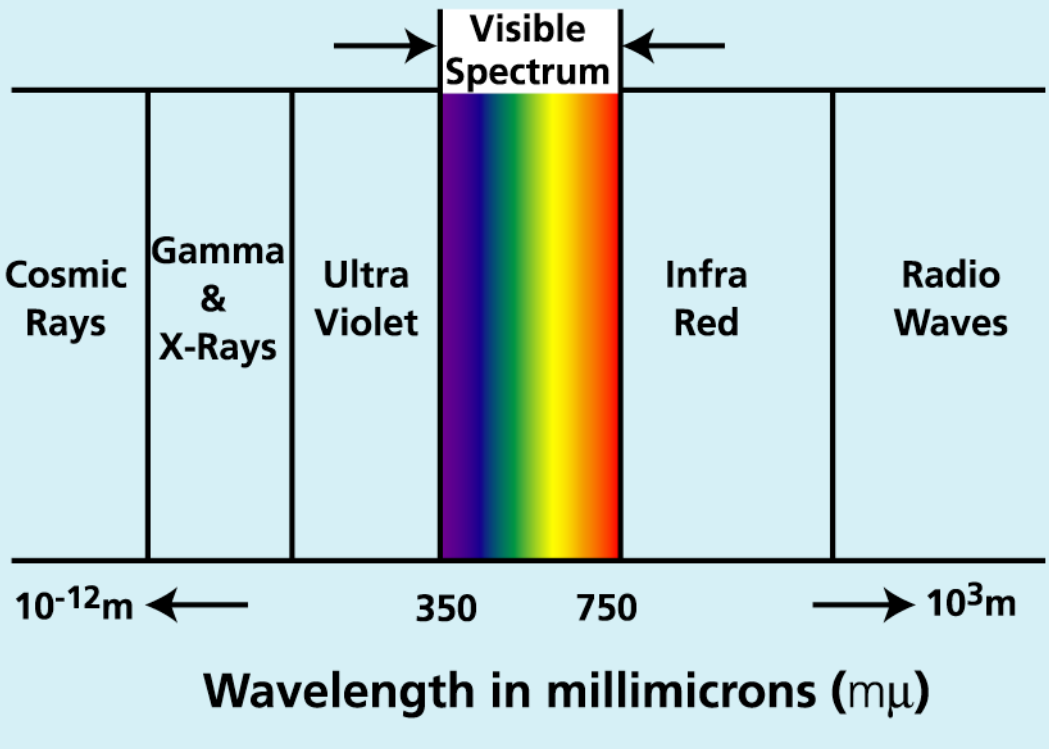
LIGHT

What is Light?

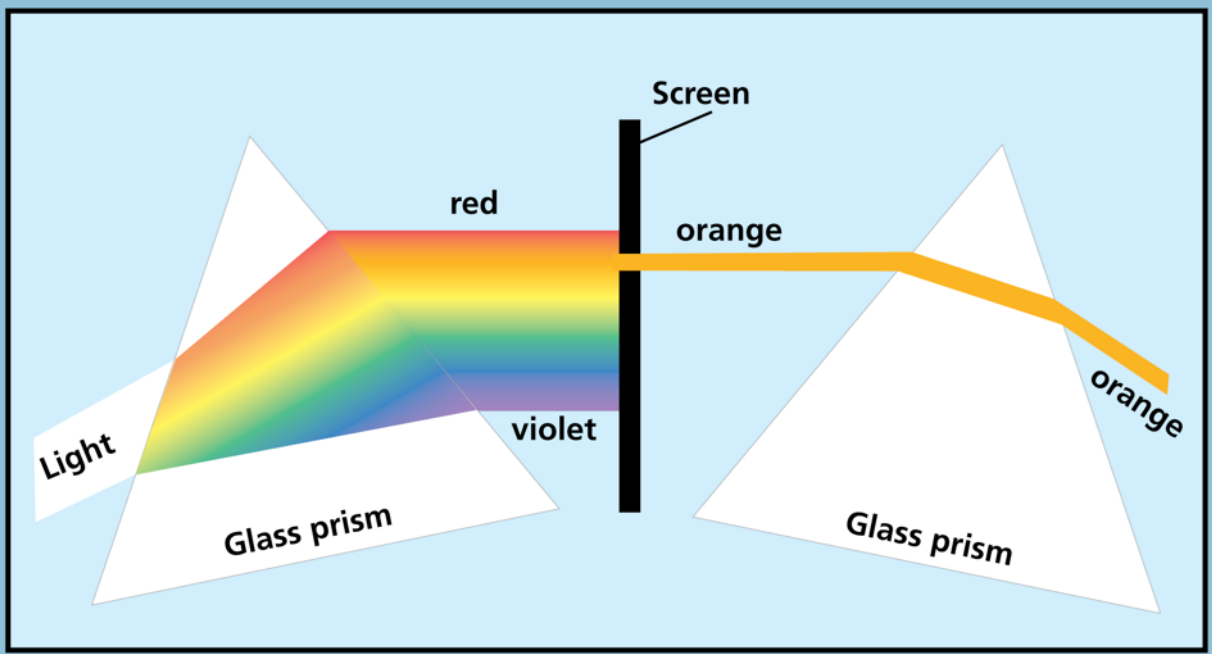
According to the Quantum Theory in Physics, light is a form of electromagnetic radiation (i.e., energy), obeying the laws of wave motion.



LIGHT

The Origin of Color

White light is made up of a spectrum of colors ranging from red, orange, yellow, green, blue, indigo, and violet.

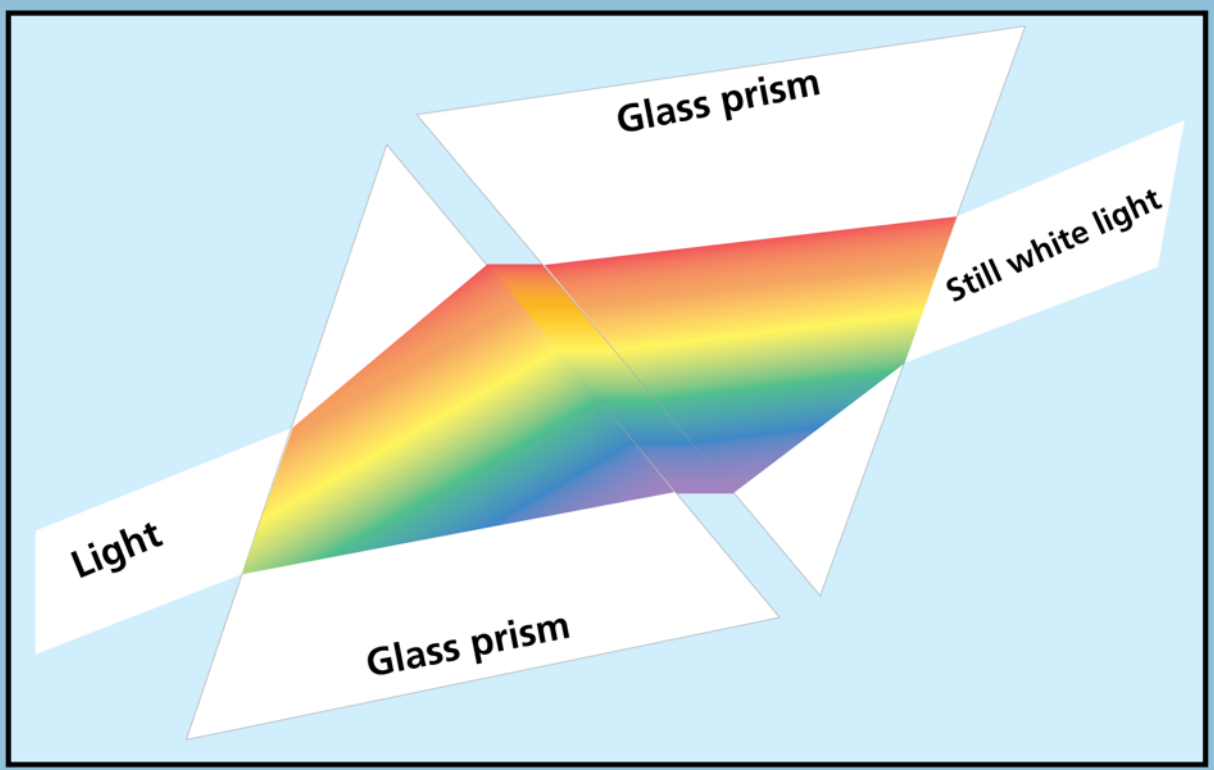


When any one of those separate color beams is passed through a second prism, it remains unchanged.

LIGHT

Components of White Light

If the spectrum of colors is passed through a second inverted prism, the colors recombine into white light.

