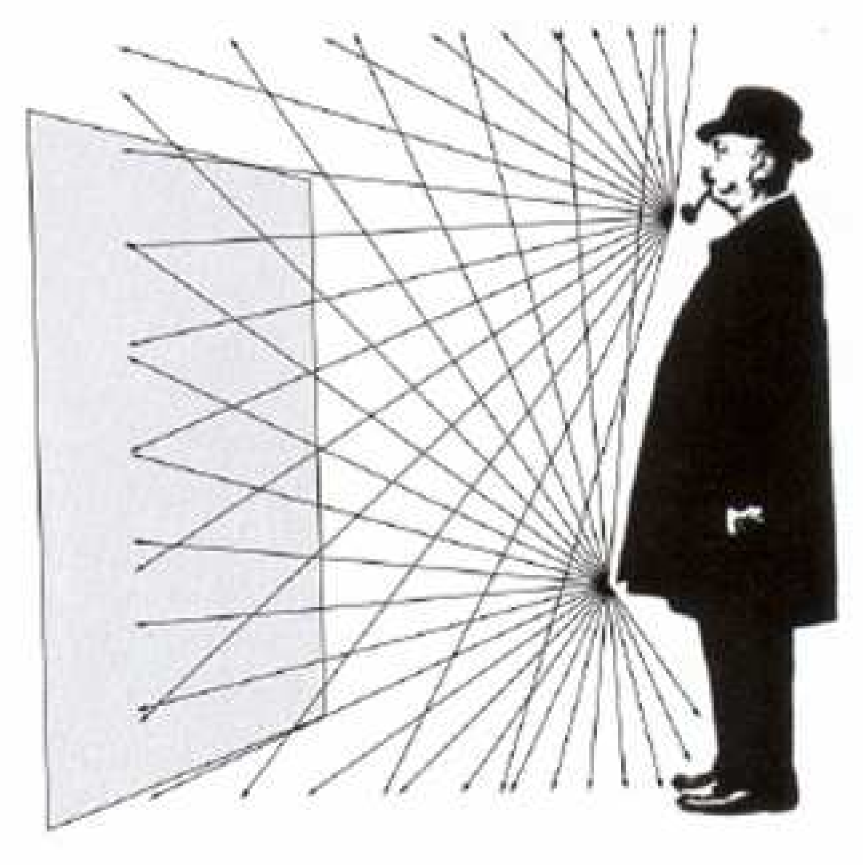
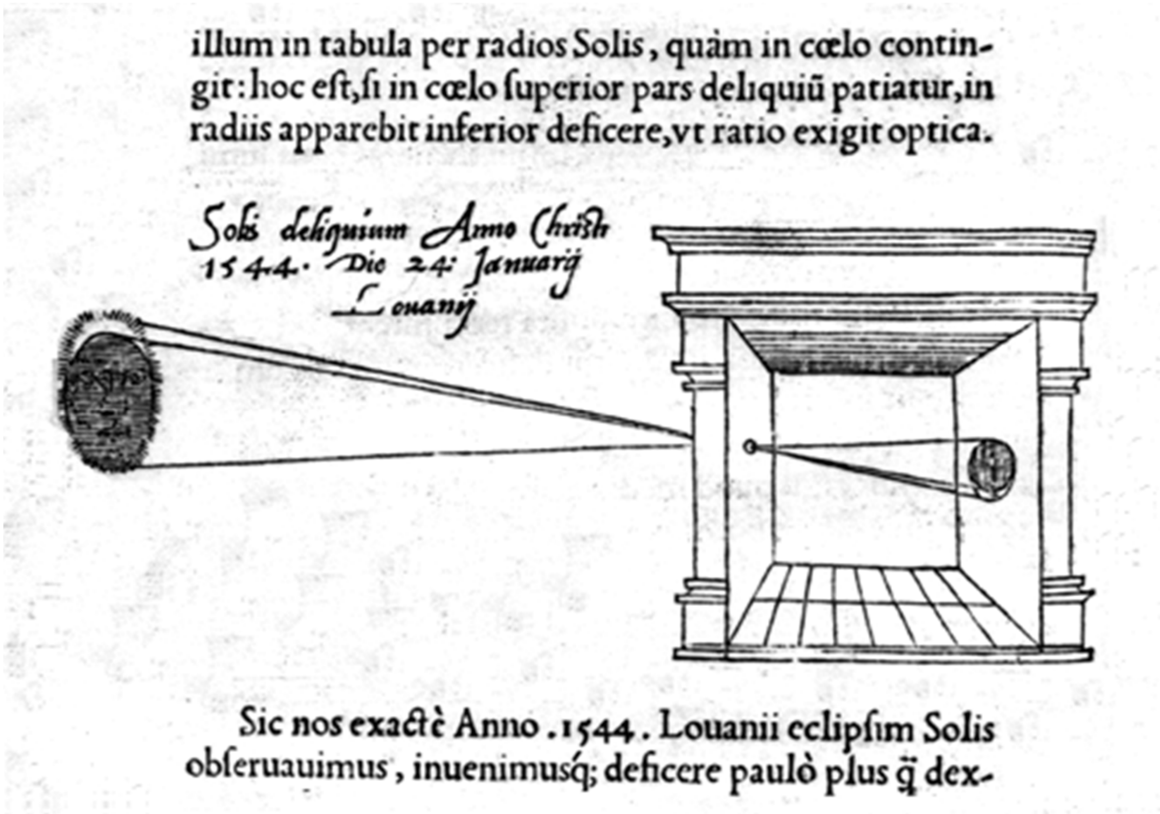
Image formation

Why there is no image on a white paper

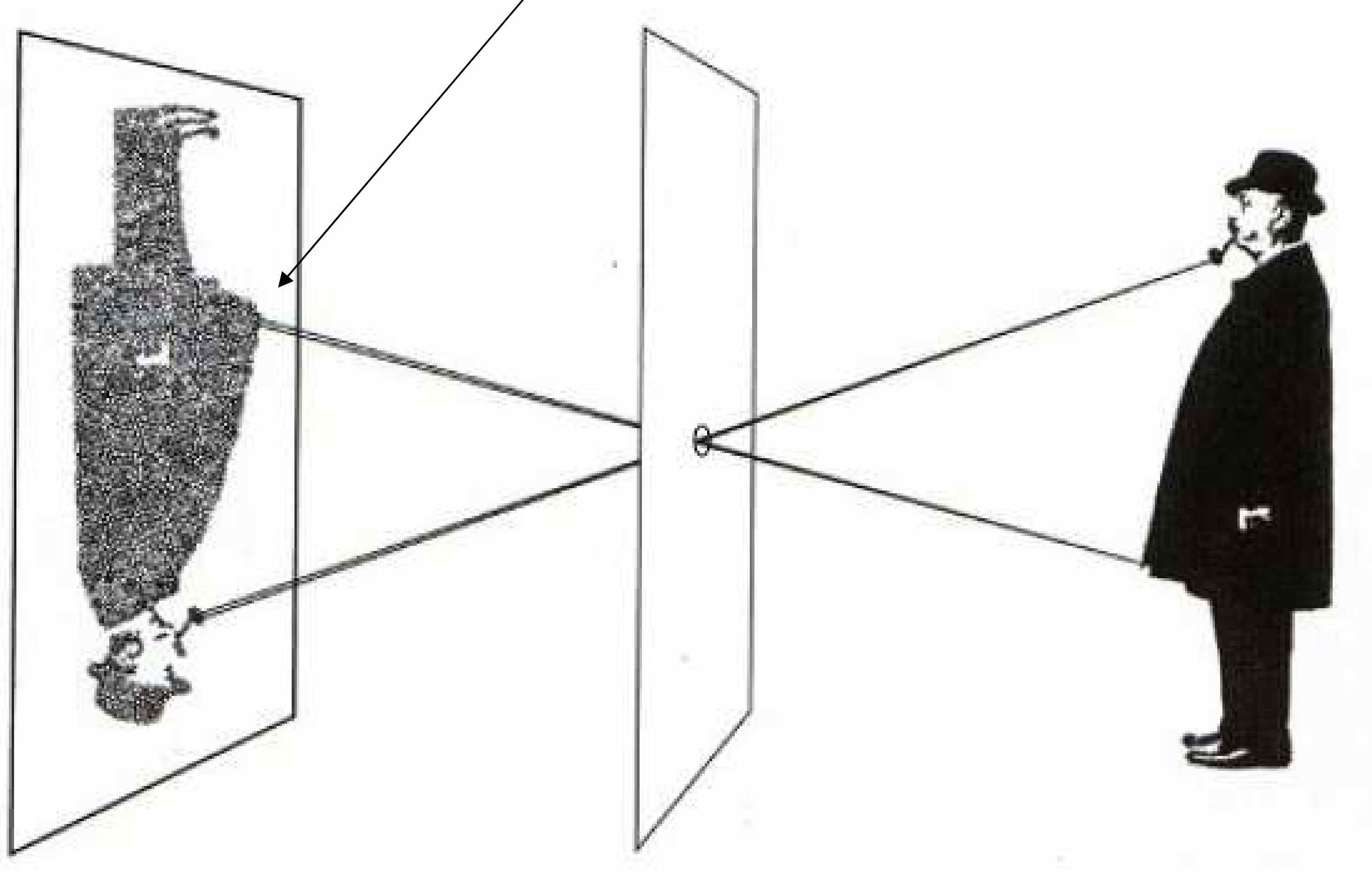


Pinhole

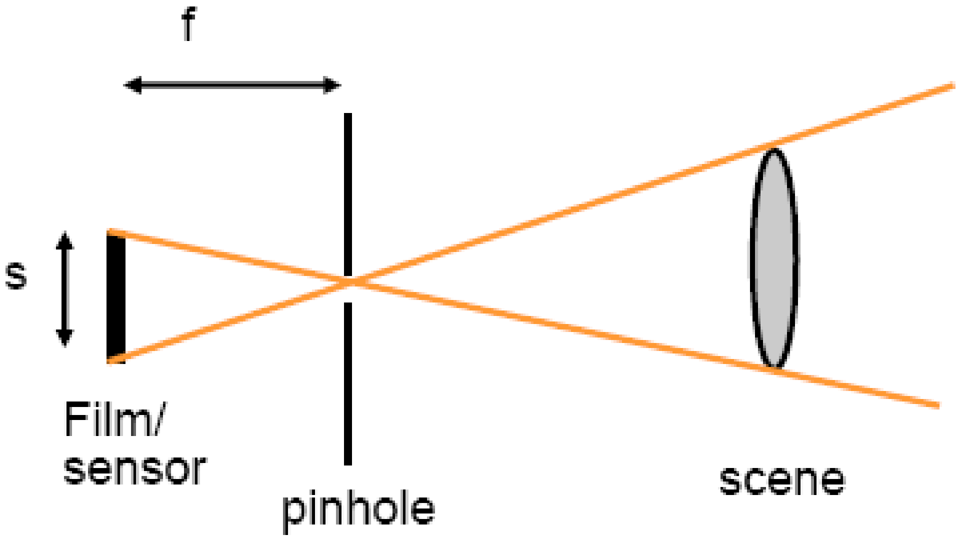

illum in tabula per radios Solis, quàm in cœlo contin-
git: hoc eſt, ſi in cœlo ſuperior pars deliquiũ patiatur, in
radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipſim Solis
obſeruauimus, inuenimusq; deficere paulò plus q̃ dex-

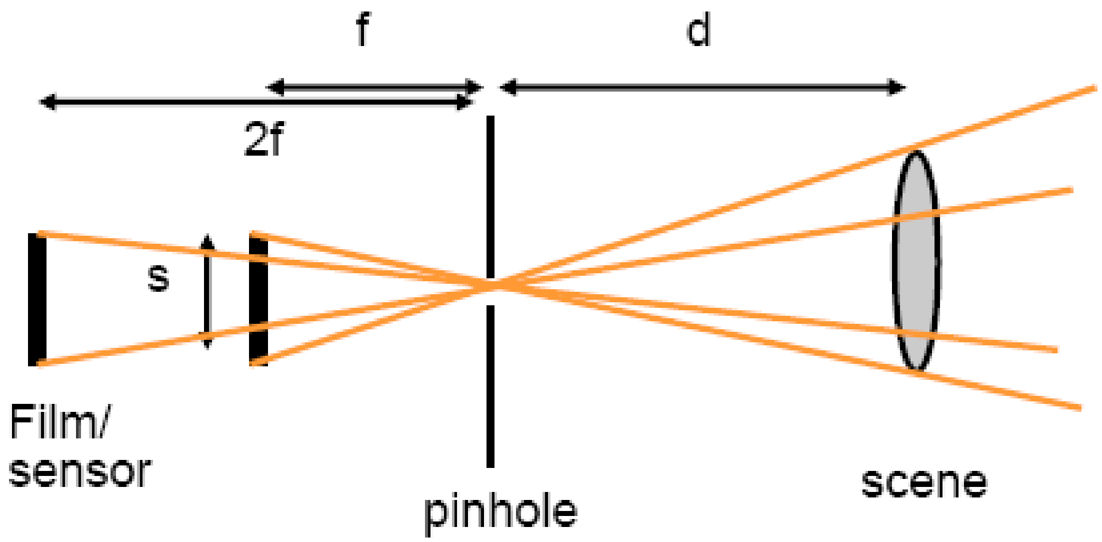
Each point in the scene projects to a single (or very small) point in the image



- The focal length *f* is the distance between the pinhole and the sensor

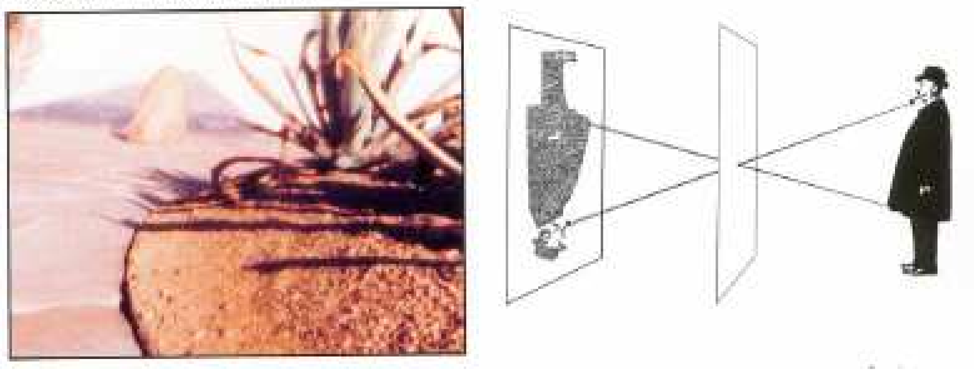


- If we double *f* we double the size of the projected object

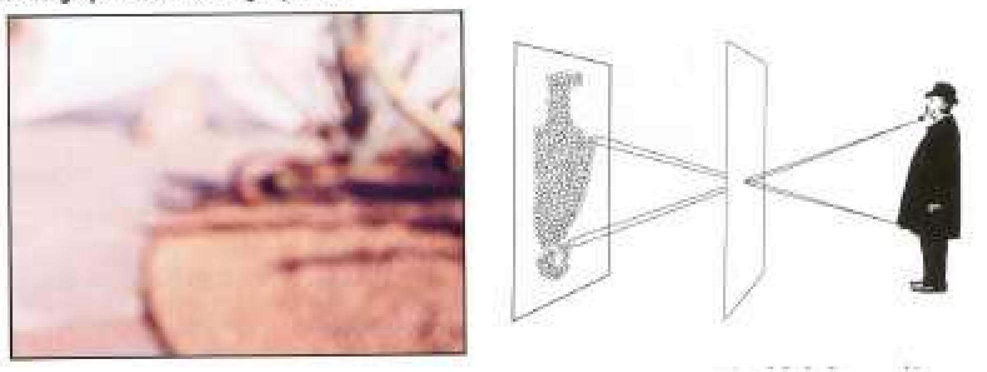


Problems:
- limited light
- the size of the pinhole limits sharpness

Photograph made with small pinhole

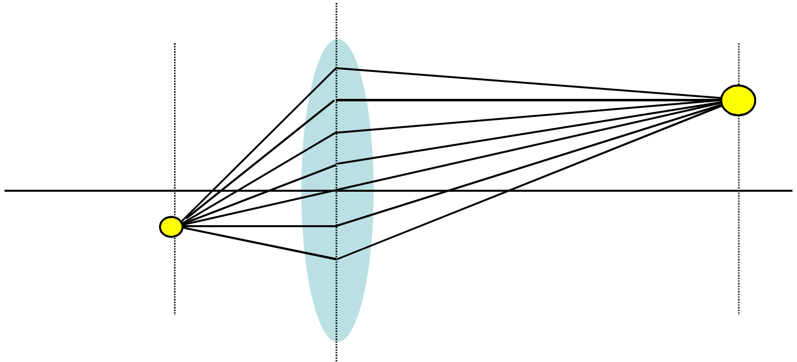


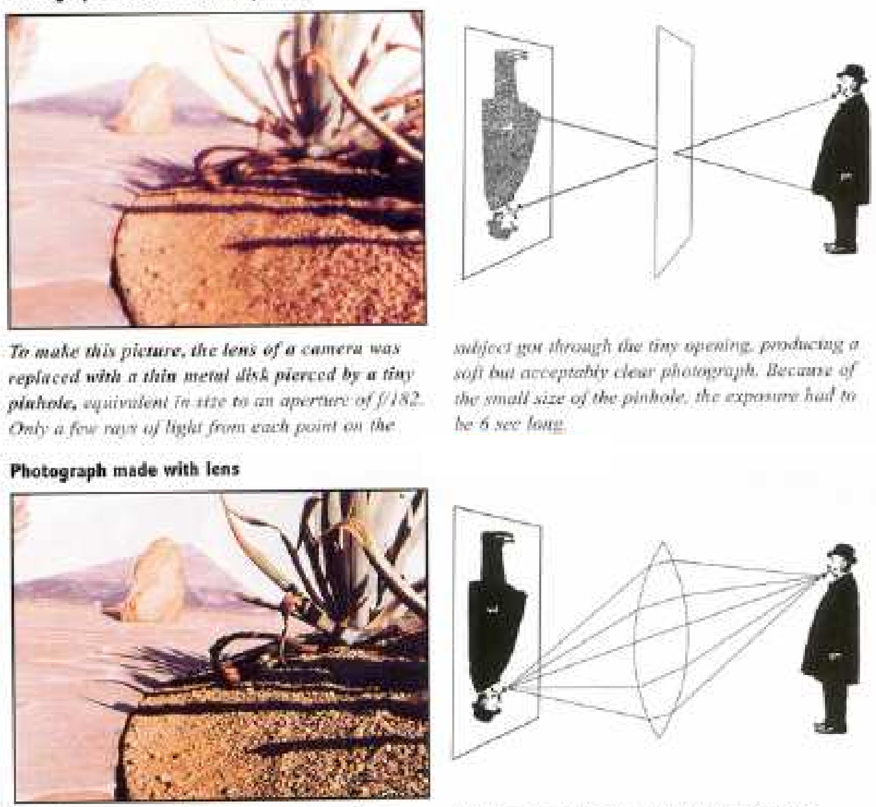
Photograph made with larger pinhole



Converging lenses

Lenses focus the light from different directions/rays (*refraction*)





