Light, the Eye, Sensors and Cameras

form of energy, electromagnetic radiation
dual nature:
-photons: travel in straight line at constant speed, which depends on the medium (vacuum: $3x10^8$ m/s), they might have different energy
-wave: *wavelength*

$$E = h\nu = c \cdot h / \lambda \qquad \text{energy}$$

# of photons

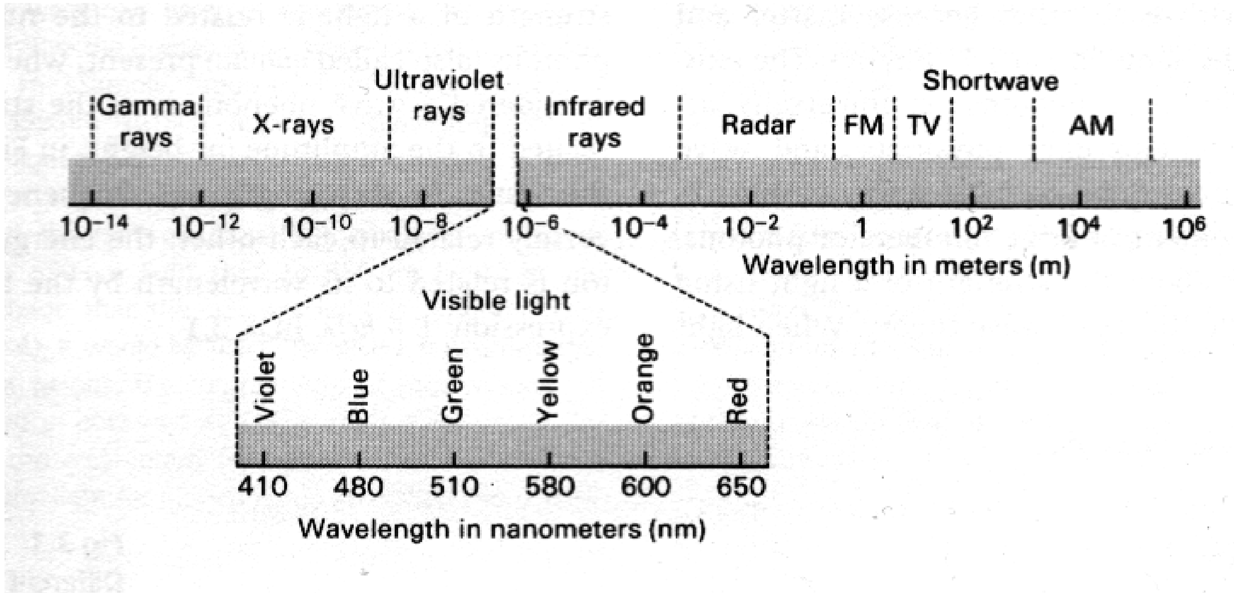
amplitude

h is the Planck's constant

c speed of the wave

ν frequency

λ wavelength


Gamma rays
X-rays
Ultraviolet rays
Infrared rays
Radar
FM
TV
Shortwave
AM
10−14
10−12
10−10
10−8
10−6
10−4
10−2
1
10²
10⁴
10⁶
Wavelength in meters (m)
Visible light
Violet
Blue
Green
Yellow
Orange
Red
410
480
510
580
600
650
Wavelength in nanometers (nm)

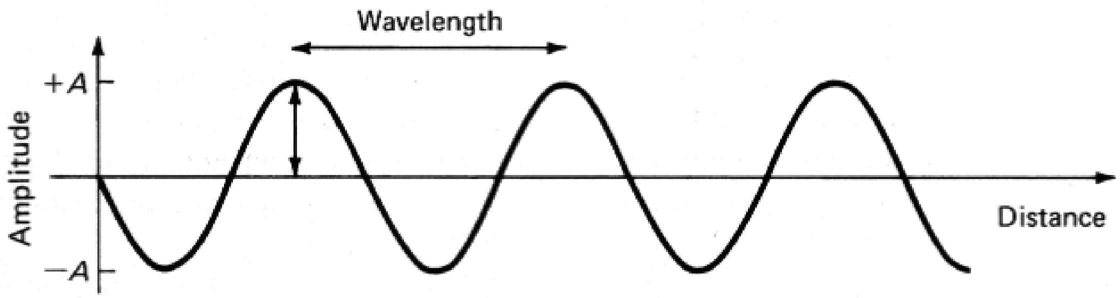
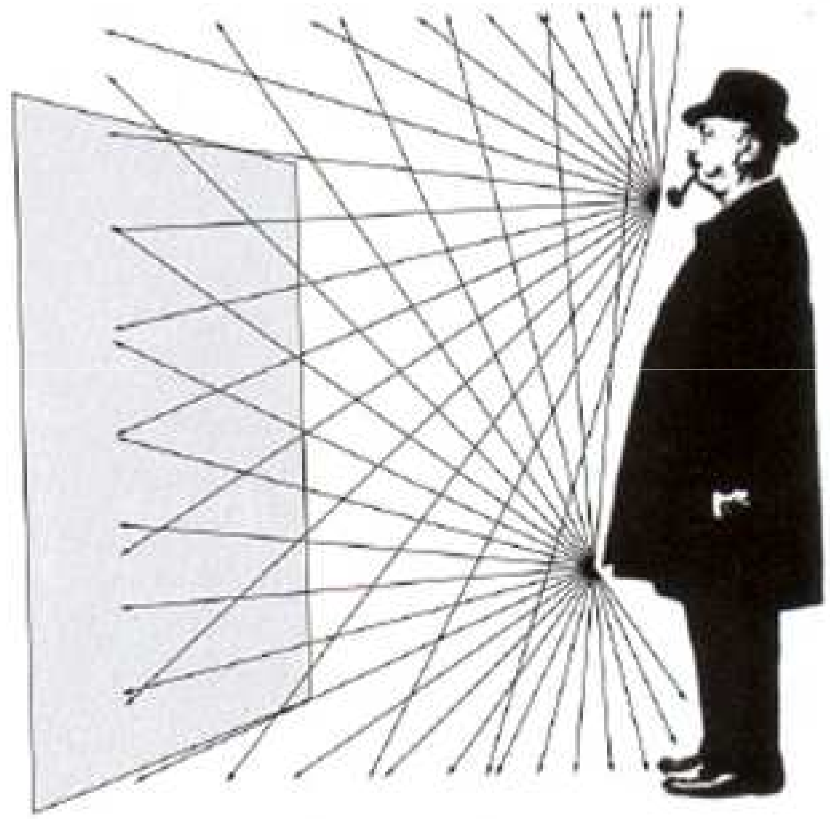

Wavelength
+A
−A
Amplitude
Distance

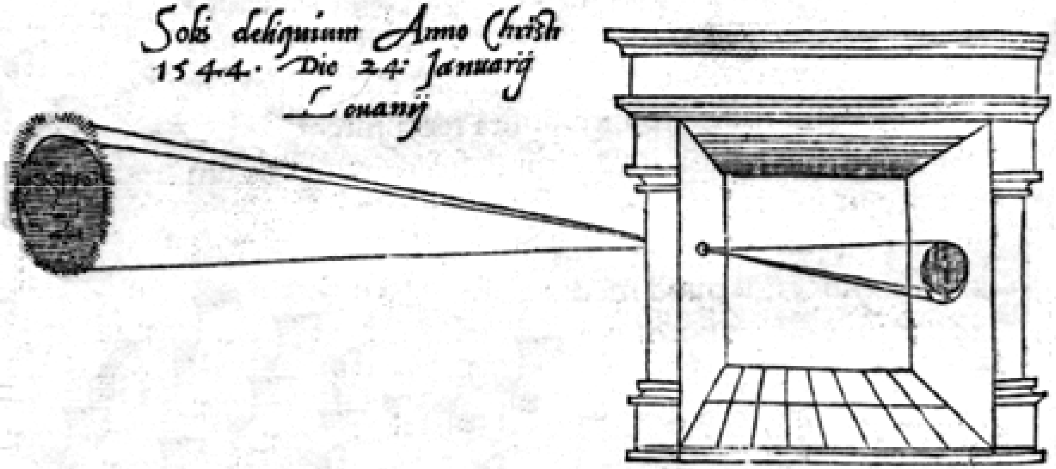
Image formation

Why there is no image on a white paper



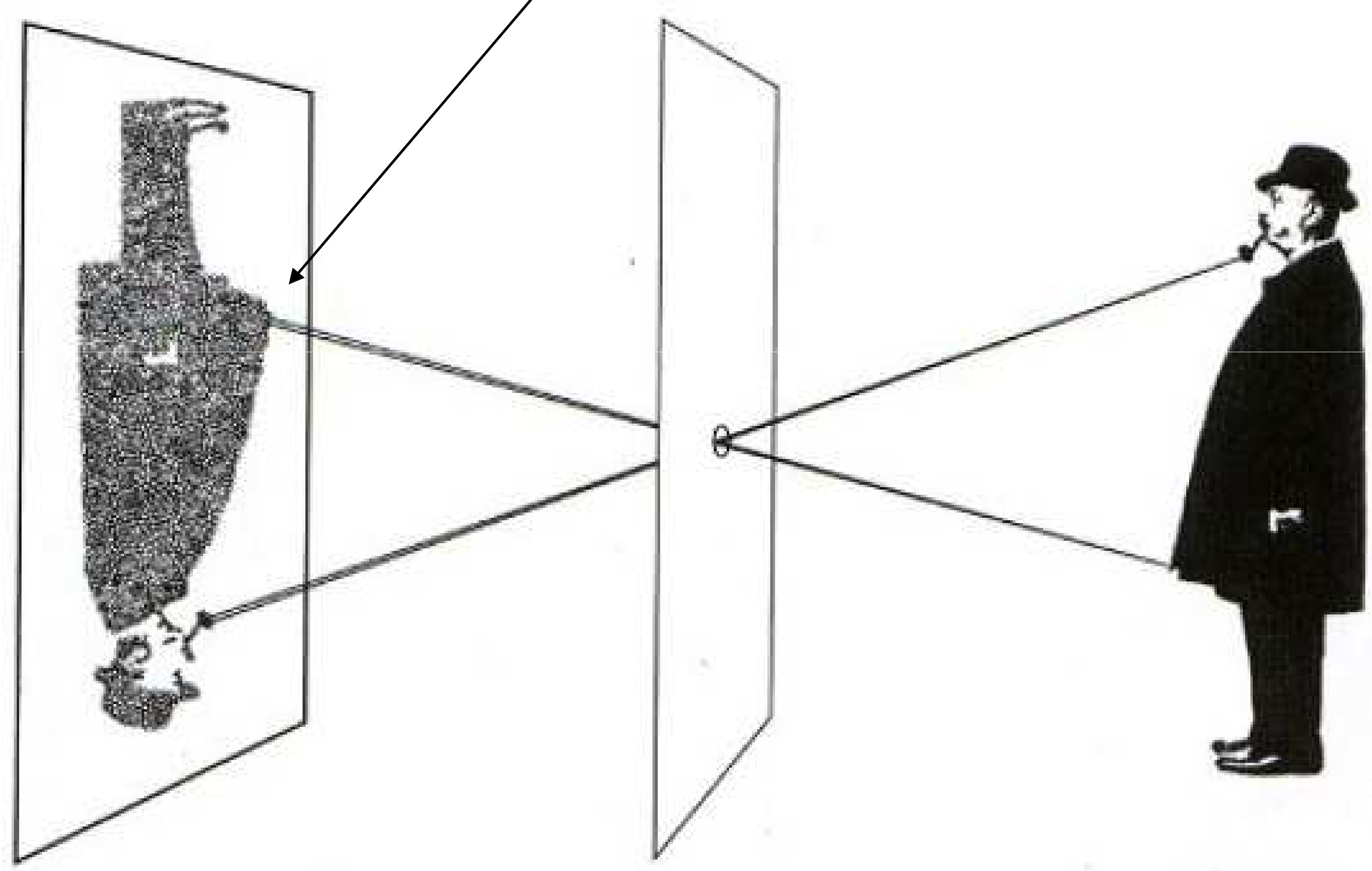
Pinhole

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.

