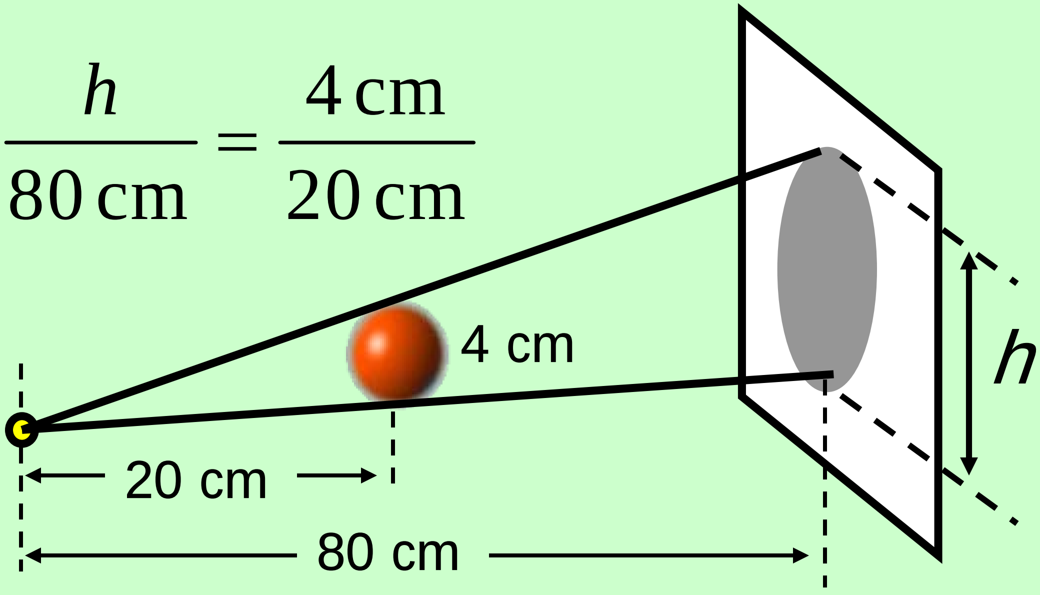
Light Rays and Shadows

A geometric analysis may be made of shadows by tracing light rays from a point light source:



The dimensions of the shadow can be found by using geometry and known distances.

Example 2: The diameter of the ball is 4 cm and it is located 20 cm from the point light source. If the screen is 80 cm from the source, what is the diameter of the shadow?



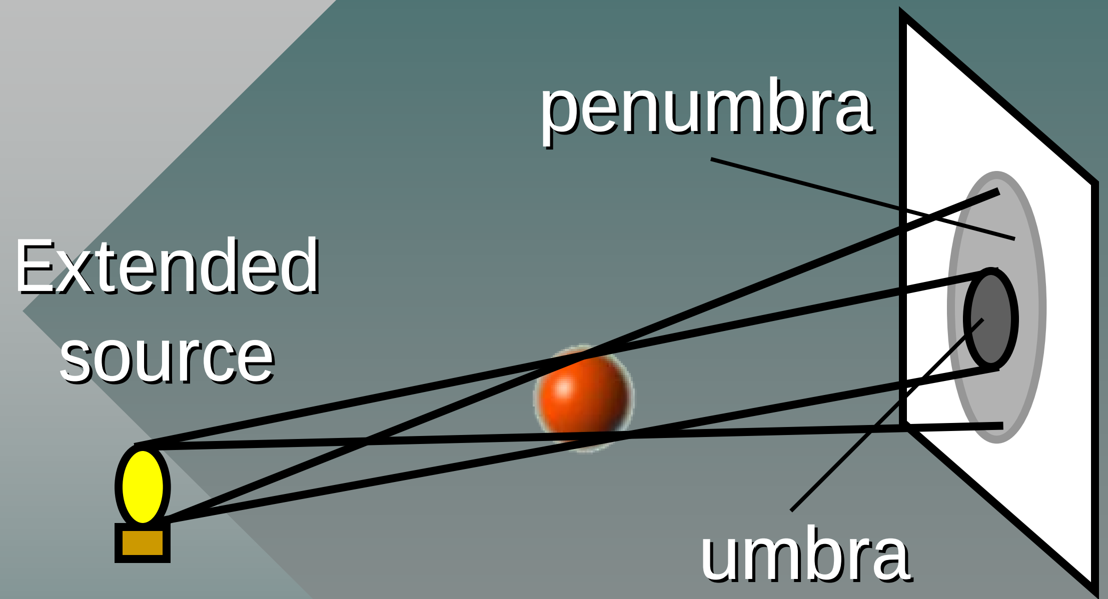
$$\frac{h}{80\,\text{cm}} = \frac{4\,\text{cm}}{20\,\text{cm}}$$