Photograph made with small pinhole

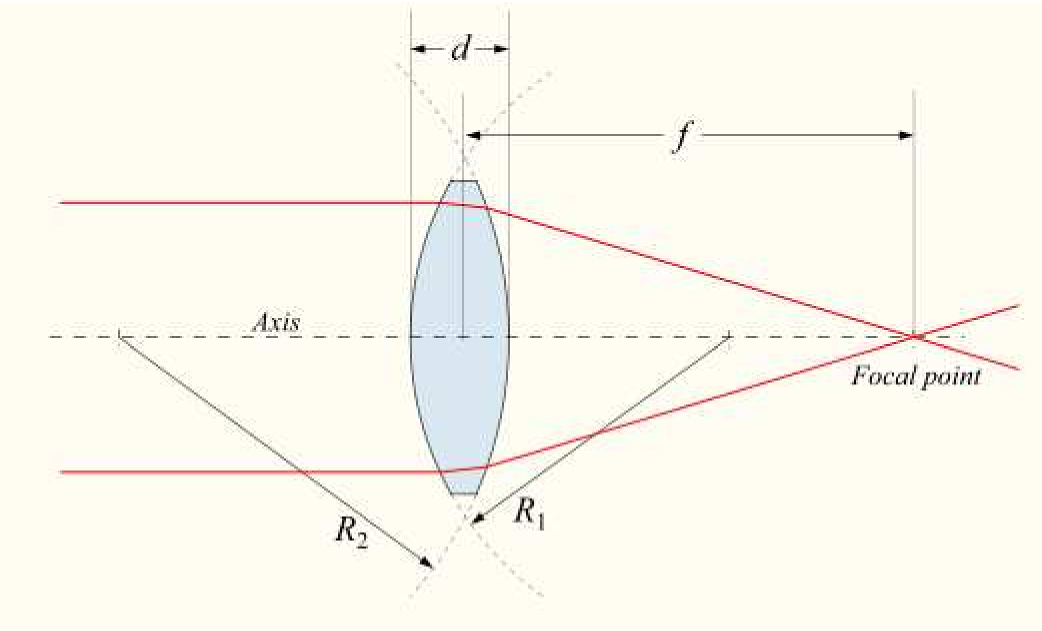
To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*

Photograph made with lens

This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec. The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.*

How to draw the rays

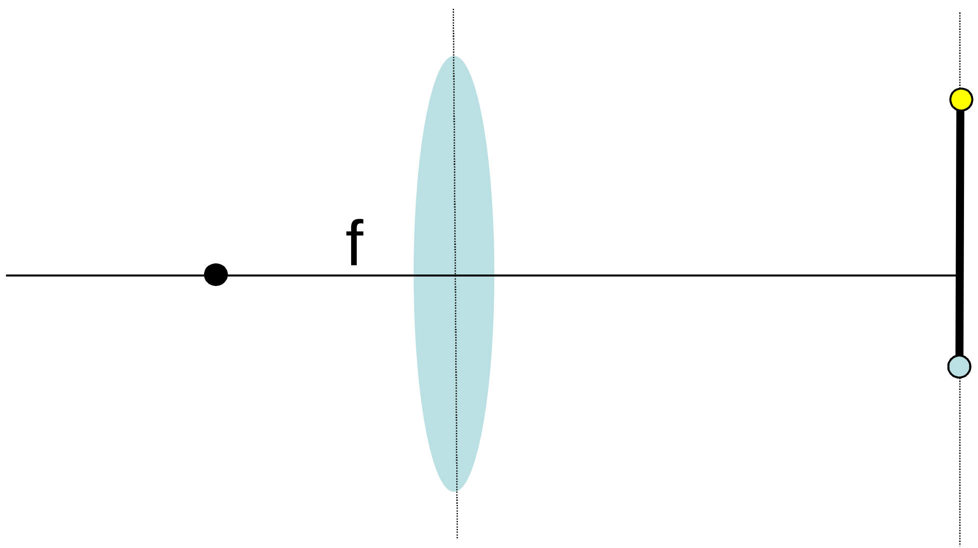
- Three rules
  1. incident rays parallel to the principal axis converge to the focal point
  2. incident rays passing through the center of the lens do not modify their direction
  3. incident rays through the focal point on the right side of the lens get reflected and travel parallel to the principal axis