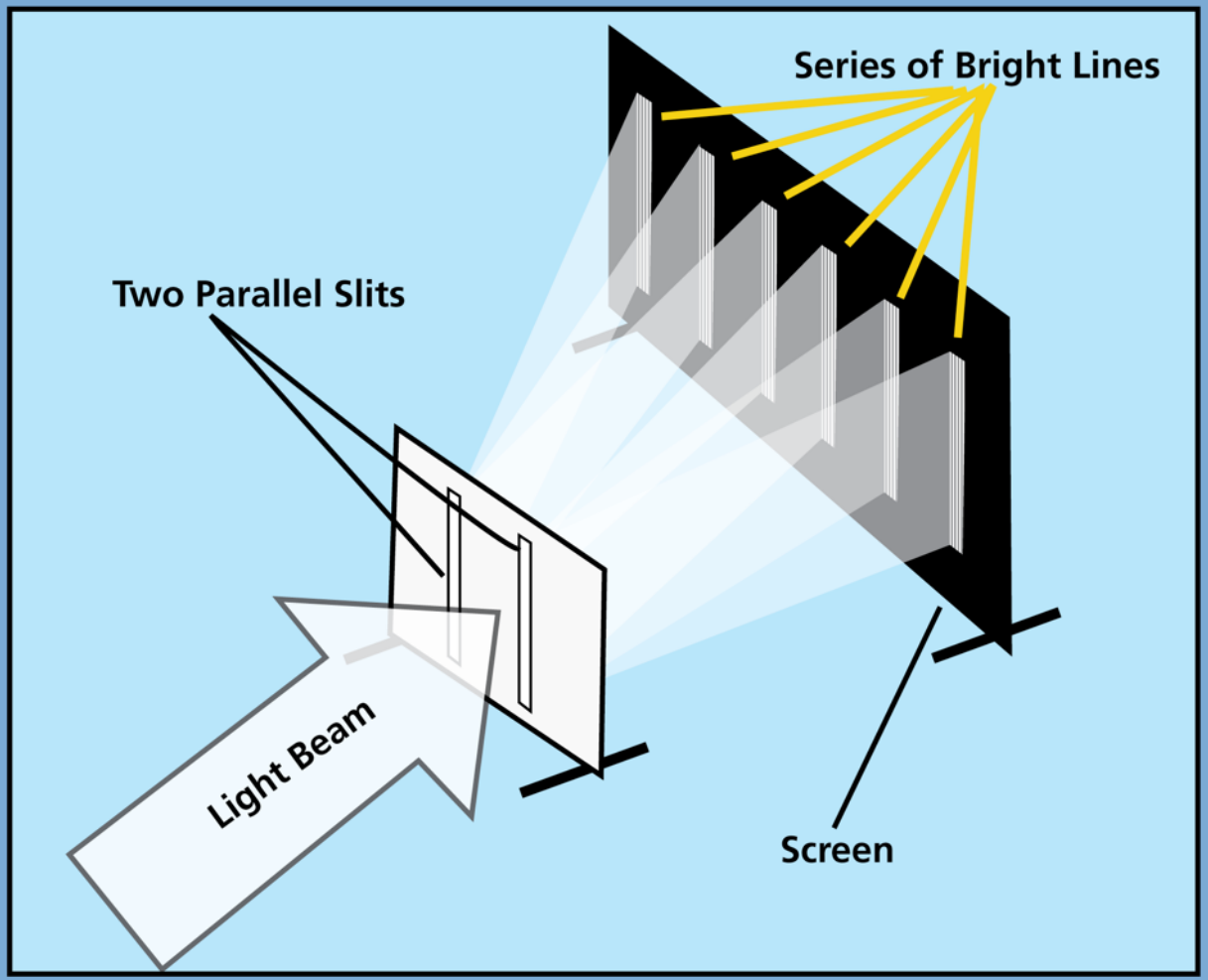


A rainbow is produced by refraction and internal reflection when sunlight passes through millions of raindrops.

LIGHT

Young's Double Slit Experiment

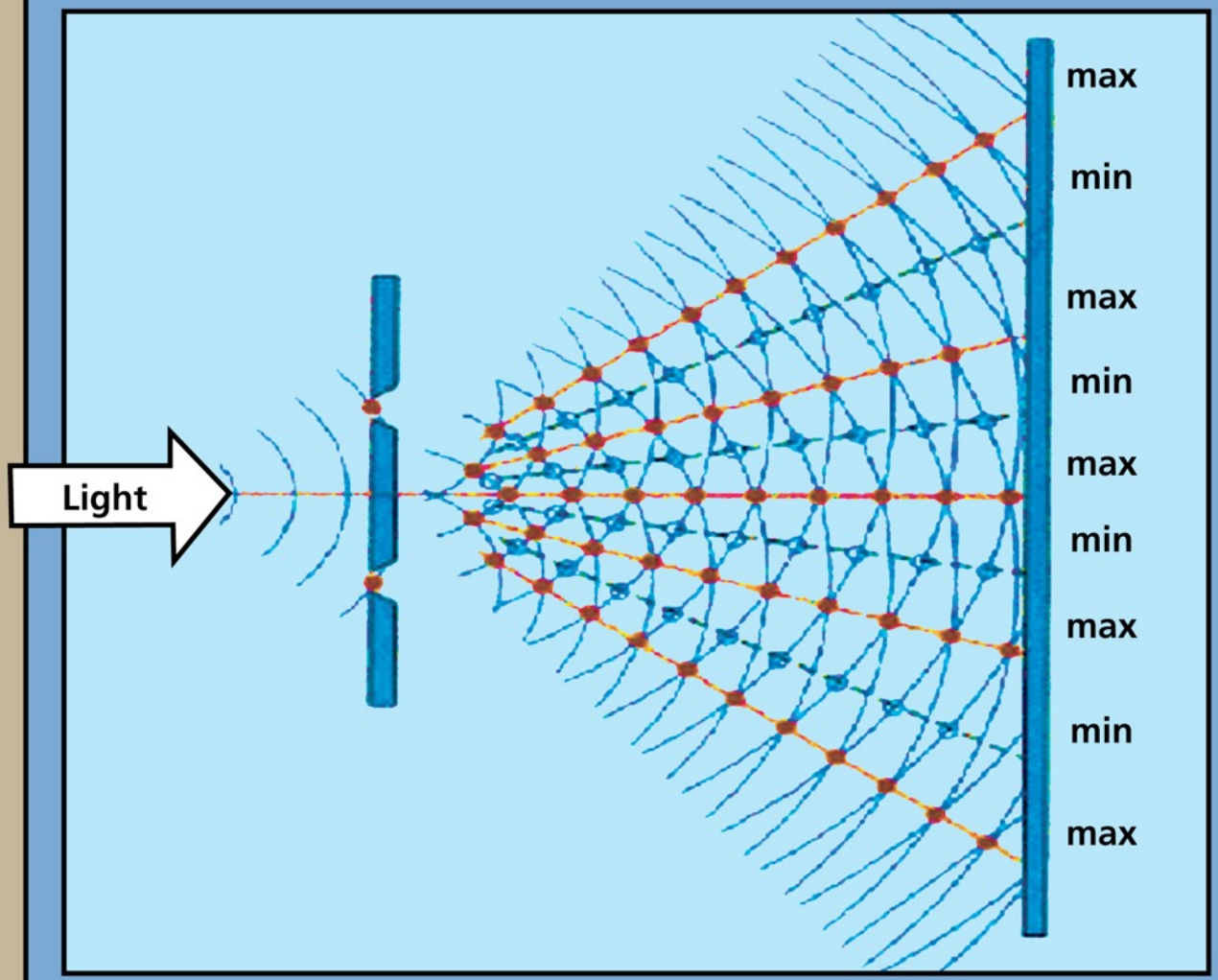
If a beam of light passes through two parallel slits then not two, but a series of bright lines, are projected on a screen.



LIGHT

Explanation of Young's Experiment

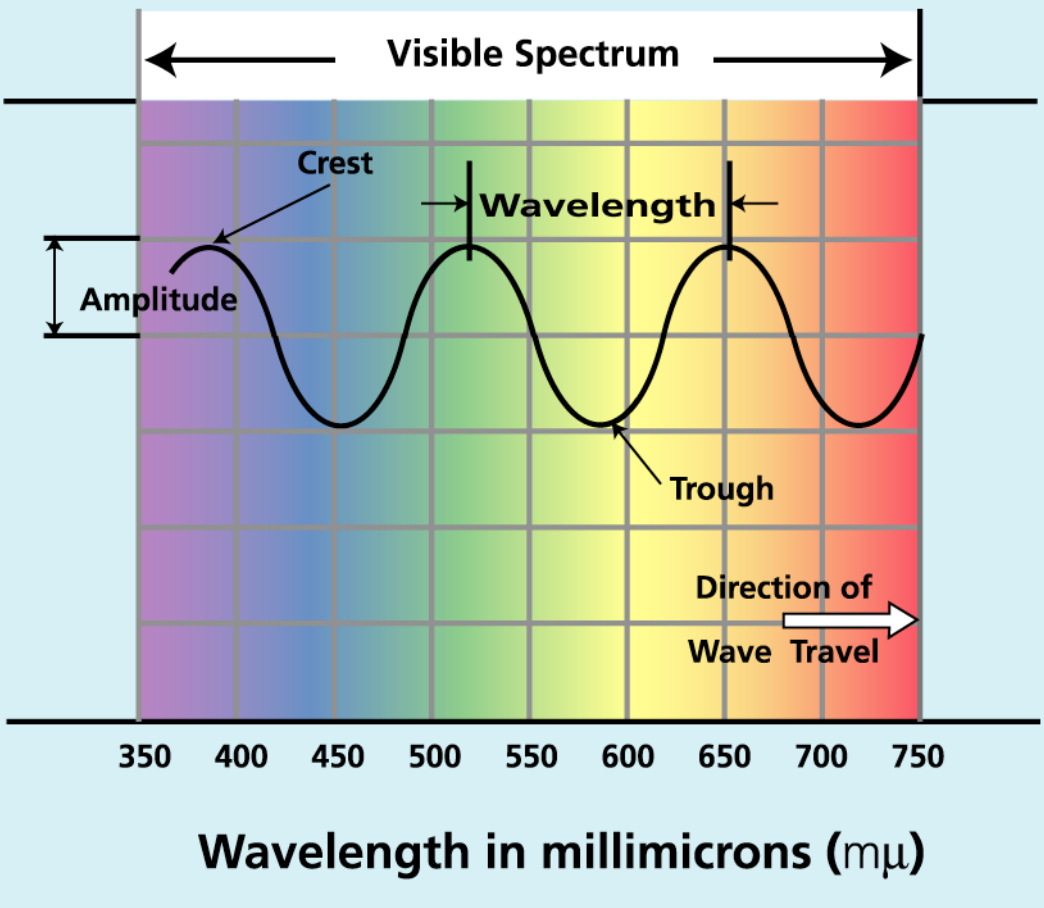
The series of bright lines on the screen is produced by the interference pattern of the light waves passing through the two parallel slits.



