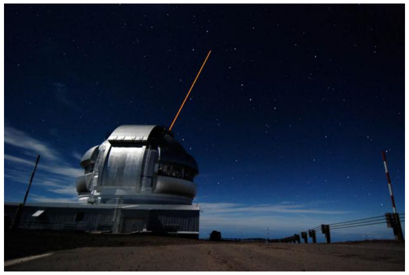
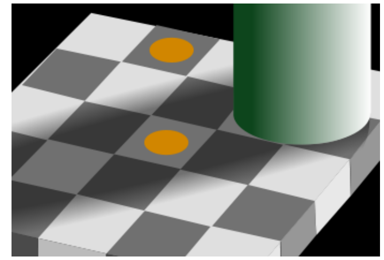
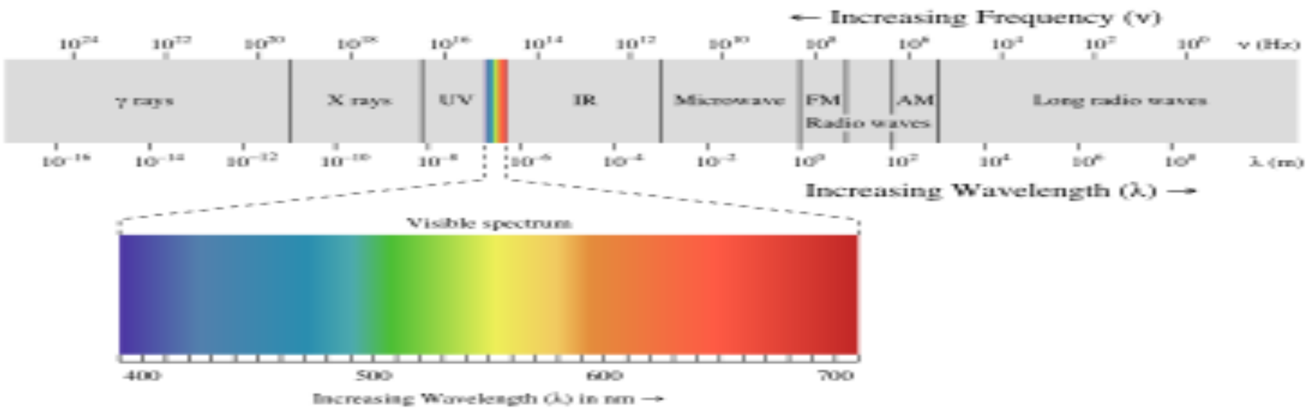
Physics 1230: Light and Color



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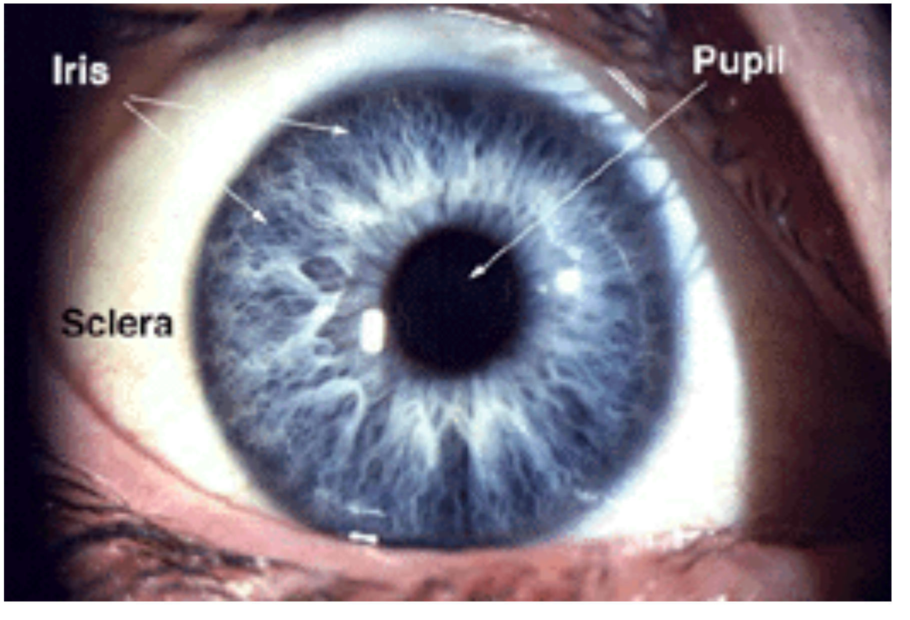
http://www.colorado.edu/physics/phys1230/

lecture 10

Optical instruments

Announcements:

- lectures 9 is posted on the class website
- midterm 2 solutions will be posted
- homework 9 is posted on D2L
  - due Thursday, April 24 in homework box in Help Room
  - solutions will be posted on D2L
- reading for this week is:
  - Ch. 6 in SL

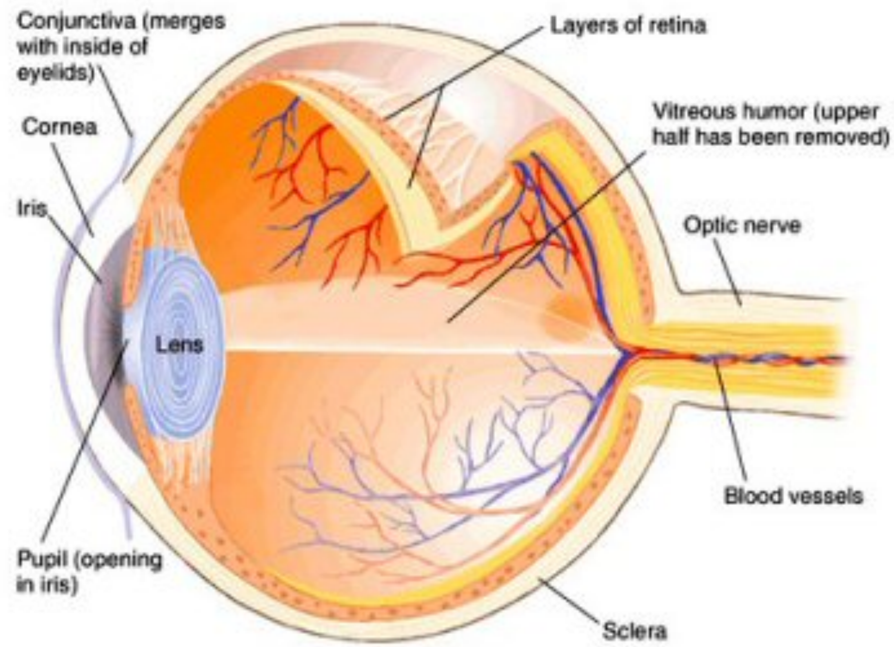


Recall

Last time

recall lecture 9: The Eye

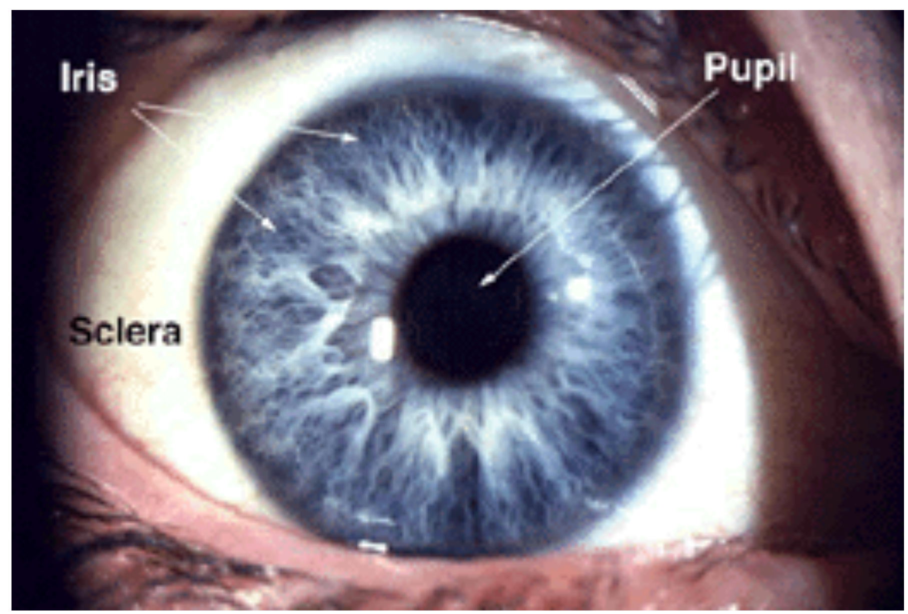
- cornea and lens: focusing system



- iris and pupil: diaphragm, controls f-number

- retina rods and cones: image formation

- persistence response: speed



- light sensitivity: speed

Today

Optical instruments

- cameras ✓

- correcting vision: glasses, contact lenses

- magnifying glass

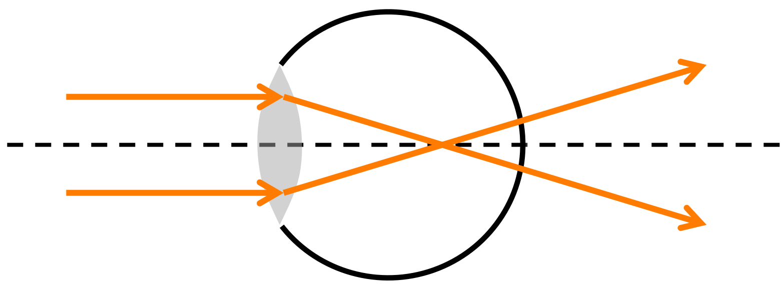
- microscope

- telescope

Imperfect vision

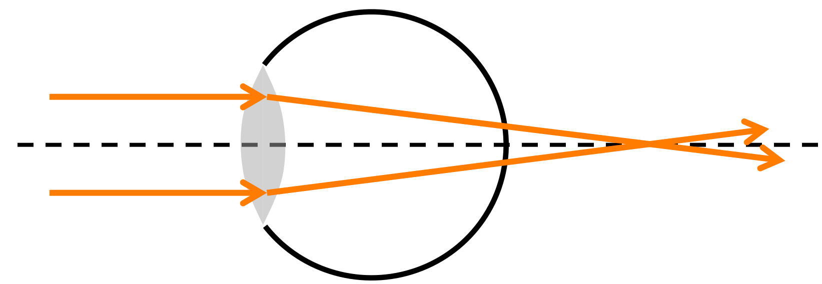
- Perfect vision: parallel rays of light coming from infinity, when eye is fully relaxed at a "far point", a distant object is *focused on the retina*

- Imperfect vision: for improperly-shaped cornea, these distant parallel rays are *not focused on the retina*



parallel rays focus in front of the retina

Myopia *(near-sighted)*



parallel rays focus past the retina

Hyperopia *(far-sighted)*

Visual accuity

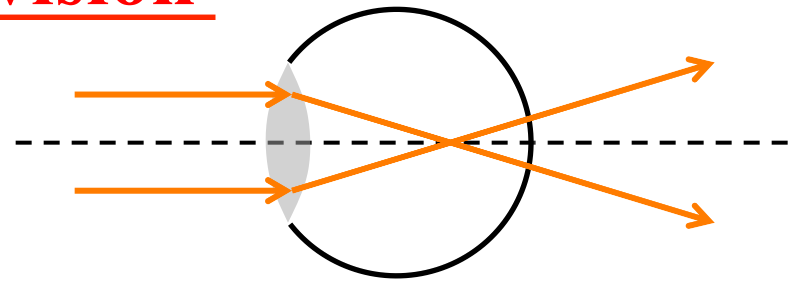
how small a letter can you see from 20 feet?

- 20/20 vision – *normal* vision
- 20/40 vision – *inferior* vision you can see a letter clearly from 20 feet that a normal person can see even from 40 feet
- 20/10 vision – *superior* vision you can see a letter clearly from 20 feet that a normal person has to move closer – to 10 feet – in order to see

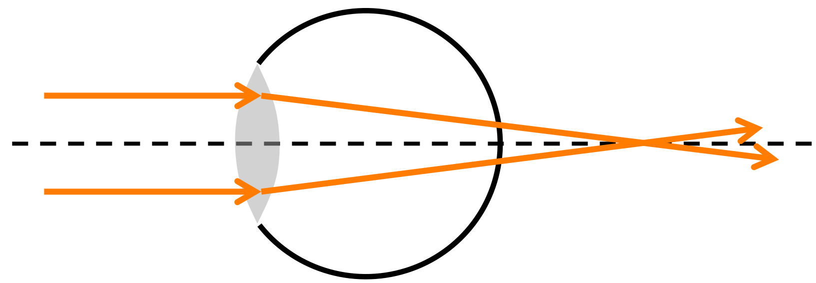
Eye problems

- Myopia – nearsightedness - see close objects clearly, only fixed by negative (diverging) lens
- Hyperopia – farsightedness – see far objects clearly, only fixed by a positive (converging) lens
- Presbyopia – stiff lens, no accommodation, fixed by bifocal glasses with both near and far focal lengths
- Cataracts – cloudy eye lens – replacement lens but will not accommodate

Imperfect vision

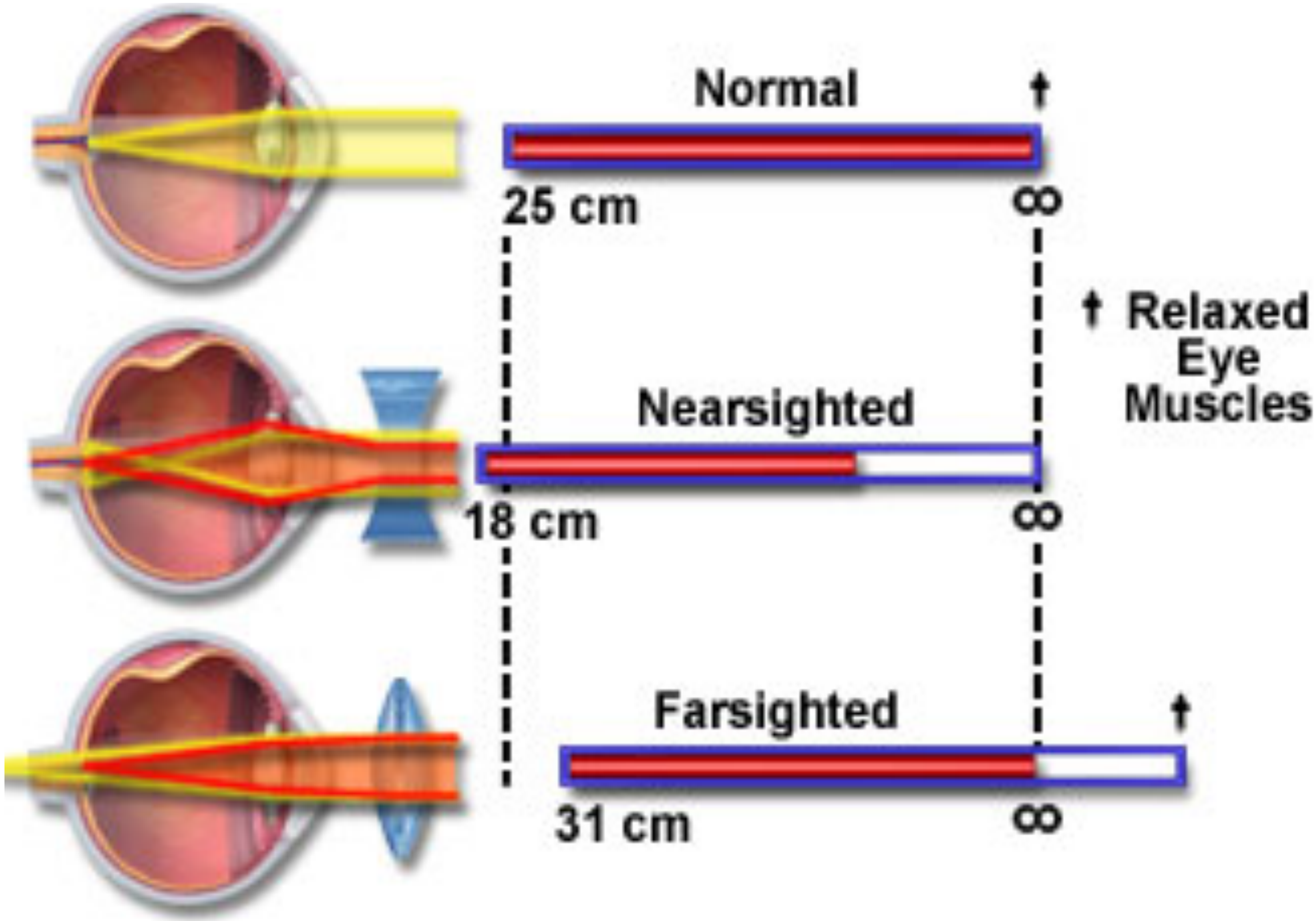


- Myopia *(near-sightedness)*:
  - cornea is too powerful
  - fully relaxed eyelens -> far point not at infinity, closer
  - distant objects focus in front of retina, appear blurry
  - corrected with a divergent lens



- Hyperopia *(far-sightedness)*:
  - cornea is not powerful enough
  - distant objects focus in behind of retina, appear blurry
  - eyelens can partially accommodate to increase power of cornea-lens system and focus distant but not near objects on the retina
  - corrected with a convergent lens

Eye accommodation: *near and far points*

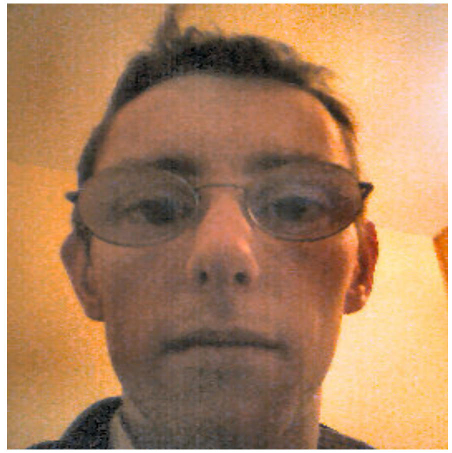


It is possible to have both a near point that is more distant than 25 cm and a far point that is closer than infinity. In this case, you need bifocals, which have two lenses in them, one to correct each imperfection

Correcting vision: glasses and contact lenses

- eye glasses:

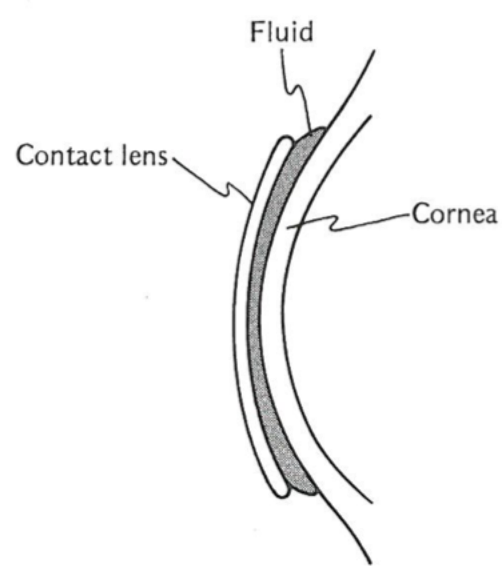
Myopia: diverging



Hyperopia: converging

Presbyopia: bifocal

- contact lenses: *Contact lenses are just a thinner and smaller version of glasses that rest directly on the cornea, with a thin layer of fluid in between*



Multiple lenses power

recall:

- The power of two lenses held together is equal to the sum of their individual powers:

$$P_{combined} = P_1 + P_2$$

- The focal length of the combined lenses is:

$$f_{combined} = 1/P_{combined}$$

- This can be used in the lens equation

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

Combining lenses using diopters

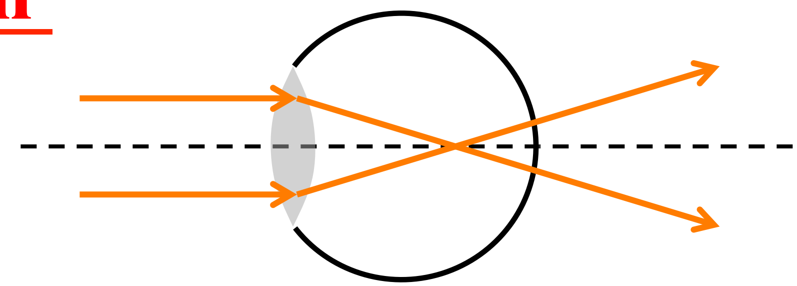
recall:

$$P_{combined} = P_1 + P_2$$

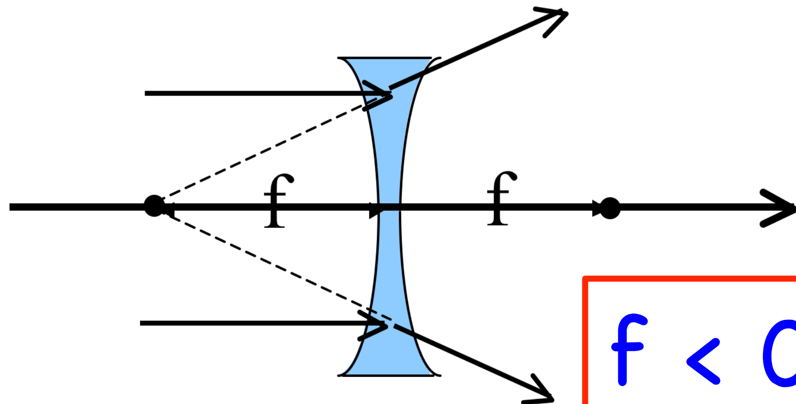
- Diopters power of a multi-lens combination?
- Example:
  - lens 1, $f_1 = 0.5$ m
  - lens 2, $f_2 = 2$ m
  - What is the power of combined lens?
  - What is the focal length $f_{combined}$ of combined lens?
- Solution:
  - power of lens 1 is 1/(0.5) = 2 diopters
  - power of lens 2 is 1/2 = 0.5 diopters
  - combined lens $P_{comb} = P_1 + P_2 = 2 + 0.5 = 2.5$ diopters
  - focal length of a combined lens, $f_{comb} = 1/P_{comb} = 0.4$m
  - only valid for *touching thin* lenses

