Image Acquisition

CHUI Chee Kong, PhD
Control & Mechatronics Group
Mechanical Engineering, NUS

Contents

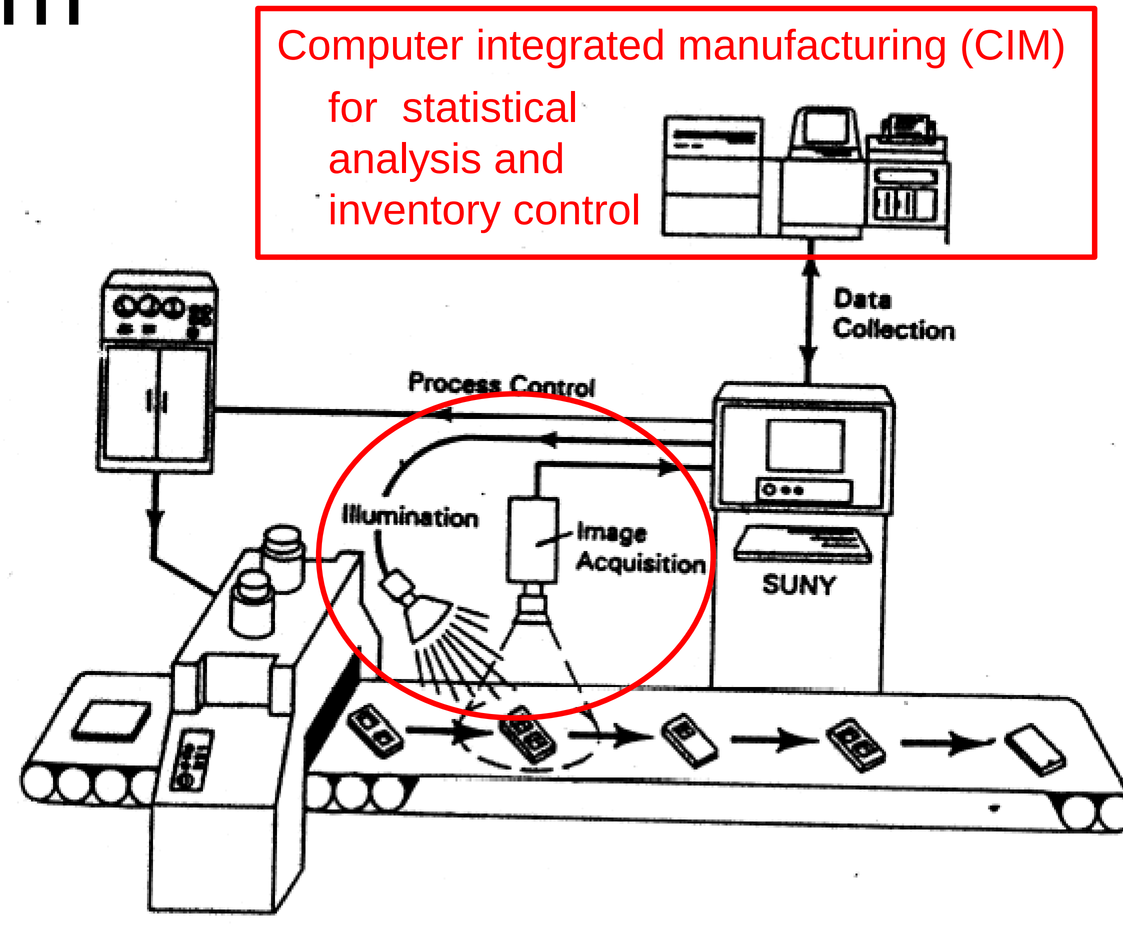
1. Overview of Machine Vision System

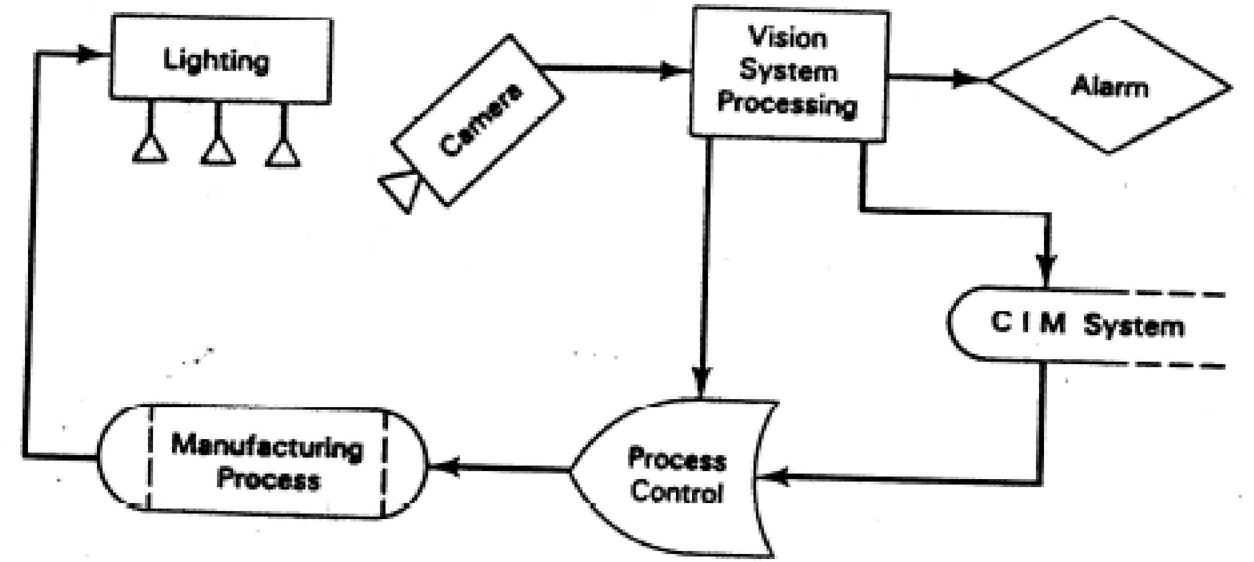
A machine vision system comprises of all necessary elements to obtain a digital representation of a visual image, to modify the data and to present the digital image data to external world.

- Three main functional components
  - Image acquisition
  - Processing
  - Output or display
    - The result is not necessarily another image.

Industrial Manufacturing Cell with Vision System

- Task: the vision system observes the object, determines if it is within specification, and generates command signals accordingly.
- <u>Image acquisition system: lights, camera and frame grabber.</u>
- Processing equipment
- Output equipment
- Control action





Processing equipment: hardware and software in the vision processing unit.

Output equipment: electronic interfacing the system to various parts of the process.

Control action: electronic signals control the unit, taking objects off the assembly line, and placing them in accept or reject containers, according to the quality.

Data is transmitted to the CIM system for statistical analysis and inventory control. When something goes wrong, an alarm will be actuated.

Image Acquisition

- The process to transform visual image of a physical object and its intrinsic characteristics into a set of digitized data which can be used by the processing unit of the system.
  - Lights (Illumination)
  - Camera
  - Frame Grabber

Four phases:
1. Illumination
2. Image formation or focusing
3. Image detection or sensing
4. Formatting camera output signal

2. Illumination

- Refers to the science of the application of lighting.
  - sources of lighting
  - design of lighting systems
- Aims to produce an effective environment for camera to see in the context of machine vision.

Illumination

- Key parameter, often limiting factor
- May require 30% of application effort
- Customized to each application effort
- Can produce effects beyond human vision (infrared, ultraviolet, X-rays, 3D information in a 2D image)
- Performance of fluorescent lamp varies
  - Regular monitoring

The fluorescent lamp output decreases as much as 15% during the first 100 hours and then continues to decrease everyday at a slower rate. The fluorescent lamps are brightest at 40ºC and are sensitive to the applied voltage.

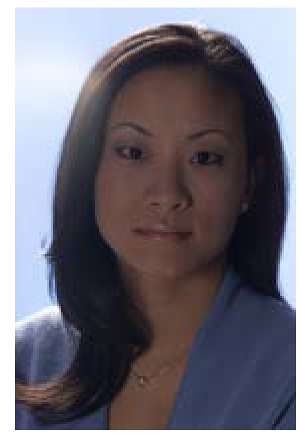
“When it comes to direction of lighting, there are 360 degrees of possibilities.”

Source: http://www.kodak.com/ek/US/en/Home_Main/Tips_Projects_Exchange/Learn/Photo_Tips_Techniques/Advanced_Techniques/Direction_of_light.htm

Top light (high front light, sunlight)

Front light

Side light



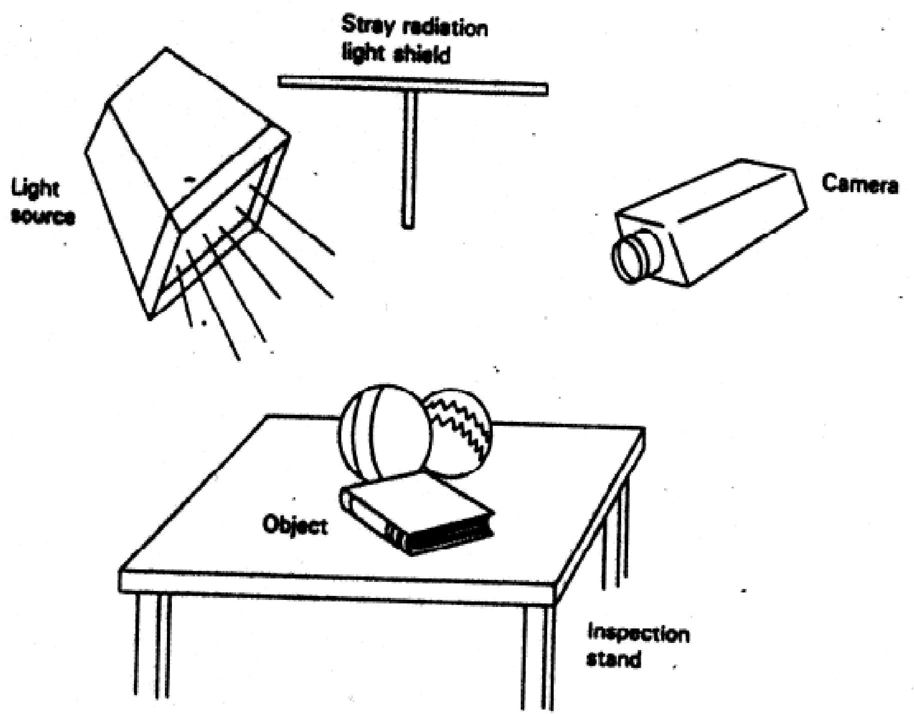
Back light

Principal kinds of lighting

- Front lighting: light source and camera on the same side relative to object
  - Useful to obtain surface texture, features and for dimensioning
- Back lighting: object between light source and camera
- Structured light: illuminating the object with a grid or regular stripes

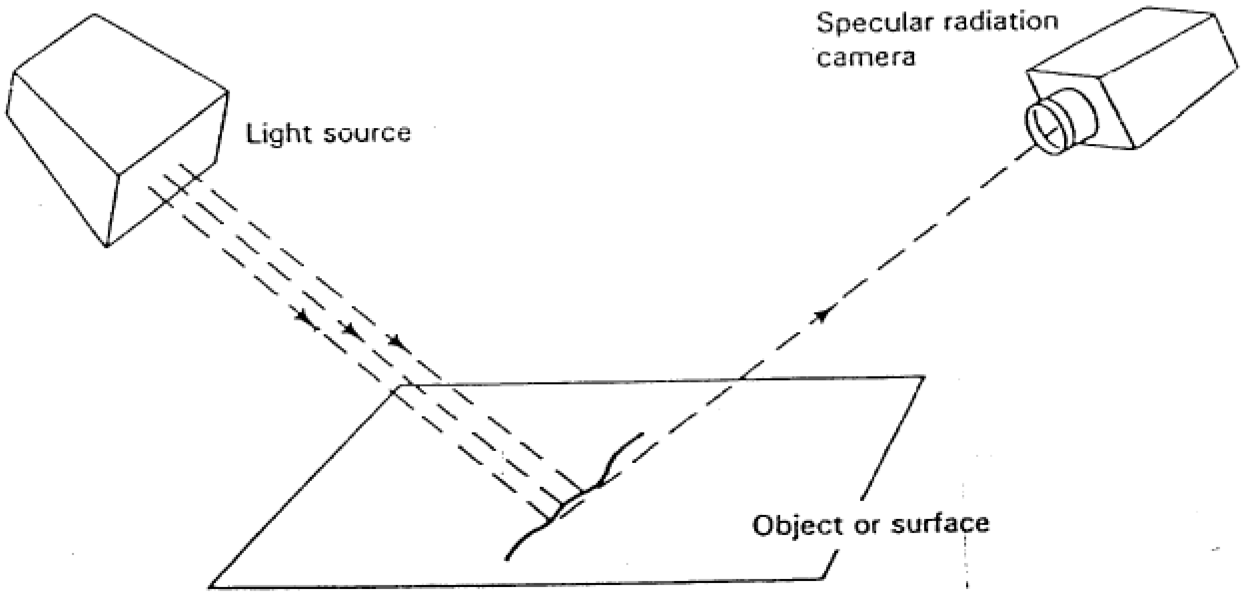
Front Lighting

Front lighting employs light reflected from the object. The illumination source and the camera are both on the same side of the object. It is useful to obtain surface texture of features as well as dimensioning.



