Human Visual System

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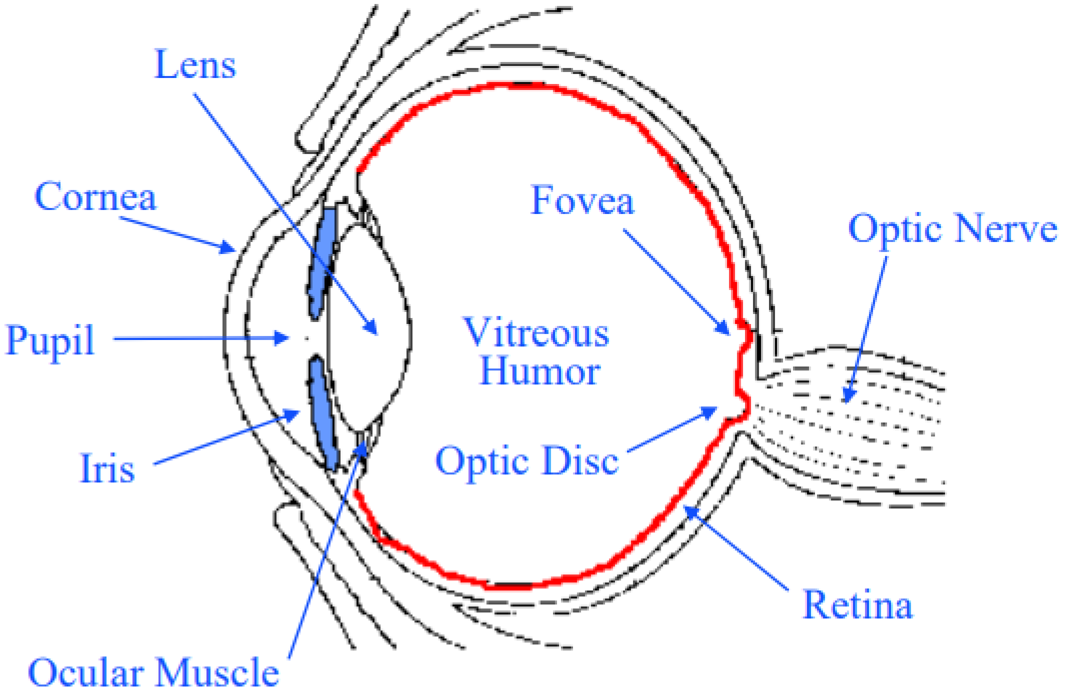
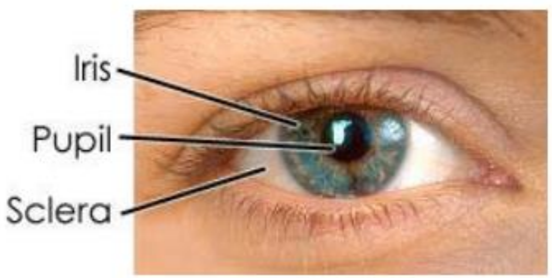
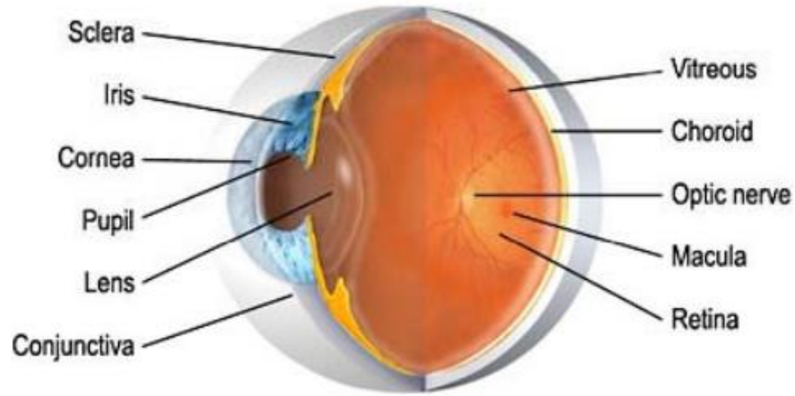
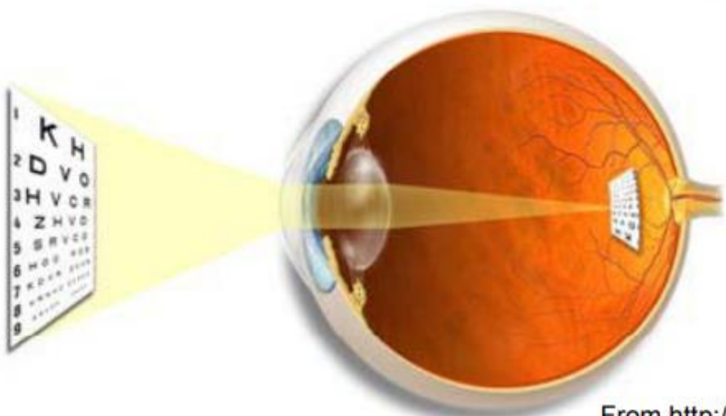
Human Eye


Lens
Cornea
Pupil
Iris
Ocular Muscle
Fovea
Vitreous Humor
Optic Disc
Optic Nerve
Retina

Eye Anatomy

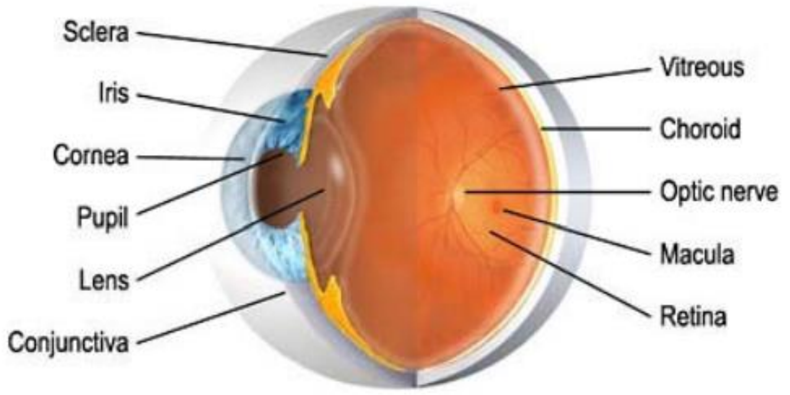






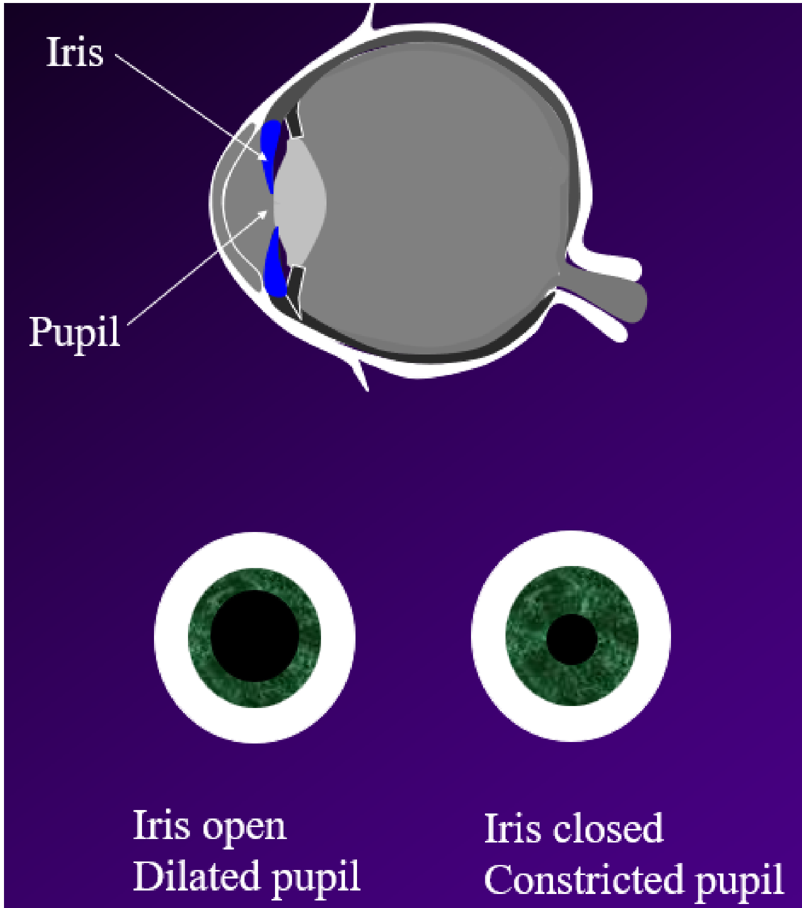
From http://www.stlukeseye.com/Anatomy.asp

Eye VS. Camera



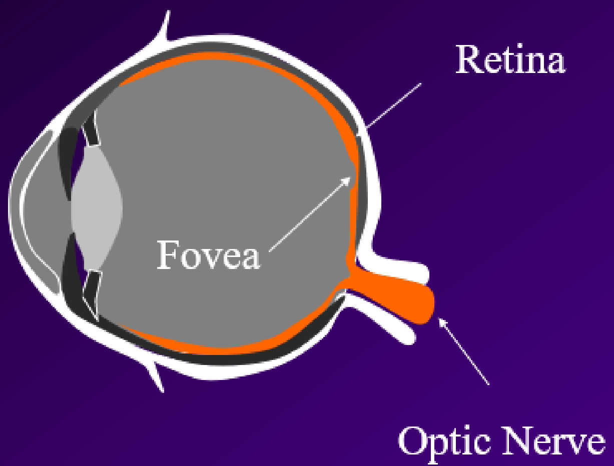
Camera components	Eye components
Lens	Lens, cornea
Shutter	Iris, pupil
Film	Retina
Cable to transfer images	Optic nerve send the info to the brain

Iris and Pupil



- Colored *iris* controls the size of the opening (*pupil*) where the light enters.
- Pupil determines the amount of light, like the aperture of a camera.

Retina



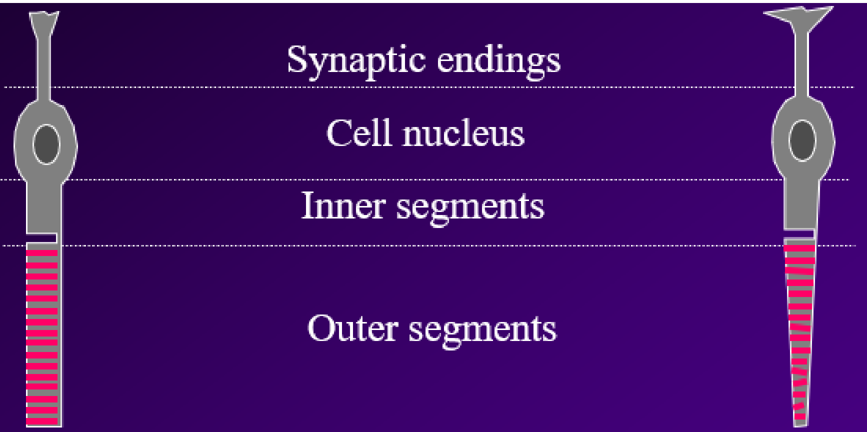
- *Retina* is the photosensitive "detector" for the eye.
- Two types of receptors in the retina: *rods* for low light level, and *cones* for color.
- Located at the center of the retina, *fovea* contains a greater concentration of cones.
- Signals from the receptors leave through the *optic nerve* to the brain.

Retinal Photoreceptors

Rods -
- Low illumination levels (Scotopic vision).
- Highly sensitive (respond to a single photon).
- 100 million rods in each eye.
- No rods in fovea.

Cones -
- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.

Rods and Cones



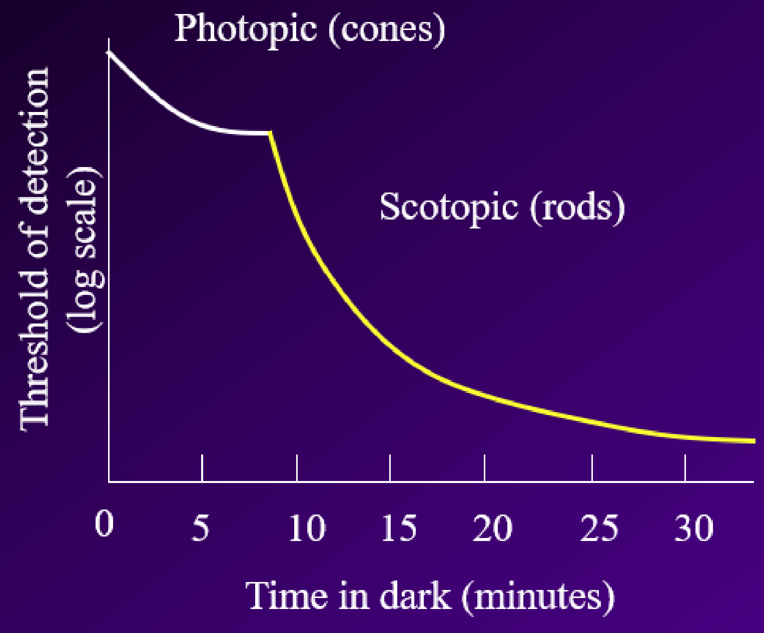
Rod

- Highly sensitive to low light level or *scotopic* conditions.
- Black and white.
- Dispersed in the periphery of the retina.

Cone

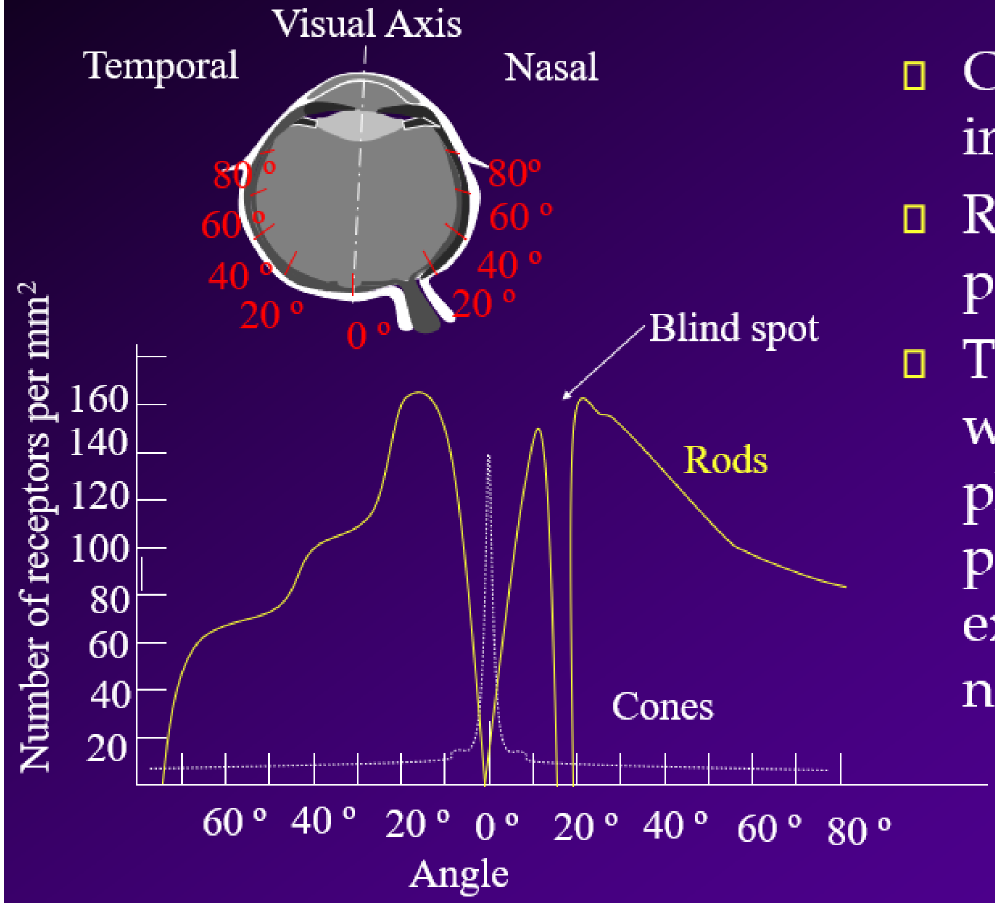
- Sensitive to high light level or *photopic* conditions.
- Three types of cones responsible for color vision.
- Concentrated in the fovea.