Imperfect vision

- Myopia *(near-sightedness)*:

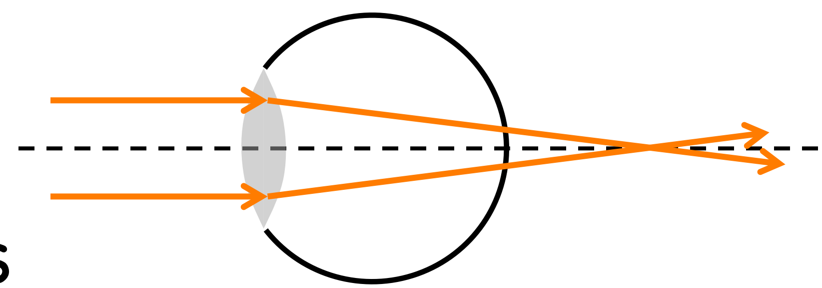


  - corrected with a divergent lens

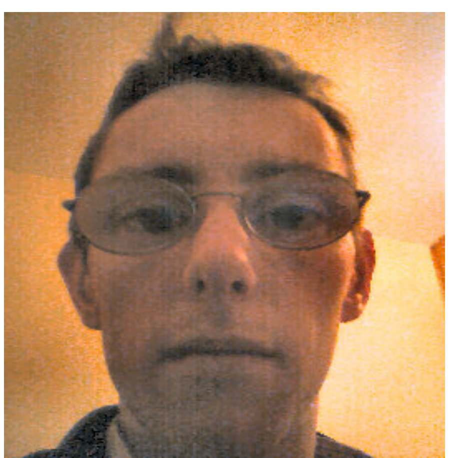


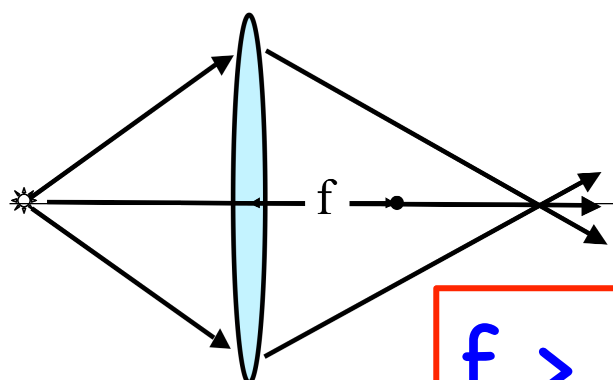
$f < 0$

- Hyperopia *(far-sightedness)*:



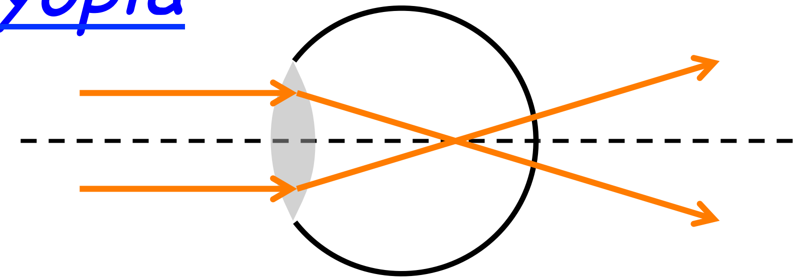
  - corrected with a convergent lens



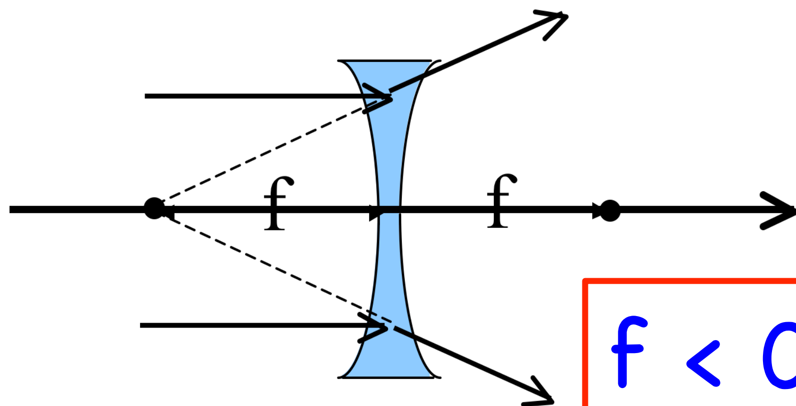


$f > 0$

Imperfect vision: *myopia*

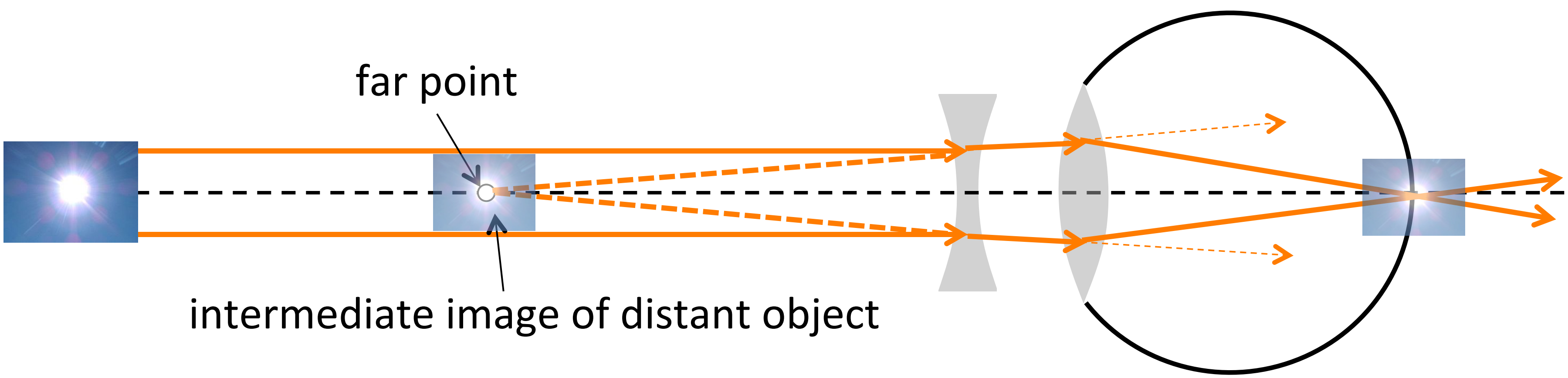


- Myopia *(near-sightedness)*:
  - corrected with a divergent lens



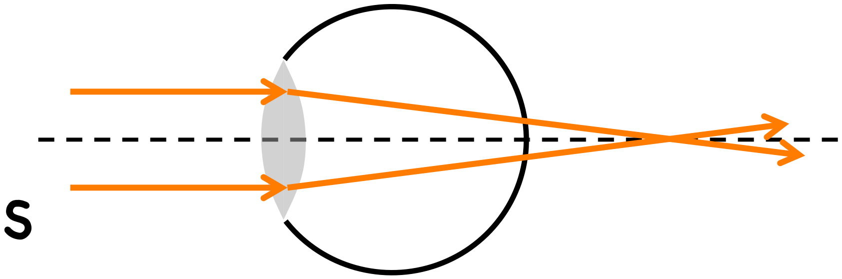
$f < 0$

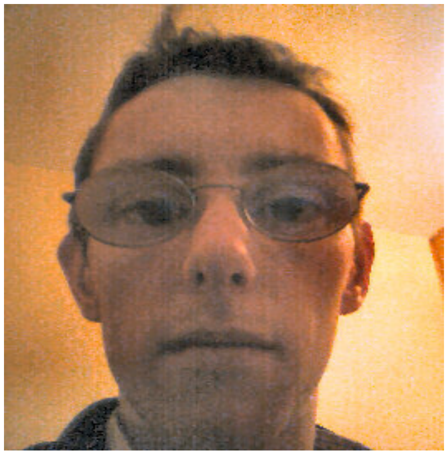
  - a divergent lens creates an ***intermediate*** image of a distant object at your "far point", so that your eye can see it even though the star is beyond your far point

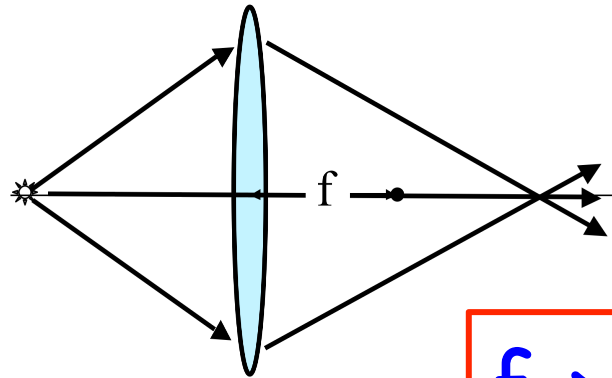


Imperfect vision: *hyperopia*

- Hyperopia *(far-sightedness)*:
  - corrected with a convergent lens

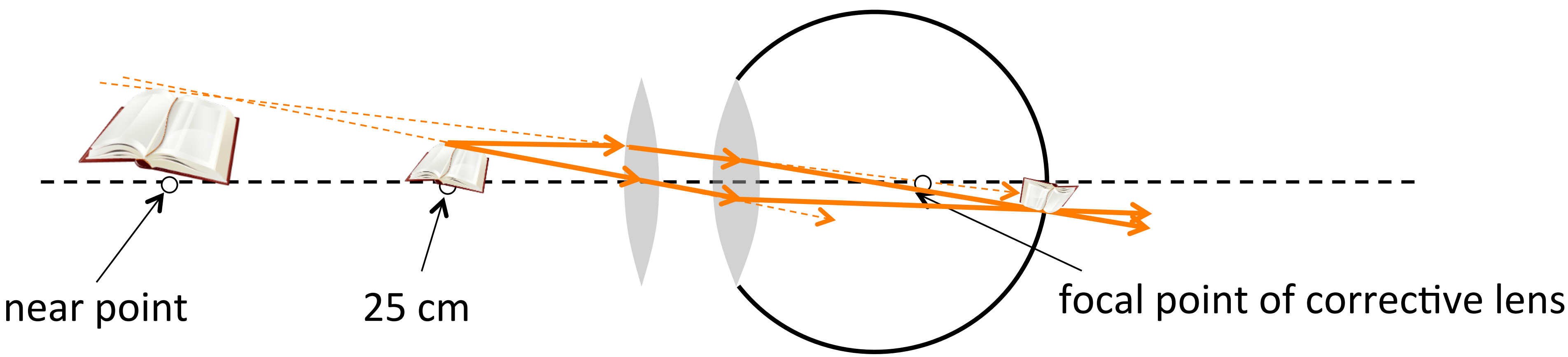






f > 0

  - a convergent lens creates an ***intermediate*** image of a book 25 cm away at your "near point", so that your eye can see it even though it is closer than your near point



Determining prescription: *myopia*

- If you are near-sighted, you want the diverging corrective lens to create an intermediate image of a distant object at your far point:
  - -> the object distance $x_o = \infty$
  - -> the image distance is your far-point, $x_i = -x_{farpoint}$
  - -> find the focal length and power from the lens equation

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

- The image distance x_i is *negative* (same side of the lens as the object)

Determining prescription: *hyperopia*

- If you are far-sighted, you want the converging corrective lens to create an intermediate image at your near point of an object at 25 cm:
  - -> the object distance $x_o = 0.25\text{m}$
  - -> the image distance is your near-point, $x_i = - x_{nearpoint}$
  - -> find the focal length and power from the lens equation

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

- The image distance x_i is *negative* (same side of the lens as the object)

clicker question

Corrective lens power

Q: A myopic eye is too powerful, say it has power of 63 diopters. What power of lens should you put on it to get a combined power of 60 diopters (normal eye)?

(a) -2 diopters
(b) -3 diopters
(c) 2 diopters
(d) 3 diopters

A: $P_{combined} = P_1 + P_2 = 63 - 3 = 60$ diopters

clicker question

Corrective lens power

Q: If a person with hyperopic eyes of power 58 diopters, wears corrective lenses of power 2 diopters, what is the focal length of the combined set of lenses?

(a) 1.5 cm (0.015 m)
(b) 1.7 cm (0.017 m)
(c) 2.5 cm (0.025 m)

A: $P_{combined} = P_1 + P_2 = 58 + 2 = 60$ diopters

$f_{combined} = 1/P_{combined} = 1/60 = 0.017\text{m}$

clicker question

Determining prescription

Q: You are near-sighted and your *far point* is 1 meter away. What is your prescription?

(a) +1 diopter
(b) -1 diopter
(c) +2 diopter
(d) -2 diopter
(e) +3 diopter

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

A: $x_o = \infty$, $x_i = -1$ meter -> $f = -1$ meter -> $P = -1$ diopters

clicker question

Determining prescription

Q: You are far-sighted and your *near point* is 1 meter away instead of 25cm. What is your prescription?

(a) +1 diopter
(b) -1 diopter
(c) +2 diopter
(d) -2 diopter
(e) +3 diopter

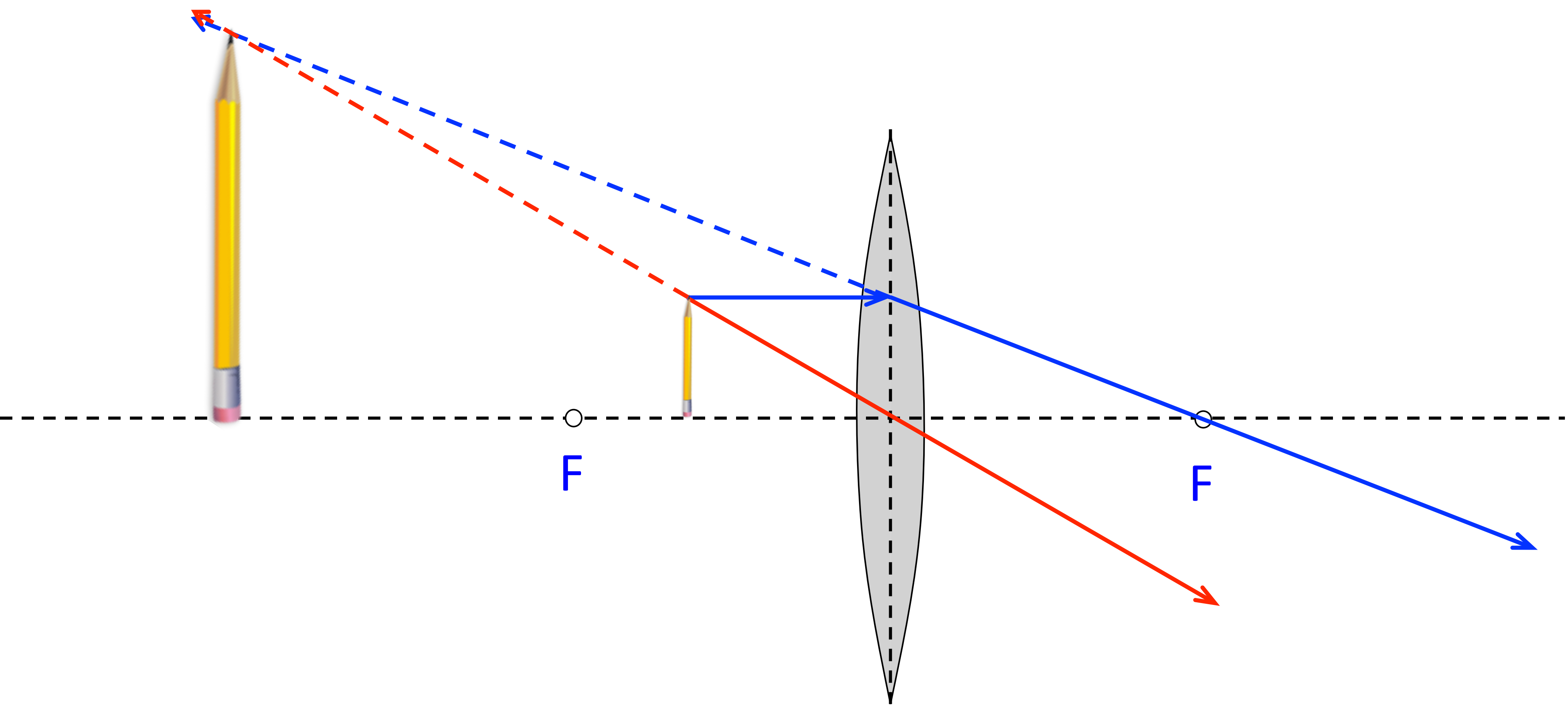
$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