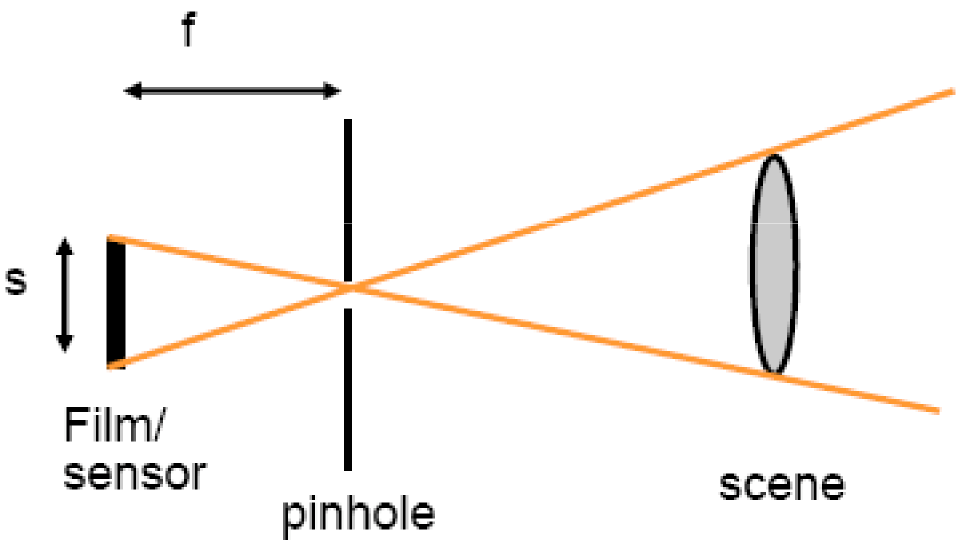


Sic nos exactè Anno .1544. Louanii eclipſim Solis
obſeruauimus, inuenimusq́; deficere paulò plus q̃ dex-

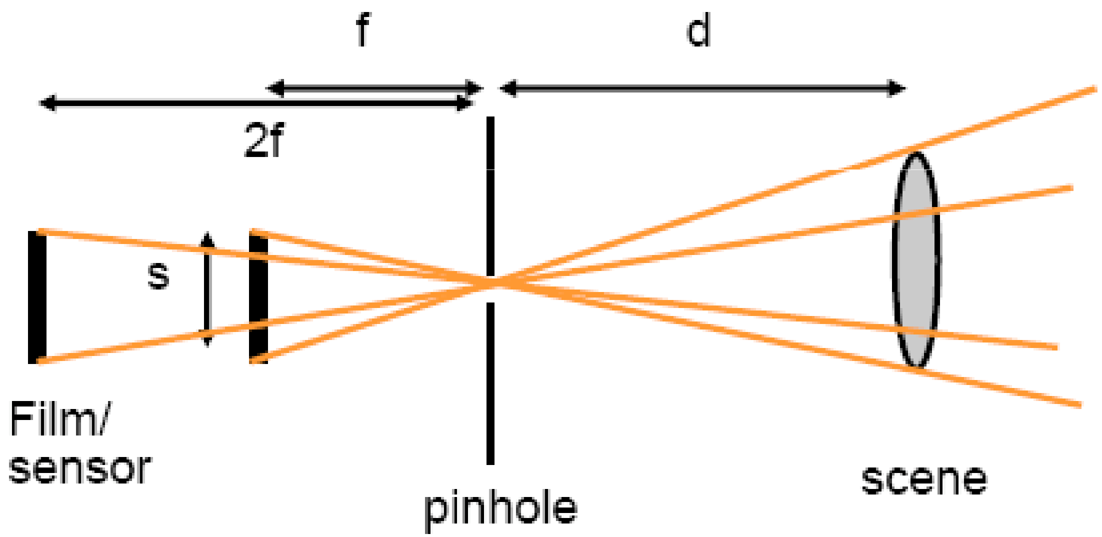
Each point in the scene projects to a single (or very small) point in the image



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

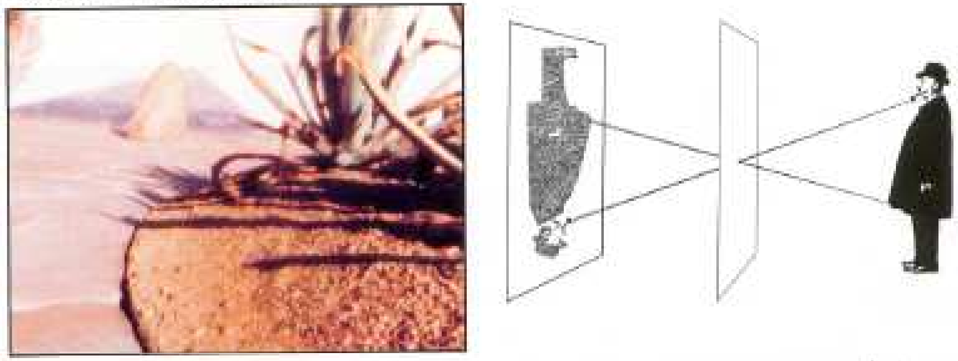


- If we double *f* we double the size of the projected object

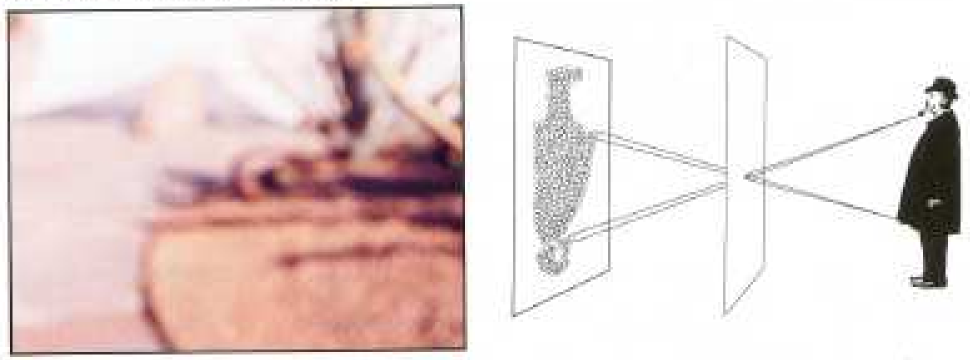


Problems:
- limited light
- the size of the pinhole limits sharpness

Photograph made with small pinhole

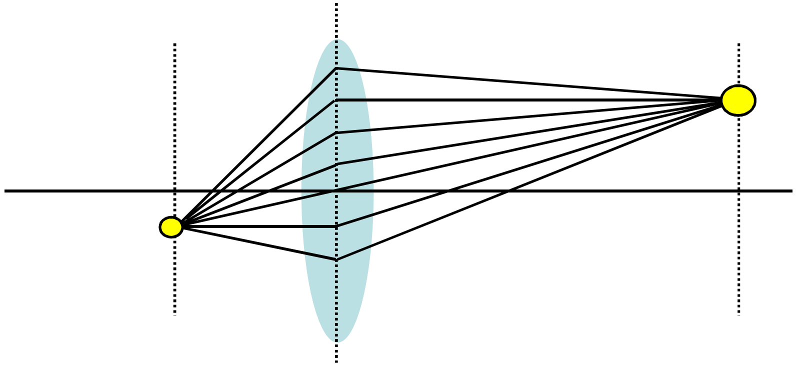


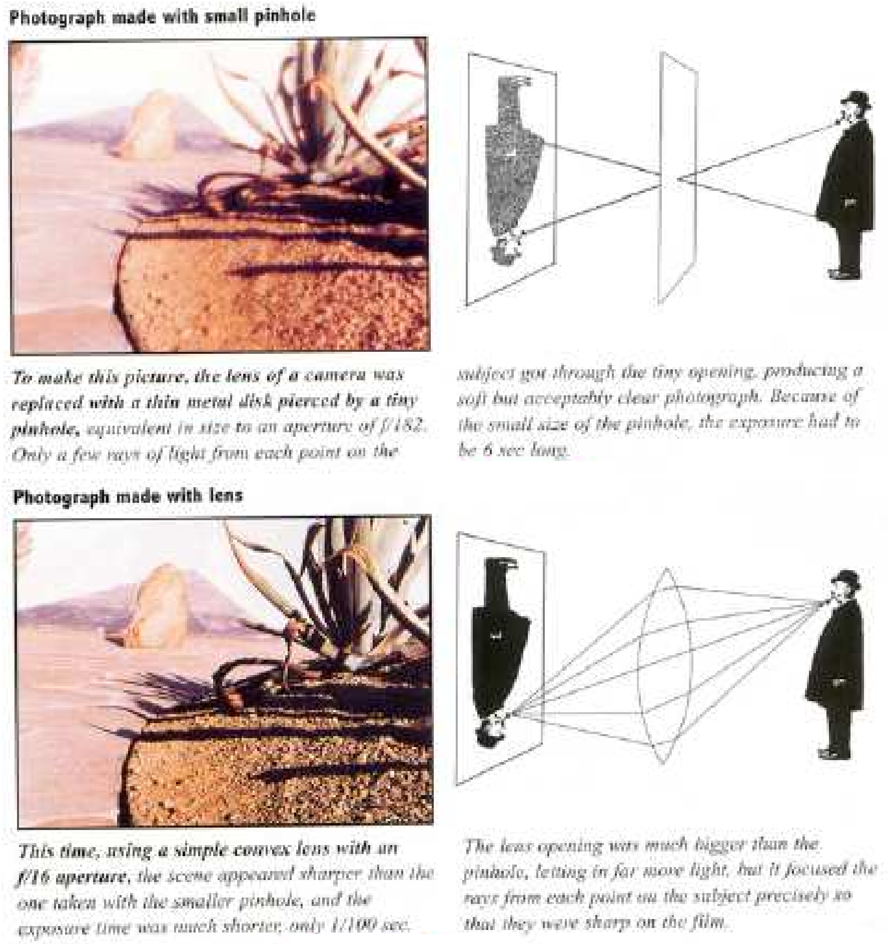
Photograph made with larger pinhole



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.*

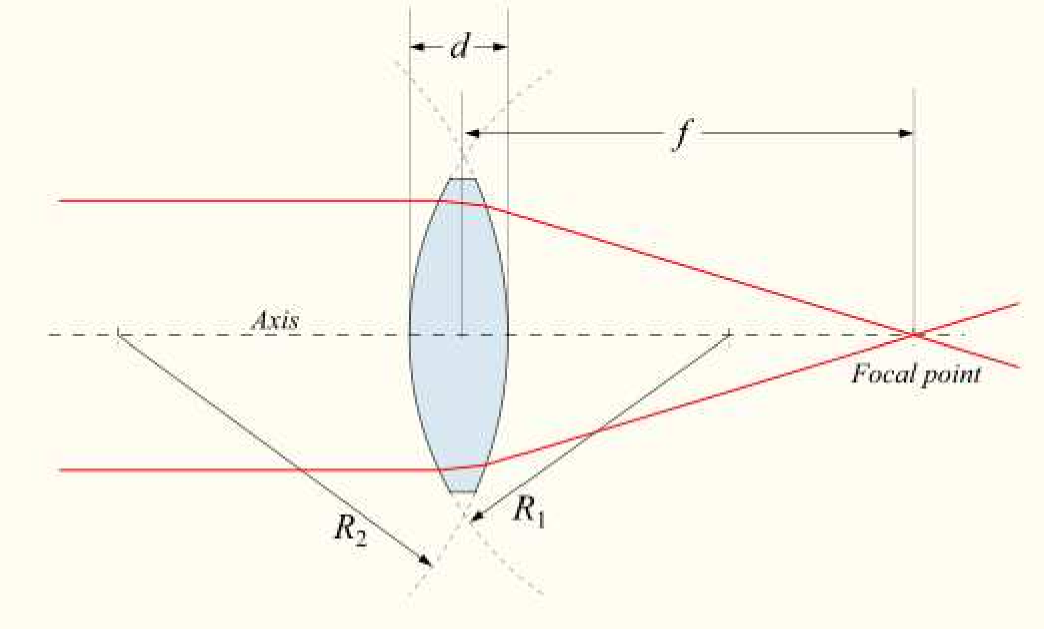
Photograph made with lens

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

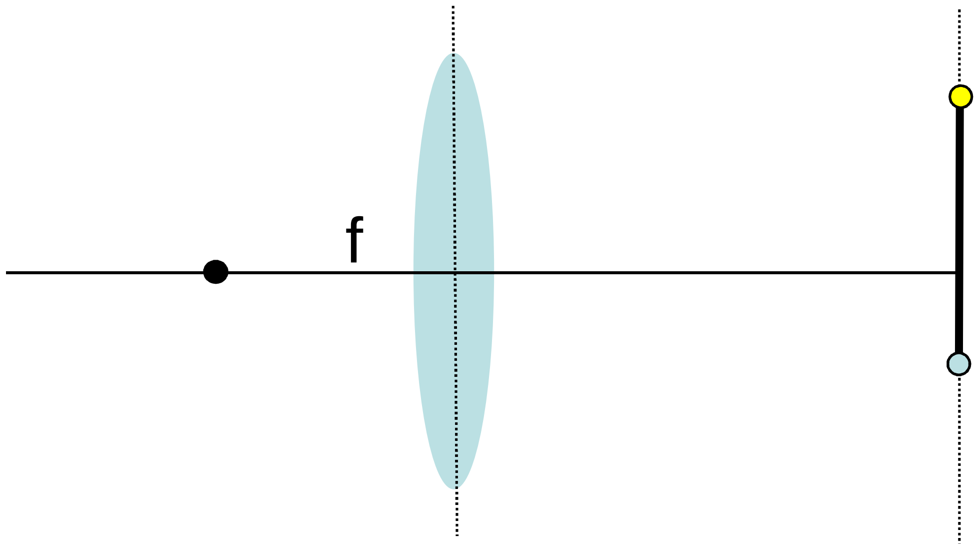
- Three rules
  1. incident rays parallel to the principal axis converge to the focal point
  2. incident rays passing through the center of the lens do not modify their direction
  3. incident rays through the focal point on the right side of the lens get reflected and travel parallel to the principal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