Adaptation

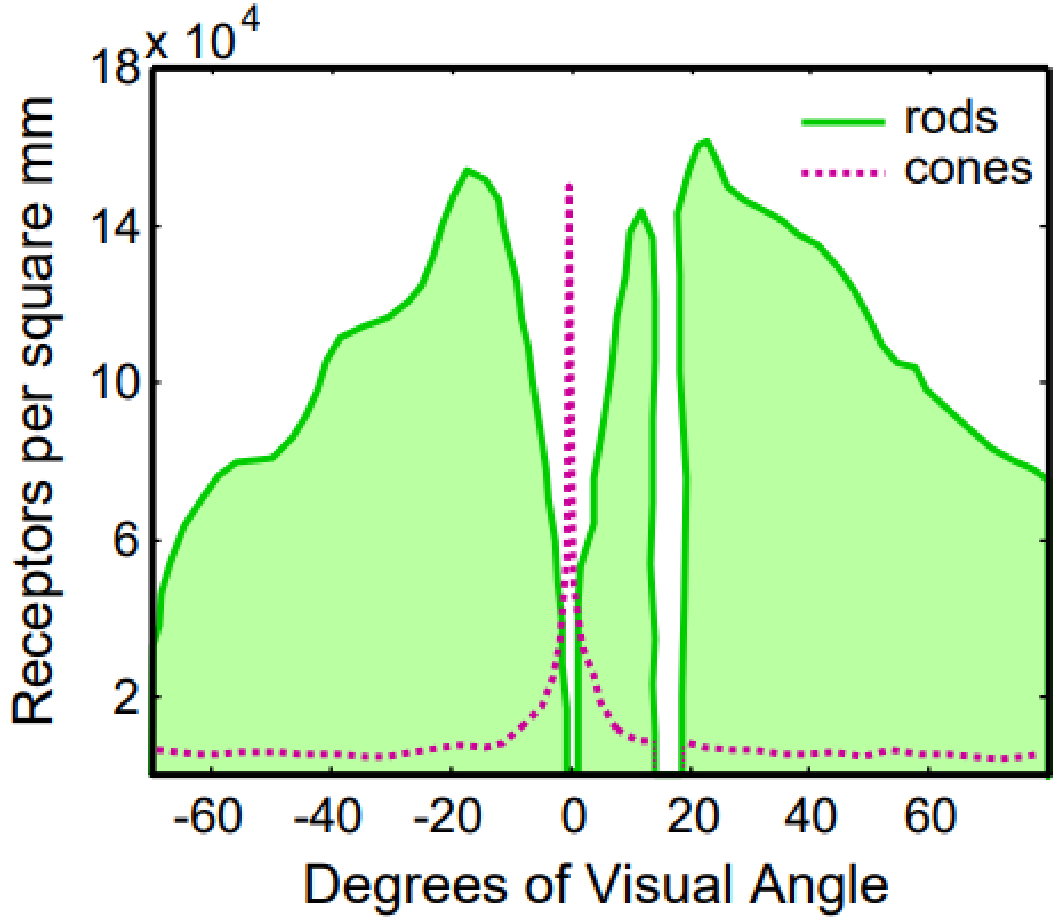


- Why can't you see immediately after you enter a movie theater from daylight?
- The threshold of detection changes with overall light level.
- The switch is quite gradual, until the sensitivities of cones and rods cross over at about 7 minutes in the dark.

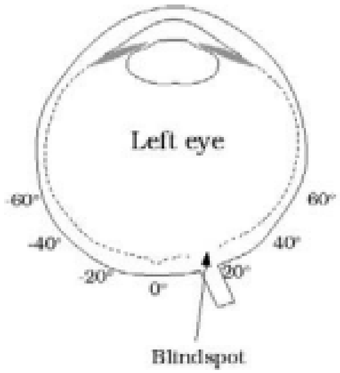
Distribution of Photoreceptors



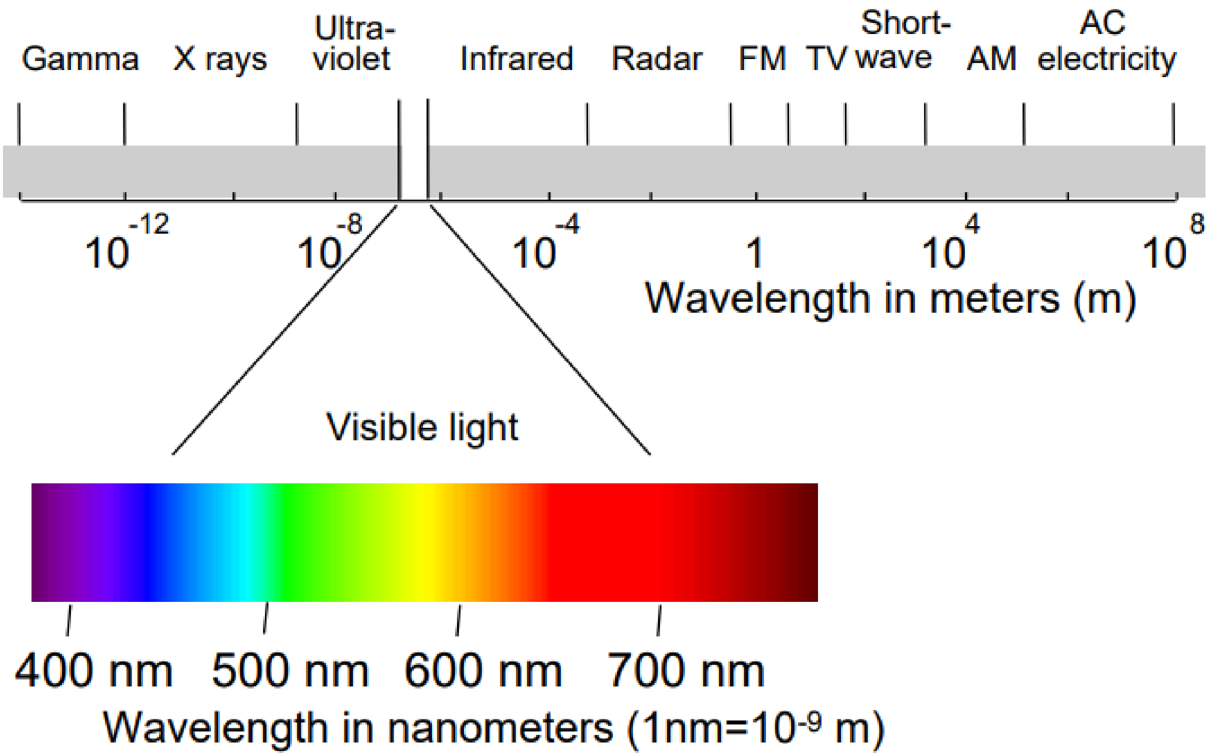
- Cones are concentrated in the fovea.
- Rods predominate the periphery.
- There is a blind spot where there are no photoreceptors, at the point where the nerves exit the eye (optic nerve).



Distribution of rod and cone photoreceptors



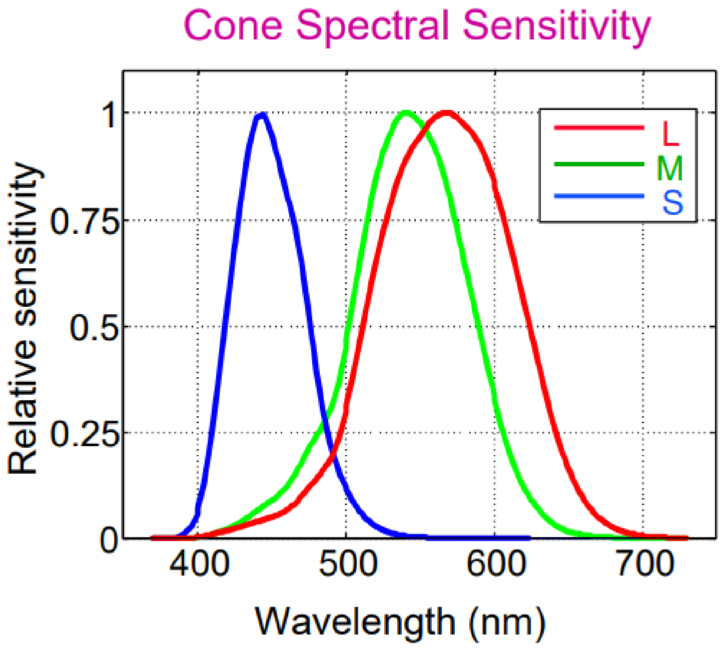
Electromagnetic Radiation - Spectrum



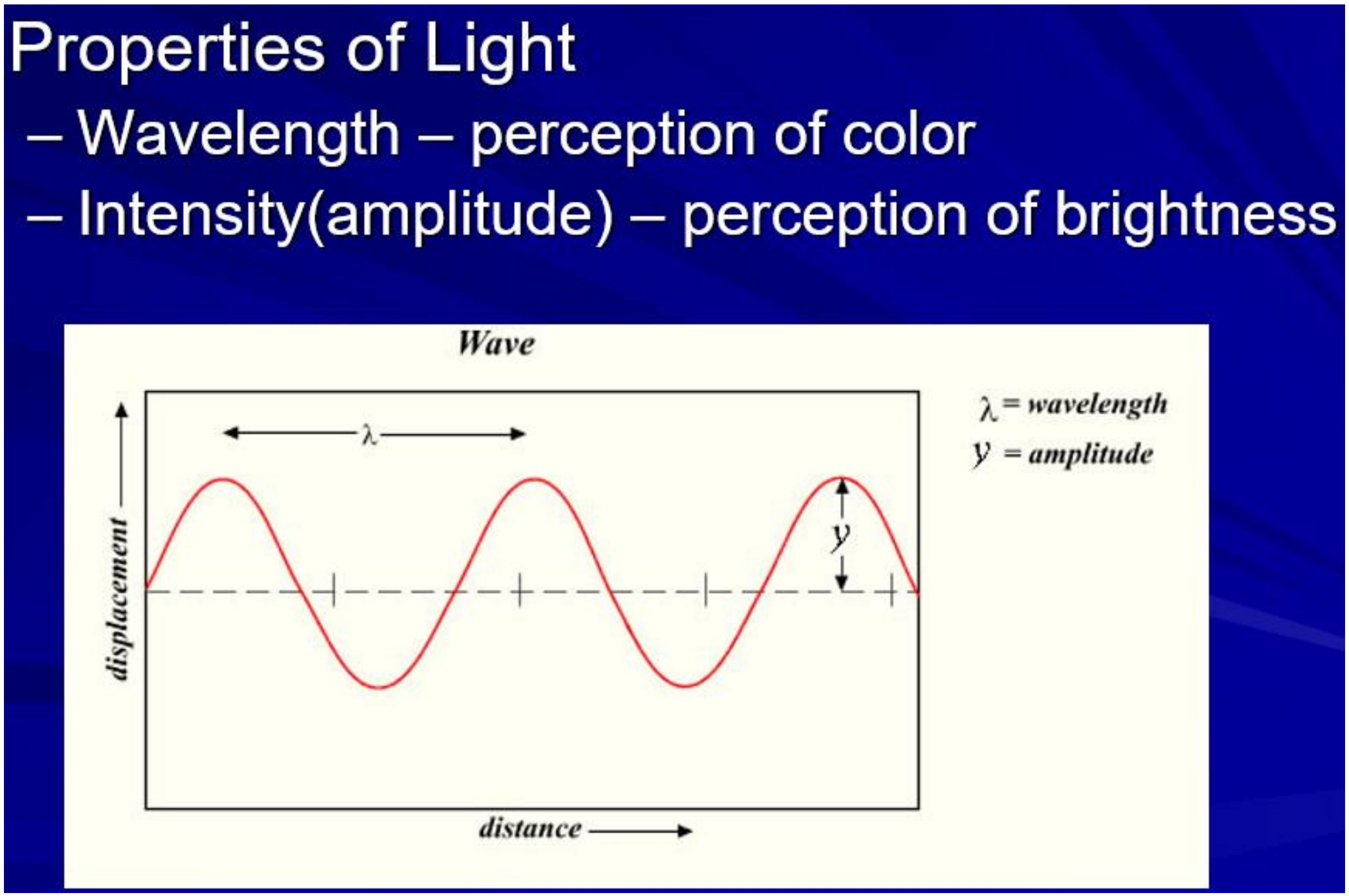
Retinal Photoreceptors

Cones -

- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.
- 3 cone types differing in their spectral sensitivity: L , M, and S cones.