A: x_o = 0.25m, x_i = -1 meter

-> 1/f = 1/0.25 - 1/1 = 4 - 1 = 3 -> f = 1/3 meter

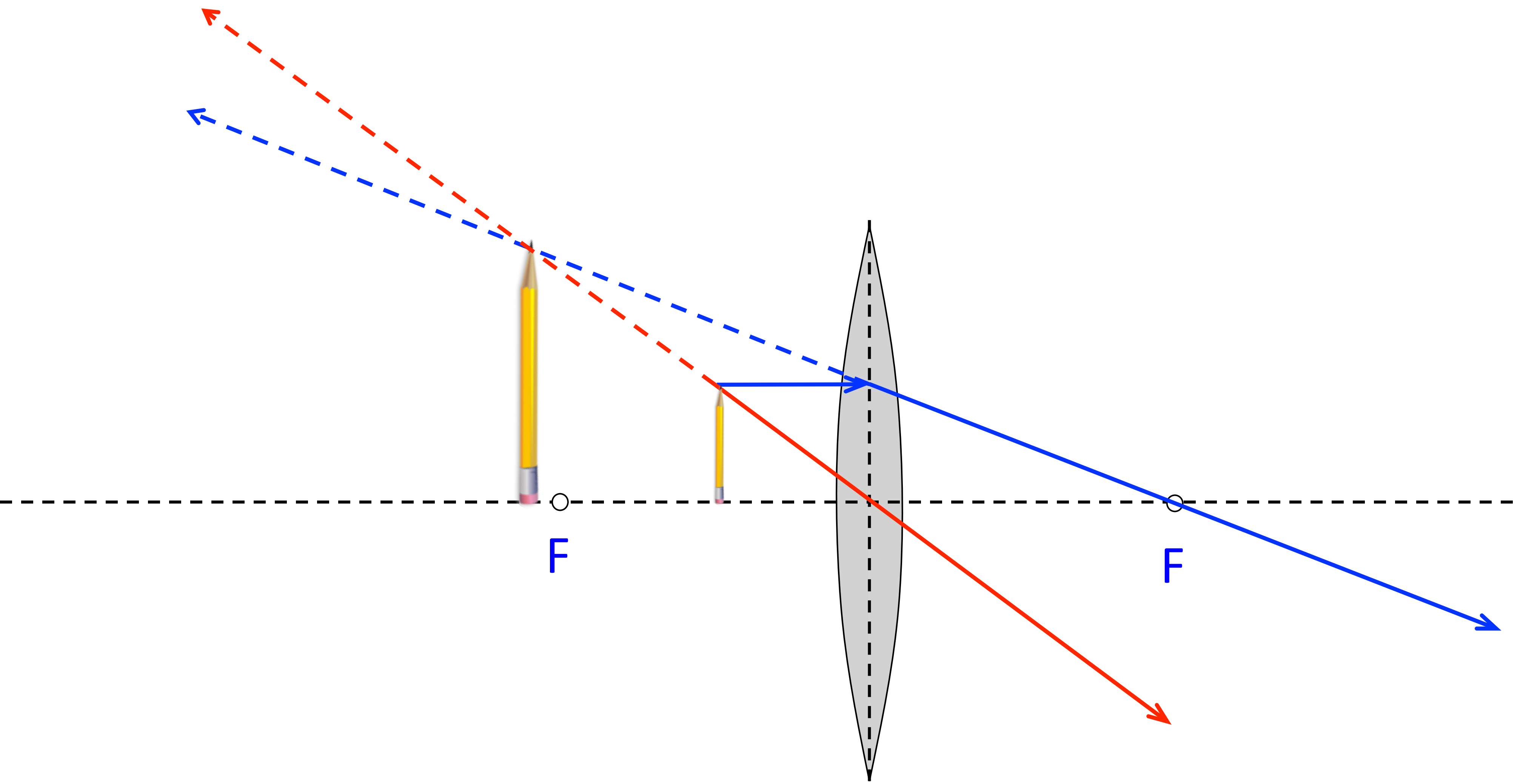
-> P = +3 diopters

Magnifying glass



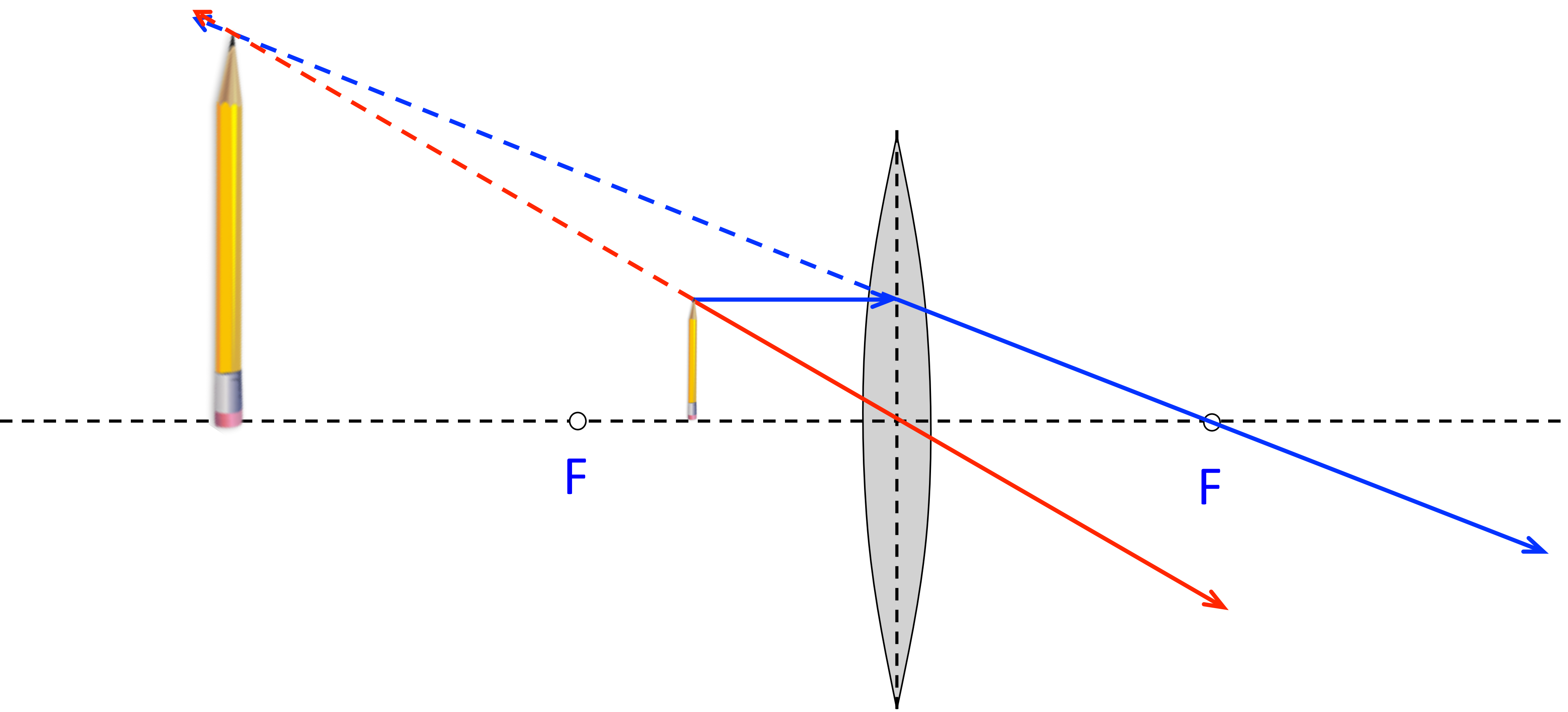
- Recall this configuration that produces an upright, magnified image

Magnifying glass



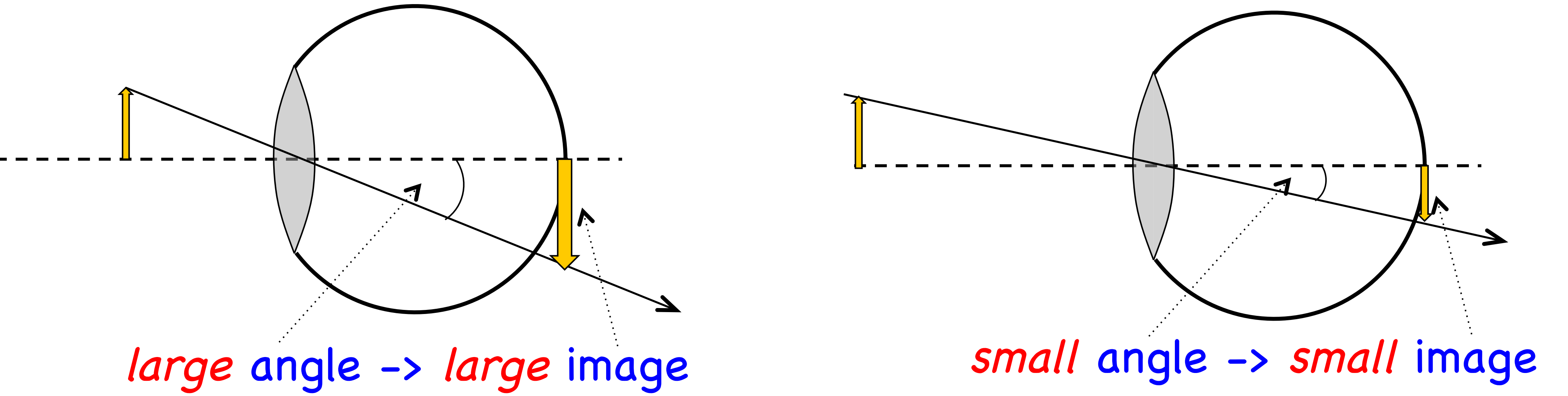
- Where should we put the lens to get the biggest image on our retina?
- If we move the object closer to the magnifying glass, the image gets smaller.

Magnifying glass



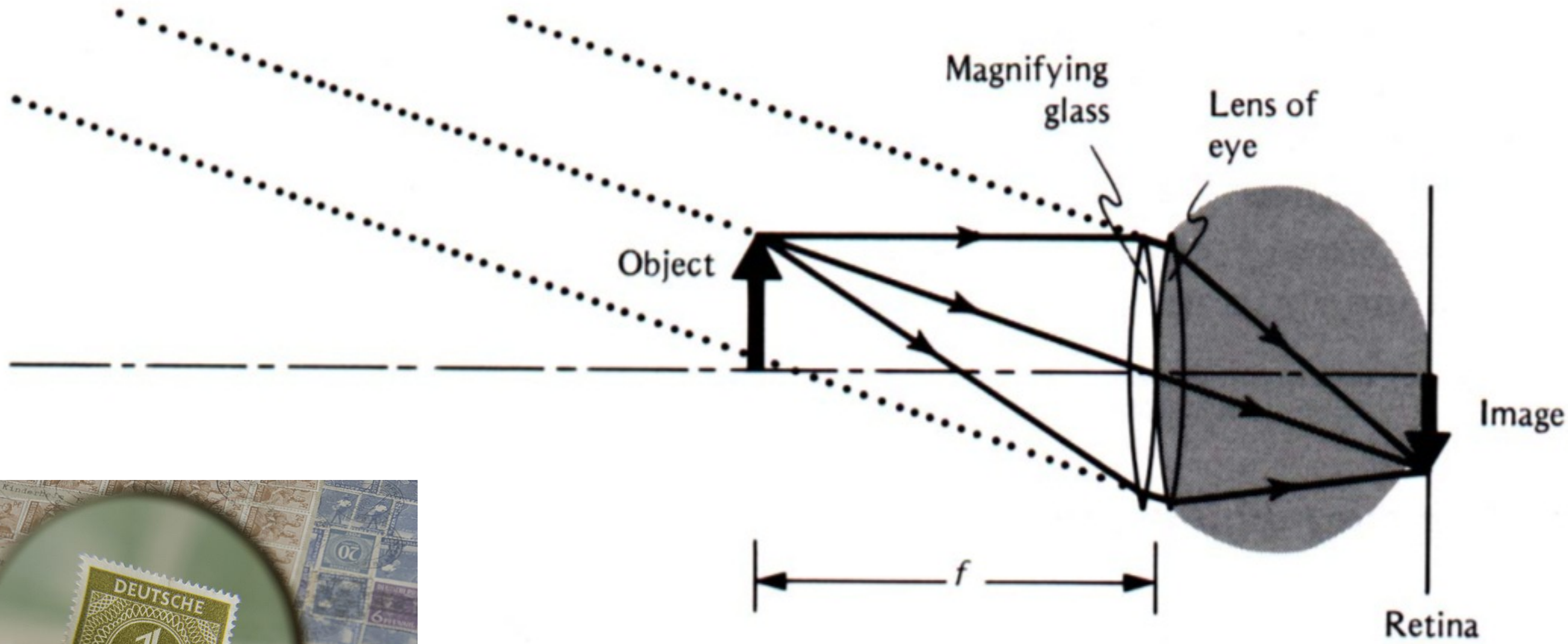
- You would think we would want to put the object close to the focal point of the lens, which would make the biggest image.
- But we want the biggest image *on our retina*

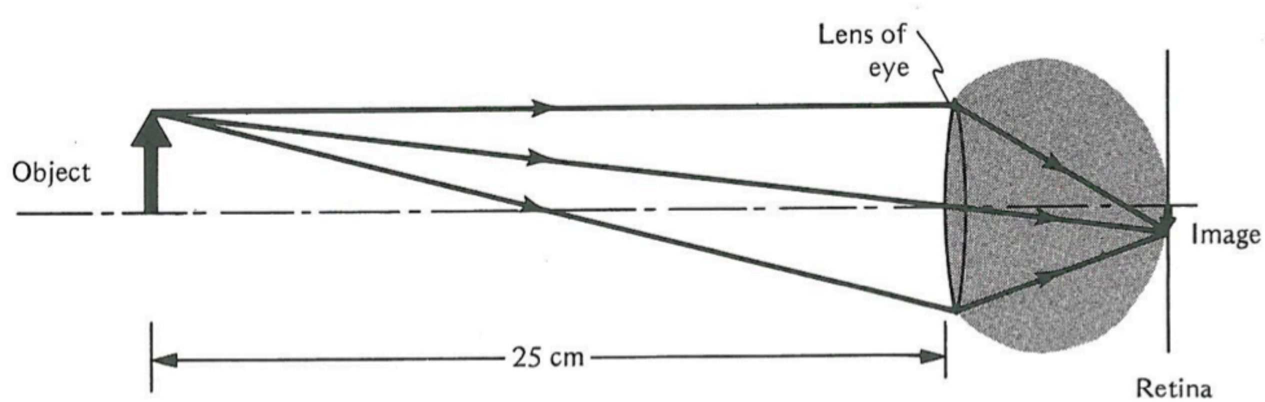
Image size on the retina



- the size of the object on your retina is related to the *angle* between the axis and the ray passing through the center of the lens
- objects look *smaller* when they are further *away*
  - so magnify by bringing object closer to the eye
  - but to stay in focus must be no closer than 25cm from the eye (near point)
  - with magnifying glass can bring objects closer to your eye and still stay in focus

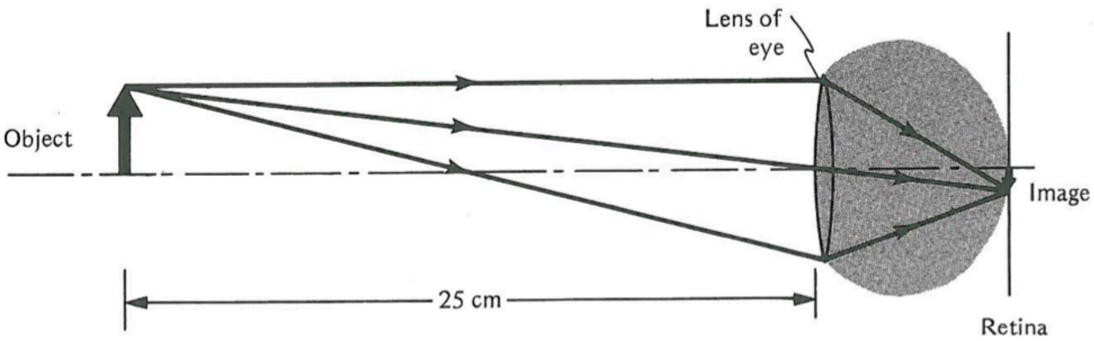
Magnifying glass

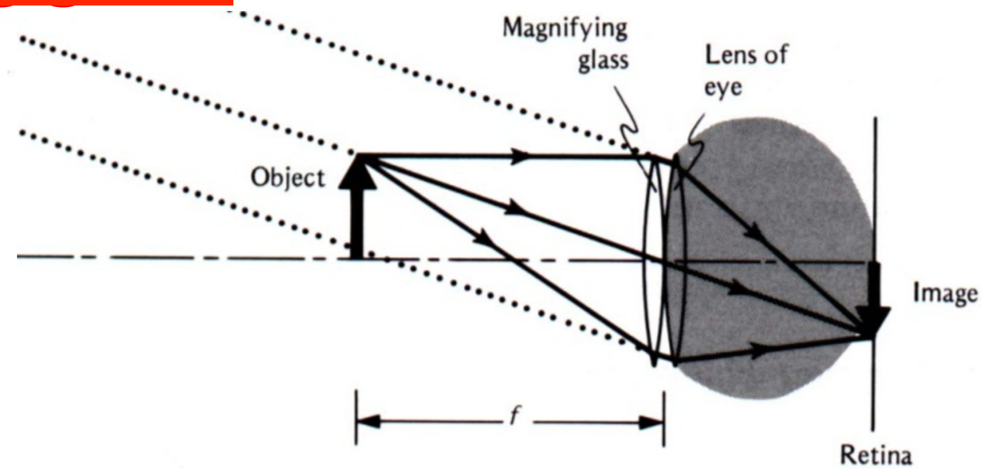


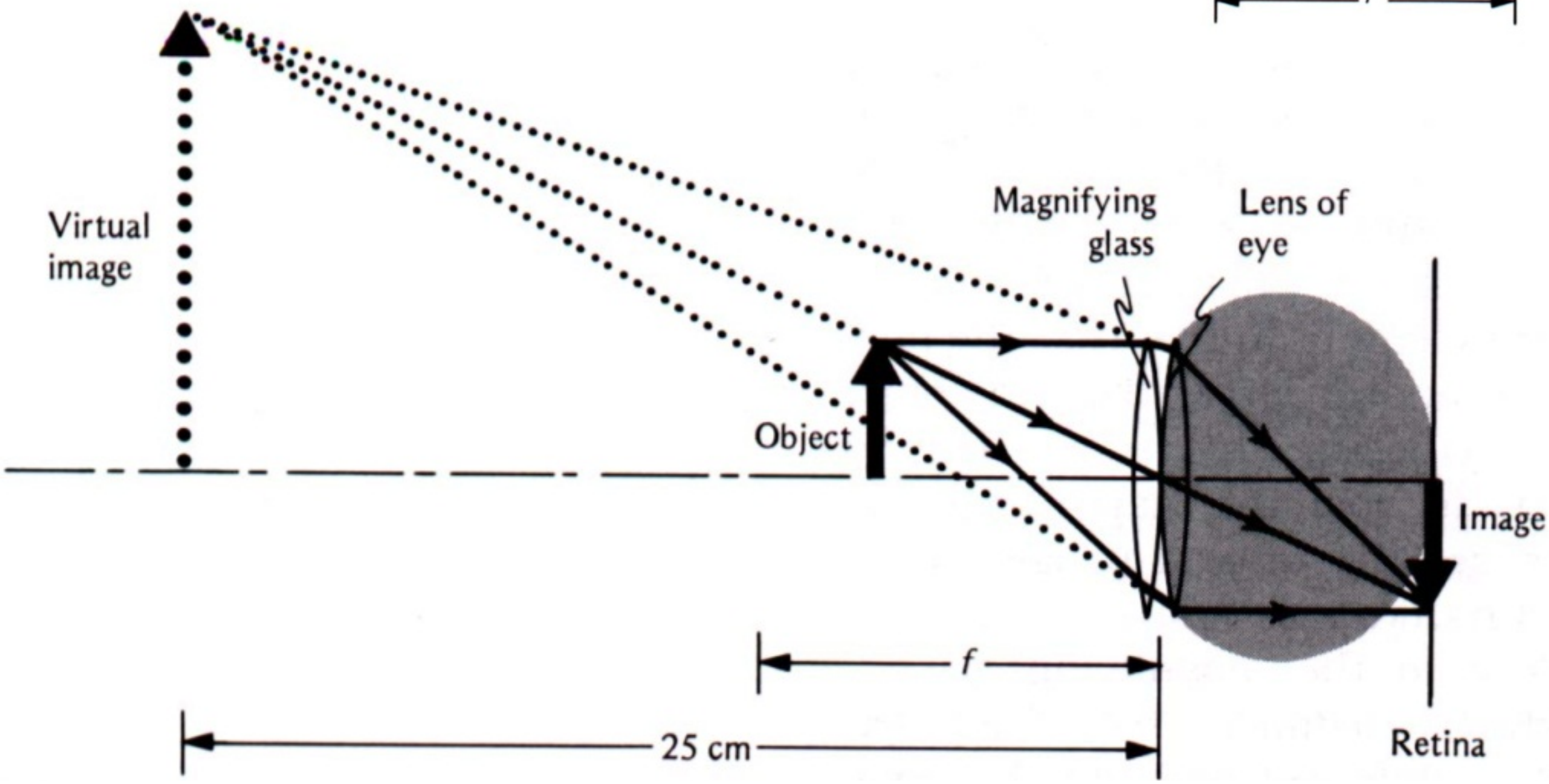


Placing an object at the focal point of the magnifying glass produces an image at infinity, which your eye can focus on (its far point) with the eyelens in its fully relaxed state

Magnifying glass

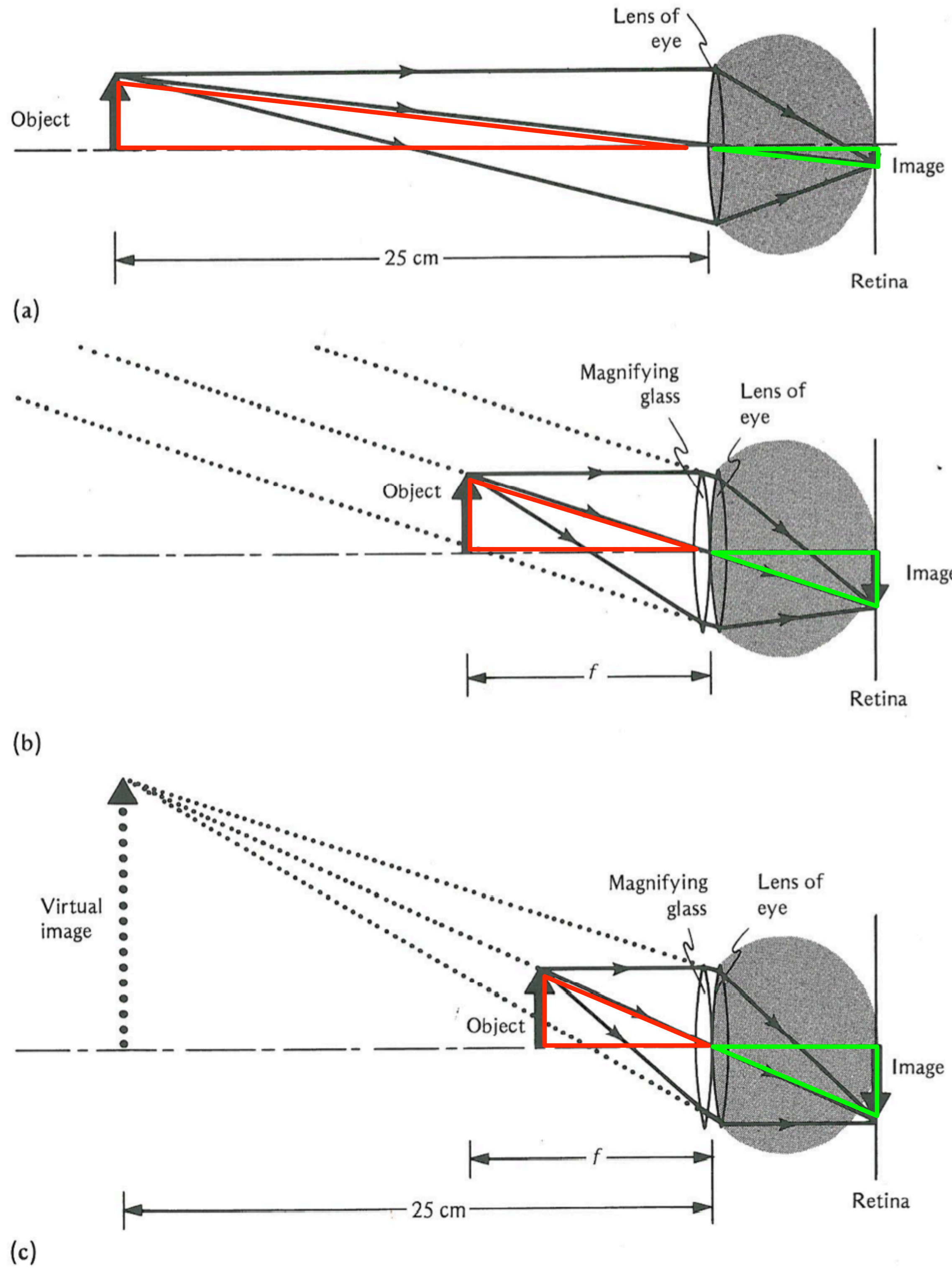






Magnify (on the retina) by moving the object closer than F, thereby increasing the angle, such that the magnifying glass' image appears at your *near point* of even closer.