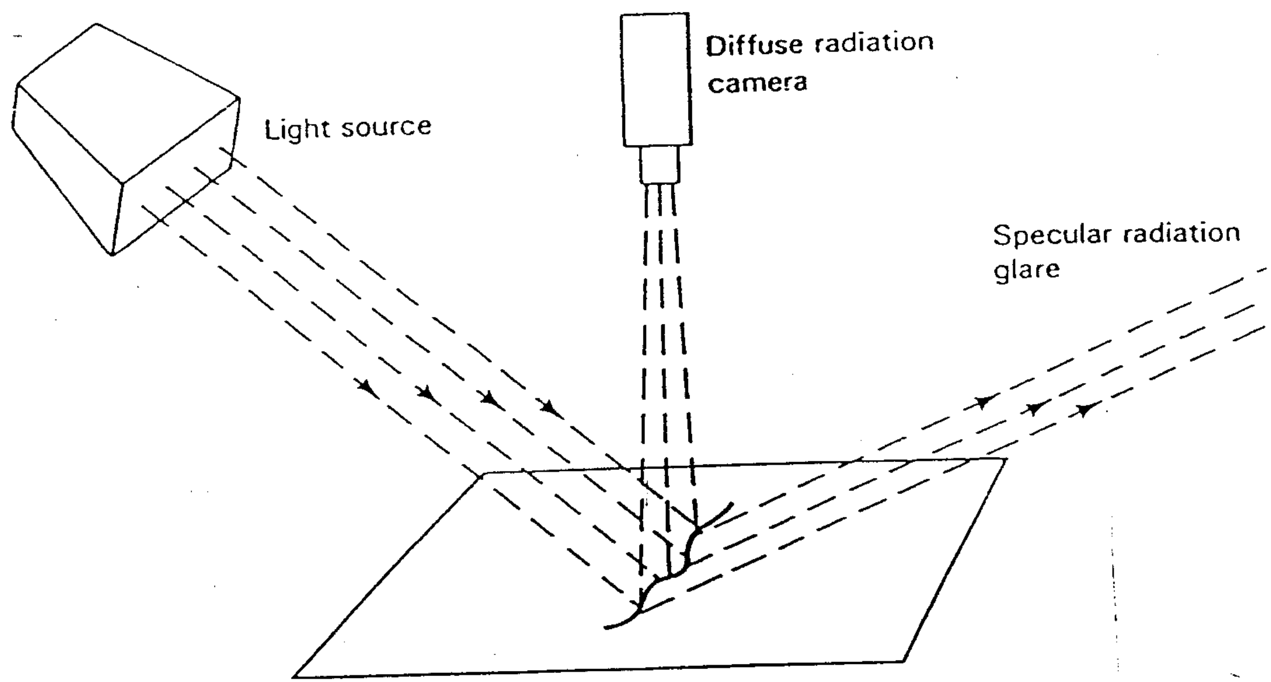
Front Lighting using Bright Field Illumination – Specular Measurement

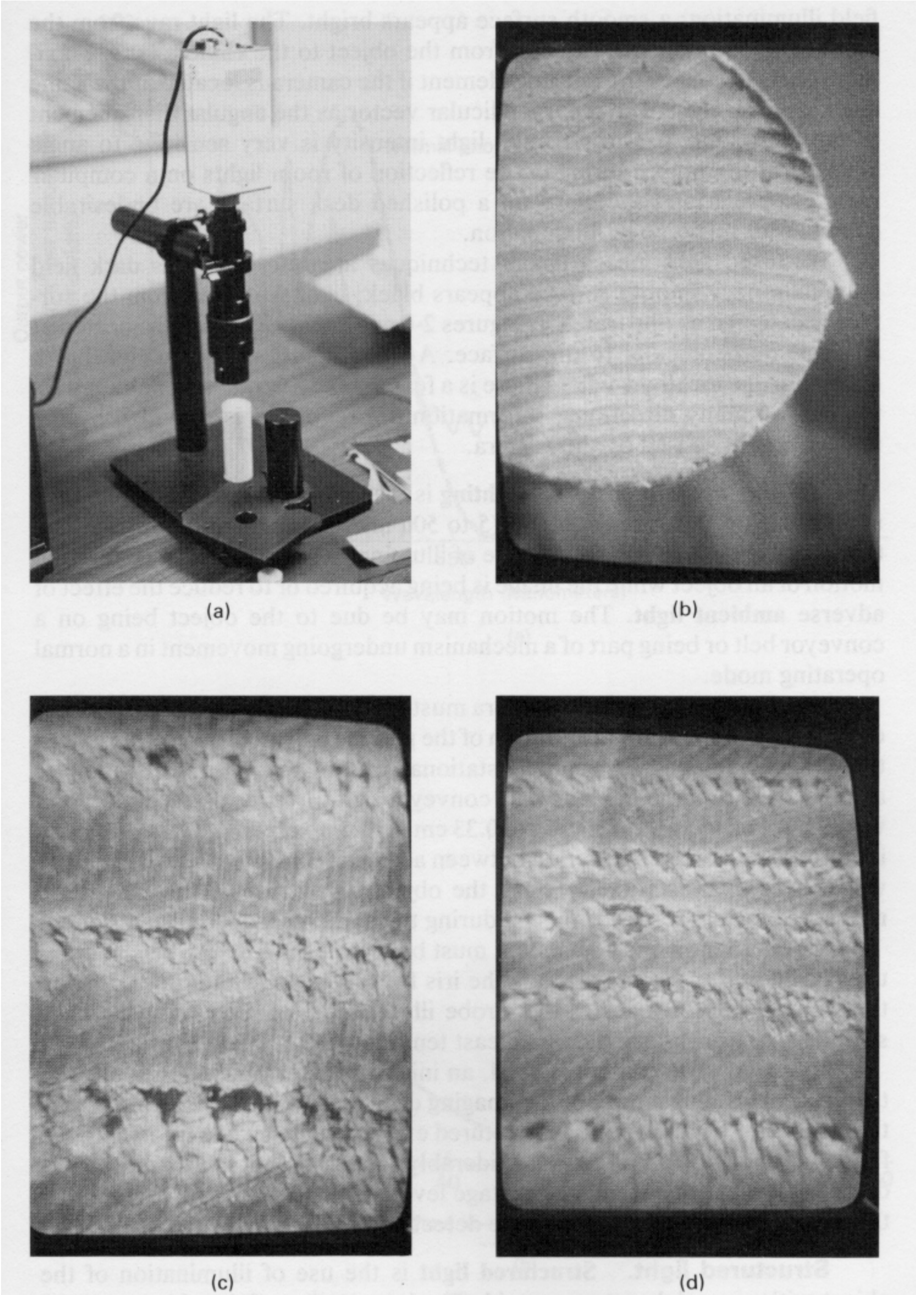
- Smooth surface are bright
- Light intensity sensitive to angle of the surface
- Defects appear as dark spots in a light field in image obtained with the camera



Front Lighting using Dark Field Illumination – Diffuse Light Measurement

- Measure diffuse light
- Smooth surfaces appear <u>dark</u>
- Light scattered from the surface is detected
- Defects show up as bright spots in a dark field in image obtained with the camera





Example of <u>Front Lighting using Dark Field Illumination</u>

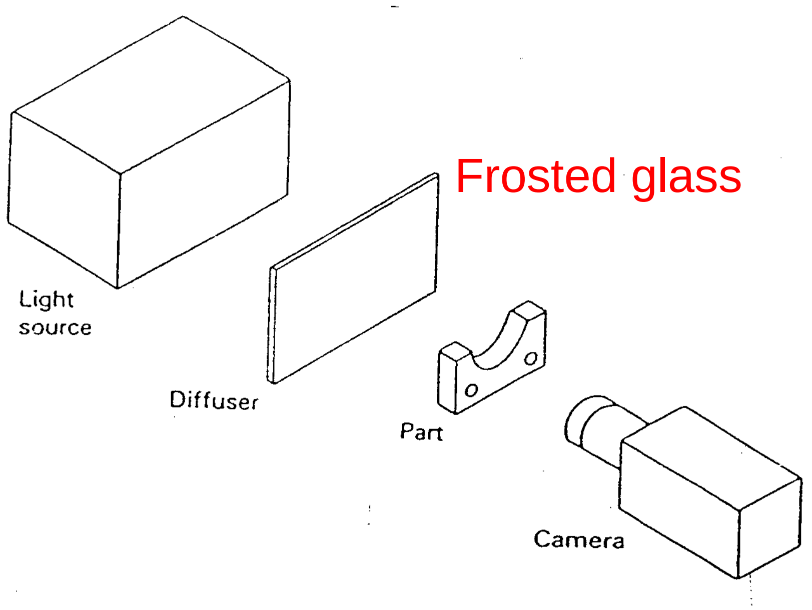
Light scattered from the surface is detected.

Information of the defects on the surface is provided by the scattered light.

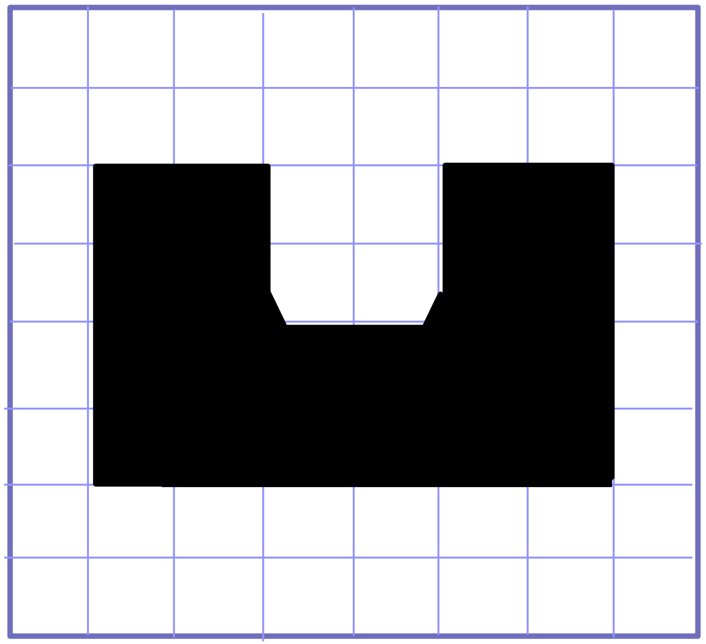
Back Lighting

- Create a silhouette of the object
- Often used to locate parts moving on a conveyer belt
- Ideal to detect foreign material and fracture in transparent objects

Back lighting is when an object is located between the light source and the camera.



Back Lighting (Continue)



Back-lighted object

15	15	15	15	15	15	15	15
15	15	15	15	15	15	15	15
15	1	0	15	15	0	1	15
15	1	0	10	10	0	1	15
15	1	0	0	0	0	1	15
15	1	0	0	0	0	1	15
15	1	1	1	1	1	1	15
15	15	15	15	15	15	15	15

Image data

Produces high contrast images, minimizes processing tasks and reduces the sensitivity of the system to illumination source variation.

Cannot be employed to obtain information on surface characteristics, or features not visible in silhouette like the presence of bolts in blind hole, and objects located on top of each other.

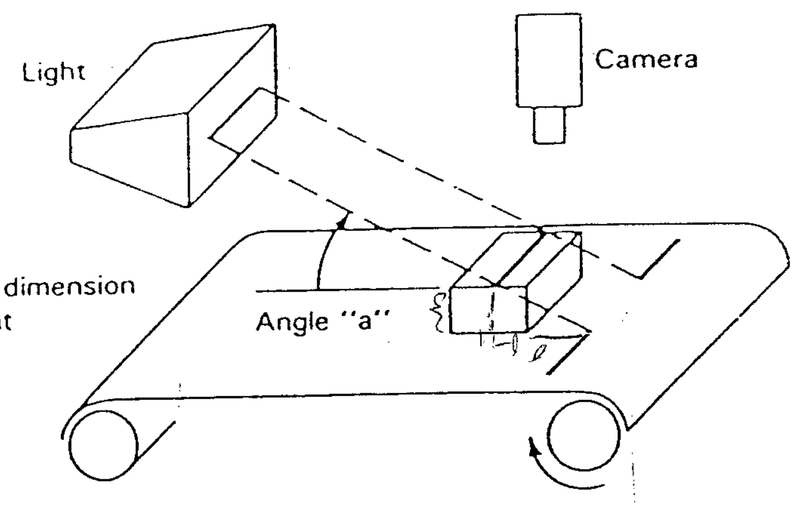
Structured Light

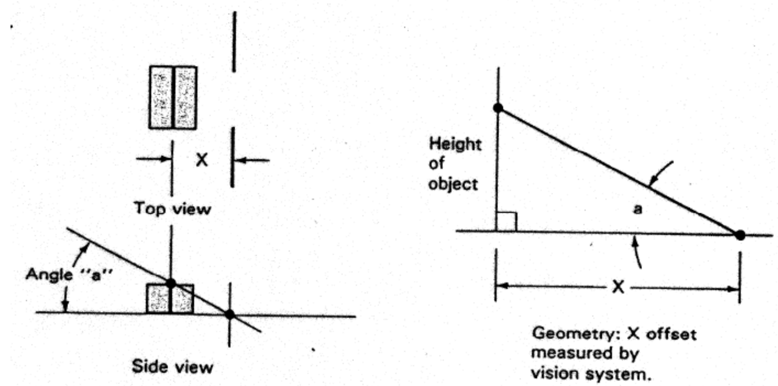
- 3D information in a 2D image
- Lighting angle and light structure (regular stripes, grids) depend on the application

Structured light is the use of the illumination of the object with a special pattern or grid. The intersection of the object and the projected illumination results in a unique pattern depending on the shape and dimensions of the object

A 3-D feature is converted to a 2-D image. Vertical and horizontal distances, as well as the shape of the surface features, can be measured.

Determining height dimension with structured light





Automated Inspection using Structured Light Scanning:
http://www.youtube.com/watch?v=lpxQBTrPBEg

3. Camera

- A camera is a device used to capture still images (photographs) or as sequences of moving images (movies or videos).
- Generally consists of
  - Lens system including an opening (aperture) at one end for light to enter.
  - Image capture for capturing the light at the other end.

Image Formation and Focusing
The image of the object is focused on the sensing element with a lens. The sensor converts the visual image to an electrical signal.

Image Detection
Image detection is done with by the image sensor of the camera. The basic concept of image sensors is that a separate electrical signal is produced for each pixel or area in the sensor depending on the amount of light energy falling on the device in each pixel area.