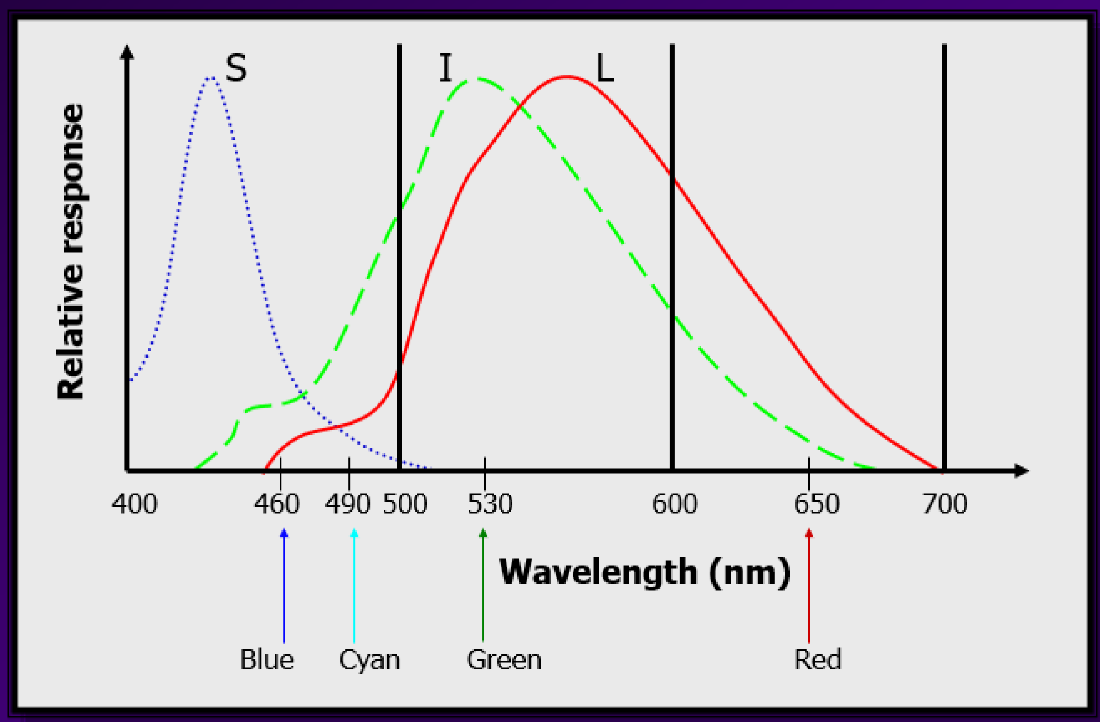


Visible Light



Human Vision

- Human Cone Response to Color
  - three cone types (S,I,L) correspond to B,G,R



Types of Vision

- Scotopic or Night Vision
  - Under dark condition
  - Only rods are active
  - Perceive only shades of grey
- Photopic or Day Vision
  - Under sunlight
  - Cones are most active
- Mesophic Vision
  - Dim light condition
  - Both cones and rods are active

Image Formation in Eye

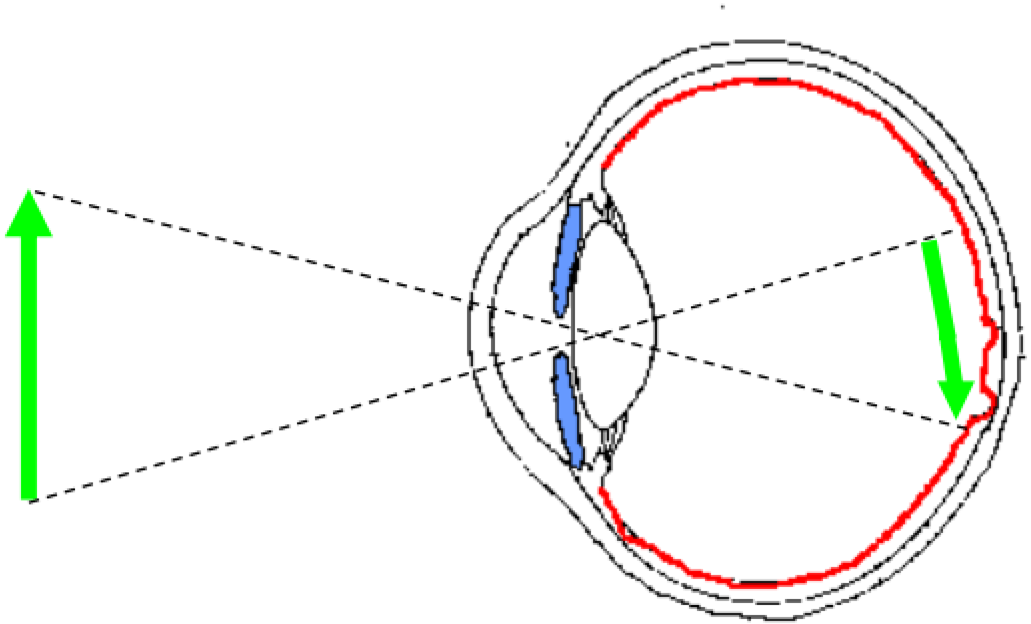
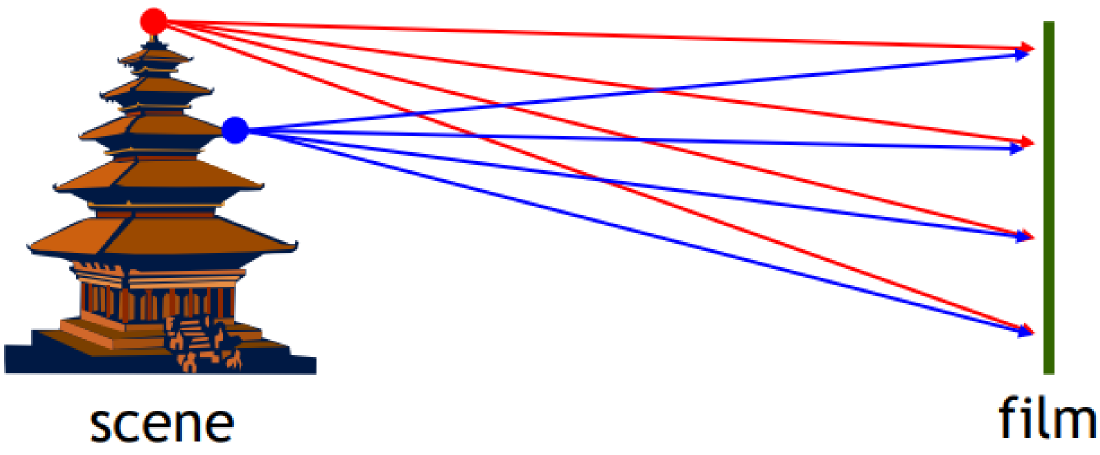
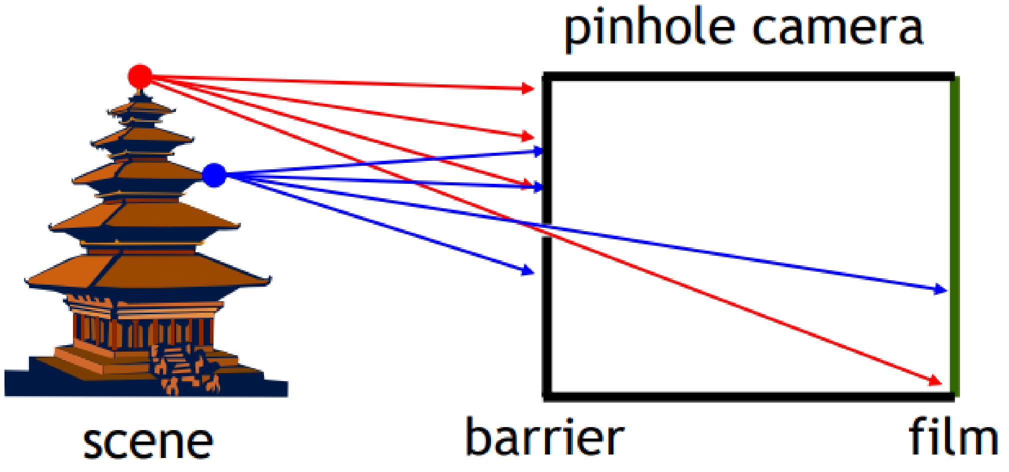


Image Formation - Optics



Put a piece of film in front of an object.

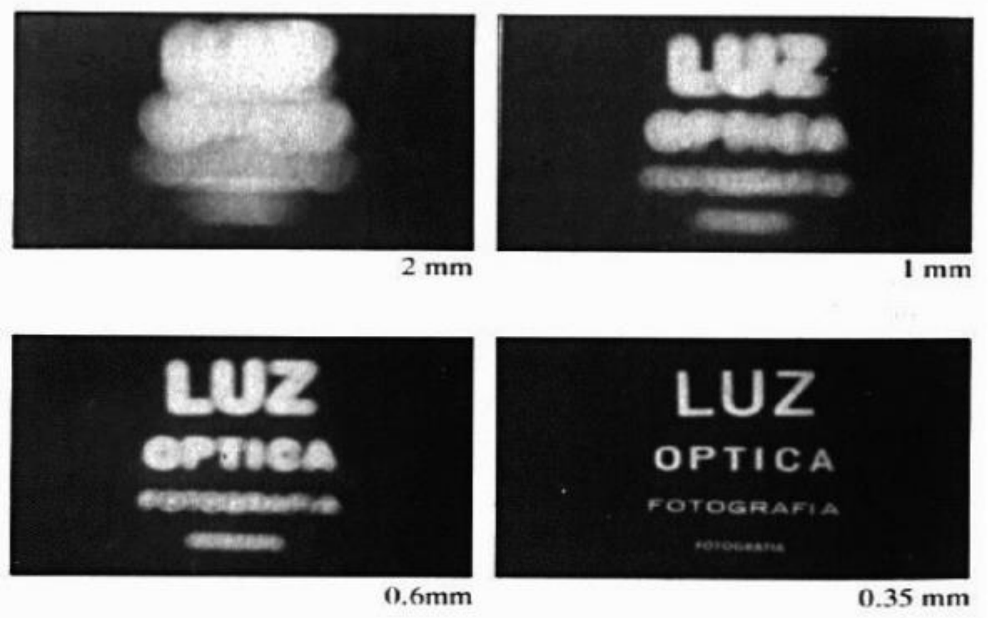
Image Formation - Optics



Add a barrier to block off most of the rays.

- It reduces blurring
- The pinhole is known as the aperture
- The image is inverted

Image Formation - Optics



Why not create the aperture as small as possible?

- Less light gets through
- Diffraction effect

Image Formation - Optics

Adding a Lens

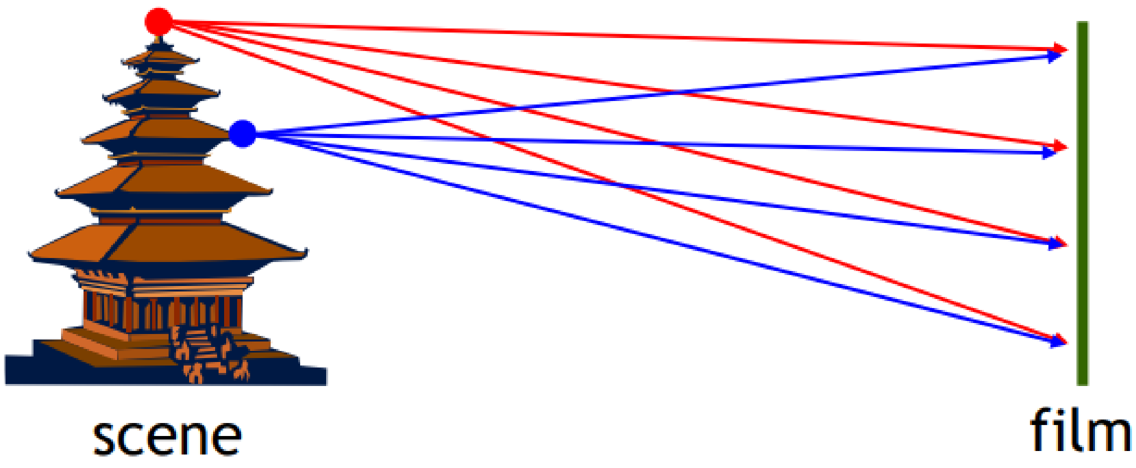
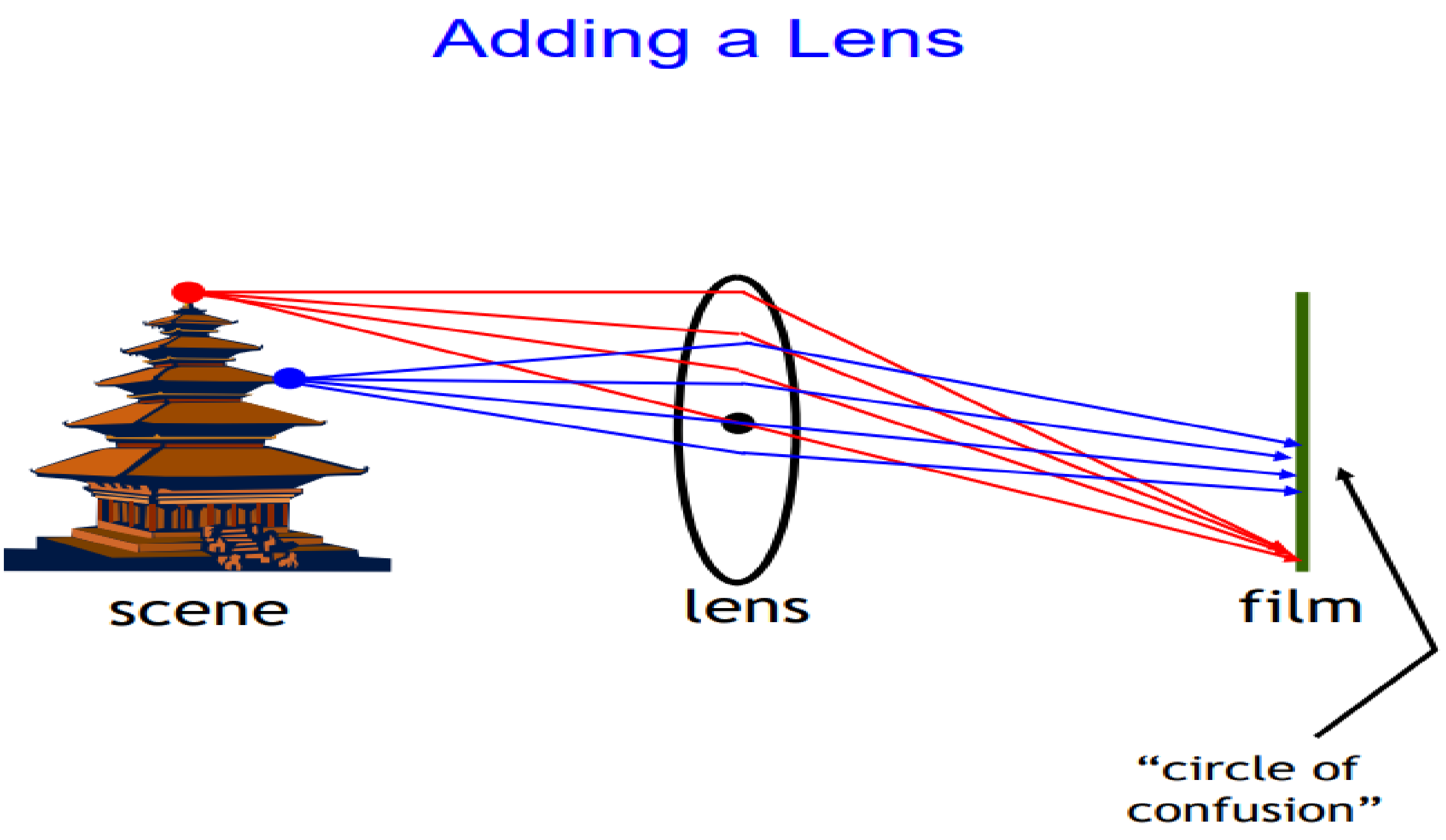
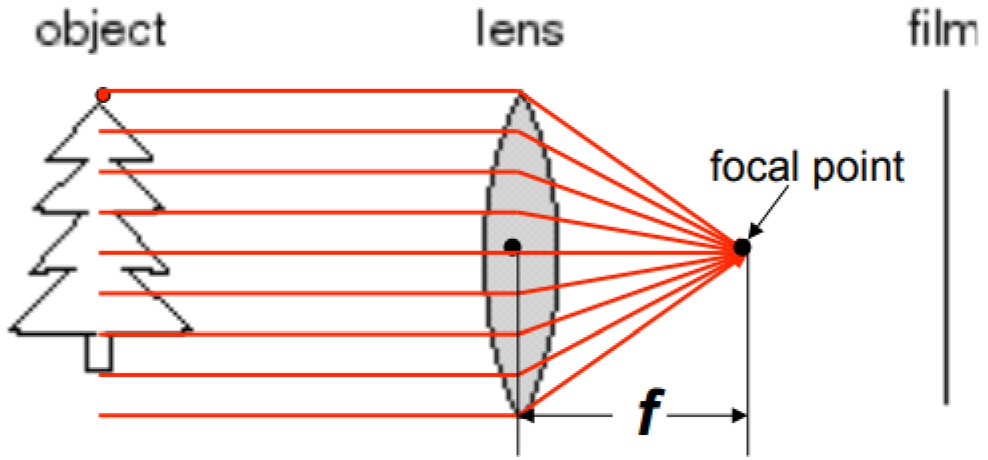
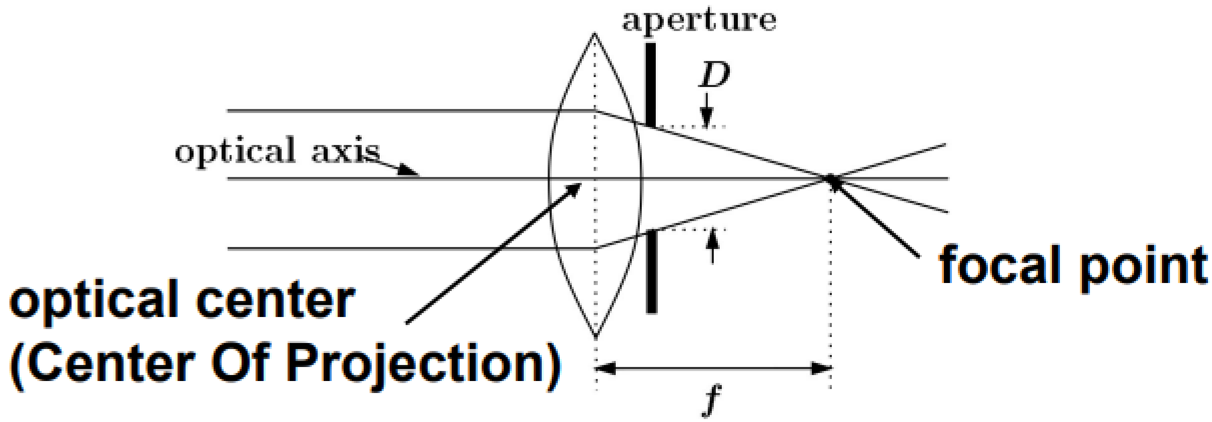