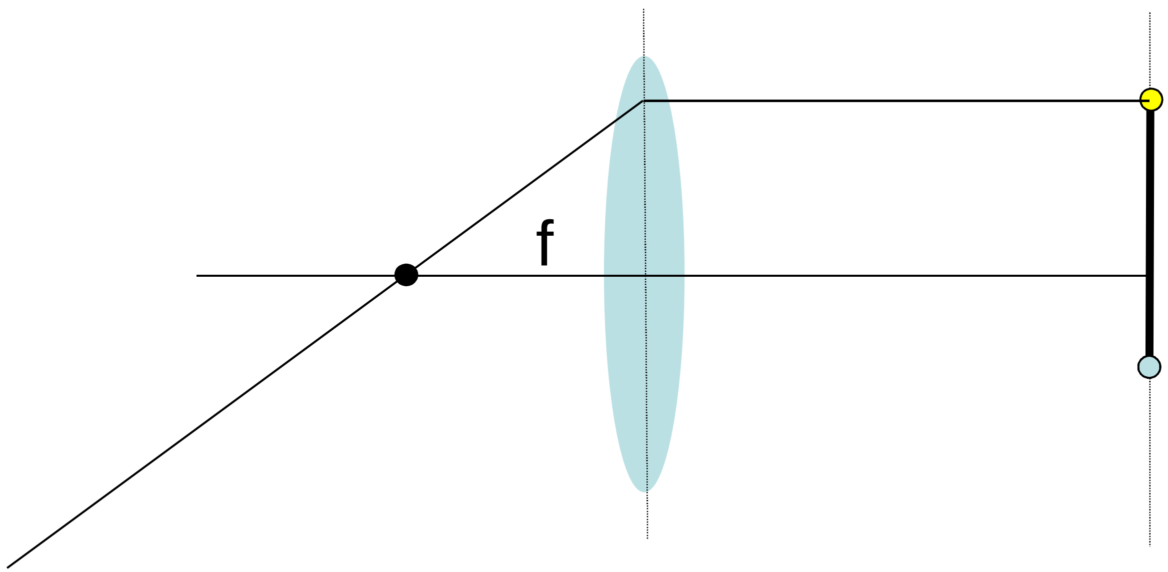
Positive (converging) lens

Thin lens approx:
d small compared to R1 and R2

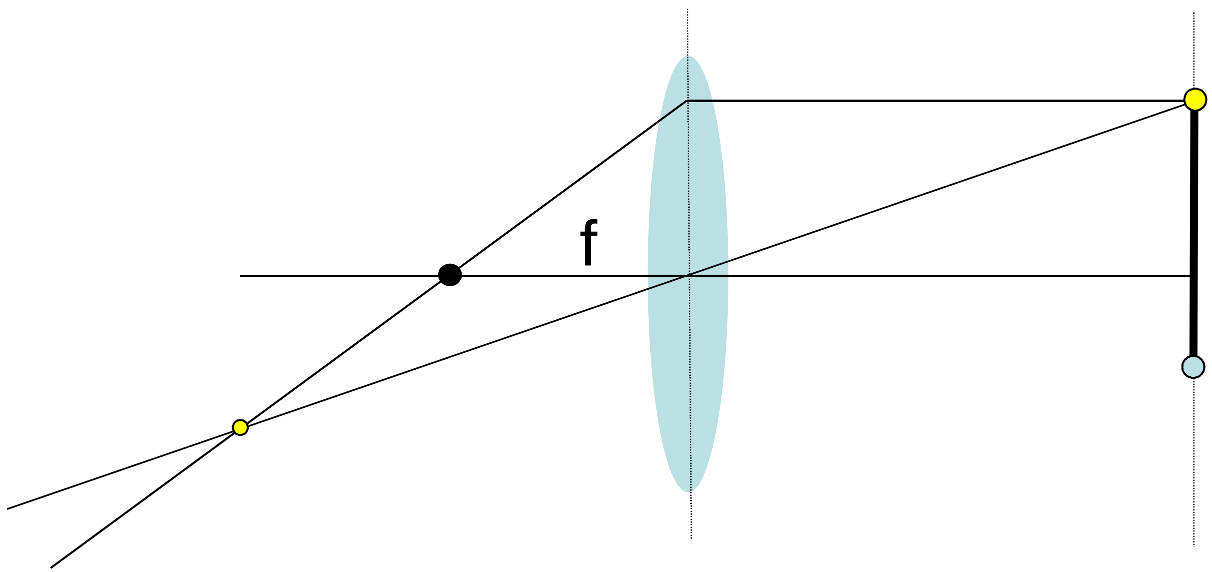
Example



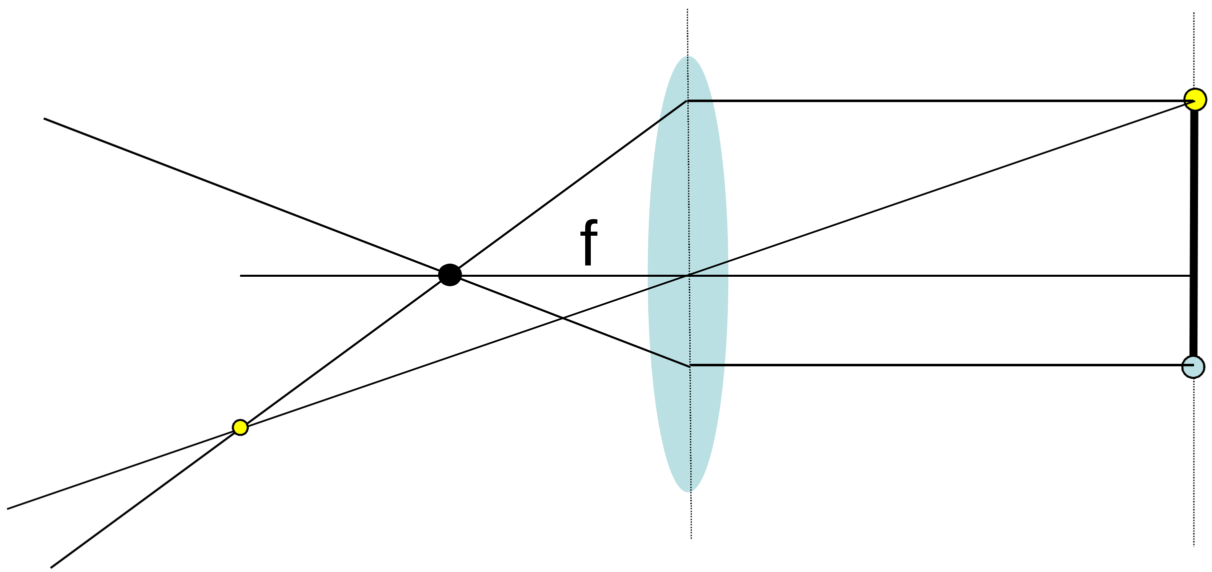
Example



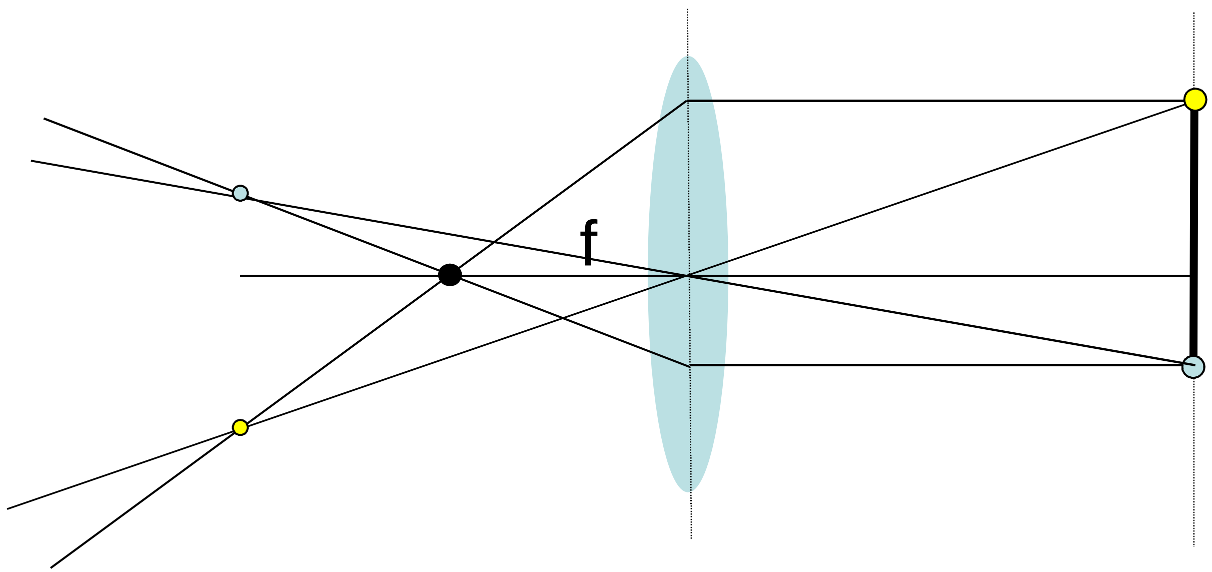
Example



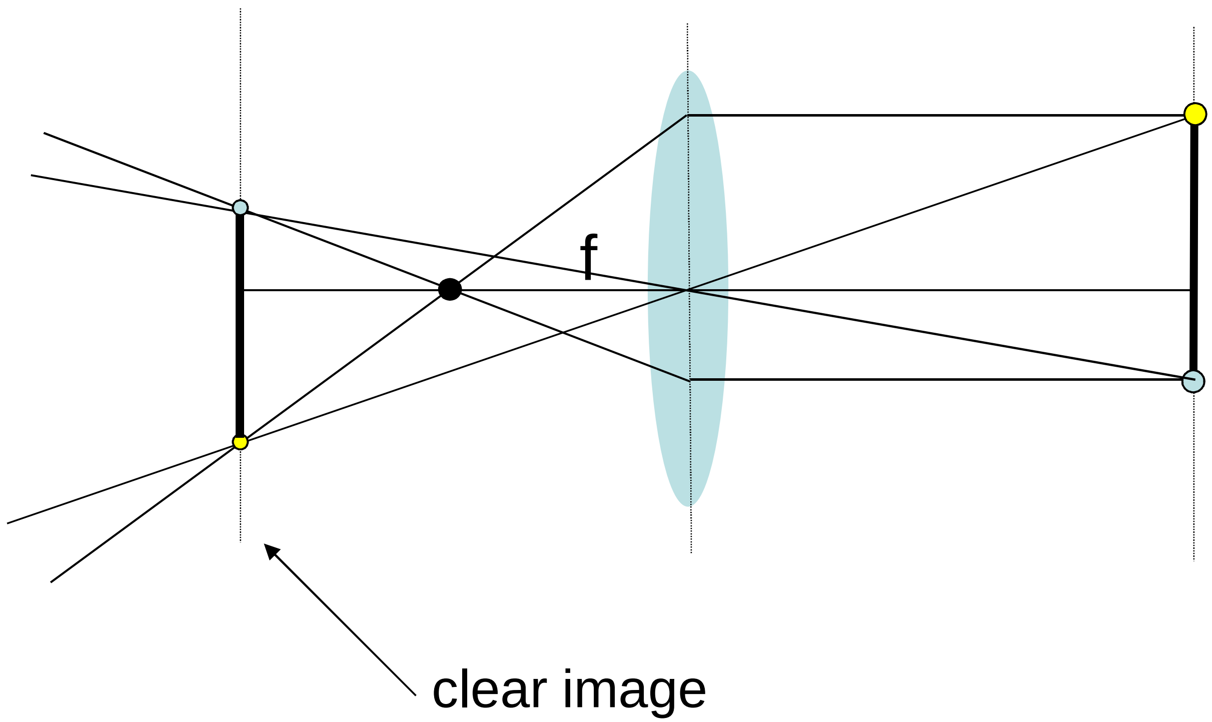
Example



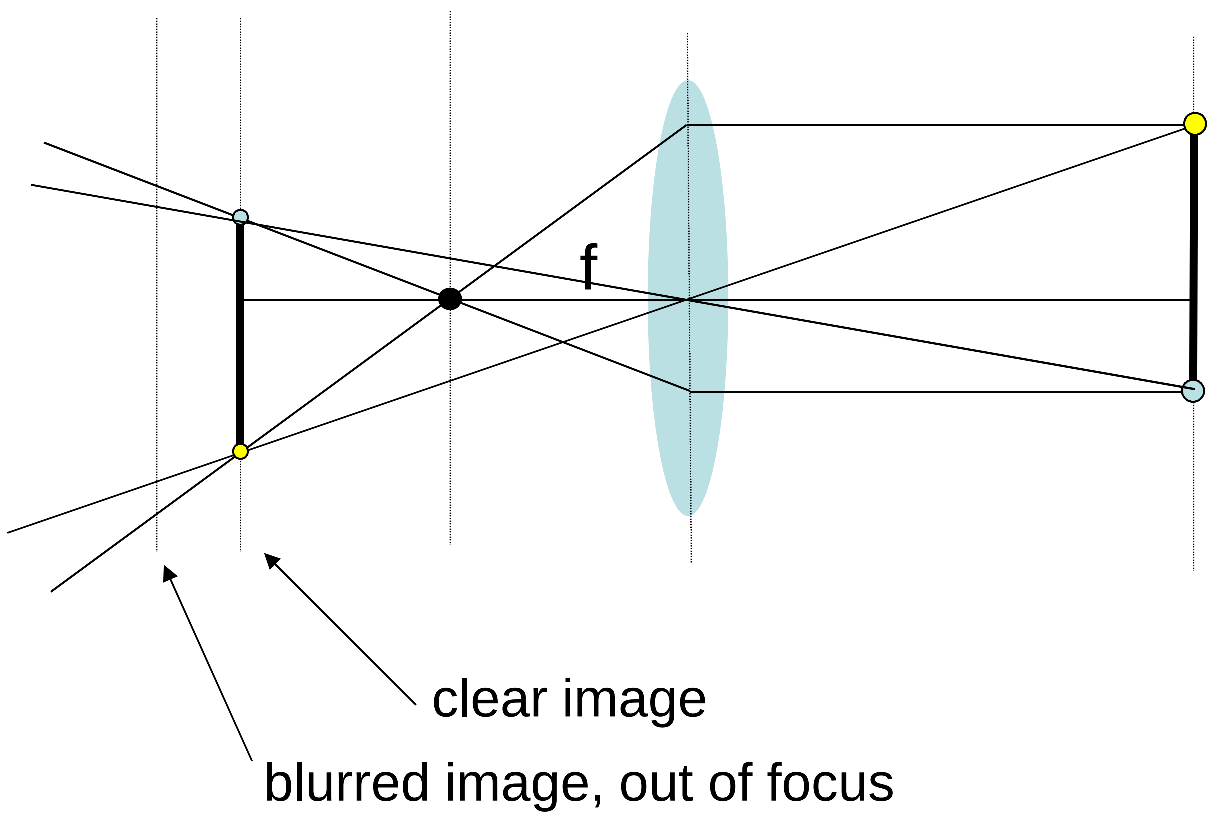
Example



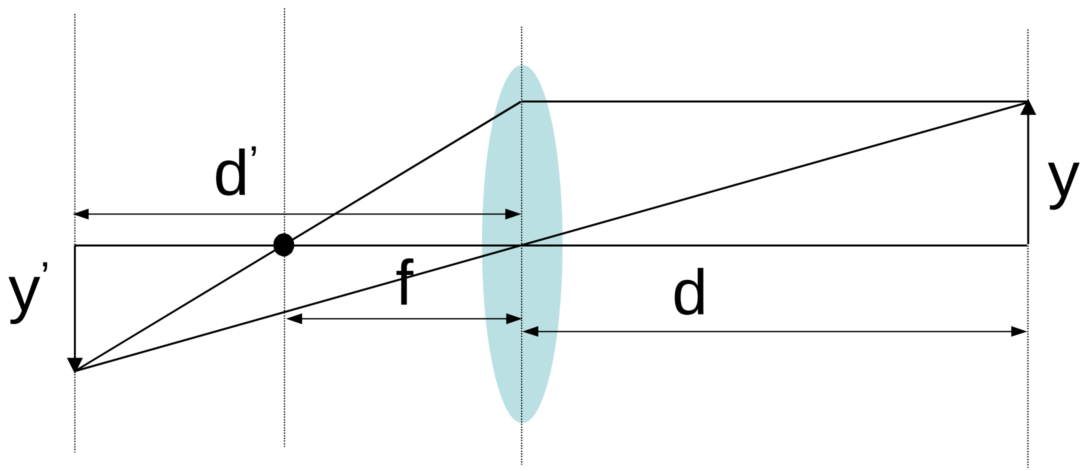
Example



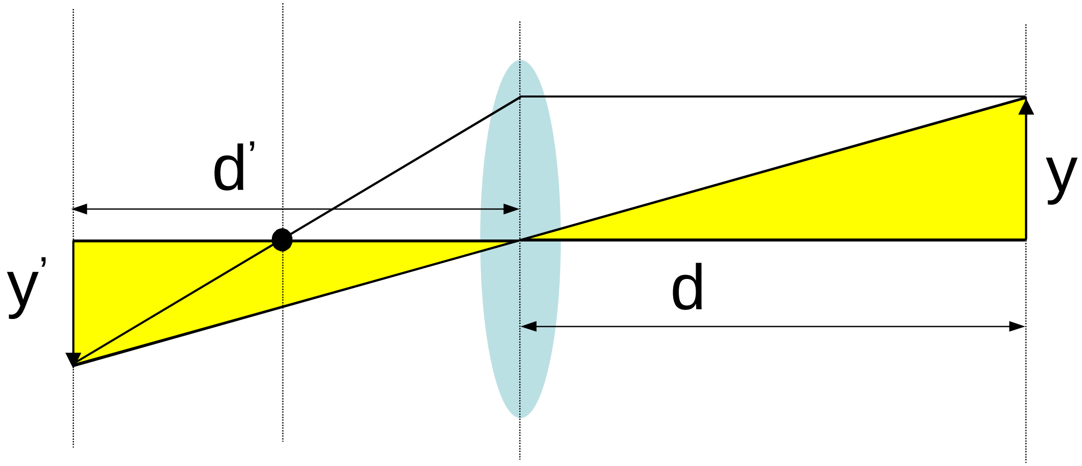
Example



Thin lens formula

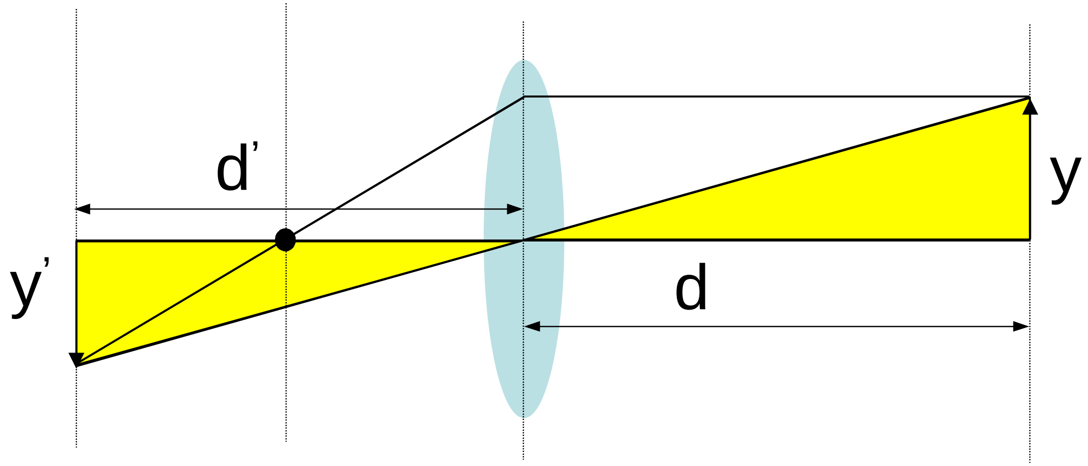


Thin lens formula

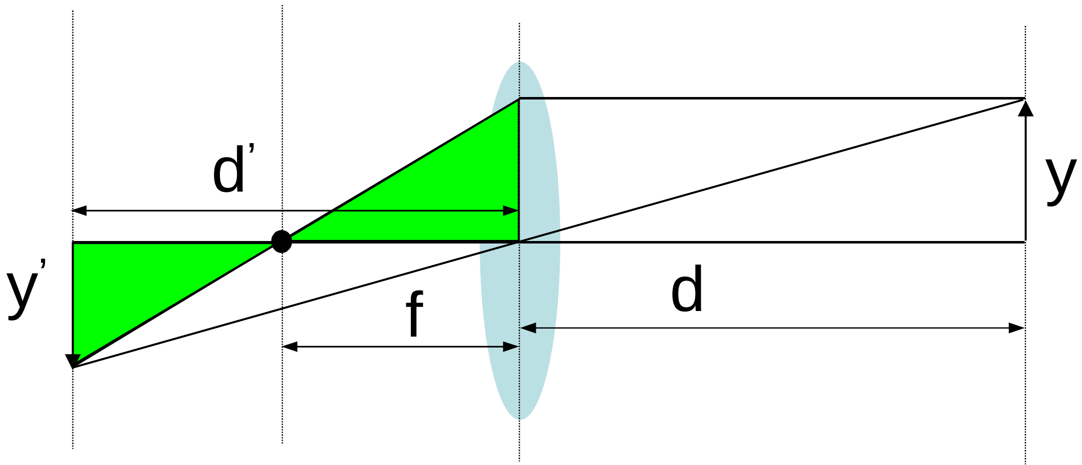


$$\frac{y'}{d'} = \frac{y}{d} \Rightarrow \frac{y'}{y} = \frac{d'}{d}$$

Thin lens formula



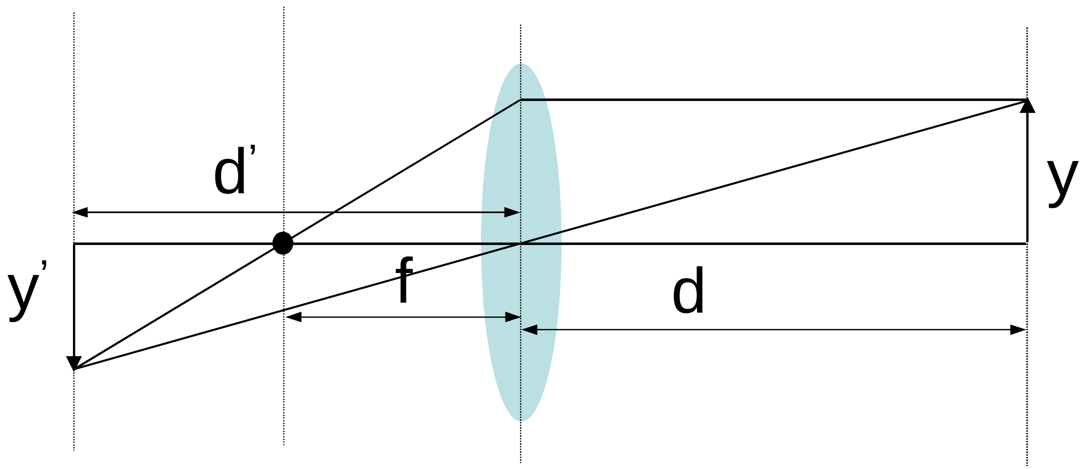
$$\frac{y'}{d'} = \frac{y}{d} \Rightarrow \frac{y'}{y} = \frac{d'}{d}$$



$$\frac{y'}{d'-f} = \frac{y}{f} \Rightarrow \frac{y'}{y} = \frac{d'-f}{f}$$

Thin lens formula

$$\begin{cases} \dfrac{y'}{y} = \dfrac{d'}{d} \\ \dfrac{y'}{y} = \dfrac{d' - f}{f} \end{cases} \qquad \frac{d'}{d} = \frac{d' - f}{f} \Rightarrow \frac{d'}{d} = \frac{d'}{f} - 1 \Rightarrow \frac{1}{d} = \frac{1}{f} - \frac{1}{d'}$$

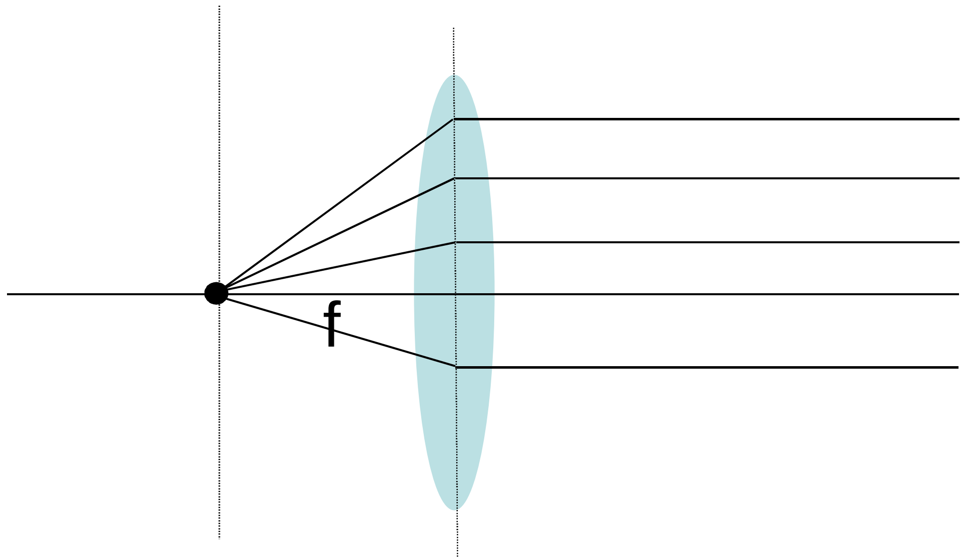


$$\frac{1}{d'} + \frac{1}{d} = \frac{1}{f}$$

Objects at infinity focus at *f*

$$\text{if } d \to \infty$$

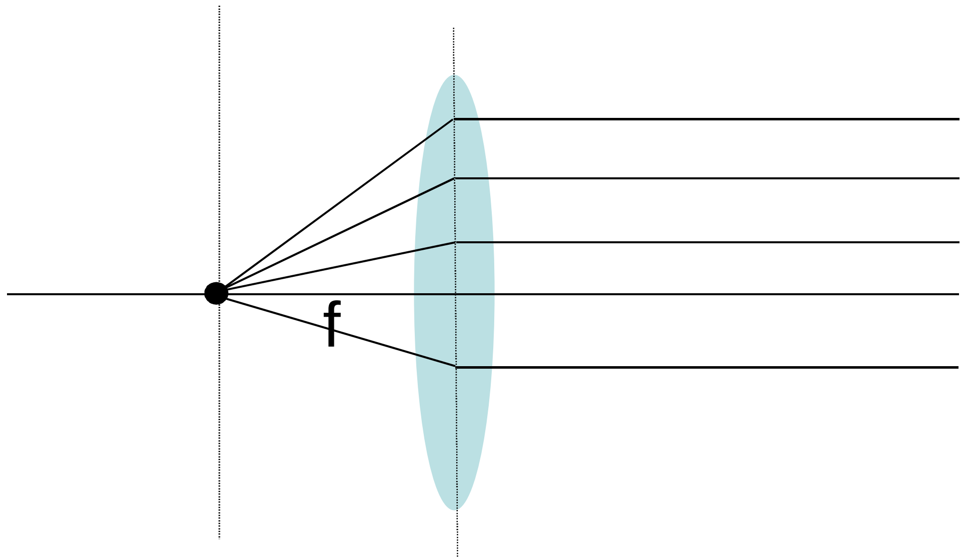
$$d' \to f$$



Objects at infinity focus at *f*

$$\text{if } d \to \infty$$

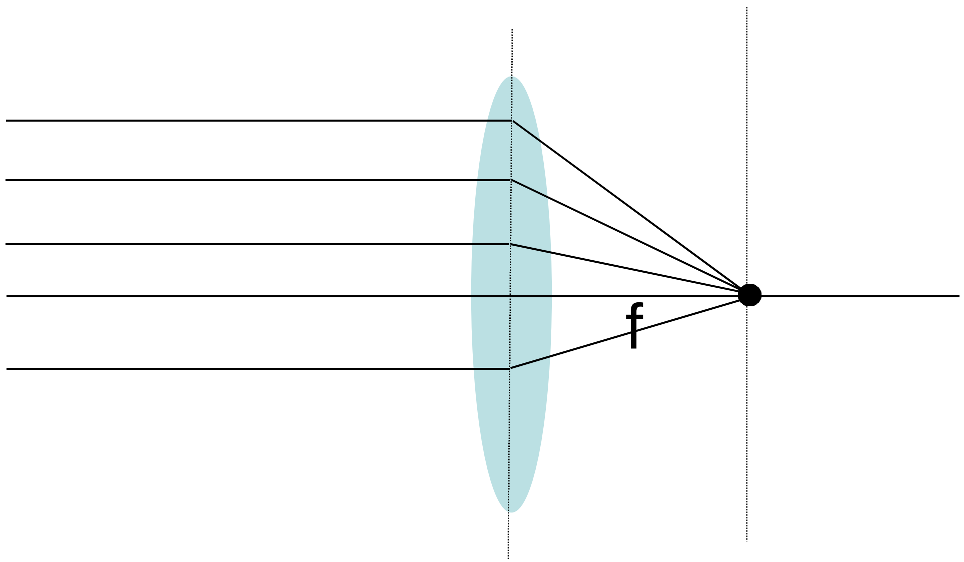
$$d' \to f$$



When the object gets closer, the focal plane moves away from *f*. At the limit:

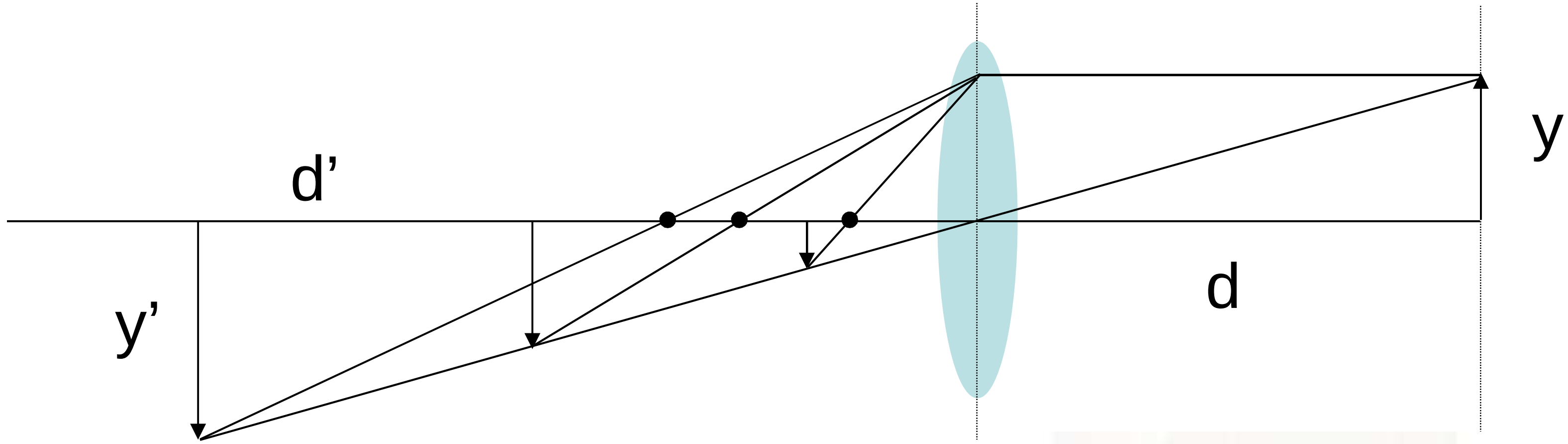
$$\text{if } d \to f$$

$$d' \to \infty$$



an object at distance *f* requires the focal plane to be at infinity

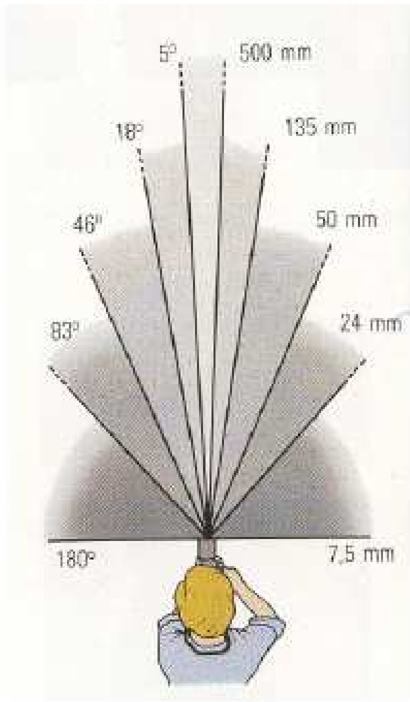
Effect of focal length on image size



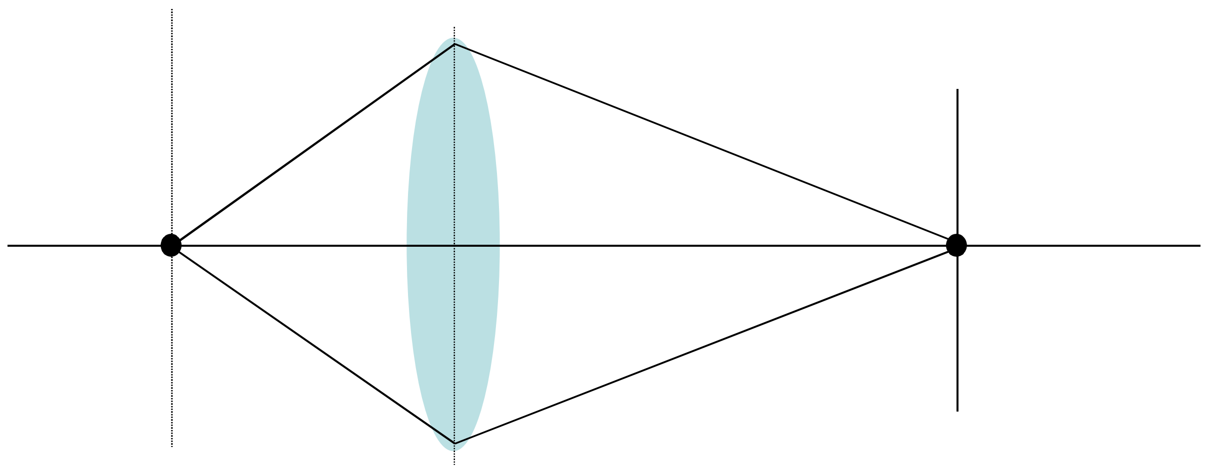
$$M = \frac{y'}{y} = \frac{d'}{d}$$

$$\frac{1}{f} = \frac{1}{d} + \frac{1}{d'} \Rightarrow M = \frac{f}{d-f} \quad , d > f$$

Effect of focal length on field of view

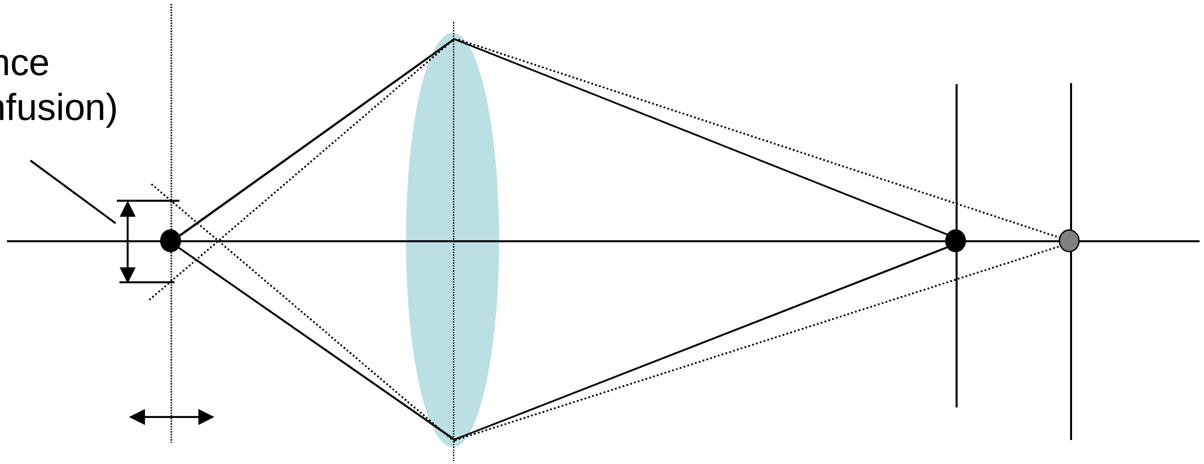


Depth of field (dof)

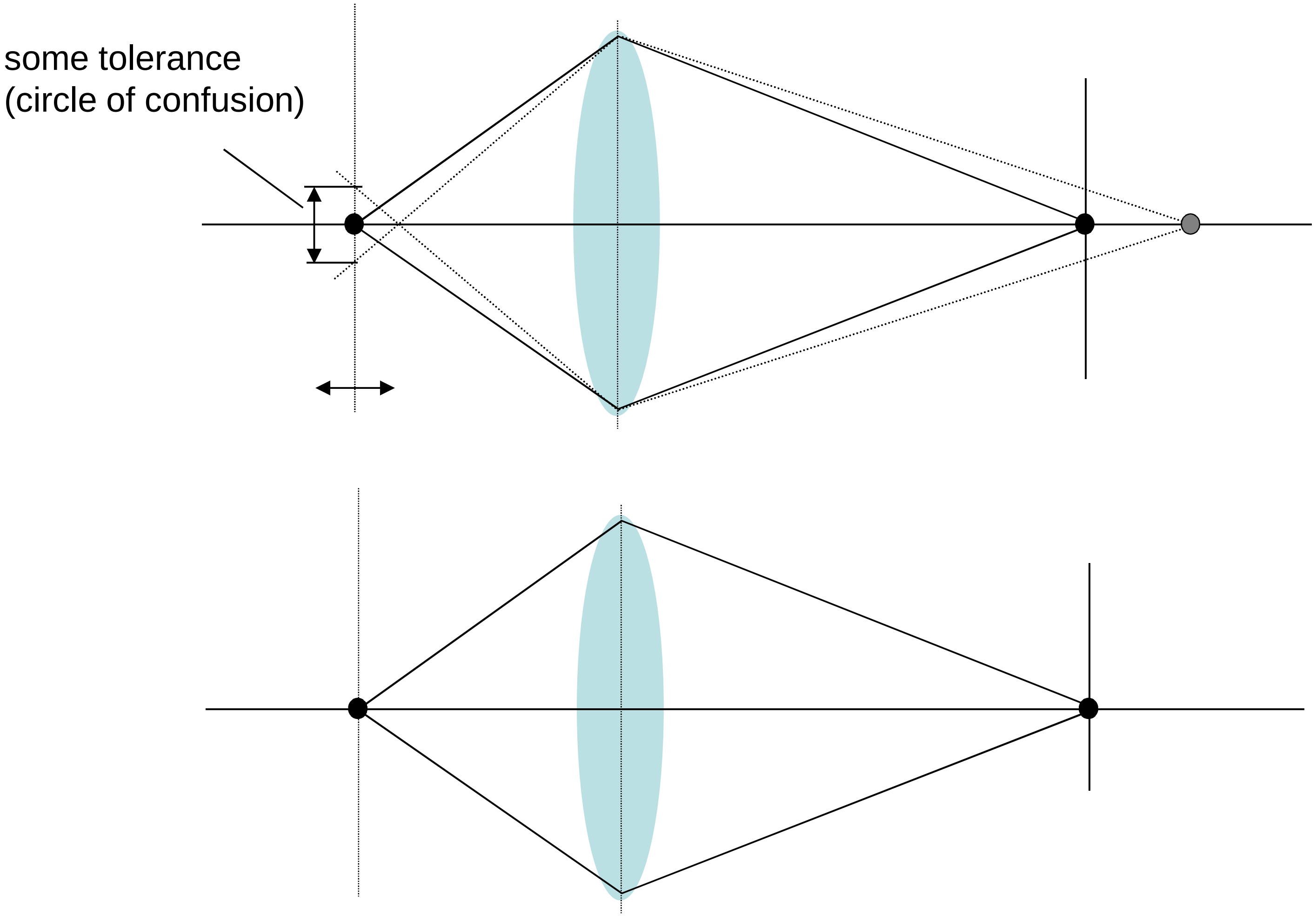


Depth of field (dof)

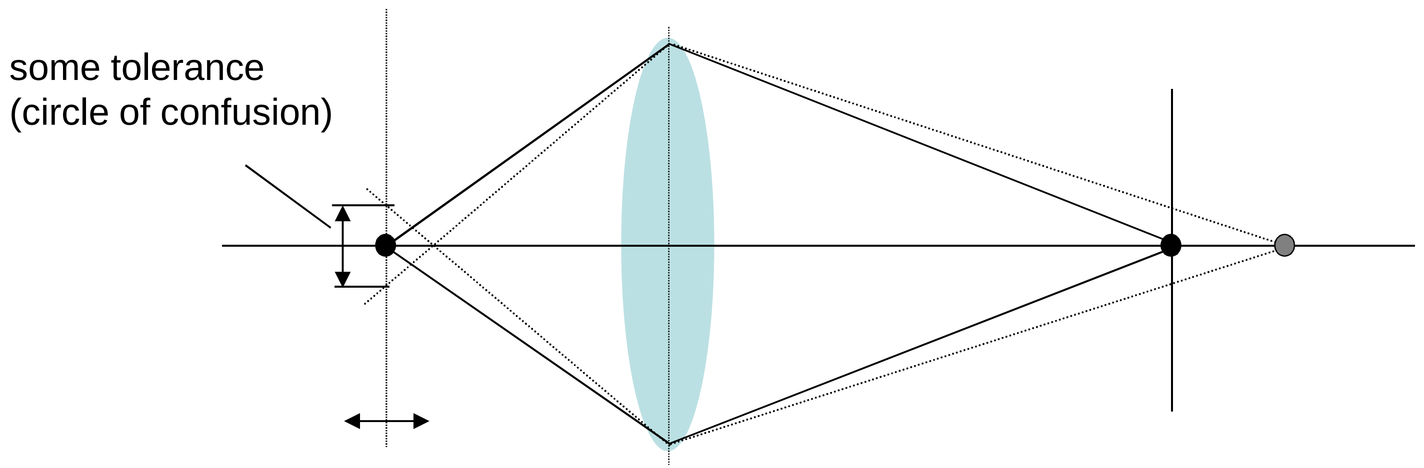
some tolerance
(circle of confusion)

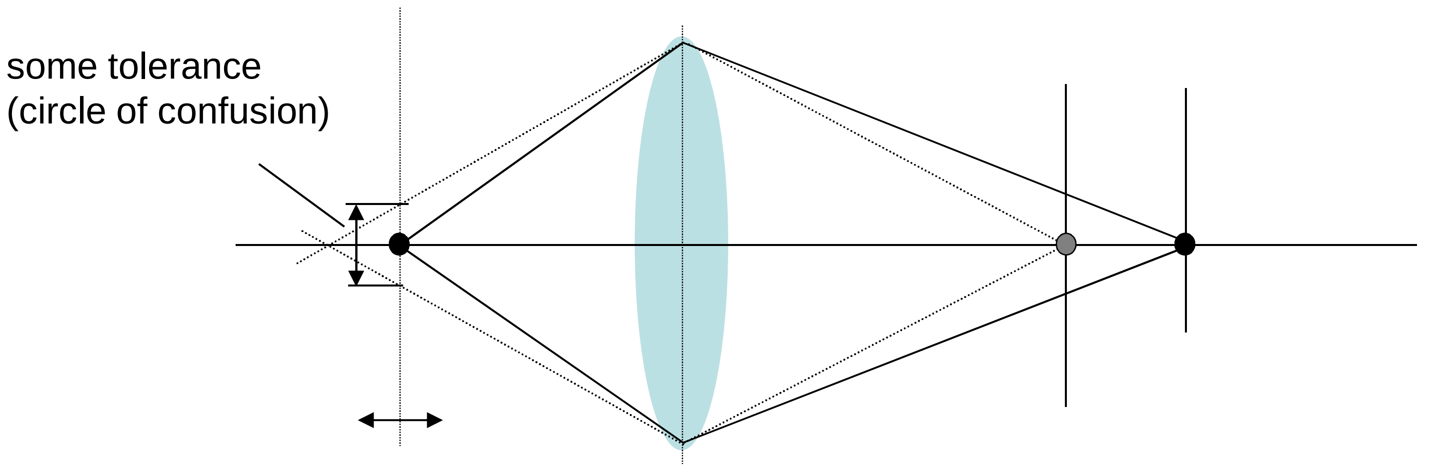


Depth of field (dof)