Camera (Continue)

- Most cameras use either CCD or CMOS photosensitive elements to capture image, both using photovoltaic principles. They capture brightness of a monochromatic image.
- A charge-coupled device (CCD) is a sensor for recording images, consisting of an integrated circuit containing an array of linked, or coupled, capacitors.
- Complementary metal-oxide semiconductor (CMOS) is a major class of integrated circuits.
- Photovoltaic principles: The energy of a photon from a light source causes an electron to leave its valence band and changes to a conduction band. The quantity of incoming photons affects macroscopic conductivity. The excited electron is a source of electric voltage which becomes electric current. The current is directly proportional to the amount of incoming energy (photons).

Camera (Continue)

- Cameras are equipped with necessary electronics to provide digitized images.
- Color cameras are similar to monochromatic ones and contain color filters.

3.1 CCD Camera

- CCD Camera is based on Charge Couple Device (CCD) technology.
- A CCD is an analog shift register consisting of a series of closely spaced capacitors.
  - It enables analog signals (electric charges) to be transported through successive stages (capacitors) controlled by a clock signal.
  - It is used to serialize parallel analog signals in arrays of photoelectric light sensors.
  - For image capturing, there is a photoactive region made of silicon and a transmission region which is the CCD.

CCD

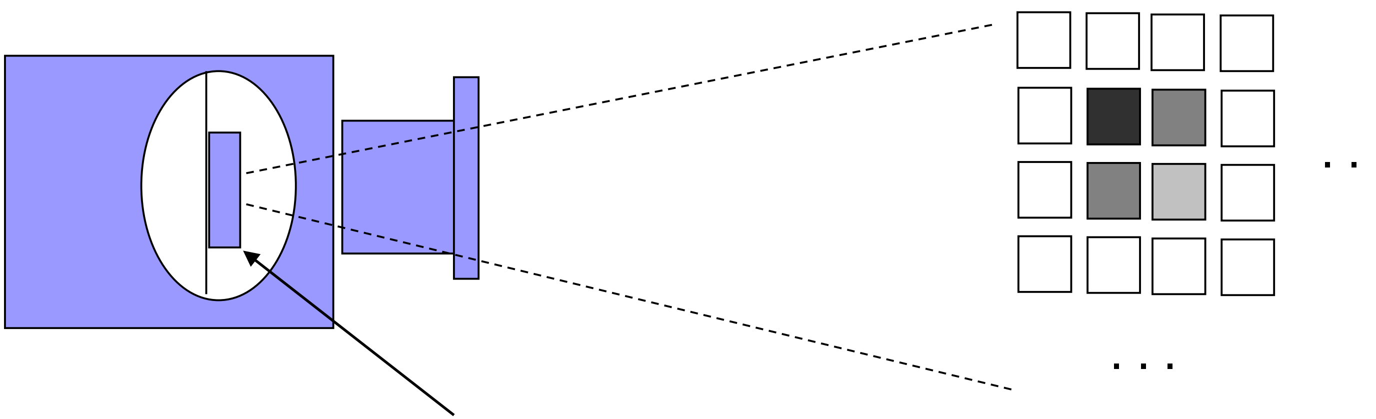
- History
  - Eugene Lally, Jet Propulsion Laboratory (1961): “Mosaic guidance for interplanetary travel” illustrated a mosaic array of optical detectors that formed a photographic image using digital processing.
  - Willard Boyle and George Smith, AT&T Bell Labs (1969): “Charge Bubble Devices”.
    - CCD could receive charge via the photoelectric effect.
    - Simple linear device to capture image.
  - Fairchild Semiconductor (1974): first commercial devices - linear 500 element device, 2D 100x100 pixel device.
  - Sony under the leadership of Kazuo Iwama first to mass produce CCD sensors for camcorders.

CCD (Continue)

- Basics of image capturing operation
  - Image is projected onto the capacitor array via the photoactive region. Each capacitor will accumulate an electric charge proportional to the light intensity at the location.
  - When the array of capacitor is completely exposed to the image (exposure time), a control circuit causes each capacitor to transfer its contents to its neighbor.
  - The last capacitor in the array moves its charge to a charge amplifier which converts the charge into a voltage.
  - By repeating this process, the control circuit converts the entire semiconductor contents of the array to a sequence of voltages that are sampled, digitized and stored in some form of memory.

CCD (Continue)

- Typical sensor size: 8.8 mm x 6.6 mm, almost 200,000 pixels



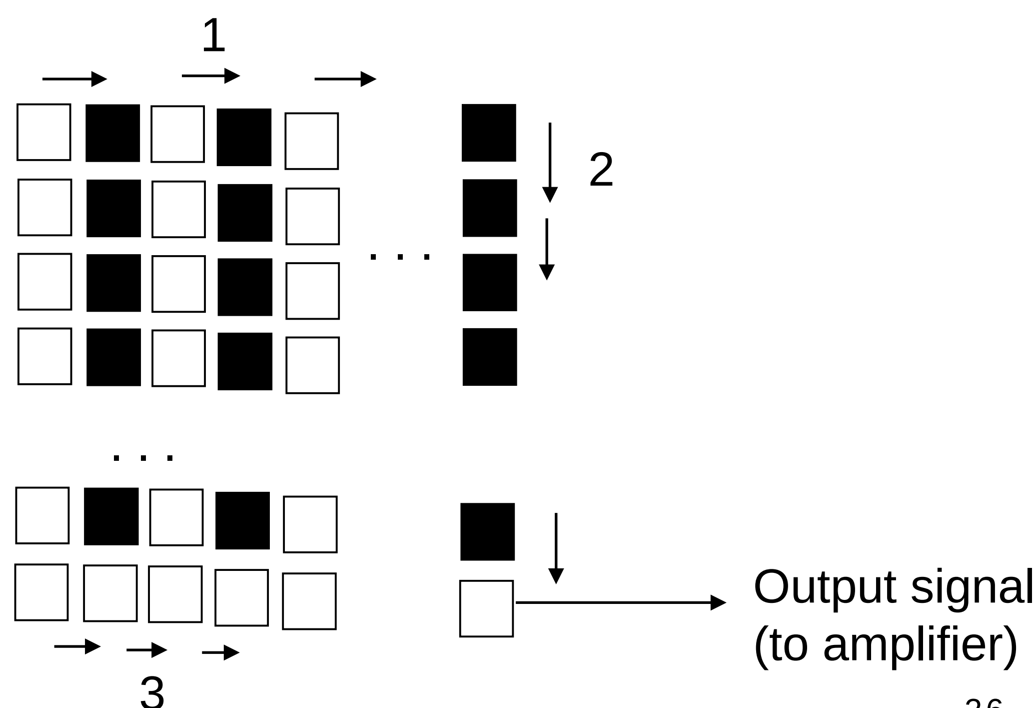
CCD sensor inside the camera

CCD (Continue)

- Two methods to read out the charges that are accumulated by the capacitors of the sensor
  - Interline transfer
  - frame transfer

Interline transfer:

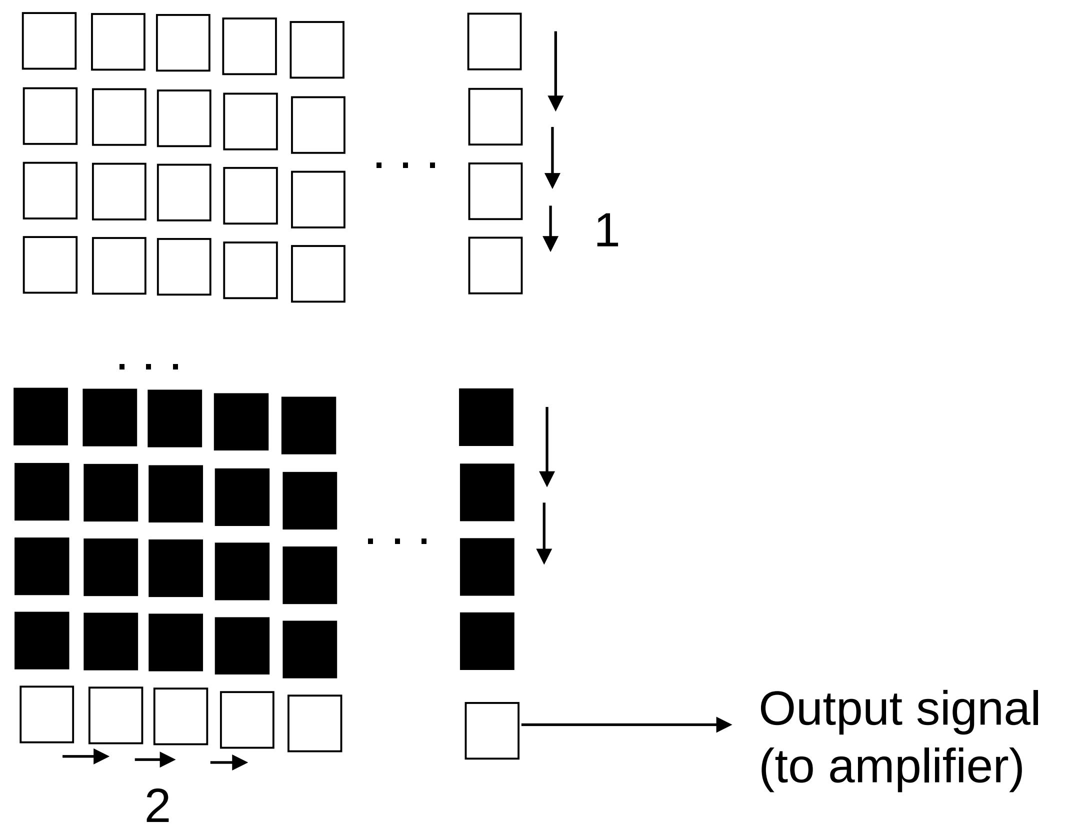
1. Charges are shifted to the shielded area.
2. The charges in the column are shifted down one cell.
3. A row of charge is then shifted out.



CCD (Continue)

Frame transfer:

1. All charges are shifted down to the shielded area.
2. Each row of charge is then shifted out.



- Other common CCD sensor: 512x256 array of photoreceptors
  - A device that detects light by capturing photons.
  - Photoreceptor = photodetector = photosensor
- Customized arrangement of the receptors possible, e.g. similar to human retina
- Low geometric distortion, price depends on the quality of the photoreceptors
- Pixel transfer rate up to 20 mega pixel per second
- Voltage signal digitalized (processing) or converted to signal (direct to monitor)

Formatting camera output signal

- NTSC color television standard and PAL (Phase Alternating Line) are most widely used color encoding system.

Monochromatic Camera

Charge amplifier – converts the charge into a voltage

Automatic gain control – changes the gain of the camera according to the amount of light in the scene. g correction performs non linear transformation of the intensity scale.

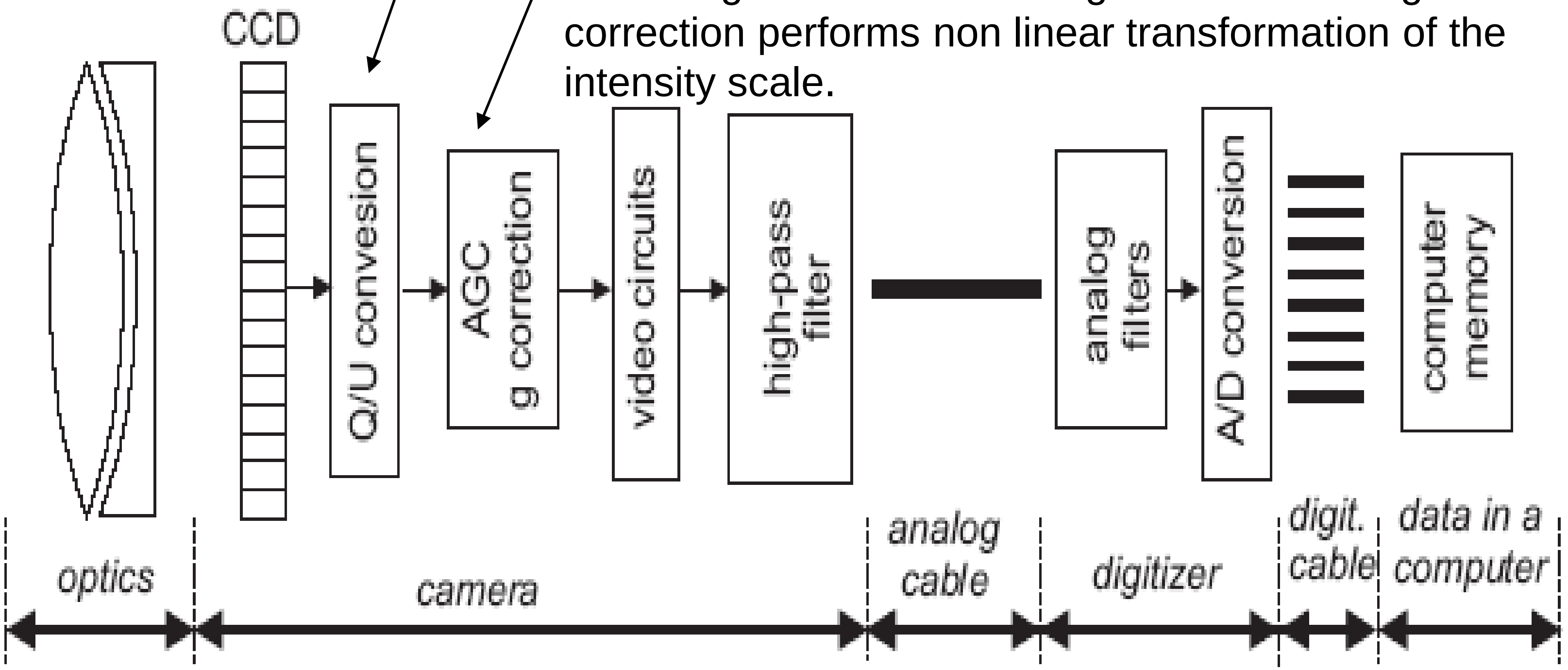


Figure 2.35: Analog CCD camera.