Magnifying glass



- Largest retinal image for normal eye for x_o = 25cm
- With magnifying glass put $x_o = f_{lens}$, forming intermediate image of the object, that can be seen by a relaxed eye
- With magnifying glass can put even closer that f_{lens} and can still be in focus

Magnifying power

- The magnifying power, or magnification of a lens is the ratio of the image sizes on the retina

$$M = \frac{\text{size of the image with lens}}{\text{size of the image without lens}}$$

- Using similar triangles from geometry, we find that

$$M = \frac{\text{object distance without lens}}{\text{object distance with lens}} = \frac{25cm}{f_{lens}(in\ cm)}$$

- Smaller f -> larger M
- Magnification: 2X, 3X, 10X,…

clicker question

Corrective lens power

Q: A magnifying glass has a focal length of 10cm. What is its magnification?

(a) 1X
(b) 1.5X
(c) 2X
(d) 2.5X
(e) 3X

A: $M = 25cm/10cm = 2.5$

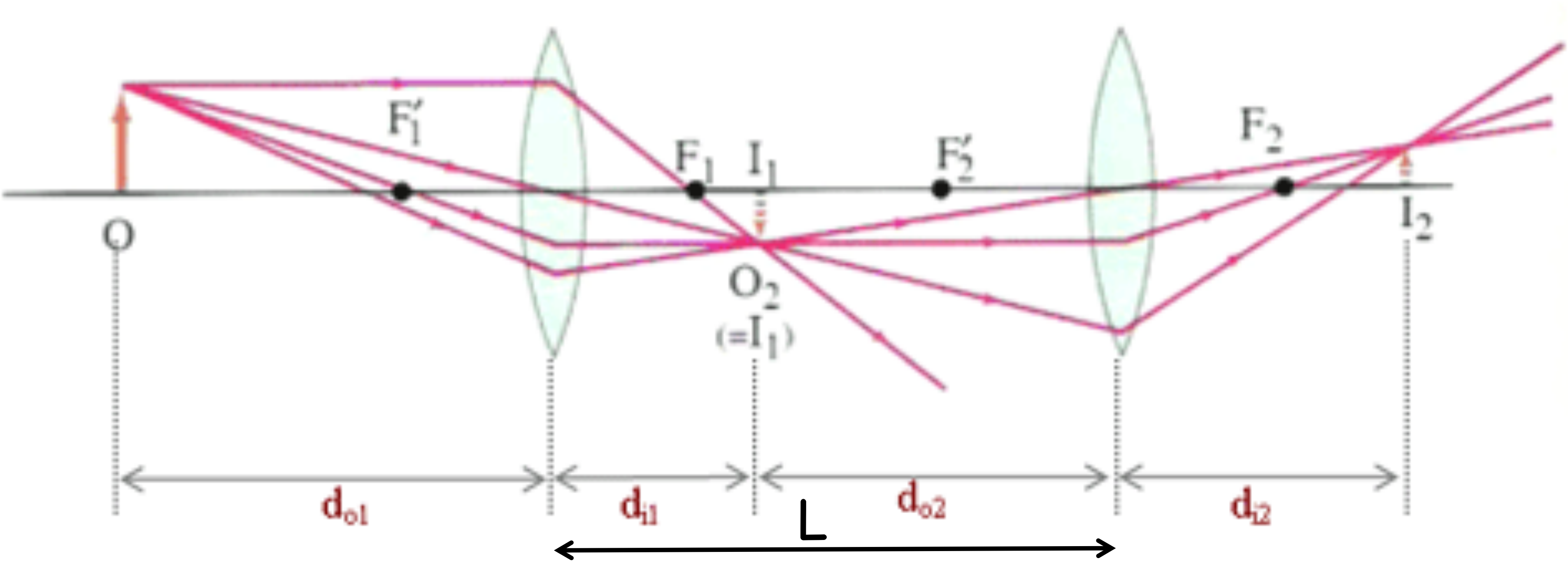
General principle

Many optical instruments can be understood step by step, as e.g., Hooke's microscope

- The first lens collects light and produces an image
- The second lens produces a new image of the first image
- The third lens produces a new image of the second image…
- …

Magnification of a series of lenses

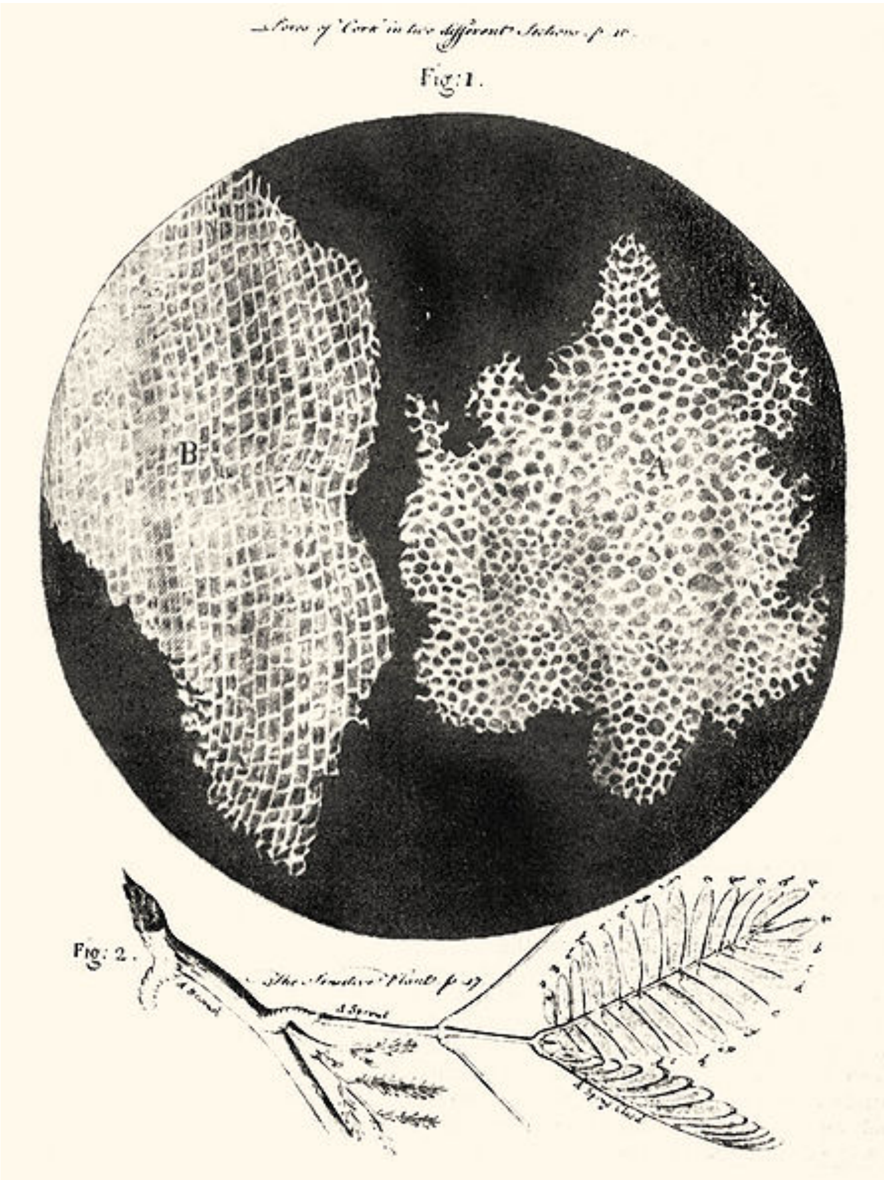
$$M_{12} = M_1 \times M_2$$

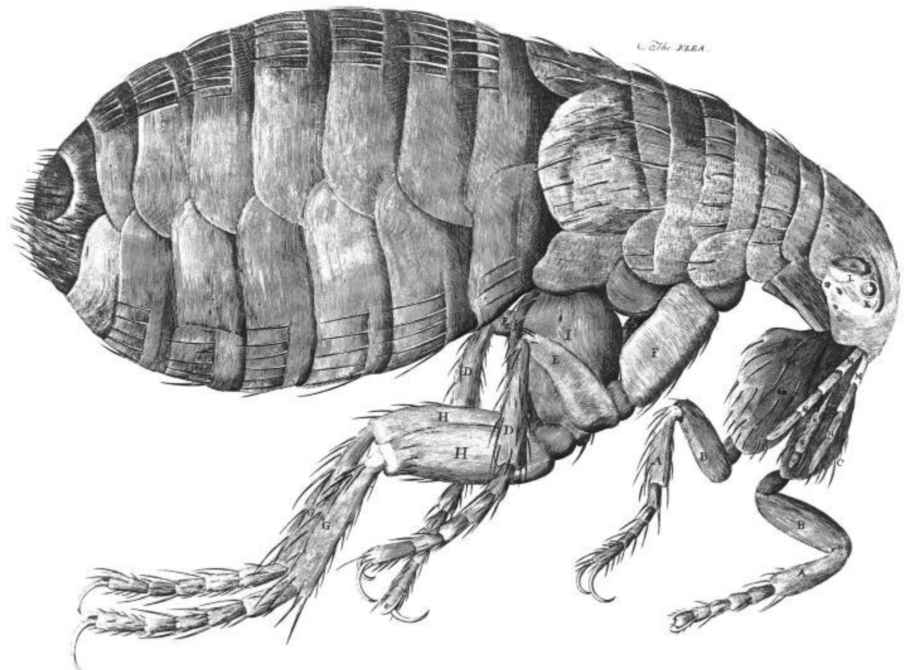


- $M_1 = -d_{i1}/d_{o1}$, $M_2 = -d_{i2}/d_{o2}$
- $d_{o2} = L - d_{i1}$
- $M_{12} = M_1 \times M_2$

Hooke's discoveries microscope

- the cell
- detailed structure of creatures, e.g., flea

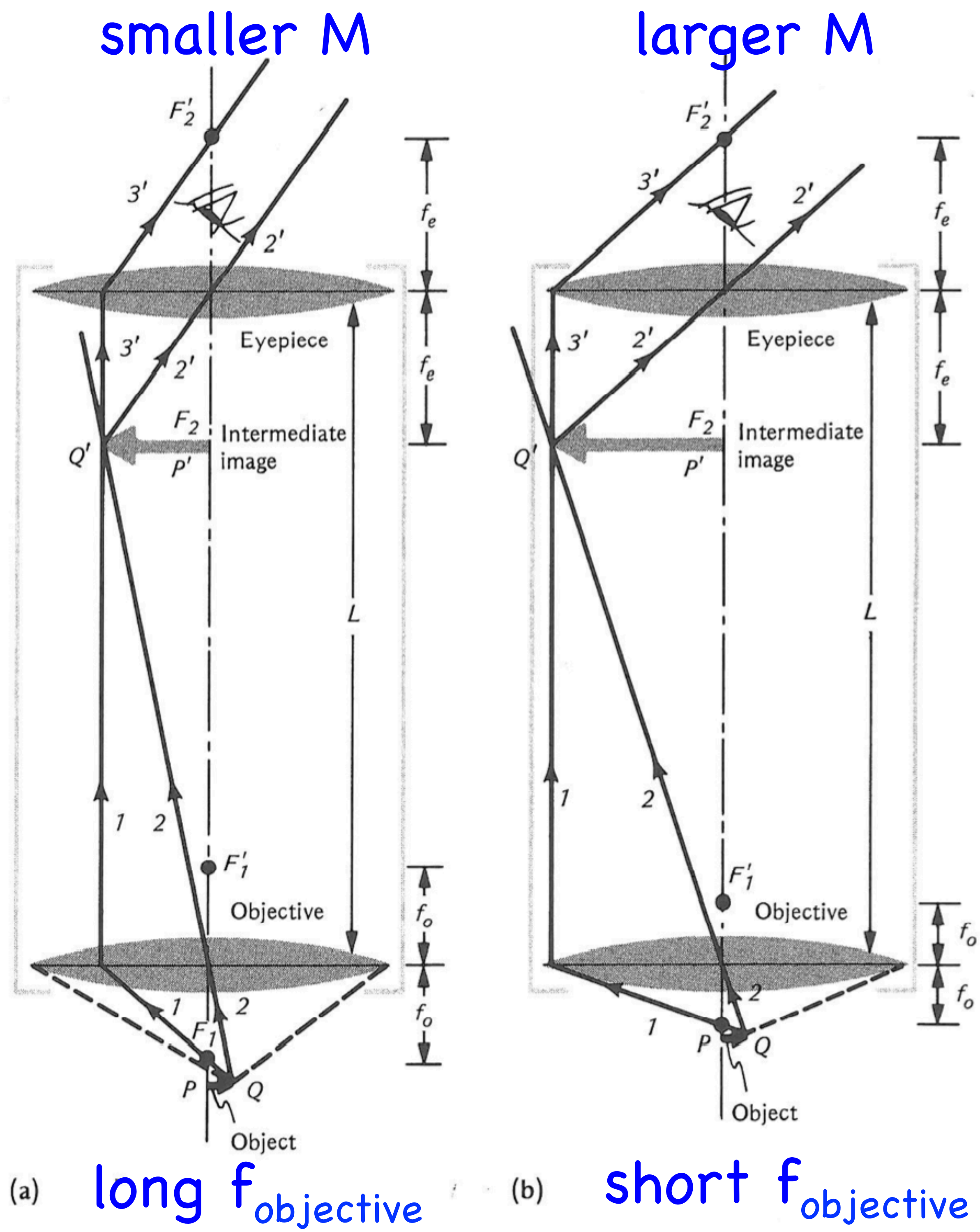




Compounded microscope

- Two lenses:
- objective lens: very short f_o
  -> *inverted, magnified by* $L/f_o >> 1$
- eyepiece lens:
  -> *used as simple magnifier*

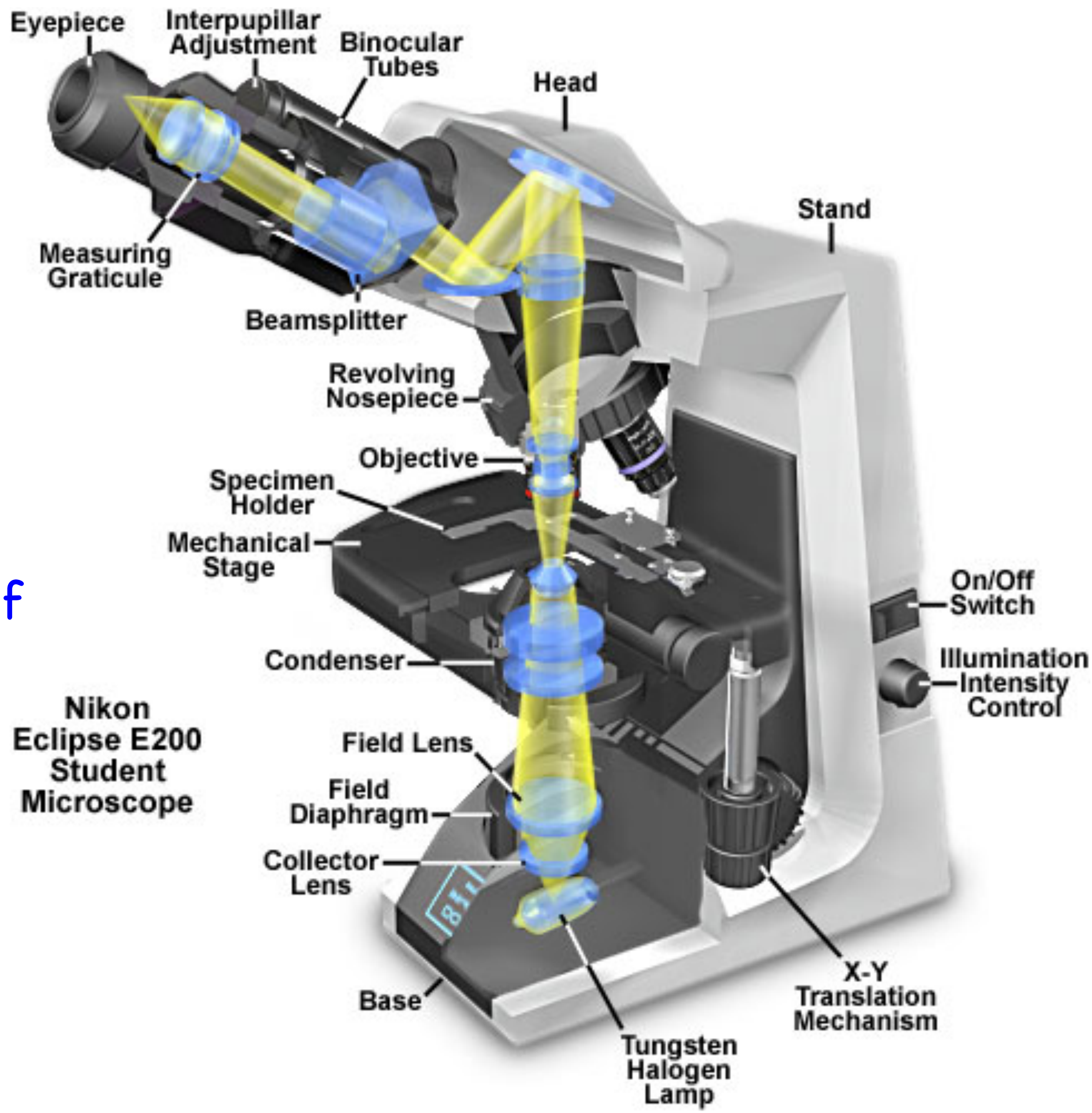
- Treat intermediate image as new object and look at it (rather than the object) with eyepiece, the magnifying glass
- Place eyepiece at f_e away from the intermediate image
- Smaller f's -> larger magnification
- Image inverted