LIGHT

Light Waves

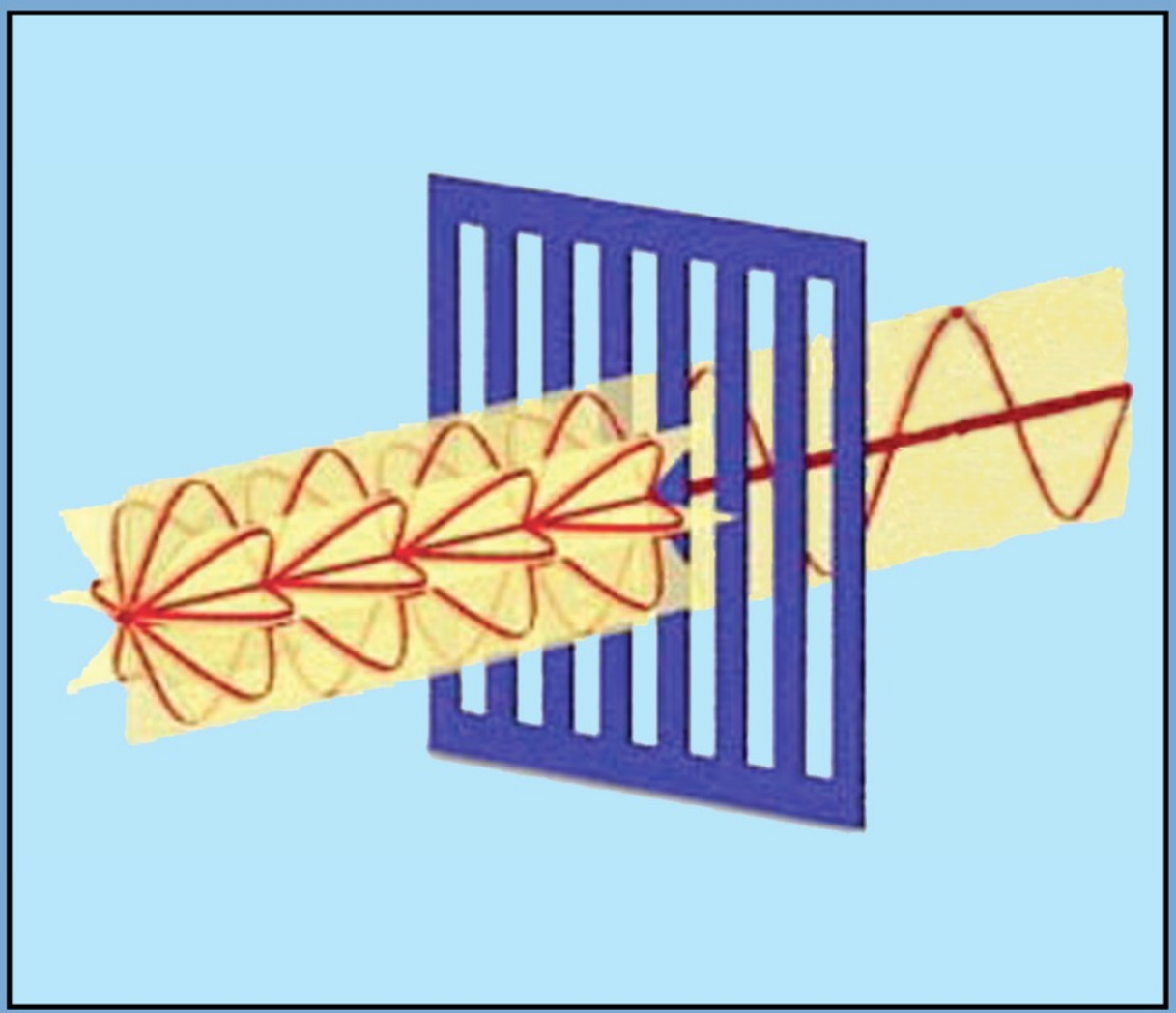
Wavelength is the distance from the crest of one wave to the crest of the next wave.



LIGHT

Polarization

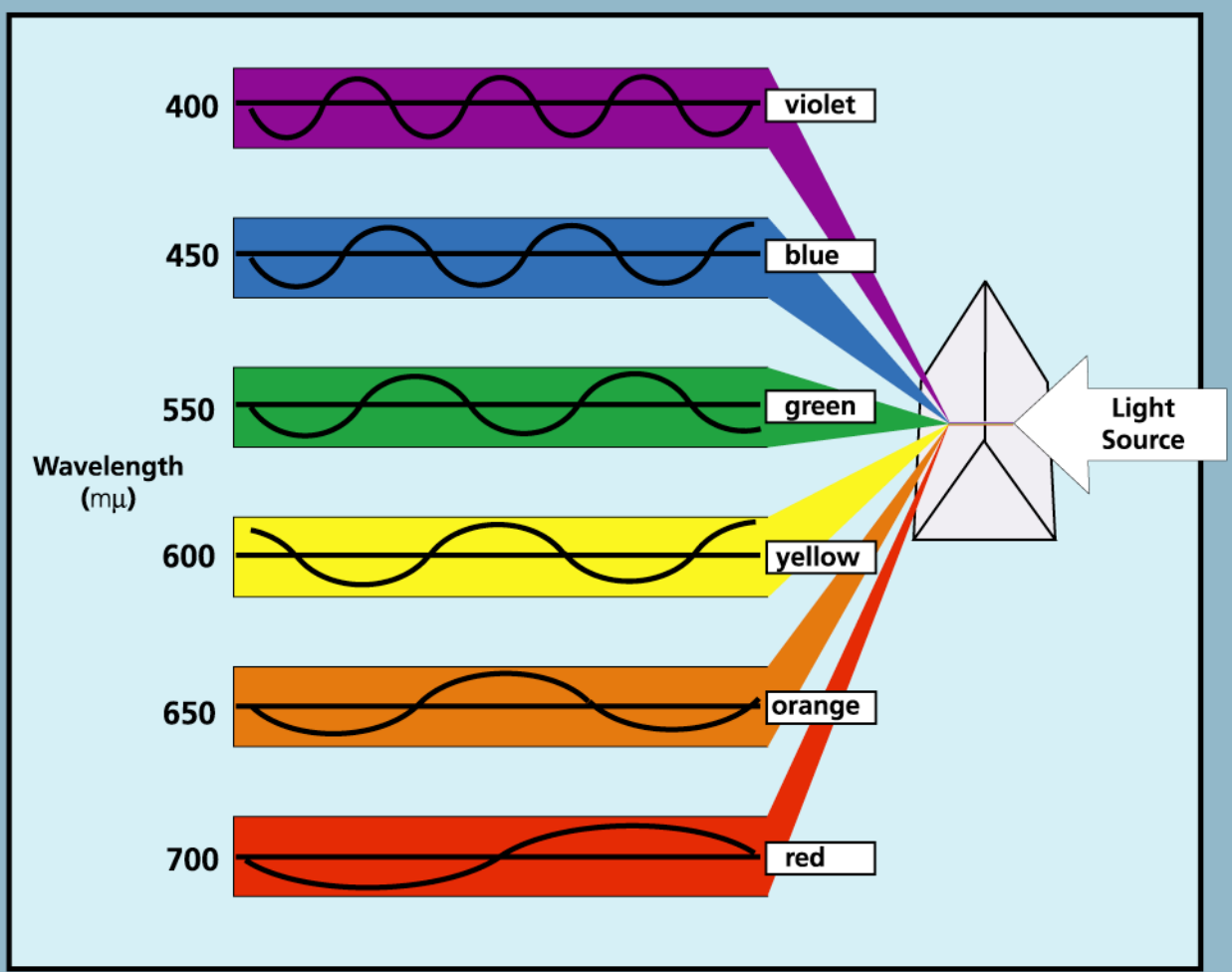
When light waves are restricted to a single plane by filtration, then the light is said to be polarized.



LIGHT

The Colors of Light

White light may be dispersed into its spectral components by passing it trough a prism.



ARTIFICIAL LIGHTING

Shades of White Light

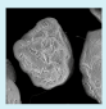
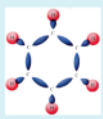
There are many shades of white light depending on the spectral distribution of the emitted radiation.

Source: IEEE Spectrum, Nov. 2010 (p. 55)

LIGHT

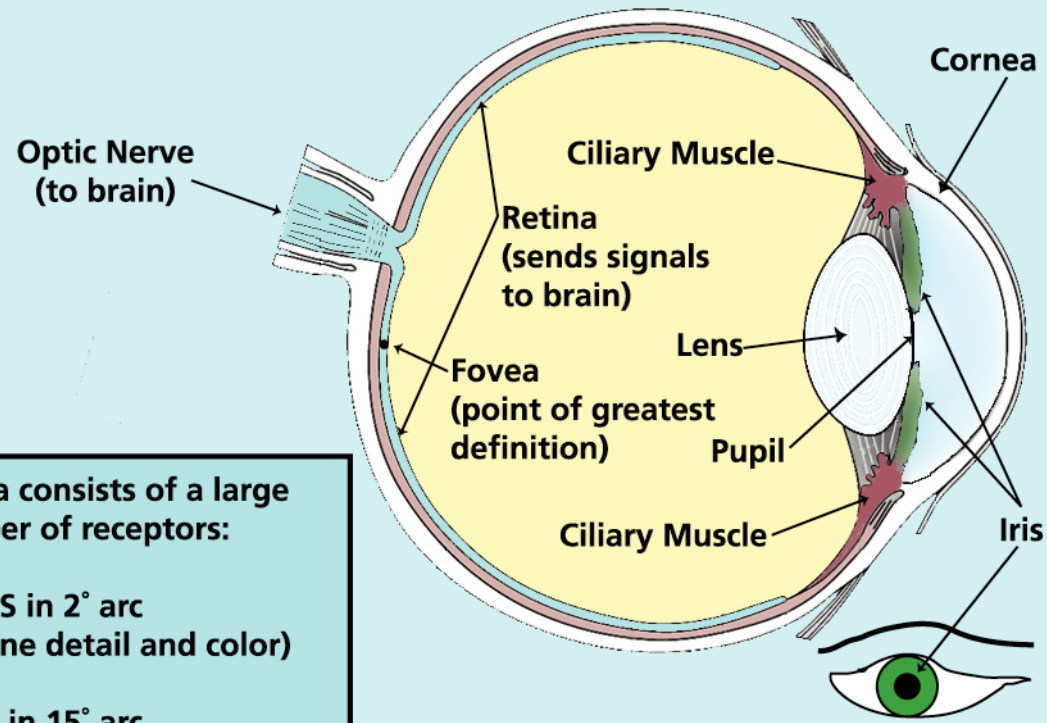
How Long is a Millimicron (mμ)?

Light waves are very small waves.

Unit	Symbol	US Equivalent	Approximate Size
METER (measures radio waves)	m	1m = 39.37 in.	A small child 
CENTIMETER	cm	0.01m (or 10^{-2} m) = 0.3937 in.	A sunflower seed 
MILLIMETER	mm	0.001m (or 10^{-3} m) = 0.039 in.	A grain of sand 
MICRON	μ	0.000001m (or 10^{-6} m) = 0.000039. in.	A small bacterium 
MILLIMICRON	mμ	0.000000001m (or 10^{-9} m) = 0.000000039 in.	A benzene molecule 

LIGHT
The Human Eye

The human eyes measure *brightness differences* and not objective light levels like a photometer (i.e., light meter).