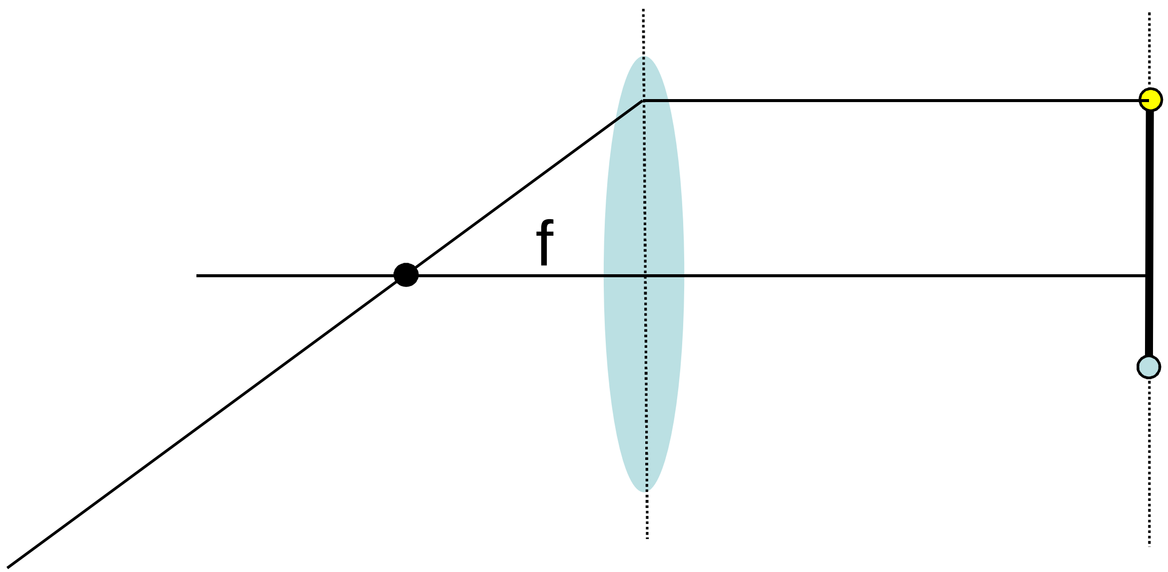
Positive (converging) lens

Thin lens approx:
d small compared to R1 and R2

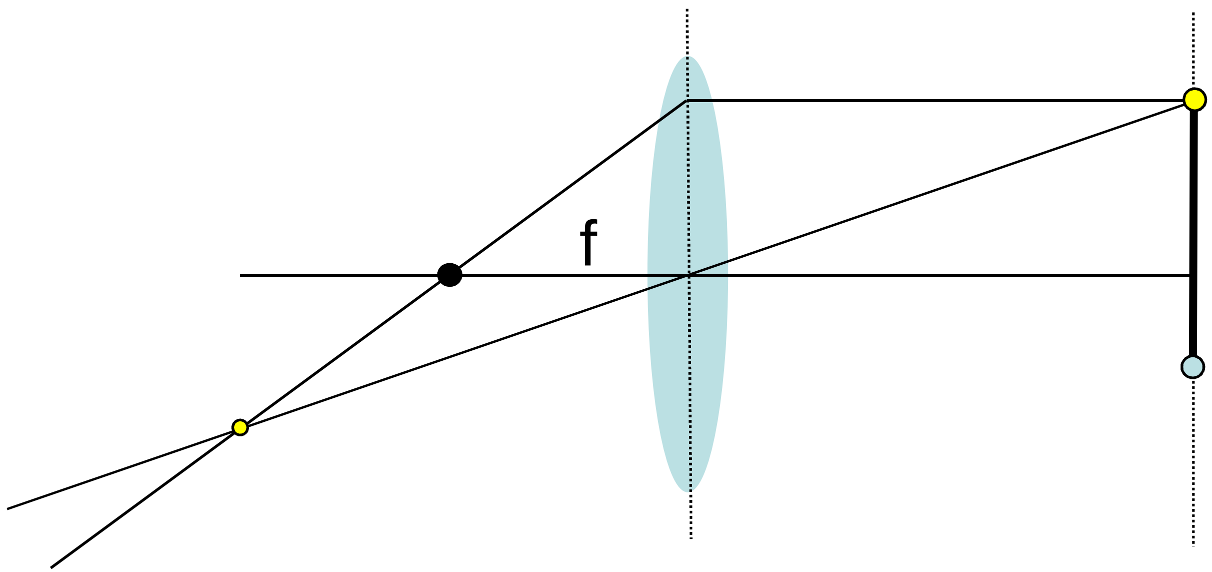
Example



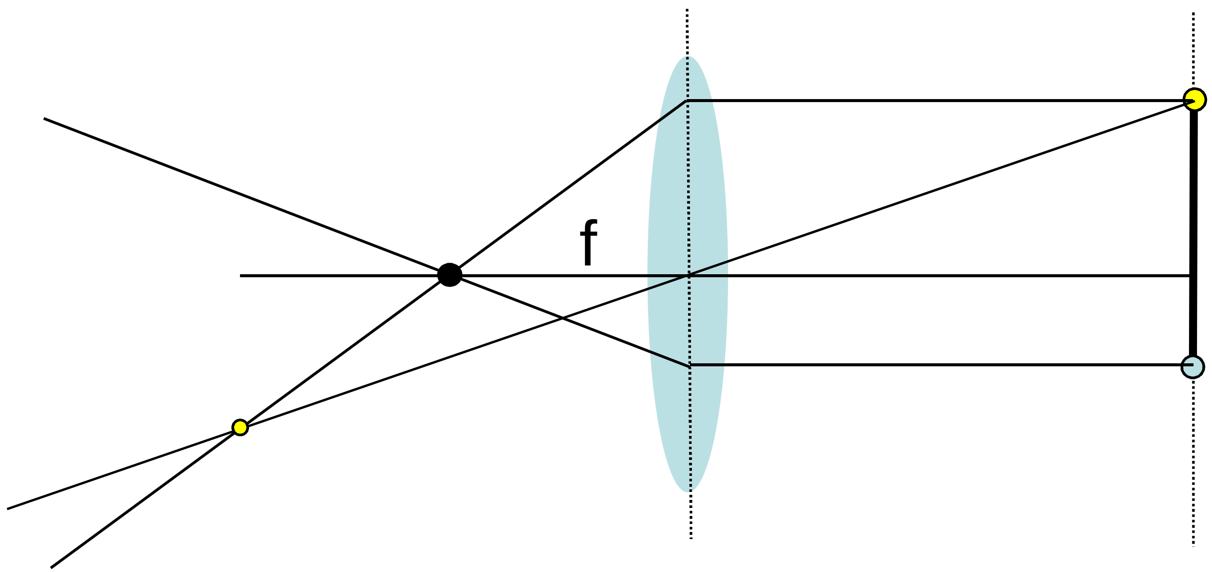
Example



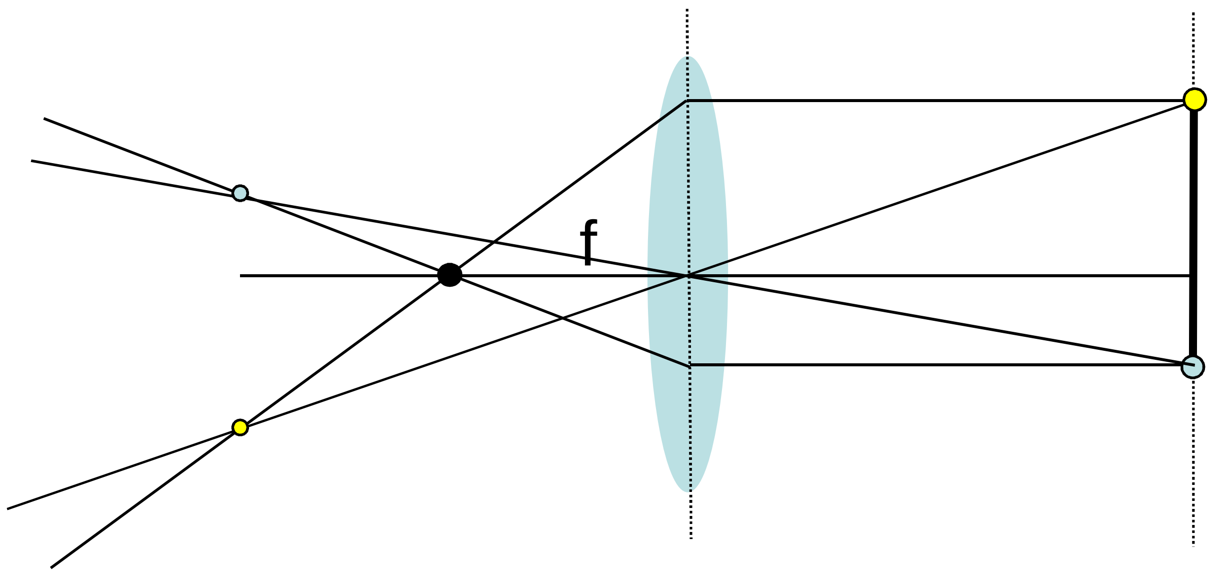
Example



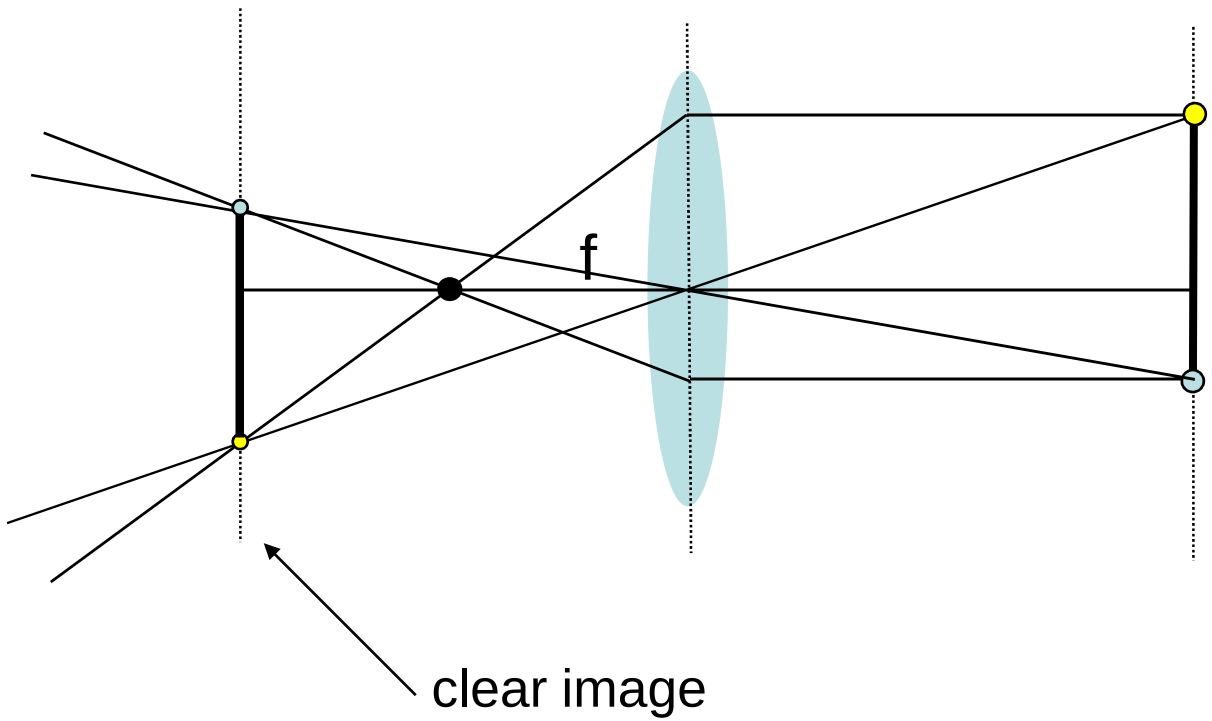
Example



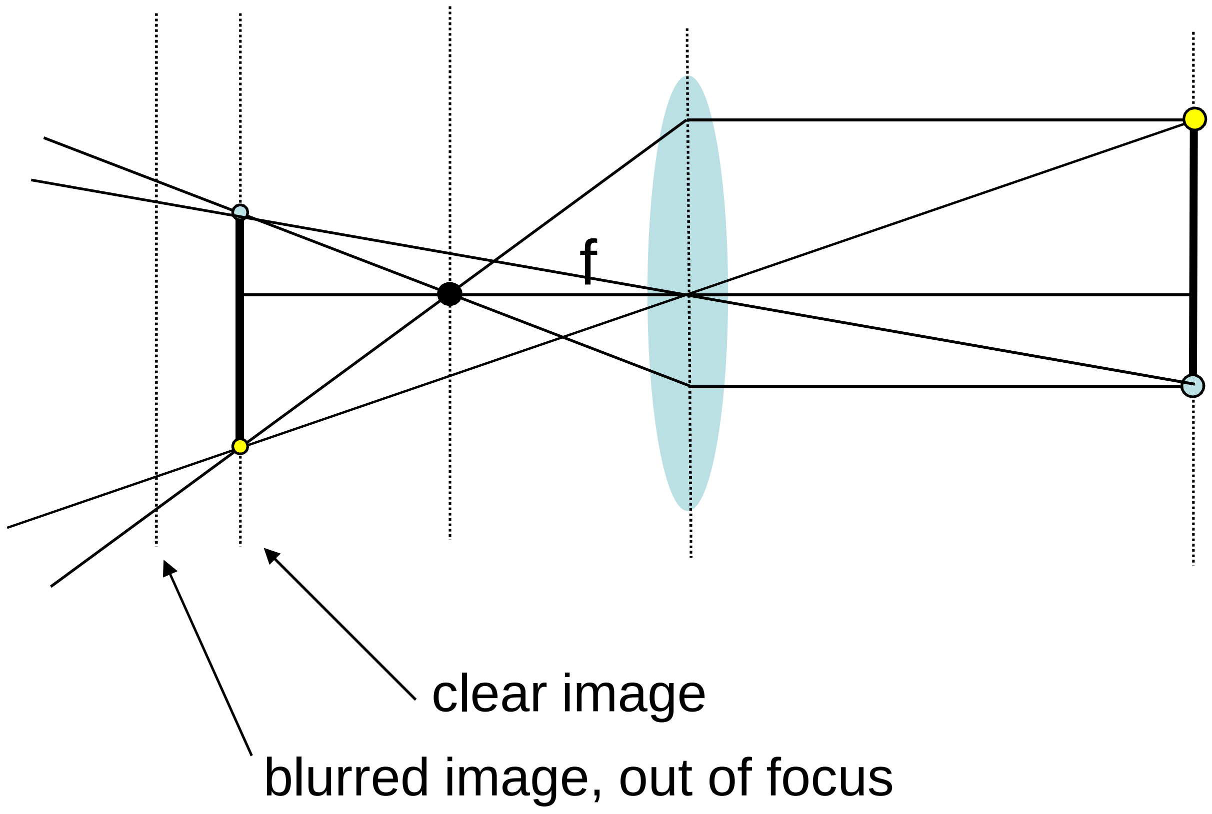
Example



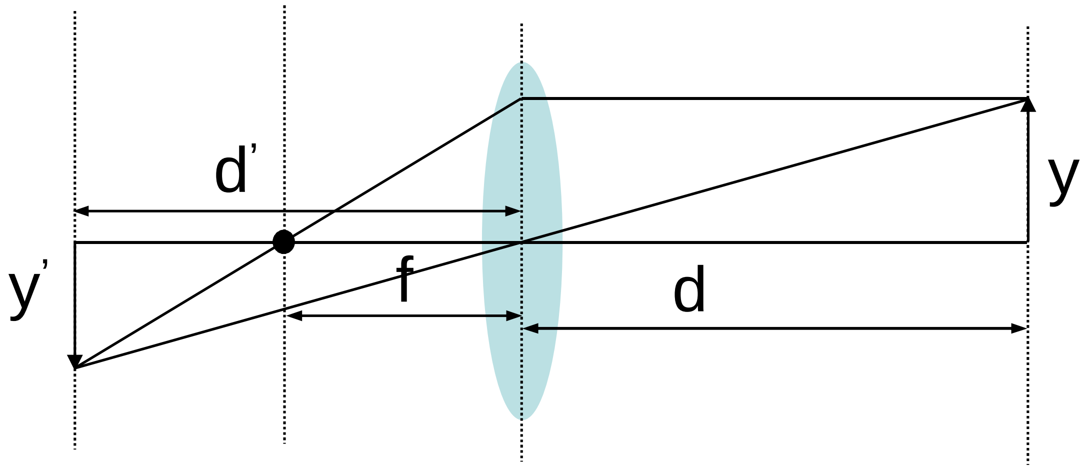
Example



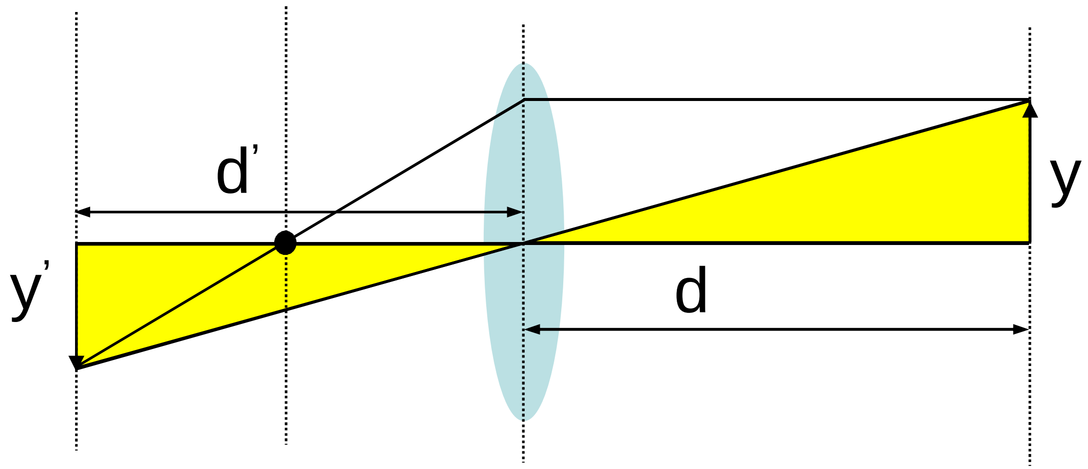
Example



Thin lens formula

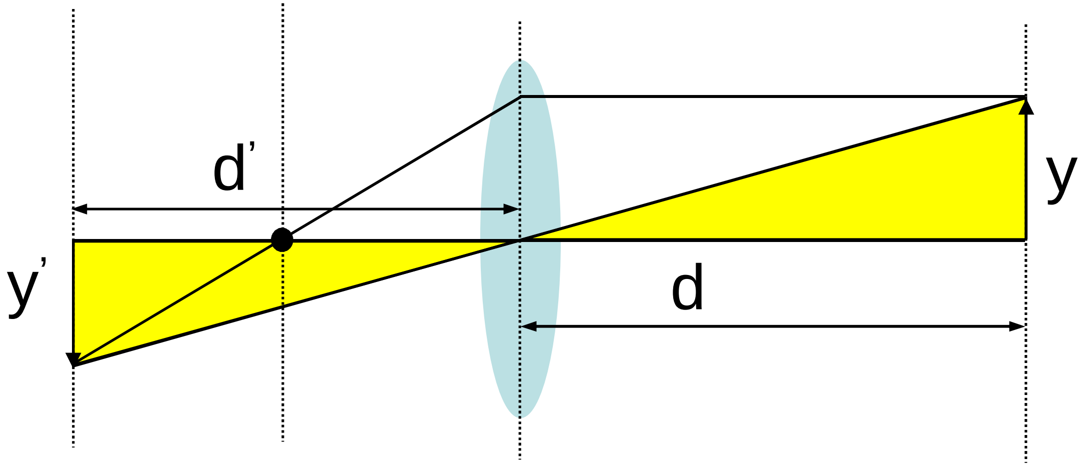


Thin lens formula