Image Formation - Optics



- A lens focuses the light onto the film/CCD.
- Rays passing through the center are not deviated.
- All parallel rays converge to one point on a plane located at the **focal length** *f*.





Pinhole VS. Lens

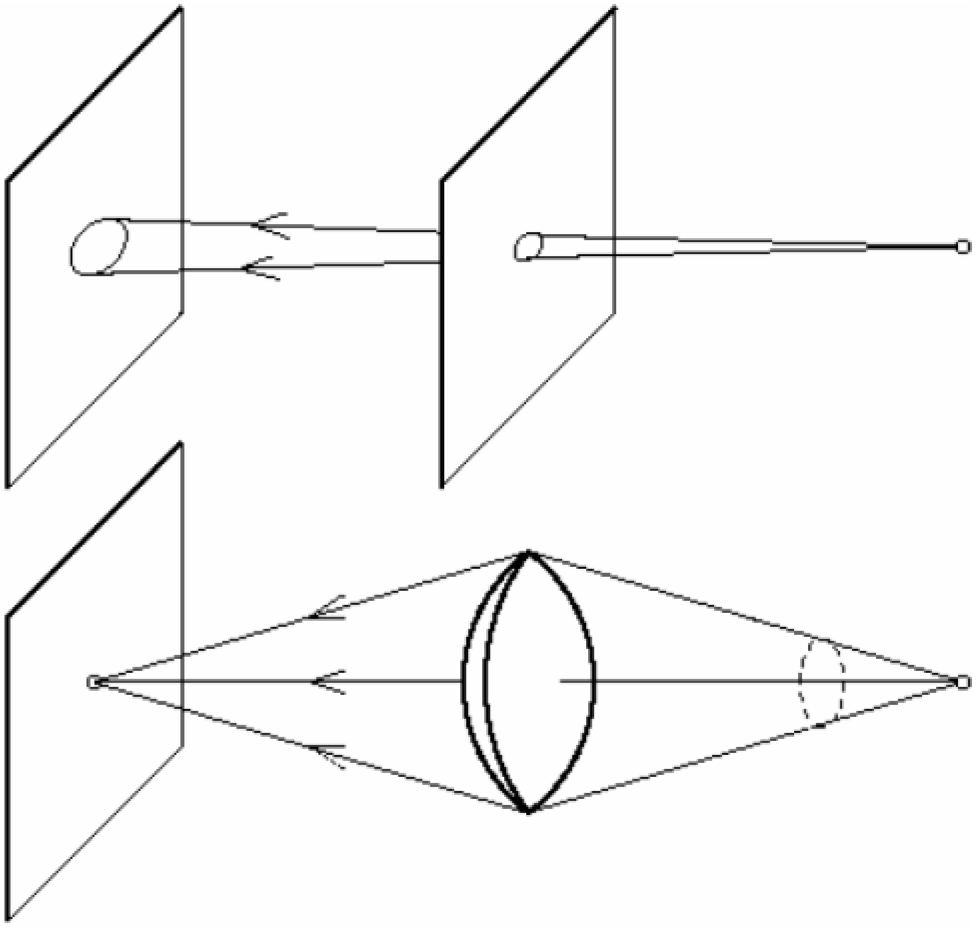
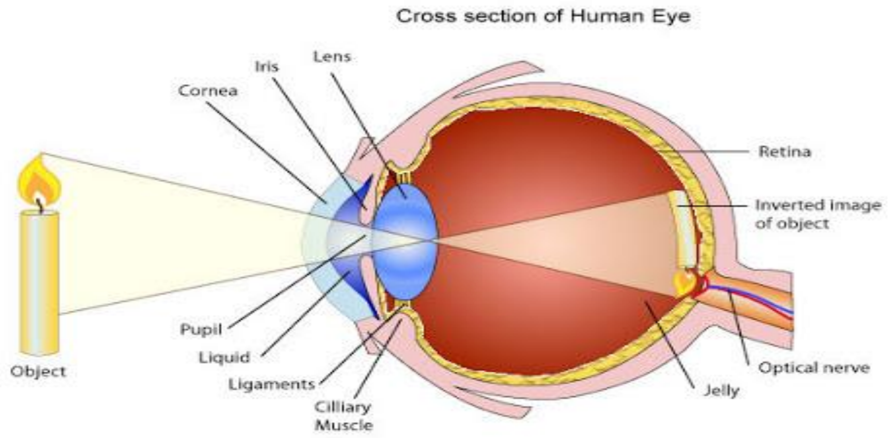
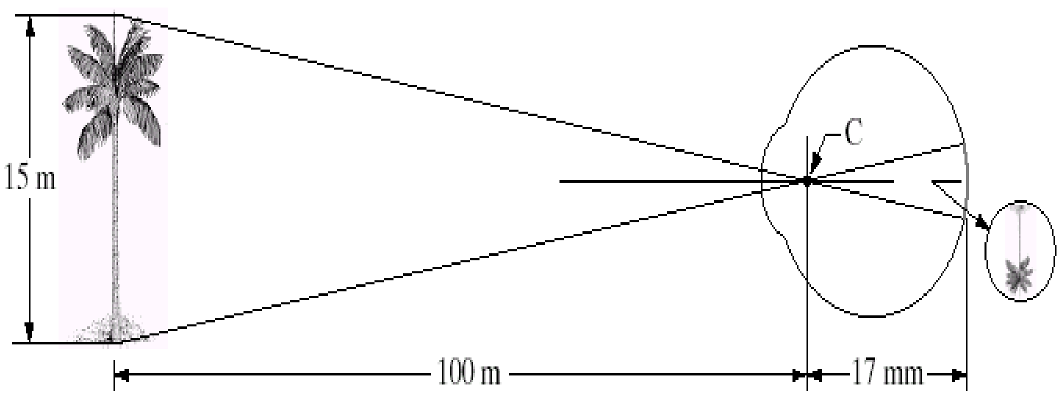


Image Formation in the Human Eye





- Muscles within the eye can be used to change the shape of the lens allowing us focus on objects that are near or far away
- An image is focused onto the retina causing rods and cones to become excited which ultimately send signals to the brain

Simple model for image formation

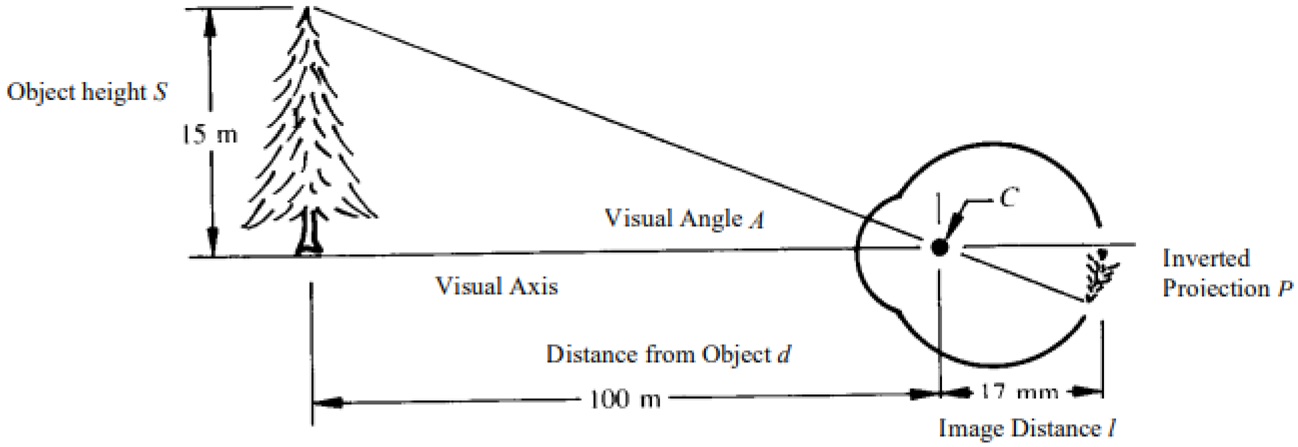


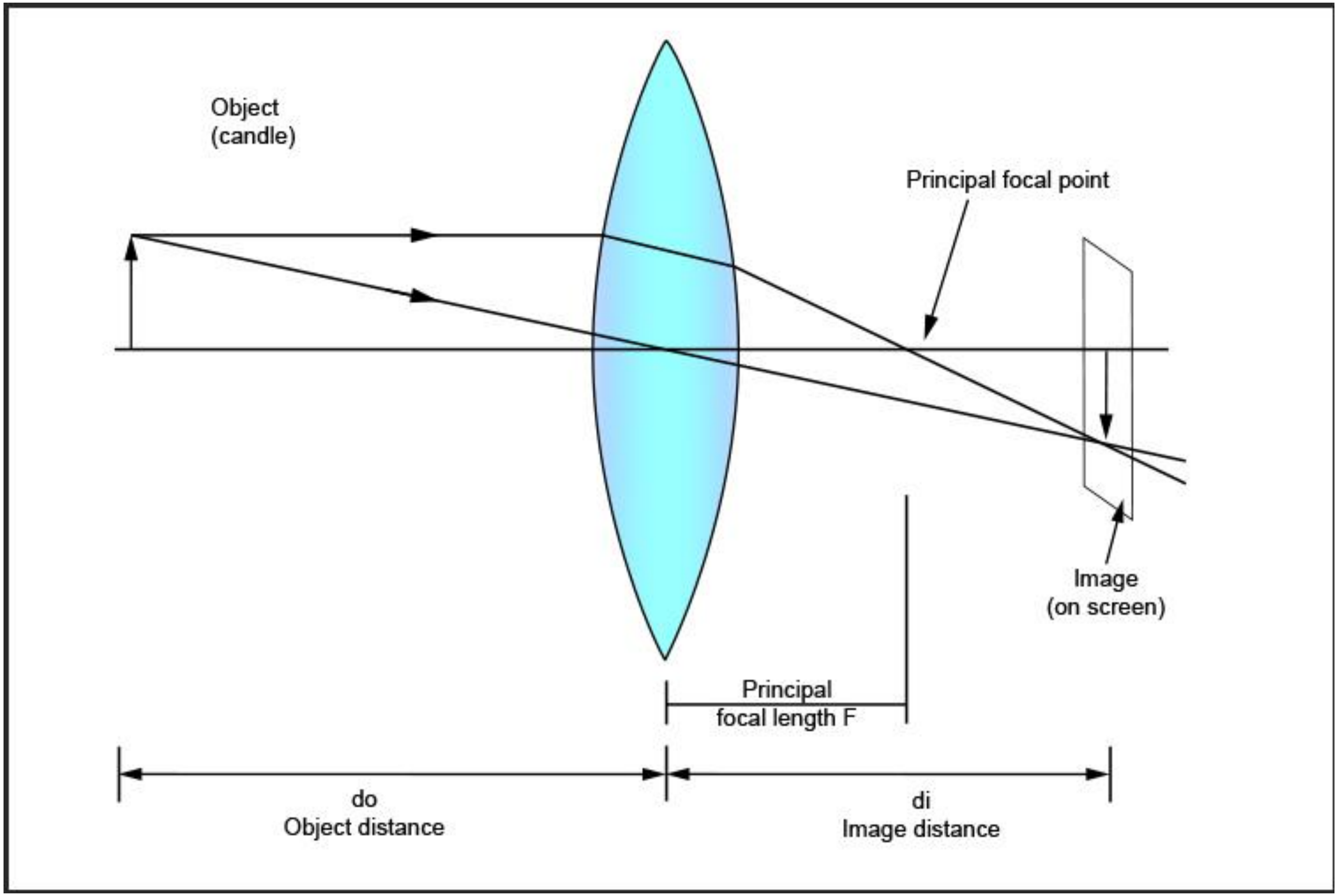
Figure 2.3 *Optical representation of the eye looking at a tree. Point C is the optical center of the lens.*