Retina consists of a large number of receptors:

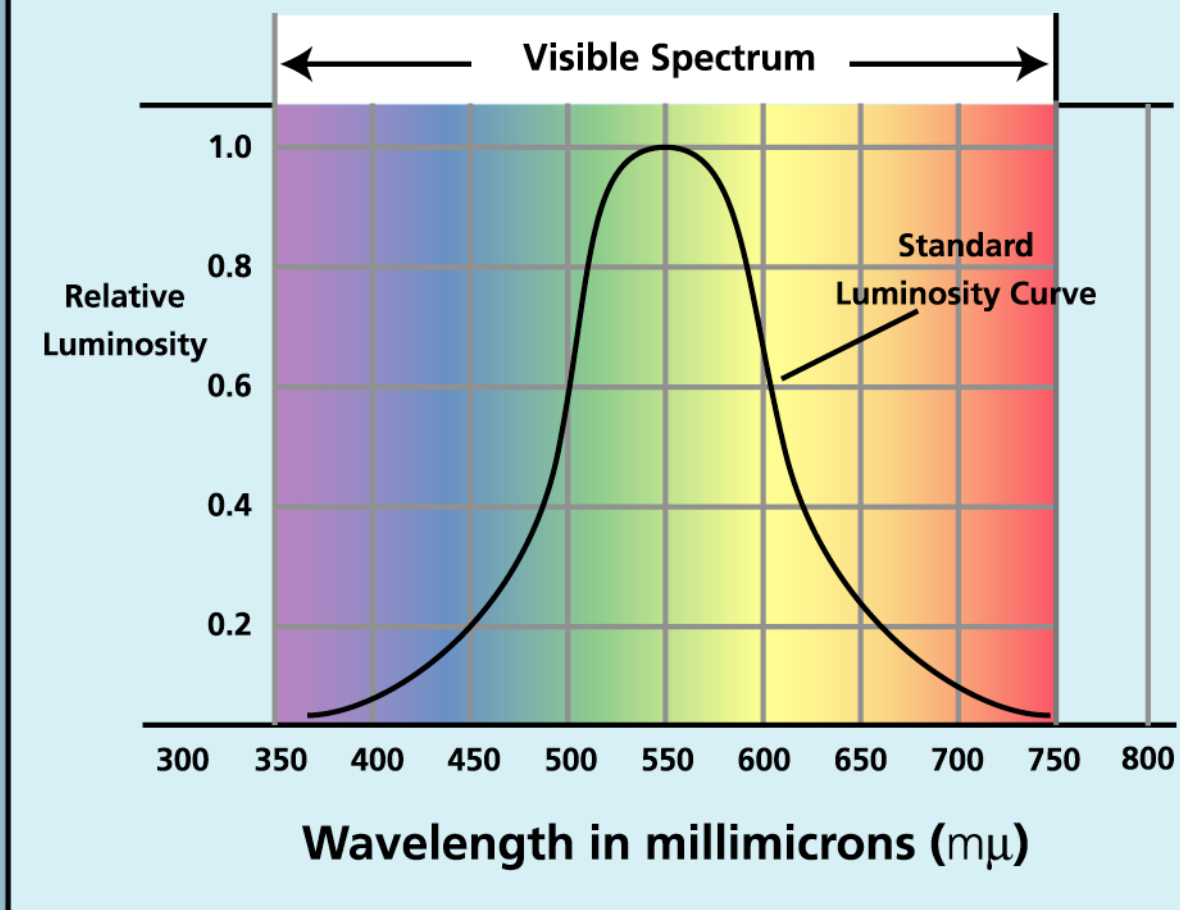
CONES in 2° arc
(for fine detail and color)

RODS in 15° arc
(for motion and brightness differences in monochrome)

LIGHT

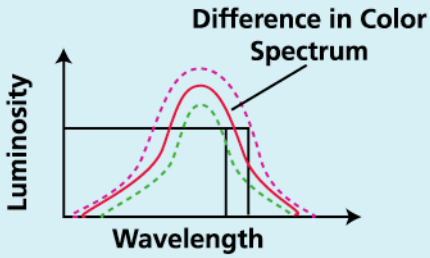
What is Luminosity

Luminosity is the ability of light to excite the sensation of brightness in the eyes. The eyes are most sensitive to yellow-green light at 550 millimicrons.

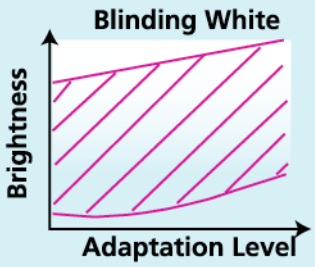


LIGHT

The Process of Seeing

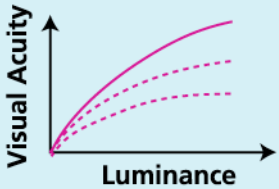


Individuals vary in their response to luminosity and this may contribute to individual differences in taste.

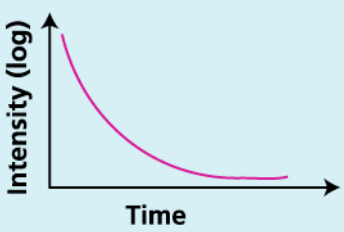


Although the eye is sensitive to a very wide range of luminosity, it takes time to see. This time is reduced by higher luminance.

Visual acuity decreases with decrease in surround brightness.



Visual acuity is the ability to resolve small visual details. Increased luminance increases visual acuity.

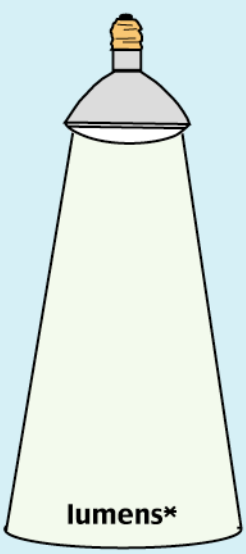


Vision speed increases with higher levels of illumination. visibility increases with increased object brightness.

LIGHT

Units of Measurement: Flux

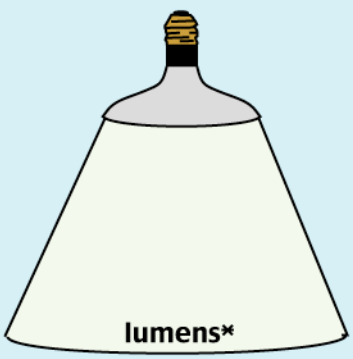
Flux is the quantity of light emitted by a light source, irrespective of direction or distribution. It is measured in **lumens**.



Incandescent
100W
1,740 lumens

Fluorescent
100W
7,800 lumens

High Pressure
Sodium
100W
9,500 lumens



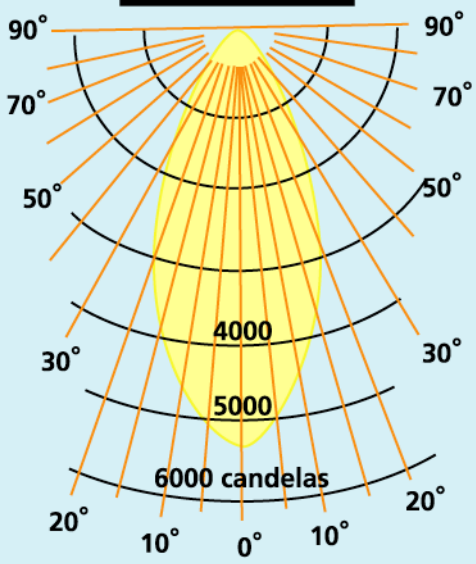
* (Although both lamps may emit the same amount (flux) of light, the intensity and width of the light beams may be very different.)

LIGHT

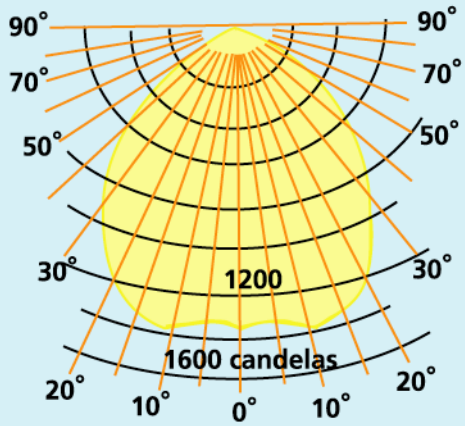
Units of Measurement: Candlepower

Candlepower or **Luminous Intensity** is the property of a light source to emit light in a particular direction. It describes the intensity of a light beam and is measured in **candelas.**

Spot Light



Flood Light



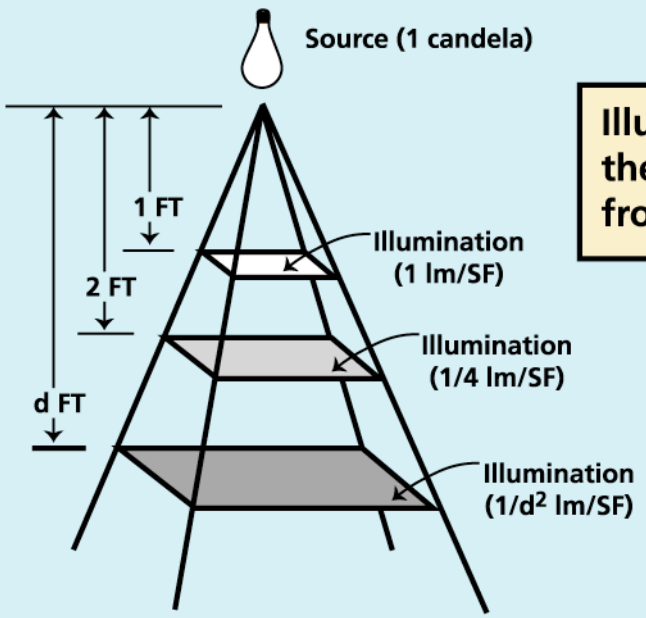
Plotted on a polar diagram the distance from the center determines the intensity of light (candelas) in that direction.

Light Flux = Luminous Intensity x Solid Angle (lm)

LIGHT

Units of Measurement: Illumination

Illumination is the amount of light flux falling on a unit area, and is measured in **footcandles (fc)** or lumens/SF.



Illumination decreases by the square of the distance from a point source.

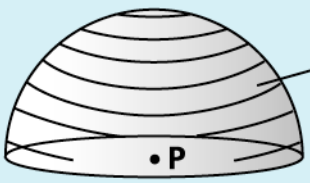
$$\text{Illumination (fc or lm/SF)} = \frac{\text{flux}}{\text{area}} = \frac{[\text{luminous intensity}] \times [\text{solid angle}]}{\text{area}} = \frac{[\text{point source}]}{(\text{distance})^2}$$

LIGHT

Units of Measurement: Luminance

Luminance is the intensity per unit area of a surface seen from a particular direction and is measured in candelas/SF (cd/SF) or foot Lamberts (fL). (1cd/SF = 3.14 fL and 1fL = 0.32 cd/SF)

1 foot Lambert = $1/\pi$ candela/SF



The luminance of a sphere is 1fL if it produces an illumination of 1 fc (or 1 lm/SF) at point P.