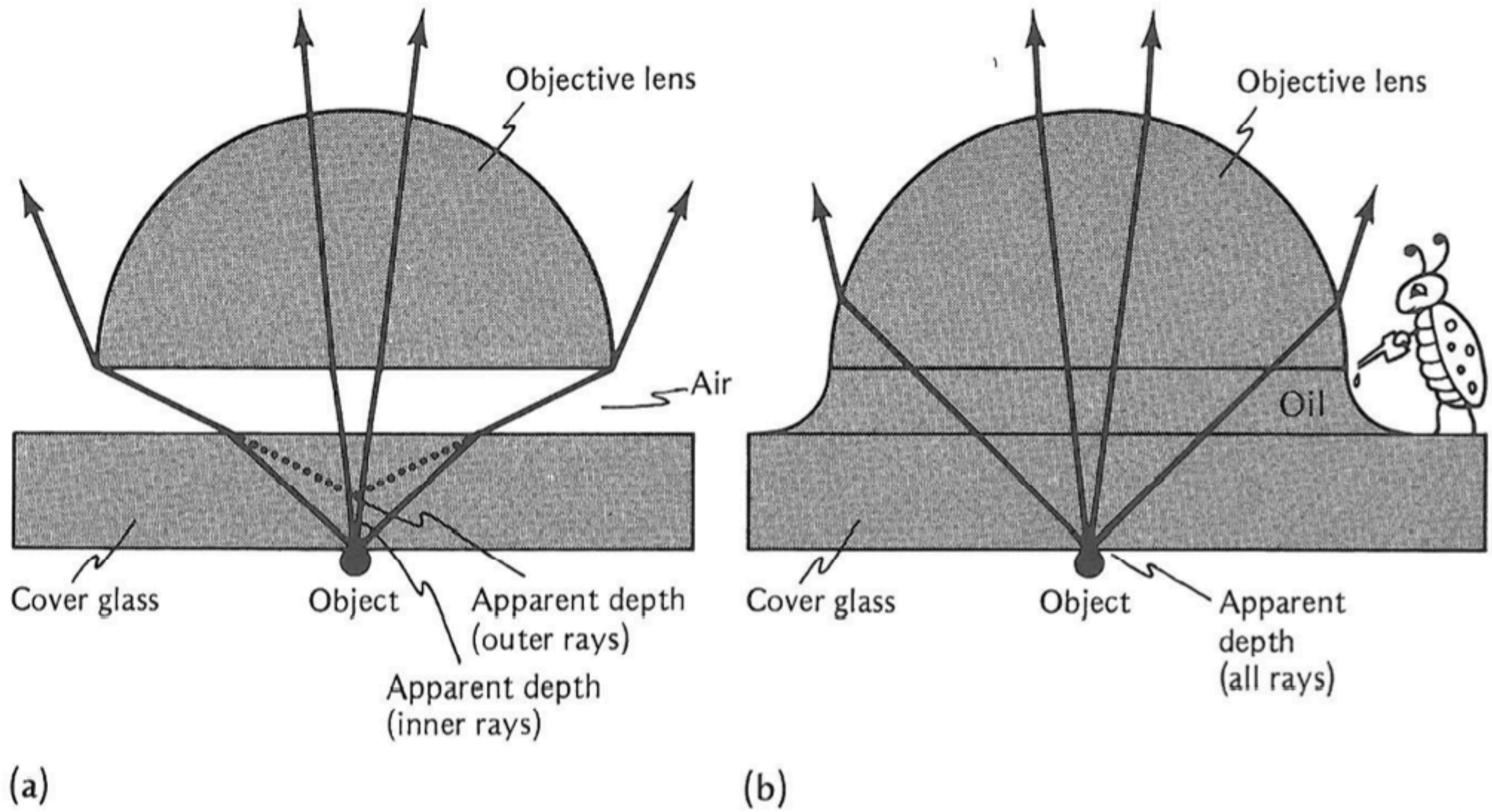
Modern binocular microscope

- quite similar to Hooke's

- beam splitter, a half-silvered mirror sends half the light to each eye



Oil-immersion microscope

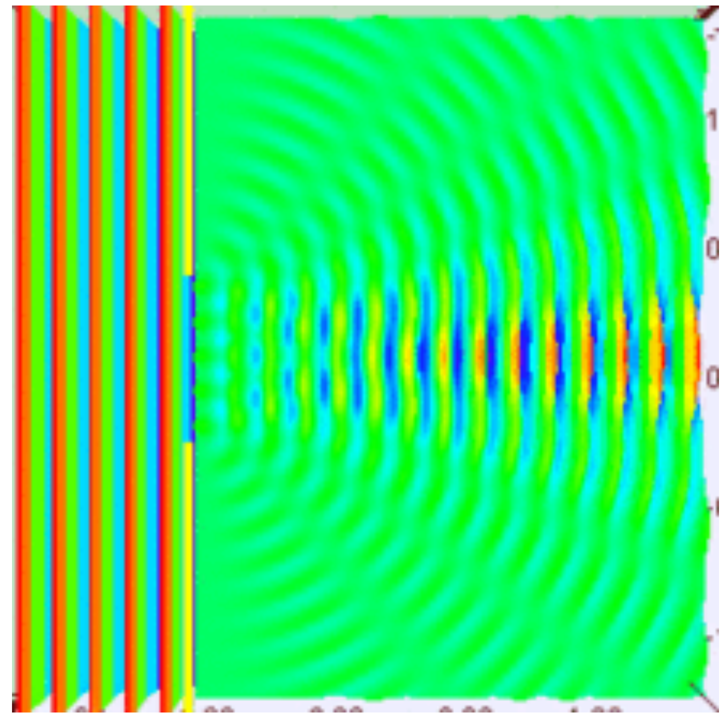


The oil immersion microscope objective (a) without oil, (b) with oil, uses index matching oil to eliminate blurring by the cover glass refraction

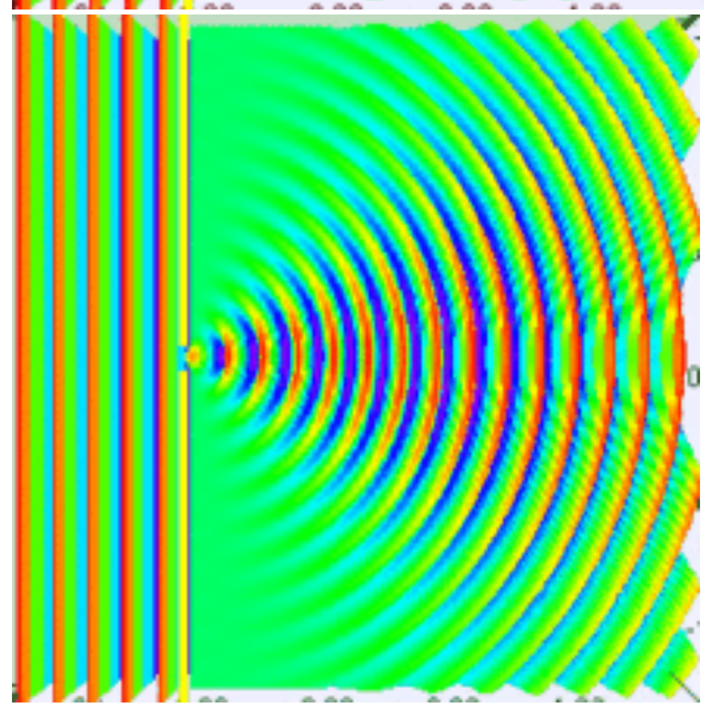
Diffraction

Breakdown of ray optics:

- $d = 5\lambda$



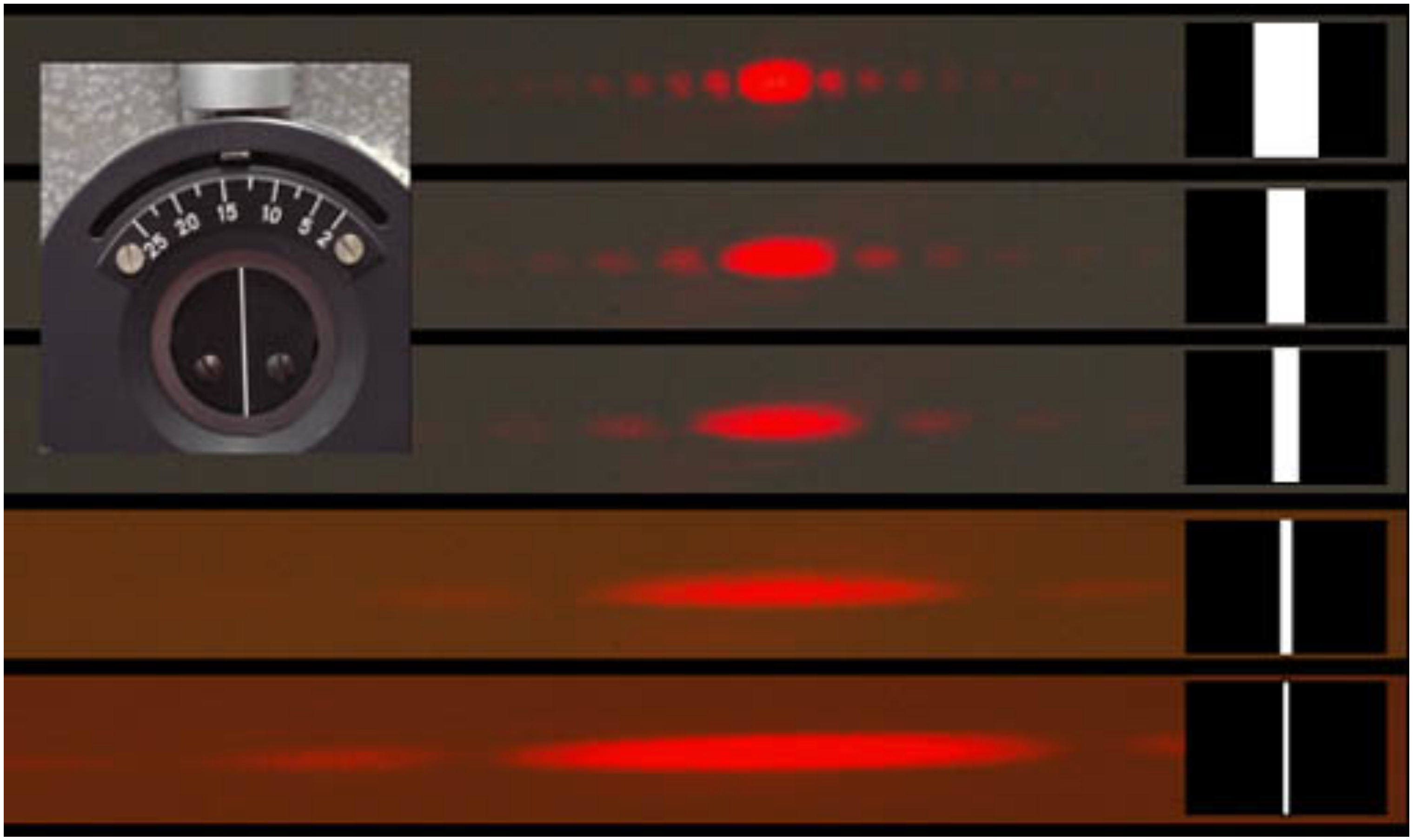
- $d = \lambda$



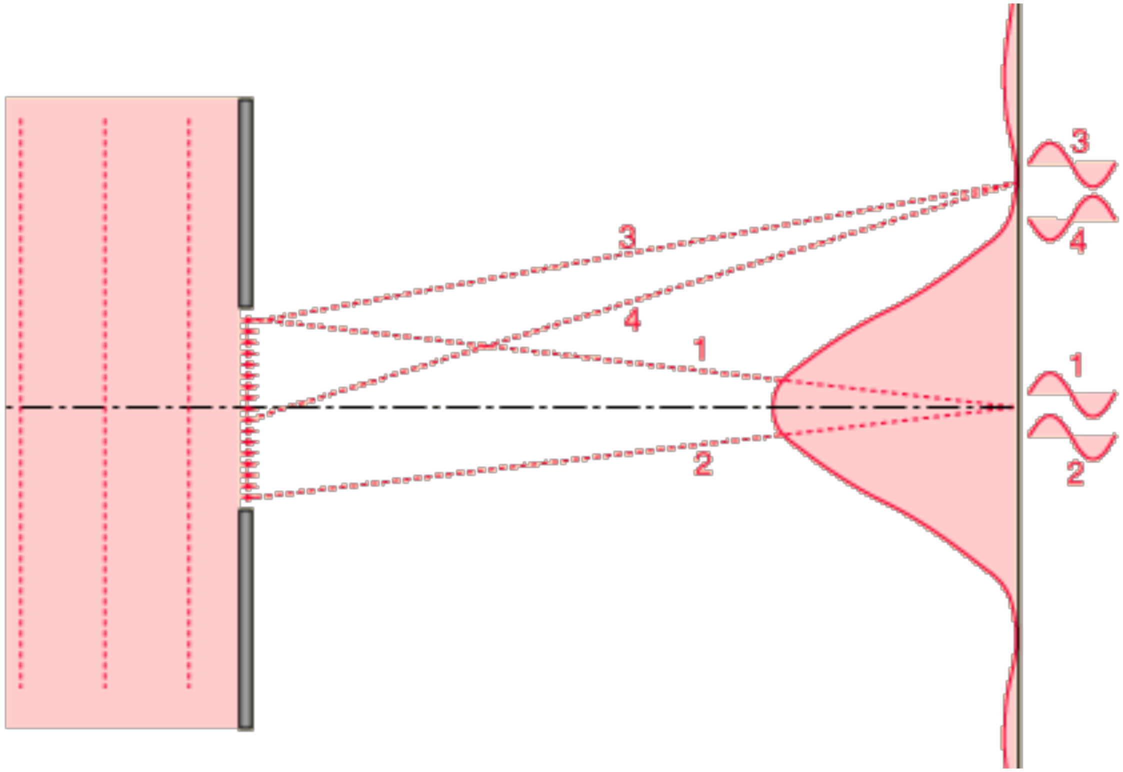
Diffraction

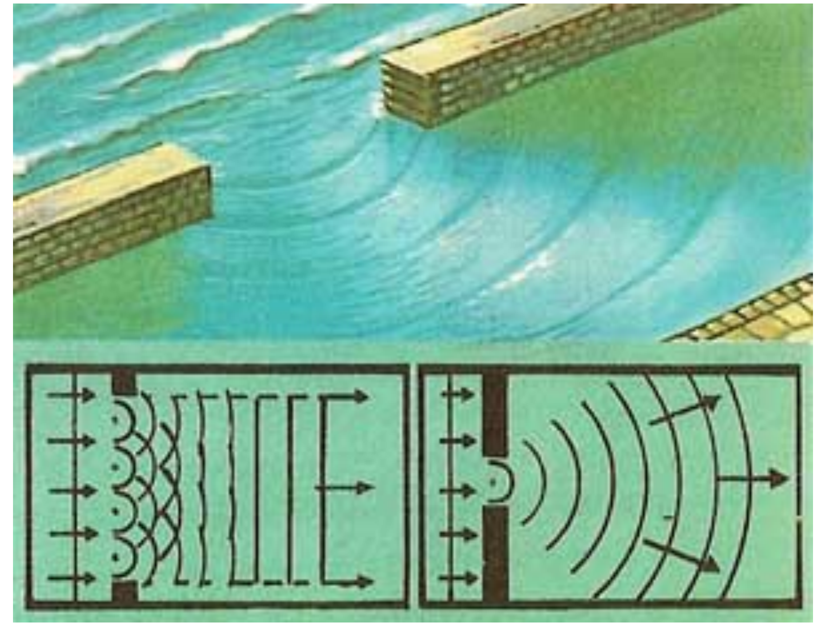
Breakdown of ray optics: *single slit, with $d \approx \lambda$*

slits



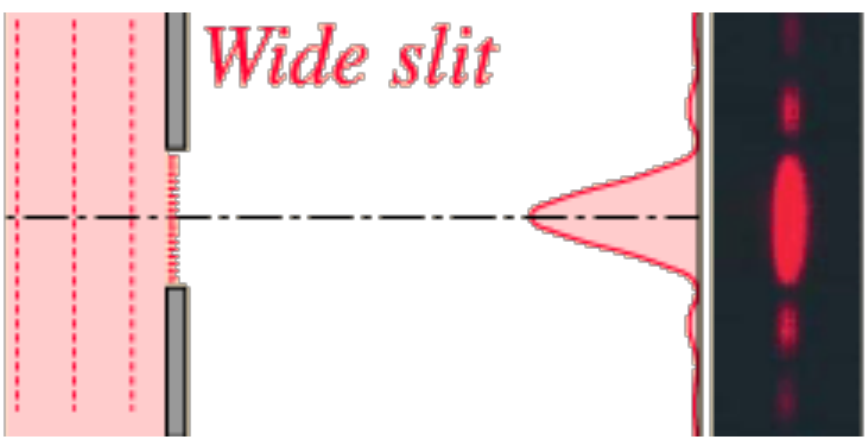
Diffraction

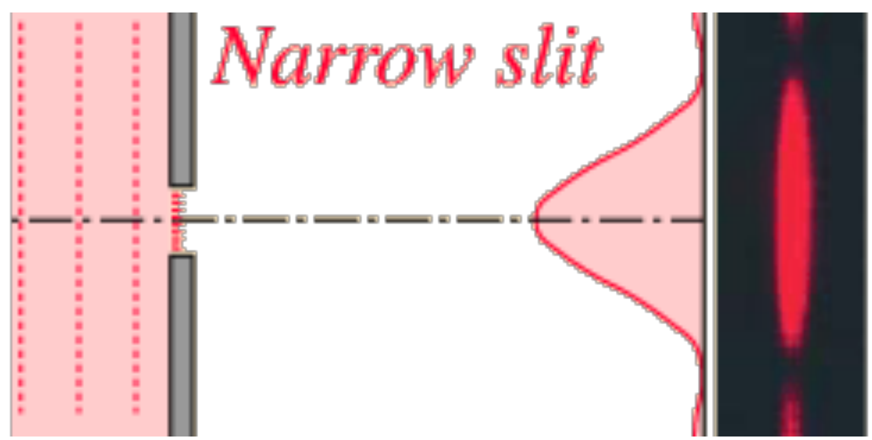




$d >> \lambda$

$d \approx \lambda$





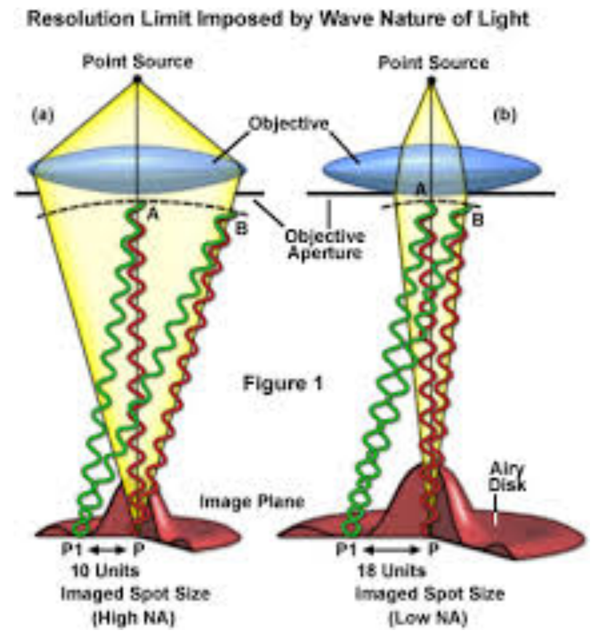
Microscope resolution

limit on

Resolution – smallest size that is not blurry

= wavelength x f-number = $(\lambda/d)f$

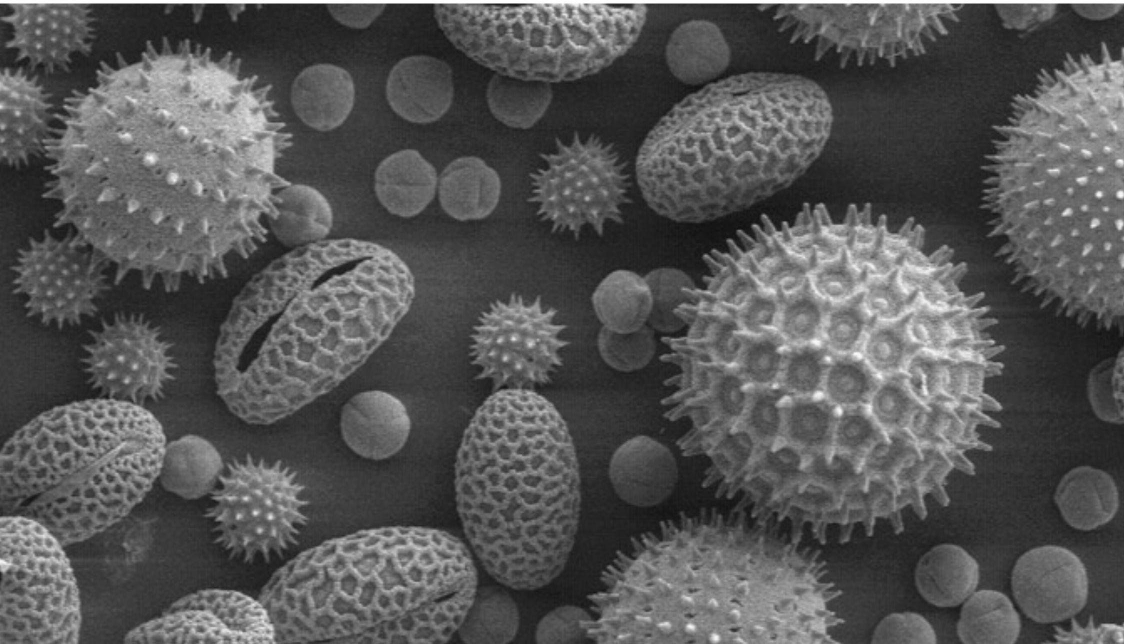
(a) (b) (c)