Simple model for image formation

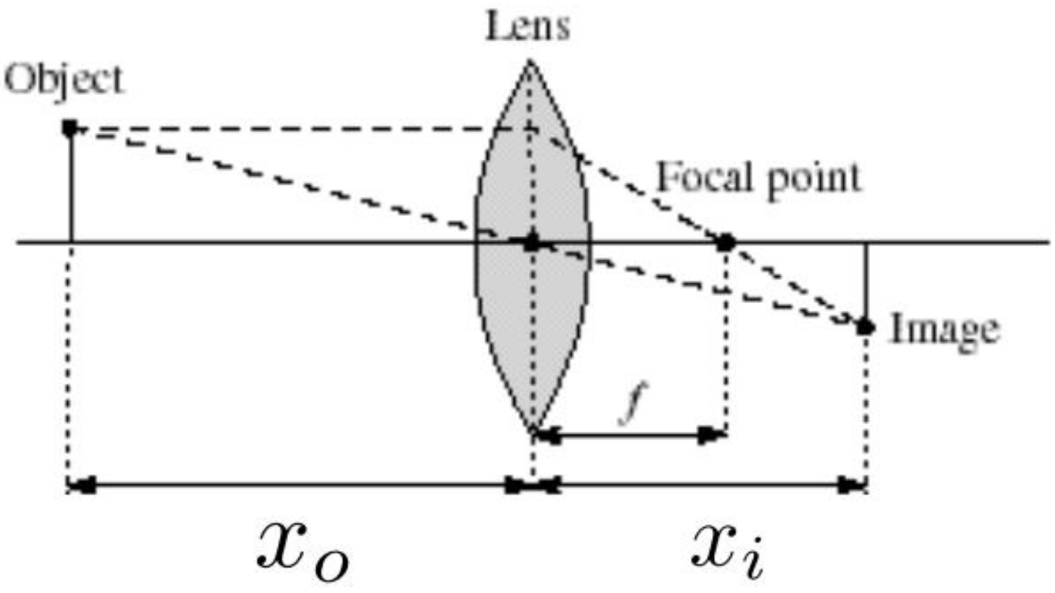
- Distance between center of lens and retina varies from 14- 17mm.
- Farther the object, smaller the refractive power of lens, larger the focal length.
- From the geometry,

$$P = l\frac{S}{d} = 17\frac{15}{100} = 2.55\text{mm}$$

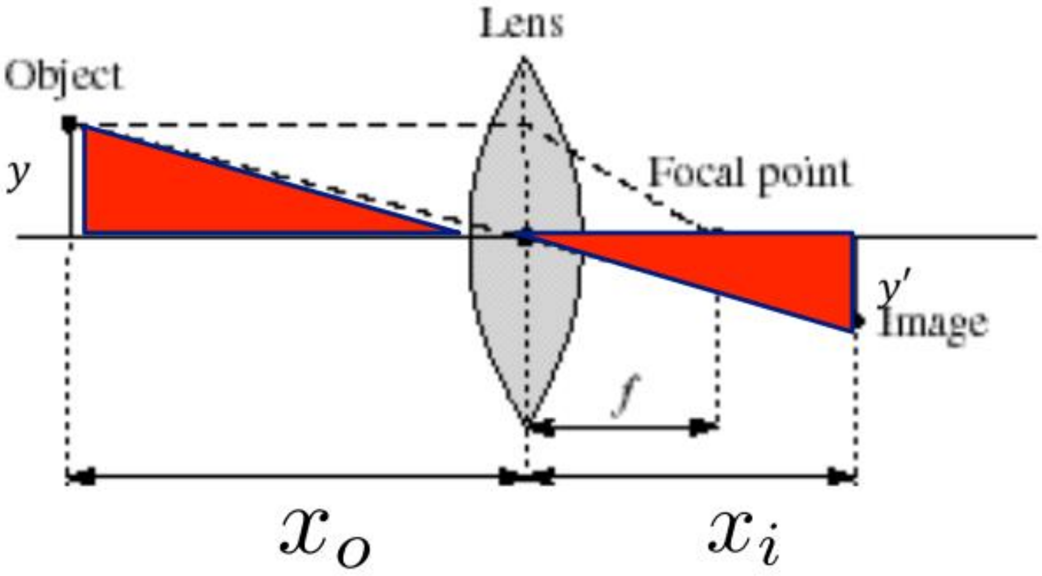
$$A = \tan^{-1}\left(\frac{S}{d}\right) = 8.53^{\circ}$$


Object
(candle)
Principal focal point
Image
(on screen)
Principal
focal length F
do
Object distance
di
Image distance

Lens Equation

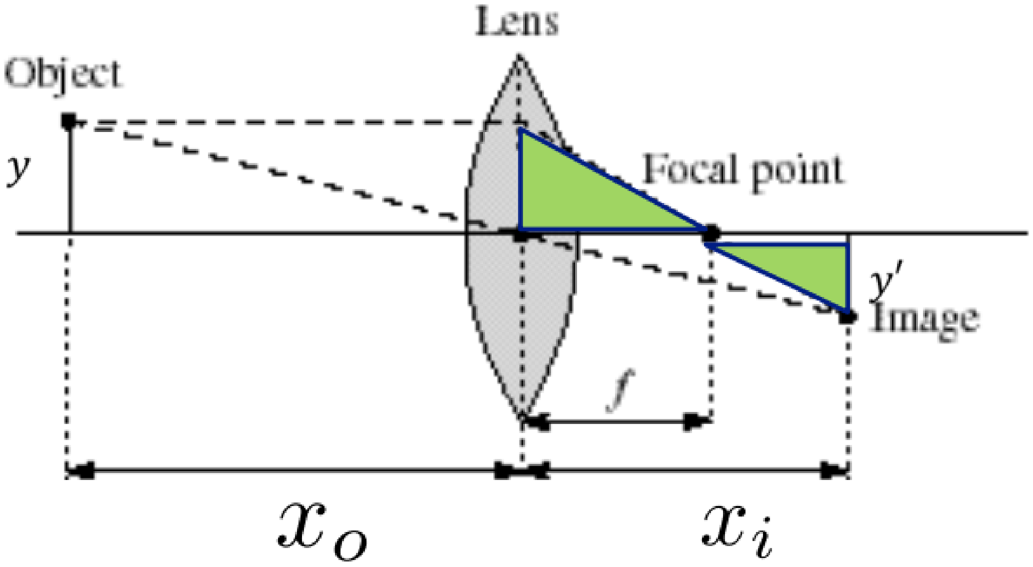


- How to relate distance of object from optical center (x_o) to the distance at which it will be in focus (x_i), given focal length f?



$$\frac{y'}{y} = \frac{x_i}{x_o}$$

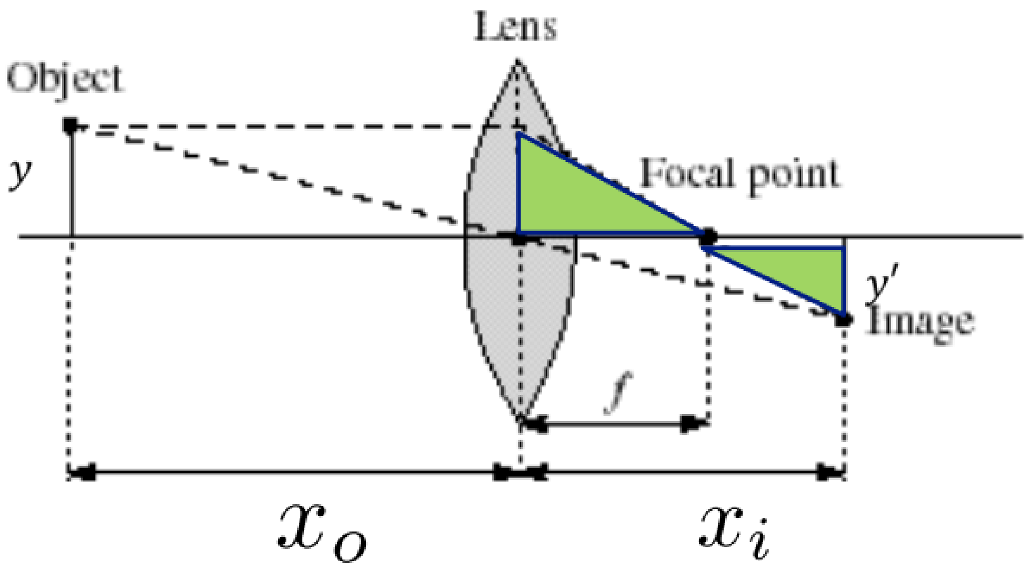
- How to relate distance of object from optical center (x_o) to the distance at which it will be in focus (x_i), given focal length f ?



$$\frac{y'}{y} = \frac{x_i}{x_o}$$

$$\frac{y'}{y} = \frac{x_i - f}{f}$$

- How to relate distance of object from optical center (x_o) to the distance at which it will be in focus (x_i), given focal length f ?



$$\frac{y'}{y} = \frac{x_i}{x_o}$$

$$\frac{y'}{y} = \frac{x_i - f}{f}$$

- Any object point satisfying this equation is in focus

$$\frac{1}{f} = \frac{1}{x_o} + \frac{1}{x_i}$$

Lens Equations

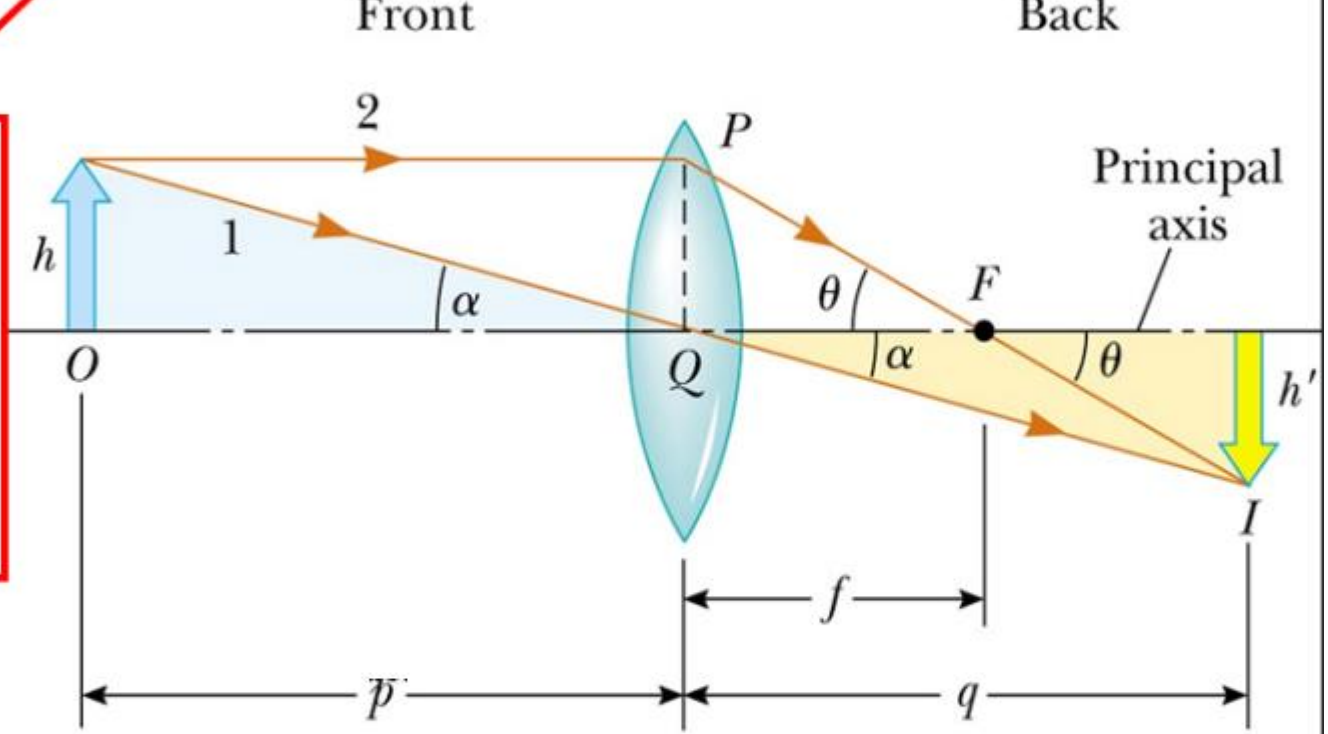
$$\tan\alpha = \frac{h}{p} = -\frac{h'}{q}$$

$$\tan\theta = \frac{h}{f} = -\frac{h'}{q-f}$$

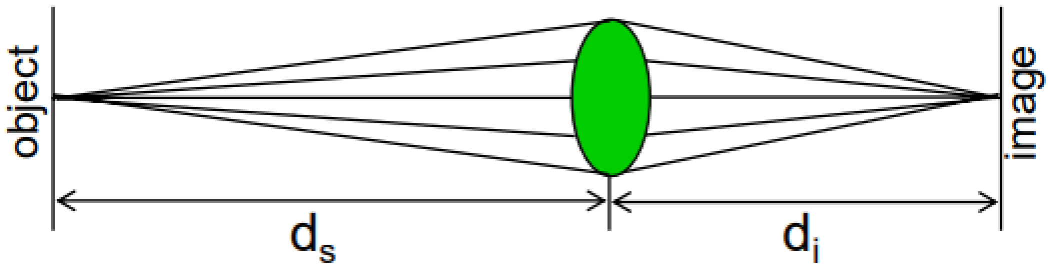
$$\frac{h'}{h} = -\frac{q-f}{f} = -\frac{q}{p}$$