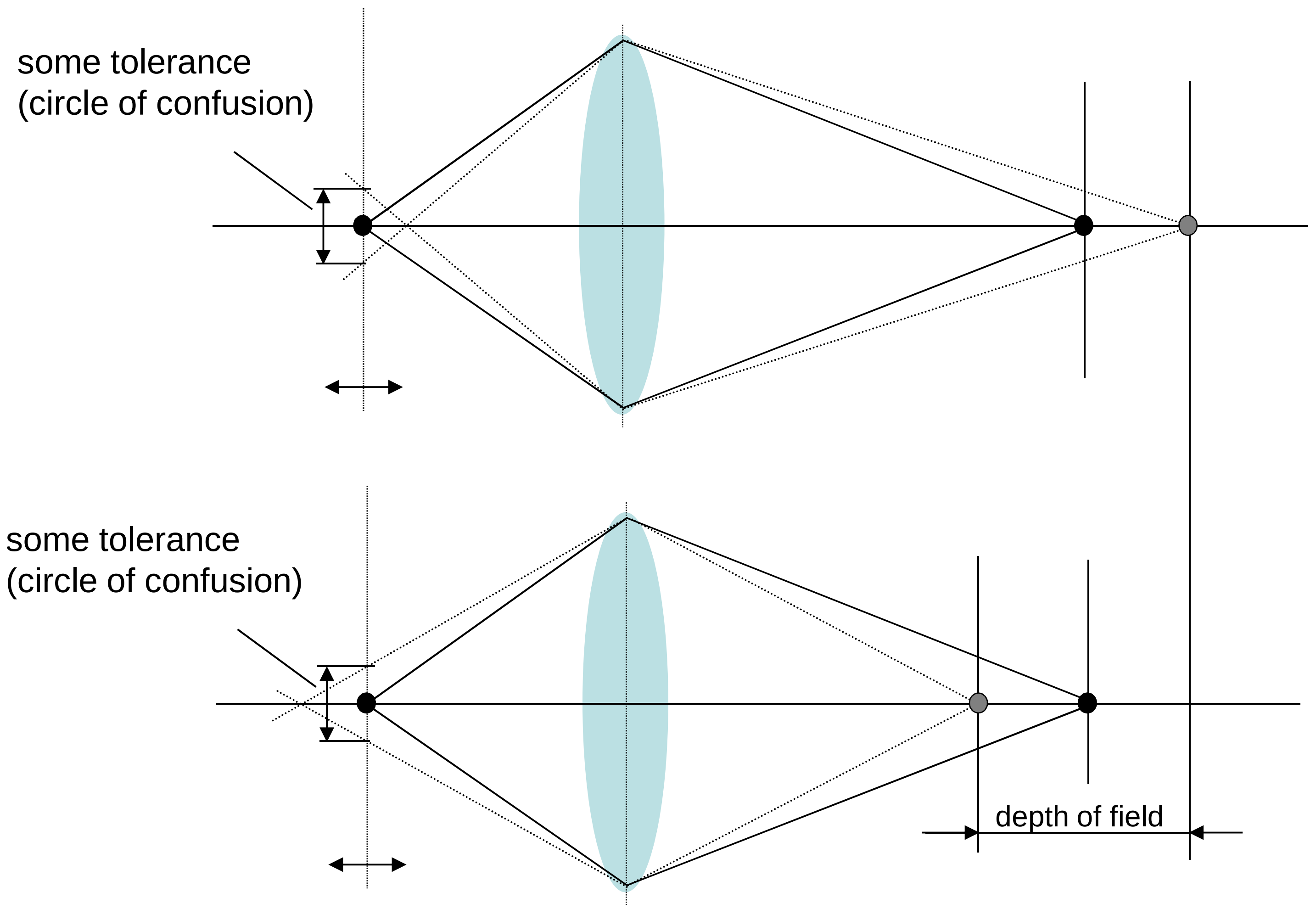


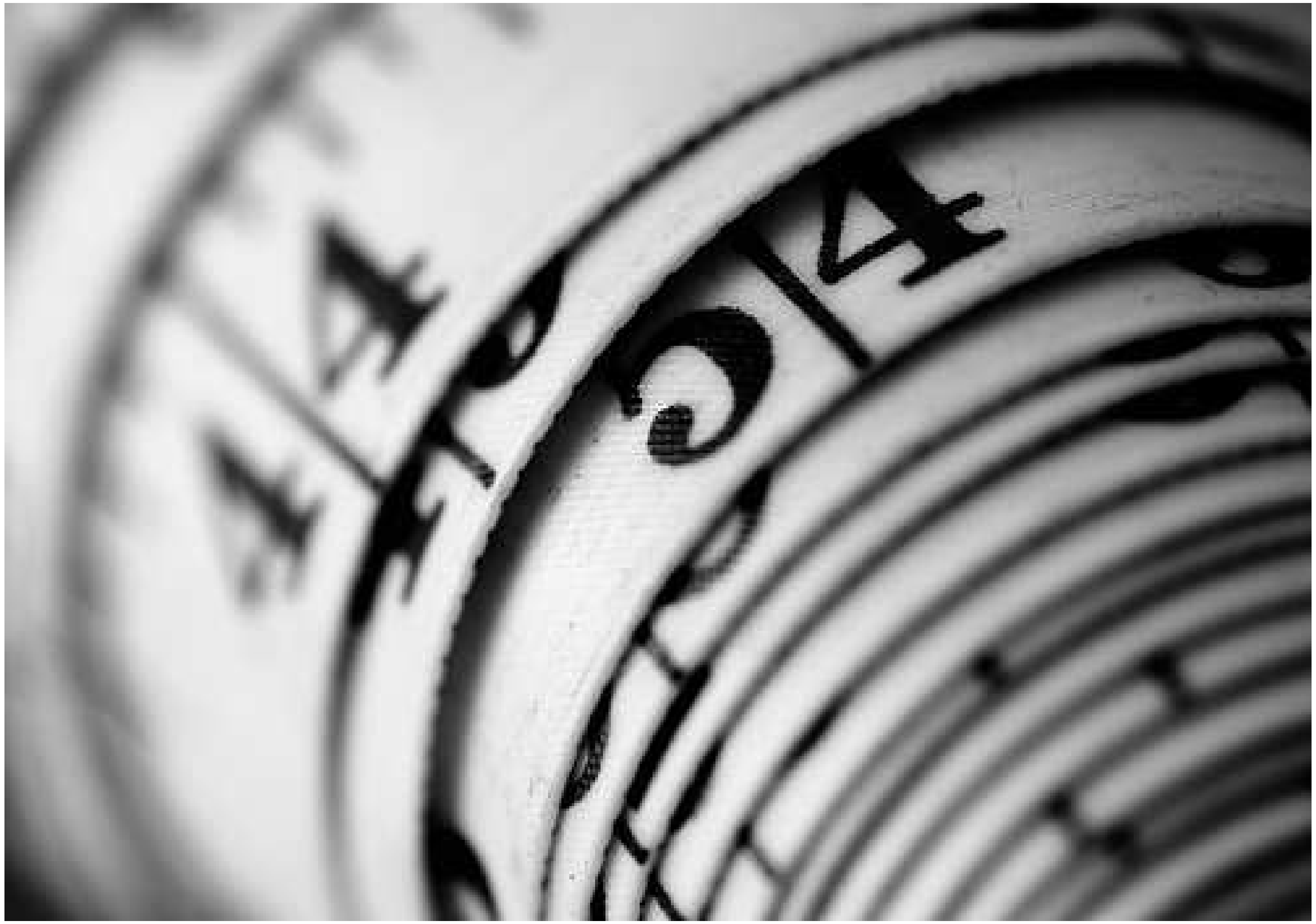
Depth of field (dof)





Depth of field (dof)





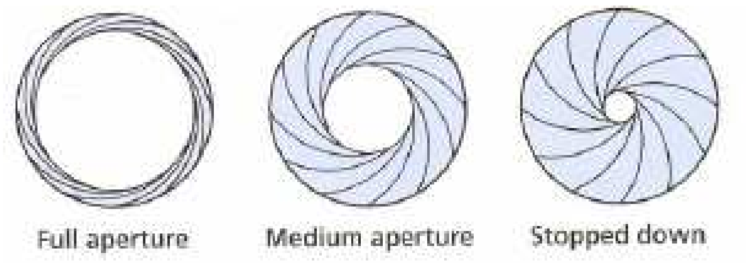
Getting the right exposure

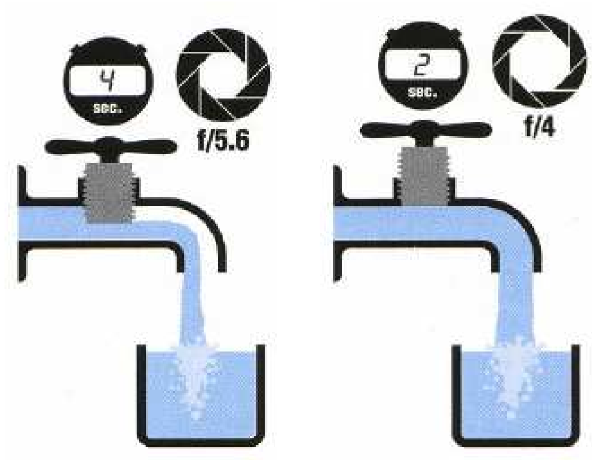
- Shutter speed: how long the sensor is exposed to light, expressed in fractions of a second

  1/30 1/60 1/125 1/500 1/1000 ...

- Aperture: diaphragm controls how much light we allow through the lens (it is expressed as a fraction of focal length):

  (f/2.0, f/2.8, f/4, f/5.6, f/8 .. f/22)





Getting the right exposure

- Shutter speed: how long the sensor is exposed to light, expressed in fractions of a second

  1/30 1/60 1/125 1/500 1/1000 ...

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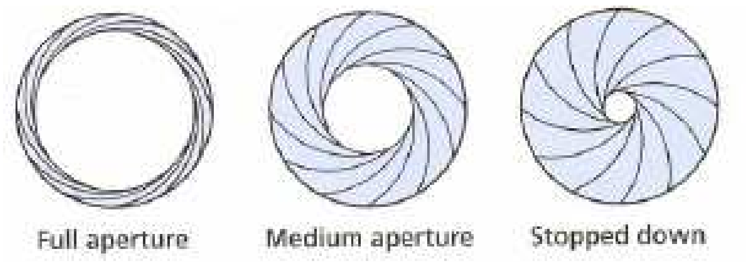
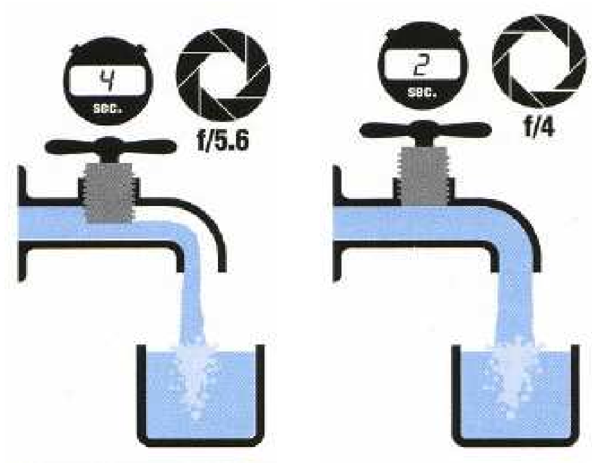
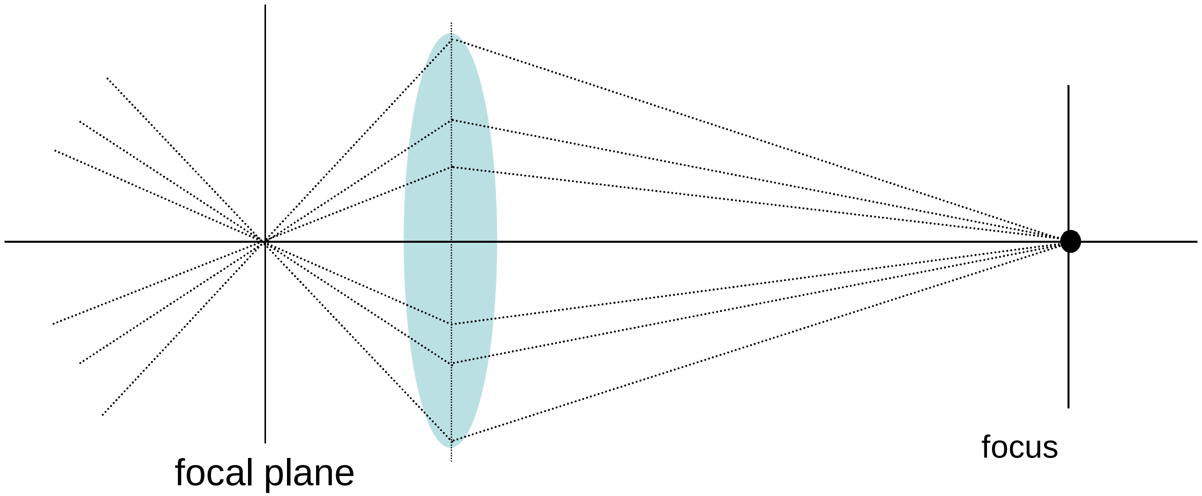
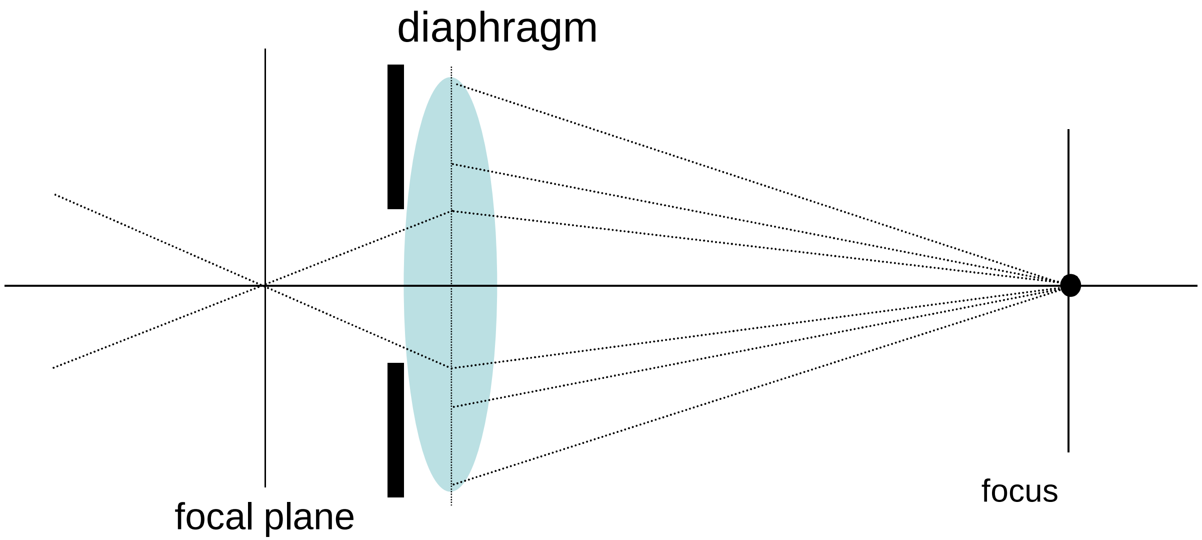
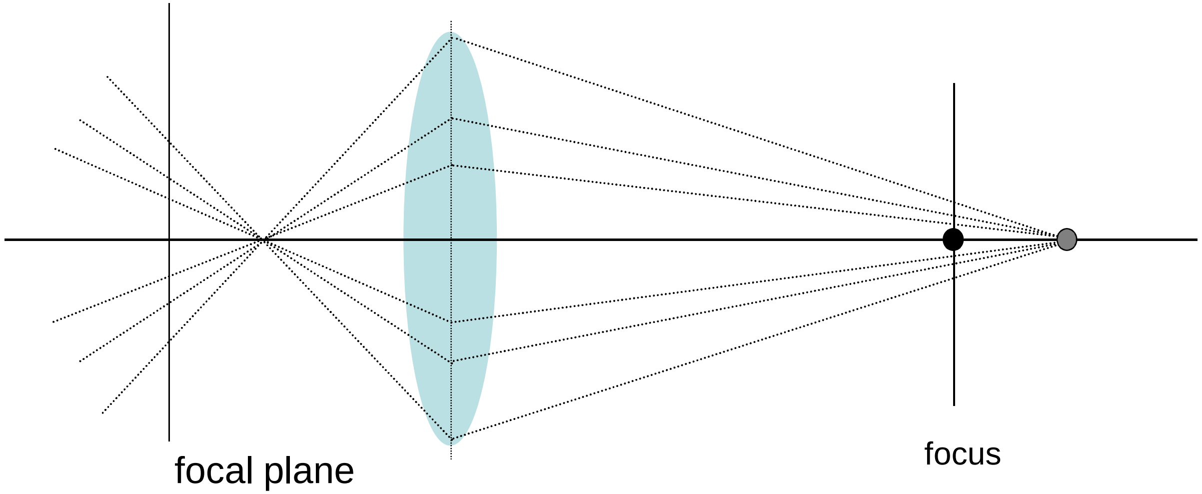
  (f/2.0, f/2.8, f/4, f/5.6, f/8 .. f/22)