- Luminance is the amount of light that is reflected off a surface and reaches the eye.
- Luminance is an objectively measured quantity and brightness is its subjective counterpart.
- Luminance is dependent on: (1) illumination level; (2) location of viewer in respect to light source; (3) specularity of light source (i.e., mirror-like reflection); and, (4) color of surface.

LIGHT

Brightness Levels

The human eye can detect luminance over a range of more than a trillion (10^{12}) to one. However, the perceived brightness of any luminance is relative and subjective.

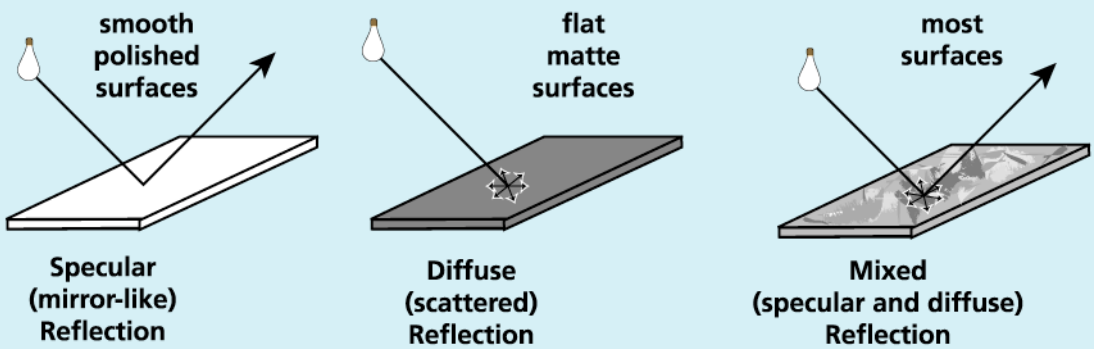
	Luminance foot Lamberts (fL) & [candelas/SF (cd/SF)]
sunlight:	450,000,000 [144,000,000]
500 watt incandescent lamp:	95,000 [30,400]
fresh snow on a clear day:	10,000 [3200]
	Eyes squint above 2000 fL
asphalt road on sunny day:	2000 [640]
north sky on a clear day:	1000 [320]
asphalt road on overcast day:	400 [128]
luminous ceiling:	200 [64]
	No contrast below 1 fL
book illuminated by candle:	0.75 [0.24]
snow in moonlight:	0.015 [0.005]
asphalt road on cloudy night:	0.0001 [0.00003]

LIGHT

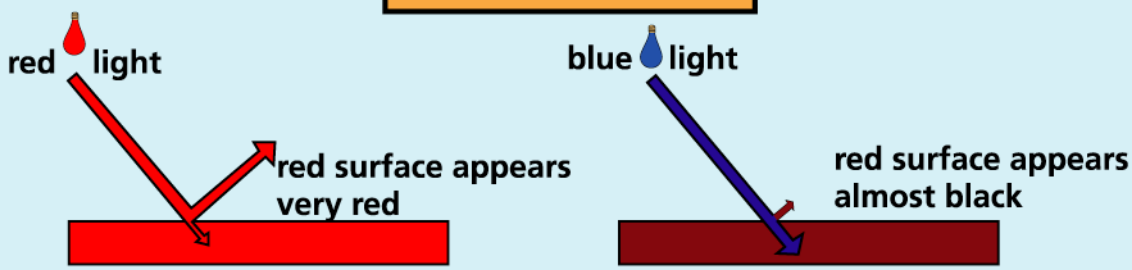
Reflectance and Transmittance

The **Reflectance Factor (RF)** is a measure of the amount of incident light reflected by a surface.
(RF of white surface ≈ 0.85 and RF of black surface ≈ 0.05)

Types of Reflection



Colored Surfaces



The perceived color of a surface depends on both the color (i.e., spectral reflectance characteristics) of the surface and the color (i.e., spectral composition) of the illumination (i.e., light source).

LIGHT

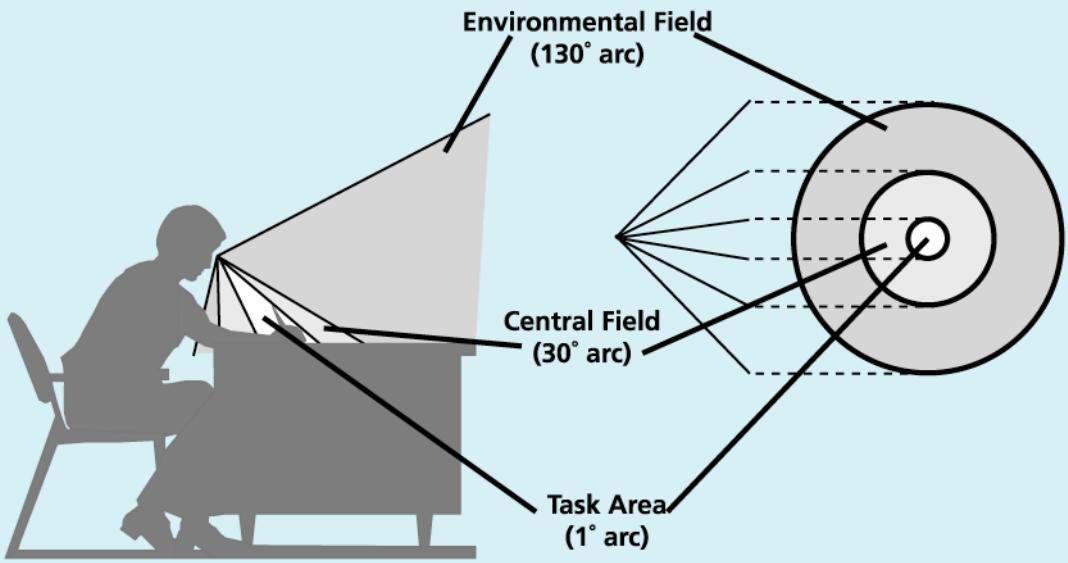
Metric and American Units

As a rule of thumb: 1fc ≈ 10 lux

Lighting Property	American Units (AS)	Metric Units (SI)	Conversion Factor
light flux	lumens (lm)	lumens (lm)	(not required)
illumination (or illuminance)	footcandles (fc)	lux (lx)	1fc = 10.764 lux
luminous intensity	candelas (cd)	candelas (cd)	(not required)
luminance	cd/SF foot Lamberts	cd/m^2	$1cd/SF = 0.09\ cd/m^2$ 1 foot Lambert = $0.03\ cd/m^2$

LIGHT
The Visual Field

Since human eyes measure brightness differences, the design of the visual field must consider not only task illumination but also the surrounding illumination levels.



Recommended Brightness Ratios

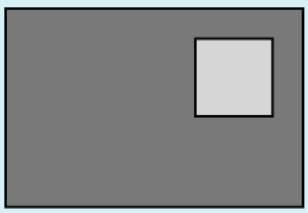
[Task Area] to [Central Field / Immediate Surround] = 3 : 1

[Task Area] to [Environmental Field (Background)] = 5 : 1

LIGHT

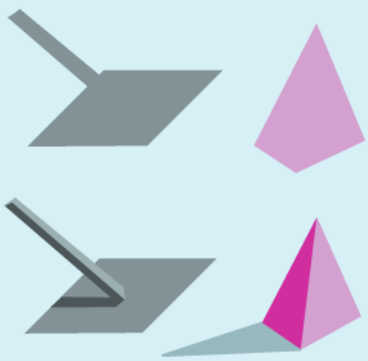
Contrast and Visual Performance

Contrast is created by the difference in brightness (i.e., luminance) of the object being viewed and the immediate surroundings.



Brightness ratio between the small square and the larger rectangle is 3 : 1.

Contrast is an important factor for visual performance, particularly in time-critical situations. High levels of illumination are required to compensate for poor contrast.

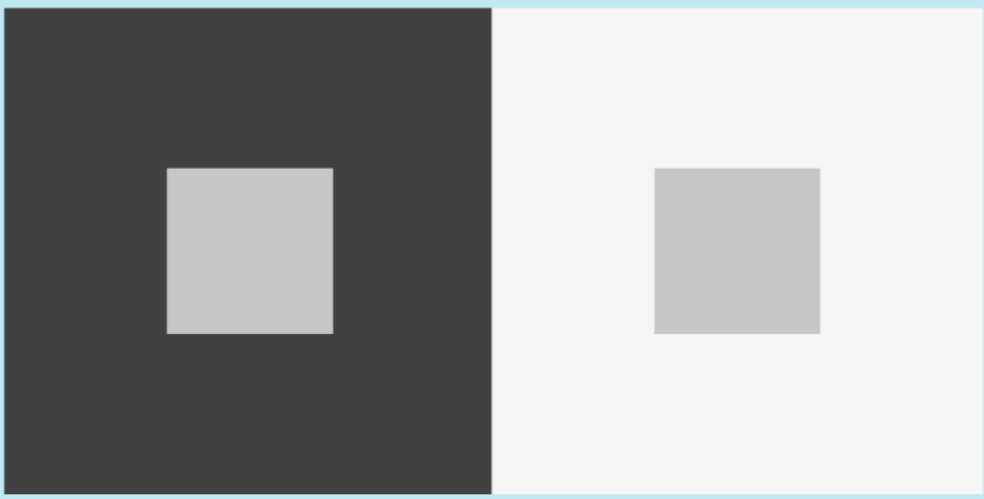


Contrast is helpful in recognizing shape and form, and for judging distances.