$$M = \frac{h'}{h} = -\frac{q}{p}$$

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$



Lensmaker's Equation

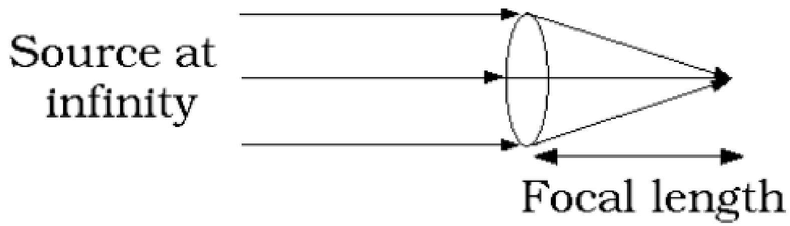


$$\frac{1}{d_s} + \frac{1}{d_i} = \frac{1}{f}$$

$d_s = source\ dist$

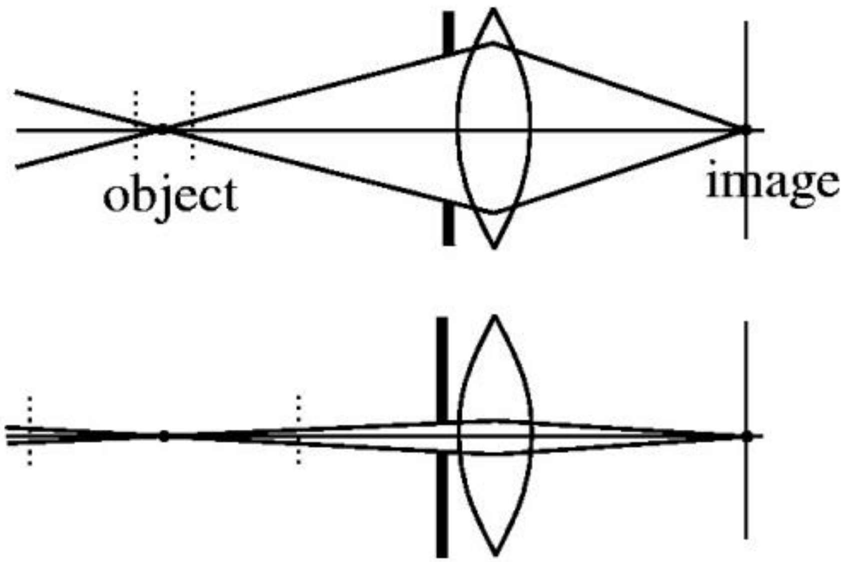
$d_i = image\ dist$

$f = focal\ length$



$$\text{Lens power (diopters)} = \frac{1}{\text{Focal length (m)}}$$

Depth of field

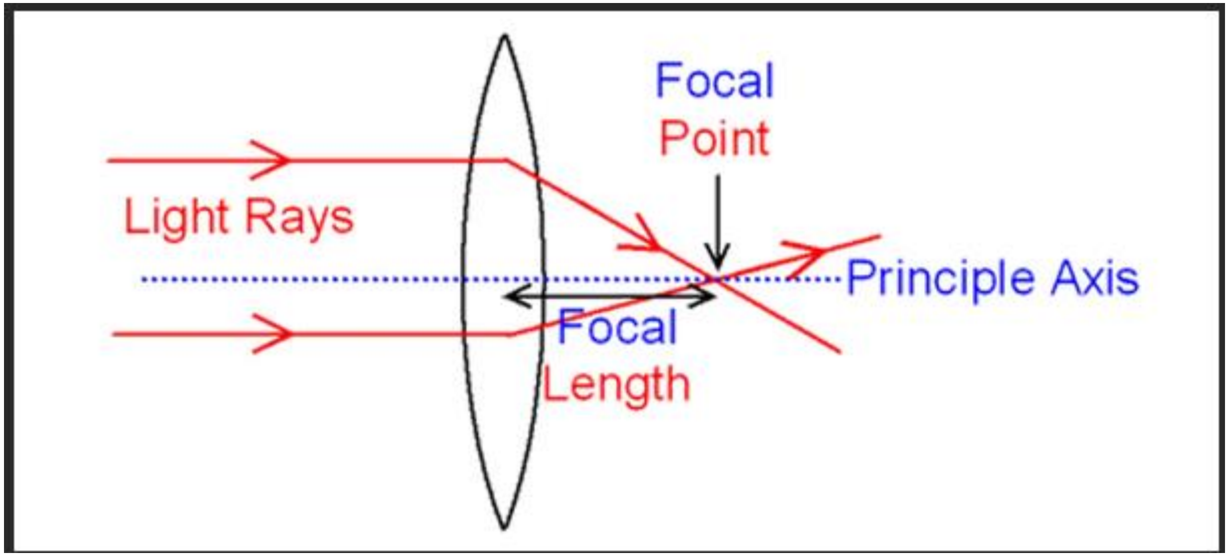


$f / 5.6$

$f / 32$

- Changing the aperture size affects depth of field
  - A smaller aperture increases the range in which the object is approximately in focus

Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field


Focal
Point
Light Rays
Principle Axis
Focal
Length

3.2 (c) Thin converging lens

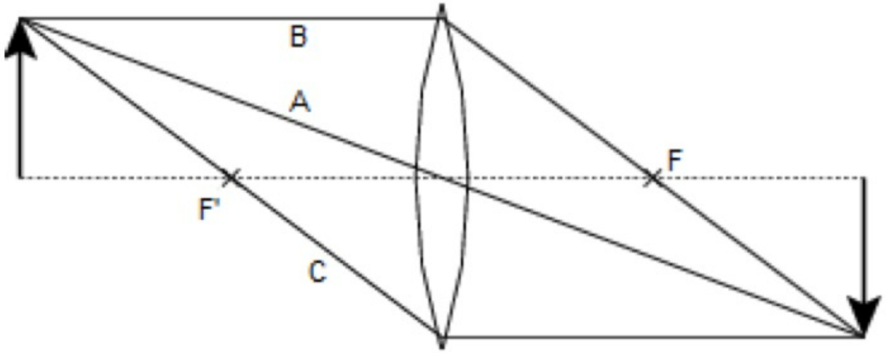
•**Principal focus**: the point where rays parallel to the principal axis converge with a converging lens.

•**Focal length**: distance from the principle focus and the optical centre.

•**Principal axis**: the line the goes through the optical centre, and the 2 foci.

•**Optical centre**: the centre of the lens

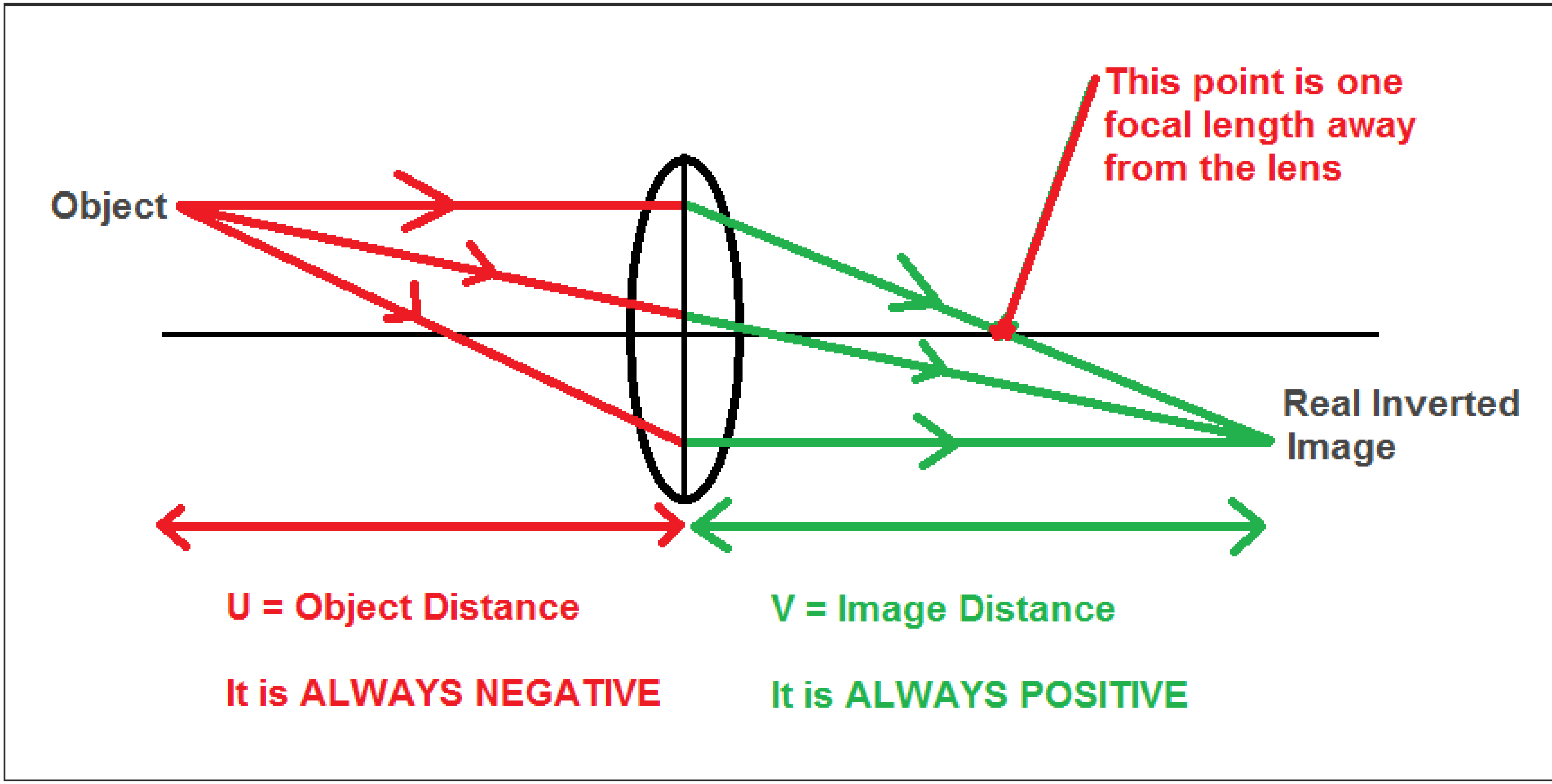
This is a **real image** (when the object is further away from the optical centre than F' is):



A) A ray through the centre of the lens passes straight through the lens.

B) A ray parallel to the principal axis passes through the focus on the other side of the lens

C) A ray through F' will leave the lens parallel to the principal axis.


This point is one focal length away from the lens
Object
Real Inverted Image
U = Object Distance
It is ALWAYS NEGATIVE
V = Image Distance
It is ALWAYS POSITIVE

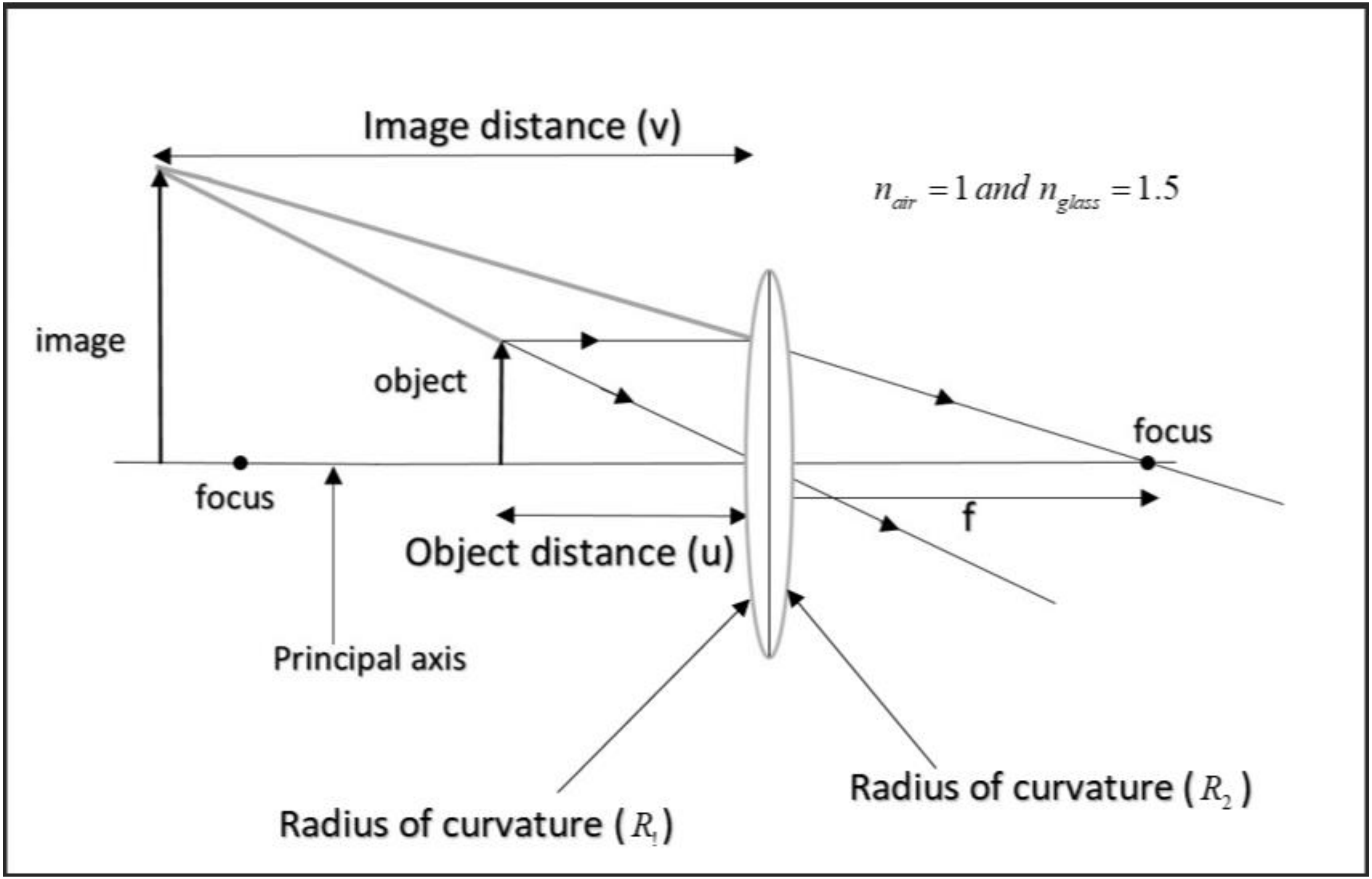
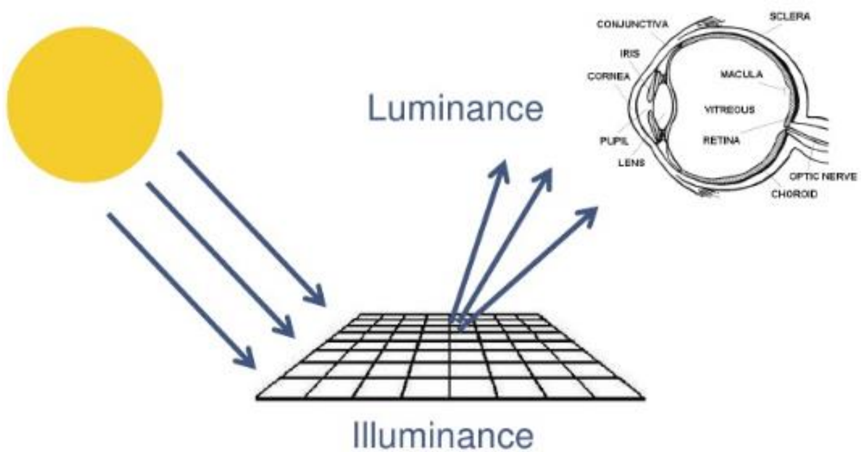


Image distance (v)
$n_{air} = 1$ and $n_{glass} = 1.5$
image
object
focus
focus
f
Object distance (u)
Principal axis
Radius of curvature (R_2)
Radius of curvature (R_1)

Light



Chromatic

- Radiance: total amount of energy that flows from light source – Watts (W)
- Luminance: measure of amount of energy an observer perceives from a light source – Lumens (lm)
- Brightness: subjective descriptor of light perception, practically impossible to measure

Image Formation

- Light source *(λ: wavelength of the source)*
  - $E(x, y, z, \lambda)$: incident light on a point *(x, y, z world coordinates of the point)*
- Each point of the scene has a reflectivity function.
  - $r(x, y, z, \lambda)$: reflectivity function
- Light reflects from a point and the reflected light is captured by an imaging device.
  - $c(x, y, z, \lambda) = E(x, y, z, \lambda) * r(x, y, z, \lambda)$: reflected light.

