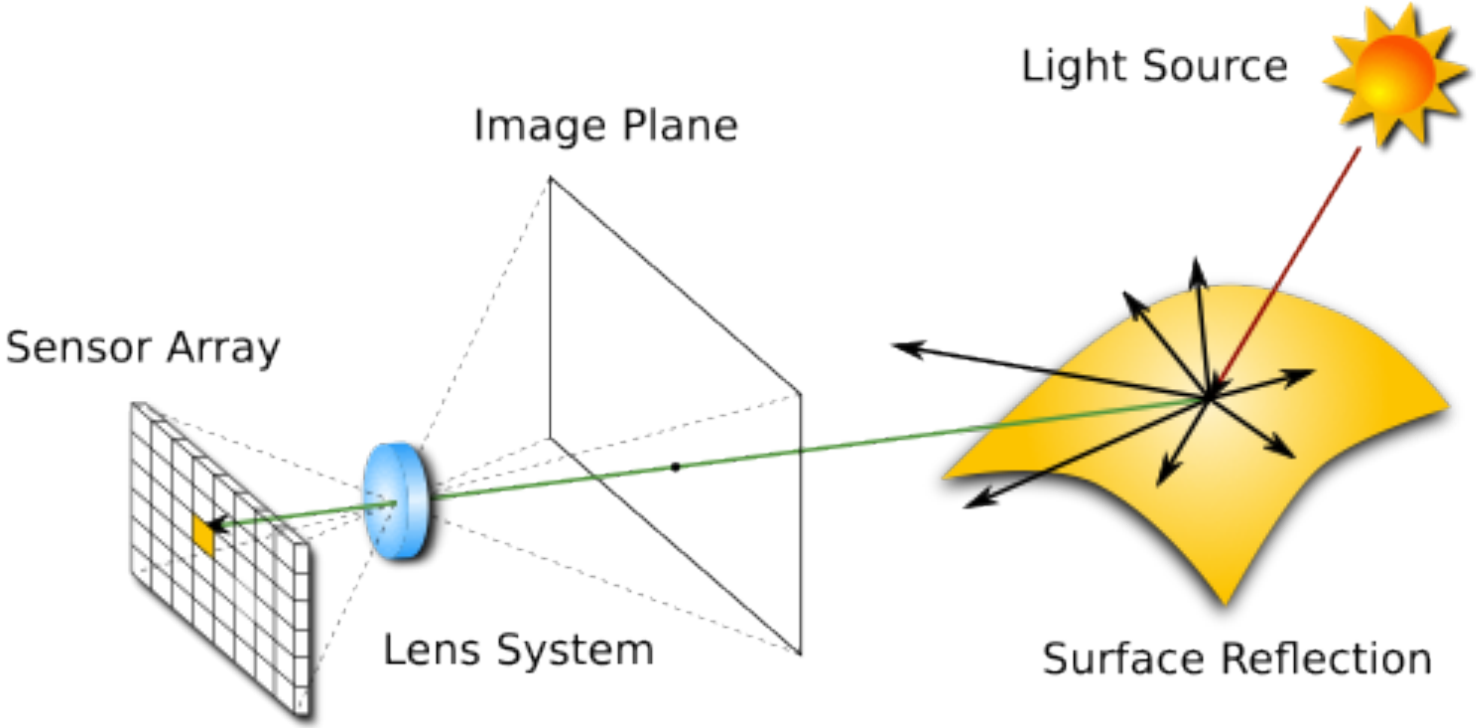
Acquisition of Images

Acquisition of images

We focus on :

1. cameras
2. illumination



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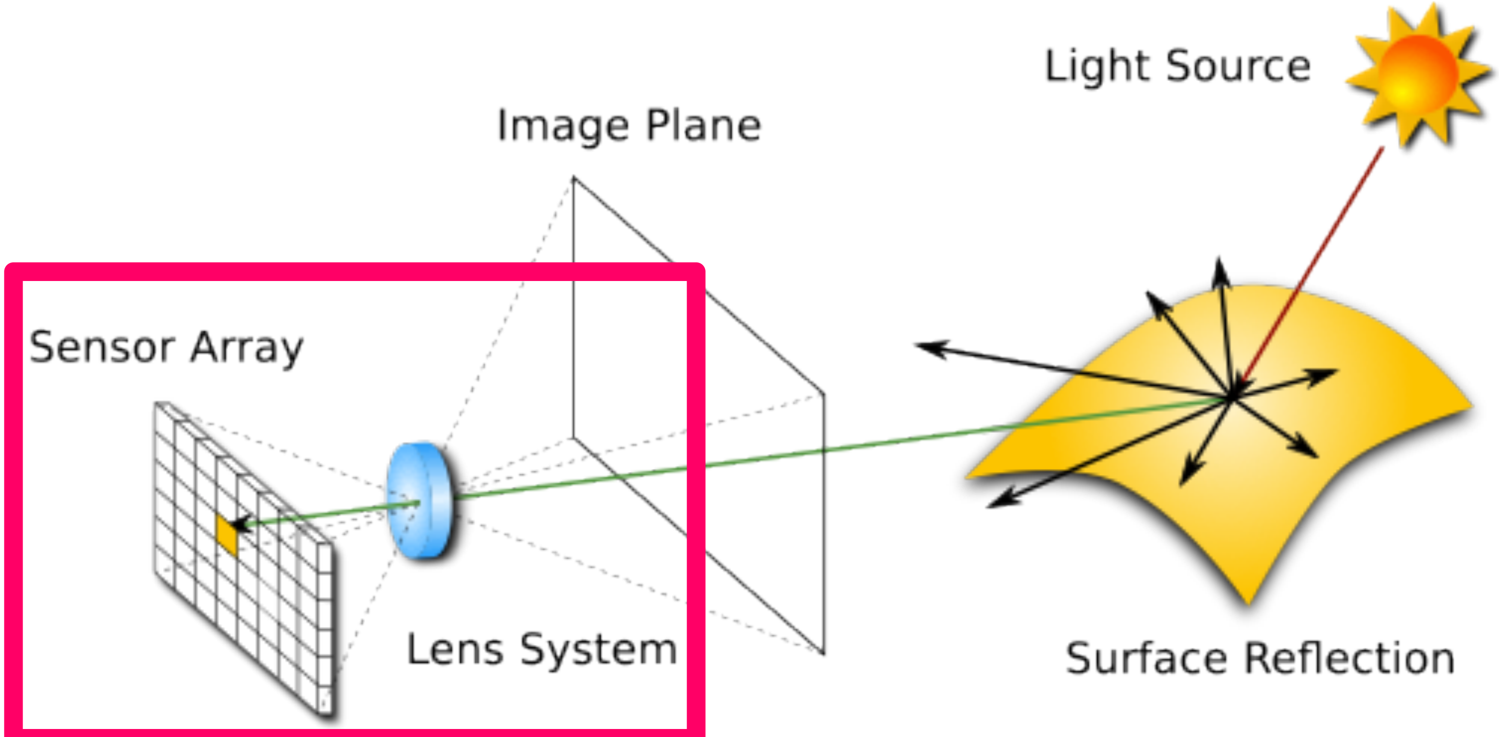

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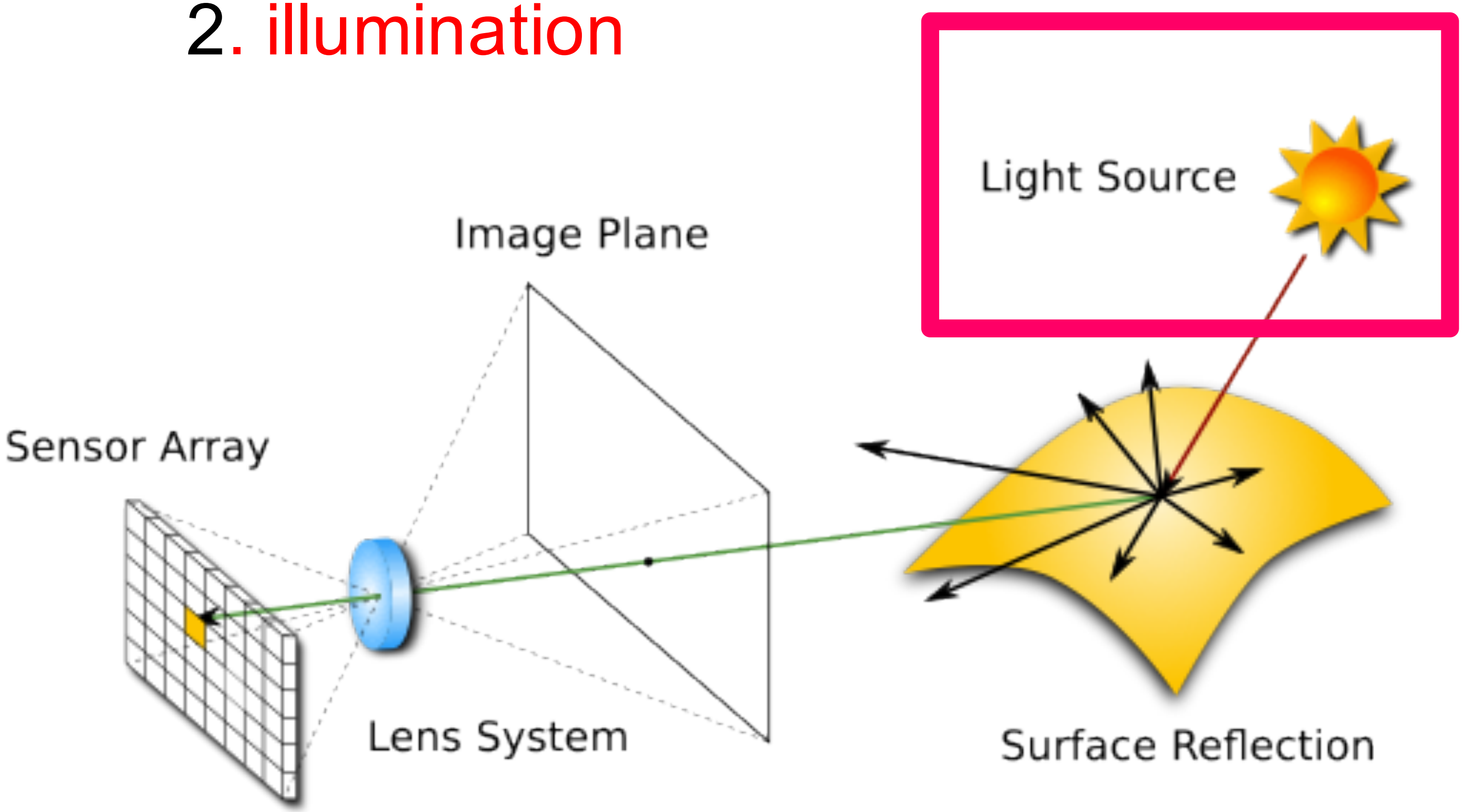
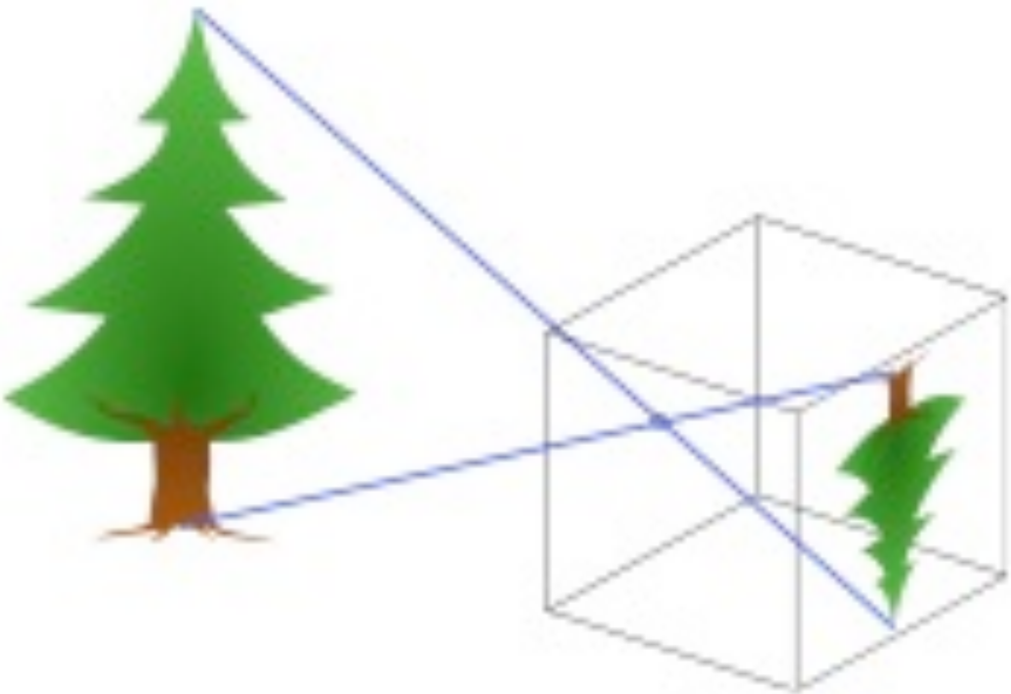


cameras

Optics for image formation

the pinhole model :



Optics for image formation

the pinhole model :

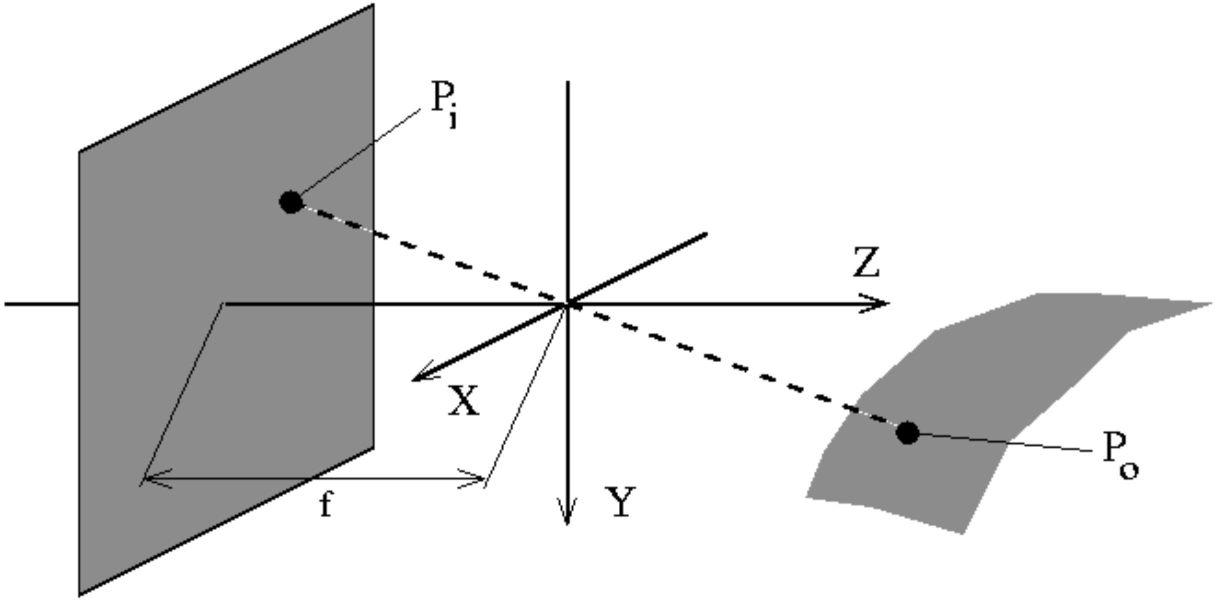
hence the name:

CAMERA

obscura

Optics for image formation

the pinhole model :



$$\frac{X_i}{X_o} = \frac{Y_i}{Y_o} = \frac{f}{-Z_o} = -m$$

(m = linear magnification)

