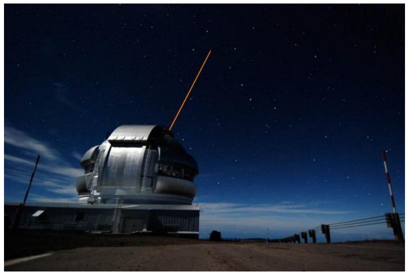
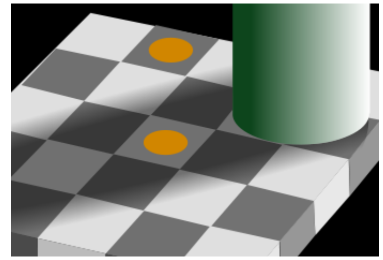
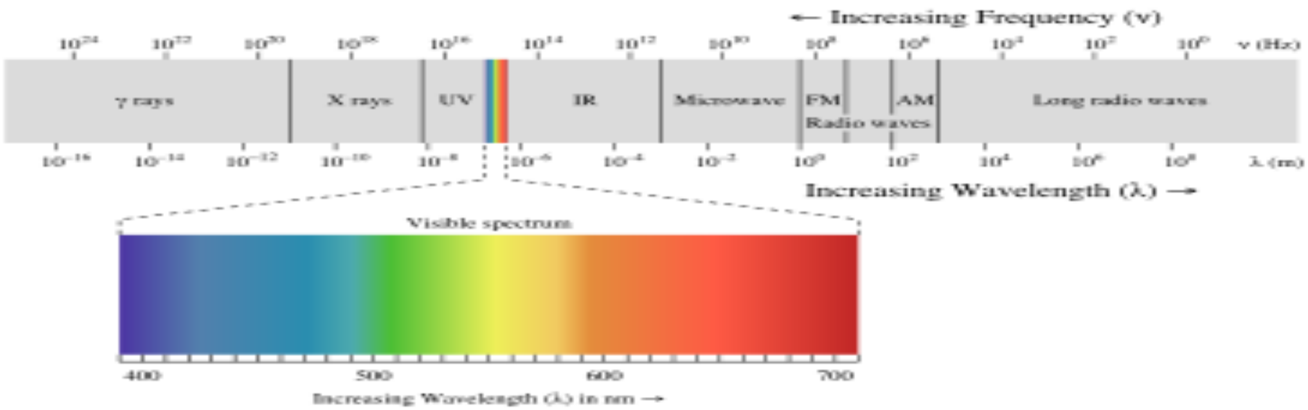
Physics 1230: Light and Color



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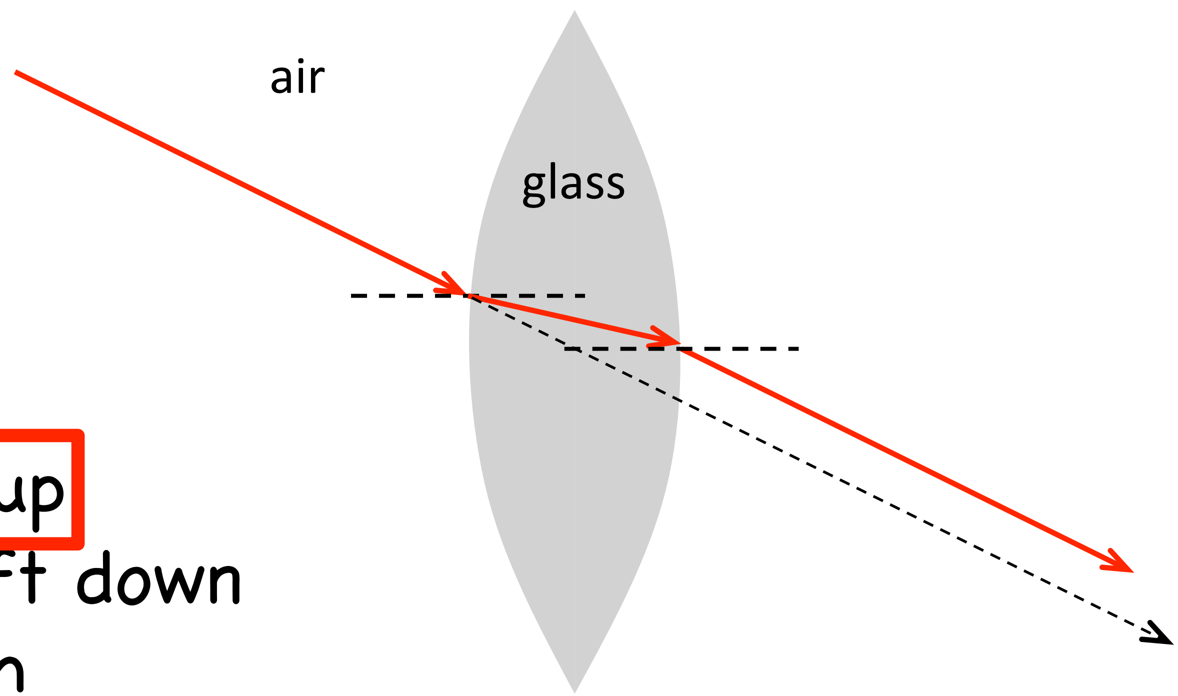
http://www.colorado.edu/physics/phys1230/