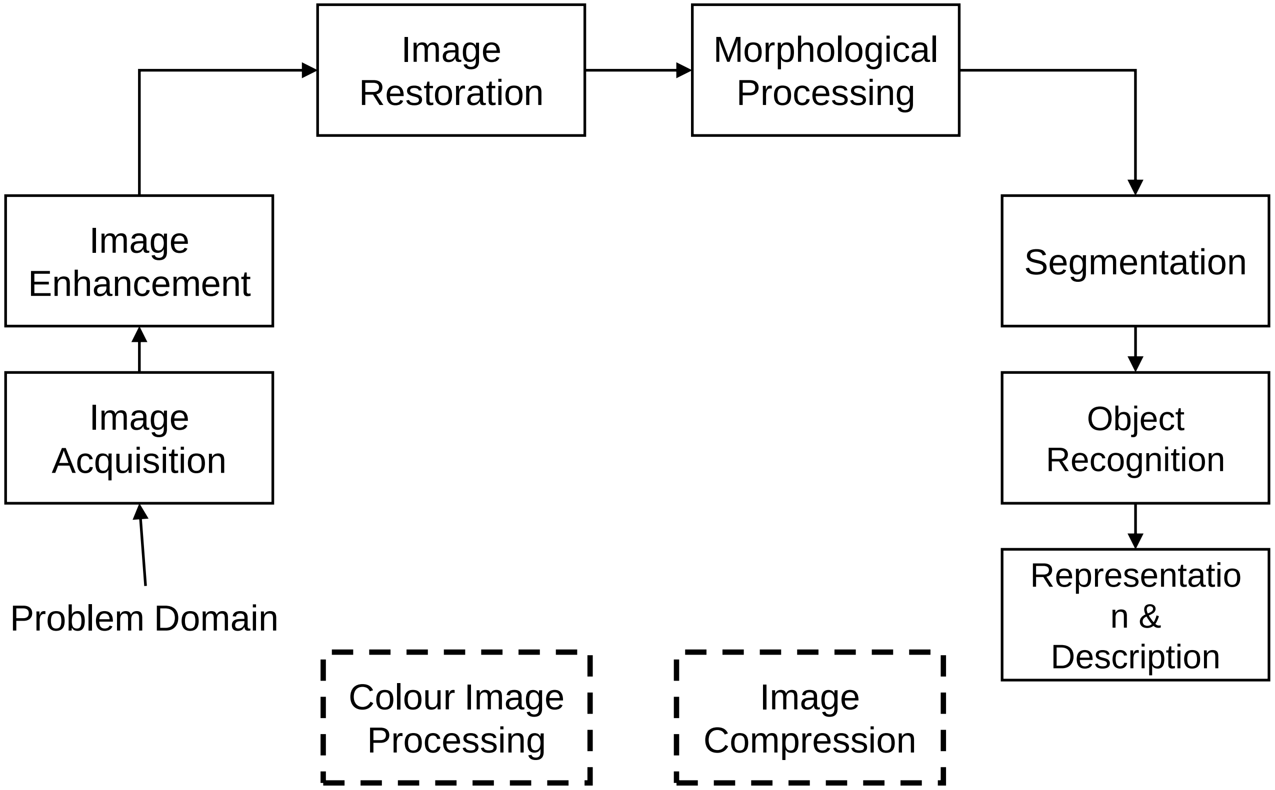
$E(x, y, z, \lambda)$

$c(x, y, z, \lambda) = E(x, y, z, \lambda)*r(x, y, z, \lambda)$

Camera($c(x, y, z, \lambda)$)

Key Stages in Digital Image Processing

Block Diagram

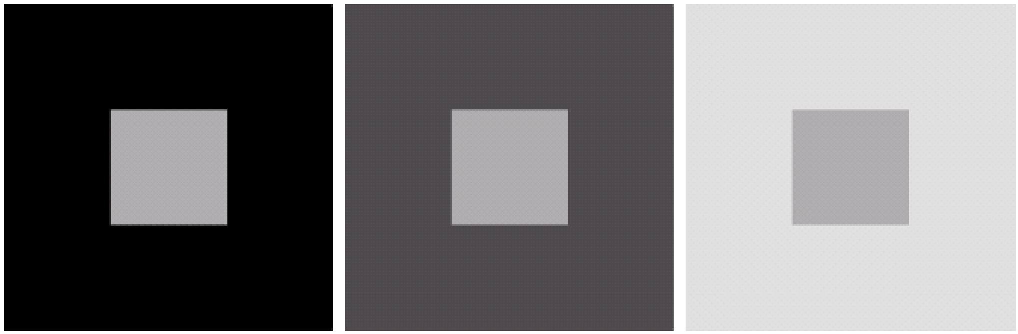


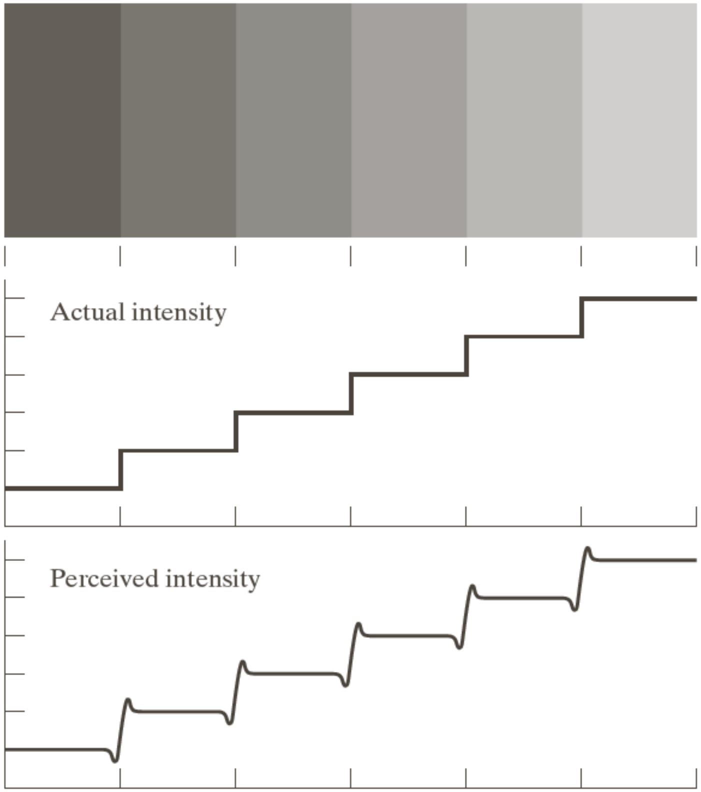
Brightness Adaptation and Discrimination

- Human visual system can perceive approximately 10^{10} different light intensity levels
- Visual system cannot operate over a large dynamic range simultaneously – rather accomplishes this large variation by changes in its overall sensitivity - > phenomenon called brightness adaptation
- However, at any one time we can only discriminate between a much smaller number – brightness adaptation
- Similarly, the perceived intensity of a region is related to the light intensities of the regions surrounding it

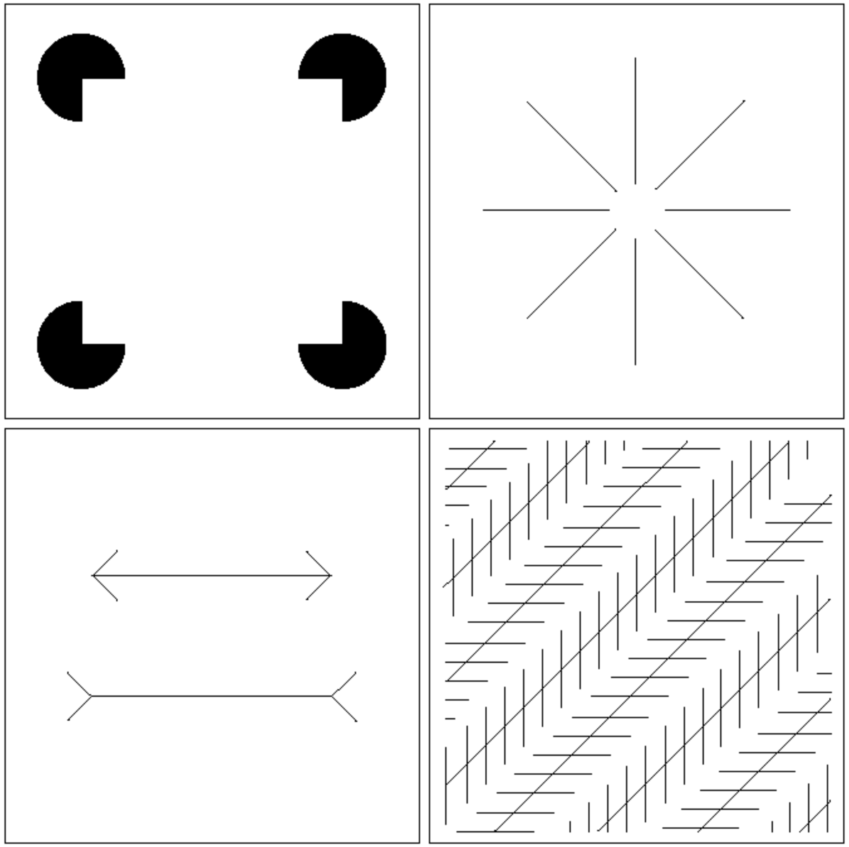
Brightness Adaptation and Discrimination

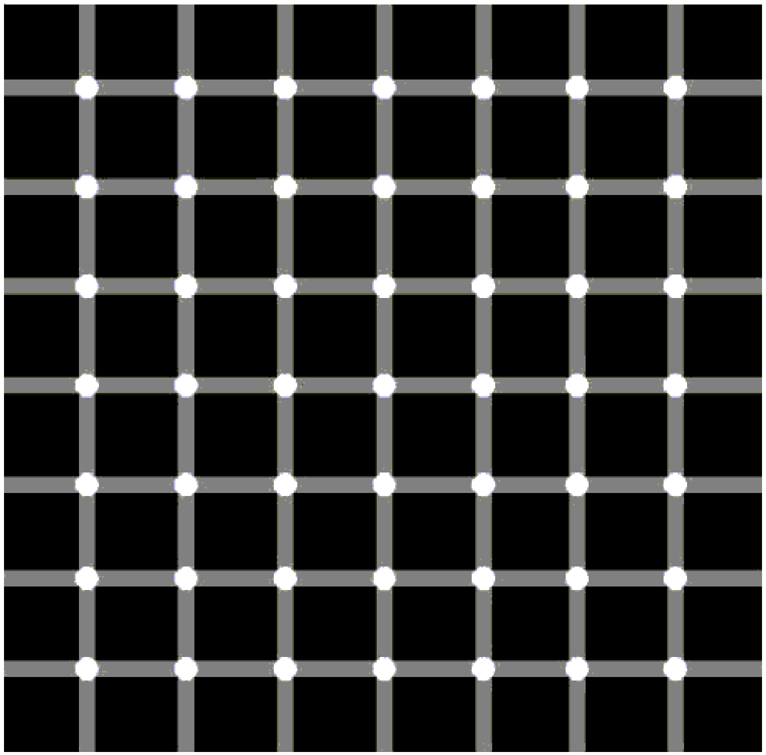
- Perceived brightness is not a simple function of intensity – 2 phenomena
- Visual system tends to undershoot or overshoot around boundary regions of different intensities – Mach Bands
- Simultaneous contrast – perceived brightness does not depend simply on its intensity





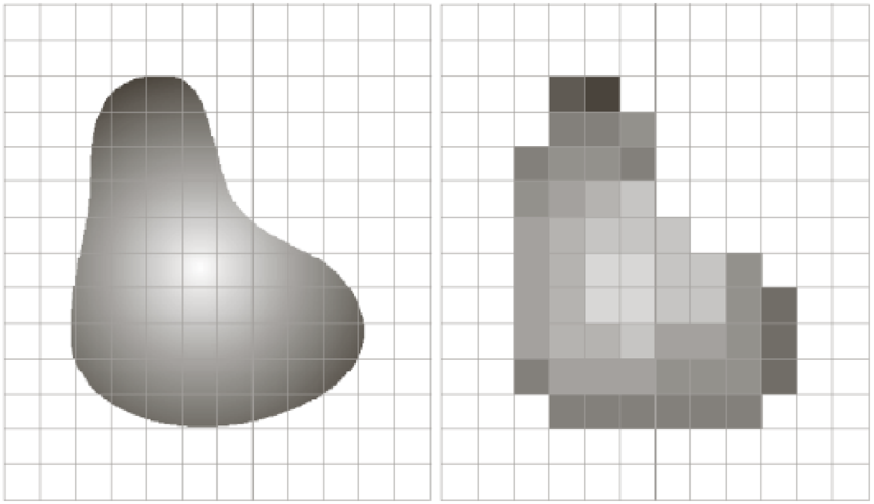
Some examples of human perception – Optical Illusions





Analog to Digital Image Conversion

- Sampling: Dividing a continuous region into small squares (pixels), taking average value of each square
- Quantization: Map each value into one in a set of discrete values



a b

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Digital Image Captured by CCD Array

- Continuous Scene -> Digital image
  - Each CCD sensor averages the light intensity in a small region and output a discretized value