The ratio of shadow to the source is same as that of ball to source. Therefore:

$$h = \frac{(4\text{ cm})(80\text{ cm})}{20\text{ cm}}$$

h = 16 cm

Shadows of Extended Objects

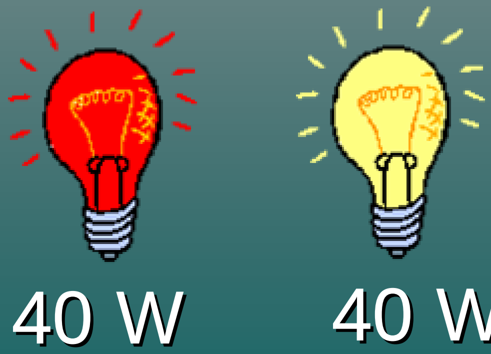


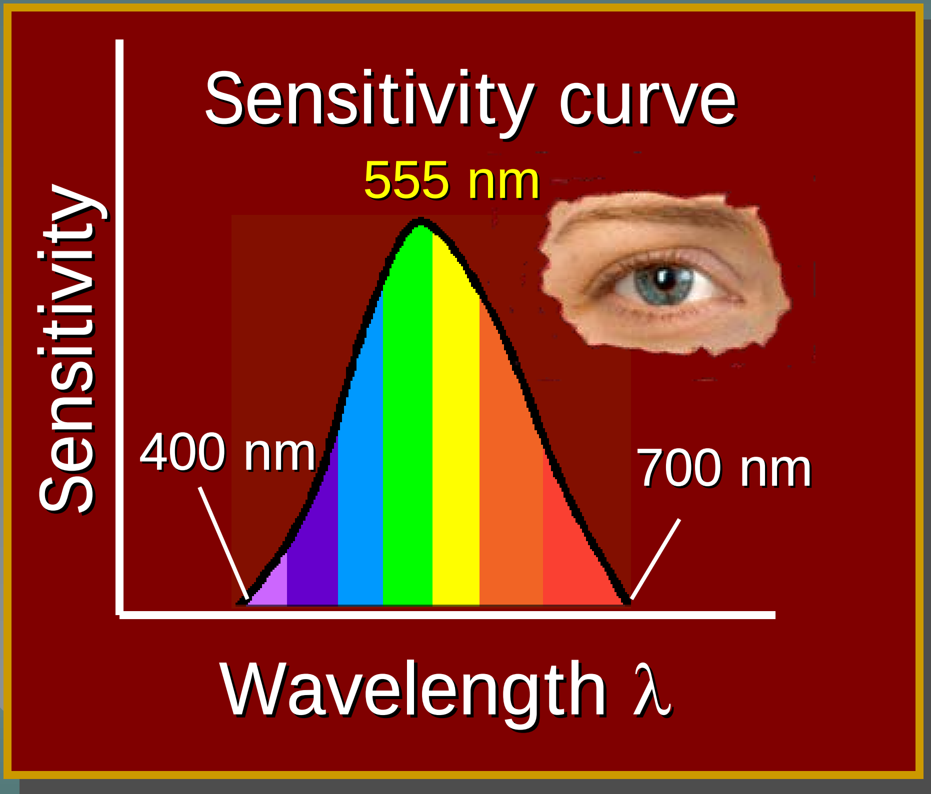
- The umbra is the region where no light reaches the screen.
- The penumbra is the outer area where only part of the light reaches the screen.

The Sensitivity Curve

Human eyes are not equally sensitive to all colors.

Eyes are most sensitive in the mid-range near λ = 555 nm.





Yellow light appears brighter to the eye than does red light.

Luminous Flux

Luminous flux is the portion of total radiant power that is capable of affecting the sense of sight.