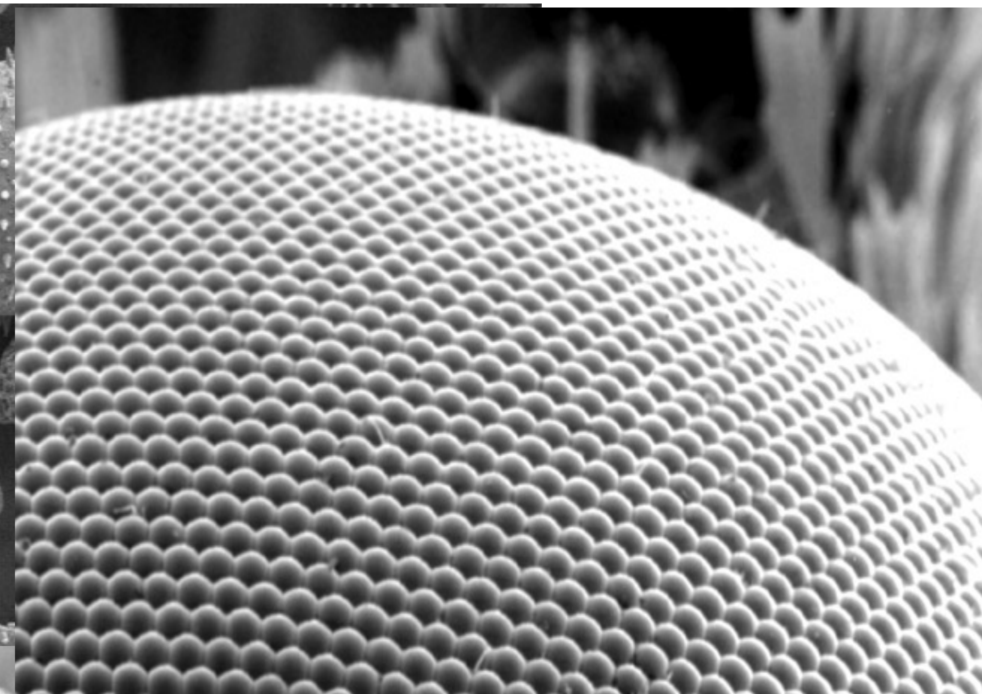


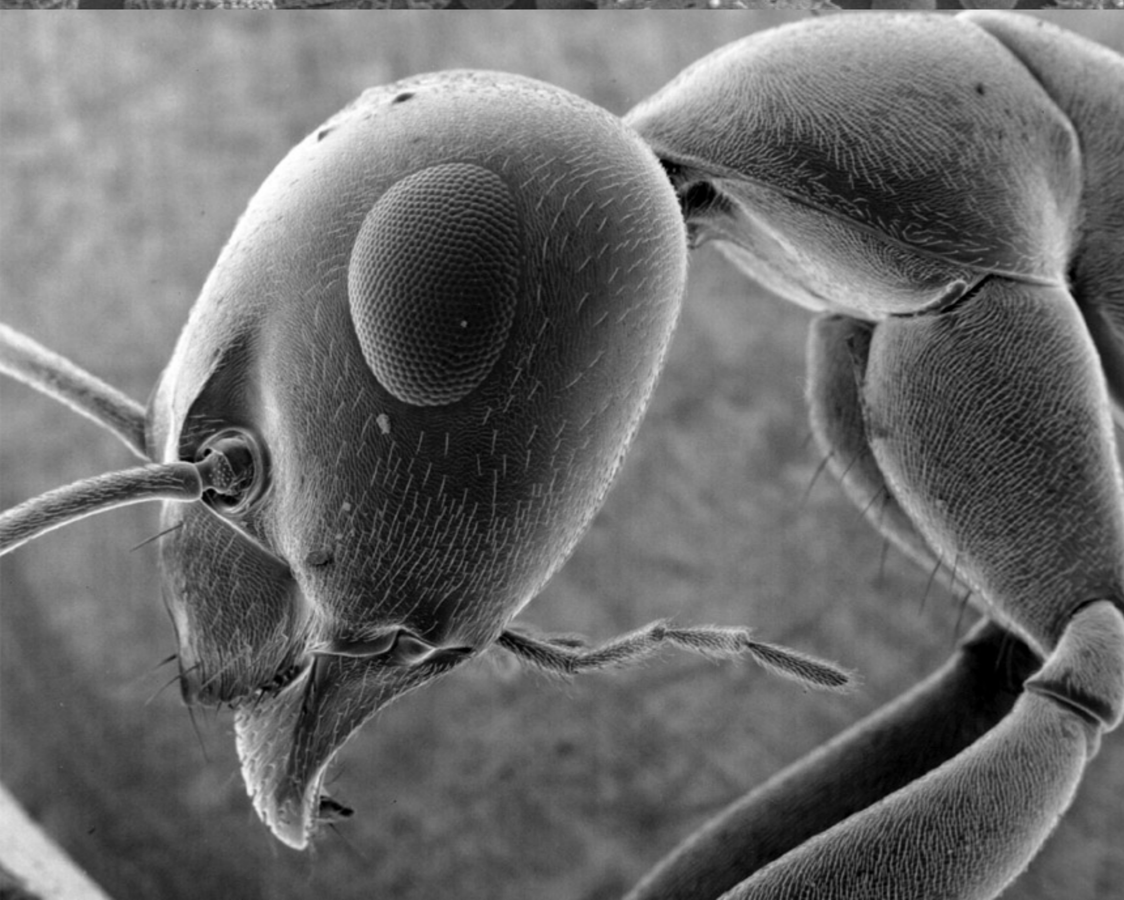
- Focus spot is limited by diffraction effects, i.e., that $\lambda \neq 0$
- Shorter wavelength -> higher resolution; can distinguish/see smaller objects
- Cannot just magnify -> image will just become blurry
- Use small λ: UV, X-rays, electron waves to enhance resolution