clicker question

Flat mirror reflection

Q: The center surfaces of a lens are approximately flat, with normals illustrated. Given what you know about refraction what does this ray really do when it enters the glass?



(a) bend up and shift up
(b) bend down and shift down
(c) go straight through

Lecture 7

Spherical lenses

Announcements:

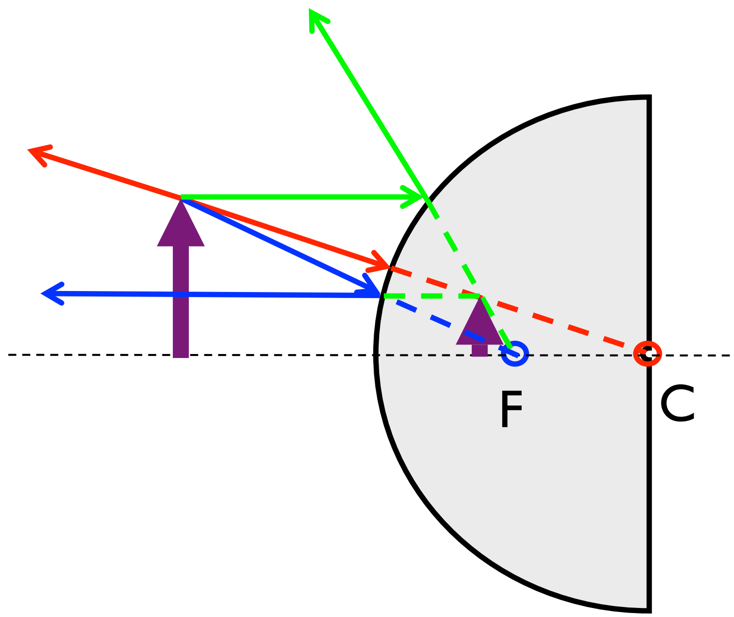
- lectures 6 is posted on the class website
- midterm 1 solutions and grades are posted
- homework 6 is posted on D2L
  - due Thursday, March 13 in homework box in Help Room
  - solutions will be posted on D2L
- reading for this week is:
  - Ch. 3, 4 in SL