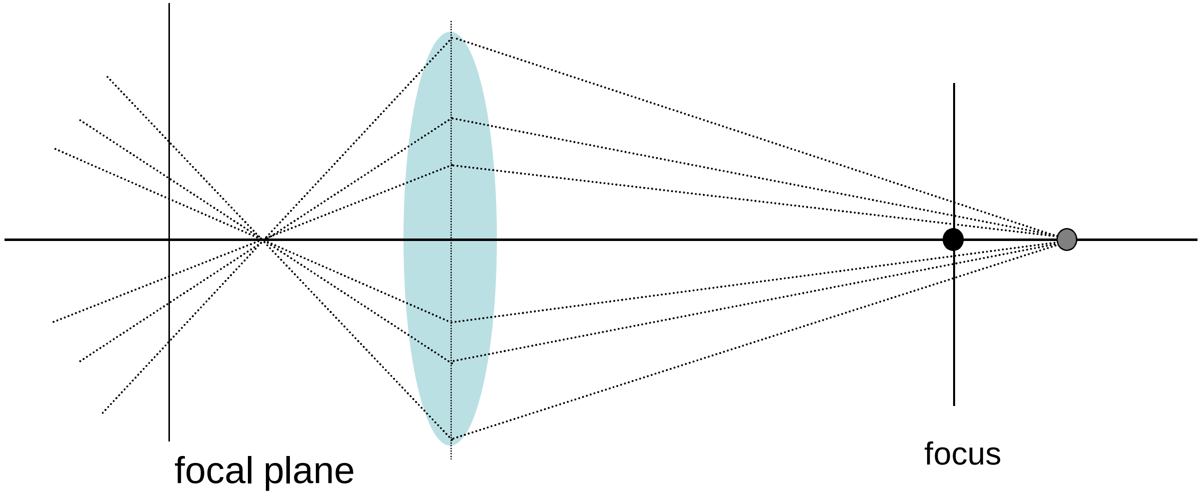


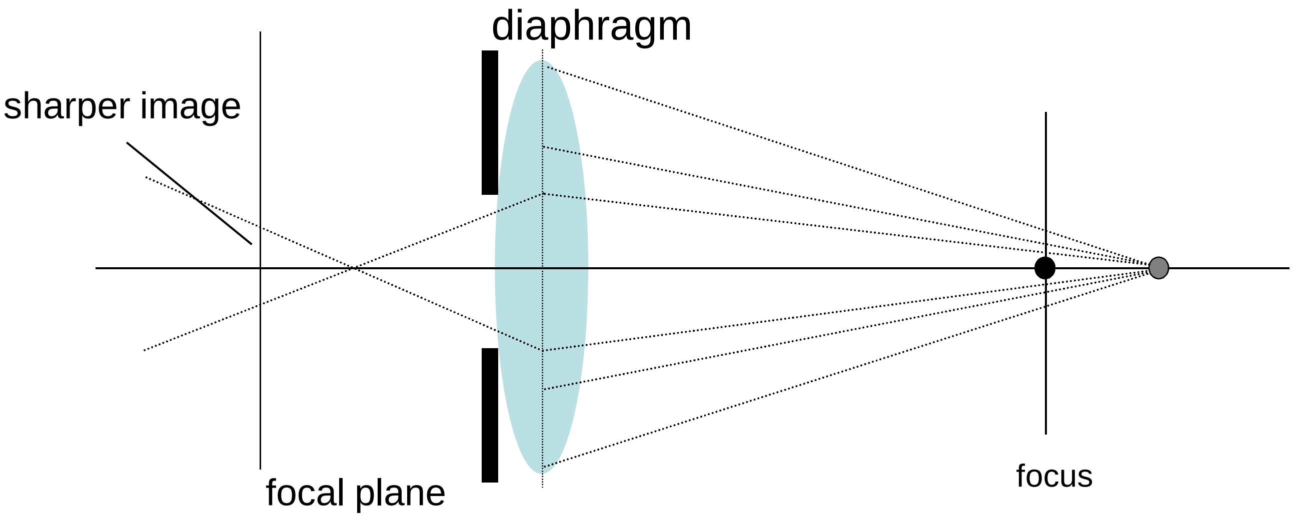



focal plane
focus

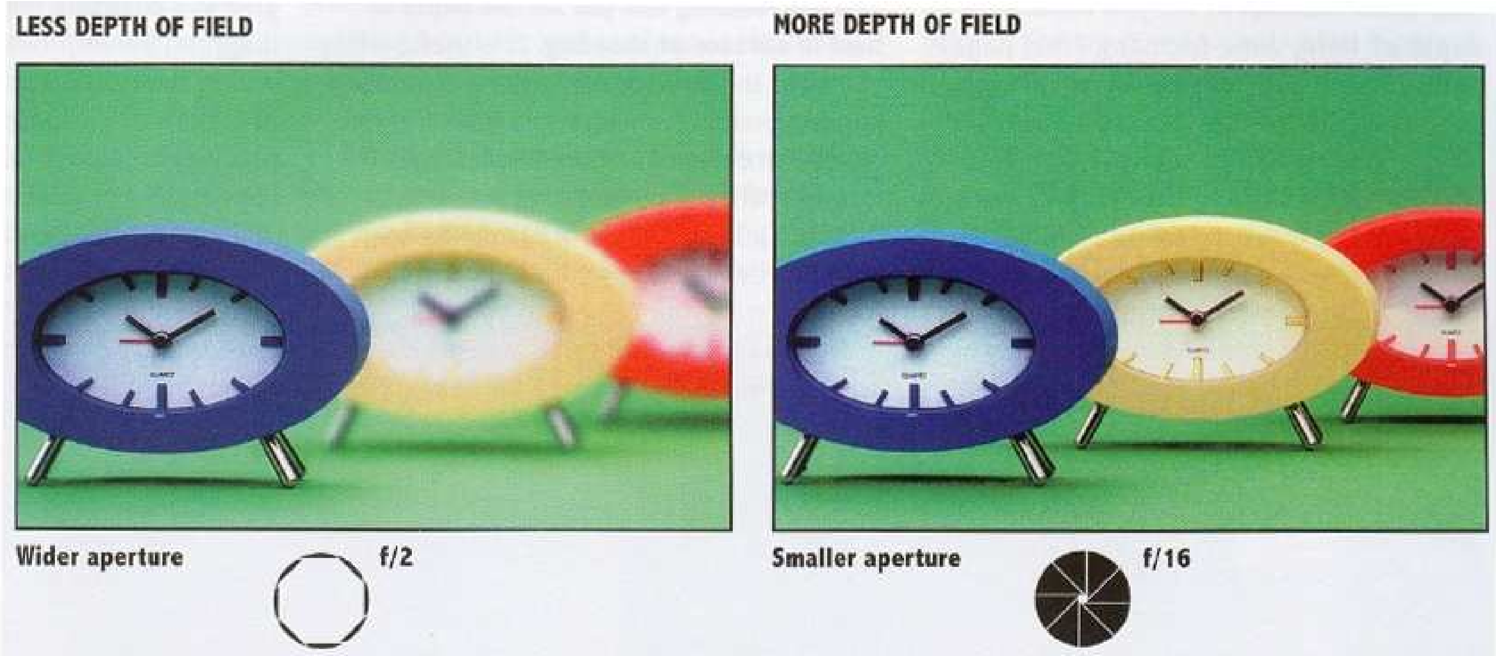

diaphragm
focal plane
focus


focal plane
focus


focal plane
focus


diaphragm
sharper image
focal plane
focus

Effect of aperture: depth of field



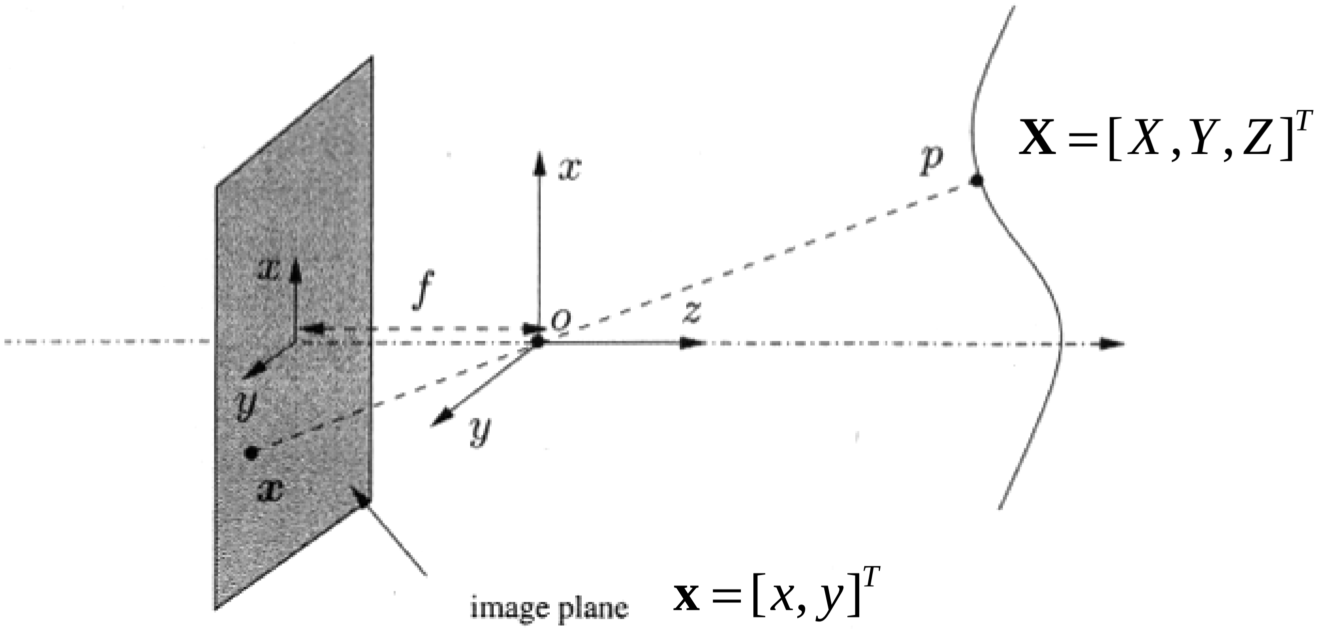
Effect of shutter speed: motion blur

Slow shutter speed

Fast shutter speed

Image formation, camera model (later)

Consider a pinhole camera, force all rays to go through the optical center

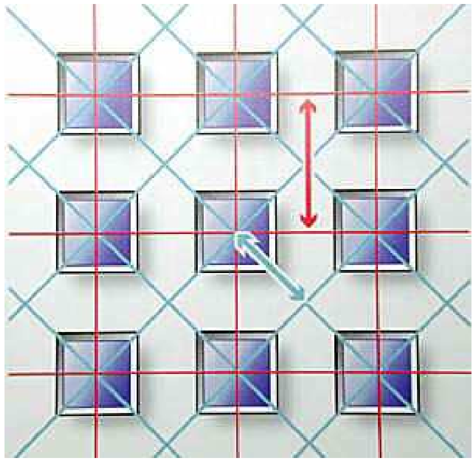


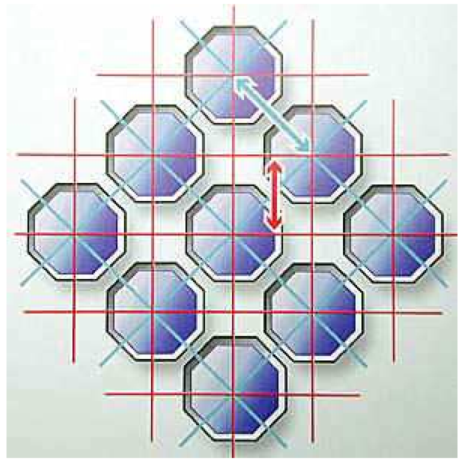
$$\begin{cases} x = \lambda X \\ y = \lambda Y \\ \mathrm{z} = \lambda Z \end{cases}$$

See: Forsyth and Ponce, Computer Vision a Modern Approach

Camera Sensors

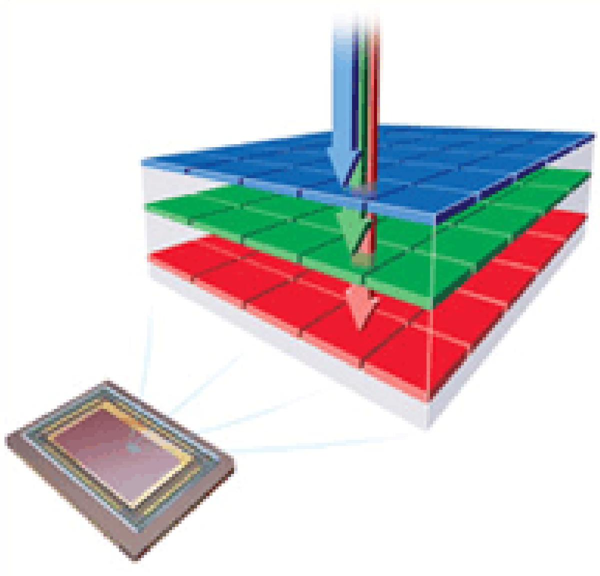
- A digital image is made up of tiny elements called *pixels*
- Photosites on the sensor capture the *brightness* of a single pixel
- The typical layout is a rectangular grid





Technologies

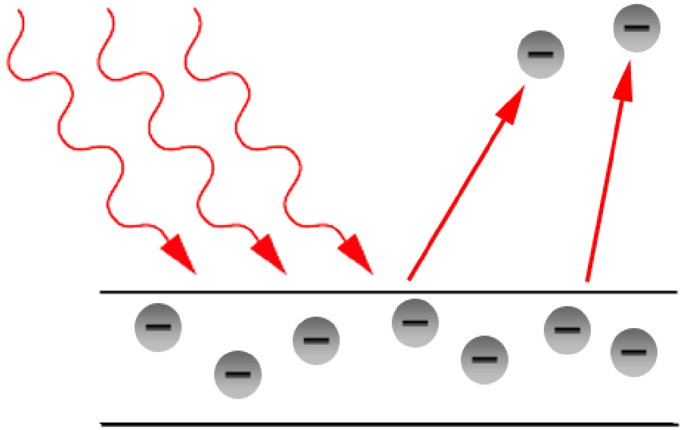
- CCD consists in photosensitive cells able to store charge produced by the light-to-electron conversion; in addition, the charge can be transferred to an interconnected, adjacent cell. In this case charges are shifted out of the sensor (bigger sensors, better quality, but additional circuitry)
- CMOS, transistors within the photosite perform charge-to-voltage conversion and allow the pixels to be read individually (higher integration, less power consumption, but less sensitive, higher noise)
- In both CMOS and CCD all photosites are sensitive to visible light, detect only brightness, not color
- Foveon: three layers of CMOS



CCD technology

- Analog shift register that enables charge to be transported through stages (capacitors) under the control of a clock signal
- BTW: and in fact was invented for totally different reasons (memory, delay lines)
- CCD refers to how the read out is performed
- Photons are converted into electrons by a special monocrystalline layer of silicon – photoelectric effect
- The photoactive region can be seen as an array of capacitors

Photoelectric effect



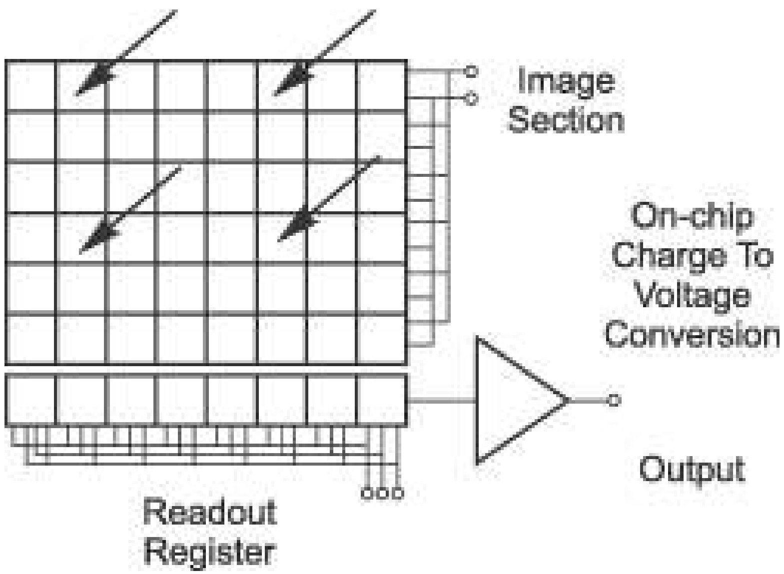
- The effect on the semiconductor is to kick electrons from the valence to the conducting band (still inside the material)

Types of CCD

- Different approaches to the problem of shuttering
- Three architectures
  - Full frame
  - Frame transfer
  - Interline transfer
- Negative effect: smearing

CCD, Full frame

- Charge readout is slow
- It requires mechanical shutter, no further electronic circuitry



CCD, Frame Transfer

- Charge transfer is faster, charge to voltage conversion is performed while charge is protected
- No mechanical shutter required

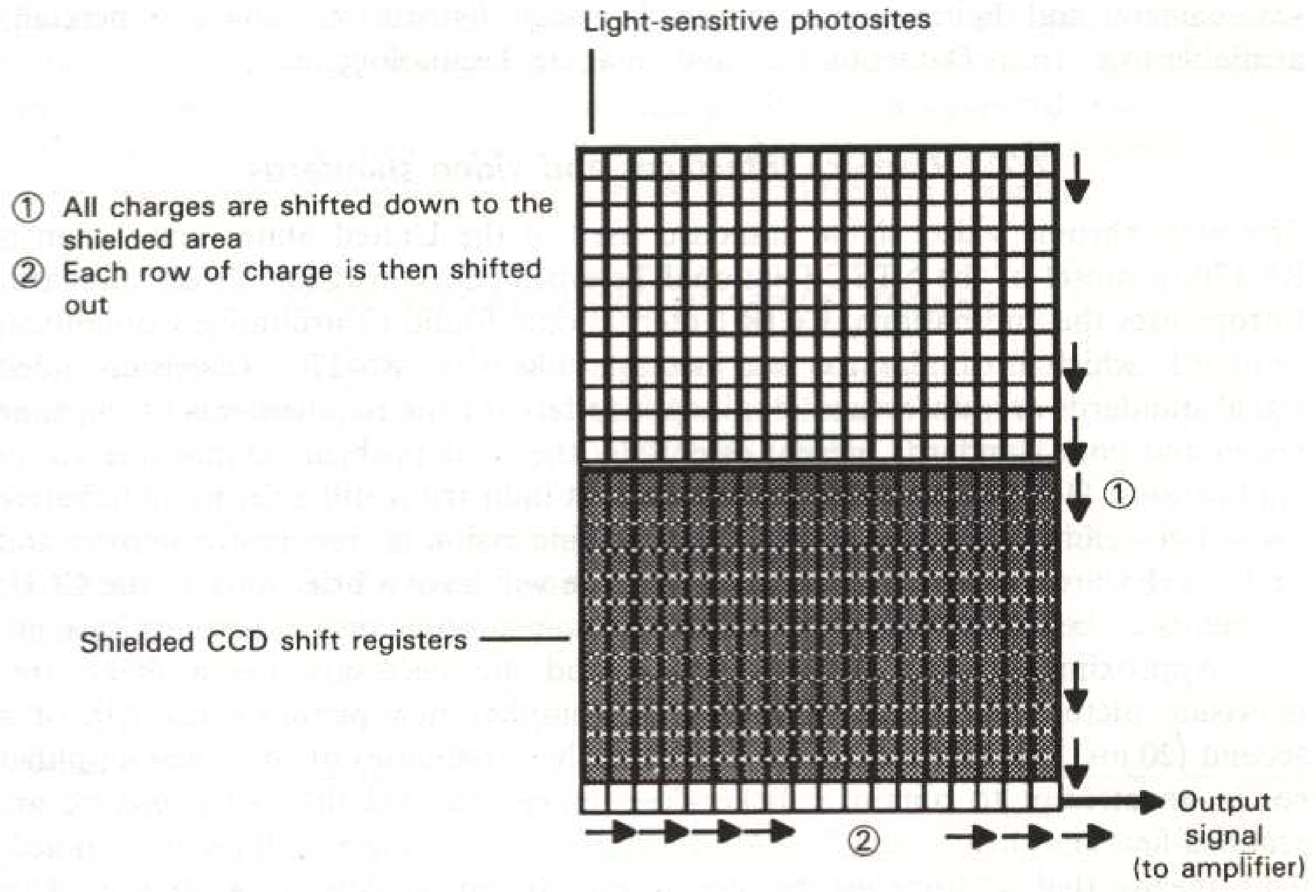


Figure 2.3 Frame transfer of charge in CCD sensors.