Monochromatic Camera (Continue)

Gamma correction or encoding of images is to compensate for properties of human vision – to ensure not too many bits are allocated for highlights that human cannot see and too few bits for shadow values that human are sensitive to.

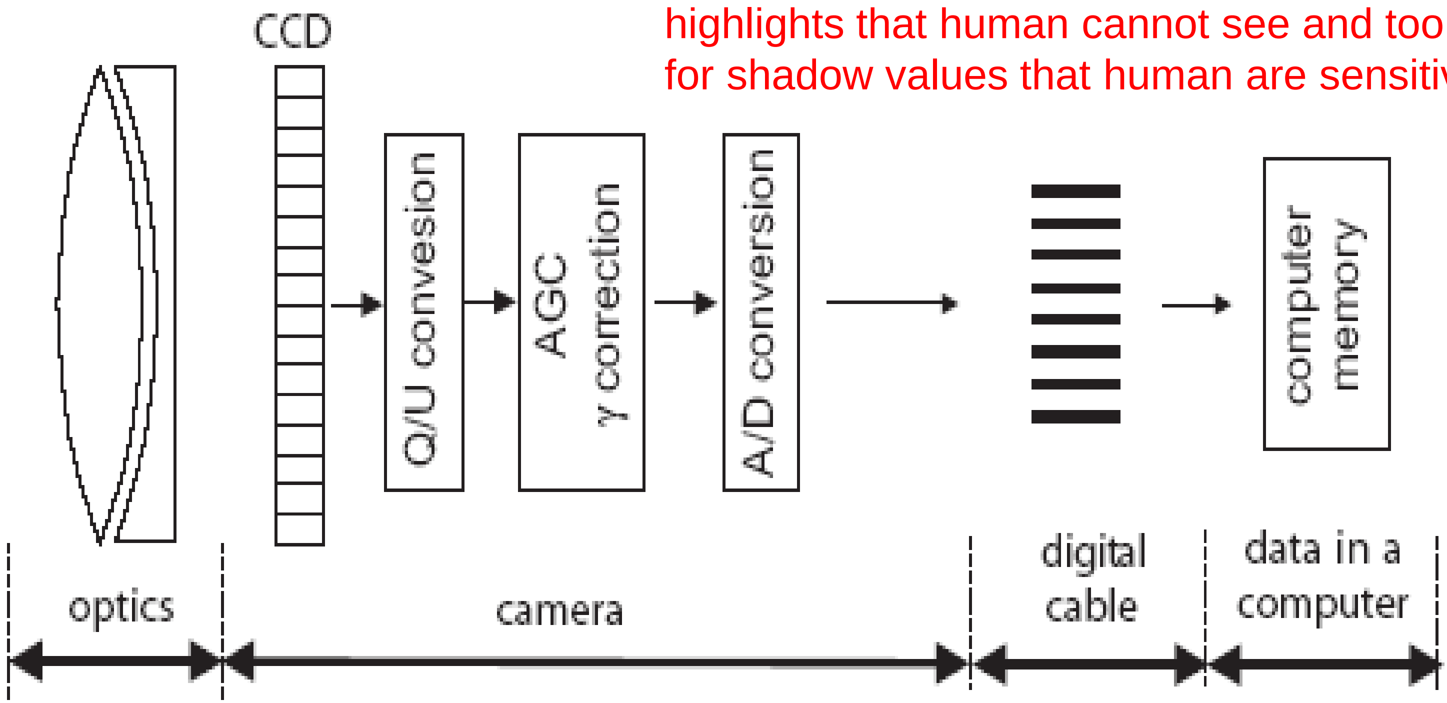


Figure 2.36: Digital CCD camera.

Monochromatic Camera (Continue)

	Analog cameras		Digital cameras
+	Cheap.	+	Cheap webcams. Dropping price for others.
+	Long cable possible (up to 300 m).	–	Shorter cable ($\approx$ 10 m for Firewire). Kilometers after conversion to optical cable. Any length for Internet cameras.
–	Multiple sampling of a signal.	+	Single sampling.
–	Noisy due to analog transmission.	+	No transmission noise.
–	Line jitter.	+	Lines are vertically aligned.

Color Camera

- Three strategies to capture color images:
  - Record three different images in succession by employing color filters in front of monochromatic camera.
    - Color sequential capture – switching colors with a color filter wheel.
  - Using a color filter array on a single sensor.
    - Integral color filter arrays (CFA) – filters of the appropriate characteristics of R,G and B are placed on the chip.
  - The incoming light is split into several color channels using a prism-like device.
    - Three-chips color – use optics to split the scene into three separate image planes and onto three CCD chips

Color Camera (Continue)

Integral color filter arrays

The property that human eye is most sensitive to green, less to red, and least to blue is used by the most common color filter for single chip camera.

G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G

Figure 2.37: Bayer filter mosaic for single chip color cameras.

3.2 CMOS Camera

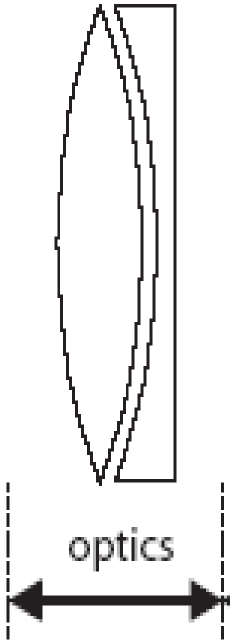
- CMOS camera system uses CMOS image sensors or CMOS active pixel sensor (APS). CMOS (Complementary metal-oxide-semiconductor) is a class of integrated circuit.
- An APS is an image sensor consisting of an integrated circuit containing an array of pixel sensors, each pixel containing a photodetector and an active amplifer.
- Most commonly used in mobile phone cameras and web cameras.

Smart Camera

- A smart camera is an integrated machine vision system which, in addition to image capture circuitry, includes a processor, which can extract information from images without need for an external processing unit, and interface devices used to make results available to other devices.
- It is an embedded system usually with CMOS image sensor.

4. Optics

- The science that describes the behavior and properties of light and the interaction of light with matter.
- The lens focuses the object's image on an array of photodiodes. The sensing elements convert the light to an electrical signal.
- Important optical parameters:
  - Magnification
  - Focal length
  - Depth of field



A lens can be defined as a refracting system consisting of at least two interfaces and at least one of which is curved.

Light

- Light is particles (photons)
  - When a particle moves, it processes momentum.
- Light is waves
  - When a wave propagates, it oscillates with a wavelength.

p : momentum

λ : wavelength

de Broglie relation : $\lambda = \dfrac{h}{p}$

Plank's constant $h \approx 6.62 \times 10^{-34}$ Joule – second

Each particle specified by frequency v,

has an energy $E = hv$.

In free space or vacuum, $v = \dfrac{c}{\lambda}$

$c \approx 3 \times 10^{8}$ m/s

In a transparent linear, homogeneous and isotropic material, the speed of light $v < c$.

Refractive index of the material, $n = c / v$

Light (Continue)

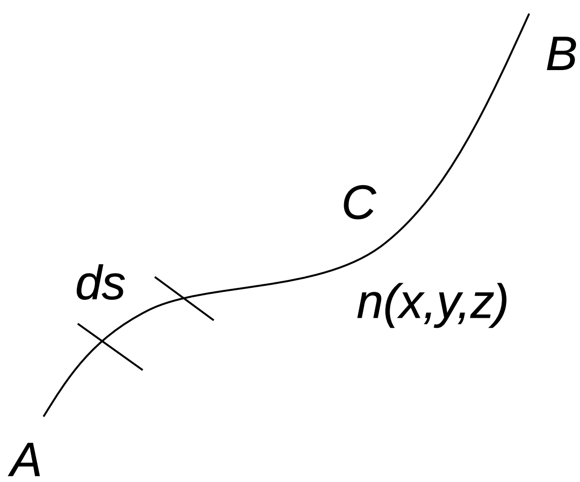
- We treat light as particles and the trajectory of these particles follows along paths (rays). Geometrical Optics
- An optical system consisting of elements such as lens and mirrors are described by tracing the rays through the system.

Fermat’s Principle

- The path of a light ray follows is an extremum in comparison with the nearby path.
- The extremum may be a minimum, a maximum or stationary with respect to variations in the ray path.
- Extremum is usually a minimum.

Fermat's Principle (Continue)

- Mathematical description



$$\delta(OPL) = \delta \int_C n(x, y, z) ds = 0$$

optical path length (OPL)

δ : a small variation

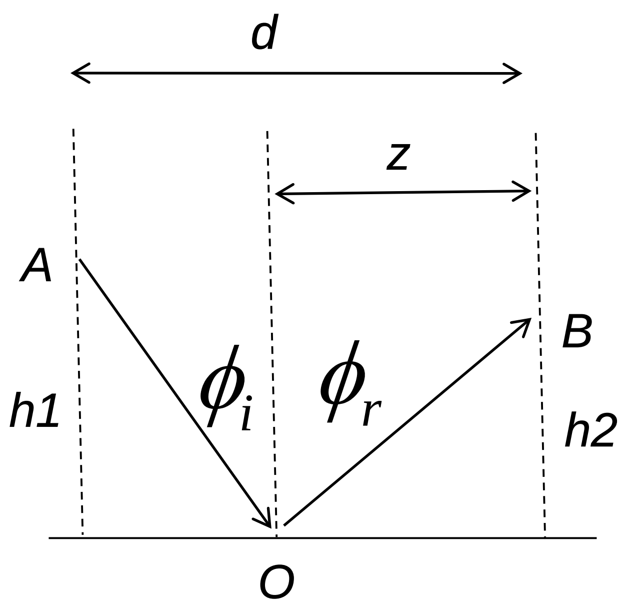
$n(x, y, z)$: position – dependent refractive index along a path C between points A and B

ds : an infinitesimal arc length

Fermat's Principle (Continue)

- A principle of least time
  - In a homogeneous medium – a medium with constant refractive index, the ray path is a straight line as the shortest OPL between the two end points is along a straight line which assumes the shortest time for the ray to travel.

Law of Reflection



Plane of incidence: incident ray, reflected ray and normal are in the same plane.

$$t = (AO + OB)/v$$

t: time required for light ray to travel the path

v: velocity of light in the medium

the medium is isotropic and homogeneous,

$$t(z) = \frac{1}{v}\left(\left[h_1^{\ 2} + (d-z)^2\right]^{0.5} + \left[h_2^{\ 2} + z^2\right]^{0.5}\right)$$

from least time principle,

$$\frac{dt(z)}{dz} = 0$$

$$\frac{d-z}{[h_1^{\ 2} + (d-z)^2]^{0.5}} = \frac{z}{[h_2^{\ 2} + z^2]^{0.5}}$$

$$\sin\phi_i = \sin\phi_r$$

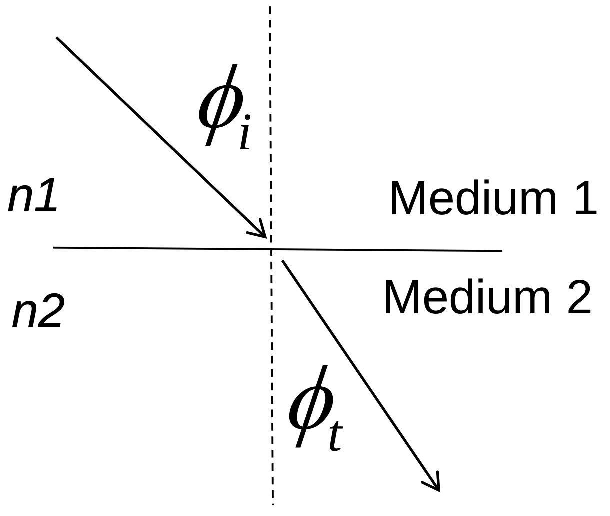
$$\phi_i = \phi_r$$

Law of Refraction

- When a ray passes from a medium of smaller refractive index into one with larger refractive index (optically denser medium), it bends toward the normal.
- If the ray travels into a medium with lower refractive index, it bends away from normal.
- At the critical angle, the refracted ray is bent away from the normal by exactly 90 degrees.
- Total internal reflection
  - Optical fiber uses principle of total reflection to guide light.

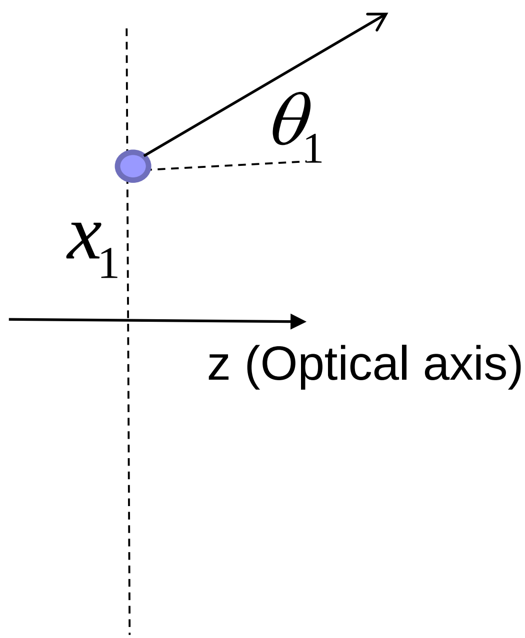
$$n_1 \sin\phi_i = n_2 \sin\phi_t$$

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



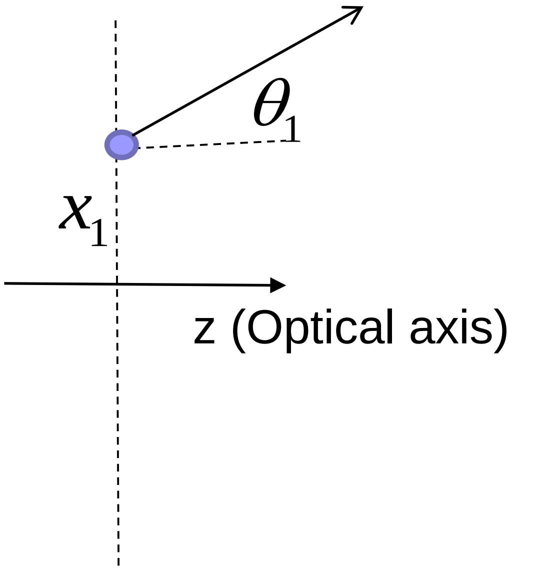
4.1 Paraxial Optics

- An optical system may comprise of a succession of spherical refraction and/or reflecting surfaces centered on the same axis – the optical axis.
- The optical axis can be taken as the z-axis which is the general direction in which the rays travel.
- Paraxial rays are rays that lie in the x-z plane and are close to the z-axis.
- A ray at a certain point along x-axis can be specified by its coordinates containing the position of the ray and direction.
- Matrices can be used to represent the operators on the ray.