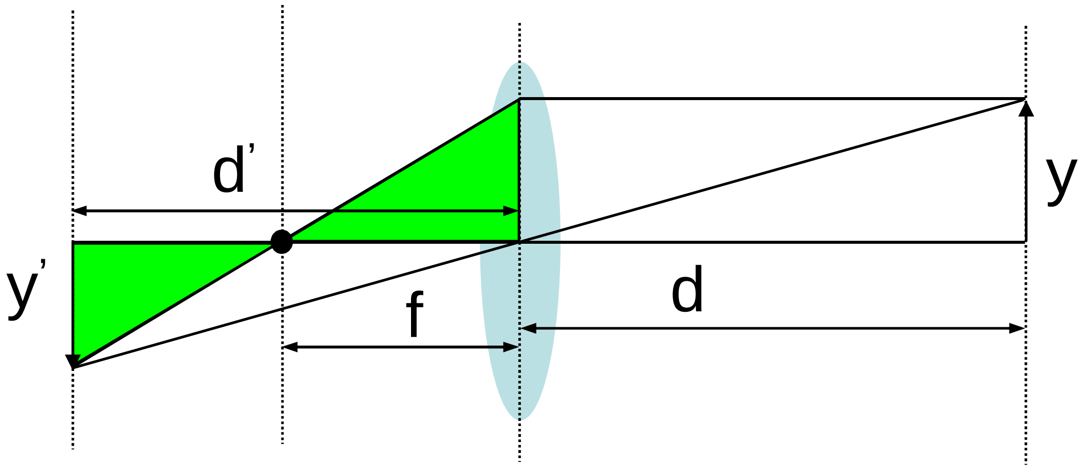


$$\frac{y'}{d'} = \frac{y}{d} \Rightarrow \frac{y'}{y} = \frac{d'}{d}$$

Thin lens formula



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

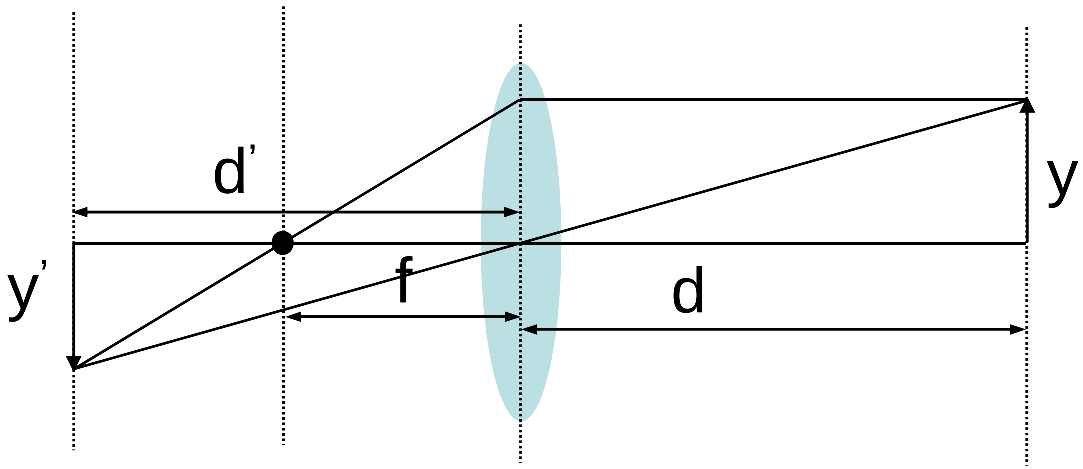


$$\frac{y'}{d'-f} = \frac{y}{f} \Rightarrow \frac{y'}{y} = \frac{d'-f}{f}$$

Thin lens formula

$$\begin{cases} \dfrac{y'}{y} = \dfrac{d'}{d} \\ \dfrac{y'}{y} = \dfrac{d'-f}{f} \end{cases}$$

$$\frac{d'}{d} = \frac{d'-f}{f} \Rightarrow \frac{d'}{d} = \frac{d'}{f} - 1 \Rightarrow \frac{1}{d} = \frac{1}{f} - \frac{1}{d'}$$