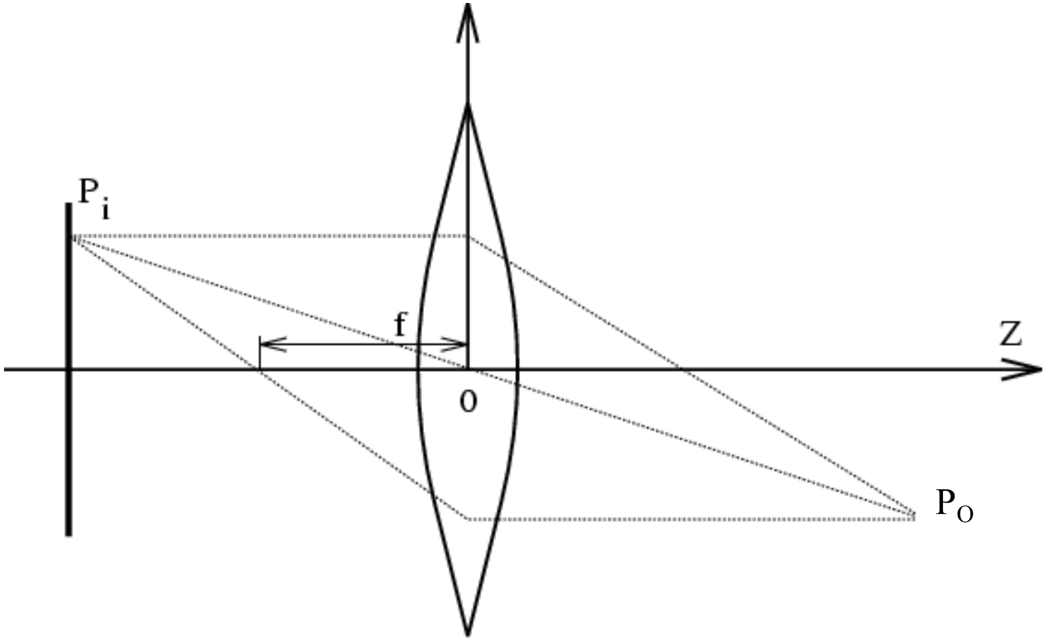
Computer Vision

Camera obscura + lens

The thin-lens equation

lens to capture enough light :

$$\frac{1}{Z_O} - \frac{1}{Z_i} = \frac{1}{f}$$

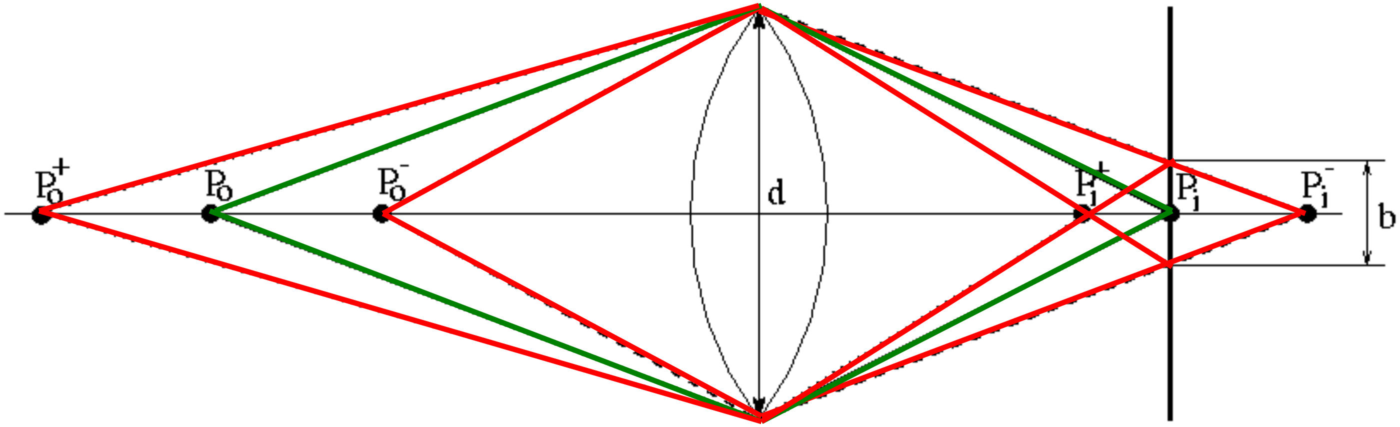


assuming

- spherical lens surfaces
- incoming light ± parallel to axis
- thickness << radii
- same refractive index on both sides

The depth-of-field

Only reasonable sharpness in Z-interval

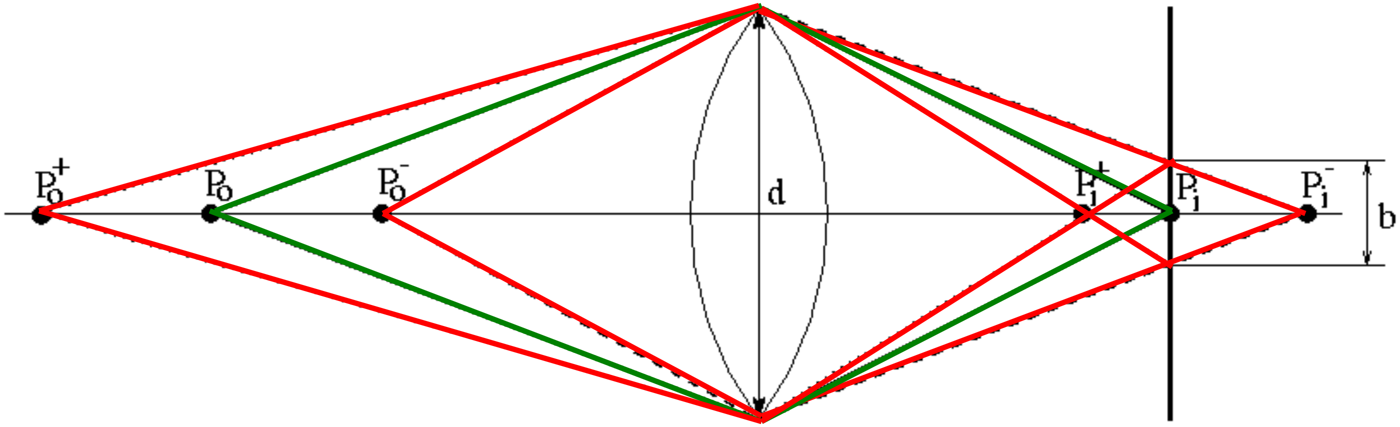


$$\Delta Z_0^- = Z_0 - Z_0^- = \frac{Z_0(Z_0 - f)}{Z_0 + f\, d / b - f}$$

decreases with d, increases with Z_0

strike a balance between incoming light (d) and large depth-of-field (usable depth range)

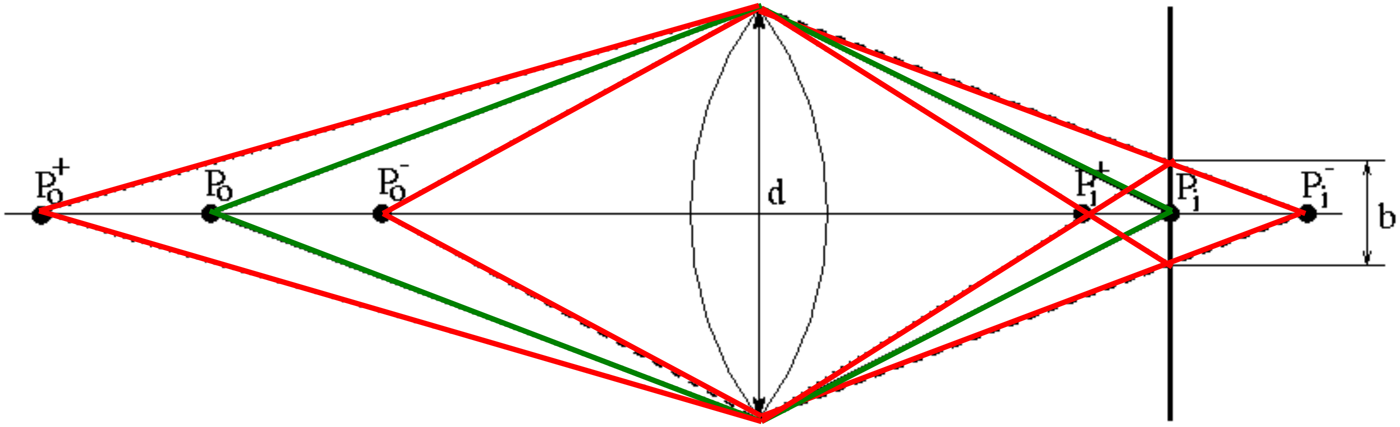
The depth-of-field



$$\Delta Z_0^- = Z_0 - Z_0^- = \frac{Z_0(Z_0 - f)}{Z_0 + f\, d / b - f}$$

Similar expression for Z_O^+ - Z_O

The depth-of-field



$$\Delta Z_0^- = Z_0 - Z_0^- = \frac{Z_0(Z_0 - f)}{Z_0 + f\,d/b - f}$$

Ex 1: microscopes -> small DoF

Ex 2: special effects -> flood miniature scene with light

Deviations from the lens model

3 assumptions :

1. all rays from a point are focused onto 1 image point

2. all image points in a single plane

3. magnification is constant

deviations from this ideal are *aberrations*

Aberrations

2 types :

1. geometrical
2. chromatic

geometrical : small for paraxial rays

chromatic : refractive index function of wavelength (Snell's law !!)

➔

Geometrical aberrations

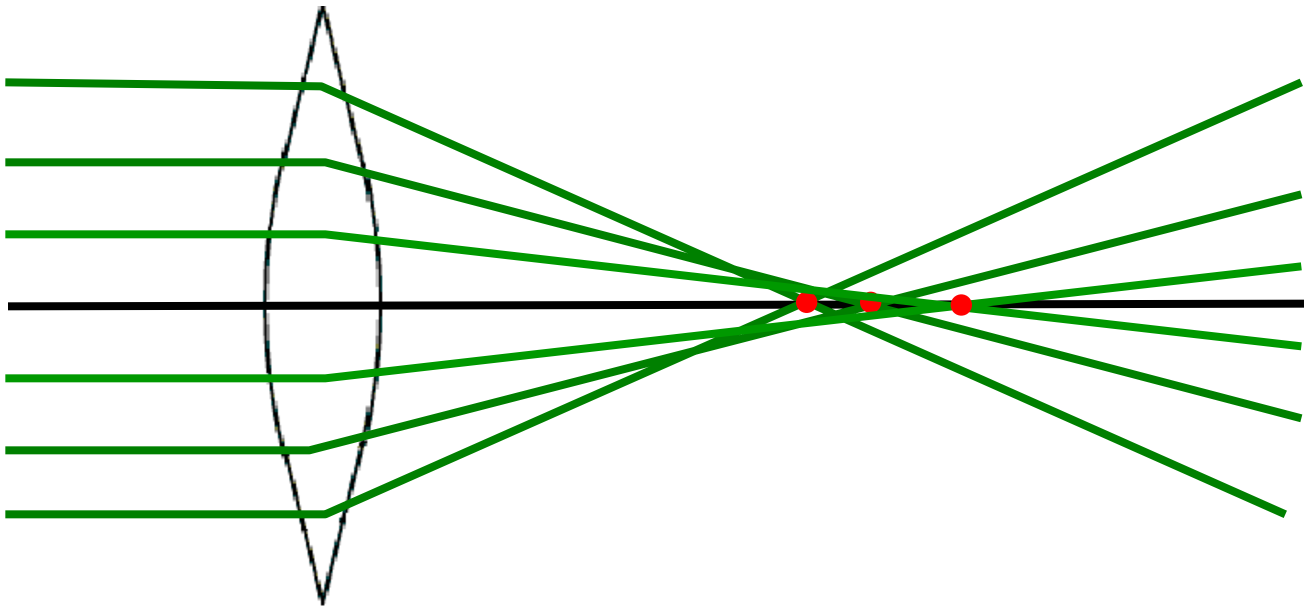
- ☐ spherical aberration
- ☐ astigmatism
- ☐ radial distortion
- ☐ coma

the most important type

Spherical aberration

rays parallel to the axis do not converge

outer portions of the lens yield smaller focal lenghts



Radial Distortion

magnification different
for different angles of inclination

barrel

none

pincushion

Radial Distortion

magnification different
for different angles of inclination

barrel

none

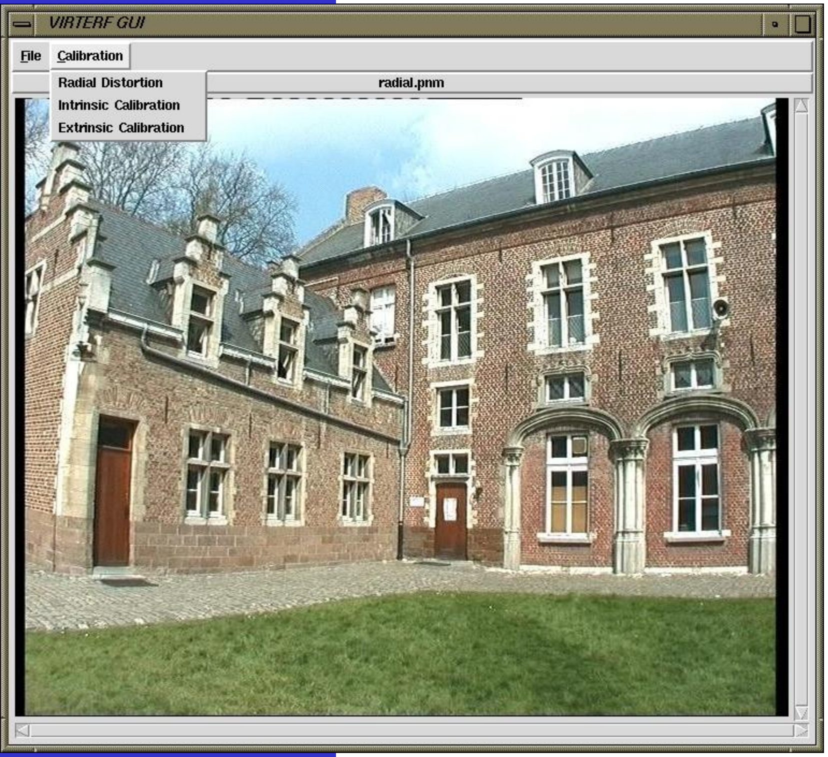
pincushion

The result is pixels moving along lines
through the center of the distortion
– typically close to the image center – over a distance d,
depending on the pixels' distance r to the center

$$d = (1 + \kappa_1 r^2 + \kappa_2 r^4 + \ldots)$$

Radial Distortion

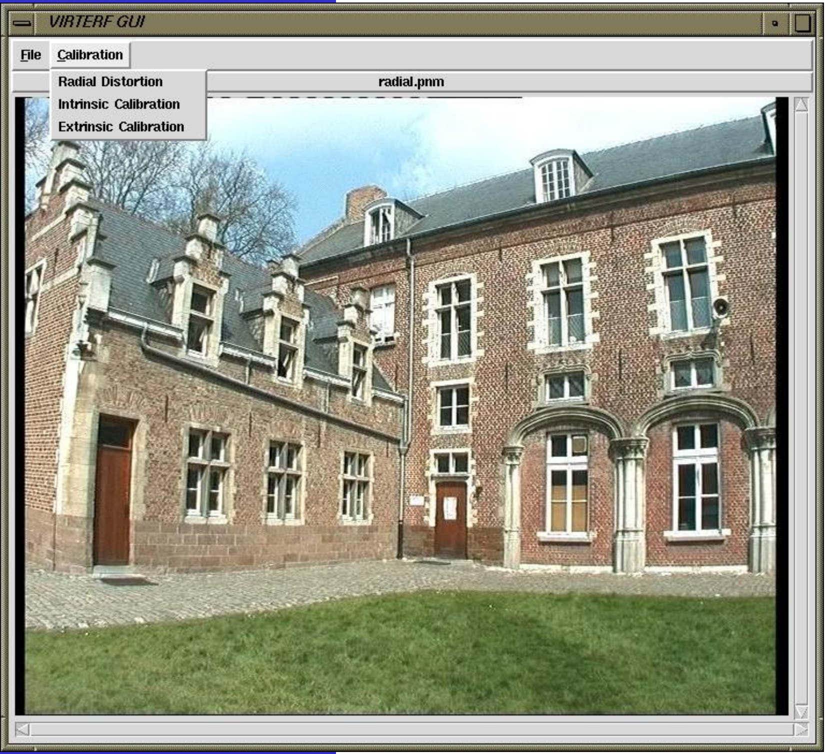
magnification different
for different angles of inclination



This aberration type can be corrected by software if the parameters (κ_1 , κ_2 , …) are known

Radial Distortion

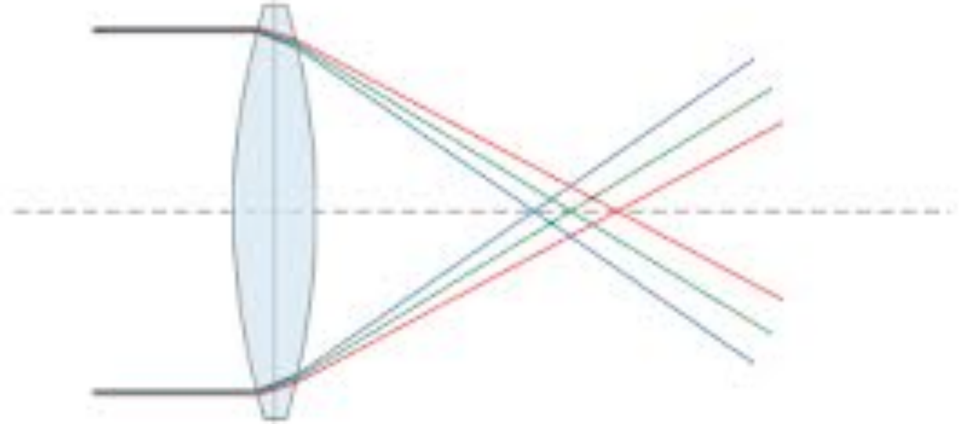
magnification different
for different angles of inclination

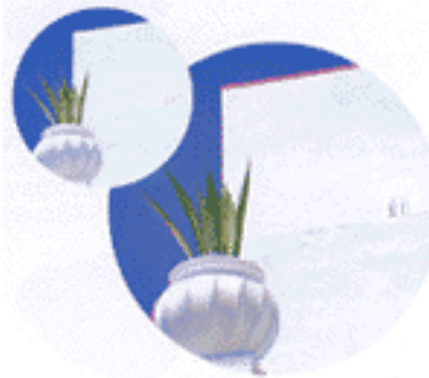


Some methods do this by looking how straight lines curve instead of being straight

Chromatic aberration

rays of different wavelengths focused in different planes

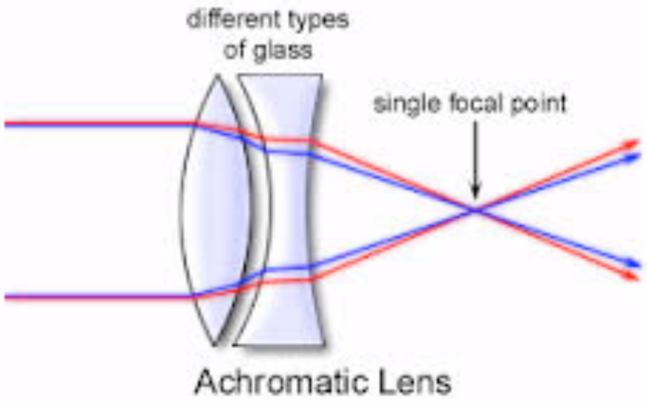




The image is blurred and appears colored at the fringe.