The Ray Transfer Matrix

- Assuming that the rays lie in the xz plane and are close to z-axis.
- A ray can be specified by its height *x* from optical axis and by its angle *θ* (in radians and anti-clockwise positive) which it makes with the z-axis.
- The angle *θ* can be replaced by *v*=*n θ* where *n* is the refractive index at z-constant plane.

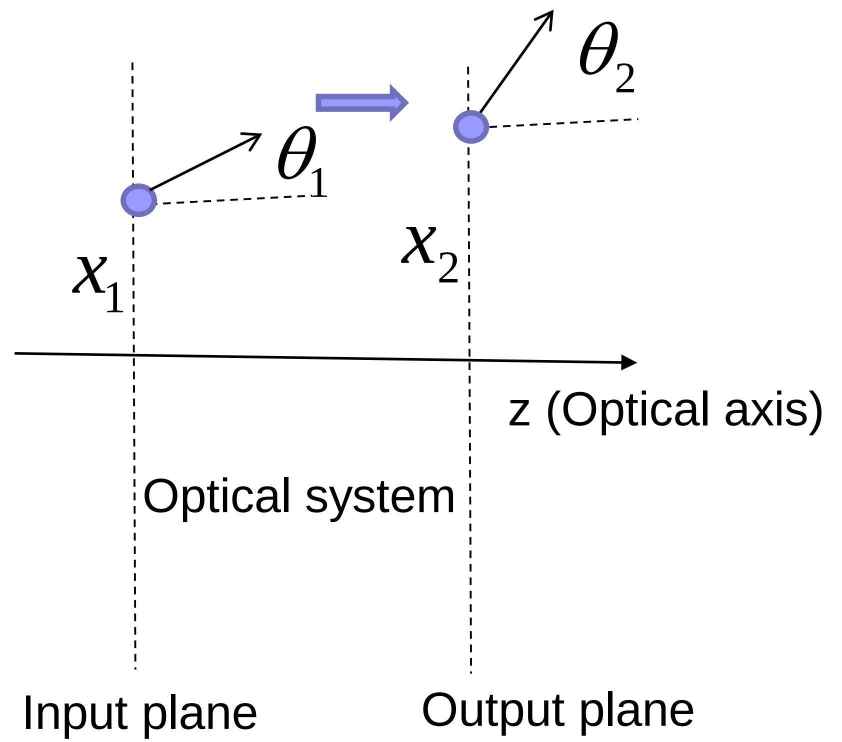


$$\begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix} \rightarrow \begin{pmatrix} x_1 \\ n\theta_1 \end{pmatrix} = \begin{pmatrix} x_1 \\ v_1 \end{pmatrix}$$

The Ray Transfer Matrix (Continue)

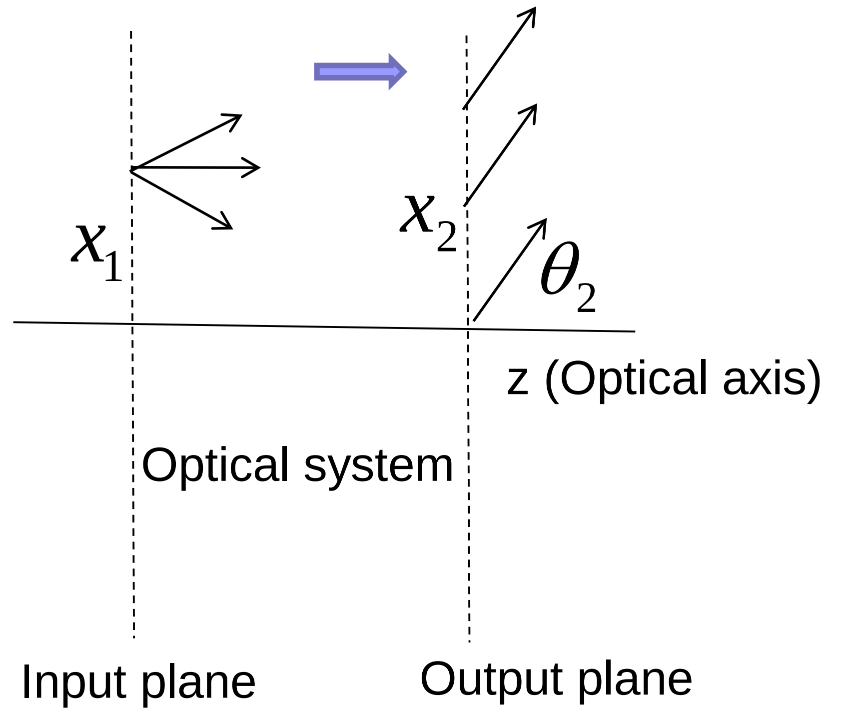
- ABCD matrix is called the ray transfer matrix.
- It can be made up of many matrices to account for the effect of a ray passing through various optical elements.

$$\begin{pmatrix} x_2 \\ v_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_1 \\ v_1 \end{pmatrix}$$



The Ray Transfer Matrix (Continue)

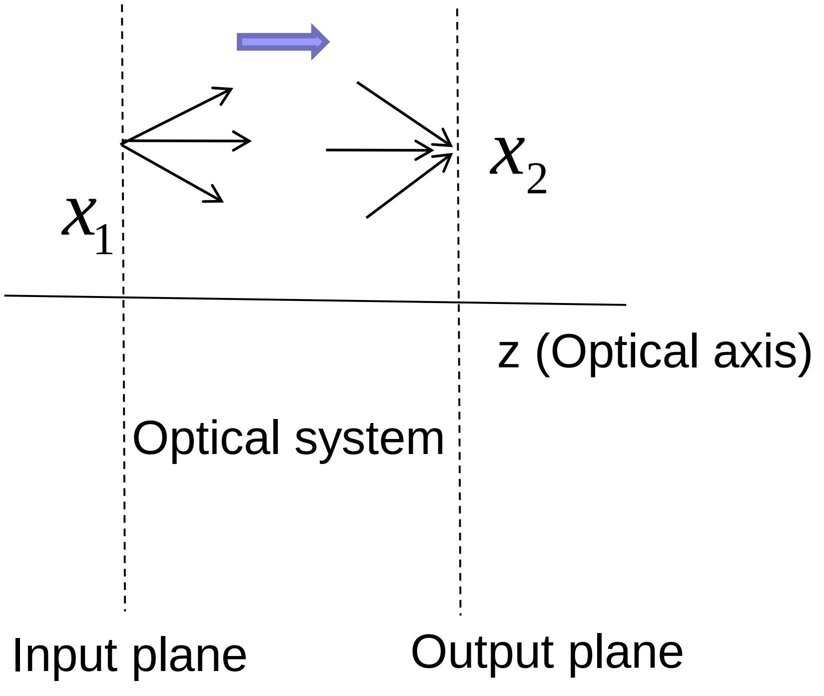
- D=0, v_2= Cx_1
  - All rays crossing the input plane at the same point x_1, emerge at the output plane making the same angle with z axis.
  - The input plane is front focal plane of the optical system.



The Ray Transfer Matrix (Continue)

- $B=0$, $x_2 = Ax_1$
  - All rays crossing the input plane at the same point x_1, pass through the same point x_2 in output plane.
  - The input and output planes are called the object and image planes.

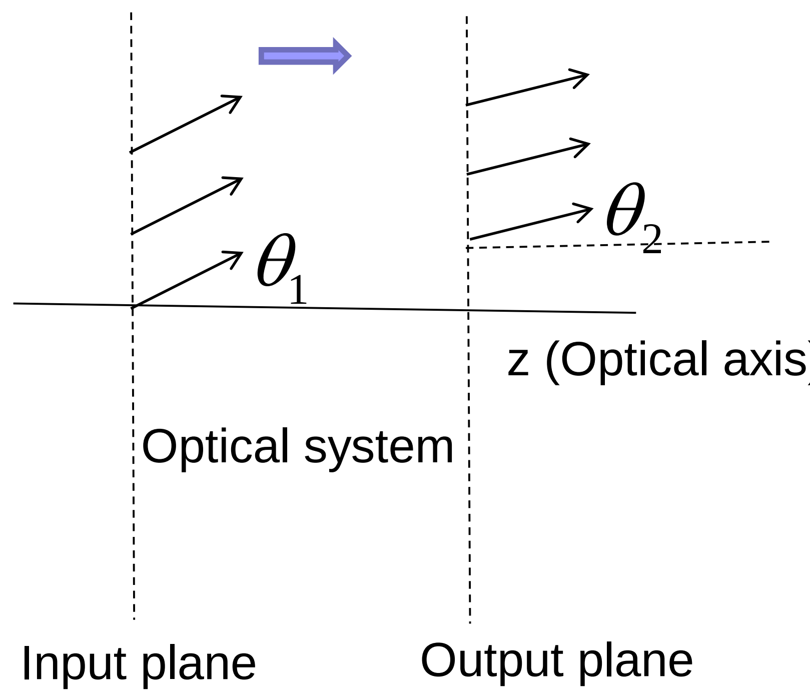
$$\boxed{\text{Magnification}: A = x_2 / x_1}$$



The Ray Transfer Matrix (Continue)

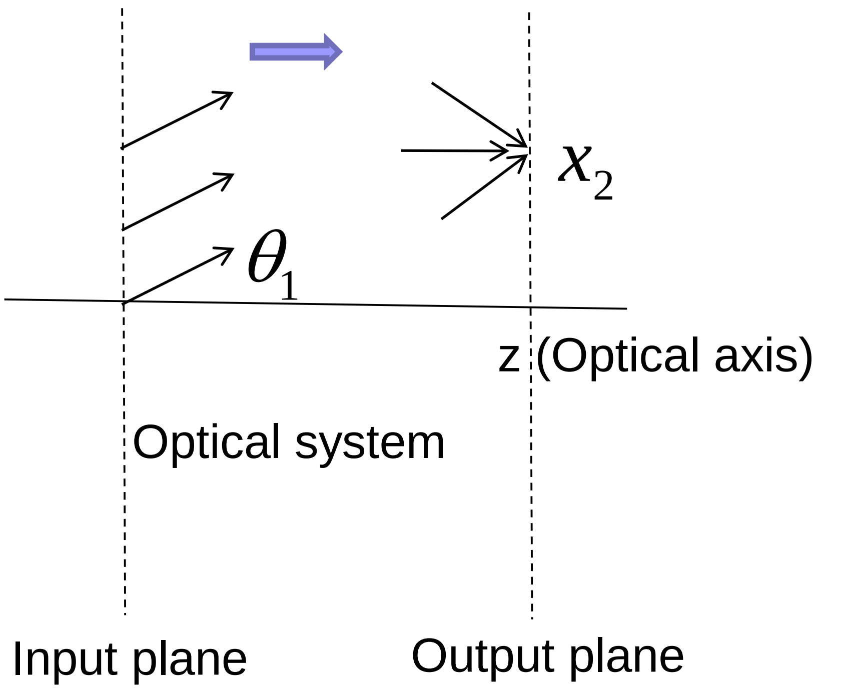
- C=0, v_2= Dv_1
  - All parallel rays entering the system will emerge parallel albeit in a new direction.

$$\boxed{\begin{array}{l}\text{Angular Magnification :}\\ D\left(n_1 / n_2\right) = \theta_2 / \theta_1\end{array}}$$



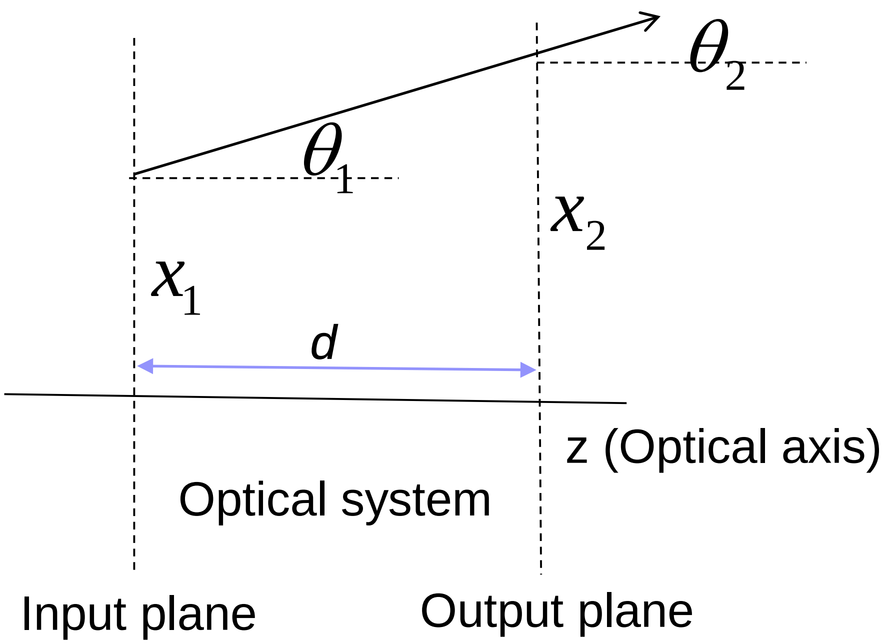
The Ray Transfer Matrix (Continue)

- $A=0$, $x_2 = Bv_1$
  - All rays entering the system at the same angle will pass through the same point at the output plane.
  - The output plane is the back focal plane of the system.
  - Intersection of the front focal and back focal planes with optical axis are front and back focal points.