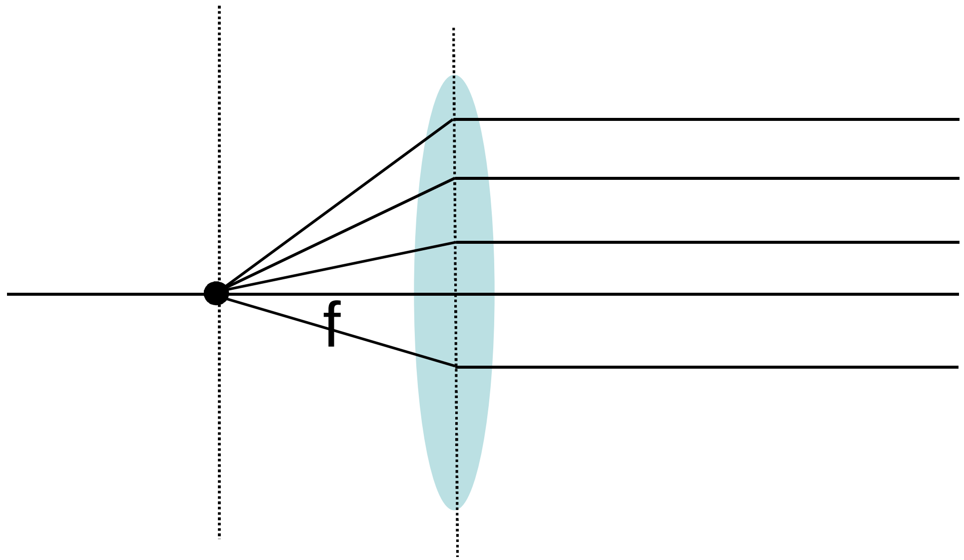


$$\frac{1}{d'} + \frac{1}{d} = \frac{1}{f}$$

Objects at infinity focus at *f*

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

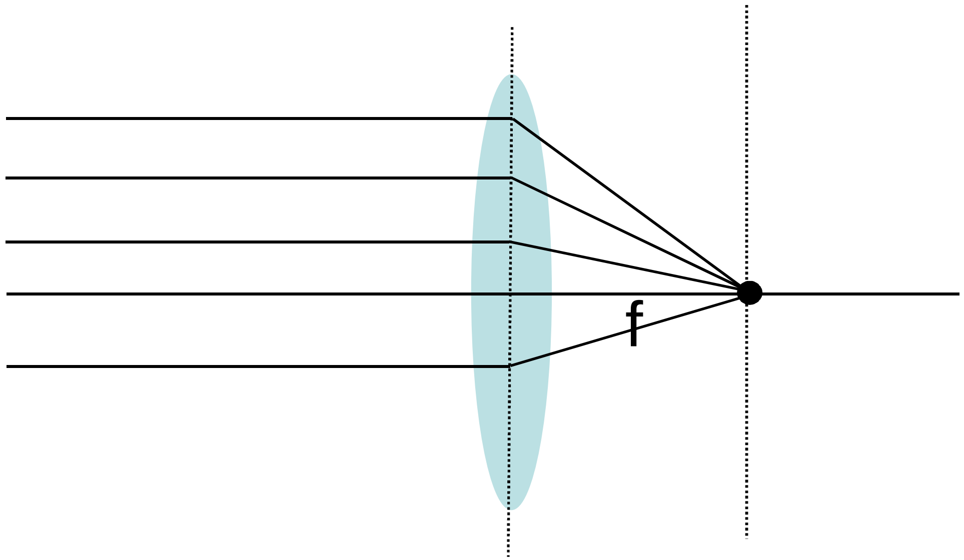
$$d' \to f$$



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

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

$$d' \to \infty$$

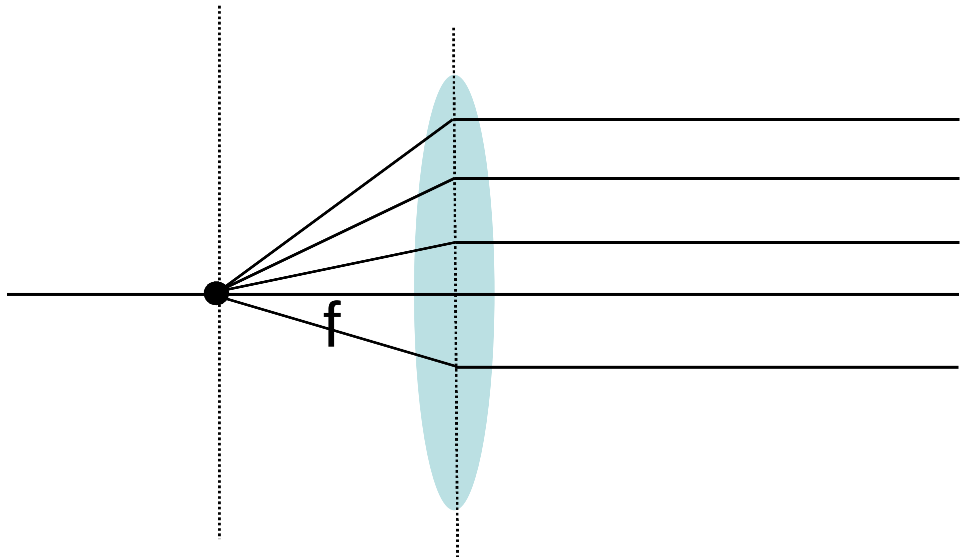


an object at distance *f* requires the focal plane to be at infinity

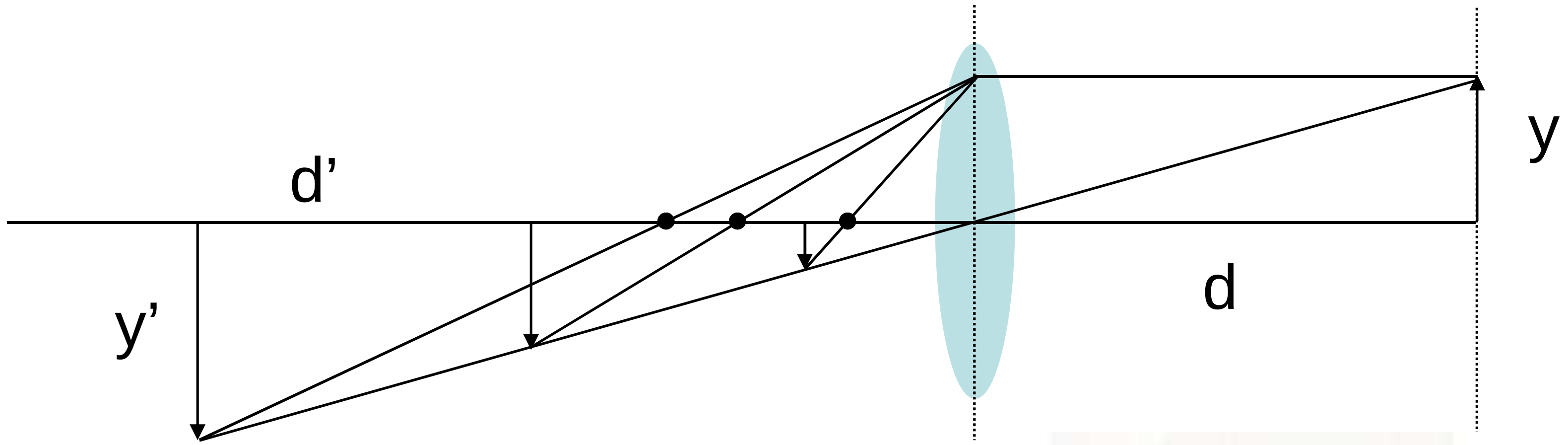
Objects at infinity focus at *f*