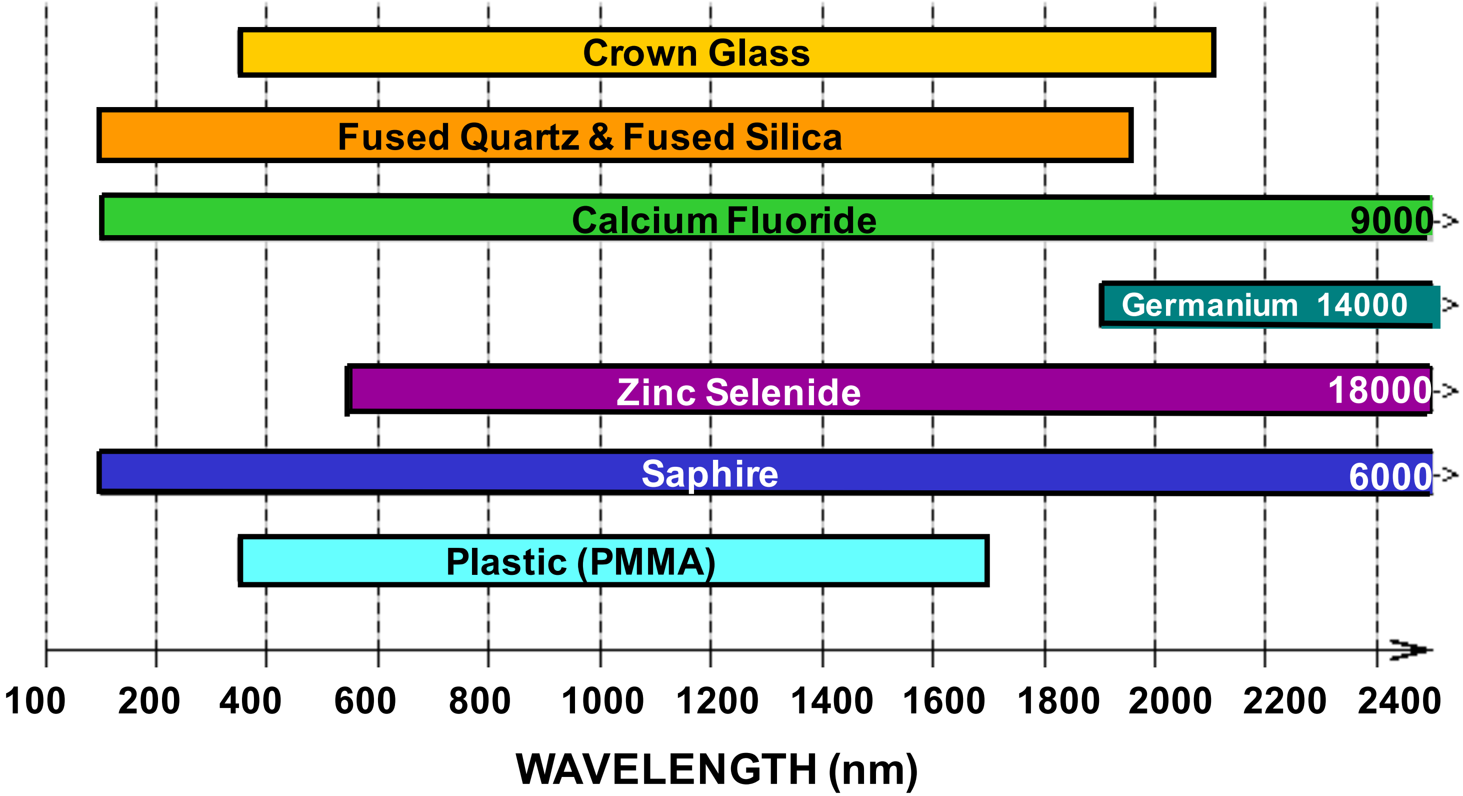
cannot be removed completely

but *achromatization* can be achieved at some well chosen wavelength pair, by combining lenses made of different glasses



sometimes *achromatization* is achieved for more than 2 wavelengths

Lens materials



additional considerations :

humidity and temperature resistance, weight, price,...

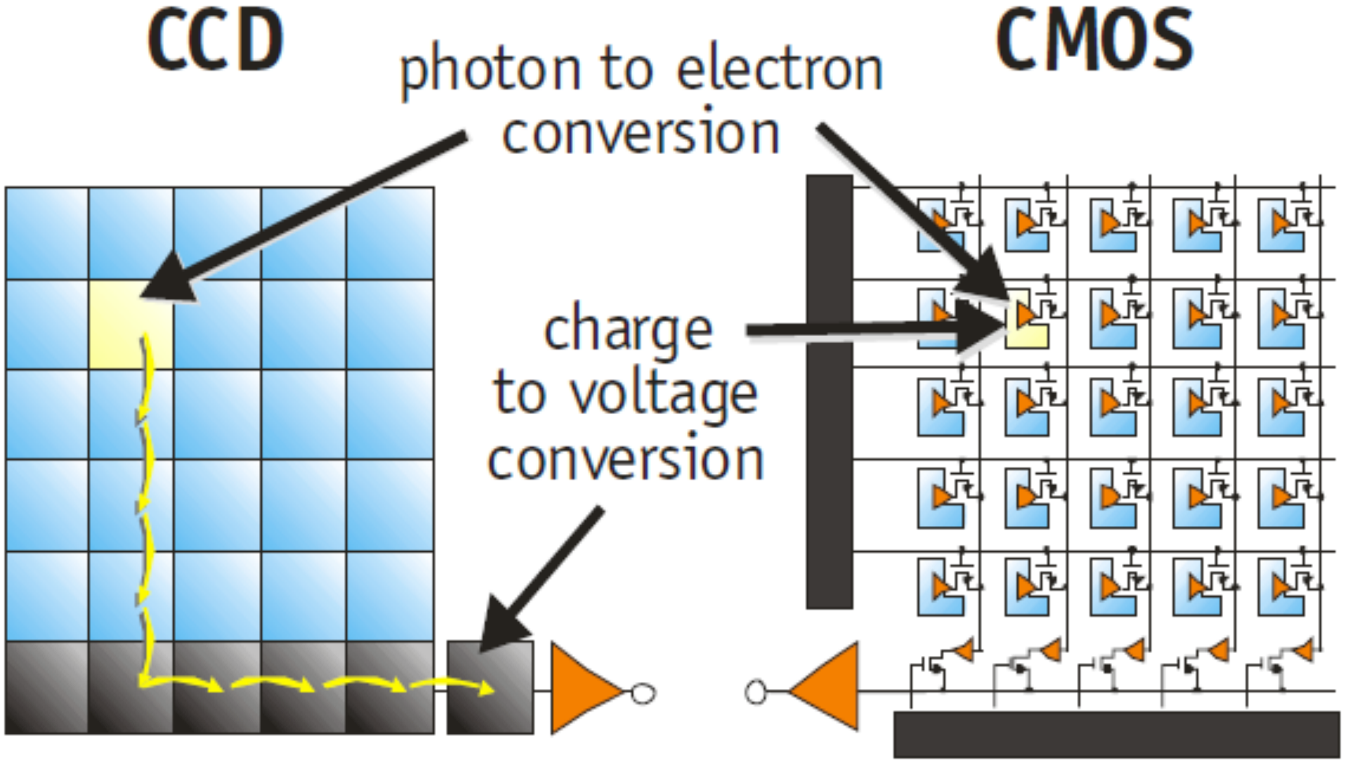
Cameras

we consider 2 types :

1. CCD

2. CMOS

Cameras



CCD = Charge-coupled device
CMOS = Complementary Metal Oxide Semiconductor

CCD

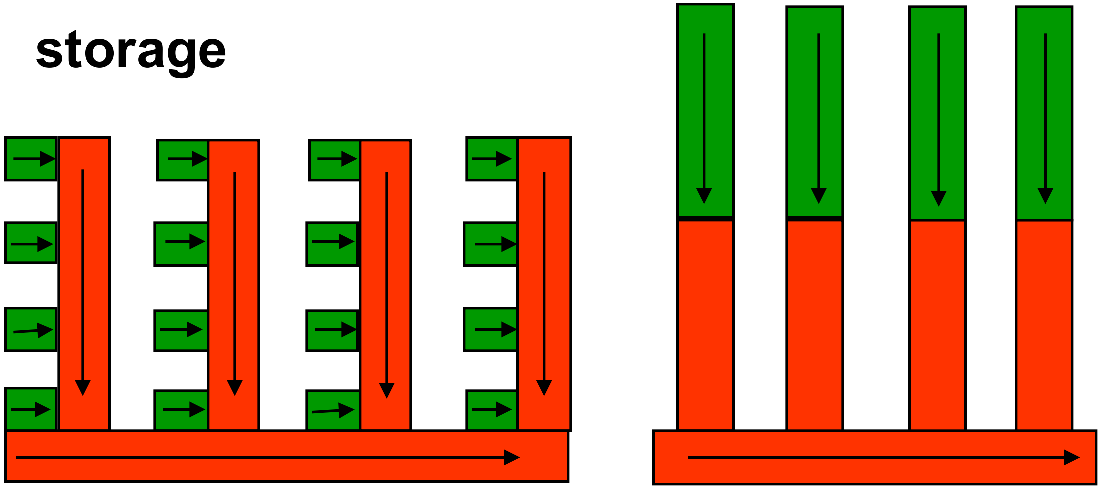
separate photo sensor at regular positions
no scanning

charge-coupled devices (CCDs)

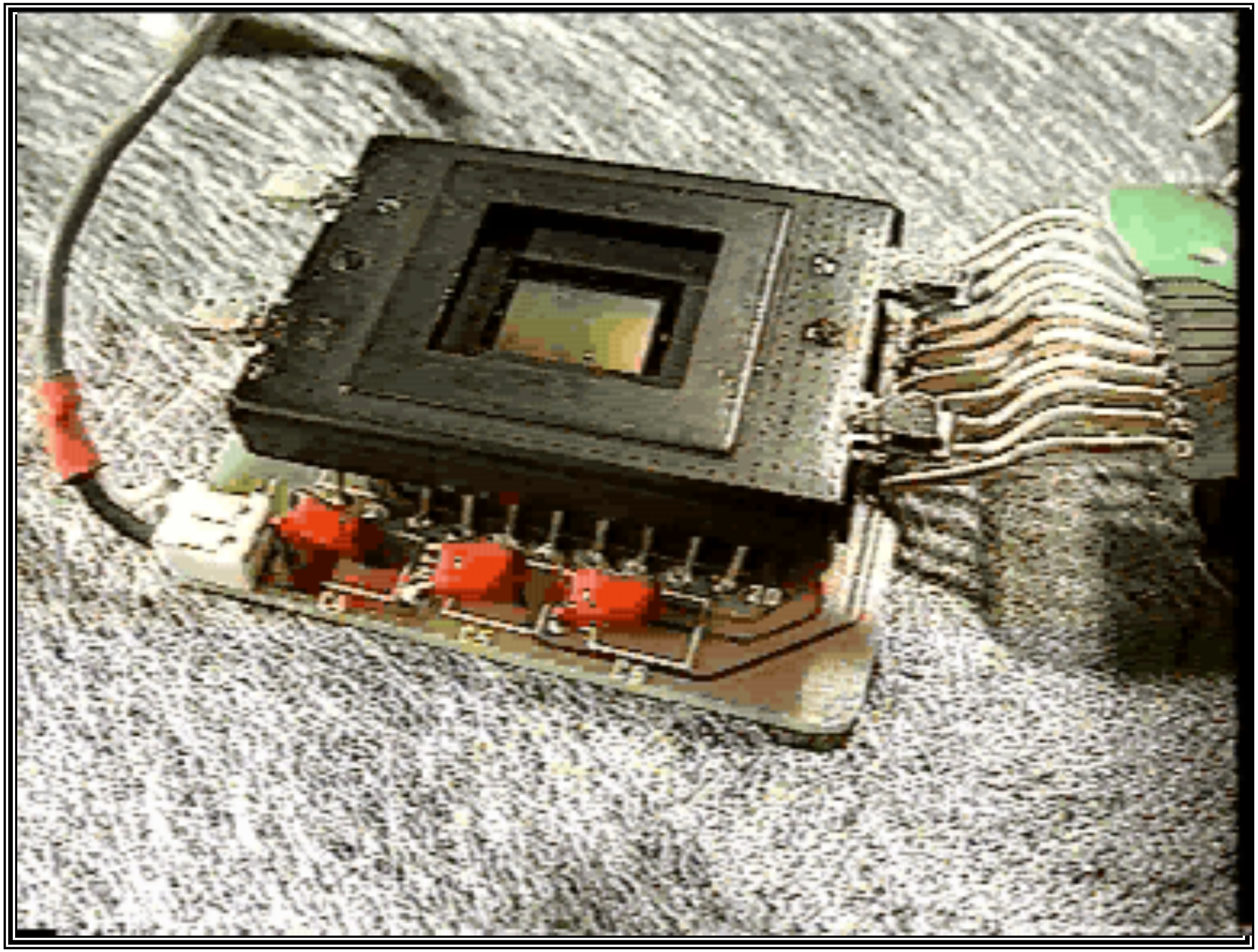
area CCDs and linear CCDs
2 area architectures :
interline transfer and *frame transfer*

🟩 **photosensitive**

🟥 **storage**

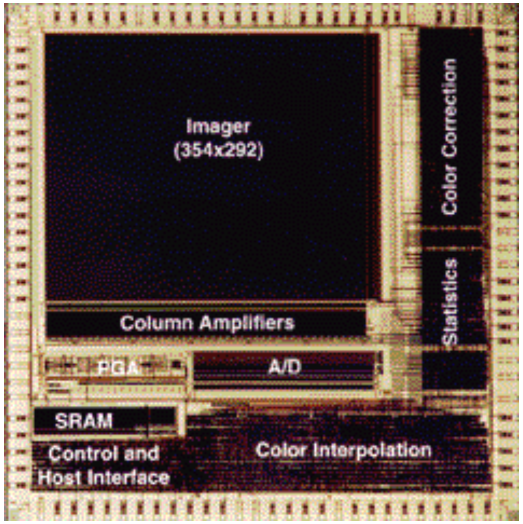


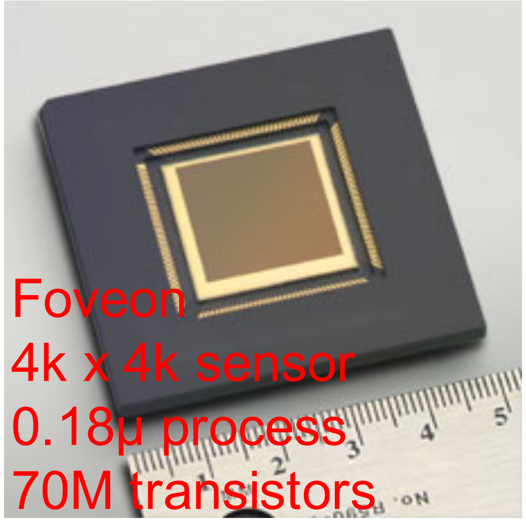
The CCD inter-line camera



CMOS

- Same sensor elements as CCD
- Each photo sensor has its own amplifier
  - More noise (reduced by subtracting ‘black’ image)
  - Lower sensitivity (lower fill rate)
- Uses standard CMOS technology
  - Allows to put other components on chip
  - ‘Smart’ pixels