Recall

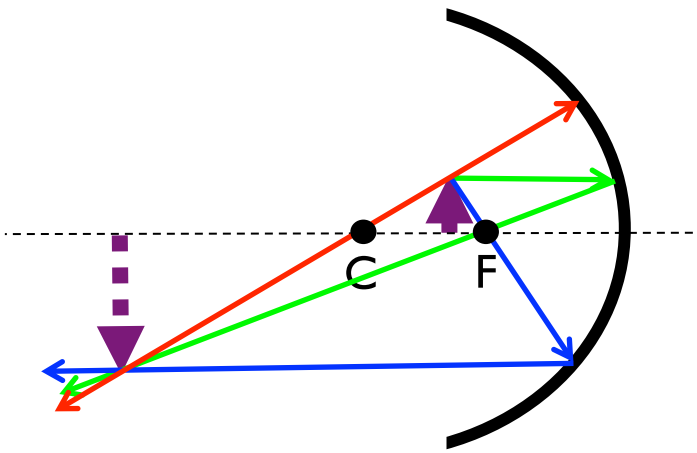
Last time

recall lecture 6: Spherical mirrors

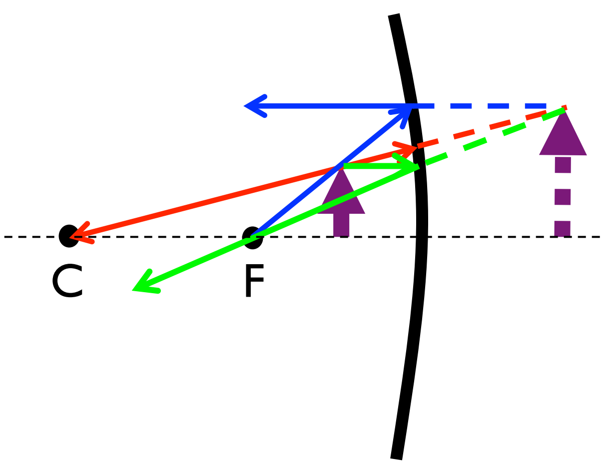
- convex and concave mirrors
  - ray tracing
  - image formation
  - applications