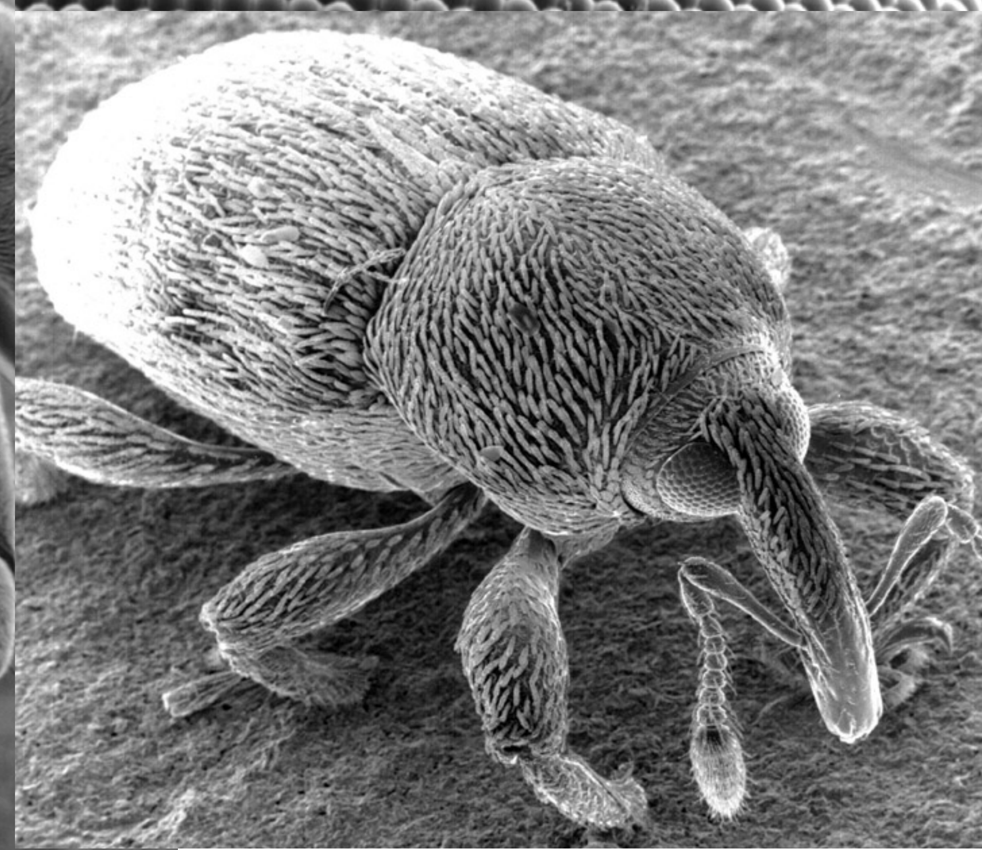
Electron microscope

λ<0.1nm

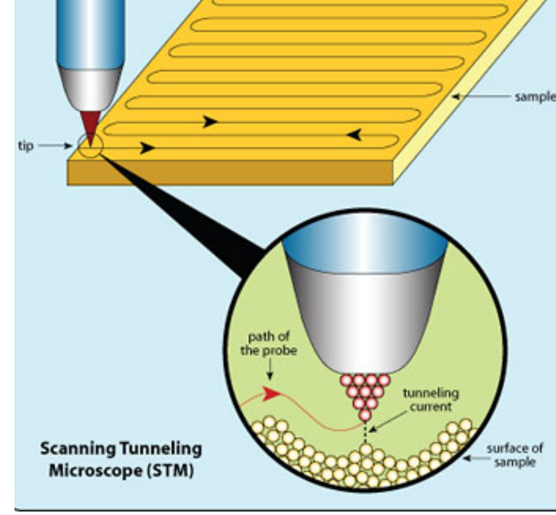


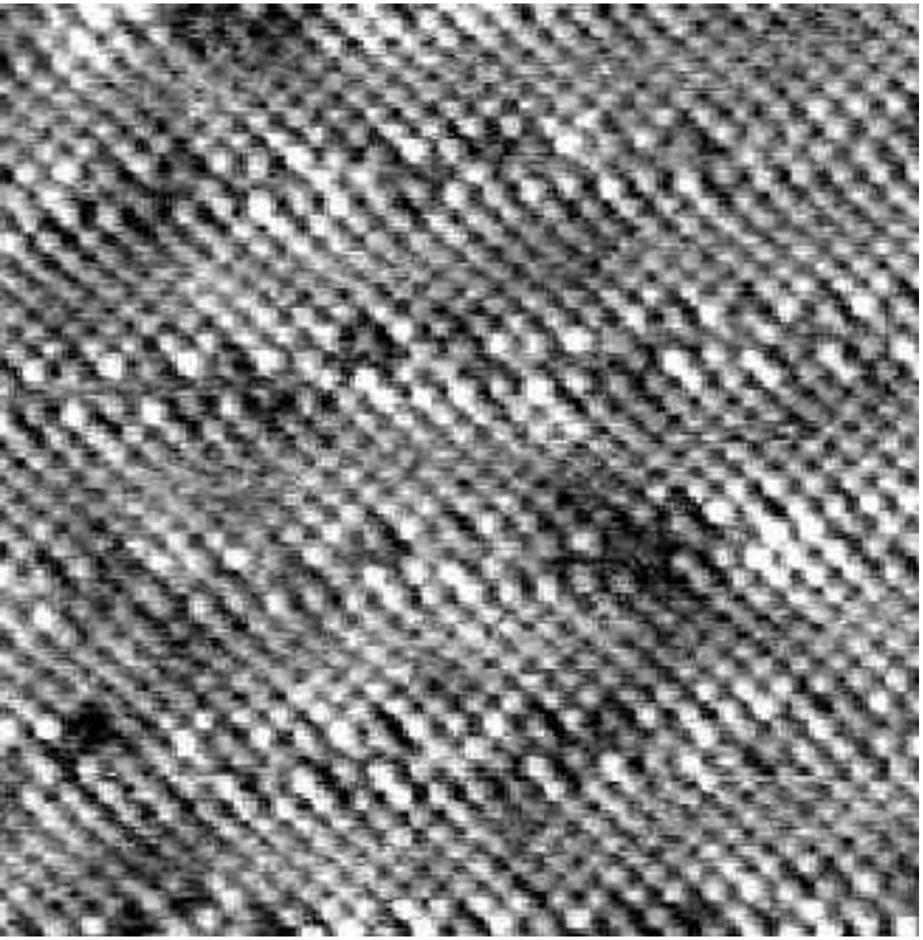


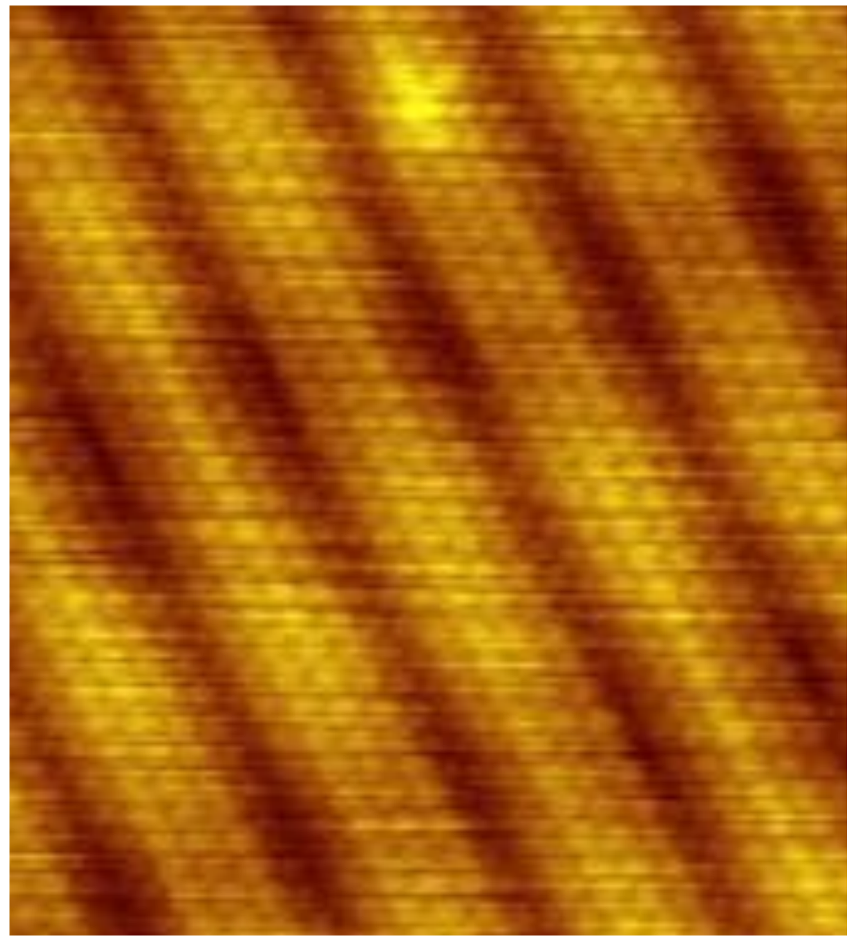




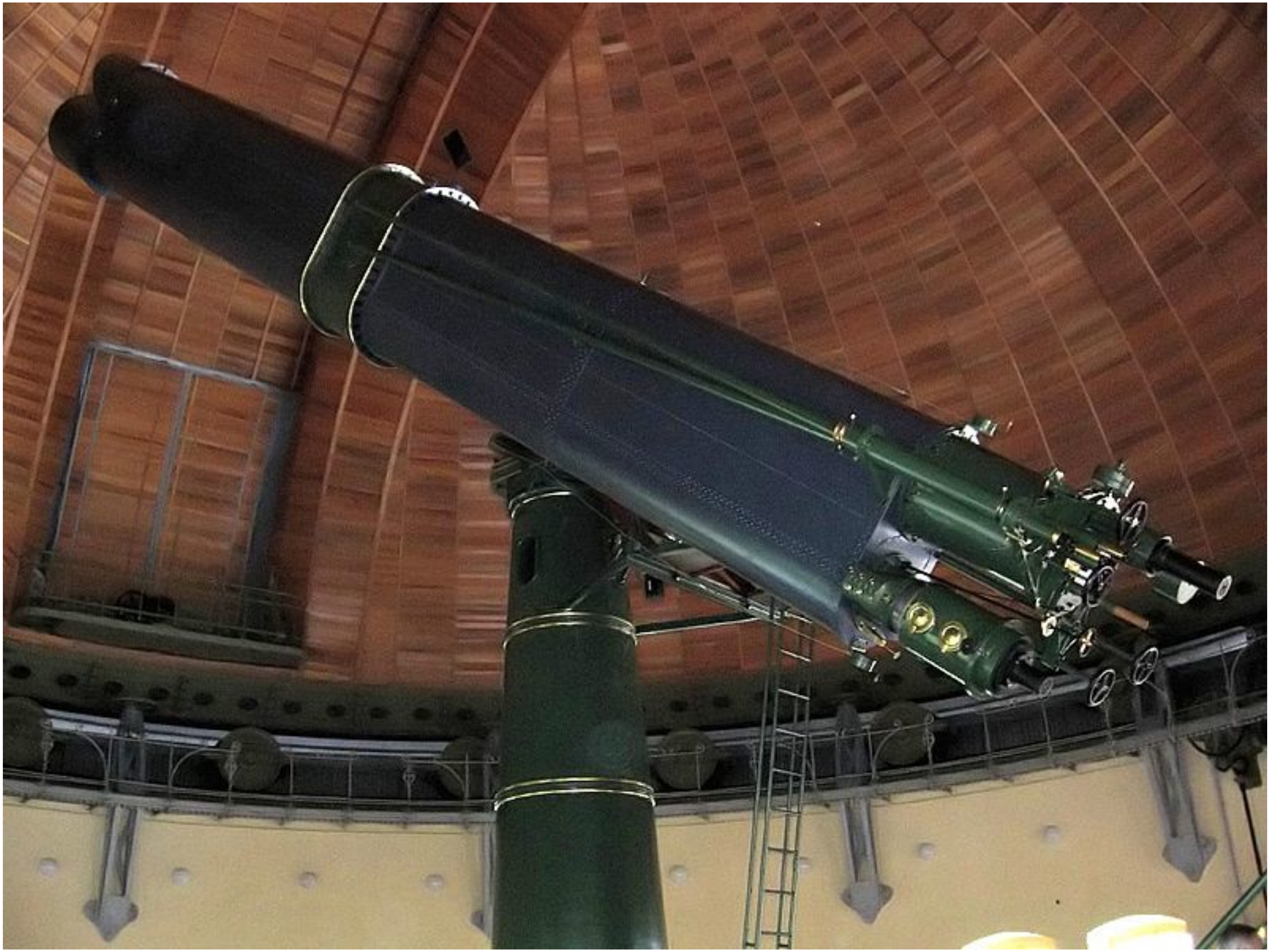
Scanning tunneling microscope







Telescopes



Great refractor

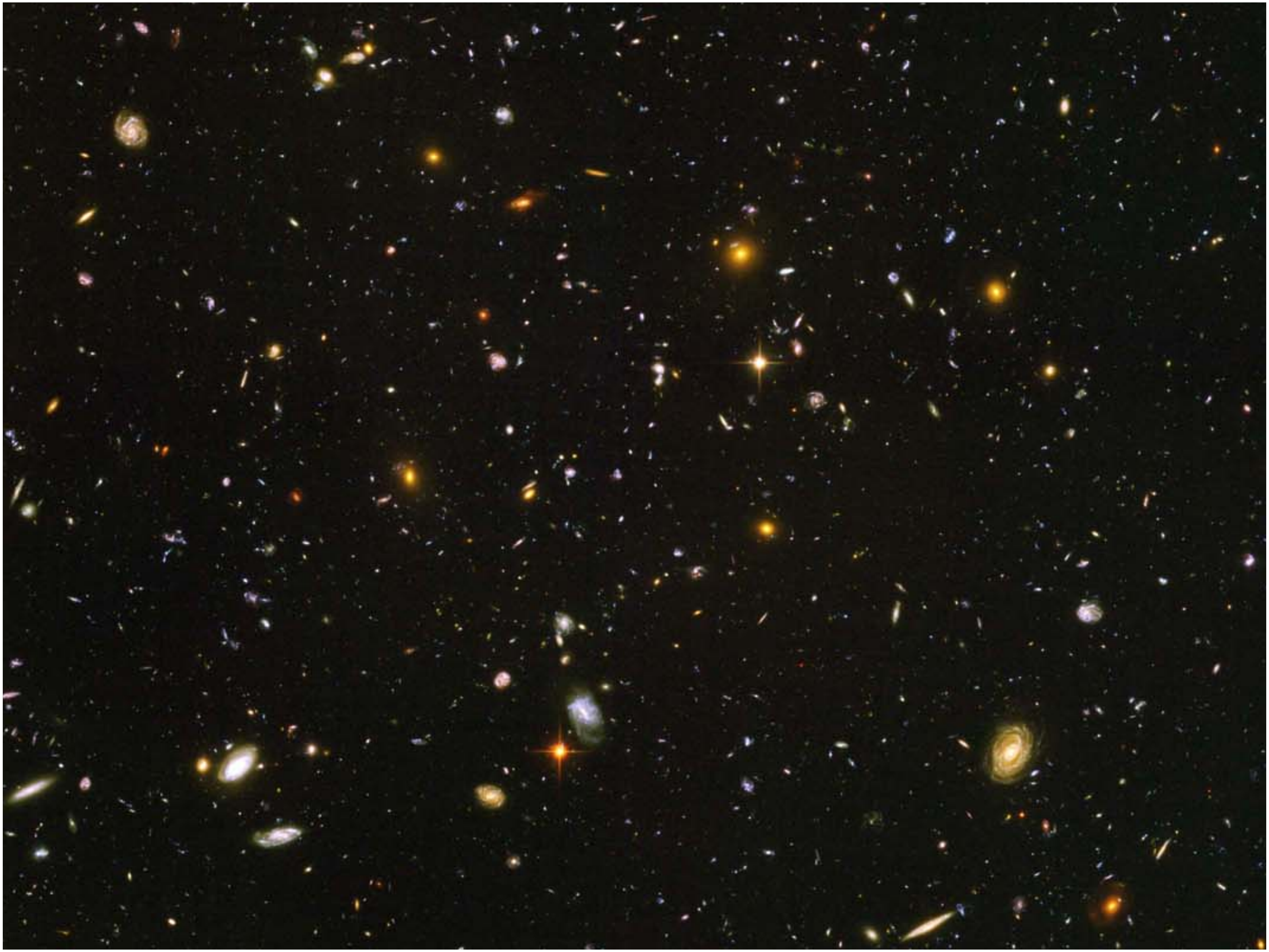
Telescopes

Great refractor

Telescopes

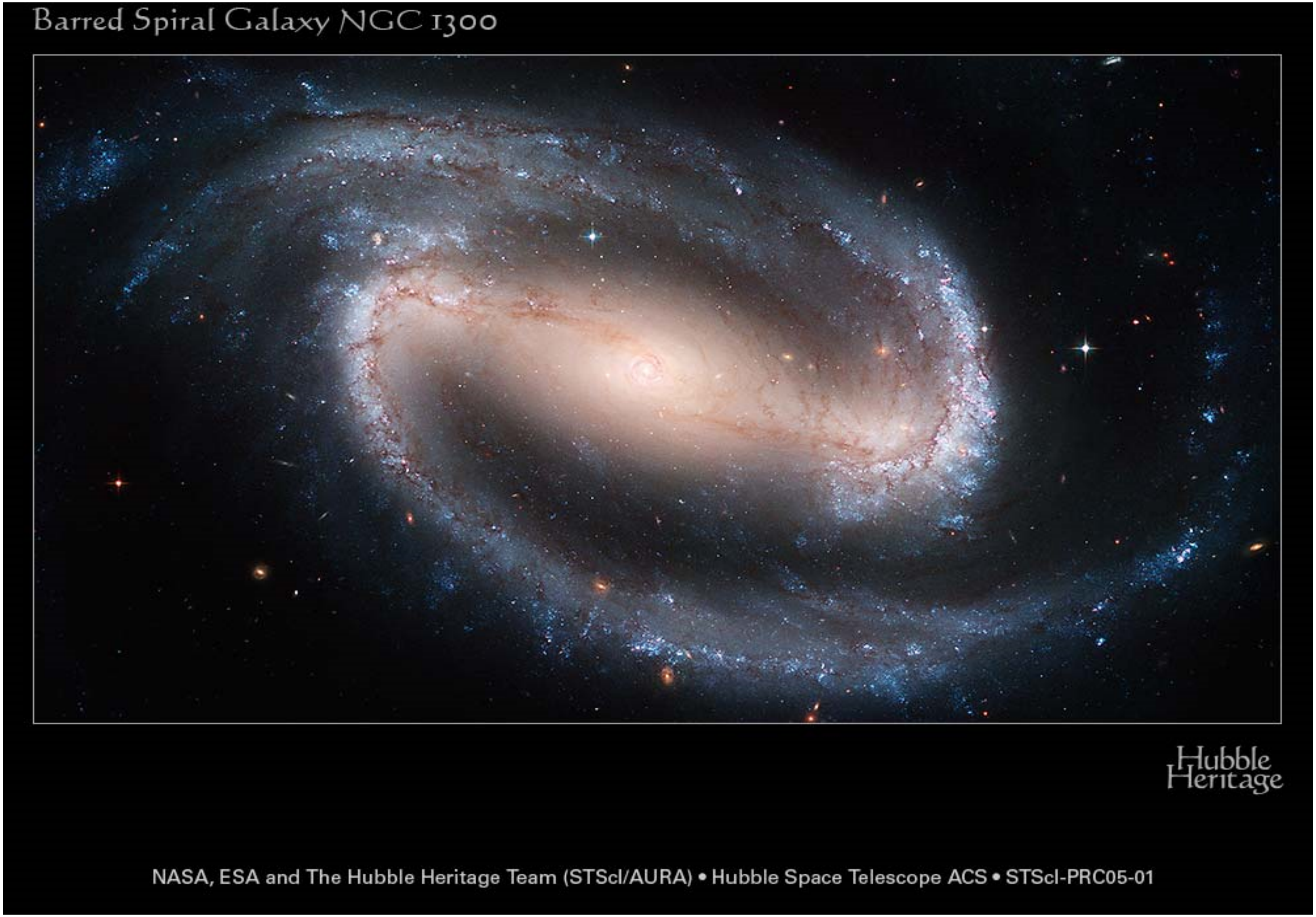
Space telescope

Telescopes



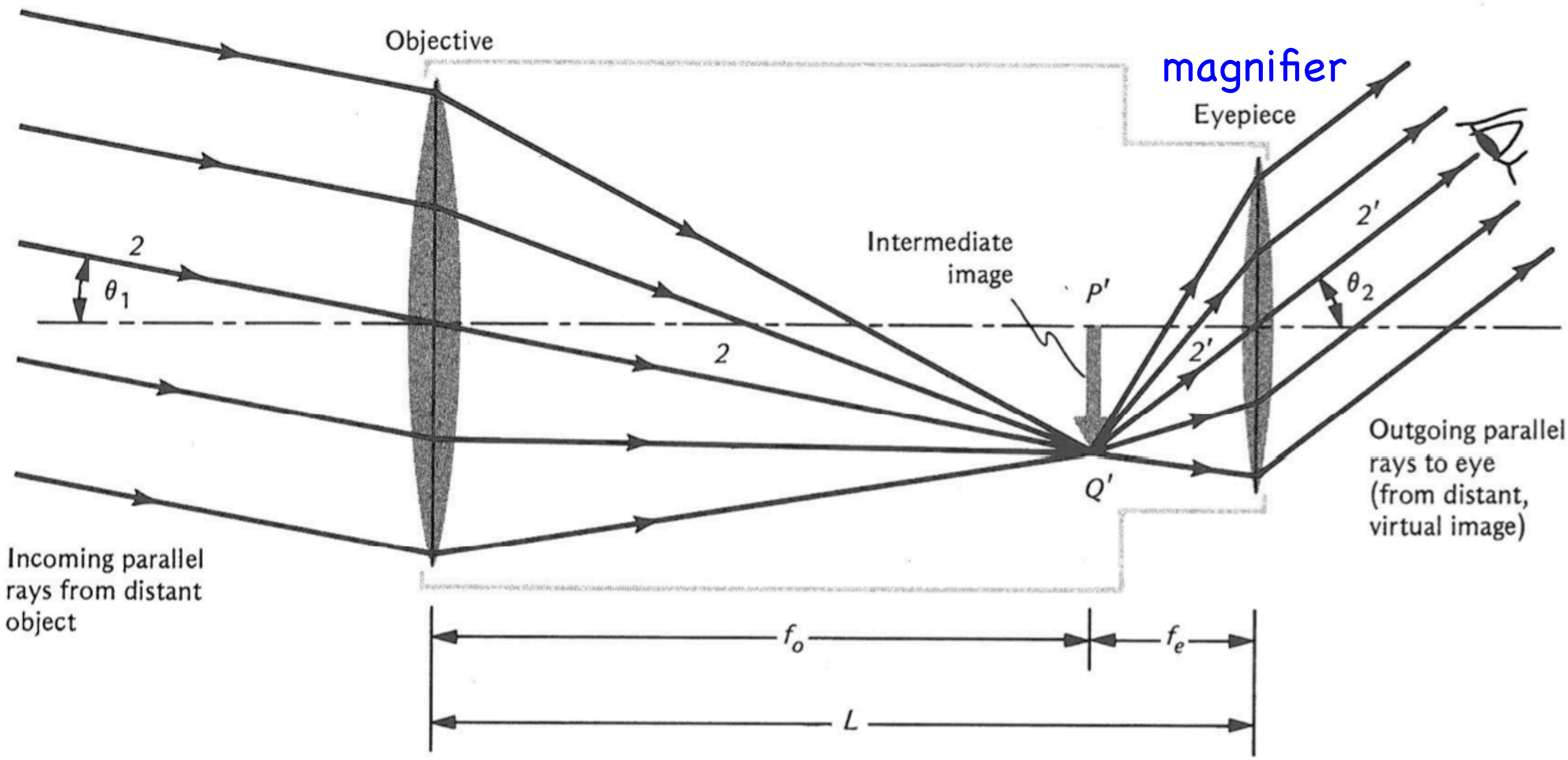
Hubble Ultra Deep Field, NASA, ESA, S. Beckwith

Telescopes



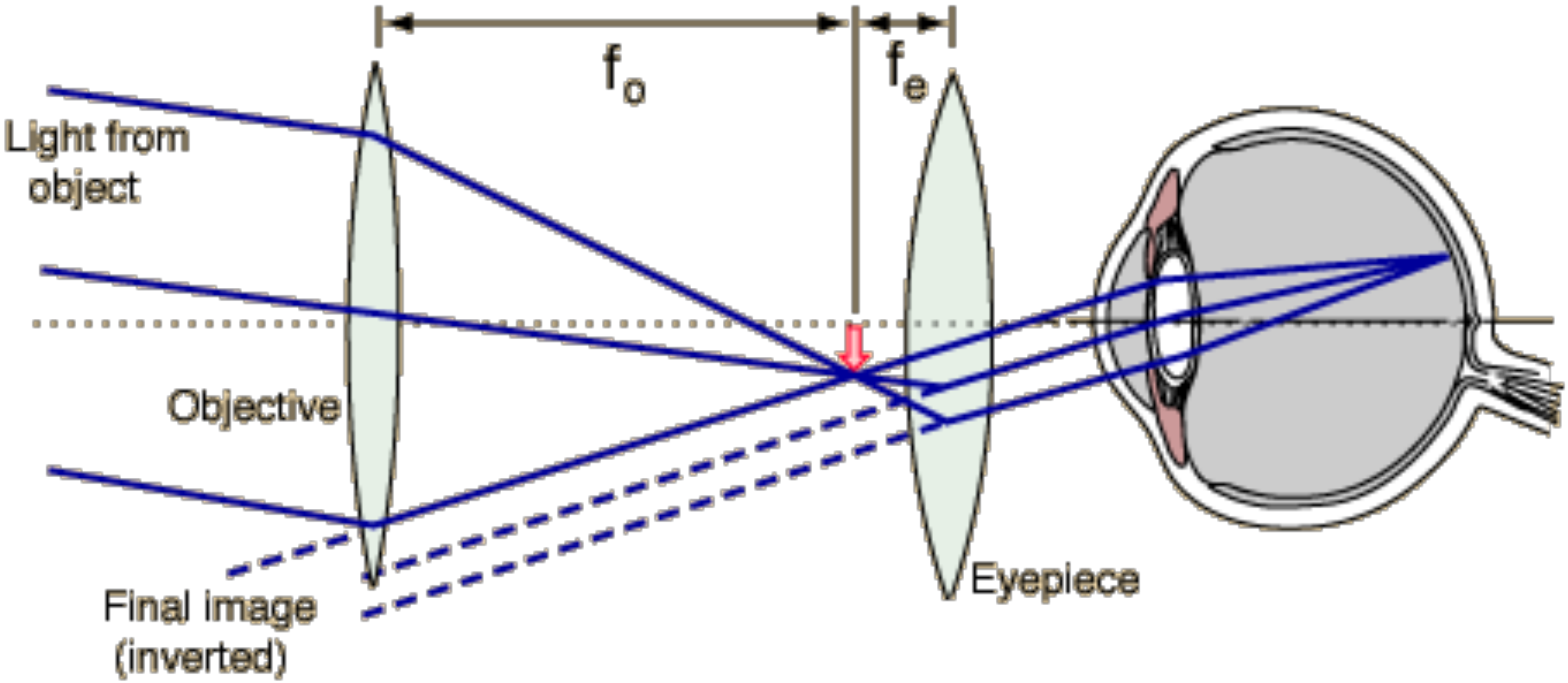
Hubble telescope

Astronomical telescope



- Look at large objects far, far away
- Intermediate image serves as a source of new rays, object for the second lens, placed at f_e
- Parallel rays -> parallel rays
- $M = -f_o/f_e$, f_o as long as possible

Astronomical telescope



- Look at large objects far, far away
- Intermediate image serves as a source of new rays, object for the second lens, placed at f_e
- Parallel rays -> parallel rays
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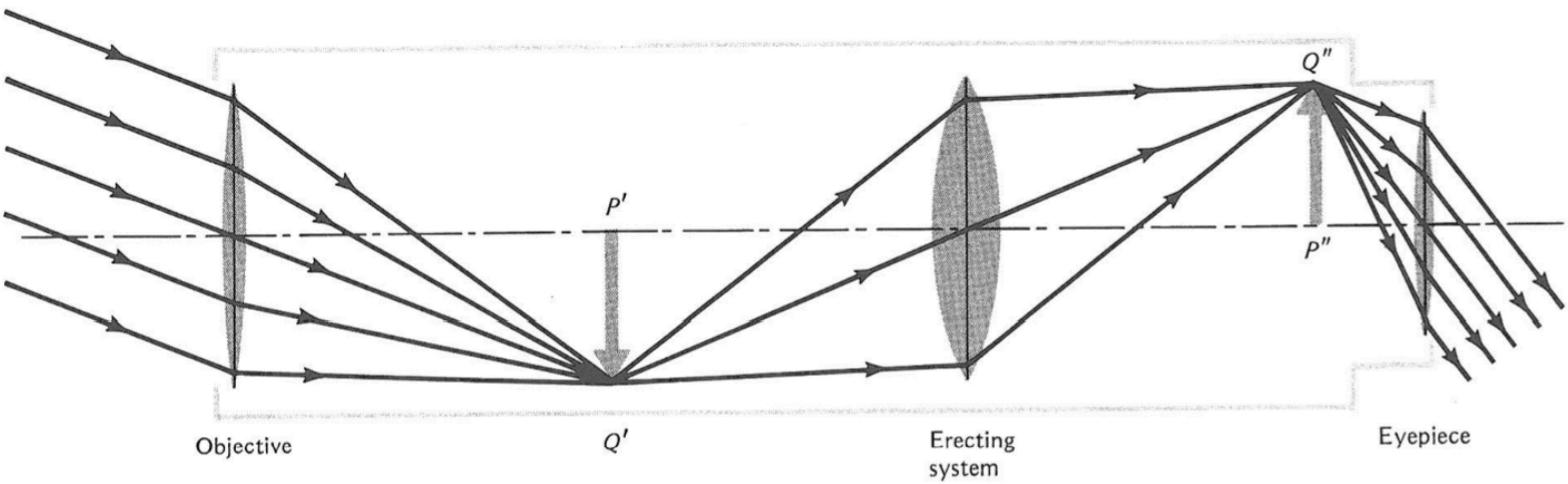
Terrestrial telescope

(looking at whales, spying on neighbors, ...)

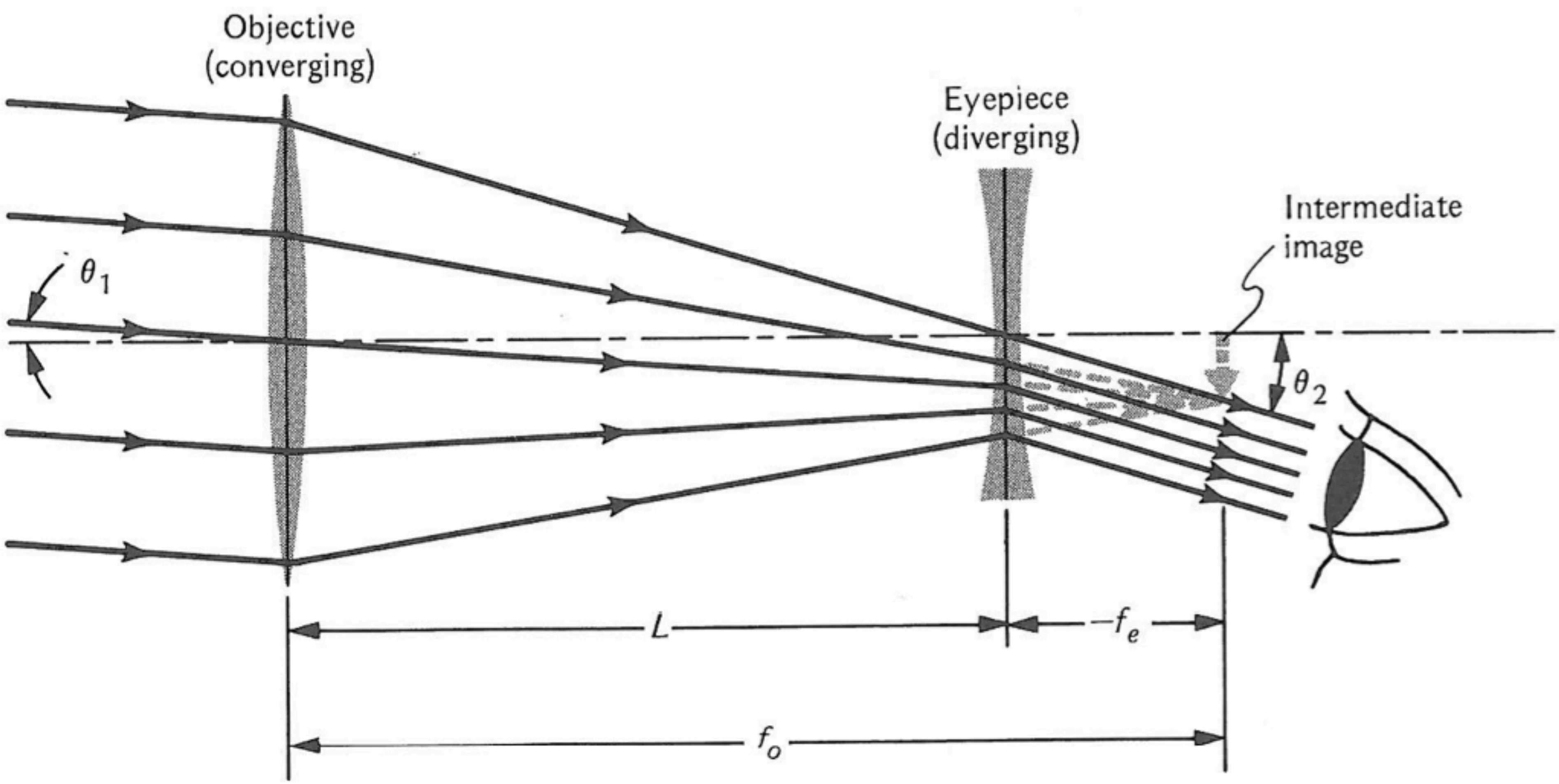


- intermediate image serves as a source of new rays
- erecting lens used to turn image right side up
- can also use a prism instead to shorten path

Galilean telescope

- invented in approximately 1600s
- 30X magnification
- tiny lens means dim image
- discoveries: craters on Moon, Phases of Venus, Moons of Jupiter

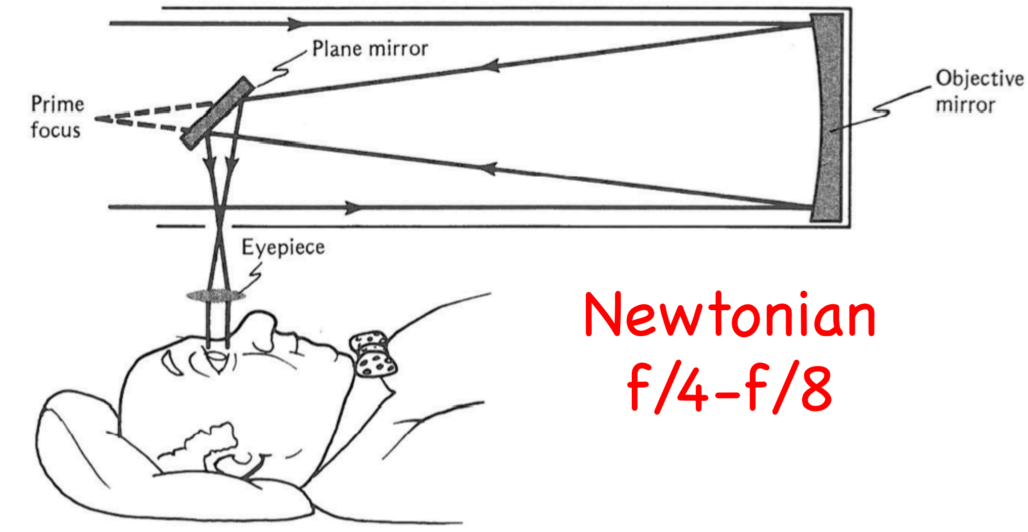
Galilean telescope



- intermediate image serves as a source of new rays
- diverging lens used for eyepiece, erect image
- eyepiece located so that f_e is at f_o
- used in inverted configuration as a door peephole