Translation Matrix

- Assuming a ray travelling a horizontal distance *d* in a homogeneous medium of refractive index *n*.



$$x_2 = x_1 + d\tan\theta_1 = x_1 + d\theta_1$$

$$n\theta_2 = n\theta_1$$

$$v_2 = v_1$$

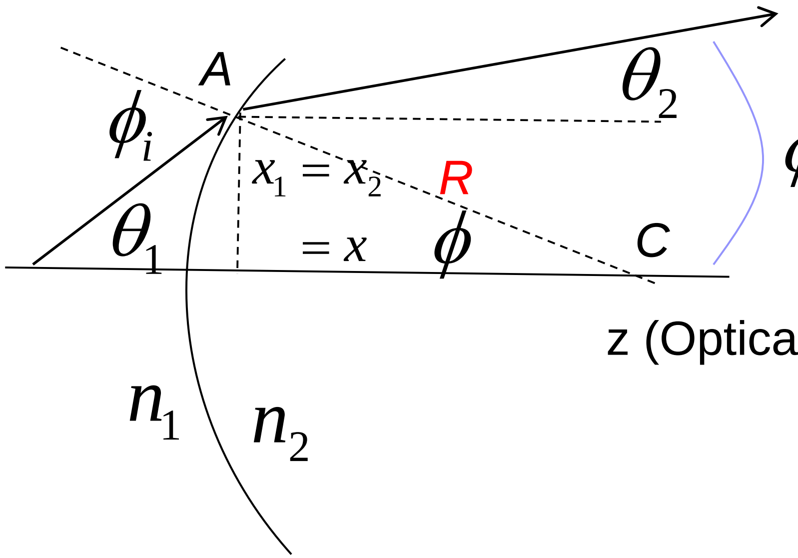
$$\begin{pmatrix} x_2 \\ v_2 \end{pmatrix} = \begin{pmatrix} 1 & d/n \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ v_1 \end{pmatrix}$$

$$T_d = \begin{pmatrix} 1 & d/n \\ 0 & 1 \end{pmatrix}$$

Refraction Matrix

- Consider a spherical surface separating two regions of refractive indices n_1 *and* n_2. Center of curved surface is *C* and radius of curvature is *R*.
- A ray strikes the surface at *A* and refracted. Φ_i is the angle of incidence and Φ_t is the angle of refraction.
- *x* is the height from *A* to optical axis.
- Radius of curvature is positive (negative) if center *C* lies to the right (left) of the surface.

Refraction Matrix (Continue)



$$\mathbf{R} = \begin{pmatrix} 1 & 0 \\ \dfrac{n_1 - n_2}{R} & 1 \end{pmatrix}$$

$\sin\phi \approx x / R \approx \phi$

Law of refraction : $n_1\phi_i = n_2\phi_t$

From geometry :

$n_1\phi_i = v_1 + n_1 x_1 / R,$

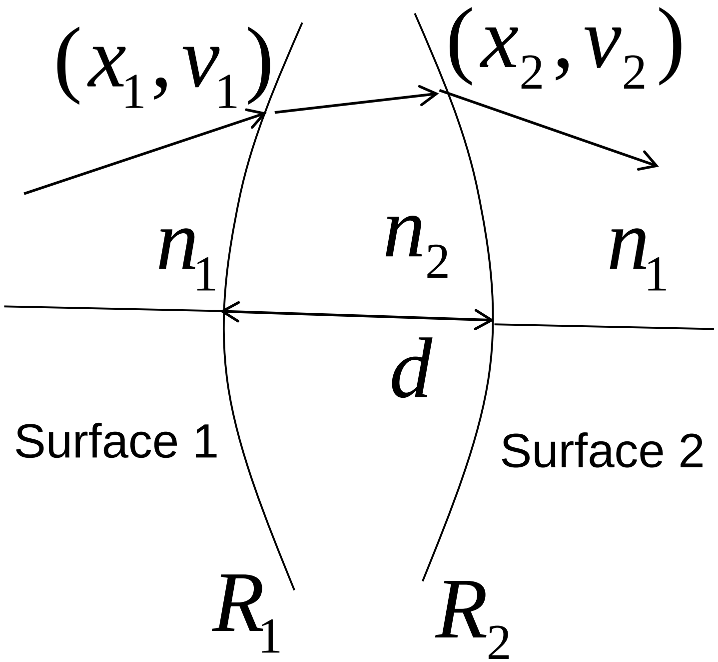
$n_2\phi_t = v_2 + n_2 x_2 / R.$

Since $x_1 = x_2, v_2 = \dfrac{n_1 - n_2}{R} x_1 + v_1$

$$\begin{pmatrix} x_2 \\ v_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -p & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ v_1 \end{pmatrix}$$

refracting power : $p = \dfrac{n_2 - n_1}{R}$

Thin-Lens Matrix



$\mathbf{S_f}$: thin – lens matrix

f : focal length

$$\begin{pmatrix} x_2 \\ v_2 \end{pmatrix} = \mathbf{S} \begin{pmatrix} x_1 \\ v_1 \end{pmatrix}$$

Thick lens

$$\mathbf{S} = \mathbf{R_2 T_d R_1} = \begin{pmatrix} 1 & 0 \\ \dfrac{n_2 - n_1}{R_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & d/n_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \dfrac{n_1 - n_2}{R_1} & 1 \end{pmatrix}$$

$d \to 0, n_1 = 1, n_2 = n$ Ideal thin lens in air

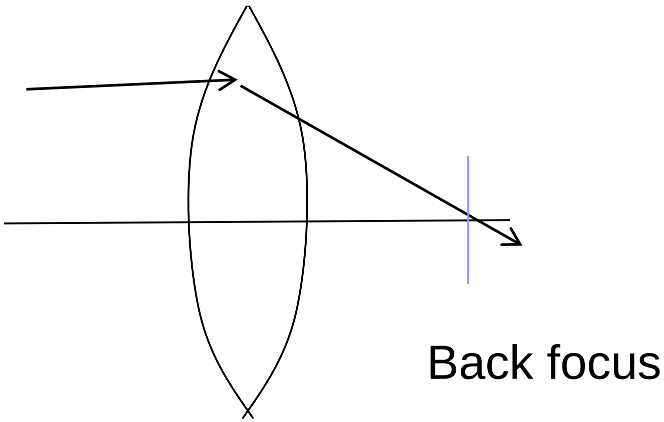
$$\mathbf{S} = \begin{pmatrix} 1 & 0 \\ -p_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -p_1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f_1 & 1 \end{pmatrix} = \mathbf{S_f}$$

$$p_1 = \frac{n-1}{R_1}, \quad p_2 = \frac{1-n}{R_2}$$

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

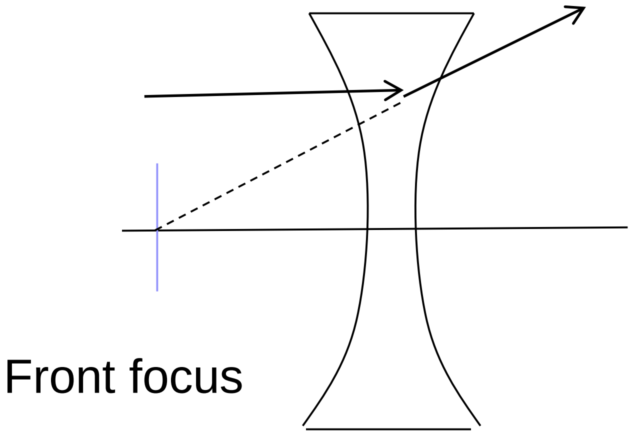
Thin-Lens Matrix (Continue)

- Ray travelling parallel to optical axis



$\boxed{R_1 > 0 \quad \text{and} \quad R_2 < 0,\ f > 0}$

Converging (convex) lens

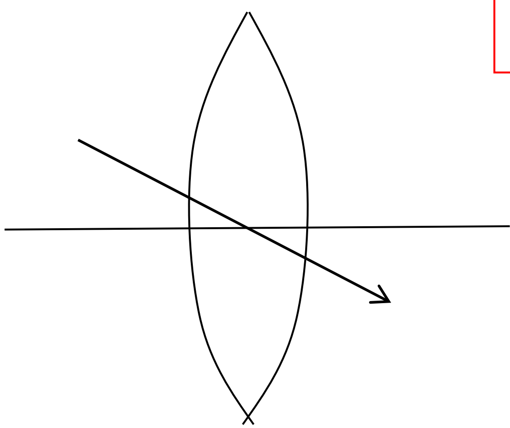


$\boxed{R_1 < 0 \quad \text{and} \quad R_2 > 0,\ f < 0}$

Diverging (concave) lens

Thin-Lens Matrix (Continue)

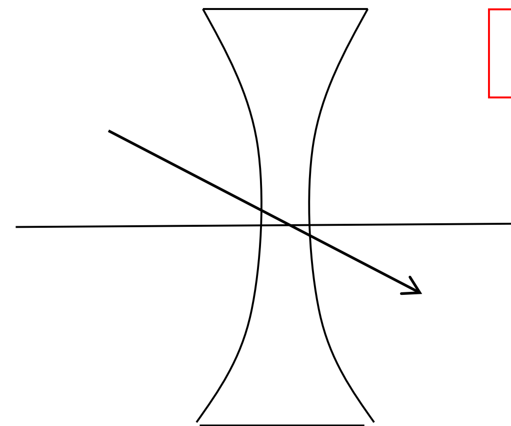
- Ray travelling through the lens center



$f > 0$

$$\boxed{\begin{array}{c}\text{input ray coordinate} = \text{output ray coordinate} \\ = (0, v_1)\end{array}}$$

Converging (convex) lens



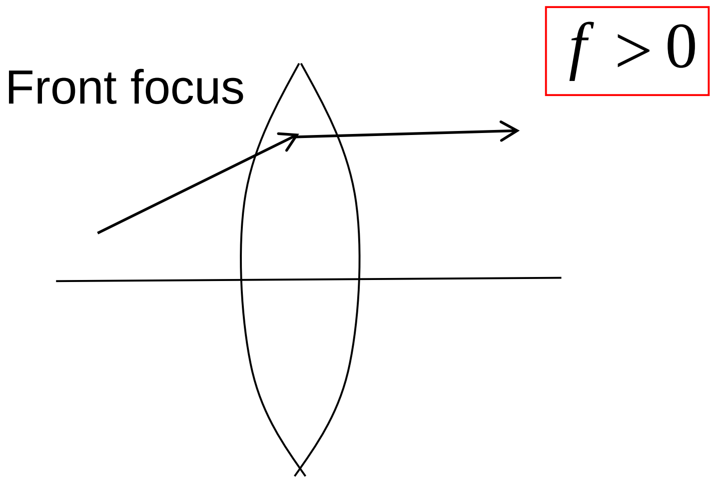
$f < 0$

$$\boxed{\begin{array}{c}\text{input ray coordinate} = \text{output ray coordinate} \\ = (0, v_1)\end{array}}$$

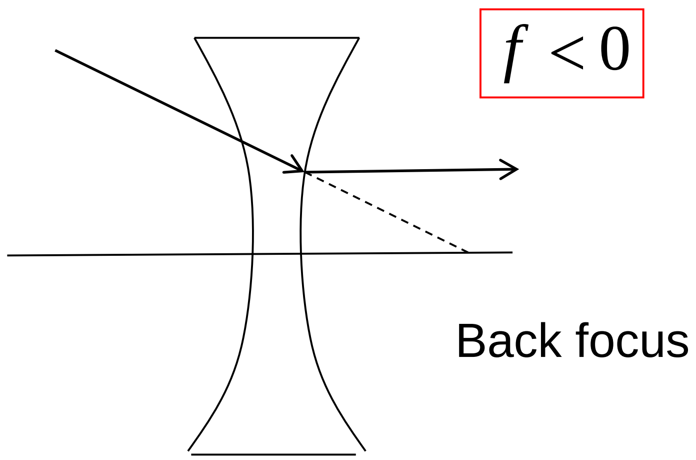
Diverging (concave) lens

Thin-Lens Matrix (Continue)

- Rays passing through the front focus of convex lens and back focus of concave lens



Converging (convex) lens

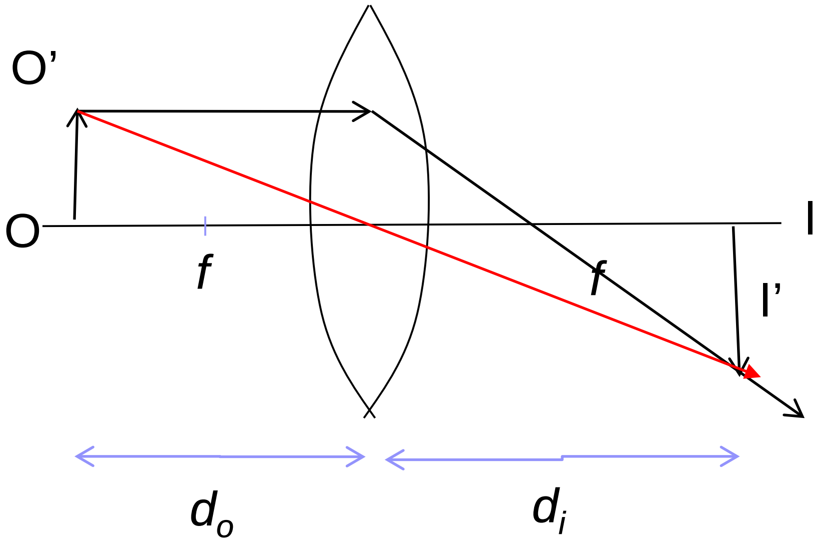


Diverging (concave) lens

Imaging by a single thin lens

- Consider an object OO' located at a distance d_o in front of a thin lens with focal length f. Assuming that an input ray originally from point O', travelling in air towards the lens. The output ray coordinate at a distance d_i behind the lens can be written in terms of input ray coordinates, two translation matrices for air and the thin lens matrix.