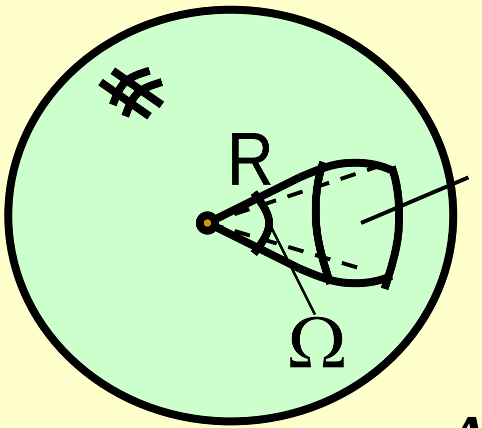
Typically only about 10% of the power (flux) emitted from a light bulb falls in the visible region.

The unit for luminous flux is the lumen which will be given a quantitative definition later.

A Solid Angle: Steradians

Working with luminous flux requires the use of a solid angle measure called the steradian (sr).

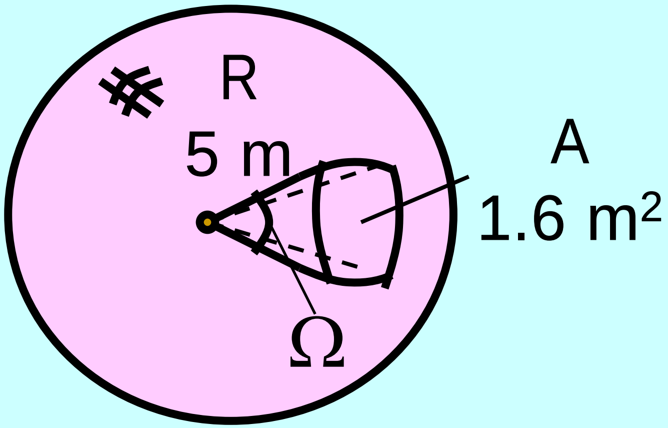
A solid angle of one **steradian** (**1 sr**) is subtended at the center of a sphere by an area *A* equal to the square of its radius (R^2).



The Steradian

$$\Omega = \frac{A}{R^2}$$

Example 3. What solid angle is subtended at the center of a sphere by an area of 1.6 m^2? The radius of the sphere is 5 m.



The Steradian $\Omega = \frac{A}{R^2}$

$$\Omega = \frac{A}{R^2}$$

$$\Omega = \frac{1.60\ \text{m}^2}{(5.00\ \text{m})^2}$$

Ω = 0.00640 sr

The Lumen as a Unit of Flux

One lumen (lm) is the luminous flux emitted from a $1/60\ cm^2$ opening in a standard source and included in a solid angle of one steradian (1 sr).

In practice, sources of light are usually rated by comparison to a commercially prepared standard light source.

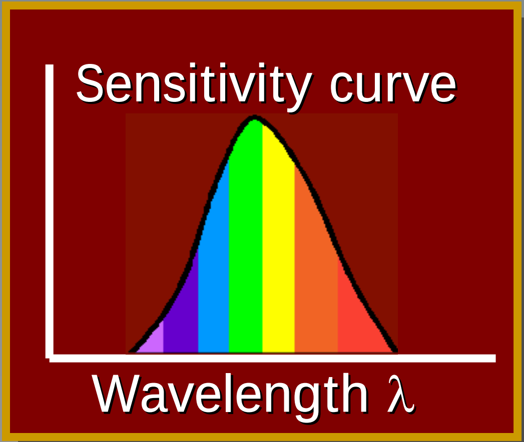
A typical 100-W incandescent light bulb emits a total radiant power of about 1750 lm. This is for light emitted in all directions.

The Lumen in Power Units

Recalling that luminous flux is really radiant power allows us to define the lumen as follows:

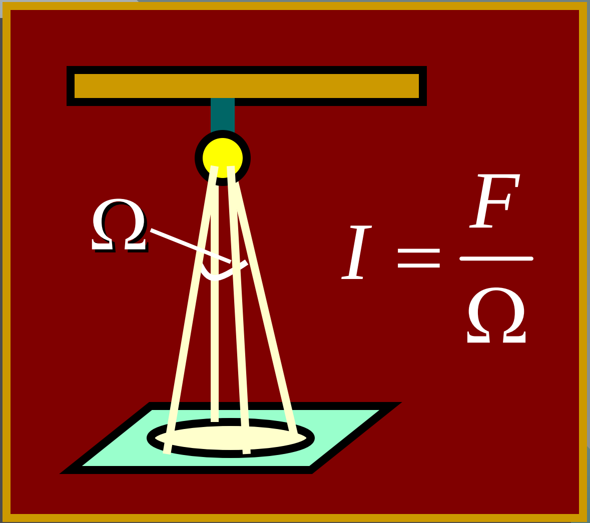
One lumen is equal to 1/680 W of yellow-green light of wavelength 555 nm.