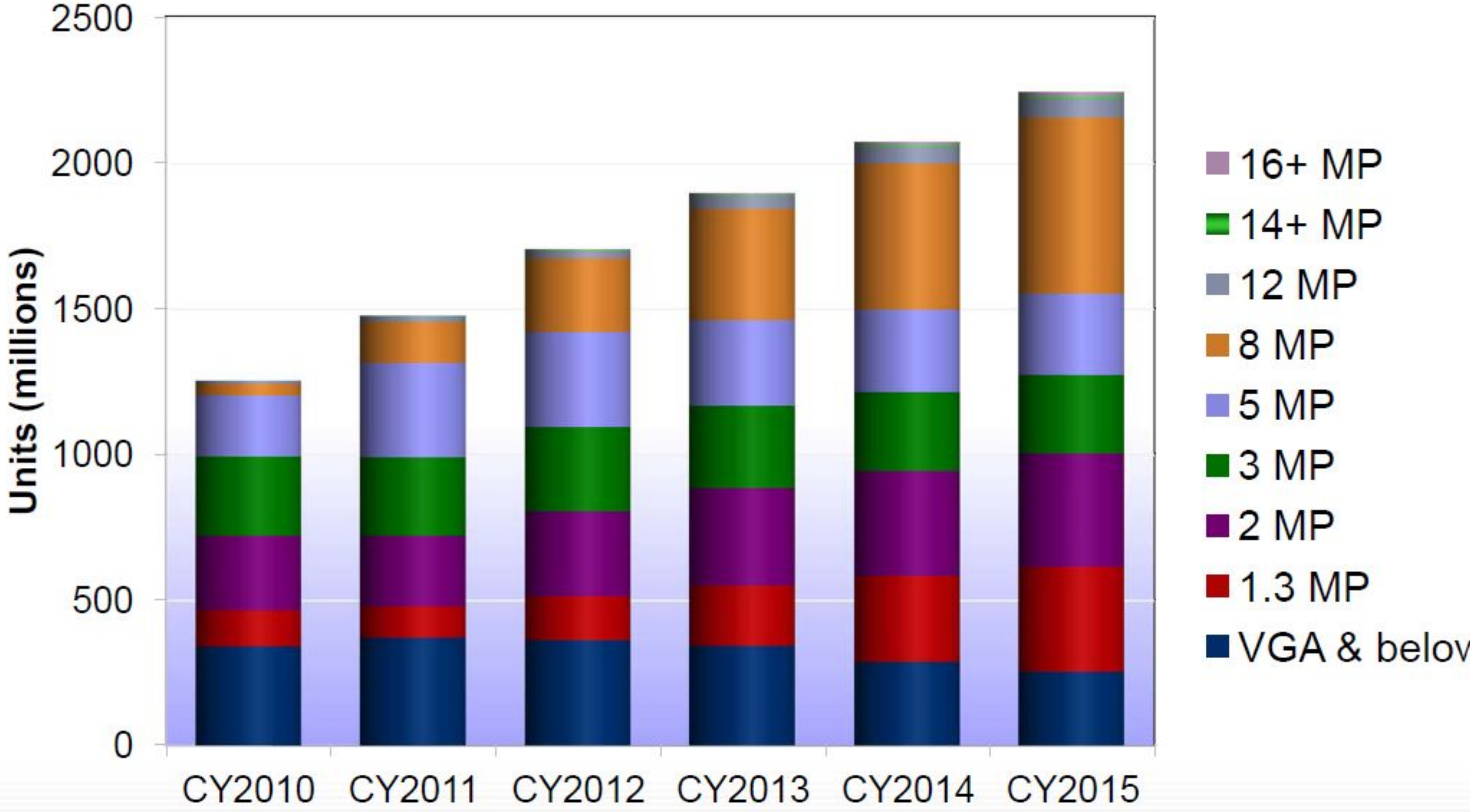



Foveon
4k x 4k sensor
0.18µ process
70M transistors

CMOS

Resolution trend in mobile phones

Volume and revenue opportunity for high resolution sensors



Source: TSR, CCD/CMOS Area Image Sensor Market Analysis, dated June 2011

CCD vs. CMOS

- Niche applications
- Specific technology
- High production cost
- High power consumption
- Higher fill rate
- Blooming
- Sequential readout

- Consumer cameras
- Standard IC technology
- Cheap
- Low power
- Less sensitive
- Per pixel amplification
- Random pixel access
- Smart pixels
- On chip integration with other components

2006 was year of sales cross-over

CCD vs. CMOS

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In 2015 Sony said to stop CCD chip production

Colour cameras

- We consider 3 concepts:

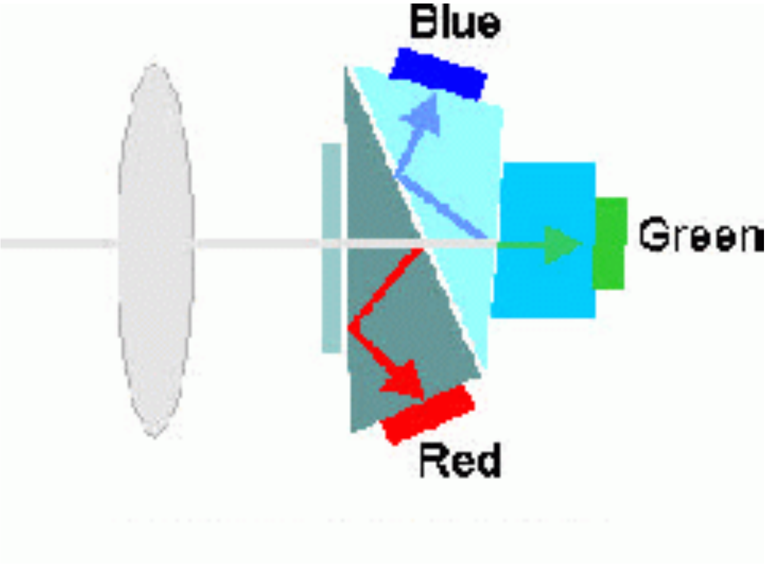
  1. Prism (with 3 sensors)
  2. Filter mosaic
  3. Filter wheel

Prism colour camera

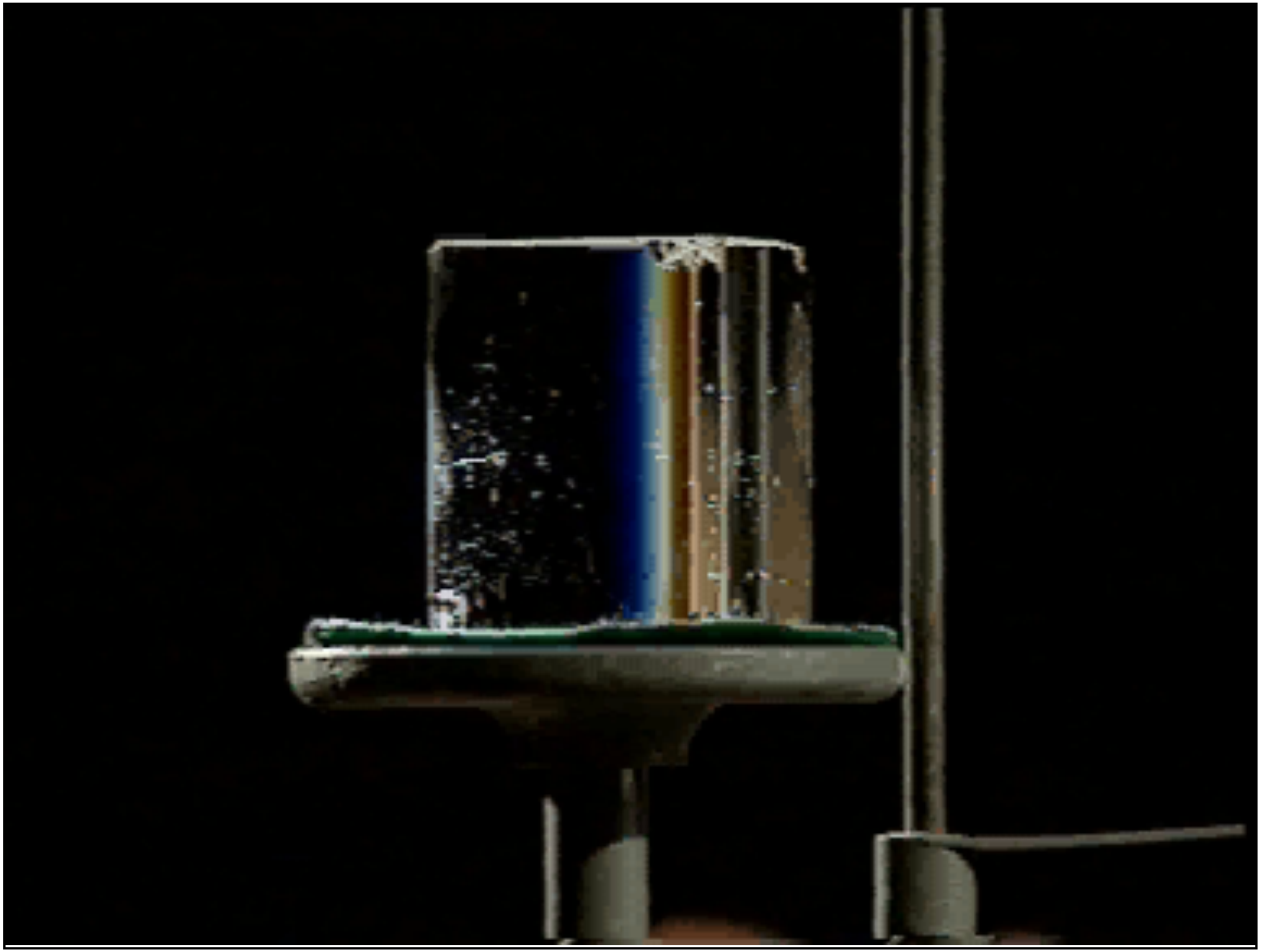
Separate light in 3 beams using dichroic prism

Requires 3 sensors & precise alignment

Good color separation

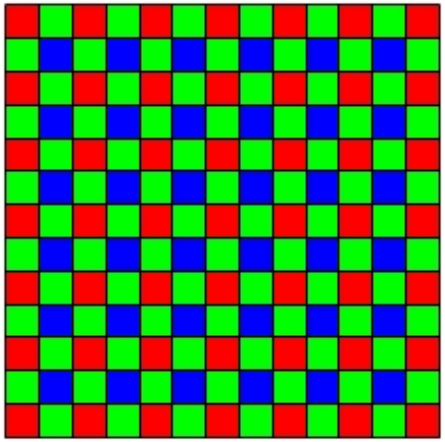


Prism colour camera

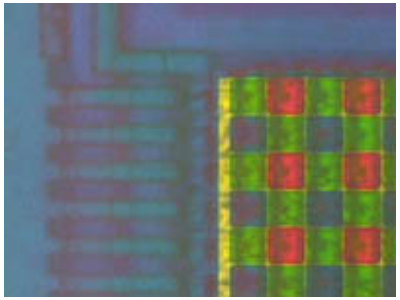


Filter mosaic

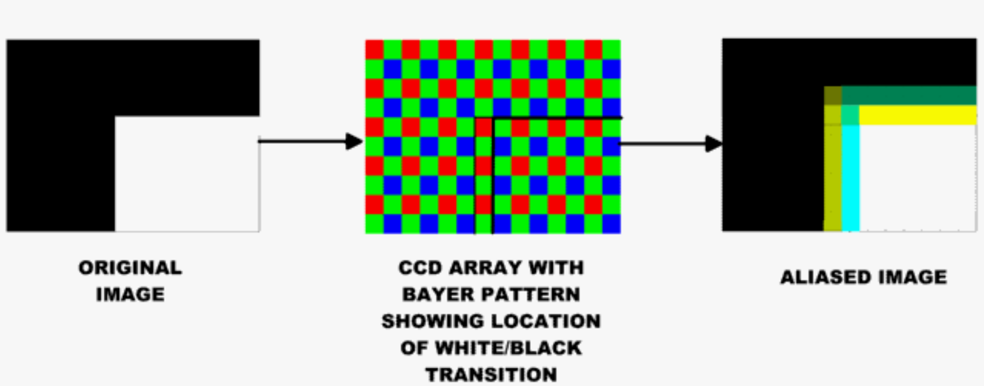
Coat filter directly on sensor



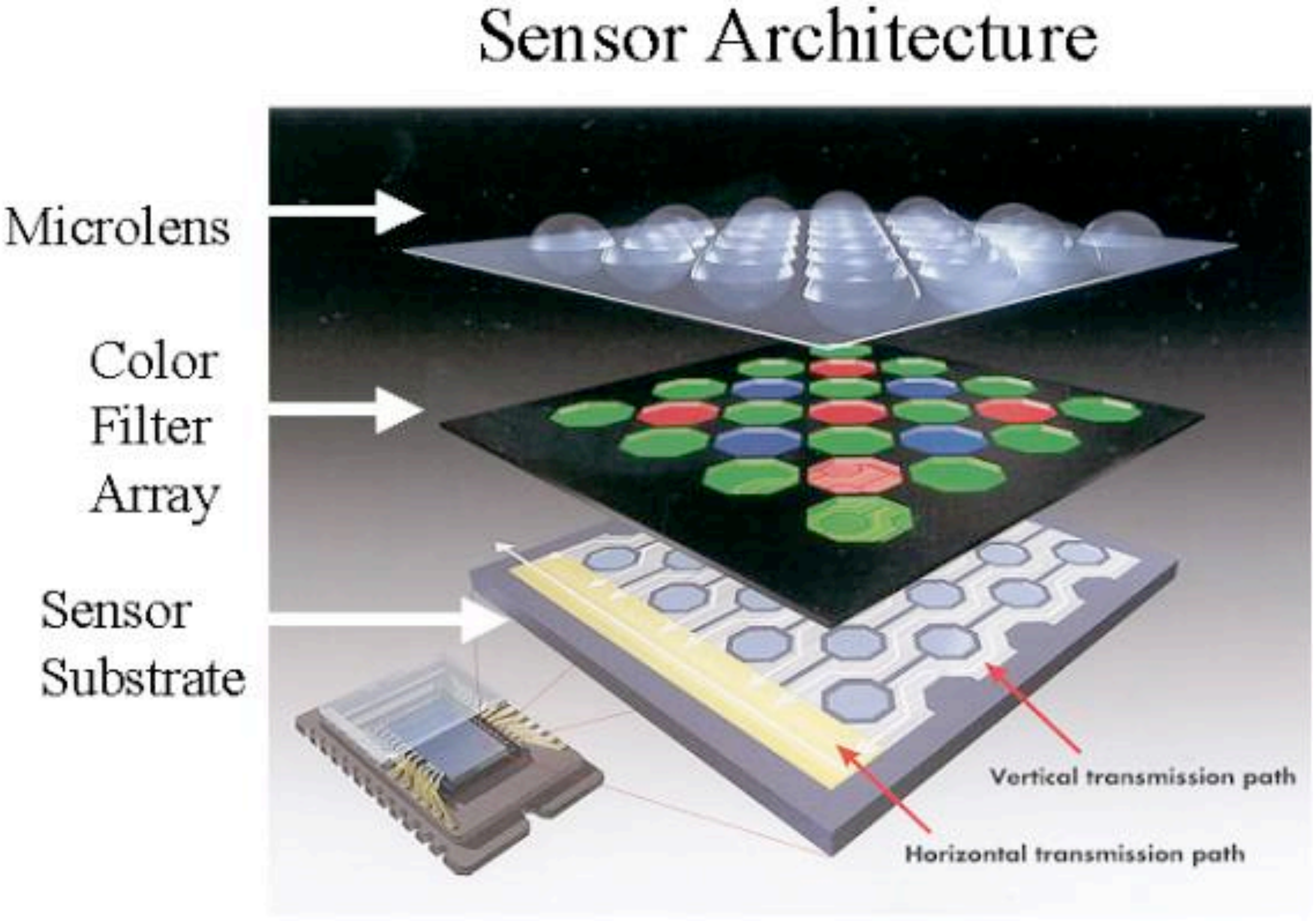
Bayer filter



Demosaicing (obtain full colour & full resolution image)



Filter mosaic



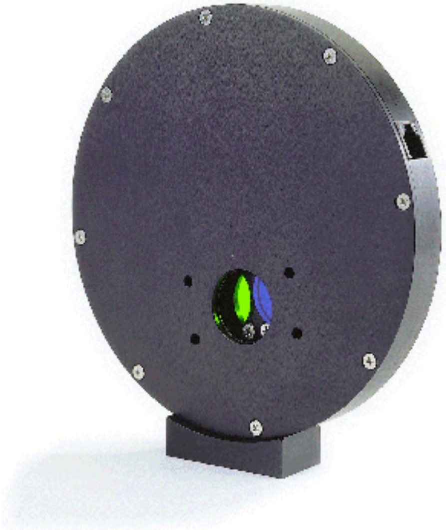
Fuji Corporation

Color filters lower the effective resolution, hence microlenses often added to gain more light on the small pixels

Filter wheel

Rotate multiple filters in front of lens

Allows more than 3 colour bands



Only suitable for static scenes

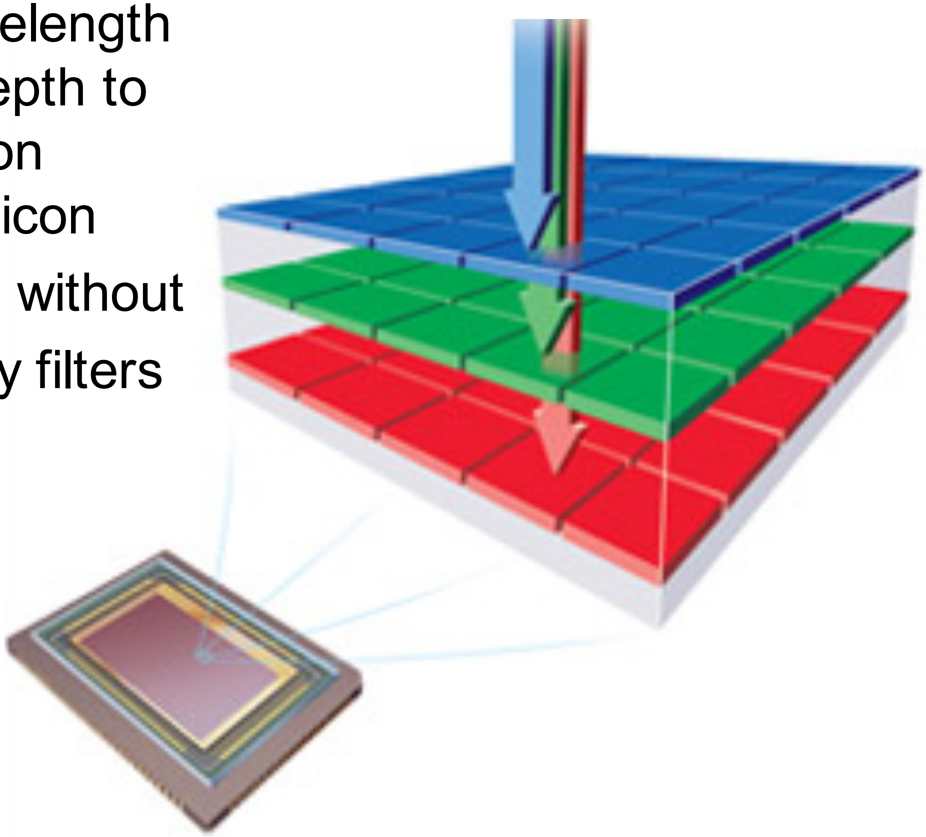
Prism vs. mosaic vs. wheel

approach	Prism	Mosaic	Wheel
# sensors	3	1	1
Resolution	High	Average	Good
Cost	High	Low	Average
Framerate	High	High	Low
Artefacts	Low	Aliasing	Motion
Bands	3	3	3 or more
	High-end cameras	Low-end cameras	Scientific applications