Example: vertical smearing

CCD, Interline Transfer

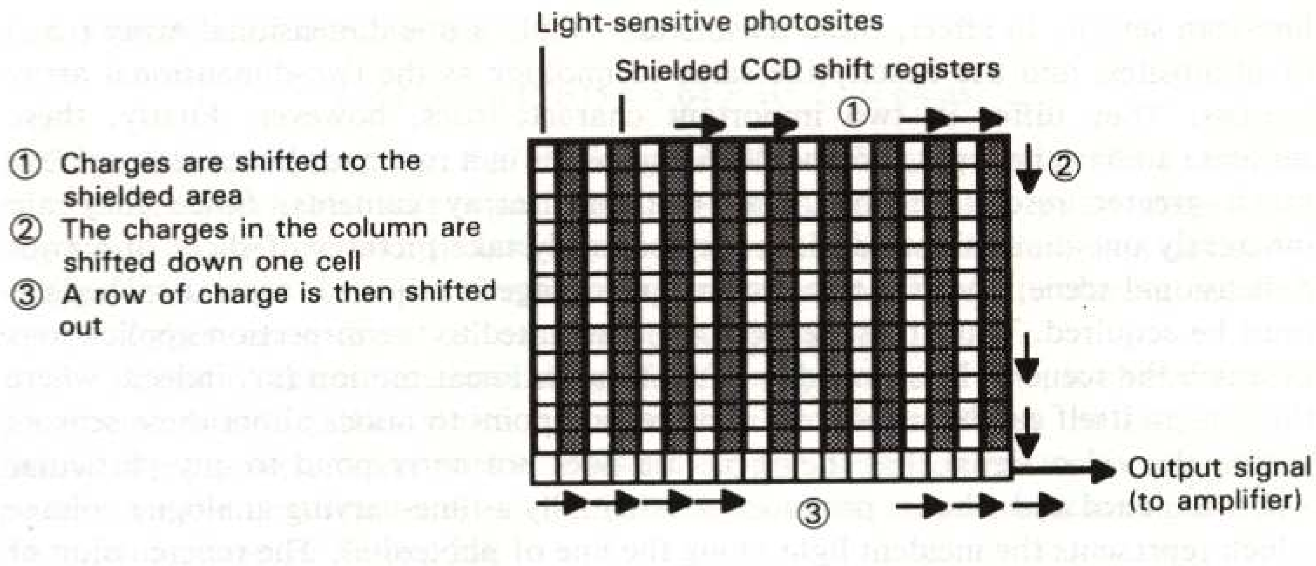


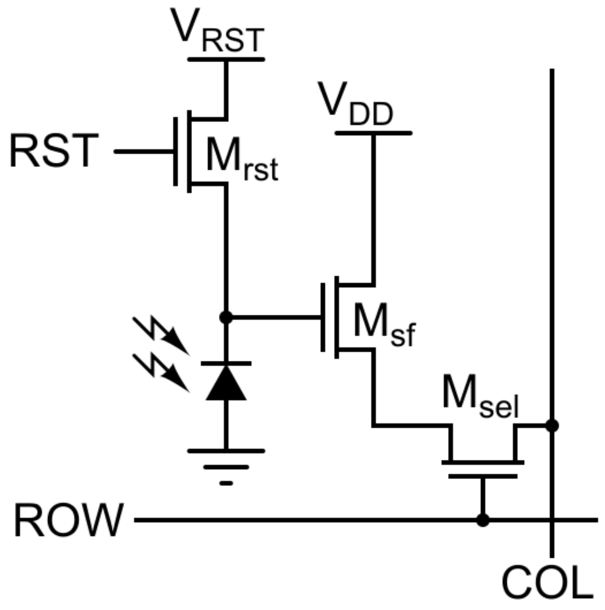
Figure 2.2 Interline transfer of charge in CCD sensors.

faster,1 pixel transfer, < 1us
fill factor 50%
modern design: use microlenses to increase fill factor up to 90%

Common parameters

- Quantum efficiency 70% -> film only 2% (of course it depends on the film sensitivity, ISO): photons to electrons ratio (depends further on the channel/color)
- Fill factor: up to 90-100% depending on the arrangement (full frame preferred for example in astronomy, minimum smear)
- Smear: < few percentage points
- Dark current (no light): thermal, should be small

CMOS technology



- Photodiode, the converter
- RST, reset signal,discharges the diode
- Msf is the read out transistor (source follower), reads the voltage, very small current, preserves charge
- Msel, selector (addressed from ROW)
- COL, output

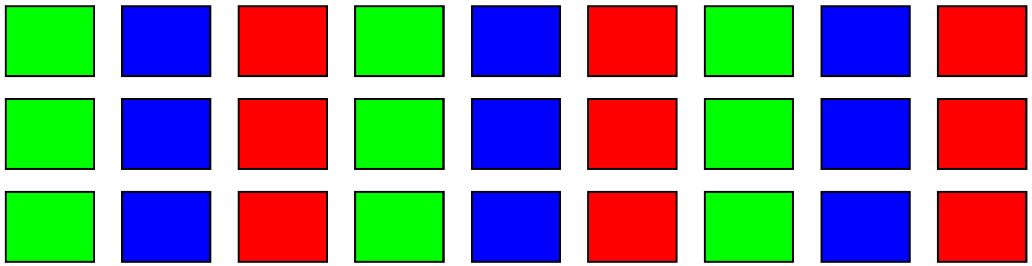
CMOS parameters

- Smallest number of transistors
- Greater sensitive area (read out circuitry take space, use microlenses to increase efficiency)

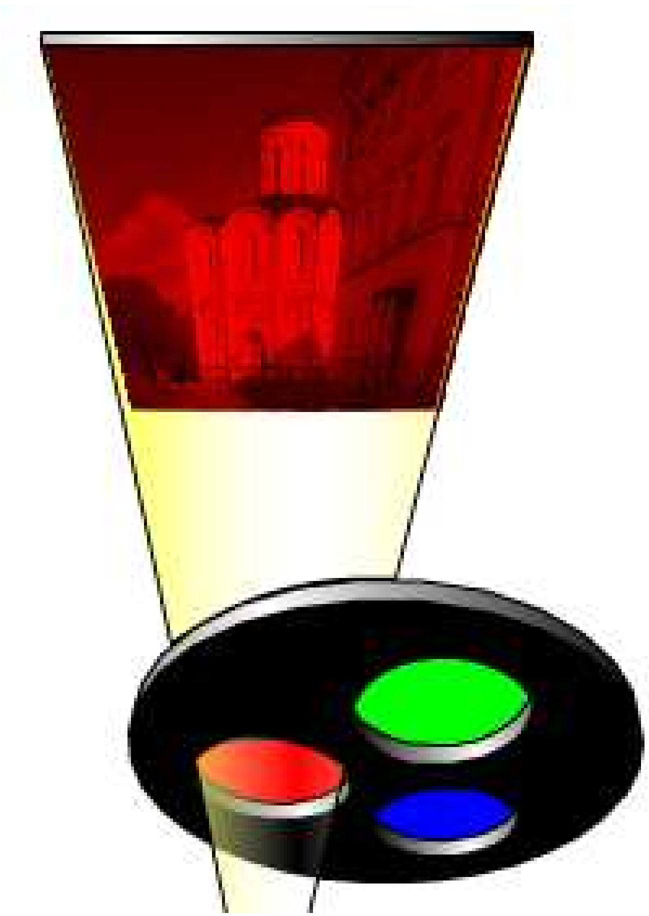
- Tradeoff: reset mechanism vs. image lag
  - Better reset → lower noise
  - .. but also more complicated electronics (affecting the fill factor)
  - … and more time, larger lags

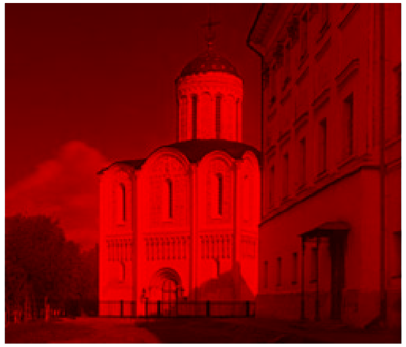
How to sense a color image

- Take 3 shots (temporal multiplexing or three different sensors)
- 3 detectors (e.g. Foveon, photographic film)
- Spatial multiplexing
  - human eye
  - sensors are made sensitive to red, green or blue using a filter coating that blocks the complementary light

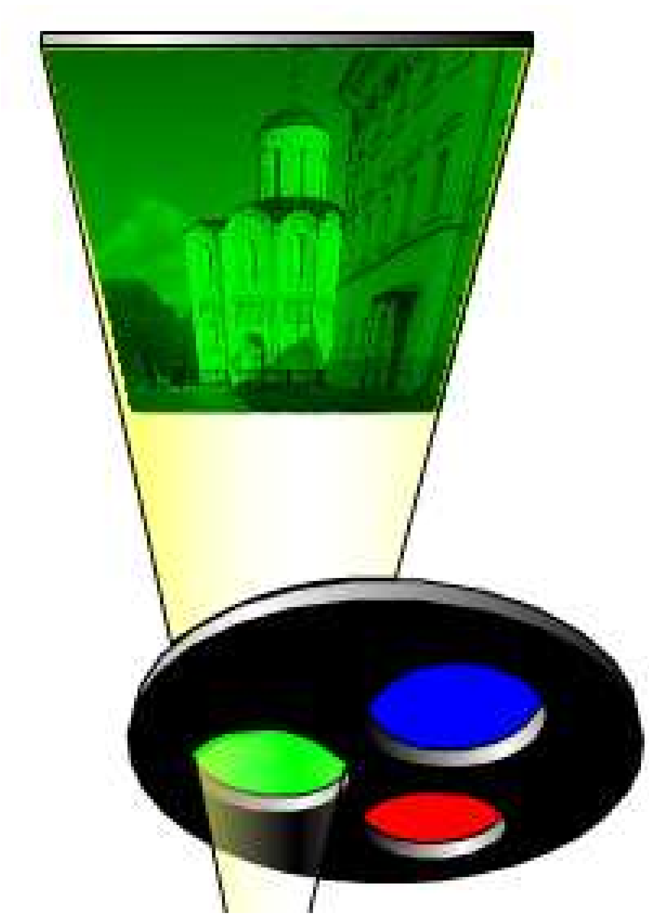


Field sequential



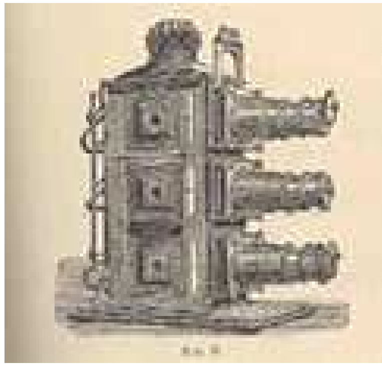


Field sequential



Field sequential

Prokudin-Gorskii (early 1900’s)

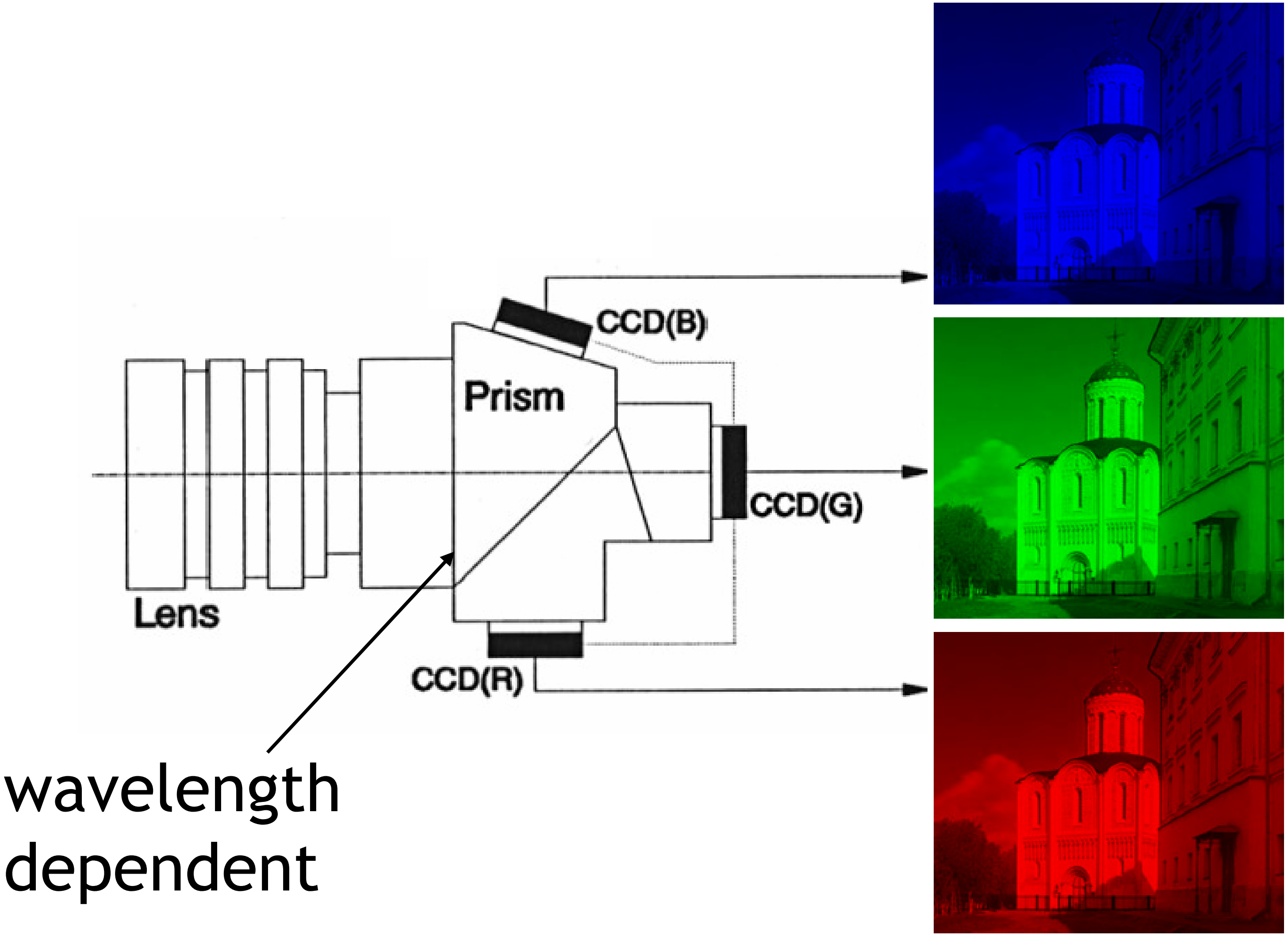


Lantern projector

SINA – 11/12

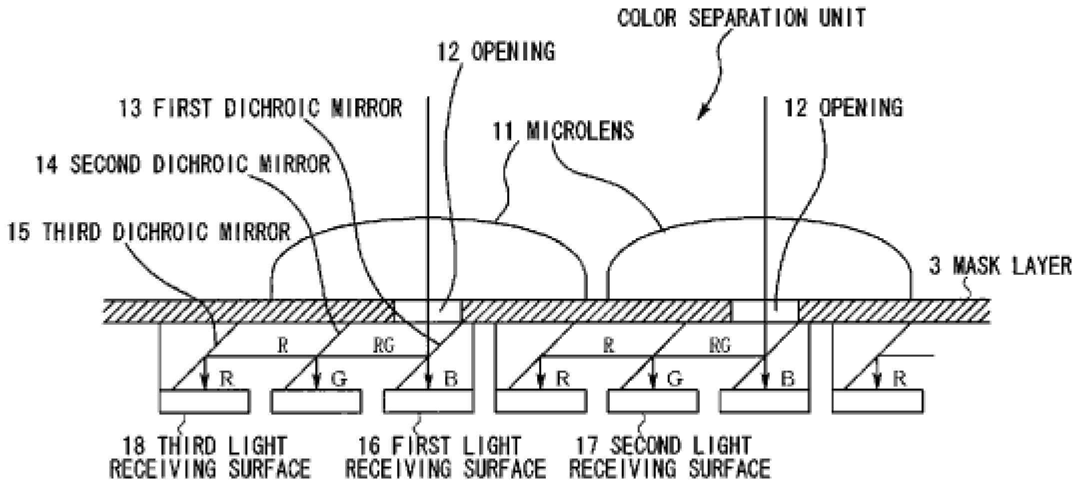
Prokudin-Gorskii (early 1900's)

Multi-chip (3CCD)



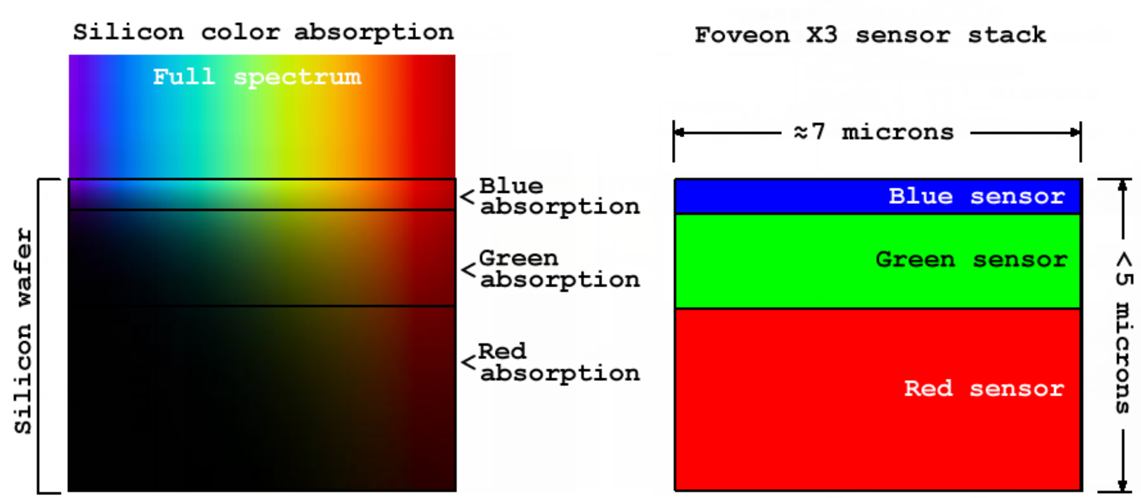
Nikon Dichronic

- Emulates multi-chip solution
- Microlense on top of triplet of photoreceptors
- Using dichroic filters wavelengths of light are separated to reach specific photoreceptors which record red, green, and blue wavelengths