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

$$d' \to f$$



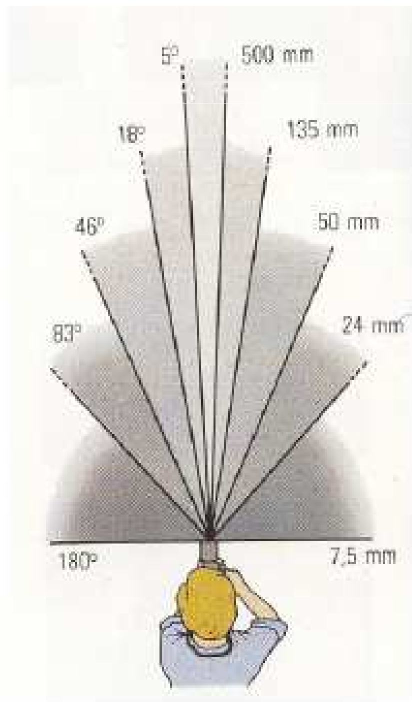
Effect of focal length on image size



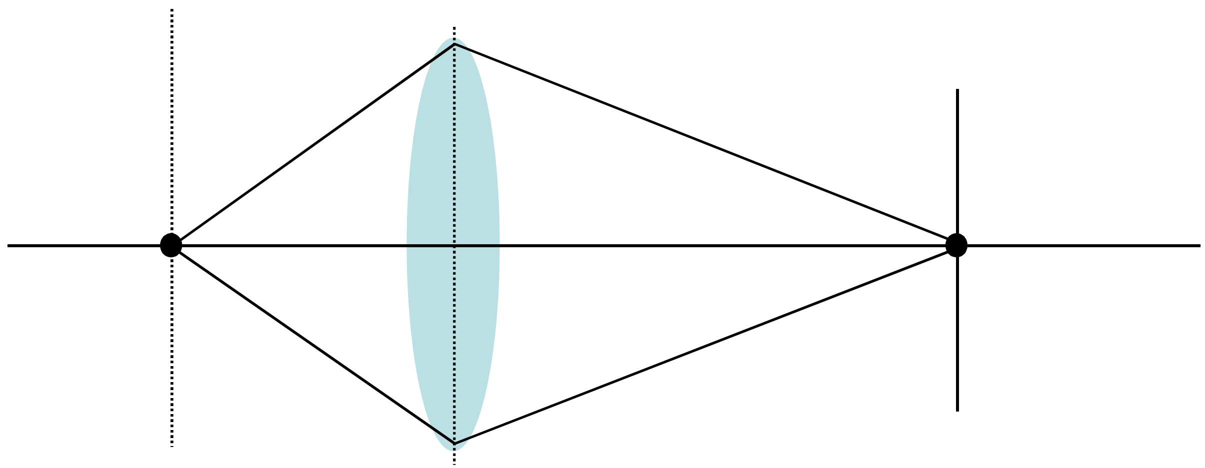
$$M = \frac{y'}{y} = \frac{d'}{d}$$

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

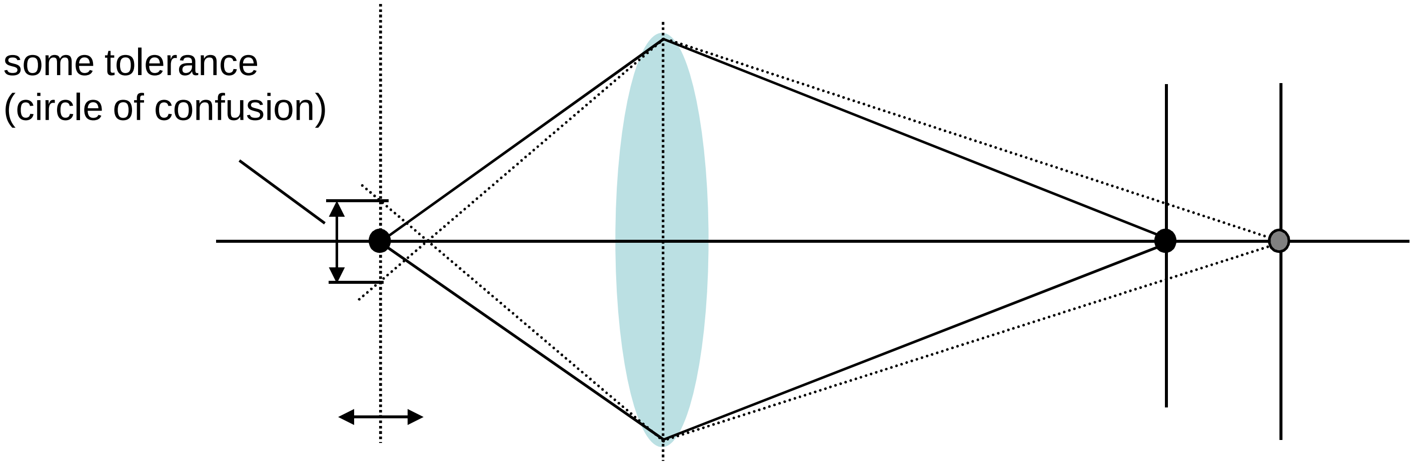
Effect of focal length on field of view



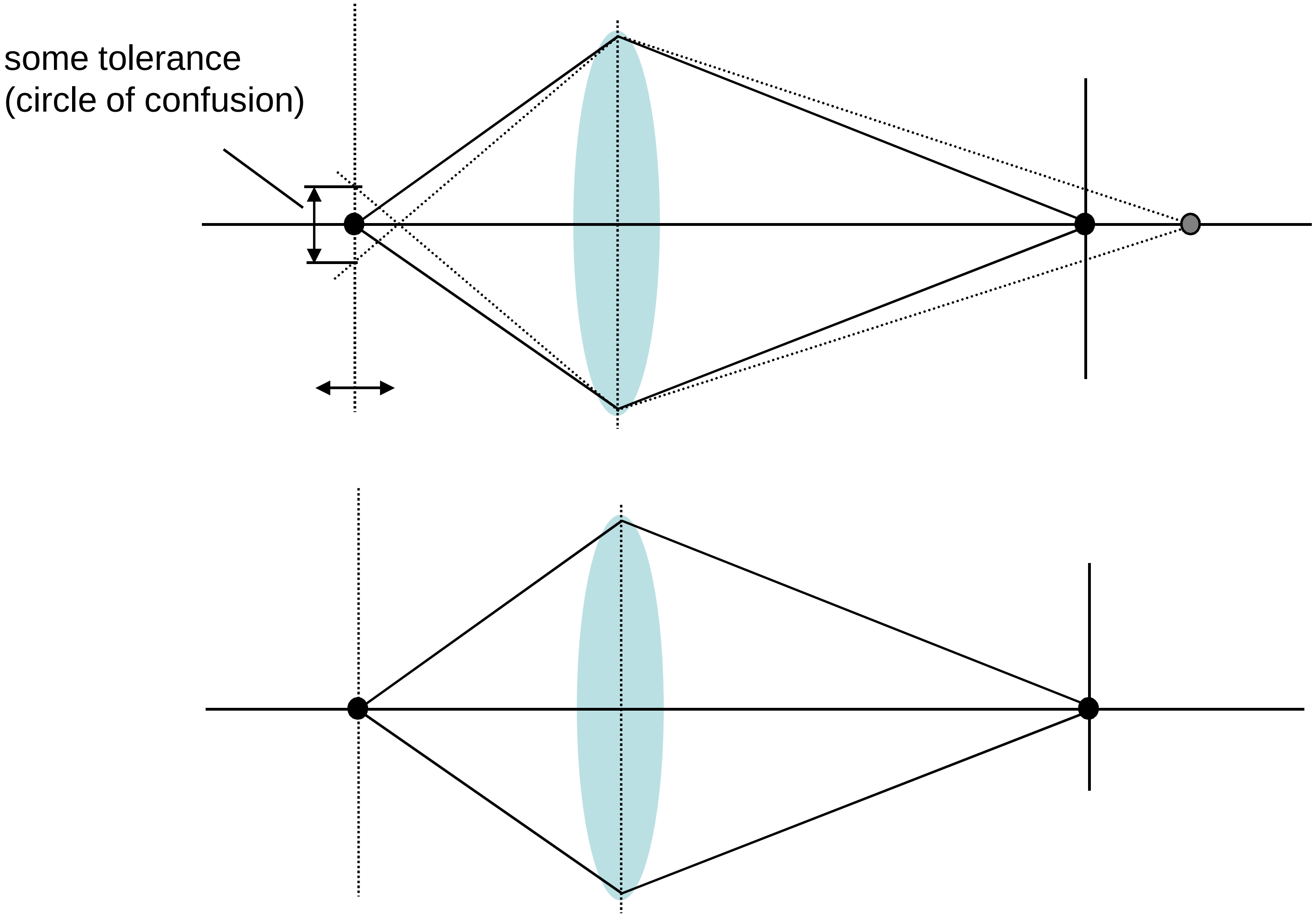
Depth of field (dof)



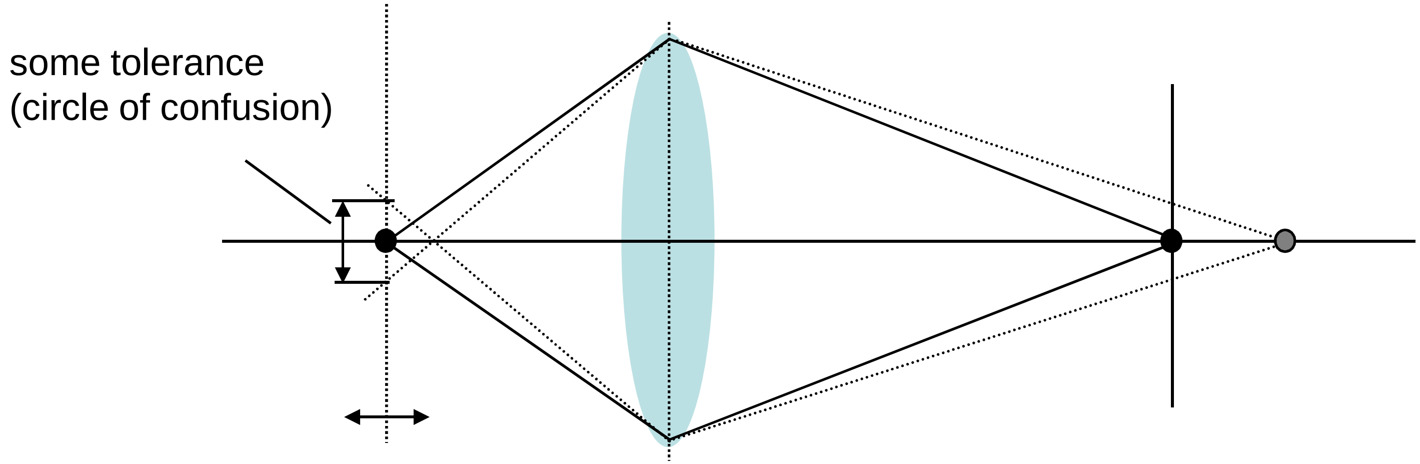
Depth of field (dof)

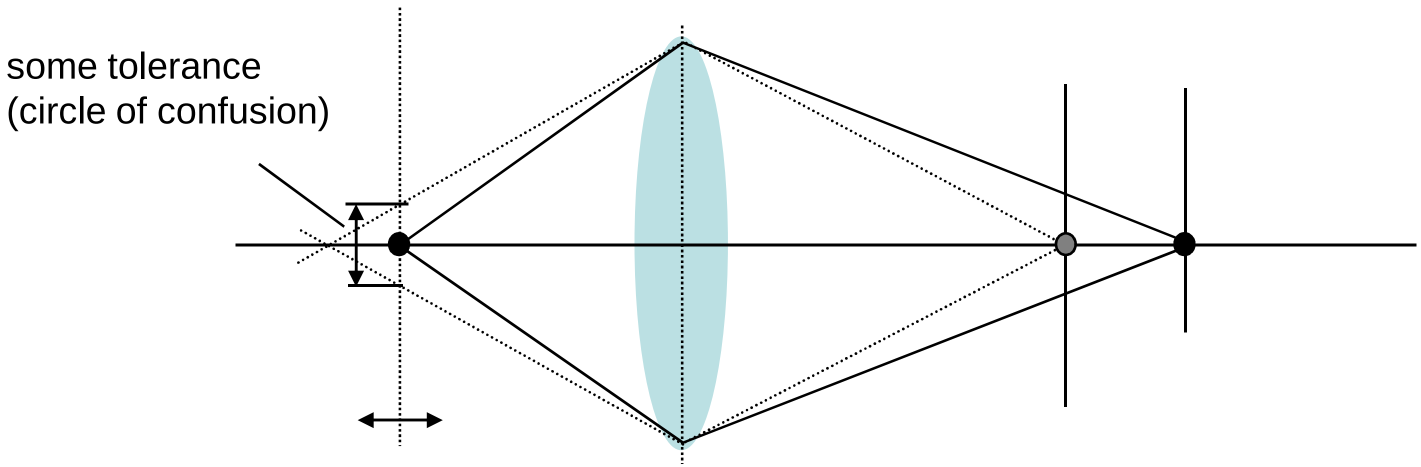


Depth of field (dof)