Odd-man-out X3 technology of Foveon

Exploits the wavelength dependent depth to which a photon penetrates silicon

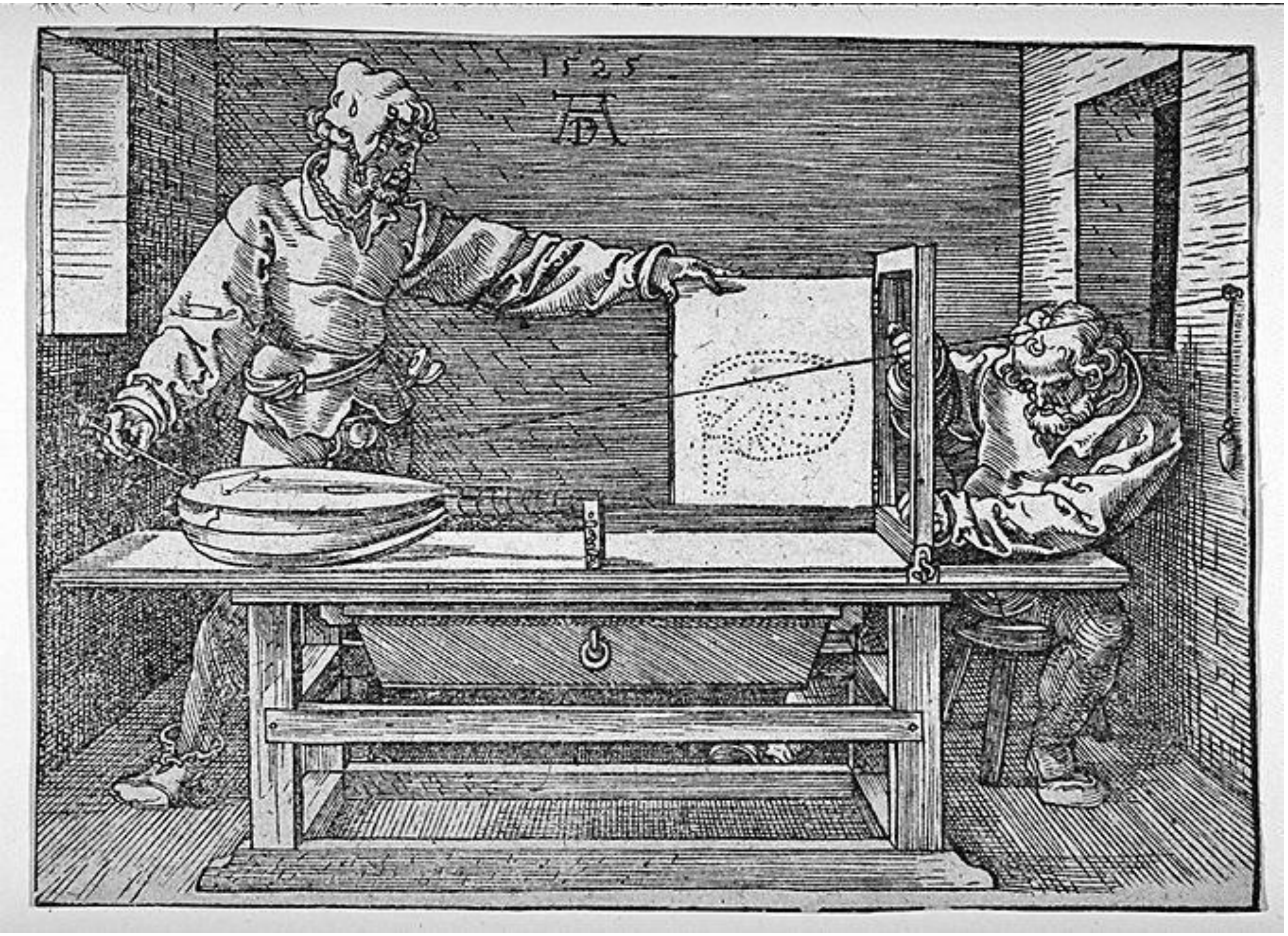
And splits colors without the use of any filters



creates a stack of pixels at one place

new CMOS technology

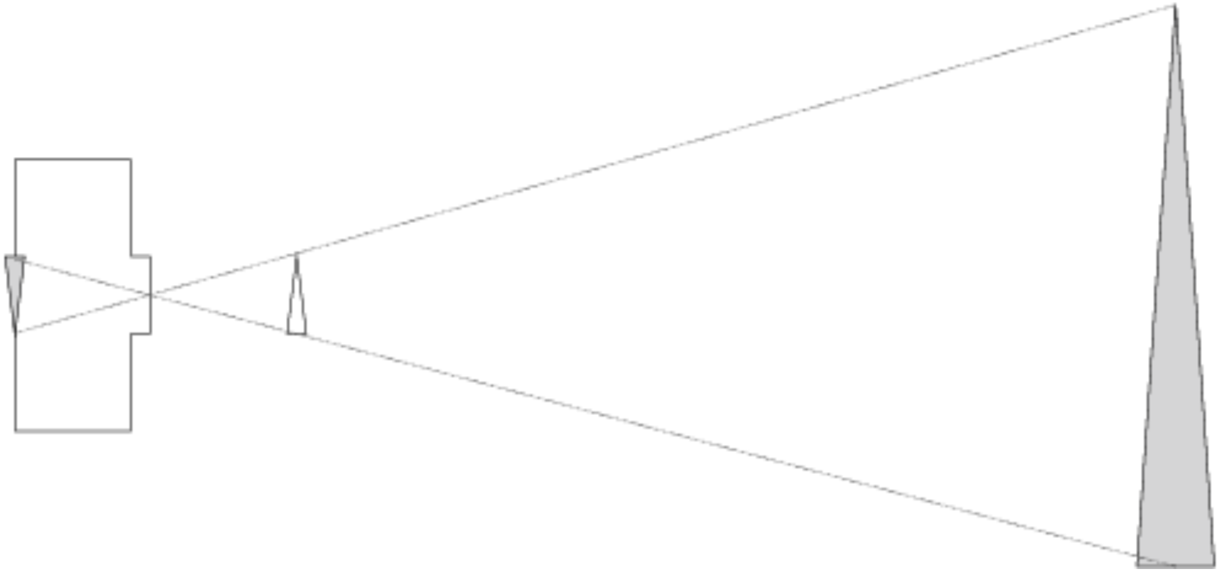
Geometric camera model
perspective projection



(Man Drawing a Lute, woodcut, 1525, Albrecht Dürer)

Models for camera projection

the pinhole model revisited :



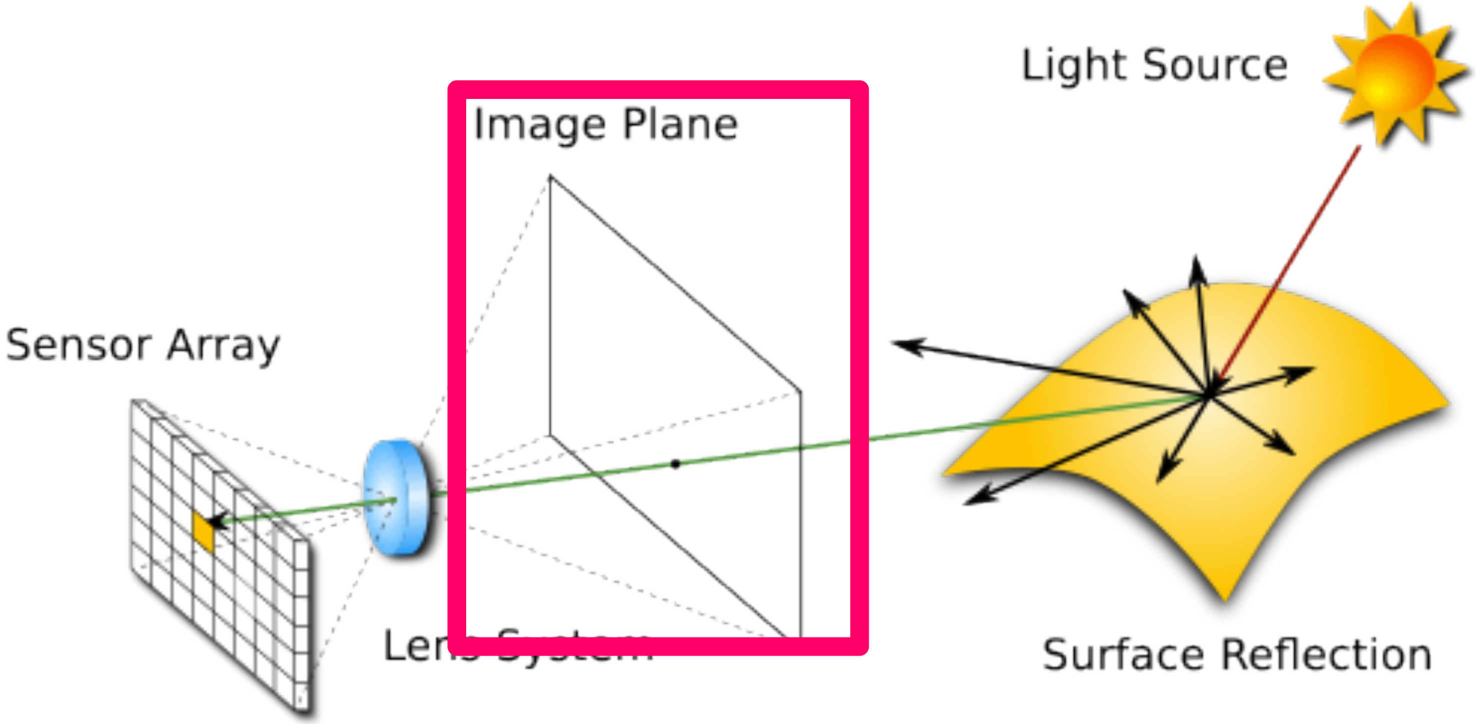
center of the lens = center of projection

notice the virtual image plane

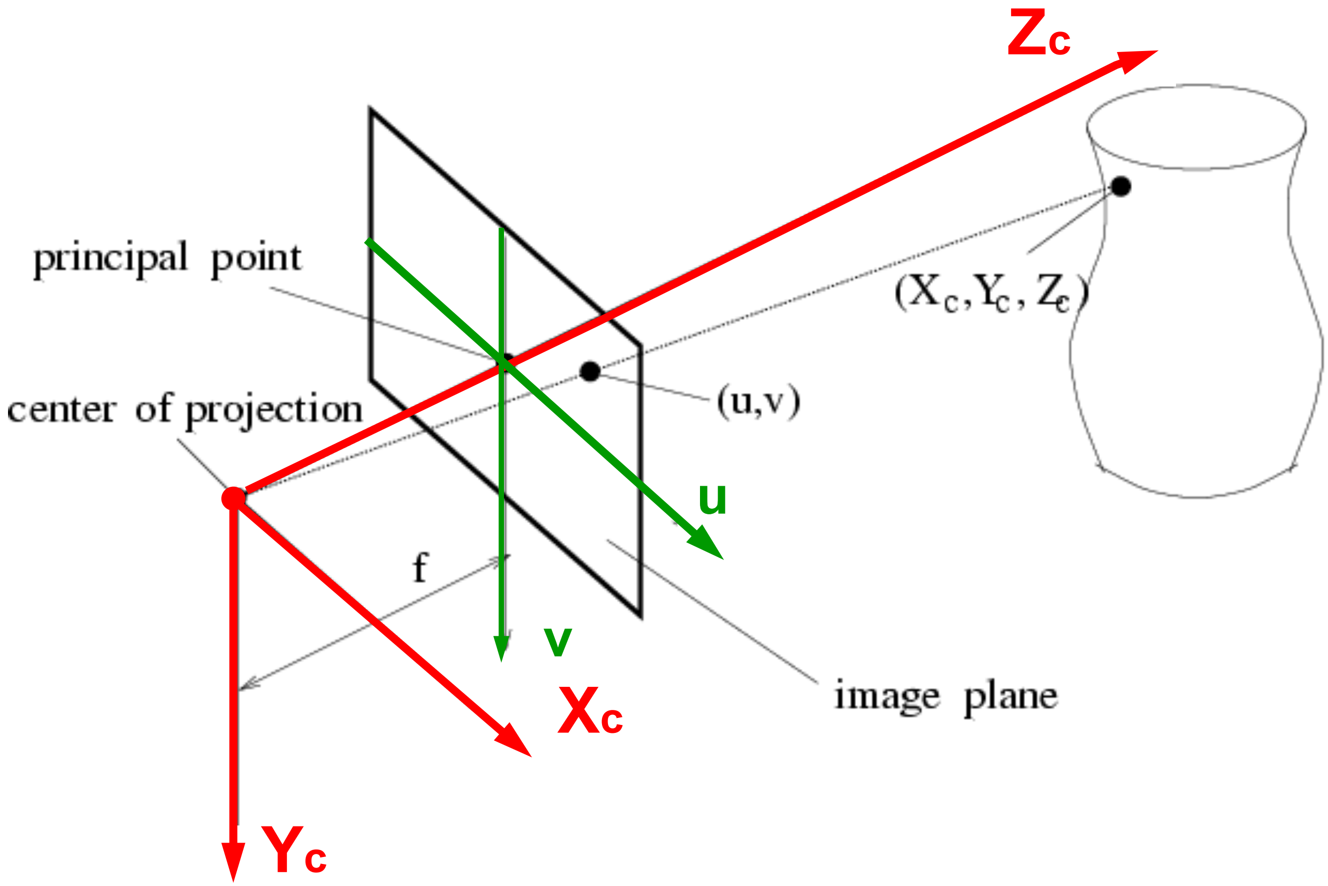
this is called *perspective* projection

Models for camera projection

We had the virtual plane also in the original reference sketch:



Perspective projection



- ❑ origin lies at the center of projection
- ❑ the Z_c axis coincides with the optical axis
- ❑ X_c-axis || to image rows, Y_c-axis || to columns

$$u = f\frac{X}{Z} \qquad v = f\frac{Y}{Z}$$

Pseudo-orthographic projection

$$u = f\frac{X}{Z} \qquad v = f\frac{Y}{Z}$$

If Z is constant ⇒ $x = kX$ and $y = kY$,
where $k = f/Z$

i.e. *orthographic* projection + a scaling

Good approximation if $f/Z \pm$ constant, i.e. if objects are small compared to their distance from the camera

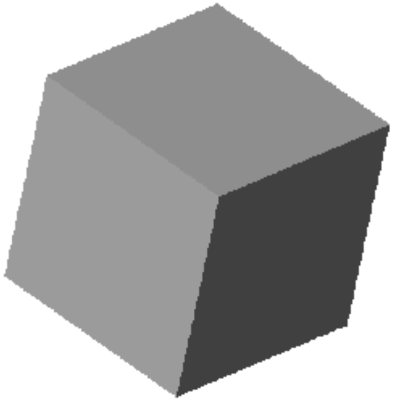
Pictoral comparison

Pseudo - orthographic

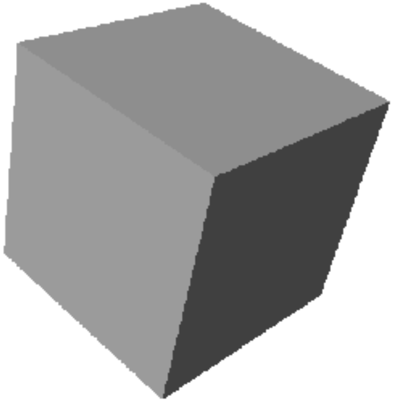
Perspective

Pictoral comparison

Pseudo - orthographic



Perspective



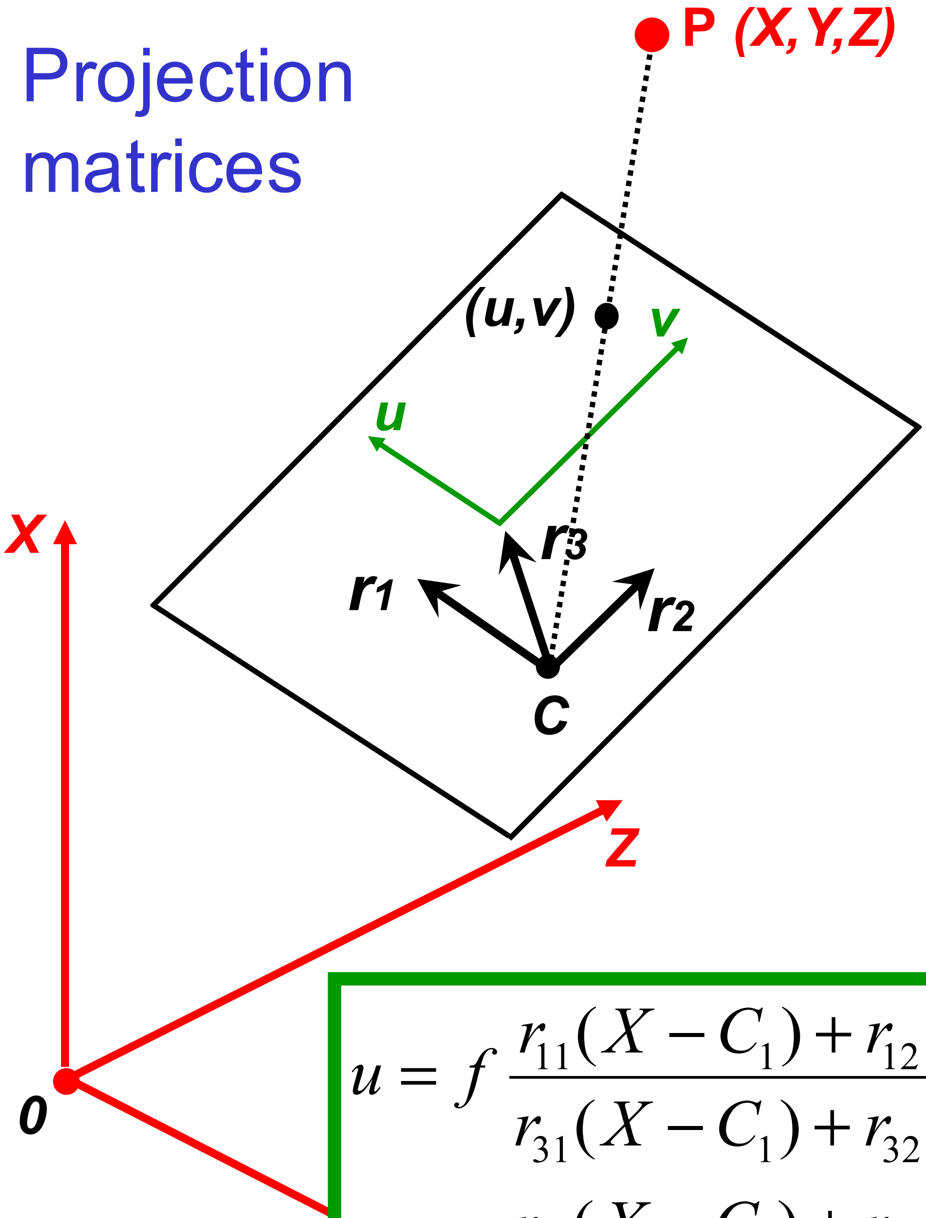
Projection matrices

the perspective projection model is incomplete : what if :

1. 3D coordinates are specified in a *world coordinate frame*
2. Image coordinates are expressed as *row and column numbers*

We will not consider additional refinements, such as radial distortions,...