A disadvantage of this approach is the need to refer to sensitivity curves to determine the flux for different colors of light.



Luminous Intensity

The luminous intensity *I* for a light source is the luminous flux per unit solid angle.



Luminous intensity:

$$I = \frac{F}{\Omega}$$

Unit is the candela (cd)

A source having an intensity of one candela emits a flux of one lumen per steradian.

Total flux for Isotropic Source

An isotropic source emits in all directions; i.e., over a solid angle of 4π steradians.

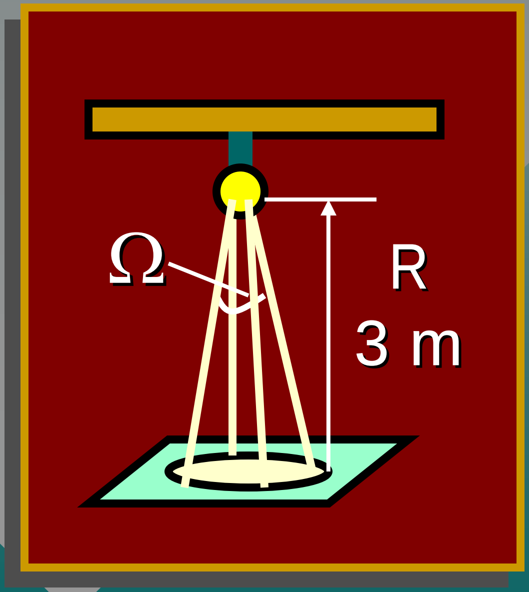
Thus, for such a source, the intensity is:

$$I = \frac{F}{\Omega} = \frac{F}{4\pi}$$

Total flux: $F = 4\pi I$

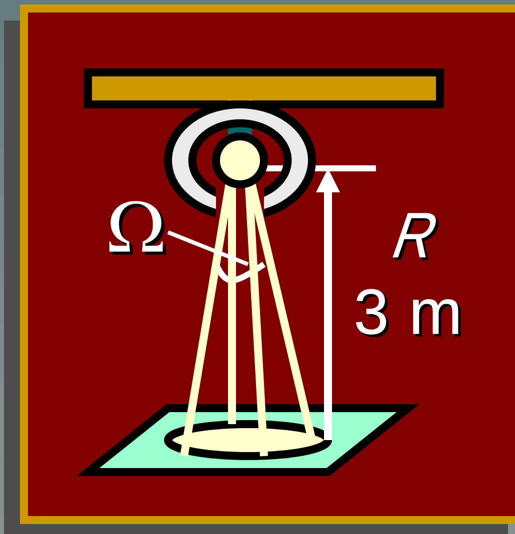
The flux confined to area A is:

$F = I\,A$



Example 4. A 30 cd spotlight is located 3 m above a table. The beam is focused on a surface area of 0.4 m^2. Find the intensity of the beam.

Total flux: $F = 4\pi I$



$$F_T = 4\pi(30\text{ cd}) = 377\text{ lm}$$

The luminous intensity of the beam depends on Ω.

$$\Omega = \frac{A}{R^2} = \frac{0.4\text{ m}^2}{(3\text{ m})^2}; \quad \Omega = 0.0444\text{ sr}$$

$$I = \frac{F}{\Omega} = \frac{754\text{ lm}}{0.0444\text{ sr}}$$

Beam Intensity:

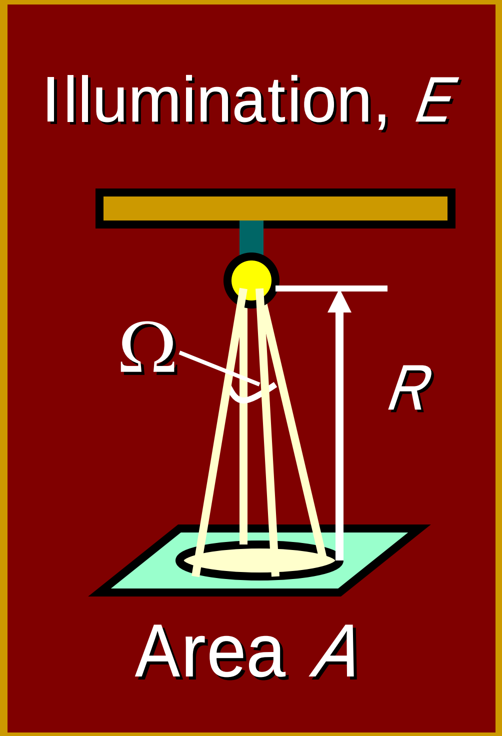
$I = 8490$ cd

Illumination of a Surface

The illumination *E* of a surface *A* is defined as the luminous flux per unit area (*F/A*) in lumens per square meter which is renamed a lux (lx).

An illumination of one lux occurs when a flux of one lumen falls on an area of one square meter.

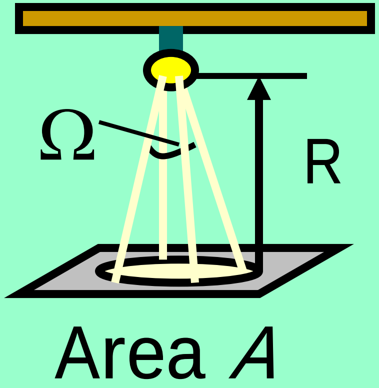
$$E = \frac{F}{A} \quad \text{Unit: lux (lx)}$$



Illumination Based on Intensity

The illumination *E* of a surface is directly proportional to the intensity *I* and inversely proportional to the square of the distance R.

$$E = \frac{F}{A}; \quad I = \frac{F}{\Omega}; \quad F = I\Omega$$



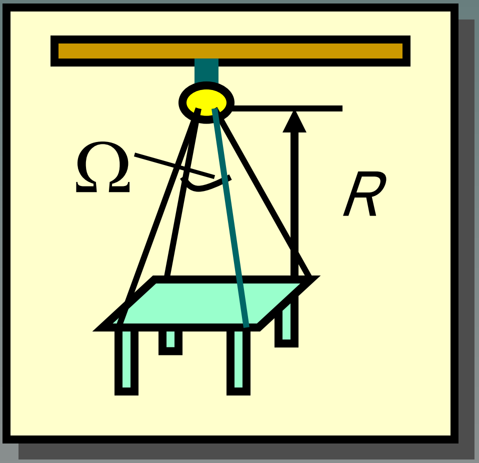
$$E = \frac{I\Omega}{A} \quad \text{but} \quad \Omega = \frac{A}{R^2} \quad \text{so that}$$

$$\text{Illumination, } E = \frac{I}{R^2}$$

This equation applies for perpendicular surfaces.

Example 5. A 400-cd light is located 2.4 m from a tabletop of area 1.2 m². What is the illumination and what flux *F* falls on the table?

$$E = \frac{I}{R^2} = \frac{400\ \text{cd}}{(2.40\ \text{m})^2}$$



Illumination: $E = 69.4\ \text{lx}$

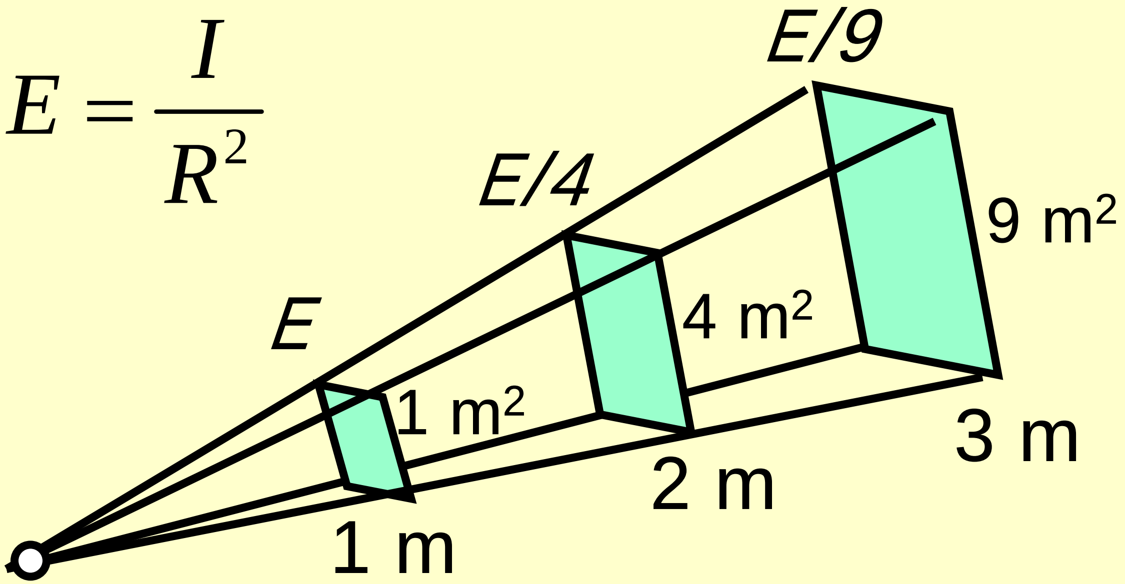
Now, recalling that $E = F/A$, we find F from:

$F = EA = (69.4\ \text{lx})(1.20\ \text{m}^2)$

$F = 93.3\ \text{lm}$

The Inverse Square Relationship

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



If the intensity is 36 lx at 1 m, it will be 9 lx at 2 m and only 4 lx at 3 m.

Summary

Light may be defined as electromagnetic radiation that is capable of affecting the sense of sight.

General Properties of Light:

- Rectilinear propagation
- Reflection
- Refraction

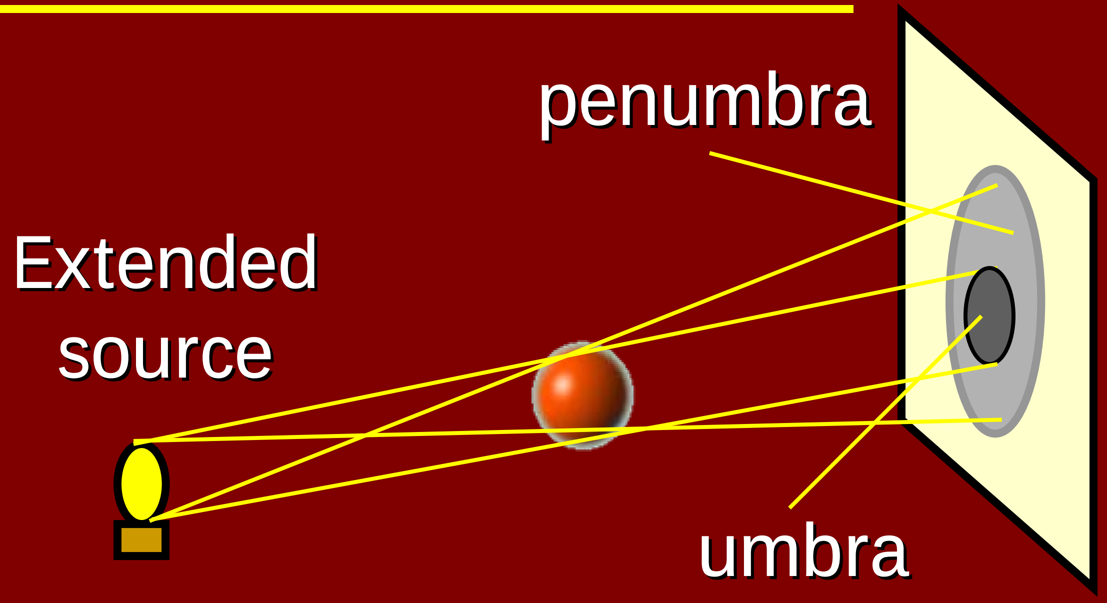
$c = f\lambda \qquad c = 3 \times 10^8$ m/s

Red, λ 700 nm

Violet, λ 400 nm

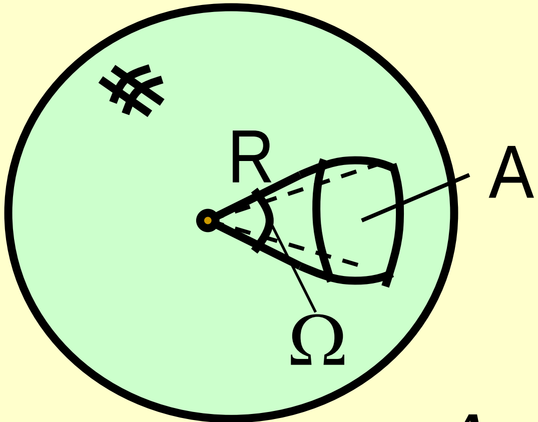
Summary (Continued)

The formation of shadows:



Luminous flux is the portion of total radiant power that is capable of affecting the sense of sight.