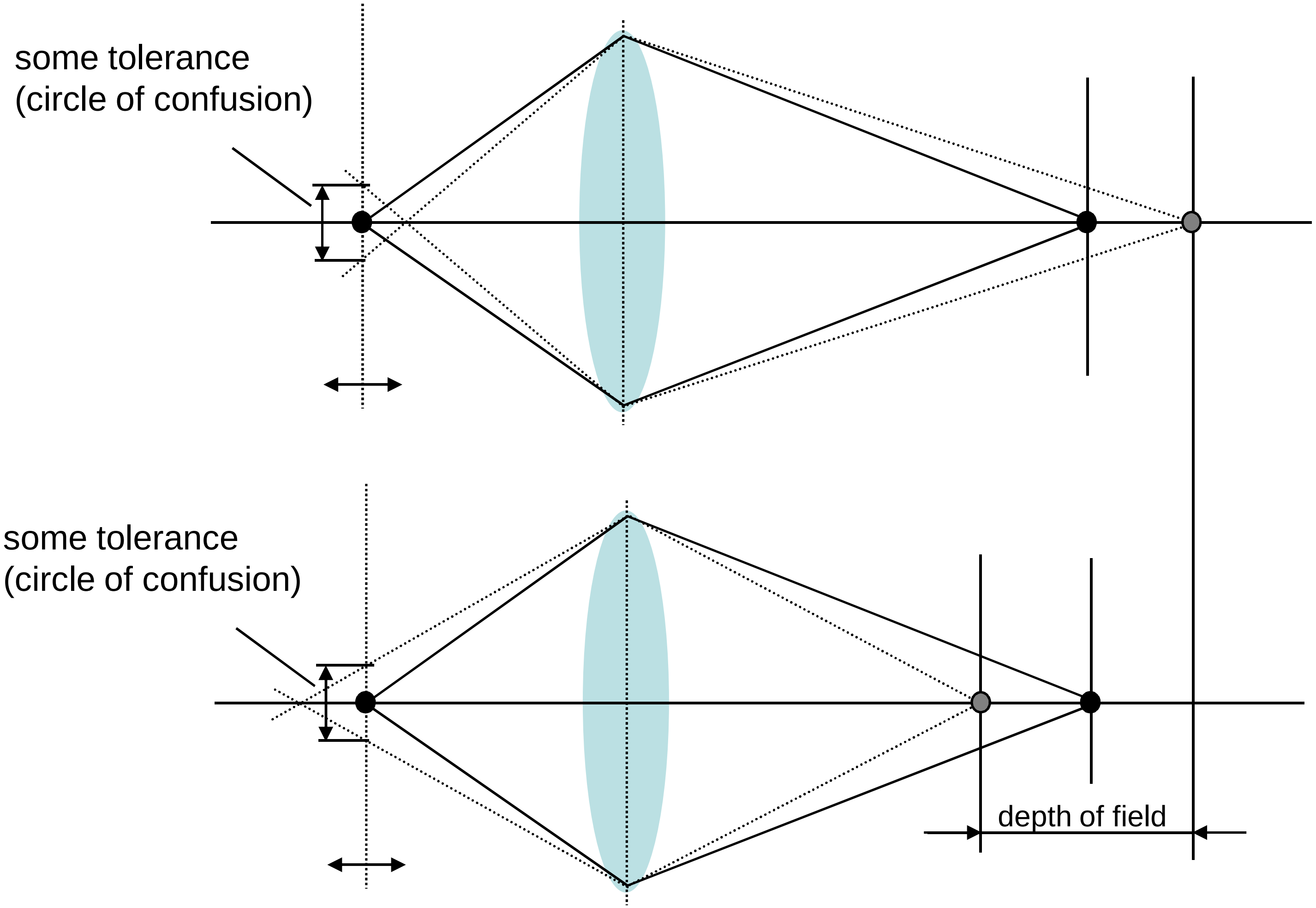


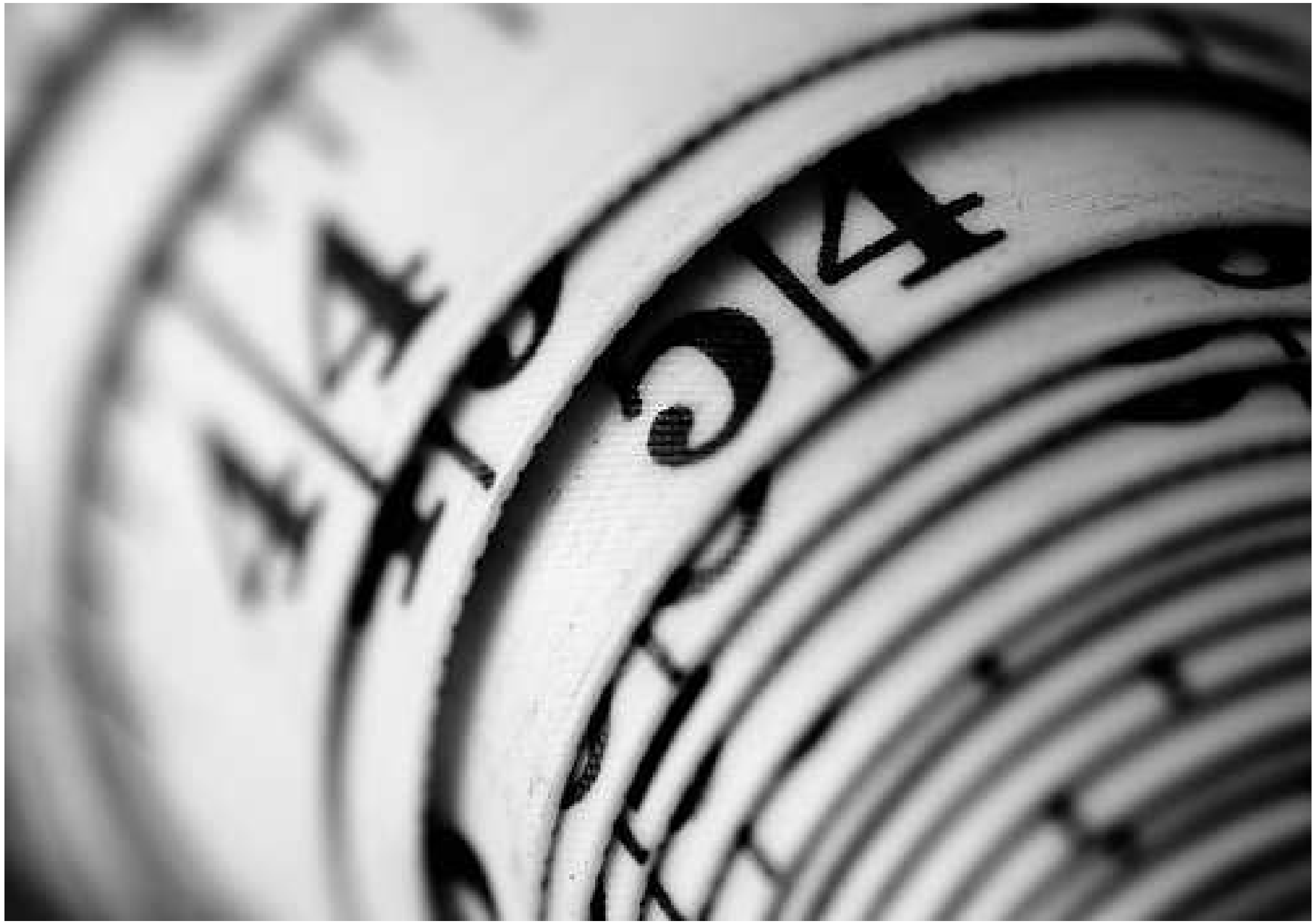
Depth of field (dof)





Depth of field (dof)





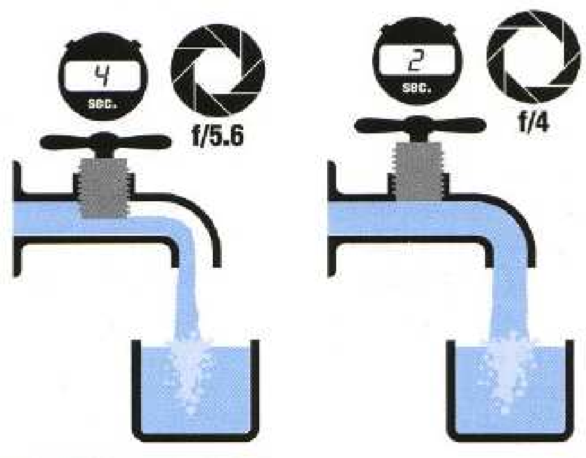
Getting the right exposure

- 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)



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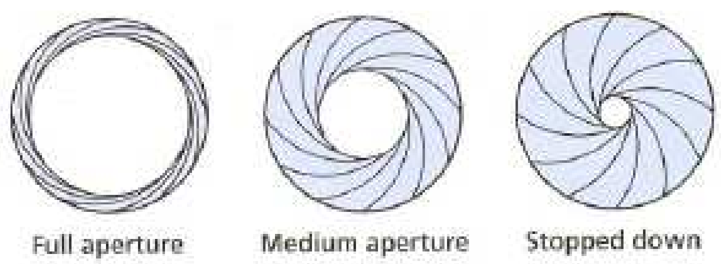
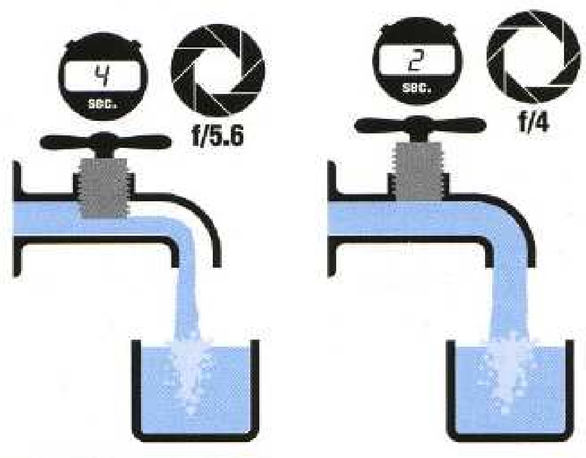
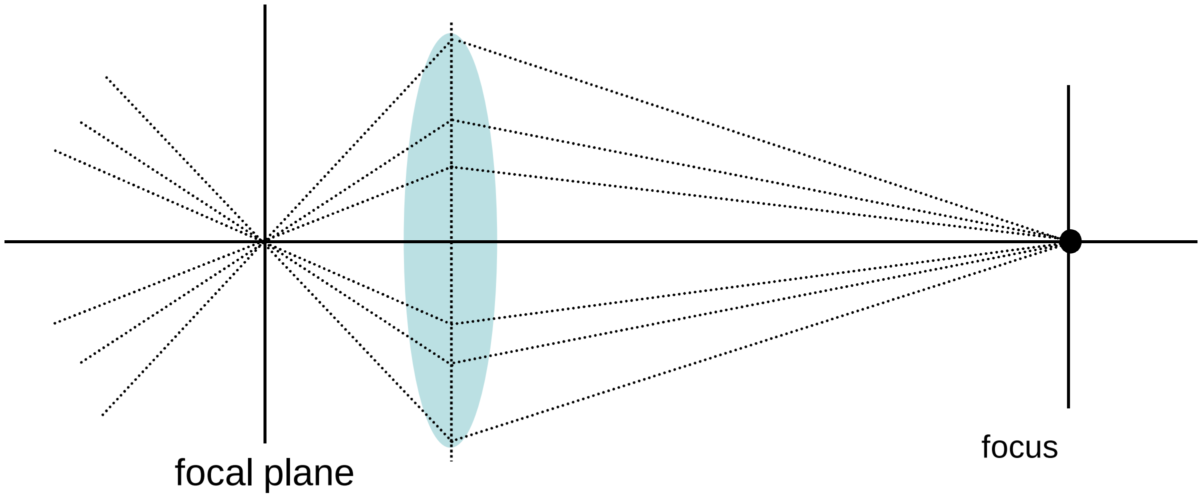
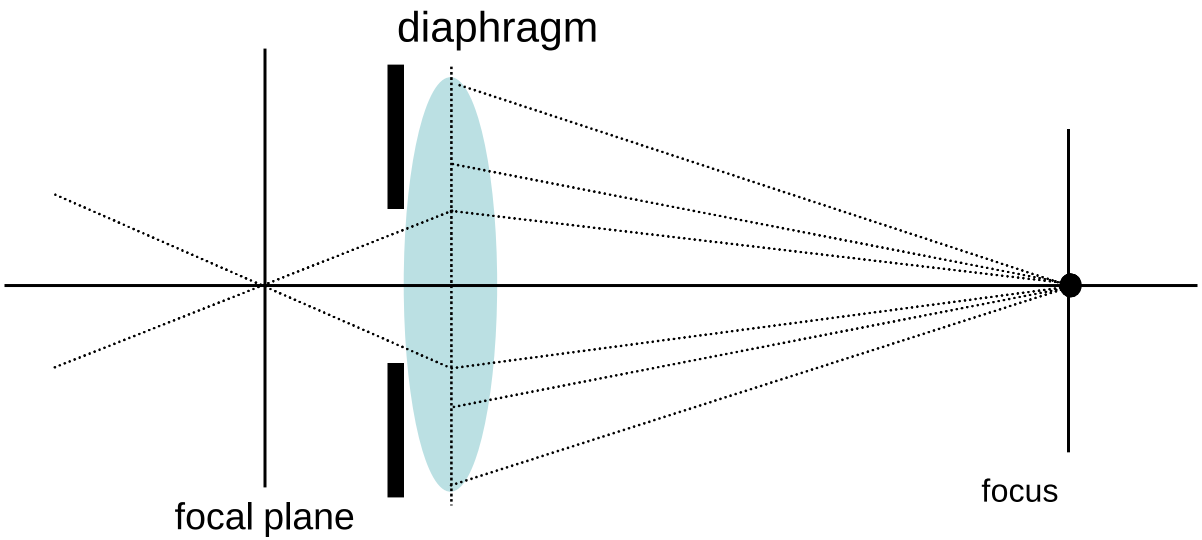
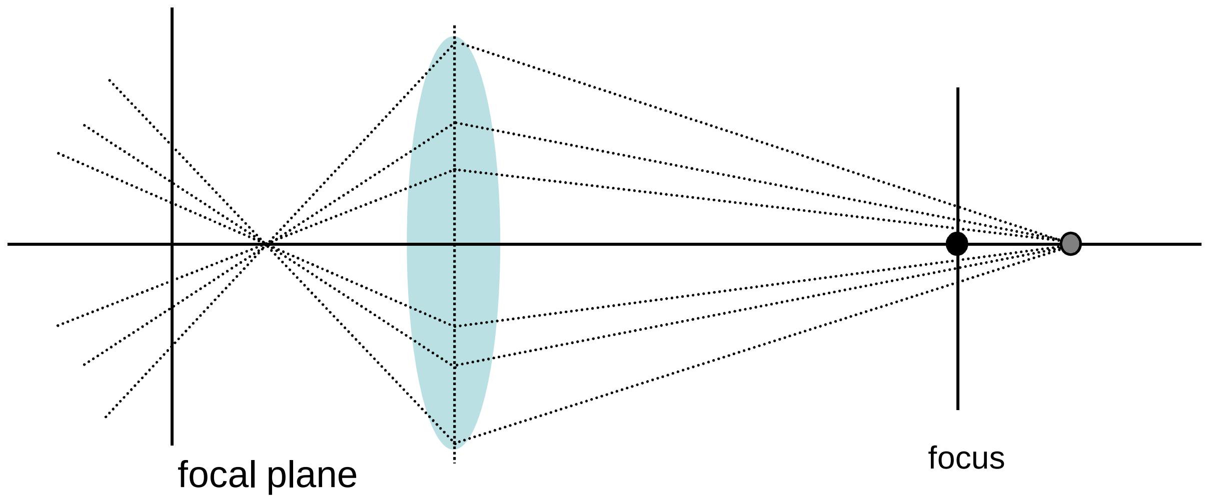
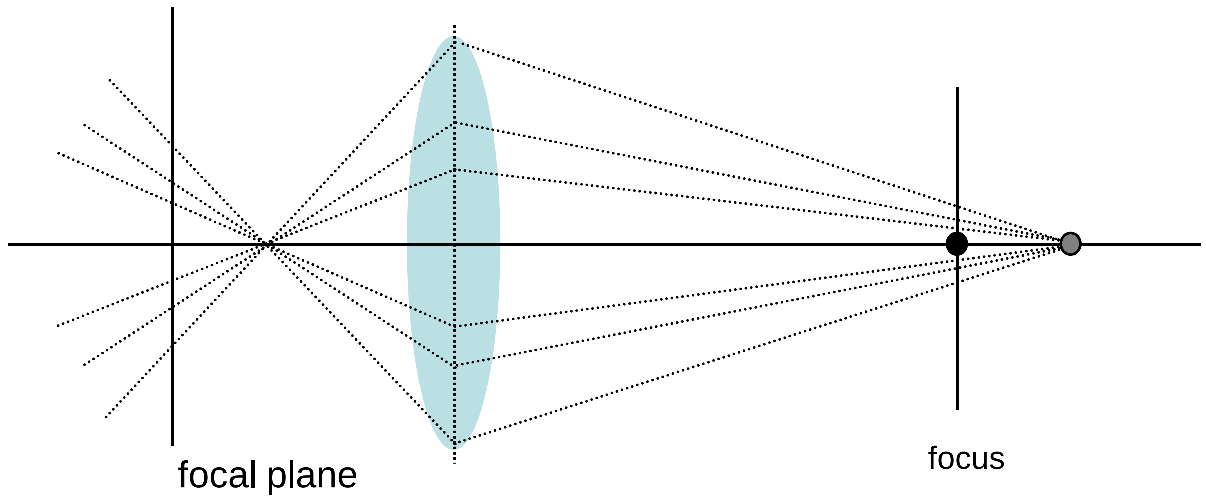