Projection matrices



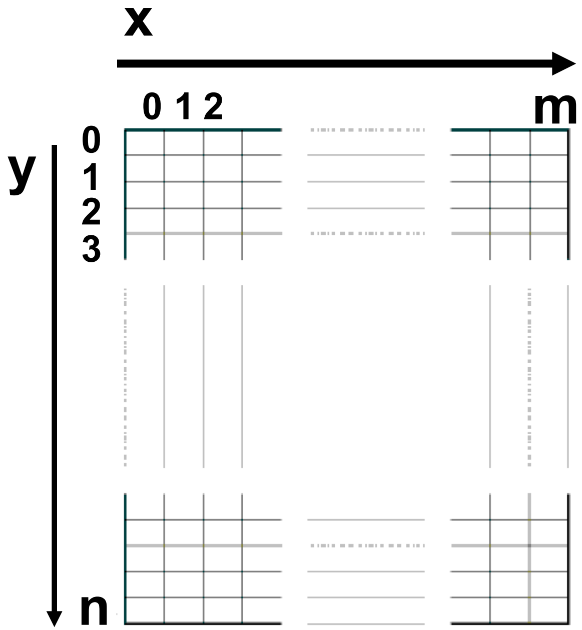
$$u = f\,\frac{\langle r_1, P - C\rangle}{\langle r_3, P - C\rangle}$$

$$v = f\,\frac{\langle r_2, P - C\rangle}{\langle r_3, P - C\rangle}$$

$$\boxed{\begin{aligned} u &= f\,\frac{r_{11}(X - C_1) + r_{12}(Y - C_2) + r_{13}(Z - C_3)}{r_{31}(X - C_1) + r_{32}(Y - C_2) + r_{33}(Z - C_3)} \\ v &= f\,\frac{r_{21}(X - C_1) + r_{22}(Y - C_2) + r_{23}(Z - C_3)}{r_{31}(X - C_1) + r_{32}(Y - C_2) + r_{33}(Z - C_3)} \end{aligned}}$$

Projection matrices

Image coordinates are to be expressed as *pixel coordinates*



$$\begin{cases} x = k_x u + s\,v + x_0 \\ y = \qquad\quad k_y v + y_0 \end{cases}$$

with :

→ (x_0, y_0) the pixel coordinates of the principal point

→

→ **NB7 :** *fully calibrated* means internally and externally calibrated

→ s indicates the skew , typically $s = 0$

Homogeneous coordinates

Often used to linearize non-linear relations

2D $$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} x/z \\ y/z \end{pmatrix}$$

3D $$\begin{pmatrix} X \\ Y \\ Z \\ W \end{pmatrix} \rightarrow \begin{pmatrix} X/W \\ Y/W \\ Z/W \end{pmatrix}$$

Homogeneous coordinates are only defined up to a factor

Projection matrices

$$\boxed{\begin{aligned} u &= f\,\frac{r_{11}(X-C_1)+r_{12}(Y-C_2)+r_{13}(Z-C_3)}{r_{31}(X-C_1)+r_{32}(Y-C_2)+r_{33}(Z-C_3)} \\ v &= f\,\frac{r_{21}(X-C_1)+r_{22}(Y-C_2)+r_{23}(Z-C_3)}{r_{31}(X-C_1)+r_{32}(Y-C_2)+r_{33}(Z-C_3)} \end{aligned}}$$

Exploiting homogeneous coordinates :

$$\tau\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f\,r_{11} & f\,r_{12} & f\,r_{13} \\ f\,r_{21} & f\,r_{22} & f\,r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\begin{pmatrix} X-C_1 \\ Y-C_2 \\ Z-C_3 \end{pmatrix}$$

Projection matrices

$$\begin{cases} x = k_x u + s\,v + x_0 \\ y = \qquad\quad k_y v + y_0 \end{cases}$$

Exploiting homogeneous coordinates :

$$\tau \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix} \tau \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

Projection matrices

Thus, we have :

$$\tau\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f\,r_{11} & f\,r_{12} & f\,r_{13} \\ f\,r_{21} & f\,r_{22} & f\,r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\begin{pmatrix} X - C_1 \\ Y - C_2 \\ Z - C_3 \end{pmatrix}$$

$$\tau\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}\tau\begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

➔

Projection matrices

Concatenating the results :

$$\tau\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} f\,r_{11} & f\,r_{12} & f\,r_{13} \\ f\,r_{21} & f\,r_{22} & f\,r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\begin{pmatrix} X - C_1 \\ Y - C_2 \\ Z - C_3 \end{pmatrix}$$

Or, equivalently :

$$\tau\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\begin{pmatrix} X - C_1 \\ Y - C_2 \\ Z - C_3 \end{pmatrix}$$

➔

Projection matrices

Re-combining matrices in the concatenation :

$$\tau\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\begin{pmatrix} X - C_1 \\ Y - C_2 \\ Z - C_3 \end{pmatrix}$$

yields the calibration matrix *K*:

$$K = \begin{pmatrix} k_x & s & x_0 \\ 0 & k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} f\,k_x & f\,s & x_0 \\ 0 & f\,k_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}$$

Projection matrices

We define $$p = \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}; \quad P = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \quad \widetilde{P} = \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

yielding

$$\boxed{\rho p = KR^t(P - C)}$$ for some non-zero $\rho \in \mathbb{R}$

or, $$\rho p = K\left(R^t \mid -R^t C\right)\widetilde{P}$$

or, $$\rho p = (M \mid t)\widetilde{P}$$ with rank $M = 3$

From object radiance to pixel grey levels

After the geometric camera model...

… a photometric camera model

2 steps:

1. from object radiance to image irradiance
2. from image irradiance to pixel grey level

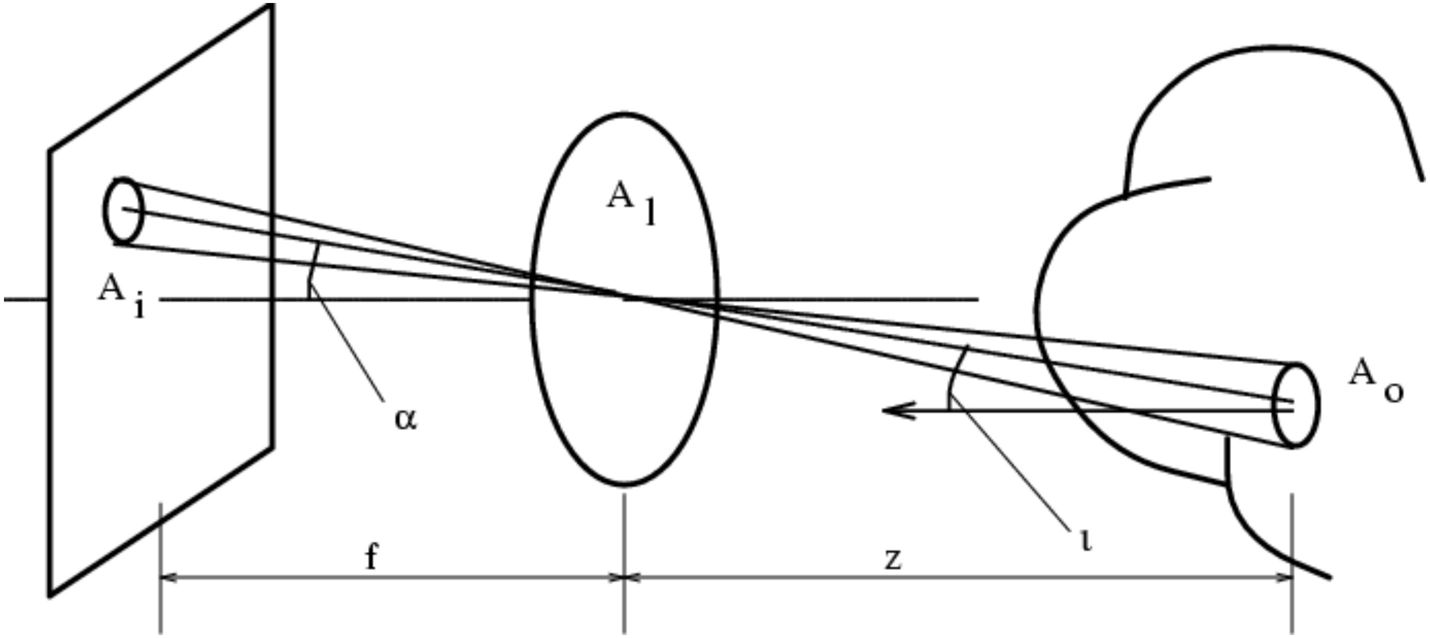
Image irradiance and object radiance

we look at the irradiance that an object patch will cause in the image

assumptions :
radiance *R* assumed known and
object at large distance compared to the focal length

Is image irradiance directly related to the radiance of the image patch?

The viewing conditions



$$I = R\frac{A_l}{f^2}\cos^4\alpha$$

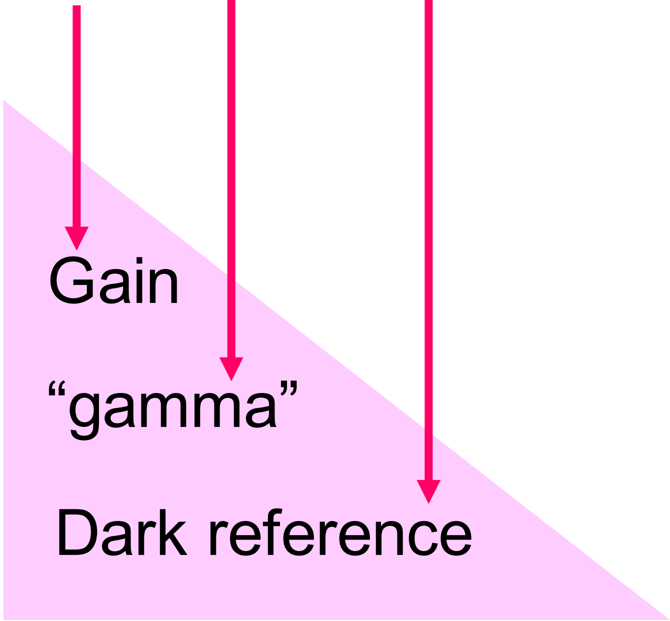
the $\cos^4$ law

The $\cos^4$ law cont'd

Especially strong effects for wide-angle and fisheye lenses

From irradiance to gray levels

$$f = g\, I^{\gamma} + d$$



Gain

“gamma”

Dark reference

From irradiance to gray levels

$$f = g\, I^{\gamma} + d$$

set w. size diaphragm	Gain
close to 1 nowadays	“gamma”
signal w. cam cap on	Dark reference

illumination

Illumination

Well-designed illumination often is key in visual inspection

The light was good, but the hot wax was a problem...

Illumination techniques

Simplify the image processing by controlling the environment

An overview of illumination techniques:

1. back-lighting
2. directional-lighting
3. diffuse-lighting
4. polarized-lighting
5. coloured-lighting
6. structured-lighting
7. stroboscopic lighting

Back-lighting

lamps placed behind a transmitting diffuser plate,
light source behind the object

generates high-contrast silhouette images,
easy to handle with *binary vision*

often used in inspection

Example backlighting

Directional and diffuse lighting

Directional-lighting

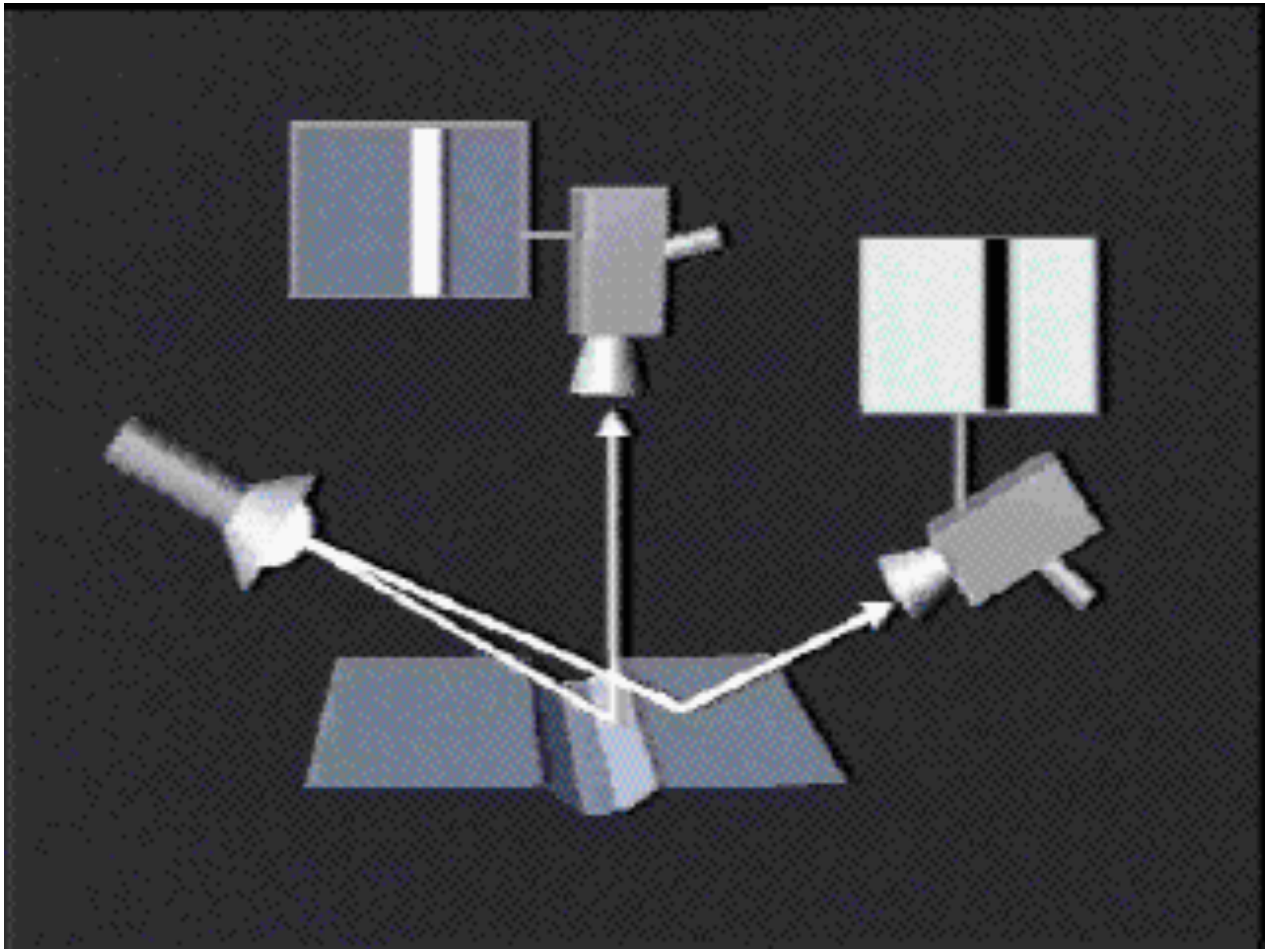
generate sharp shadows
generation of specular reflection
(e.g. crack detection)