Imaging by a single thin lens (Continue)



$$\begin{pmatrix} x_i \\ v_i \end{pmatrix} = \mathbf{T_{d_i} S_f T_{d_o}} \begin{pmatrix} x_o \\ v_o \end{pmatrix}$$

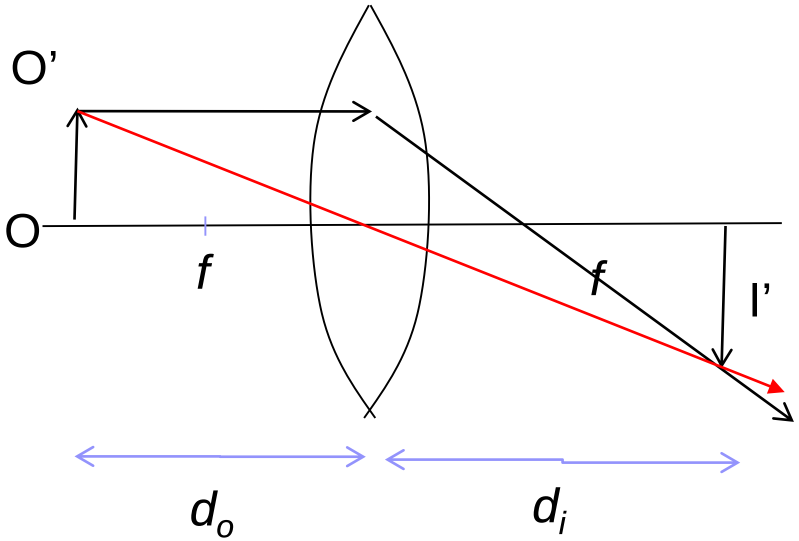
$$= \begin{pmatrix} 1 & d_i \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & d_o \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_o \\ v_o \end{pmatrix}$$

$$= \begin{pmatrix} 1 - d_i/f & d_o + d_i - d_o d_i/f \\ -1/f & 1 - d_o/f \end{pmatrix} \begin{pmatrix} x_o \\ v_o \end{pmatrix}$$

$$= \mathbf{S} \begin{pmatrix} x_o \\ v_o \end{pmatrix}$$

S is the optical system or system matrix. It is a ray transfer matrix.

Imaging by a single thin lens (Continue)



By setting $d_o + d_i - d_o d_i / f = 0$,

thin – lens formula : $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

$$\begin{pmatrix} x_i \\ v_i \end{pmatrix} = \begin{pmatrix} 1 - d_i / f & 0 \\ -1/f & 1 - d_0 / f \end{pmatrix} \begin{pmatrix} x_o \\ v_o \end{pmatrix}$$

$$\frac{x_i}{x_o} = M = 1 - \frac{d_i}{f} = \frac{f - d_i}{f} = \frac{f}{f - d_o} = -\frac{d_i}{d_o}$$

Lateral magnification :

$M > 0 \rightarrow$ erect image

$M < 0 \rightarrow$ inverted image

4.2 Aperture and Focal Point

- An aperture is an opening through which light is admitted.
- Focal point is a point onto which collimated light parallel to the axis is focused.
  - Collimated light is light whose rays are nearly parallel.

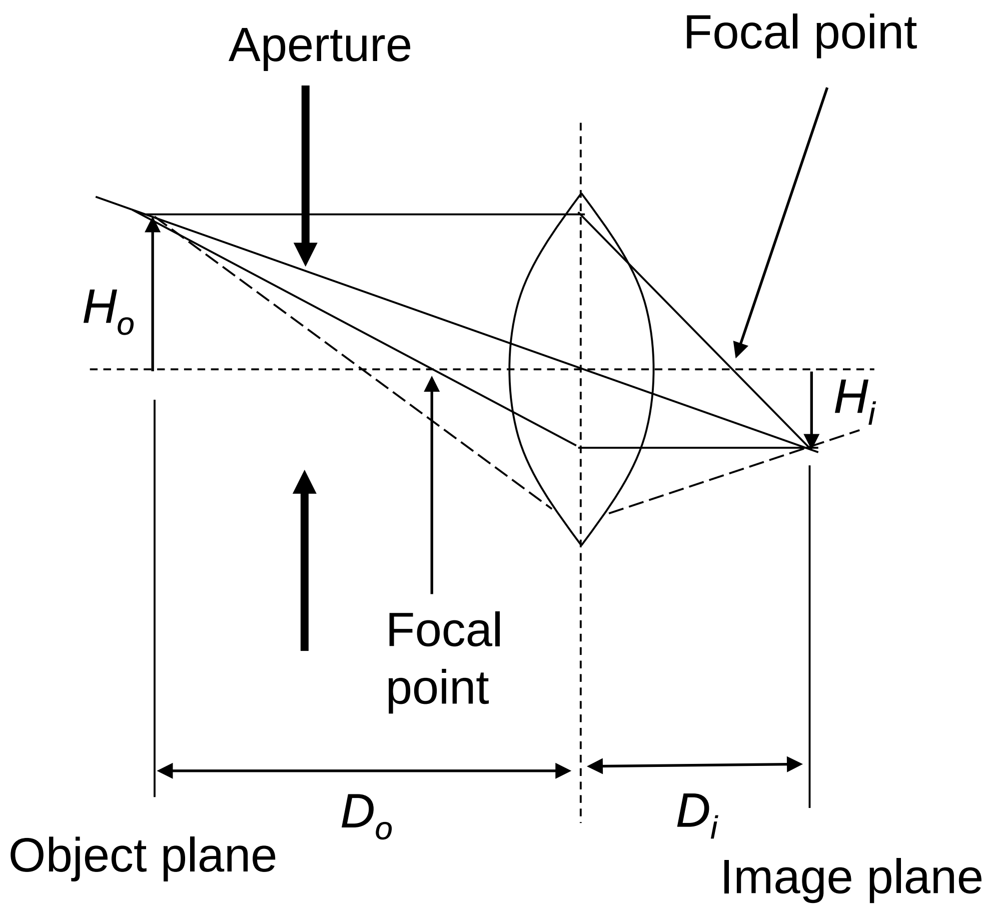
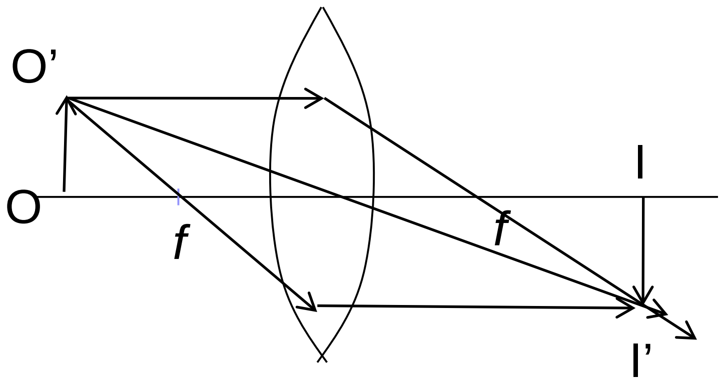
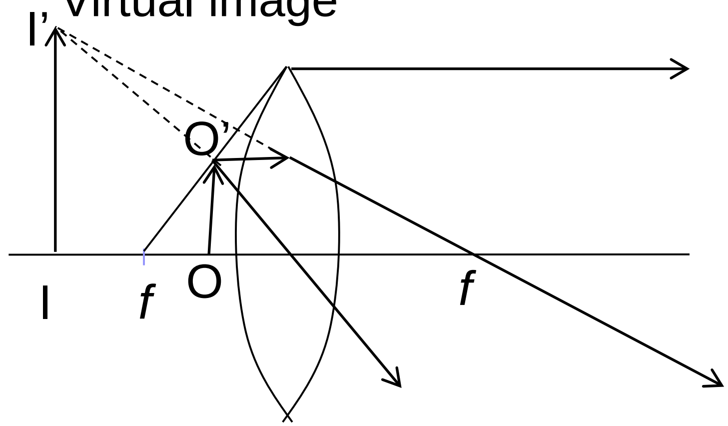


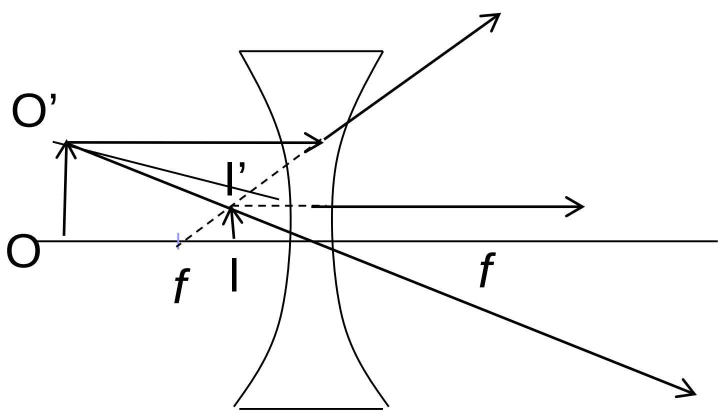
Image Characteristics



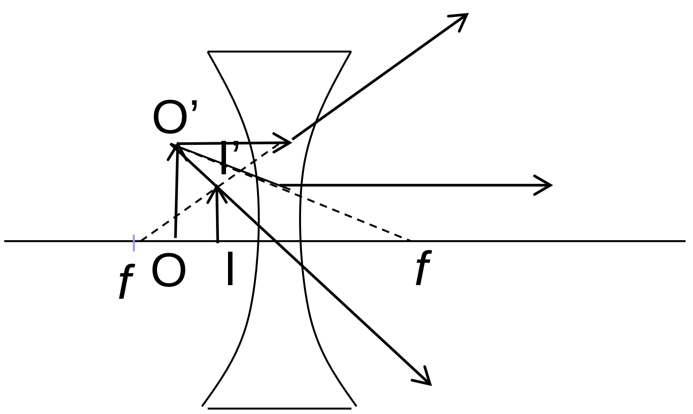
Real inverted image

Virtual image





Virtual erect image



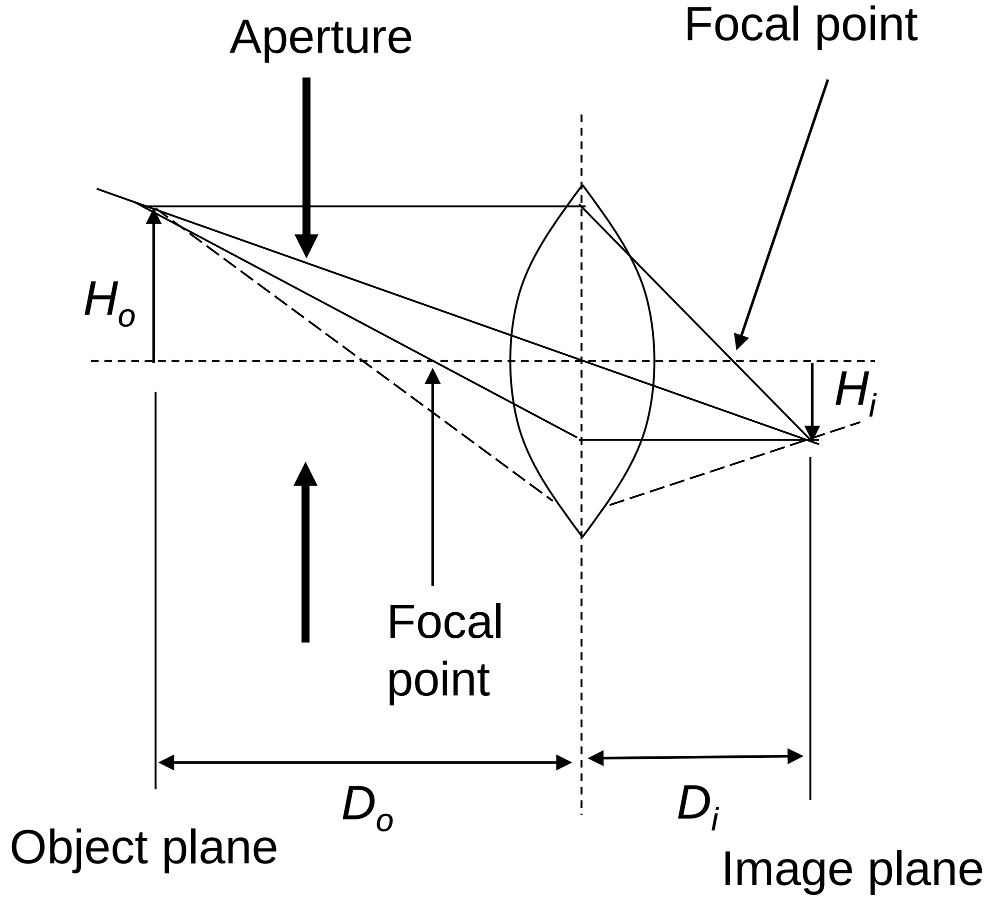
Virtual erect image

$\boxed{\text{Recall Magnification : } A = x_2 / x_1}$

Magnification

- m = magnification
  - H_i: *image size*
  - H_o: *object size*
- m << 1: macroworld
  - typical industrial automation systems
- m >> 1: microscope

$$\boxed{m = \frac{H_i}{H_o} = \frac{D_i}{D_o}}$$



Given a 100 x 100 array of photoreceptors to acquire an image of size 4 x 4 mm of an object of size 80 x 80 mm. What are the magnification, pixel size and pixel size on the object?