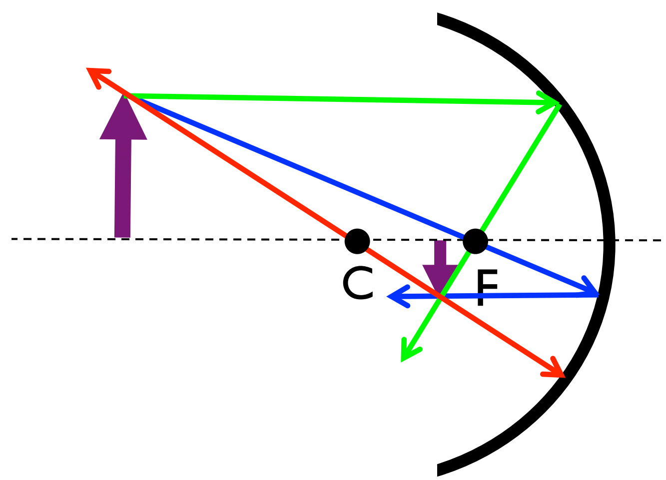


Concave solar concentrator



Convex traffic safety mirror

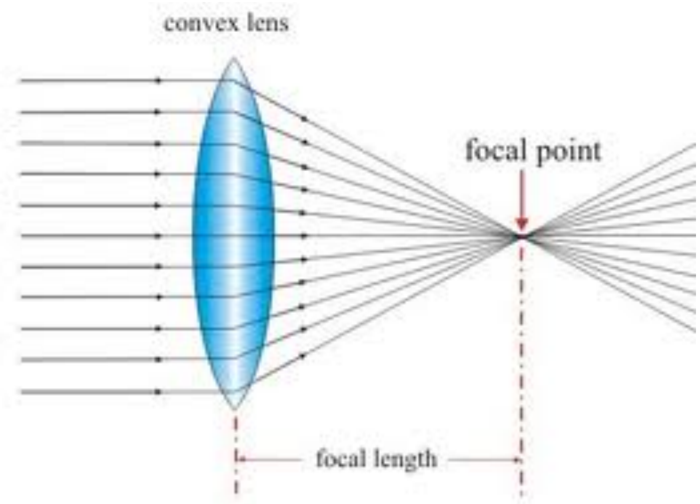


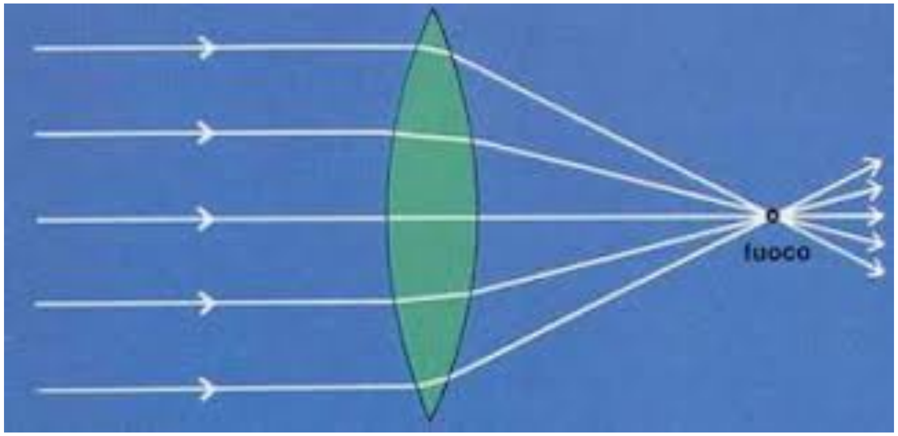


Today

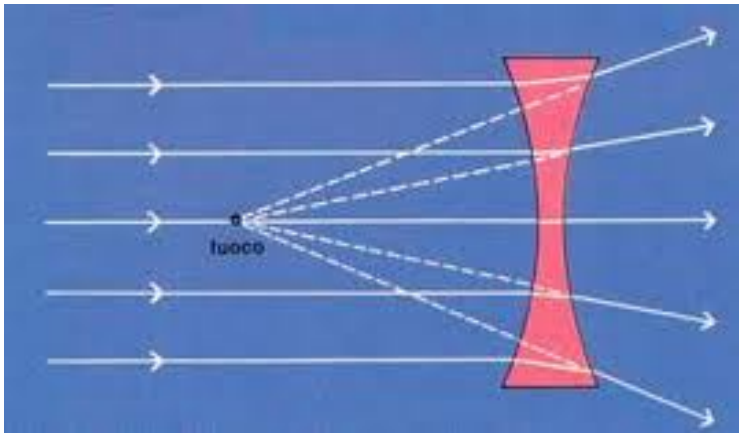
Spherical lenses

- convex and concave lenses
  - ray tracing
  - image formation
  - applications



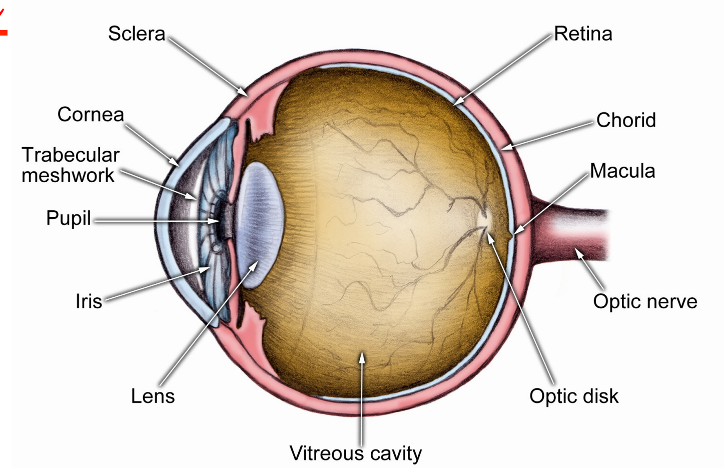


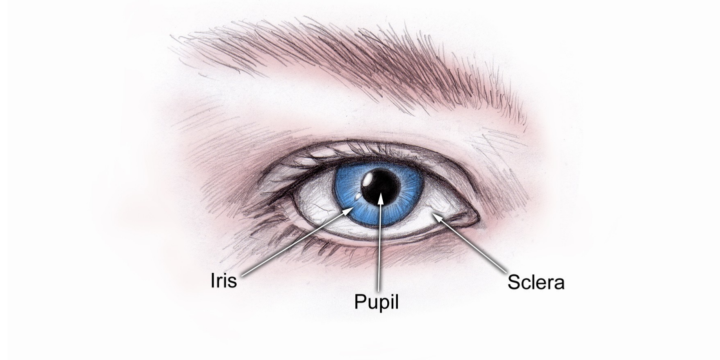
converging lens "bi-convex" has two convex surfaces