shadows and shading yield information about shape

Diffuse-lighting

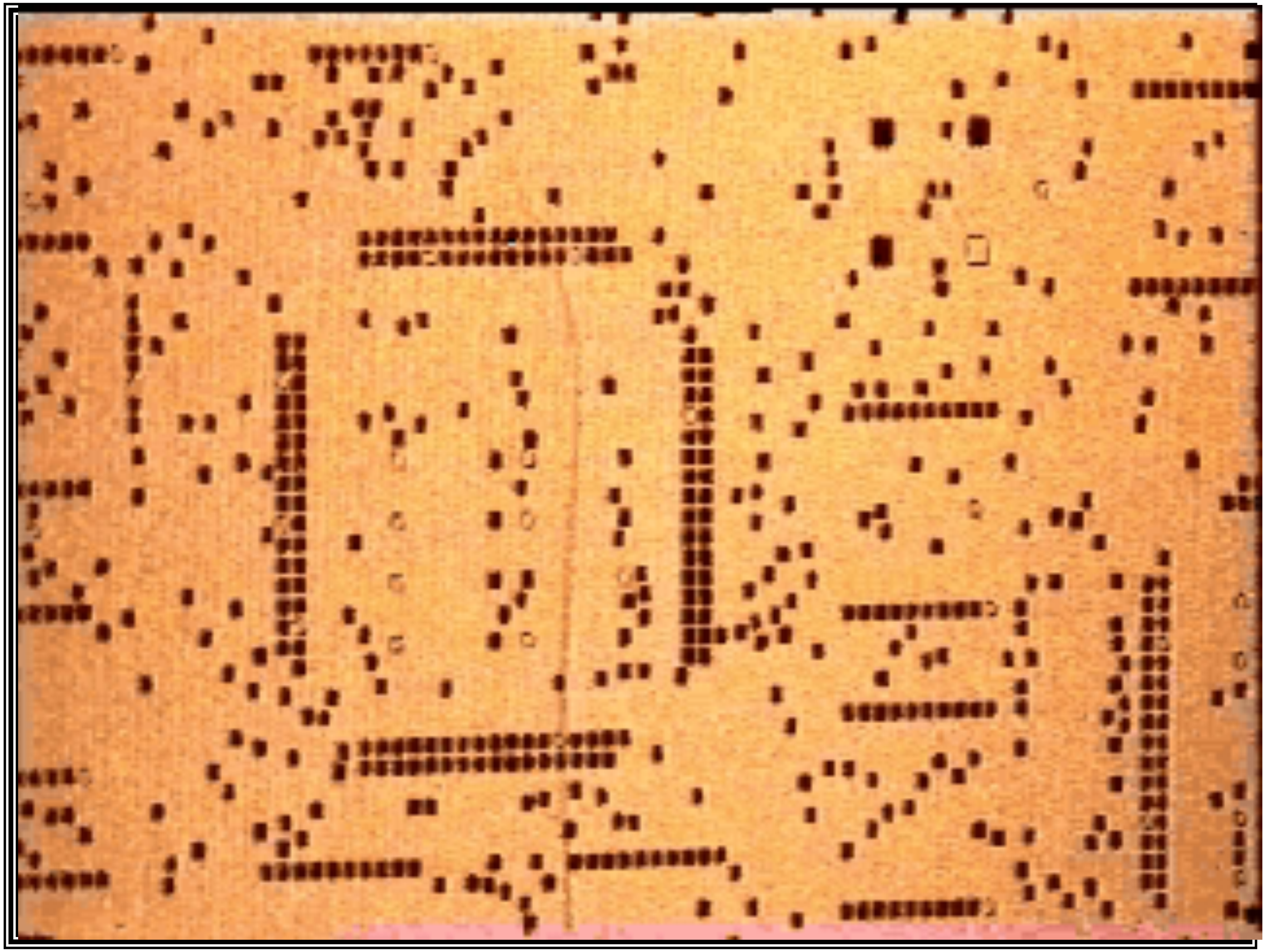
illuminates uniformly from all directions
prevents sharp shadows and large intensity variations over glossy surfaces

Crack detection

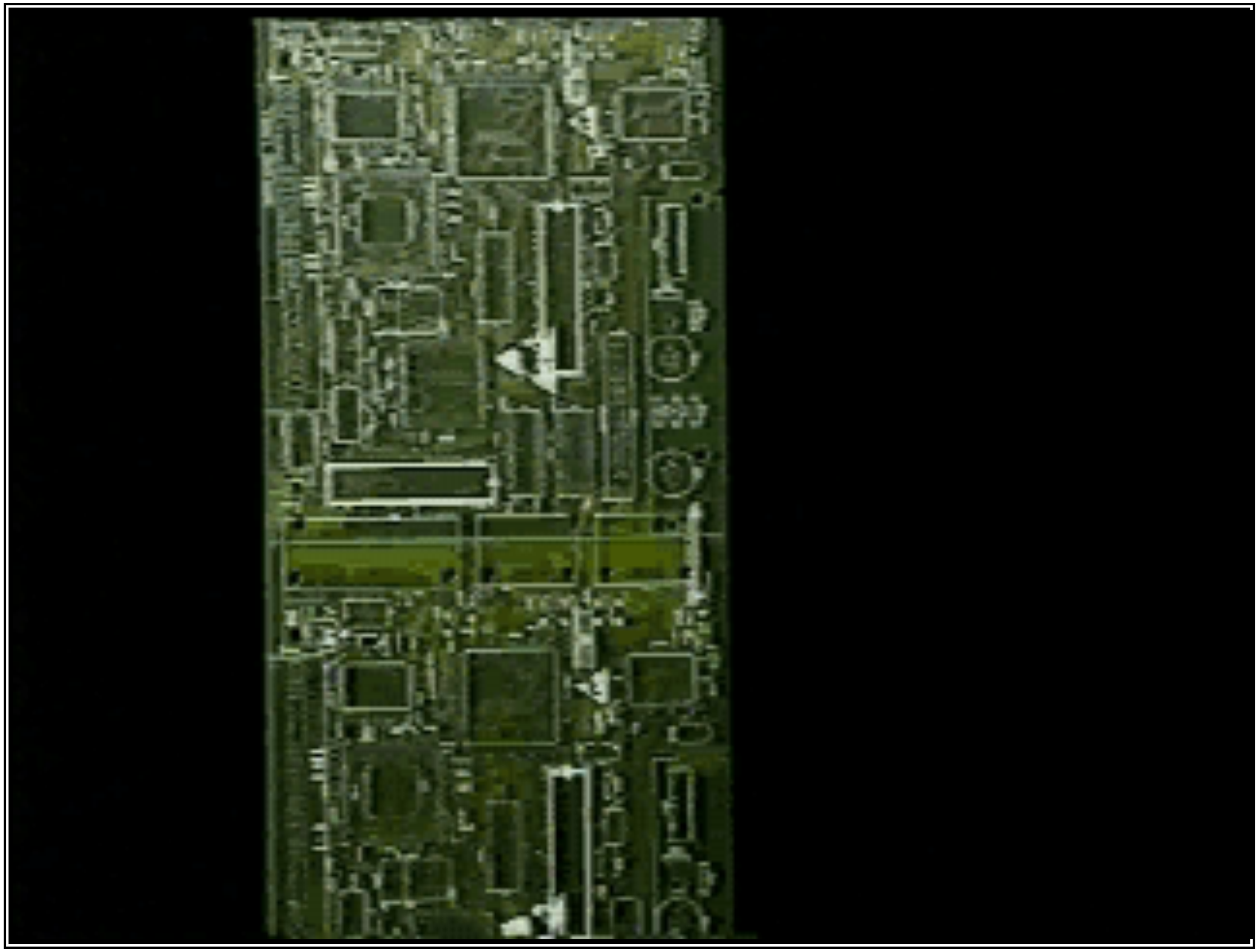


Computer Vision

Example directional lighting



Example diffuse lighting



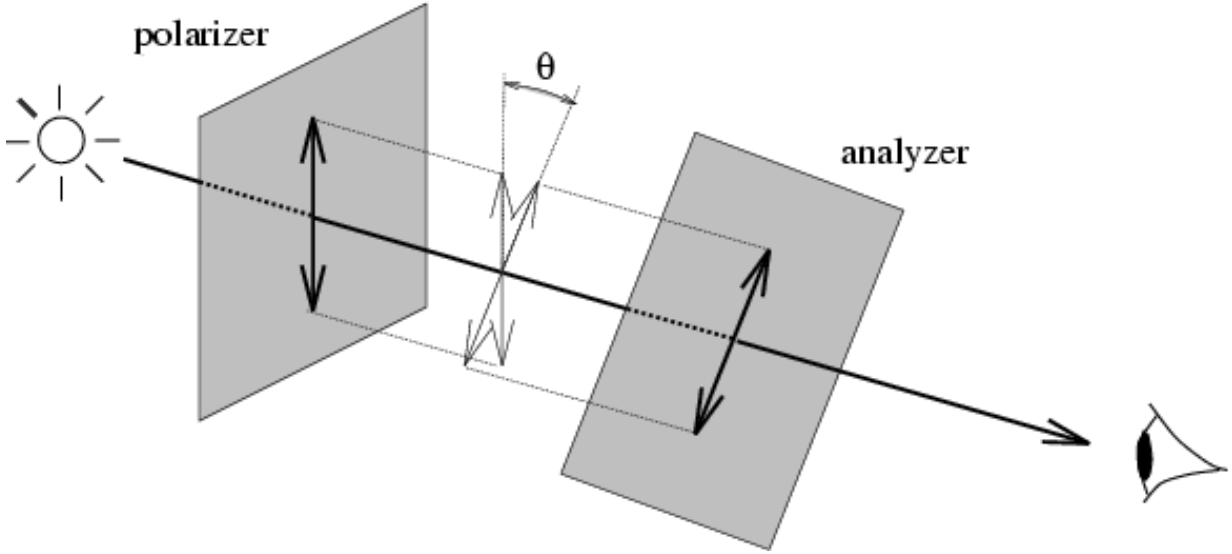
Polarized lighting

2 uses:

1. to improve contrast between Lambertian and specular reflections
2. to improve contrasts between dielectrics and metals

Polarised lighting

polarizer/analyzer configurations



law of Malus :

$$I(\theta) = I(0)\cos^2\theta$$

Polarized lighting

2 uses:

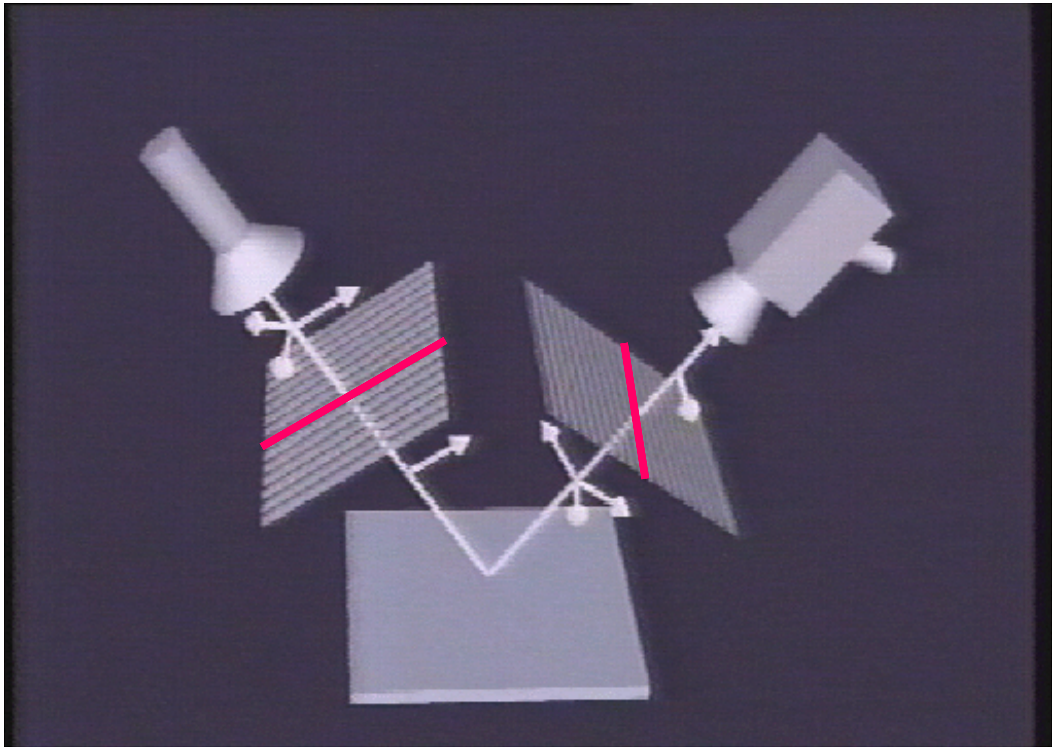
1. to improve contrast between Lambertian and specular reflections

2. to improve contrasts between dielectrics and metals

Polarized lighting

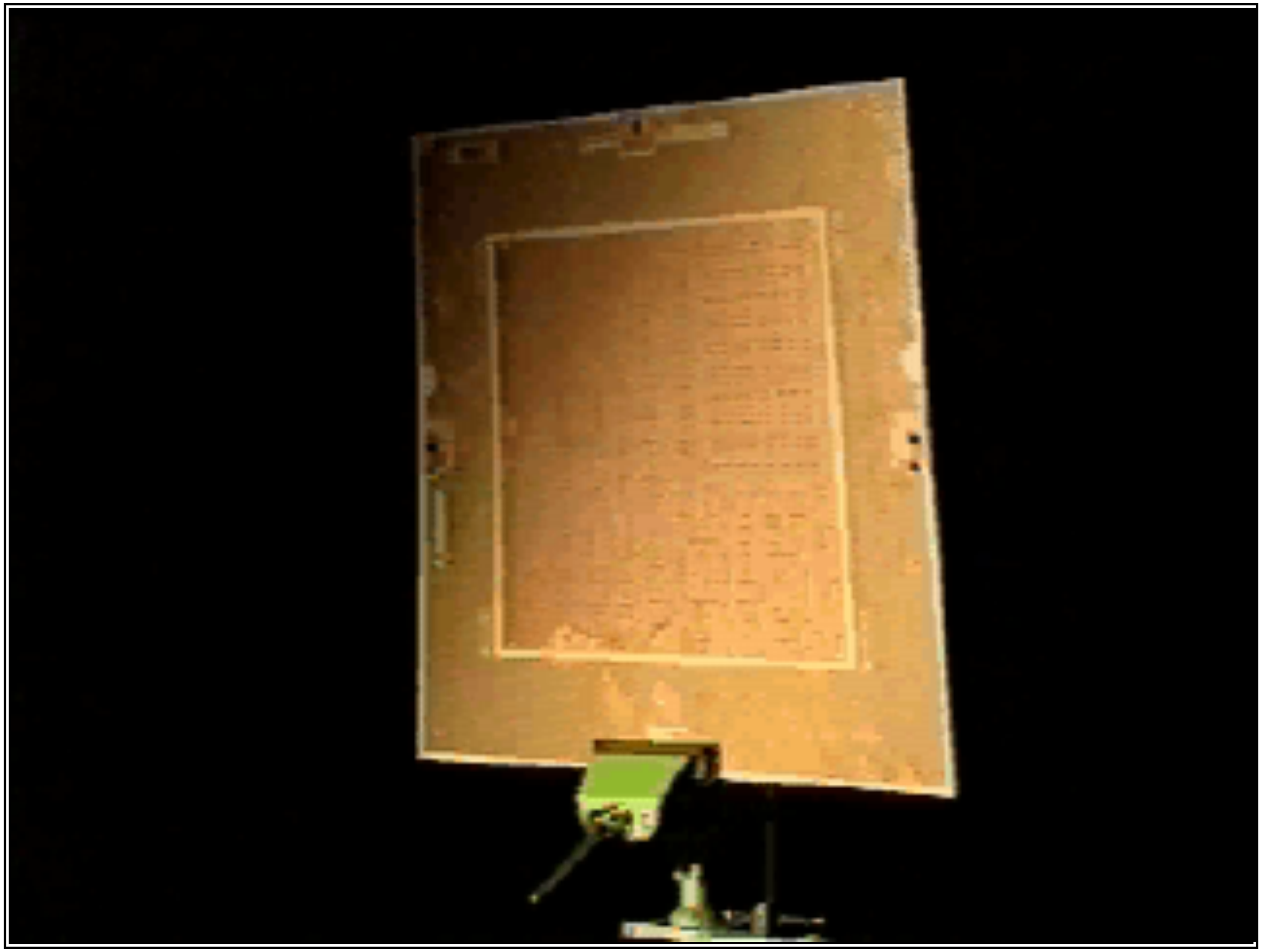
specular reflection keeps polarisation :
diffuse reflection depolarises

suppression of specular reflection :



polarizer/analyzer crossed
prevents the large dynamic range caused by glare

Example pol. lighting (pol./an.crossed)