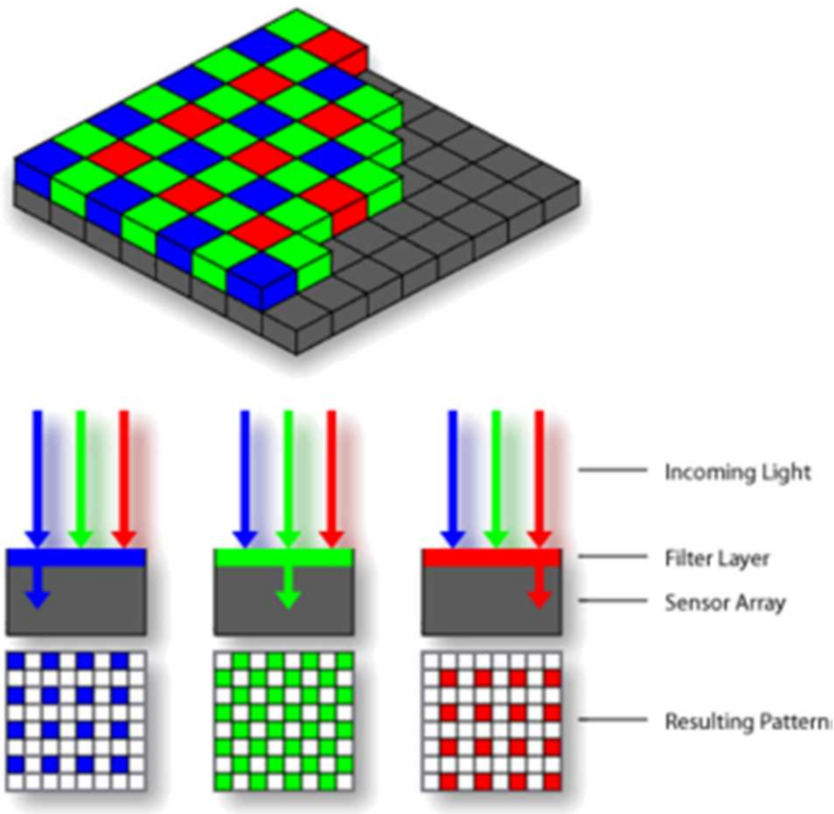
Foveon X3

- Employed in cameras by Sigma
- CMOS technology
- Three layers of photodiodes
- Silicon absorbs different "colors" at different depth, each layer captures a different color
- Advantage: no spatial multiplexing



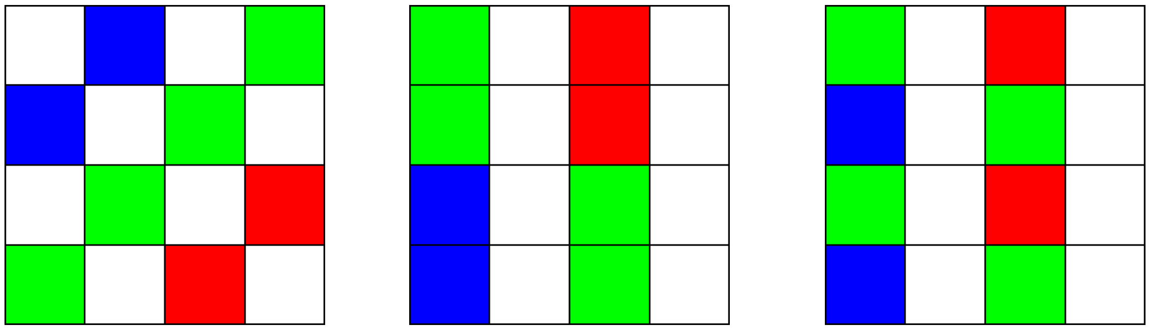
Bayer Pattern

- Invented by E. Bayer at Kodak in 1976, it is a way to arrange RGB filter on a squared grid of photosensors
- 50% green, 25% red, 25% blue
- mimic eye's greater sensitivity to green wavelengths
- need *demosaicing* to interpolate the color information from neighbor units



source: http://en.wikipedia.org/wiki/Bayer_filter

- Alternative sensor announced in 2007 by Kodak, add “panchromatic”, that are sensitive to all wavelengths
- Increase sensitivity to light, because panchromatic cells do not filter light



Demosaicing

- Reproduce the original image
- Avoid artifacts
- Often must be efficient

1 Simple nearest neighbor, take the missing colors from the nearest pixel

R_{11}	G_{12}	R_{13}	G_{14}	R_{15}	G_{16}	R_{17}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}	B_{26}	G_{27}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}	G_{36}	R_{37}

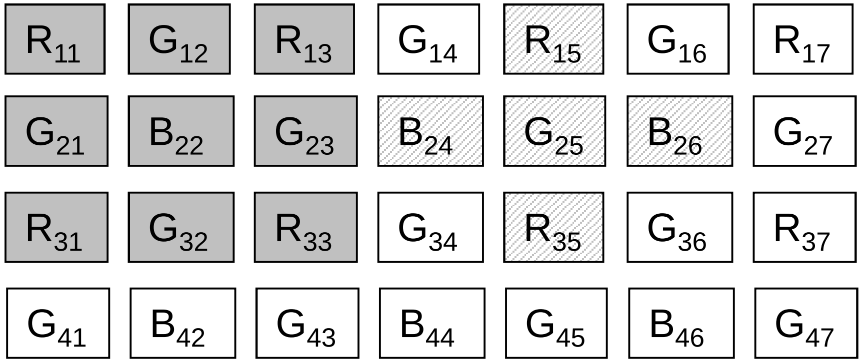
$$R_{11} = R_{11} \qquad R_{12} = R_{13}$$

$$G_{11} = G_{12} \qquad G_{12} = G_{12}$$

$$B_{11} = B_{22} \qquad B_{12} = B_{22}$$

...etc

2 Bilinear interpolation



$$R_{22} = 0.25 \cdot \left(R_{11} + R_{13} + R_{31} + R_{33} \right)$$

$$G_{22} = 0.25 \cdot \left(G_{12} + G_{21} + G_{23} + G_{32} \right)$$

$$B_{22} = B_{22}$$

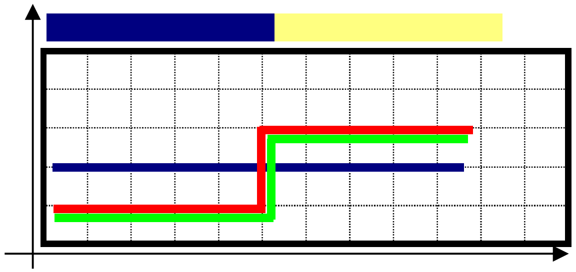
$$R_{25} = 0.5 \cdot \left(R_{15} + R_{35} \right)$$

$$G_{25} = G_{25}$$

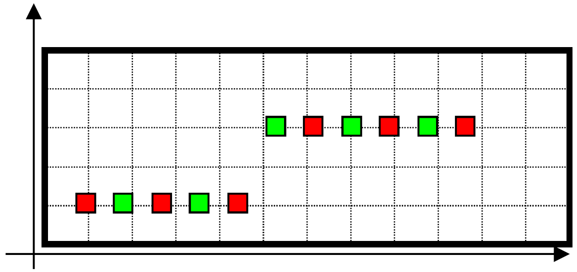
$$B_{25} = 0.5 \cdot \left(B_{24} + B_{25} \right)$$

3 More sophisticated methods to reduce artifacts (but computationally more expensive)...

Artifacts: color “fringes”

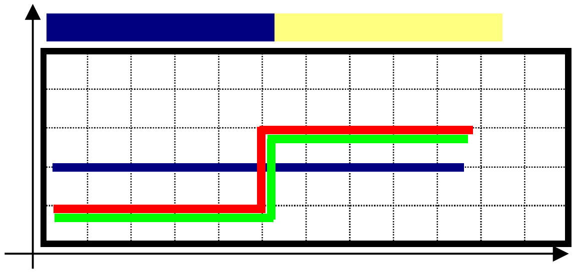


Original signal, an edge from blue (0,0,128) to yellow (255,255,128). Only one scanline shown.

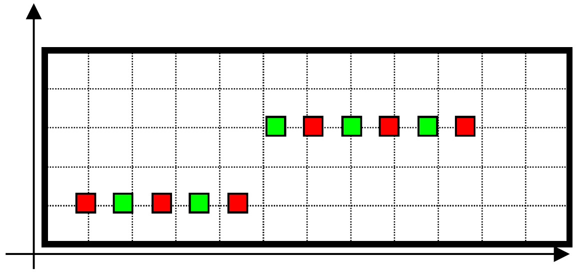


Subsampled Bayer pattern (red scanline)

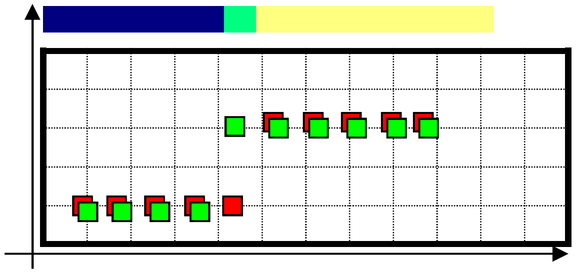
Artifacts: color “fringes”



Original signal, an edge from blue (0,0,128) to yellow (255,255,128). Only one scanline shown.

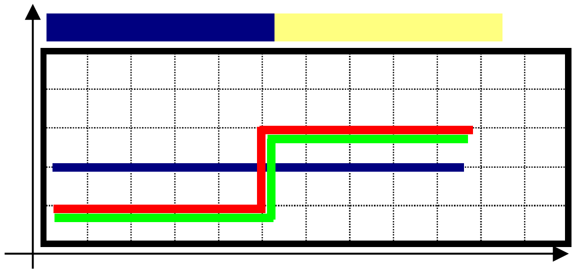


Subsampled Bayer pattern (red scanline)

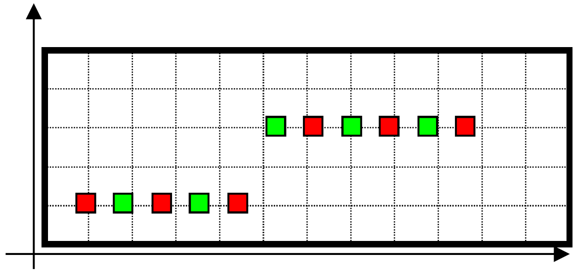


Nearest neighbor color reconstruction.

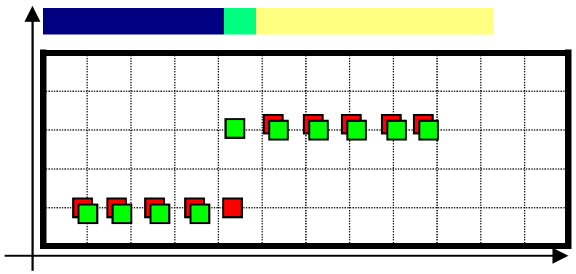
Artifacts: color “fringes”



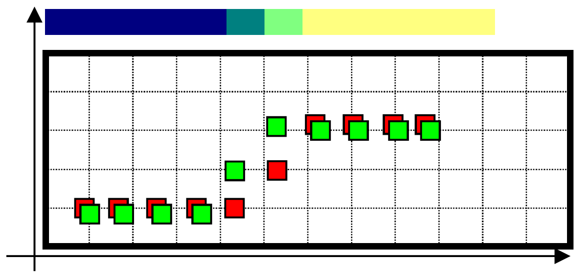
Original signal, an edge from blue (0,0,128) to yellow (255,255,128). Only one scanline shown.



Subsampled Bayer pattern (red scanline)

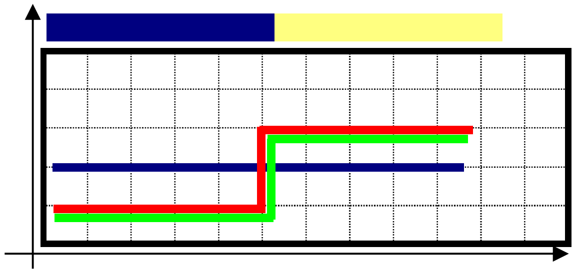


Nearest neighbor color reconstruction.

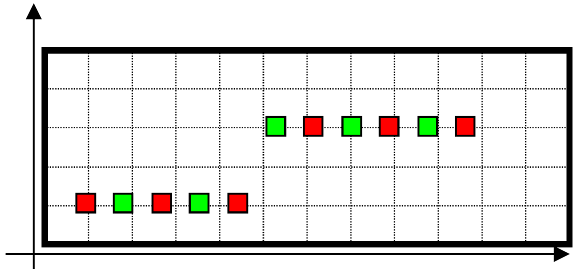


Linear interpolation.

Artifacts: color “fringes”

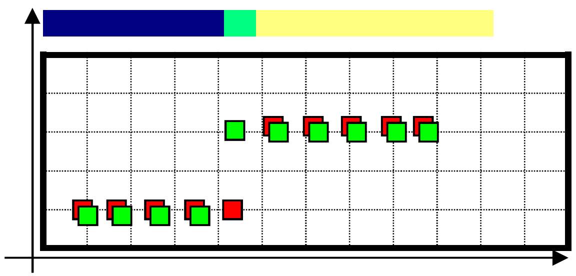


Original signal, an edge from blue (0,0,128) to yellow (255,255,128). Only one scanline shown.

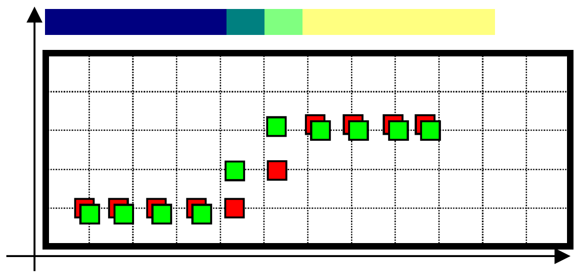


Subsampled Bayer pattern (red scanline)

color fringes



Nearest neighbor color reconstruction.



Linear interpolation.

adapted form: A.Lukin, D.Kubasov, Graphicon 2004

Constant Hue-Based Interpolation

Limit abrupt hue changes (“fringes”) across pixels.

Consider R and B the chrominance values, G is assigned the luminance.
Define hue as: (R/G, B/G)

- First, G values are computed by bilinear interpolation
- Bilinear interpolation of the **hue values** for the R and B channels
- R and B values reconstructed accordingly:

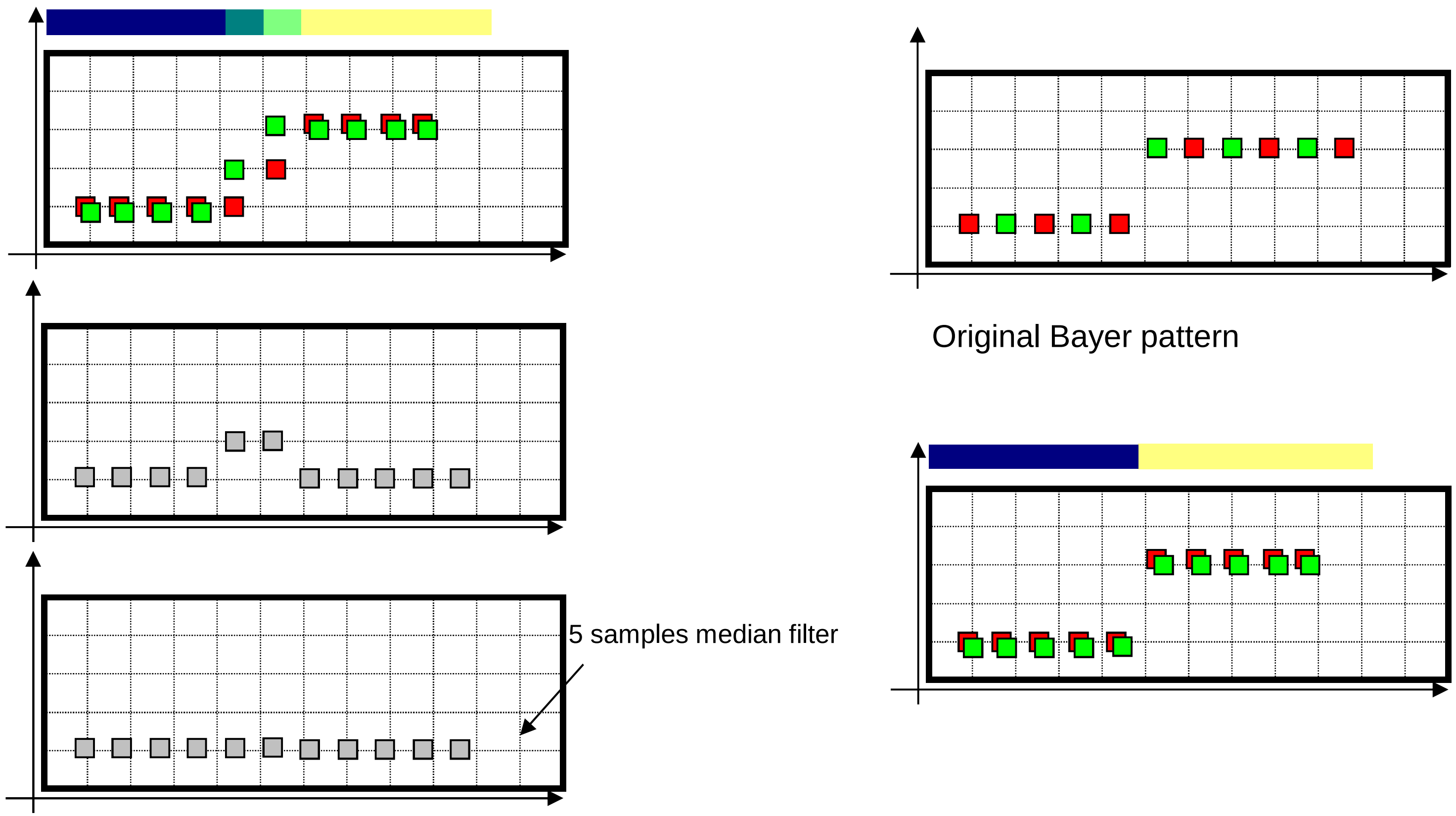
R_{11}	G_{12}	R_{13}	G_{14}	R_{15}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}
G_{41}	B_{42}	G_{43}	B_{44}	G_{45}

$$R_{22} = G_{22} \cdot 0.25 \cdot (R_{11}/G_{11} + R_{13}/G_{13} + R_{31}/G_{31} + R_{33}/G_{33})$$
$$G_{22} = 0.25 \cdot (G_{12} + G_{21} + G_{23} + G_{32})$$
$$B_{22} = B_{22}$$

$$R_{33} = R_{33}$$
$$G_{33} = 0.25 \cdot (G_{23} + G_{34} + G_{43} + G_{32})$$
$$B_{33} = G_{33} \cdot 0.25 \cdot (B_{22}/G_{22} + B_{24}/G_{24} + B_{44}/G_{44} + B_{42}/G_{42})$$

Median-Based Interpolation

- Perform bilinear interpolation of all channels
- Filter differences e.g. R-G and B-G, with a median filter
- Add the median filtered image to the sampled data, to get the missing channel



Median-based interpolation