Summary (Continued)



The Steradian

$$\Omega = \frac{A}{R^2}$$

Total flux: $F = 4\pi I$

Luminous intensity:

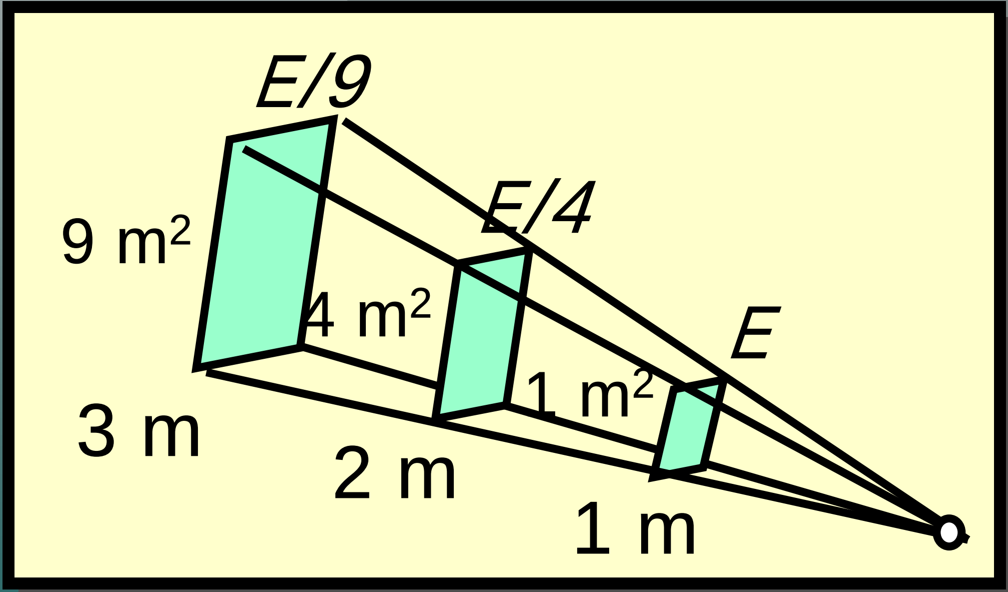
$$I = \frac{F}{\Omega}$$

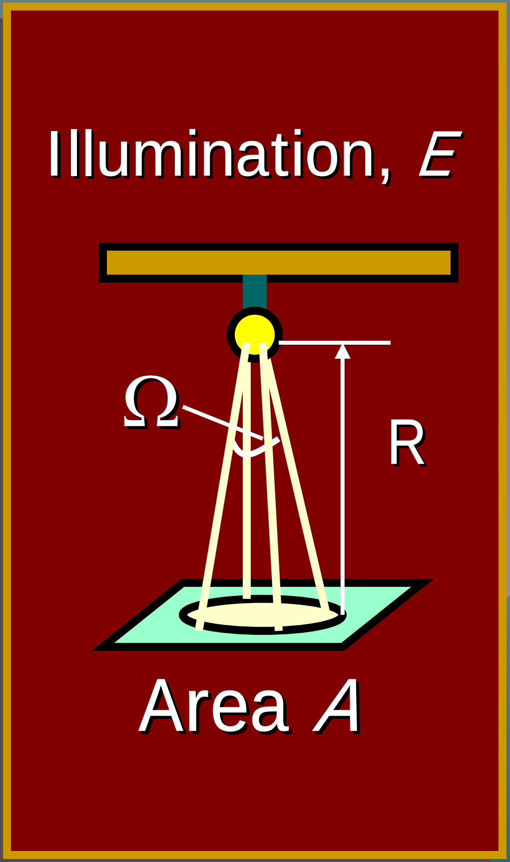
Unit is the candela (cd)

$$E = \frac{F}{A}$$ Unit: lux (lx)

Summary (Cont.)

$$\text{Illumination, } E = \frac{I}{R^2}$$





CONCLUSION: Chapter 33
Light and Illumination