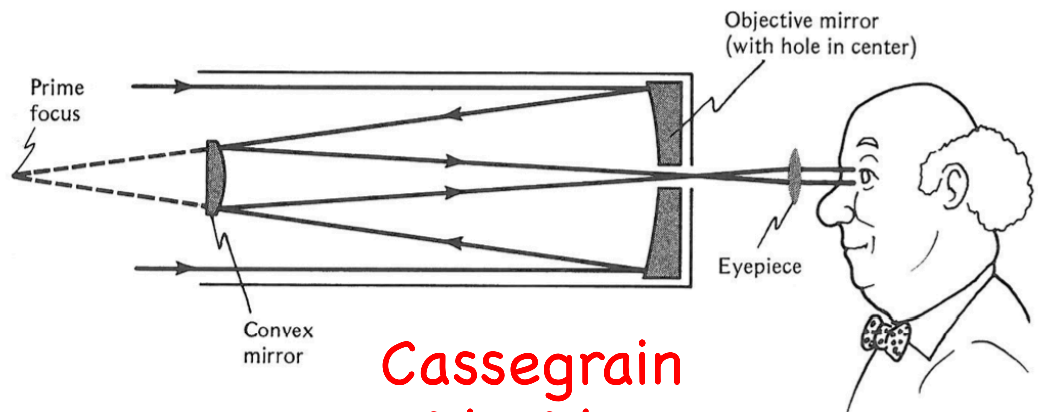
Reflecting telescope

- Avoids heavy, expensive objective lens', whose size limits f/number
- Replace by two concave mirrors
- No chromatic aberration
- Design used in most large telescopes



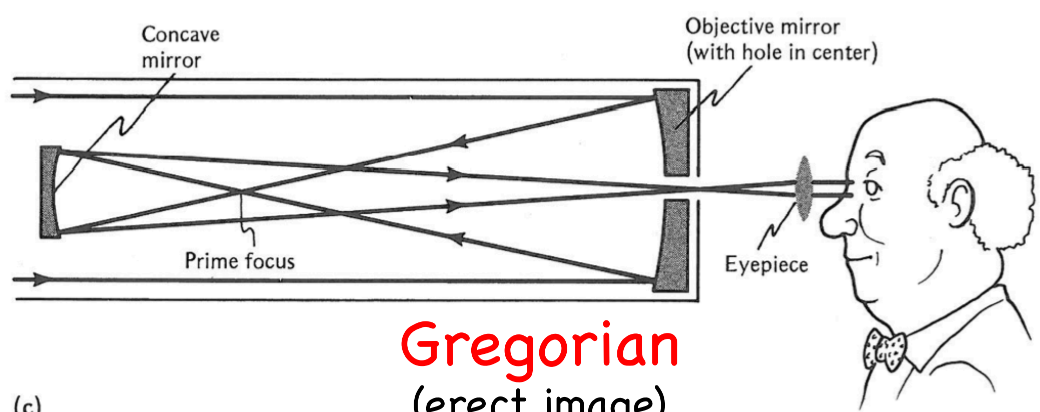
(a)

Newtonian
f/4–f/8



(b)

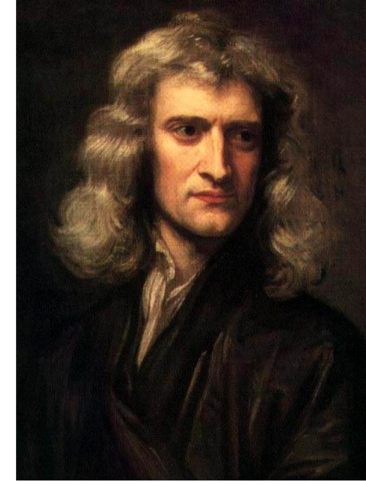
Cassegrain
f/7–f/12



(c)

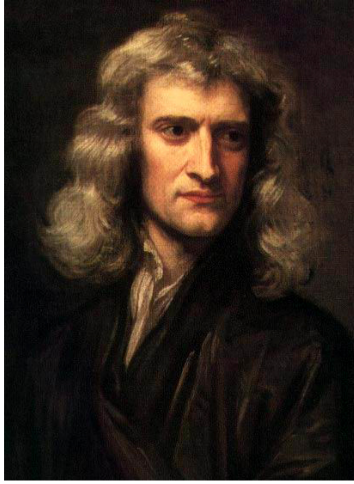
Gregorian
(erect image)

Newton’s reflecting telescope



IsaacNewton
1689 (age 46)

Newton's reflecting telescope



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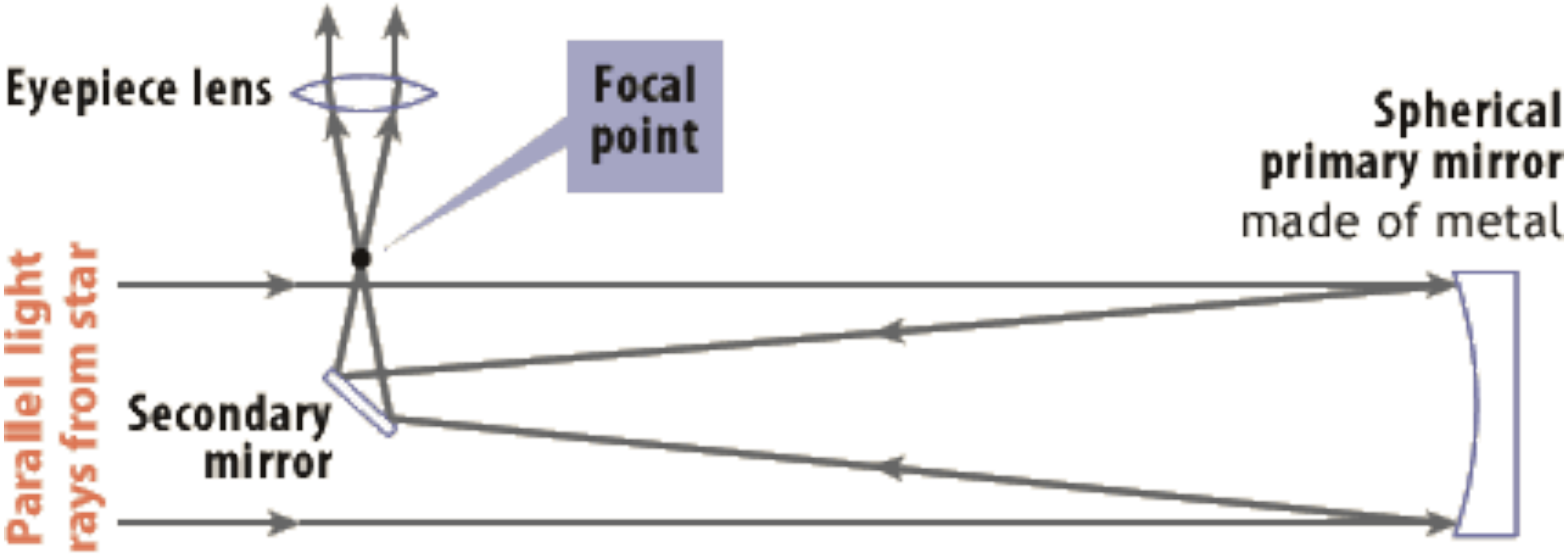
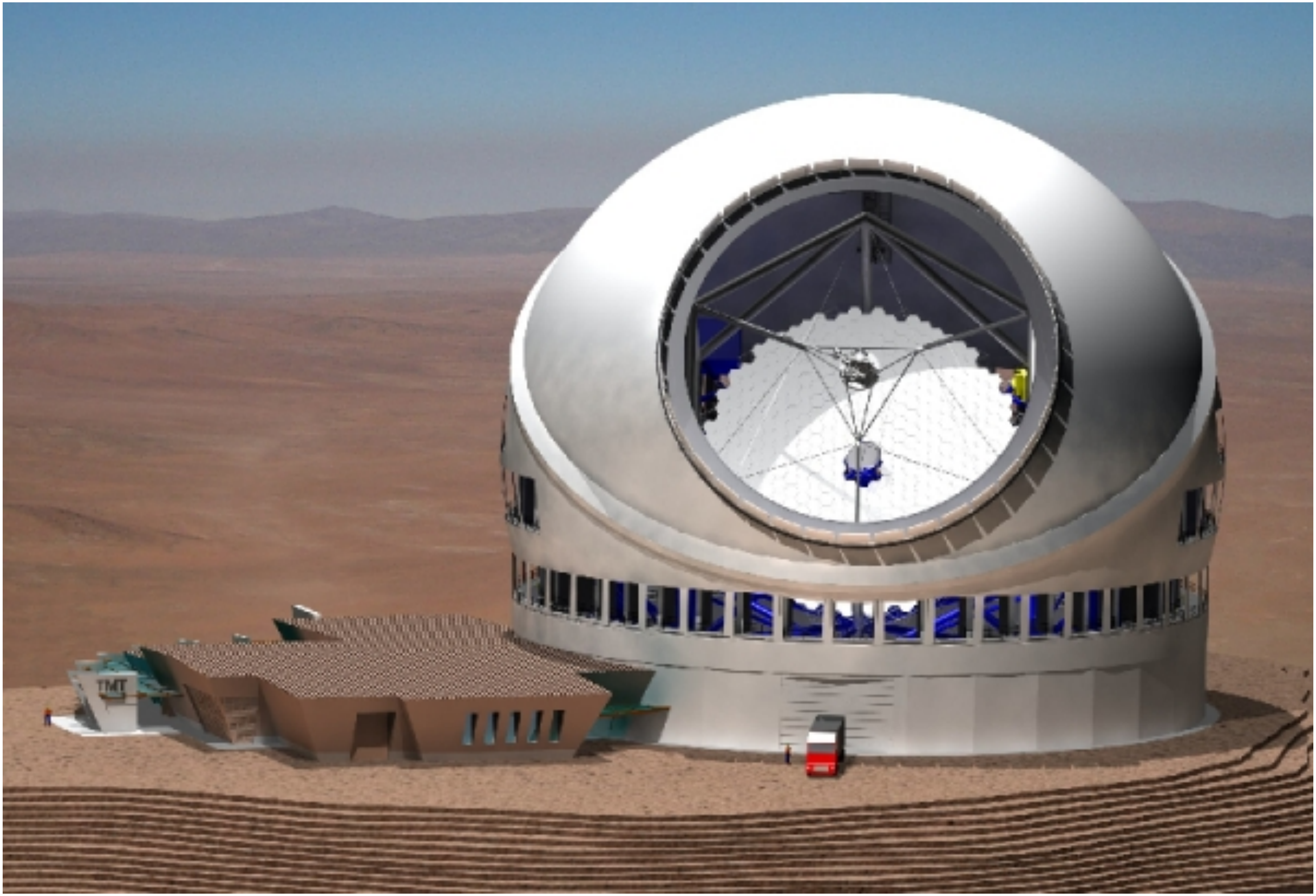


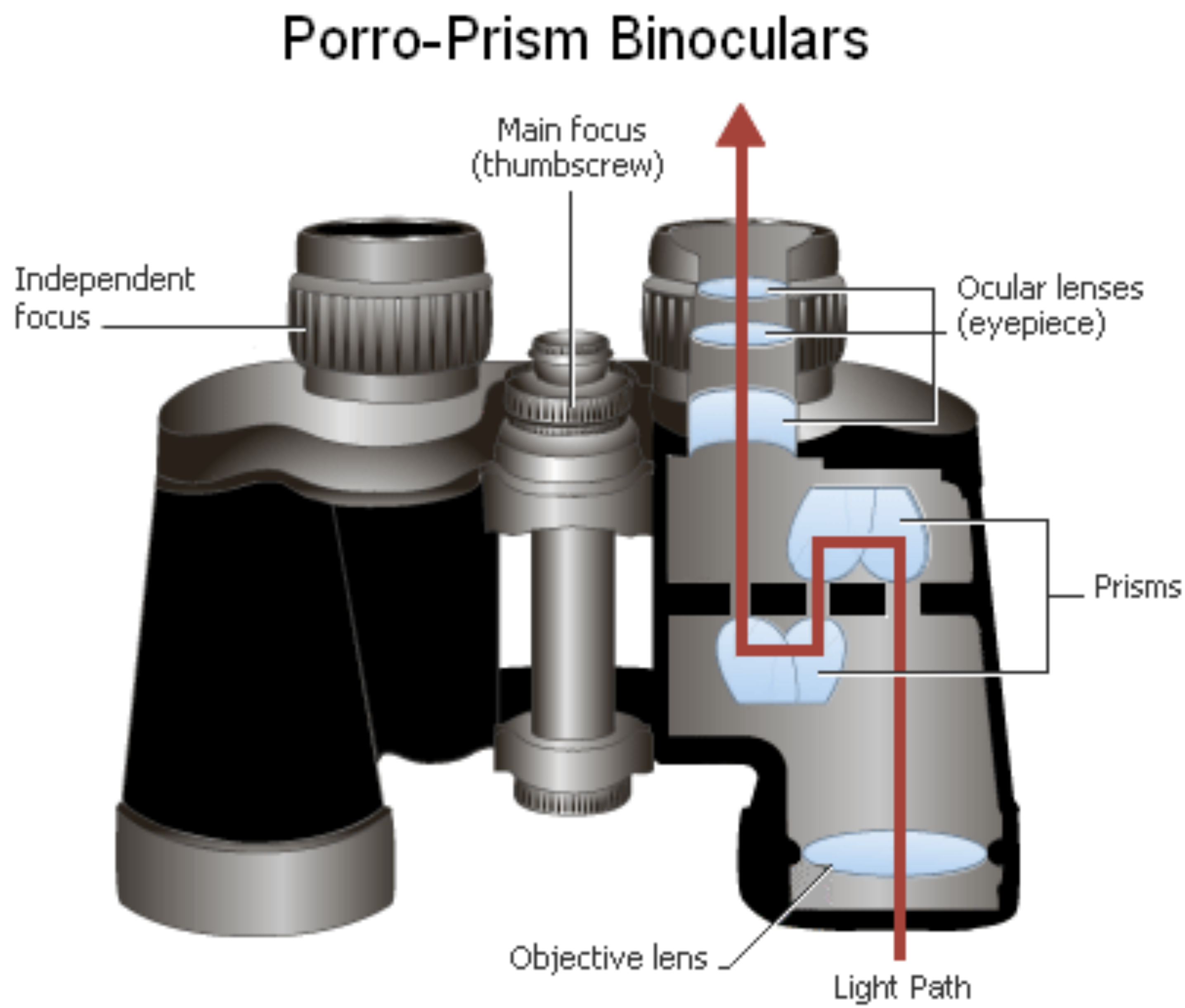
advantage: no chromatic aberration

Magellan telescope



24.5 meters diameter, segmented

Binoculars



Simply folded telescopes for each eye

Binoculars

What does 7 x 50 binoculars mean?

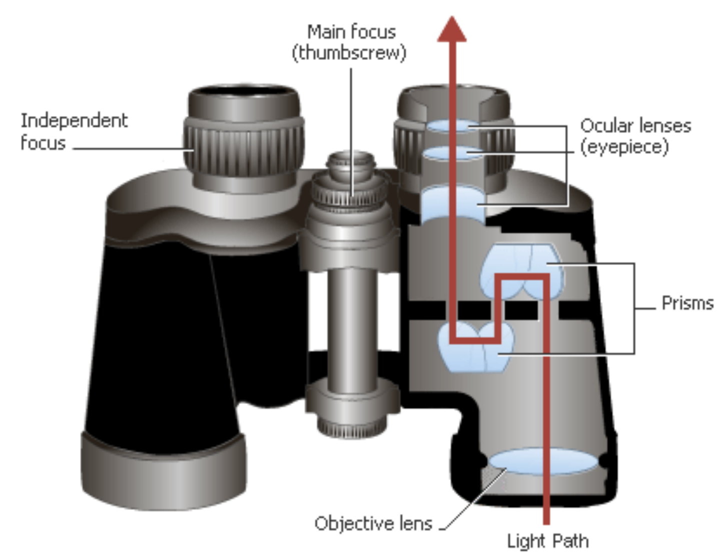
7x is the magnification

50 is the diameter of the front lens
(the objective lens) in millimeters

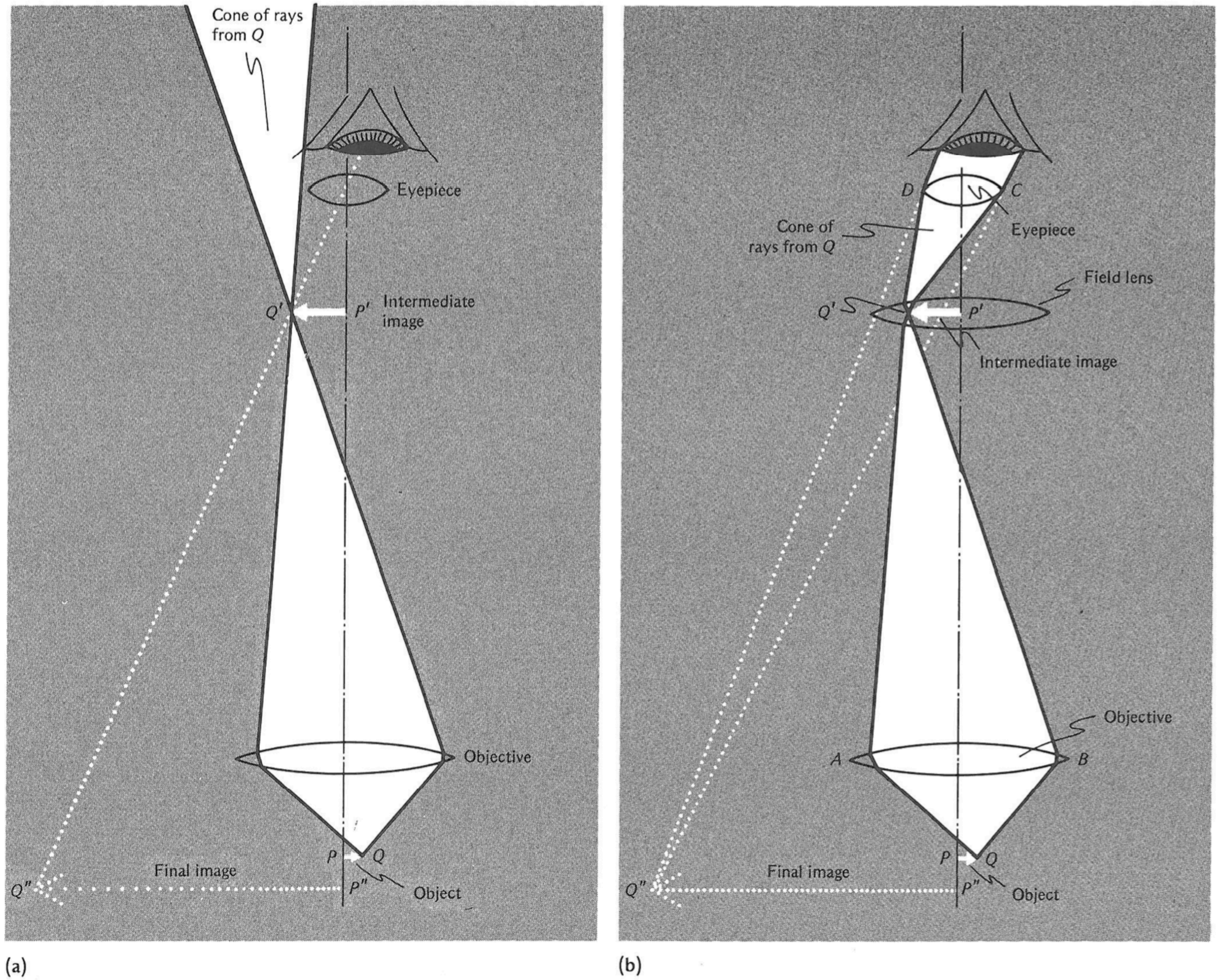
6 x 30 binoculars are easy to carry

7 x 50 binoculars are heavy, but these give
a brighter image

15 x 80 binoculars need a tripod



Field lens



- field lens at interm. image creates full illumination
- eliminates vignetted image of the final image