Pixel size on array is the distance between sensor elements, and is given by dividing the dimension of array by the number of elements in the same direction.

$$\text{magnification} = \frac{\text{image}}{\text{object}} = \frac{4}{80} = \frac{1}{20}$$

$$\text{pixel size} = \frac{4}{100} = 0.04\text{mm}$$

$$\text{pixel size on object} = \text{pixel size} \times \frac{\text{object}}{\text{image}} = 0.04 \times \frac{20}{1} = 0.8\text{mm}$$

Pixel size on object can also be given by $H_o = H_i / m$.

4.3 Focal Length and Depth of Field

- A camera focuses its lens at a single point but there is a zone that stretches in front of and behind this focus point that still appears sharp. This zone is known as the depth of field.

Focal Length

- f is a measure of how strongly an optical system converges (focuses) or diverges (diffuses) light.
- A system with a shorter focal length has greater optical power than one with a long focal length.
- From the focal length f, the distance D_o at which the object is sharp can be computed.
- Example: m=0.05, f=35.7mm, D_o=750 mm
  - For a lens system with m=0.05, distance between object and lens (camera) is 750 mm, we need a focus length f = 35.7 mm.

p = optical power (or refractive power) = $1/f$

$$D_o = f\left(1 + \frac{1}{m}\right)$$

Depth of Field

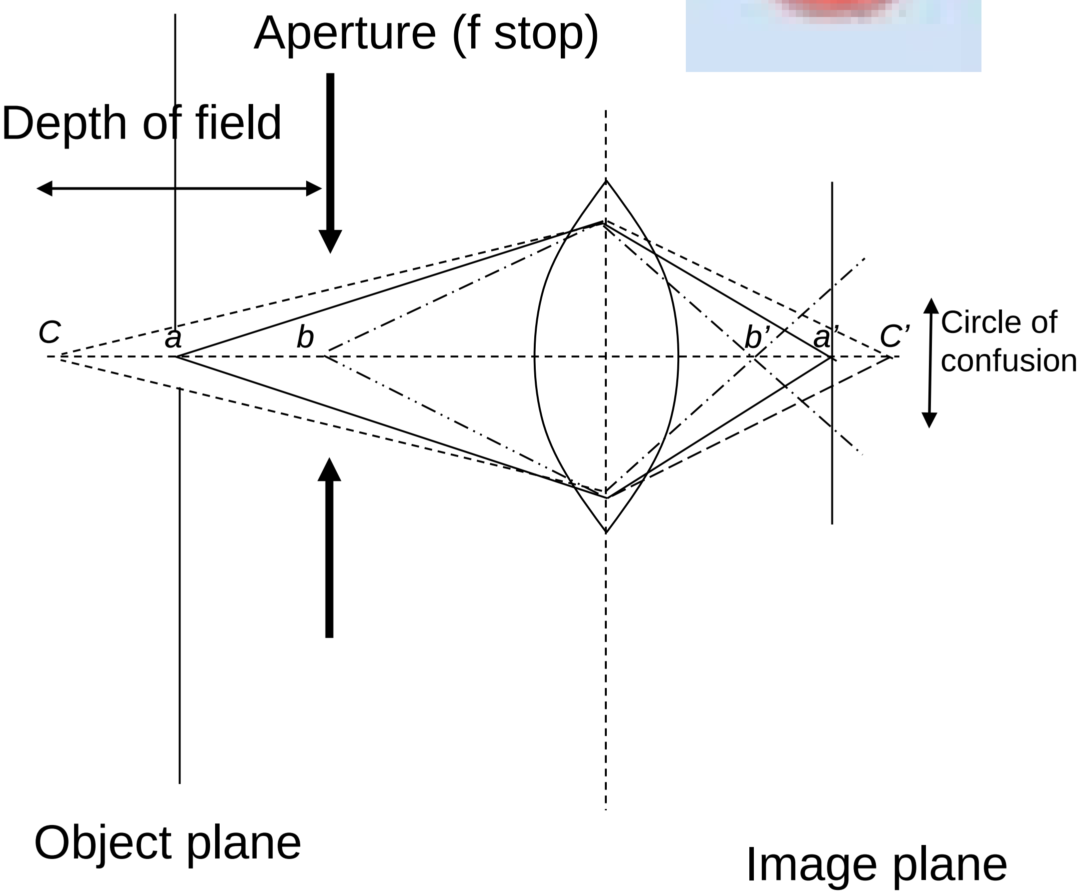
Depth of field is the portion of a scene that appears sharp in image.
Circle of confusion is an optical spot caused by a cone of light rays from a lens not coming to a perfect focus when imaging a point source

$$\text{depth of field} = \frac{2\,\alpha\;f/\,(m+1)}{m^2}$$

α : pixel size

$f/$: aperture size(f – stop)

m : magnification



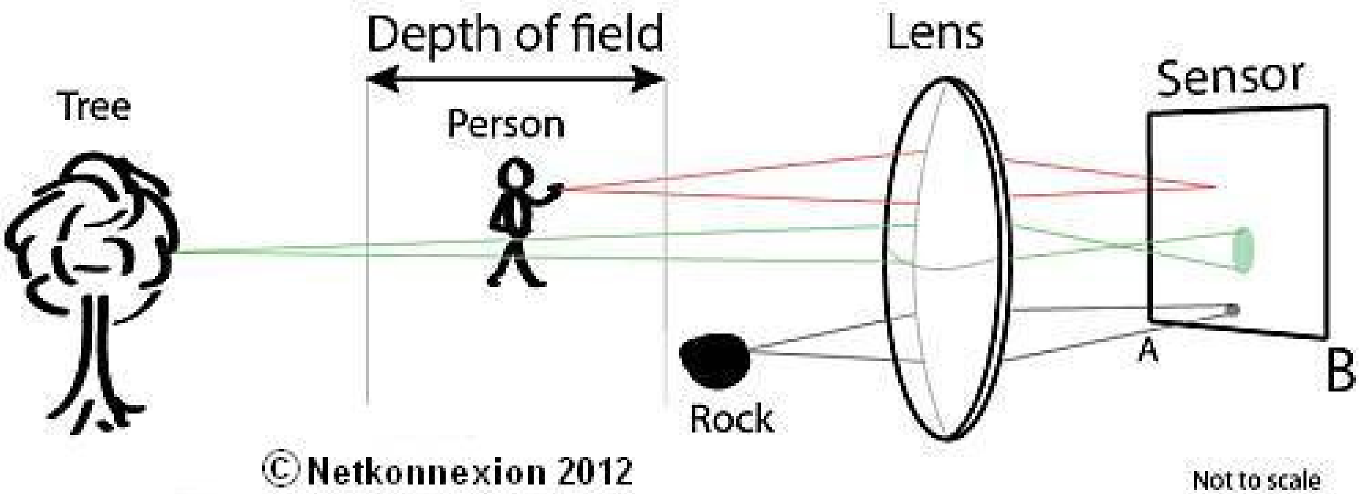


Diagram showing various sizes of Circles of Confusion (CoC). They are sized according to the focus (not to scale). Only those CoCs projected from inside the Depth of Field are sharp. Our eyes cannot perceive them well as they form sharp points. The ones we do see are projected from outside the depth of field. When we are able to see the CoC it is said to be unsharp.

Source: http://www.photokonnexion.com/?page_id=4373

Depth of Field (Continue)

- f-stop is the discrete step the f-number is adjusted in a camera.
- f-number is the focal length divided by the effective aperture diameter.
- Standard f-stop scale: f/1, f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32, …

200 mm f/4 lens: the diameter of lens = 200/4 = 50 mm.
f-number = 4 since 200 mm/50 mm = 4.

Given f=40 mm and f-stop = 8, what are the diameter of aperture opening and f-number?

- Diameter of aperture opening (or effective aperture diameter)
  = f/f-stop = 40/8 = 5 mm
- f-number = f/(effective aperture diameter)
  = 40 mm/5 mm = 8

“Smaller F-stop number (Larger apertures) produce a shallower depth of field.”

Source: http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Image taken on a 200 mm lens

f/8.0

Depth of field is ‘deep’ – more of the picture appears sharp.

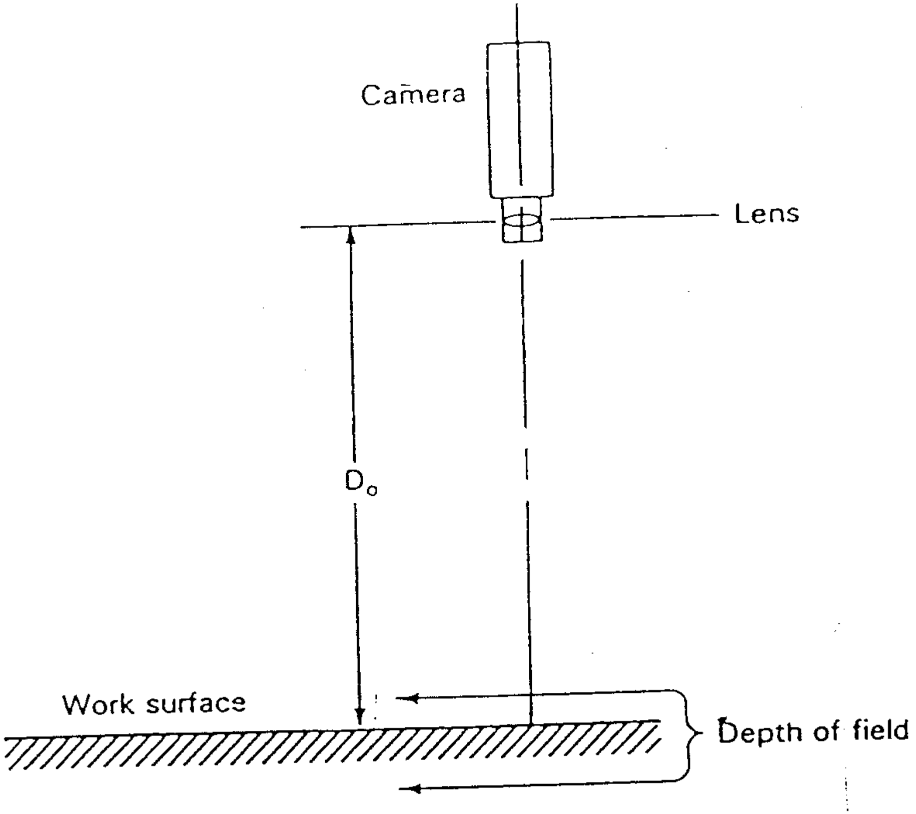
f/5.6

f/2.8

Depth of field is ‘shallow’ – a narrow zone appears sharp.

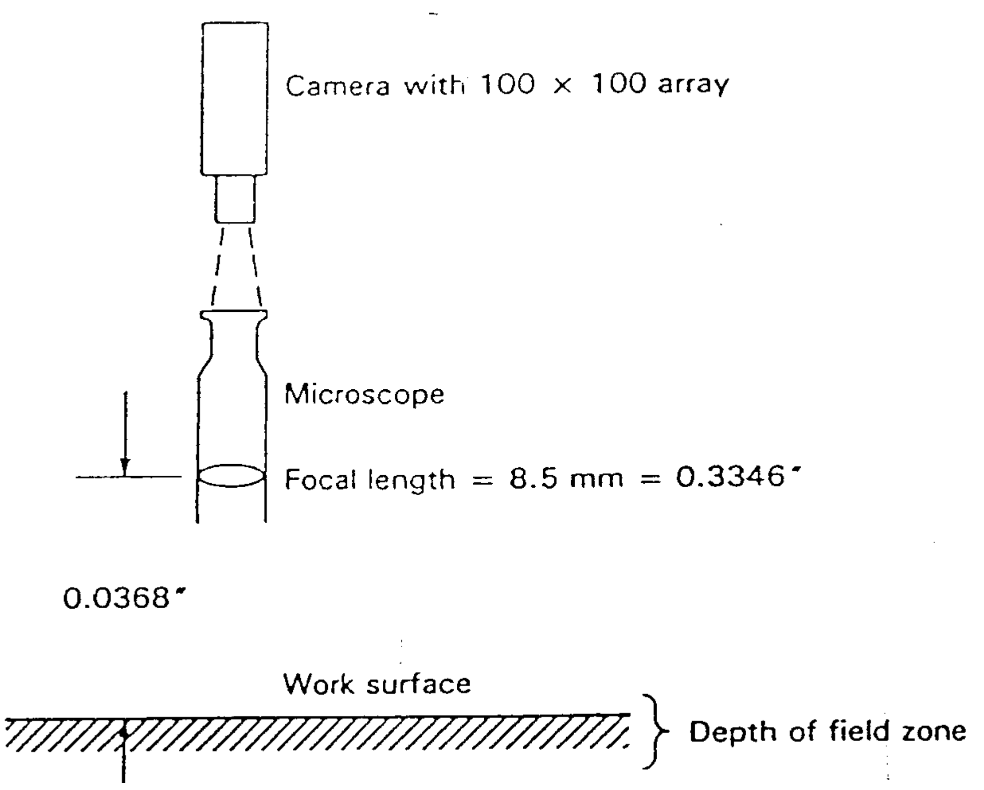
Depth of Field: Macroworld

- 7.6 x 7.6 mm size 200 x 200 array sensor
- f-stop = 16, magnification = 1/20
  - pixel size = 7.6/200 = 0.038 mm
  - depth of field = $(2*0.038*16*(1+1/20))*20^2$ = 511 mm)
- In typical industrial applications (m << 1), the depth of field problem is not sufficient.



Depth of Field: Optical Microscope

- 3.8 x 3.8 mm sensor array
  - Pixel size = 3.8/100 = 0.038 mm
  - If m = 100 and f-stop=16
    - Depth = (2*0.038*16*(1+100))/10000 = 12 micrometers
- In microscopy, the depth is limited, 3D vision is hardly possible.



5. Frame Grabber

Formatting camera output signal

- An electronic device that captures individual, digital still frames from an analog video signal or a digital video stream.
- In a typical machine/computer vision system, the frame grabber also displays, stores or transmits the captured video frame in raw or compressed digital form.