LIGHT

The Simultaneous Contrast Effect

The human eye must be able to judge the relative impact of *luminance* and *reflectance* to recognize a gray surface whether viewed in bright sunshine or in the shade. This ability is referred to as *Lightness Constancy.*

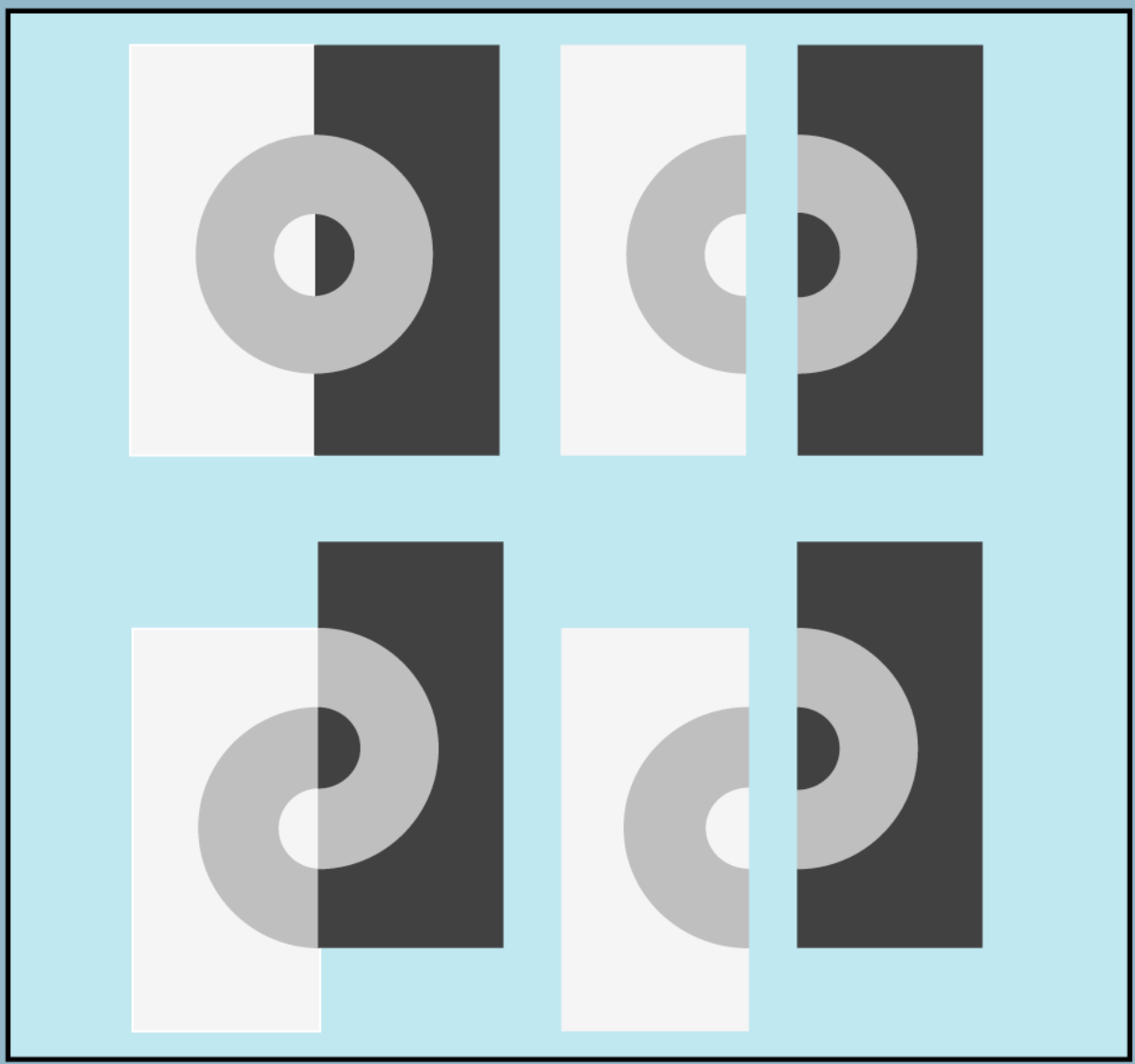


Our *Lightness Constancy* capabilities are not fool proof. The same gray square appears lighter or darker depending on the *surround*.

LIGHT

Variations of the Koffka Ring Illusion

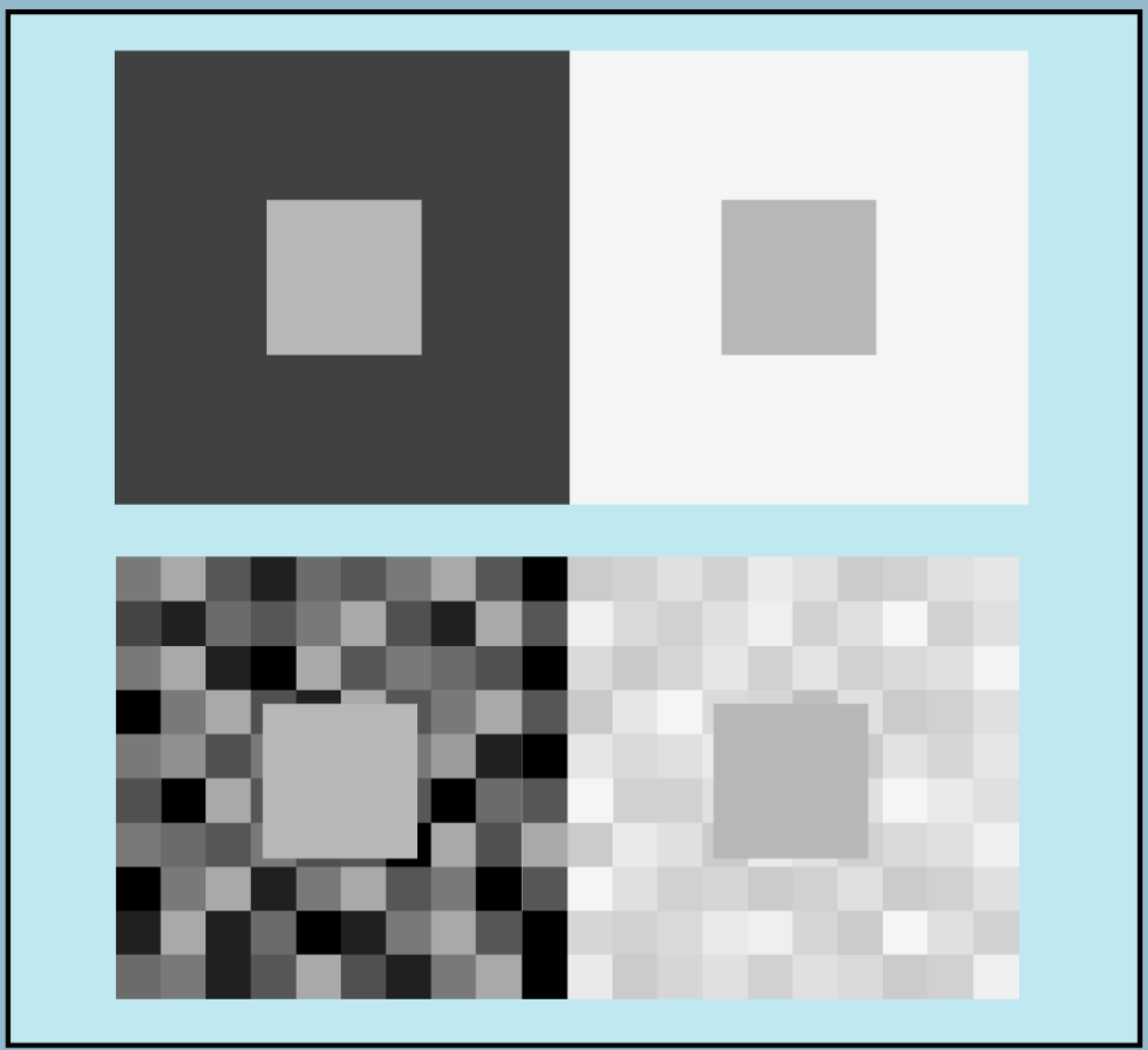
Horizontal *division* of the visual stimulus into two parts or vertical relative relocation can also fool our *Lightness Constancy* capabilities.



LIGHT

The Impact of Articulation

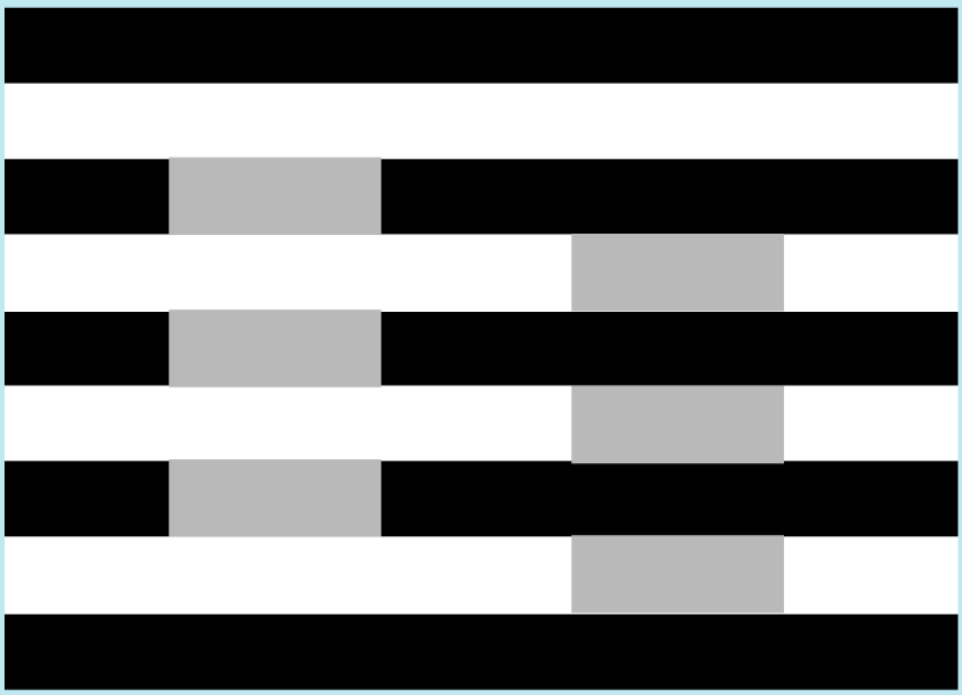
Lightness Constancy **capabilities are slightly enhanced by articulation (i.e., the number of distinct surfaces or patches within a region).**



LIGHT

The Impact of T-Junctions

The gray rectangles on the left side should appear darker than those on the right side, however, the long white border and short black border on the left side reverses the illusion.



LIGHT

Revisiting Lighting Terminology

Objective phenomena are physical quantities that can be measured with physical devices.

1. ***Luminance*** is the amount of light that reaches the eye from a surface.
2. ***Illuminance*** or ***Illumination*** is the amount of light incident on a surface.
3. ***Reflectance*** is the proportion of light reflected from a surface.

Subjective reactions to stimuli are governed by the way in which a stimulus is processed by the human senses.