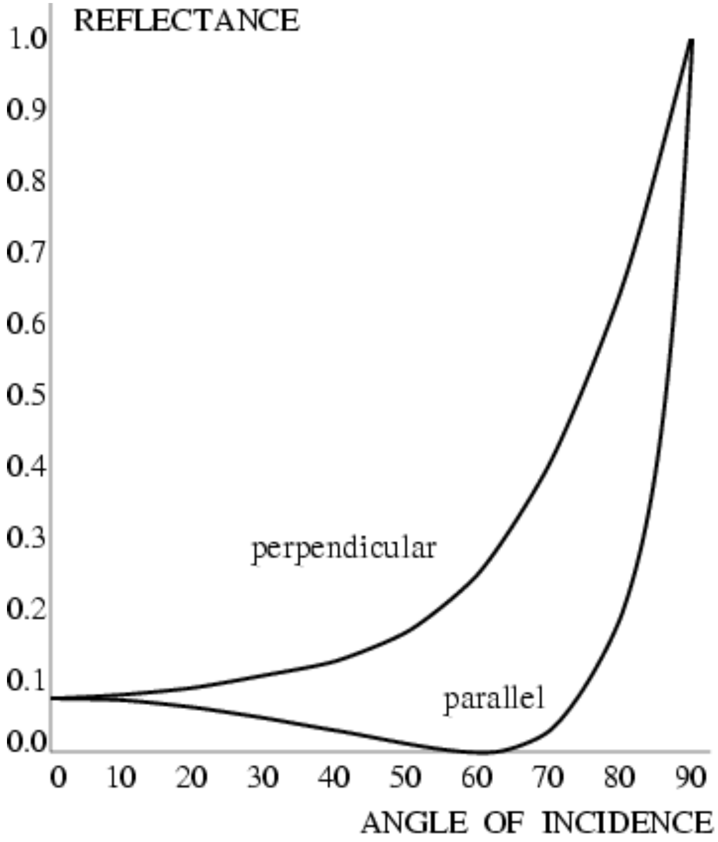
Polarized lighting

2 uses:

1. to improve contrast between Lambertian and specular reflections

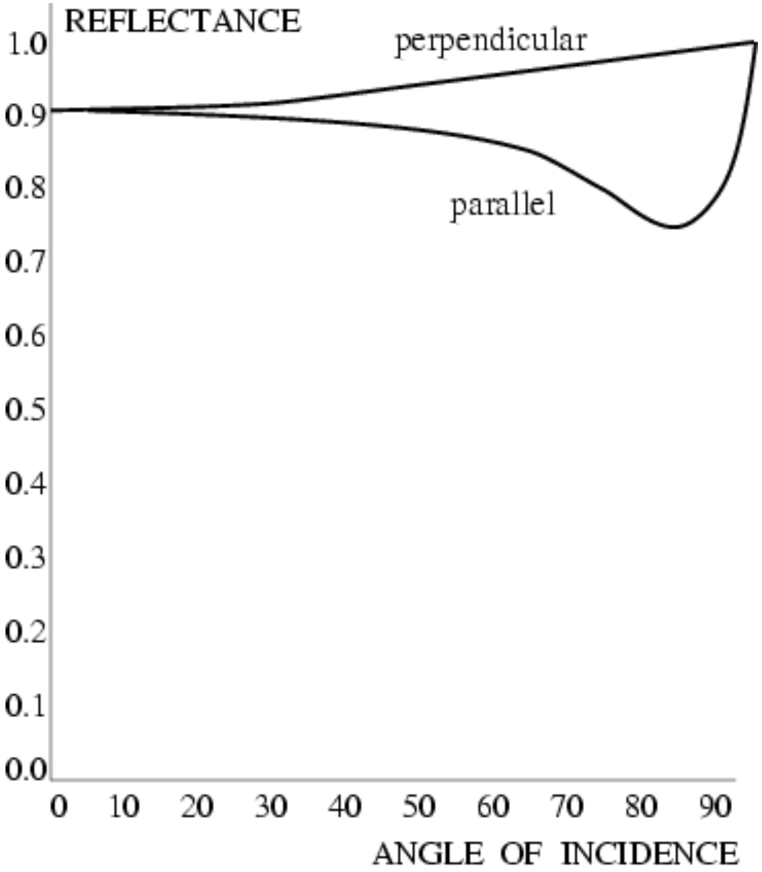
2. to improve contrasts between dielectrics and metals

Reflection : dielectric



Polarizer at *Brewster angle*

Reflection : conductor

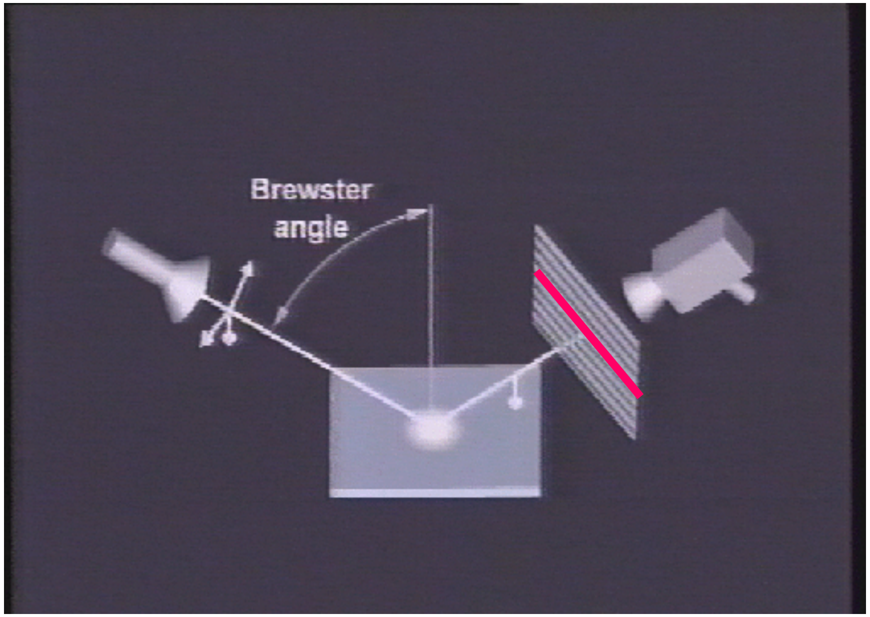


strong reflectors
more or less preserve polarization

Polarised lighting

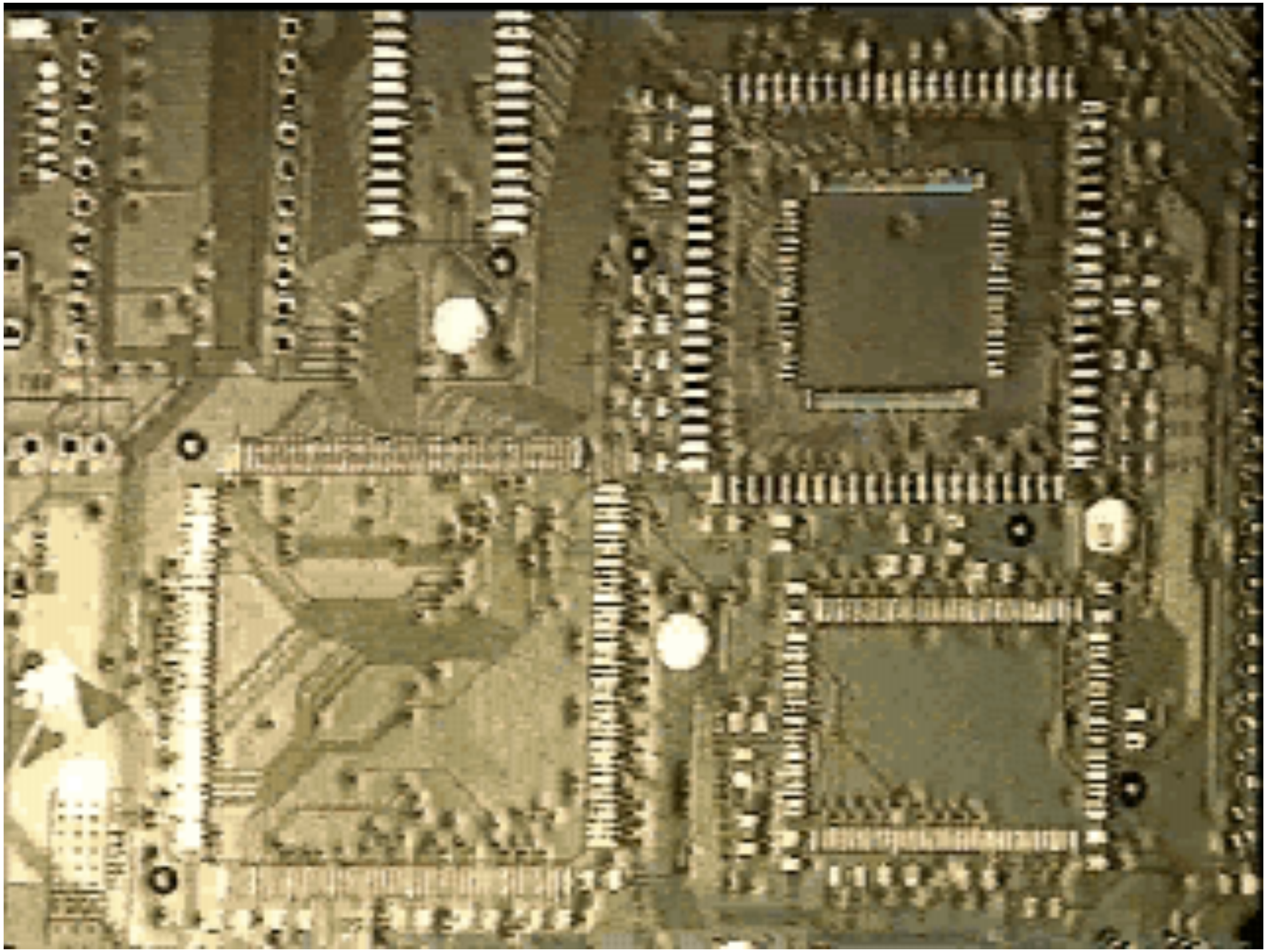
distinction between specular reflection from dielectrics and metals;
works under the Brewster angle for the dielectric
dielectric has no parallel comp. ; metal does

suppression of specular reflection from dielectrics :



polarizer/analyzer aligned
distinguished metals and dielectrics

Example pol. lighting (pol./an. aligned)



Coloured lighting

highlight regions of a similar colour

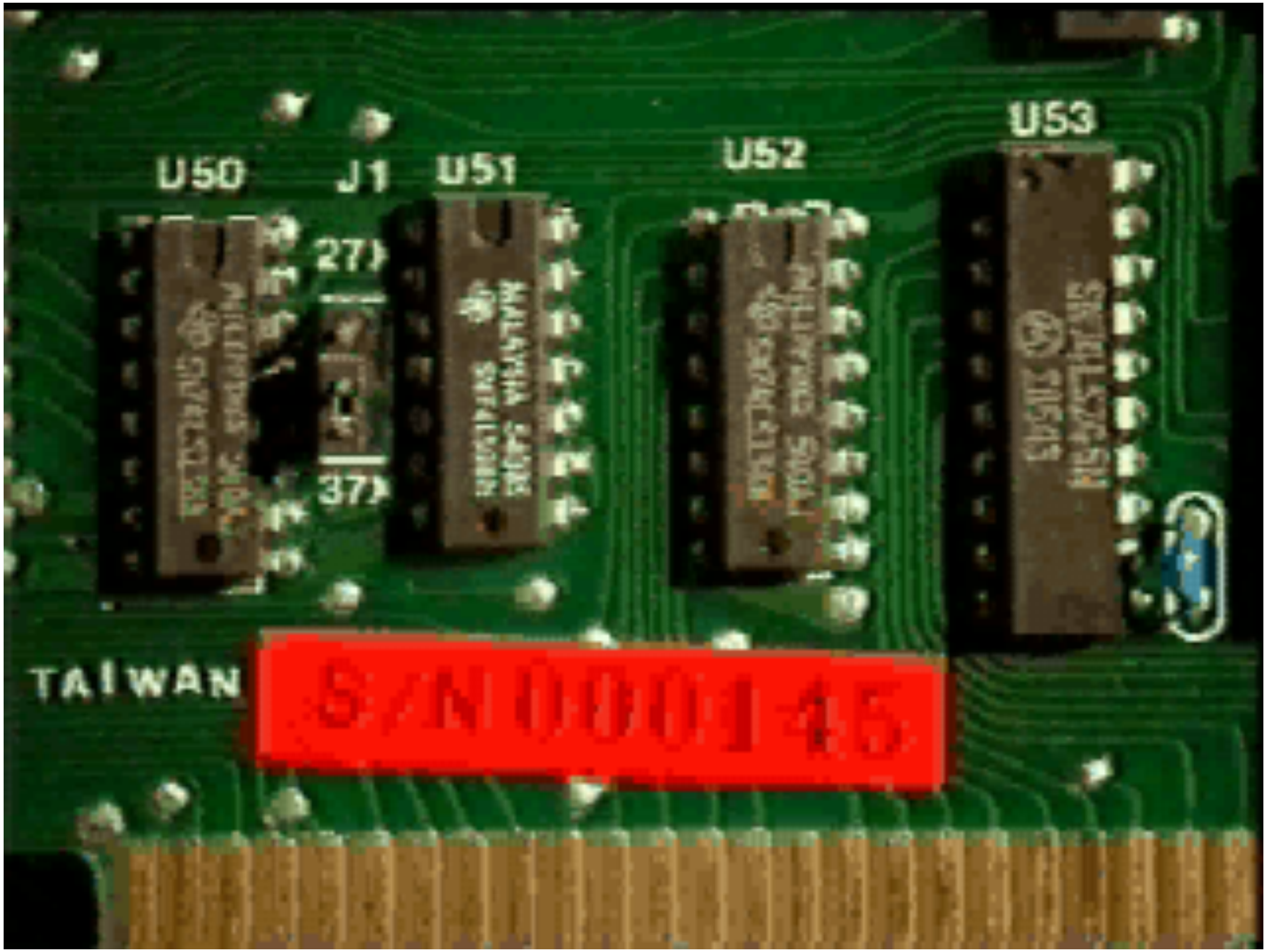
with band-pass filter: only light from projected pattern (e.g. monochromatic light from a laser)

differentiation between specular and diffuse reflection

comparing colours ⇨ same spectral composition of sources!

spectral sensitivity function of the sensors!

Example coloured lighting



Coloured lighting

Example videos: weed-selective herbicide spraying

Coloured lighting

Structured and stroboscopic lighting

spatially or temporally modulated light pattern

Structured lighting

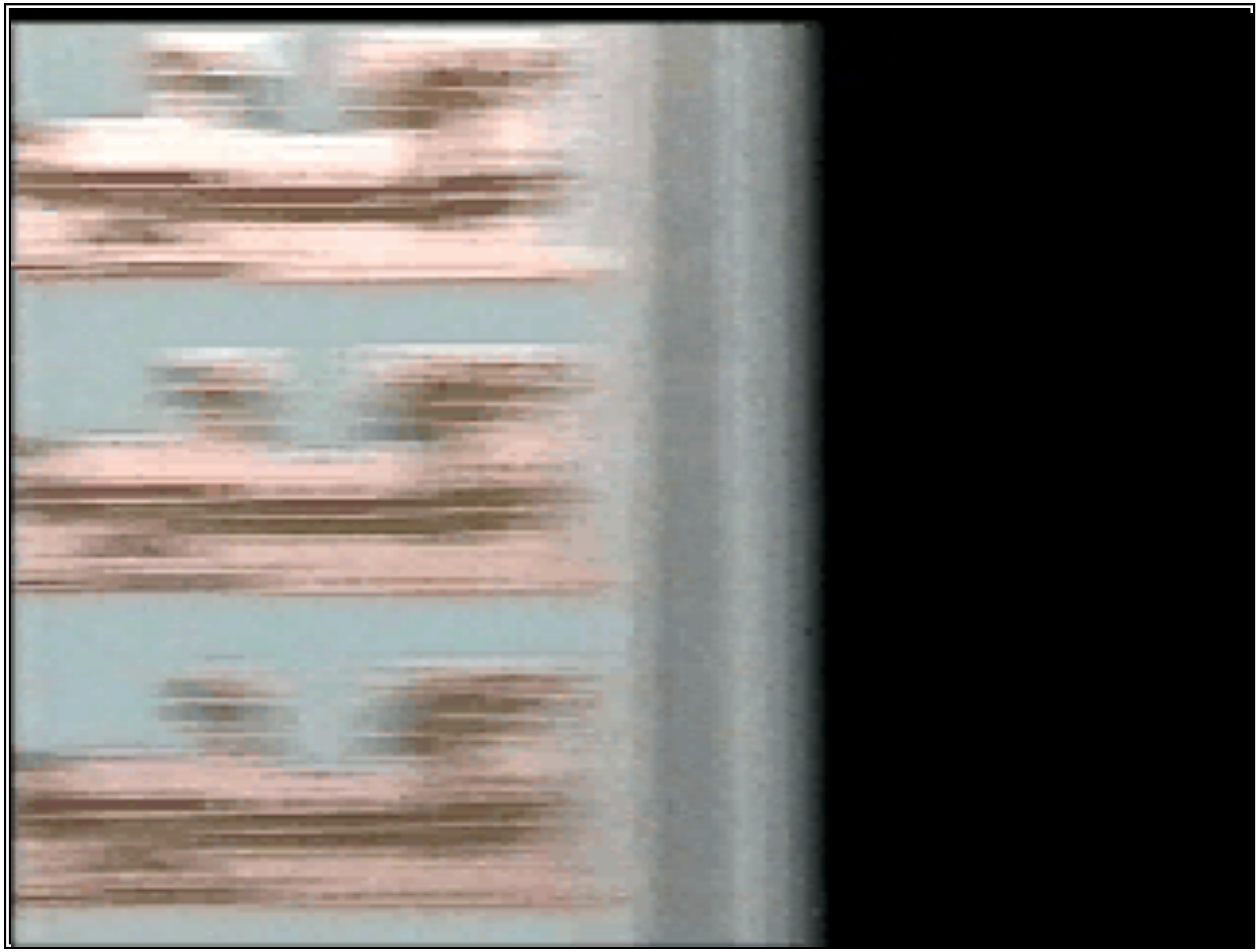
e.g. : 3D shape : objects distort the projected pattern
(more on this later)

Stroboscopic lighting

high intensity light flash

to eliminate motion blur

Stroboscopic lighting



Application

Example videos: vegetable inspection

Application