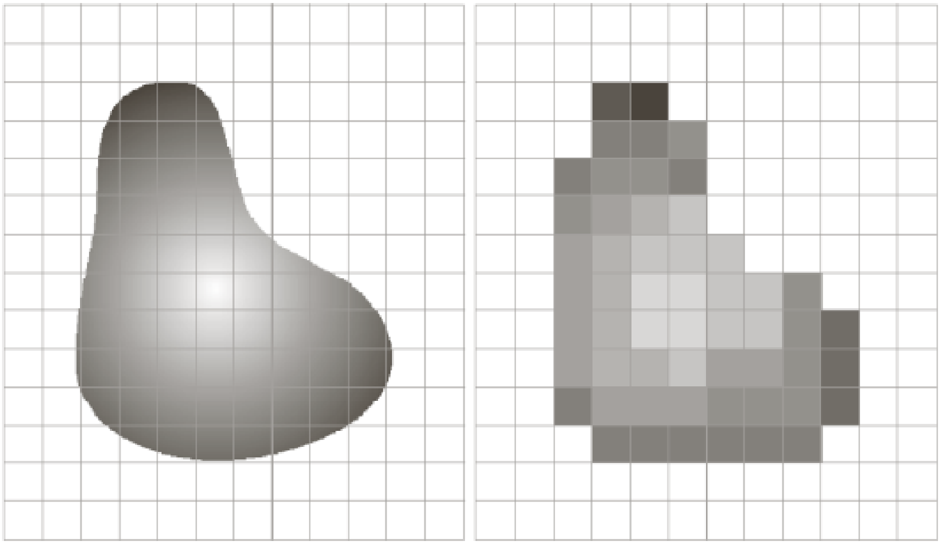
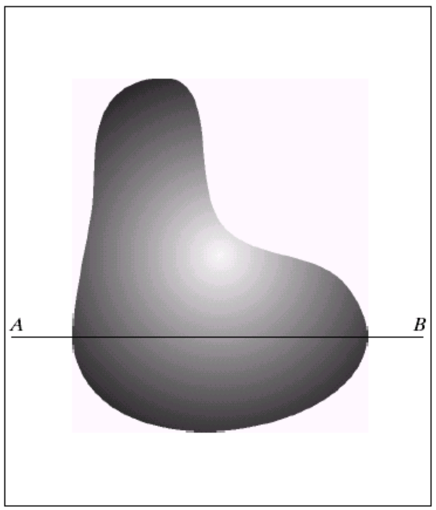
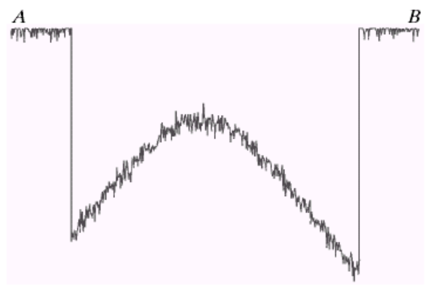
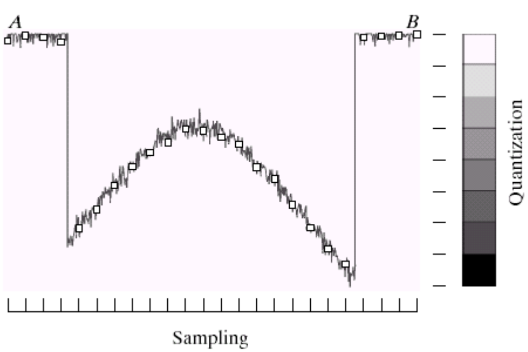


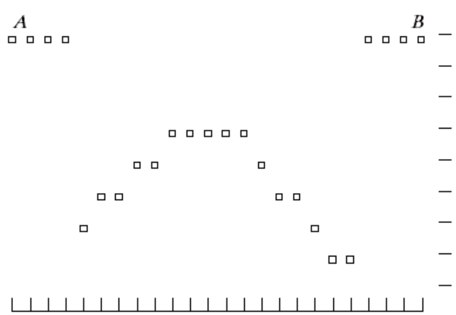
FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Image Sampling and Quantization









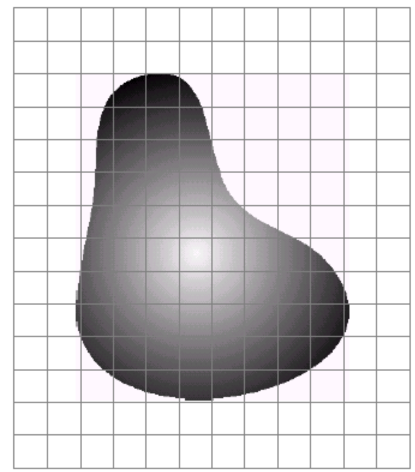
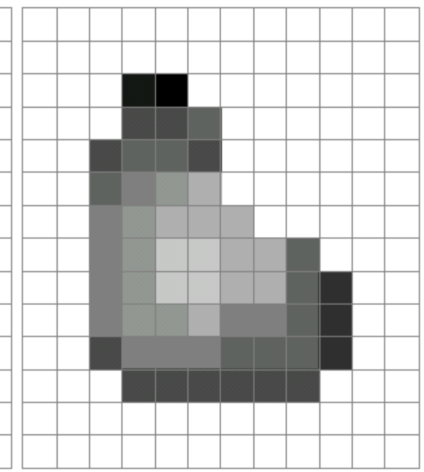
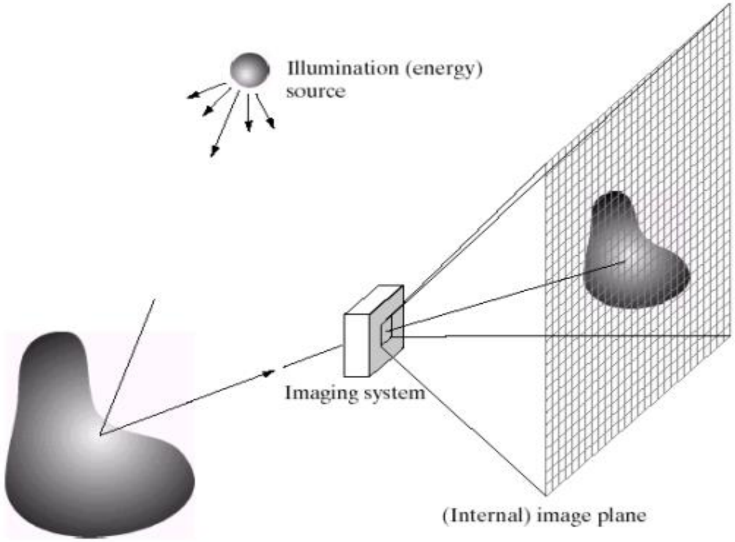


Image captured

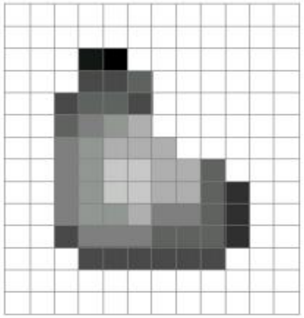


After sampling and quantization

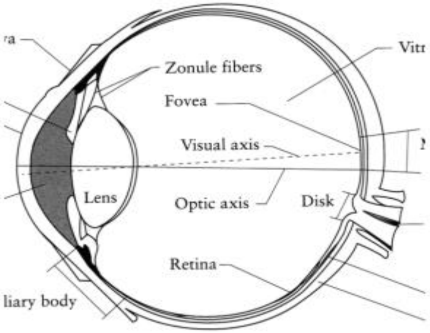
Image Formation



Film



Digital Camera



The Eye

Digital Camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - CMOS
  - http://electronics.howstuffworks.com/digital-camera.htm

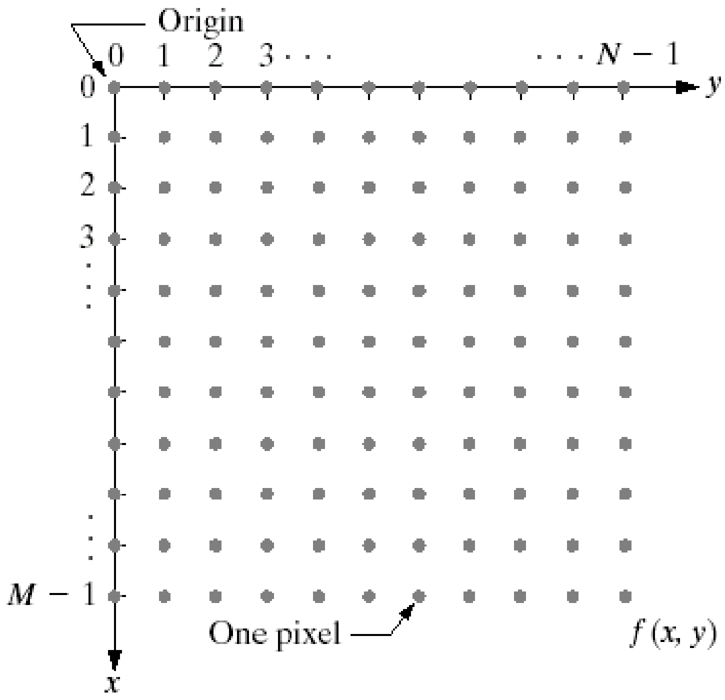
Representing digital images - Pixels

- Result of sampling and quantization = matrix of real numbers

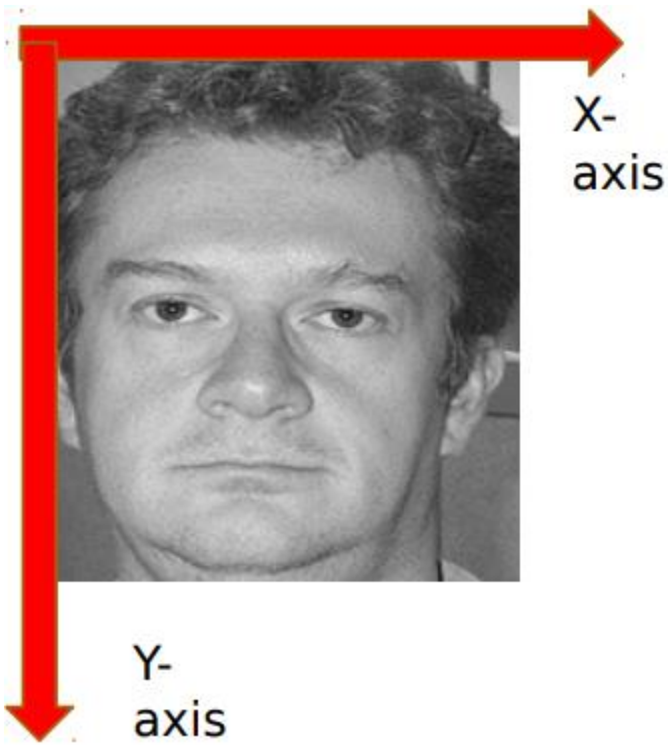
complete $M \times N$ digital image in the following compact matrix form:

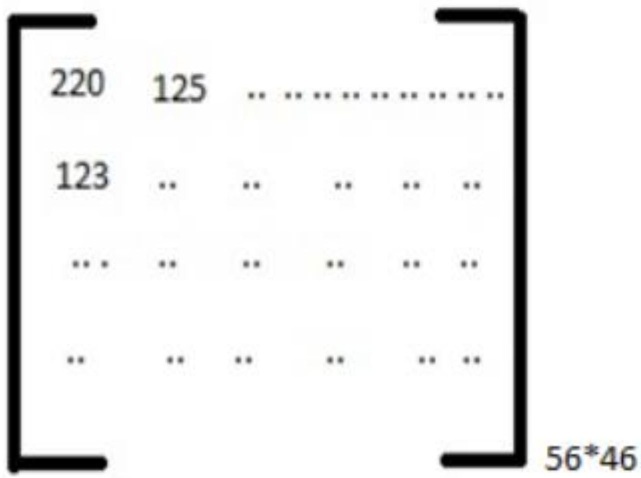
$$f(x, y) = \begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0, N-1) \\ f(1,0) & f(1,1) & \cdots & f(1, N-1) \\ \vdots & \vdots & & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1, N-1) \end{bmatrix}.$$

- Each element of this matrix is called an image element/ pixel element/ pixel or pel



What is an Image?





Types of Images

RGB Image

Grayscale Image

Binary Image

Grayscale Image Specification

- Each pixel value represents the brightness of the pixel. With 8-bit image, the pixel value of each pixel is 0 ~ 255
- Matrix representation: An image of MxN pixels is represented by an MxN array, each element being an unsigned integer of 8 bits

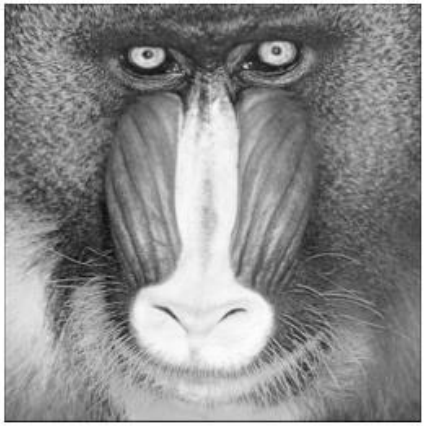
$$M = \begin{bmatrix} 160 & 162 & \cdots & 166 & 154 \\ 162 & 158 & \cdots & 122 & 69 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 60 & 55 & \cdots & 79 & 94 \\ 58 & 55 & \cdots & 99 & 109 \end{bmatrix}$$

Color Image Specification

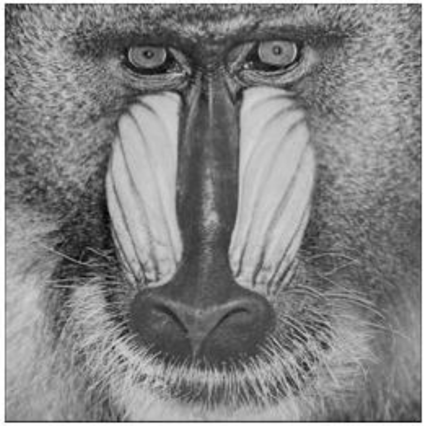
- Three components
  - M = {R, G, B}

$$R = \begin{bmatrix} 73 & \cdots & 87 \\ \vdots & \ddots & \vdots \\ 27 & \cdots & 17 \end{bmatrix}, G = \begin{bmatrix} 66 & \cdots & 98 \\ \vdots & \ddots & \vdots \\ 36 & \cdots & 13 \end{bmatrix}, B = \begin{bmatrix} 31 & \cdots & 61 \\ \vdots & \ddots & \vdots \\ 36 & \cdots & 14 \end{bmatrix}$$

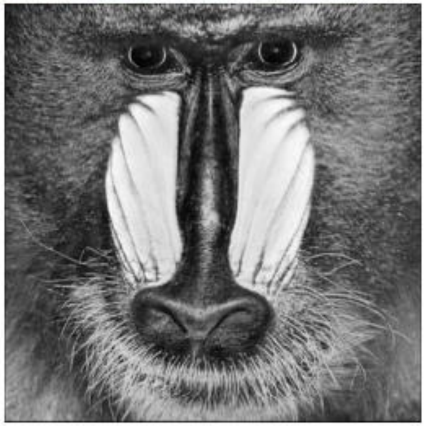
R



G



B



Red nose is brightest!

Blue Cheek is brightest

Representing digital images - Pixels

- Digitization process requires decisions about values of M, N and number of discrete gray levels L, for each pixel
- Number of gray levels: L = 2^k

- Number of bits, b, required to store a digitized image: b = M x N x k

References

- Most of the images and content in the PPT were taken from R. C. Gonzalez, R. E. Woods, Digital Image Processing, Addison Wesley, Pearson Publication, 4th Edition.

- Also images and videos in the PPT were taken from Coursera Course on "Fundamentals of Digital Image and Video Processing" by NorthWestern University and Coursera Course on 'Brain and Space' from Duke University

Thank you