4. ***Lightness*** is the perceived reflectance of a surface and depends on the ability of the human visual system to judge the reflectance of the surface within the context of the various luminances in the scene.
5. ***Brightness*** is the perceived intensity of light coming from the viewed image itself rather than the entire scene.

LIGHT

Influence of Surface Reflectance

Reflectance is the percentage of light falling on a surface that is reflected (the remainder of the incident light is absorbed and/or transmitted).

$$\text{Luminance (fL)} = \left[\text{illumination level (fc)}\right] \times \left[\frac{\text{reflectance (\%)}}{100}\right]$$

Type of Material or Surface Finish	Reflectance* (%)
Metals:	
Aluminum, brushed	60%
Aluminum, etched	80%
Aluminum, polished	70%
Stainless steel	55%
Tin	70%
Masonry:	
Brick, dark buff	35%
Brick, light buff	45%
Brick, red	20%
Cement, gray	20%
Granite	20%
Limestone	50%
Marble, polished	60%
Plaster, white	50%
Sandstone	30%
Terra-cotta, white	70%

Type of Material or Surface Finish	Reflectance* (%)
Glass:	
Clear or tinted	5%
Reflective	25%
Ground cover:	
Asphalt	5%
Concrete	40%
Grass and other vegetation	20%
Snow	70%
Paint:	
White	80%
White porcelain enamel	70%
Wood:	
Light birch	40%
Mahogany	10%
Oak, dark	10%
Oak, light	30%
Walnut	10%

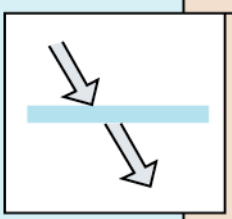
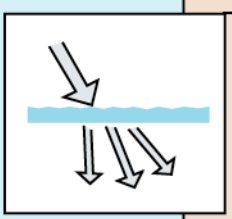
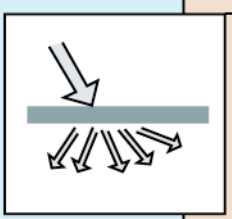
*(Approximate (i.e., typical) reflectance values.)

LIGHT

Transmittance of Translucent Materials

Transmittance is the percentage of light that is transmitted through a material.

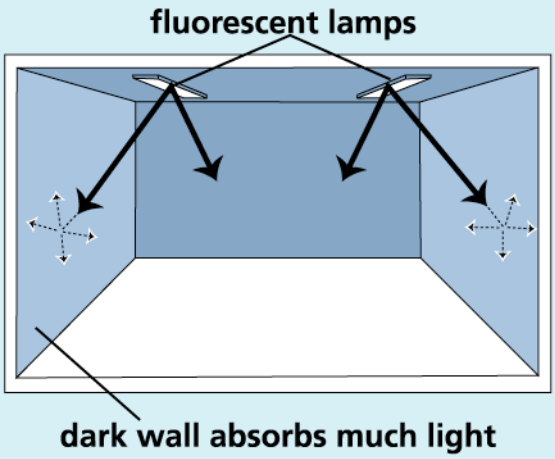
$$\text{Luminance (fL)} = \left[\text{illumination level (fc)}\right] \times \left[\frac{\text{transmittance (\%)}}{100}\right]$$

	Type of Material		Transmittance %
	**Direct Transmission**		
	clear glass (or plastic)		90%
	transparent colored glass:	blue	5%
		red	10%
		green	15%
		amber	40%
	**Spread Transmission**		
	etched glass (toward source)		85%
	etched glass (from source)		70%
	**Diffuse Transmission**		
	alabaster		40%
	glass block		60%
	marble		20%
	reinforced plastic		45%

LIGHT

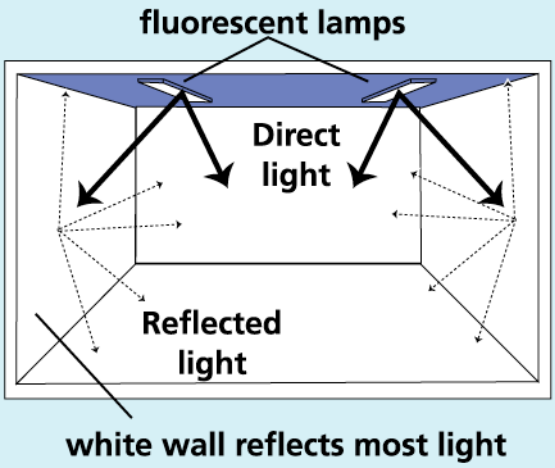
Surface Reflectance: Nighttime

Low-Reflectance Room Surfaces



Room appears dark and gloomy for an office, but may be intimate and relaxing for a restaurant.

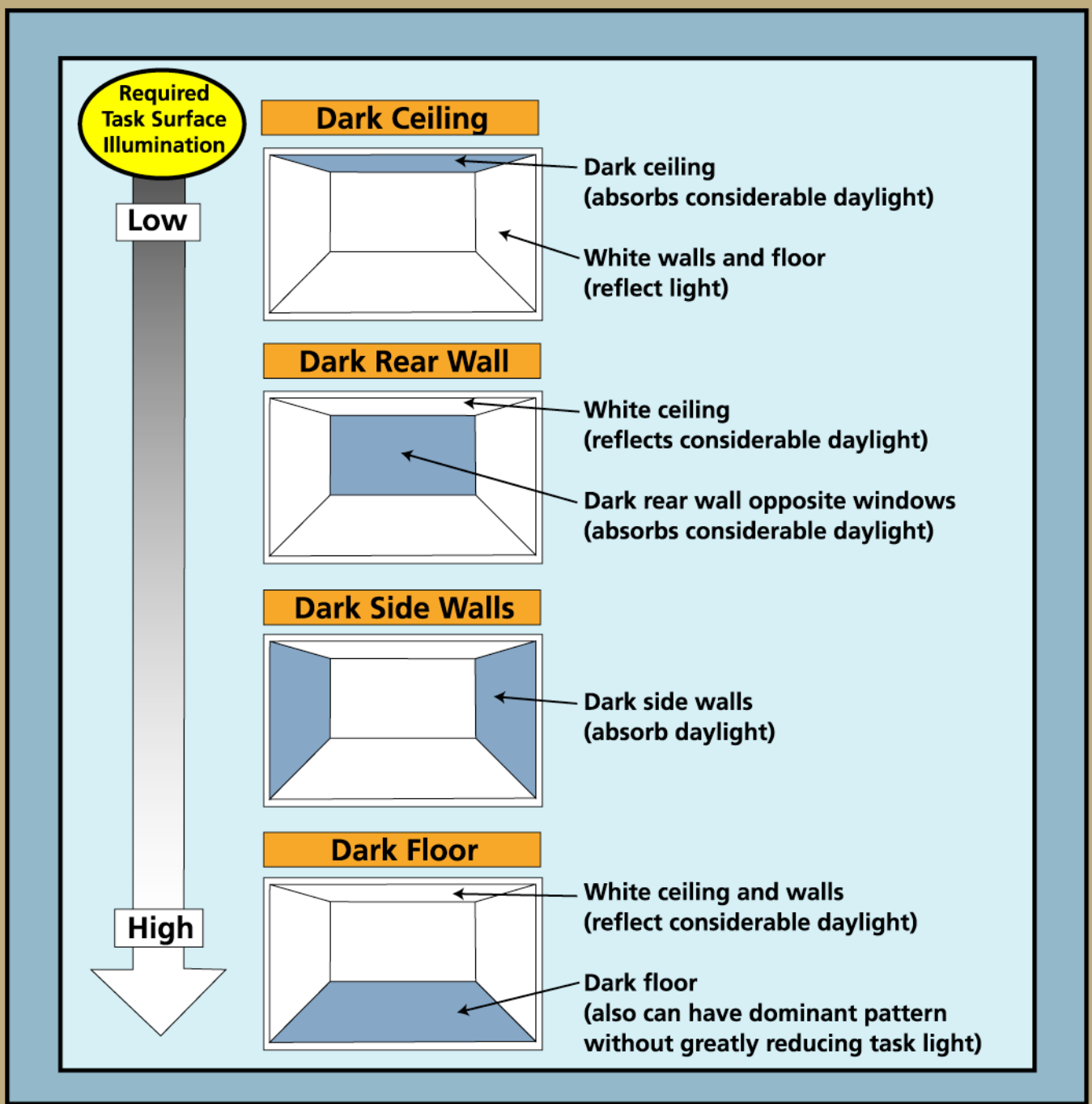
High-Reflectance Room Surfaces



Room appears bright and cheerful, but walls could dominate the visual field.

LIGHT

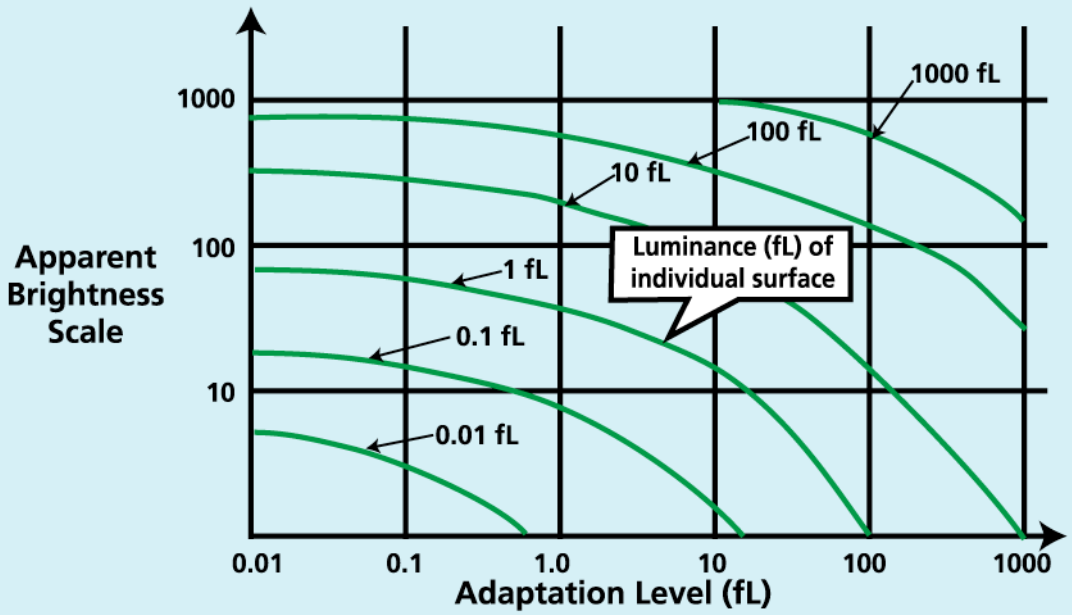
Surface Reflectance: Daytime



LIGHT

The Apparent Brightness Concept

In any visual environment the human eyes adapt to the general brightness level of the space. This **Adaptation Level** serves as an involuntary reference standard through which that person subjectively perceives the apparent brightness of any individual surface in that space.