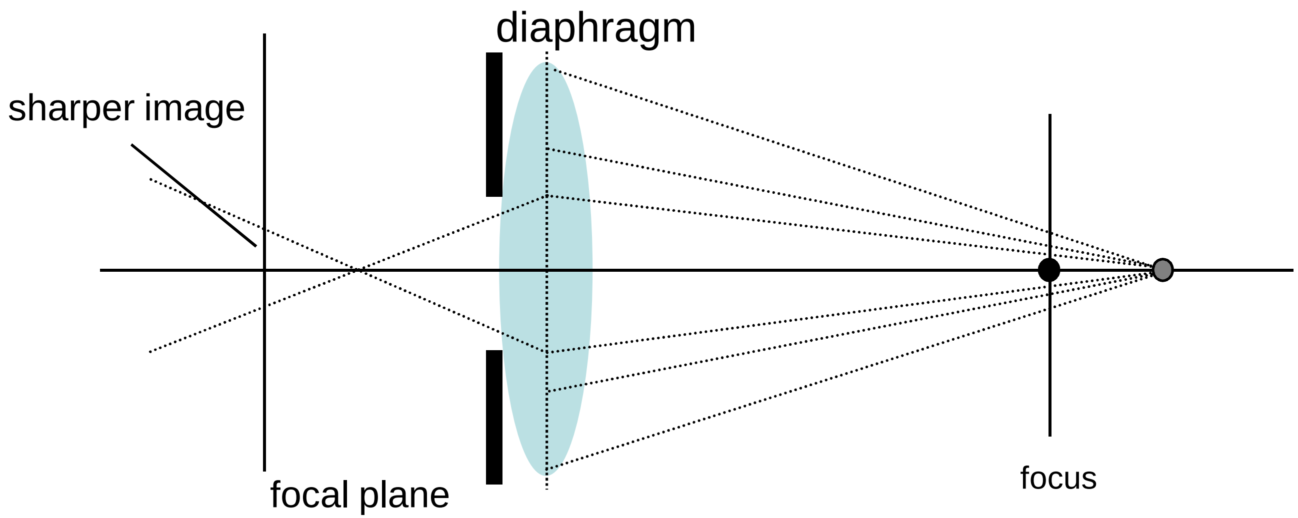



focal plane
focus

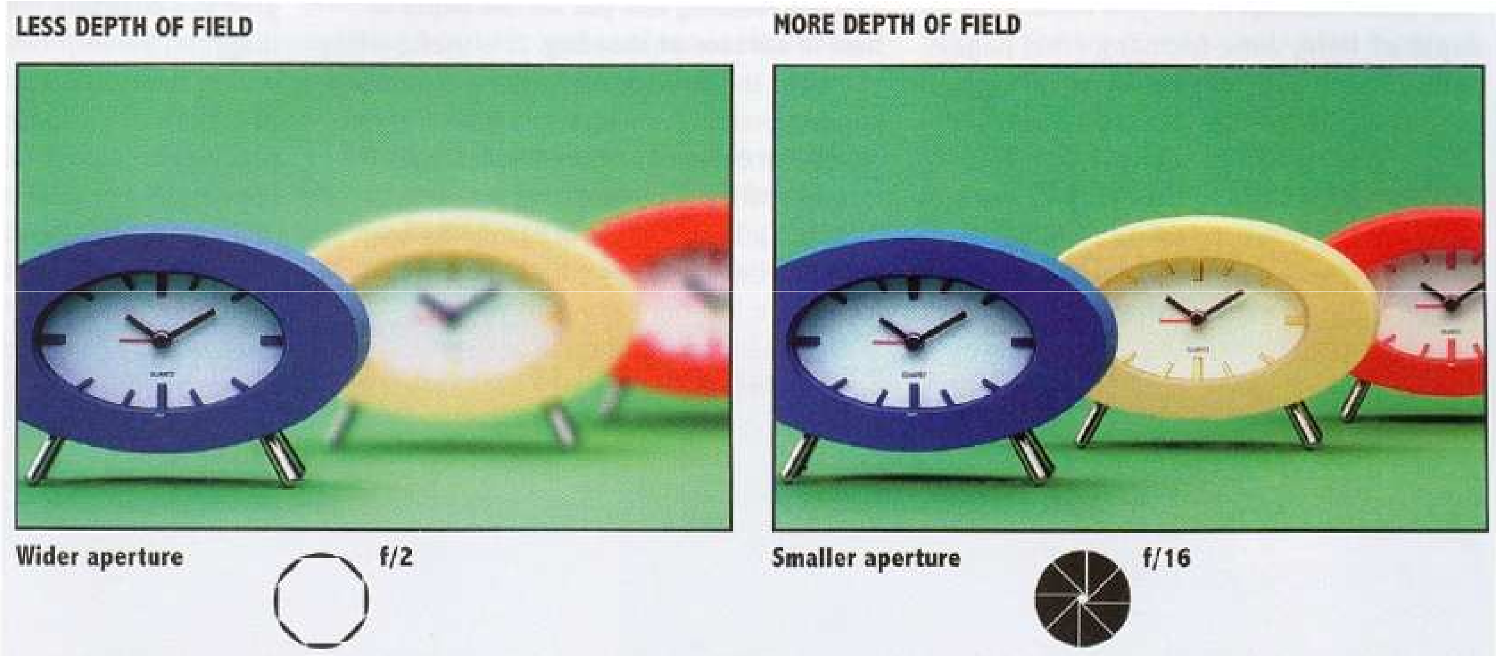

diaphragm
focus
focal plane


focal plane
focus

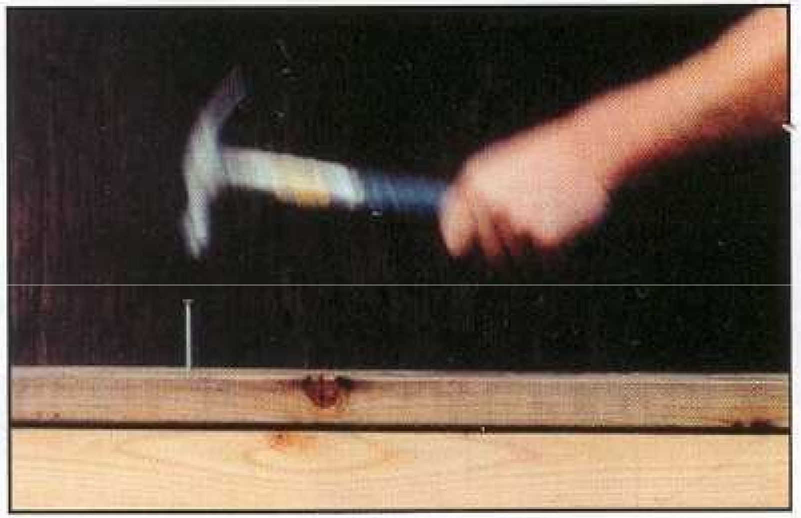

focal plane
focus


diaphragm
sharper image
focal plane
focus

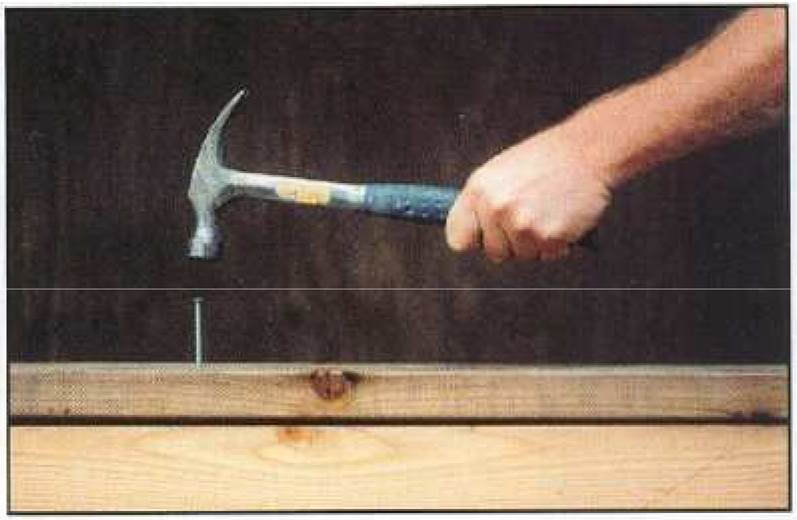
Effect of aperture: depth of field



Effect of shutter speed: motion blur



Slow shutter speed



Fast shutter speed