The **Adaptation Level** is calculated as the average luminance of all surfaces in the visual field.

LIGHT

How Much Light Do We Need?

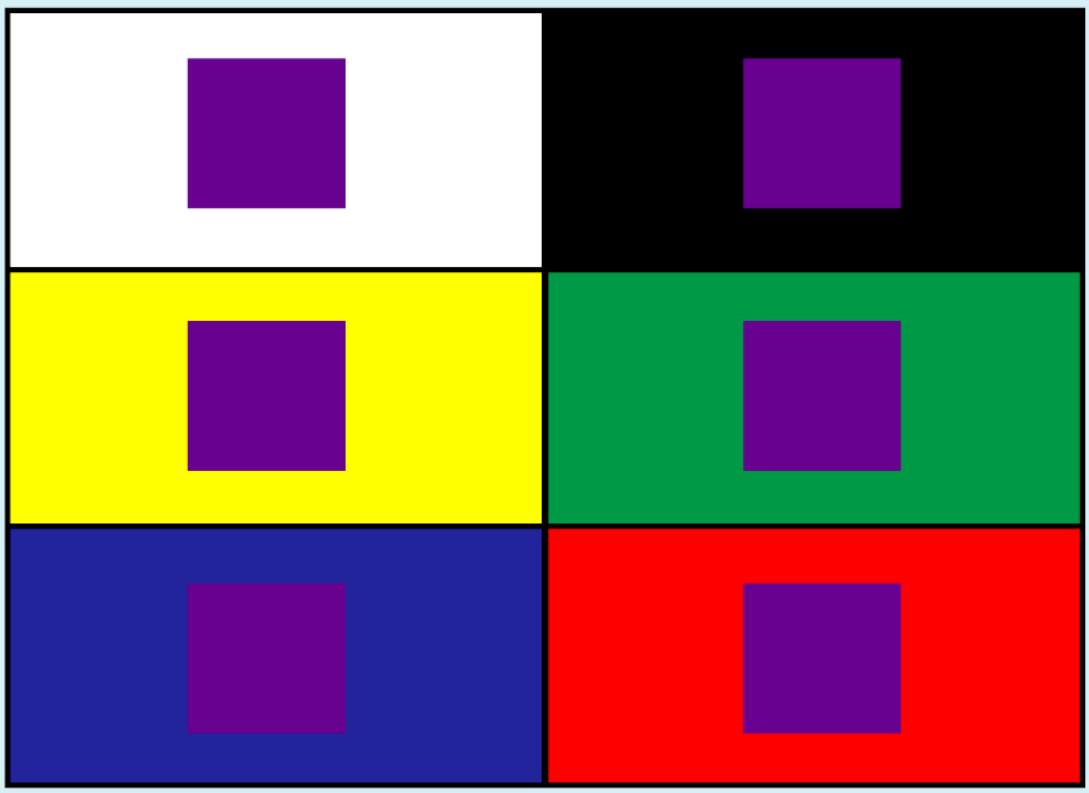
The required task illumination level depends on the visual intensity of the task and the background illumination (i.e., the Adaptation Level).

Class of Visual Task or Type of Work	Local Illumination (fc)	Background Illumination (fc)
Casual Seeing: corridors, storage areas, etc.	10-15 fc	10-15 fc
Intermittent Tasks: casual reading and writing, cursory inspection, etc.	20-30 fc	10-15 fc
Prolonged Tasks: machine work, office work, prolonged reading and writing.	40-50 fc	15-25 fc
Severe Prolonged Tasks: with small detail and poor contrast.	60-70 fc	20-25 fc
Very Intense Visual Tasks: watch repairs, gauge inspection, etc.	150-300 fc	25-90 fc

LIGHT

The Appearance of Colored Surfaces

The perceived appearance of a colored surface depends not only on the spectral distribution of the light source, but also on the color(s) of the surrounding surface(s).

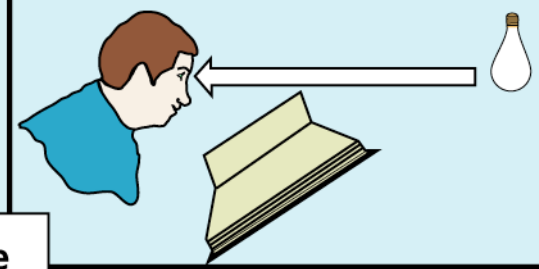


LIGHT

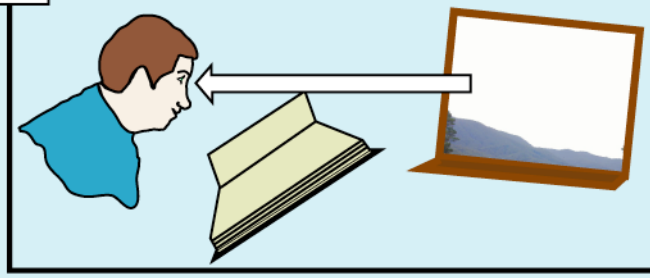
The Nature of Glare

Glare is caused by excessive brightness in the visual field and depending on the degree may produce discomfort or visual disability.

Direct Glare

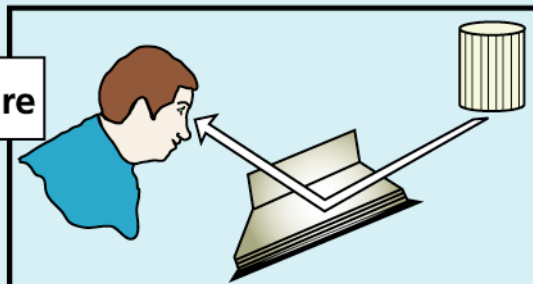


Bare light source in visual field.



Bright sky seen through window.

Reflected Glare



Veiling light reflected from task surface.

LIGHT
Discomfort Glare

Discomfort Glare is caused by excessive brightness differences between sections of the visual field.

- It is annoying, but does not prevent the observer from seeing details
- Occurs quite frequently in artificially lit building spaces, due to inadequate shielding of light sources.
- The degree of Discomfort Glare is primarily related to the location and type of light source, the nature of the task, and the luminance of the surrounding visual field.
- The principal mitigation method is to shield the offending light source from the direct view of the observer.

LIGHT

Discomfort Glare Factors

Discomfort Glare is Governed by:

1. The luminance of the glare source
2. The apparent area of the glare source.
3. The general **Adaptation Level**.
4. The location of the glare source relative to the observer.
5. The luminance of the immediate surround of the glare source.

Adaptation Level is defined as the average luminance of all surfaces in the visual field.

LIGHT

Disability Glare

Disability Glare appears to be caused entirely by an excessive illumination on the eyes due to the glare source which produces nervous interaction within the network of light receptors in the retina.

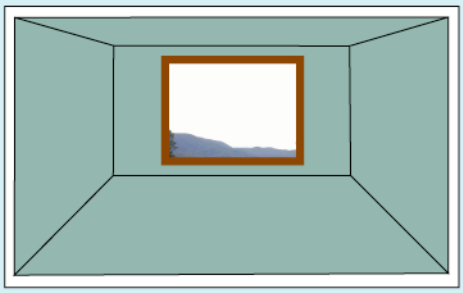
- Reduces visual performance by preventing an observer from seeing details around the border of the glare source.
- Unlikely to occur in artificially lit building spaces because artificial light sources are normally not sufficiently bright.
- Most commonly occurs when a very bright sky can be seen through the window from within a poorly lit building space (e.g., a window at the end of a corridor).
- Mitigation methods include: (1) reducing the brightness of the glare source; and, (2) increasing the luminance of the visual field surrounding the glare source.

LIGHT

Control of Glare from Daylight

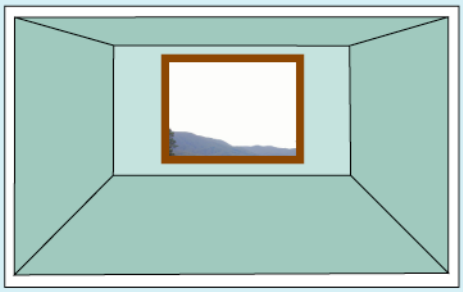
The Problem:

Bright sky seen through window becomes a source of Disability Glare.



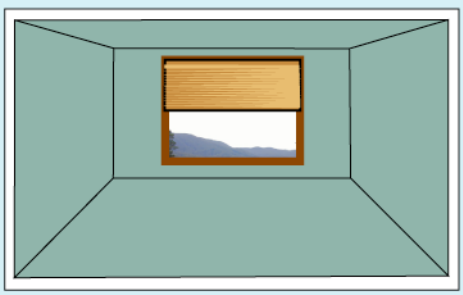
Solution Approach (A):

Raise illumination level around window by increasing artificial lighting.
[Increases energy Consumption.]



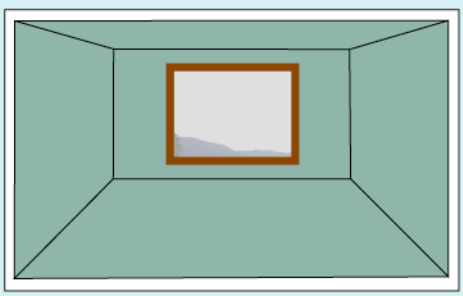
Solution Approach (B):

Block view of sky by means of shading devices or blinds.
[Reduces daylight availability.]



Solution Approach (C):

Use special anti-glare or tinted glass to reduce the brightness of the window.
[Reduces daylight penetration.]



LIGHT

Reflected Glare

Reflected Glare can occur when a light source is reflected from a task surface into the eyes of the viewer.

- It produces a Veiling Reflection that causes Disability Glare (e.g., viewer cannot read text on glossy book page).
- A light source causing Reflected Glare may not be excessively bright (i.e., over-brightness is not the cause of Reflected Glare).
- Mitigation methods include: (1) changing the relative positions of task surface and viewer (e.g., tilting the task surface (book); tilted shop windows); (2) using matte task surfaces; and, (3) changing the shielding angle of the reflected light source.

LIGHT

Perception of Brightness Differences

The brightness (luminance) of the immediate surround greatly influences the perception of a glare source, such as a window.