diverging lens "bi-concave" has two concave surfaces

Lenses everywhere

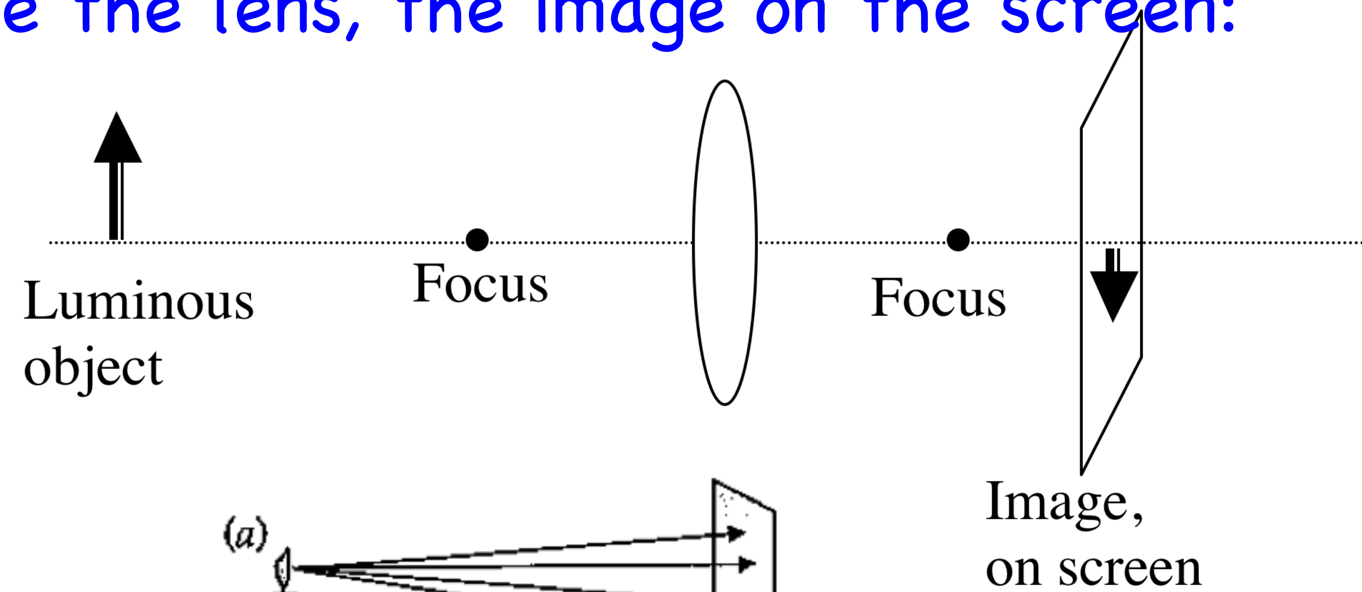




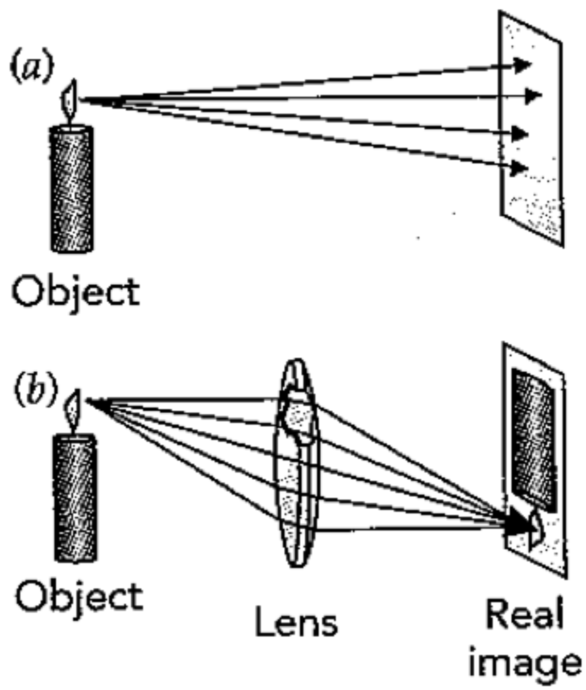
clicker question

Simple camera

Q: If you remove the lens, the image on the screen:

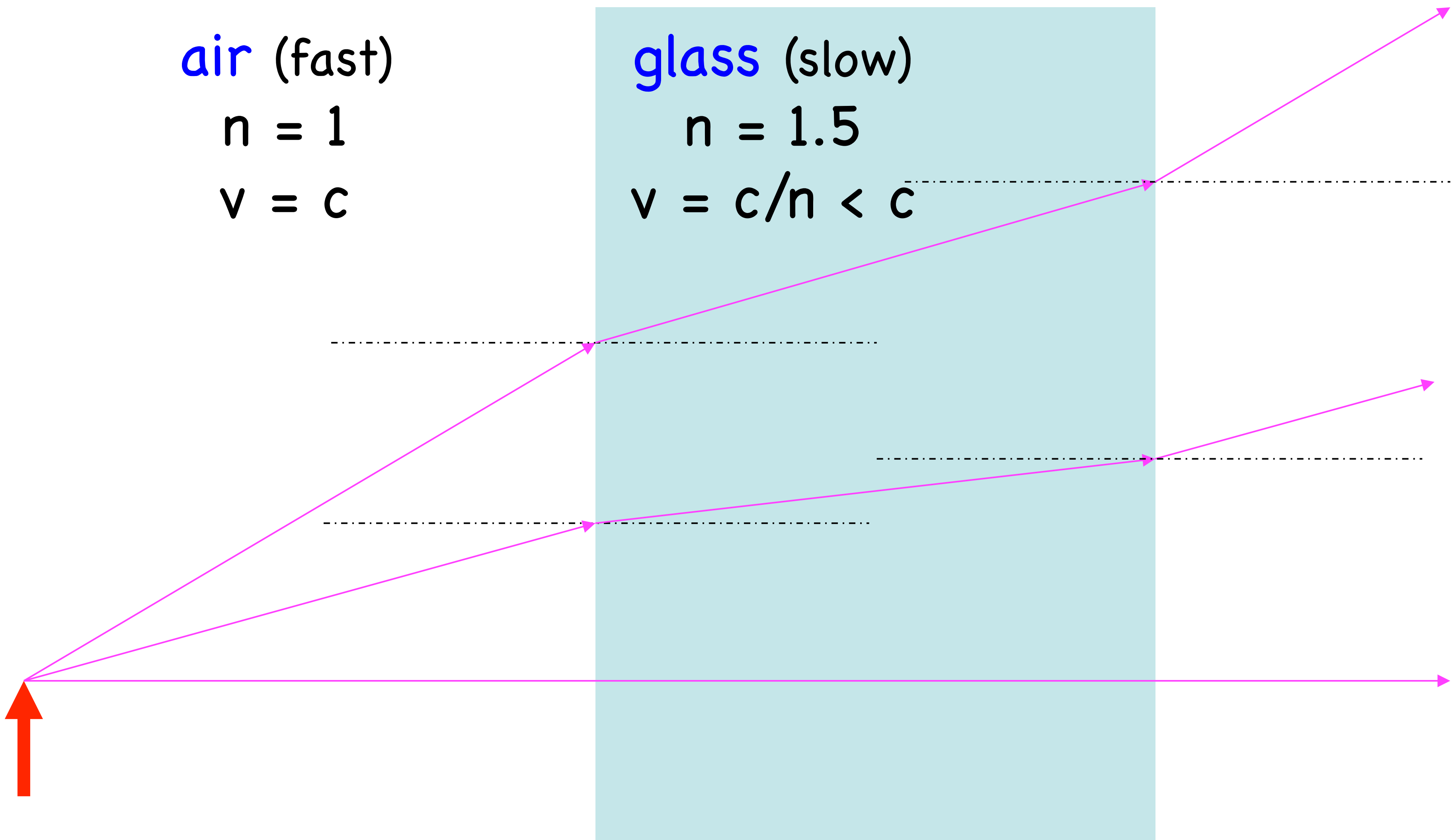


(a) remains the same
(b) gets a bit dimmer
(c) becomes fuzzier
(d) becomes upright
(e) disappears



There is no image without a lens as rays diverge in all directions. Recall how we used pin camera to isolate one ray. Now a lens focuses all the rays. This is a simple camera.

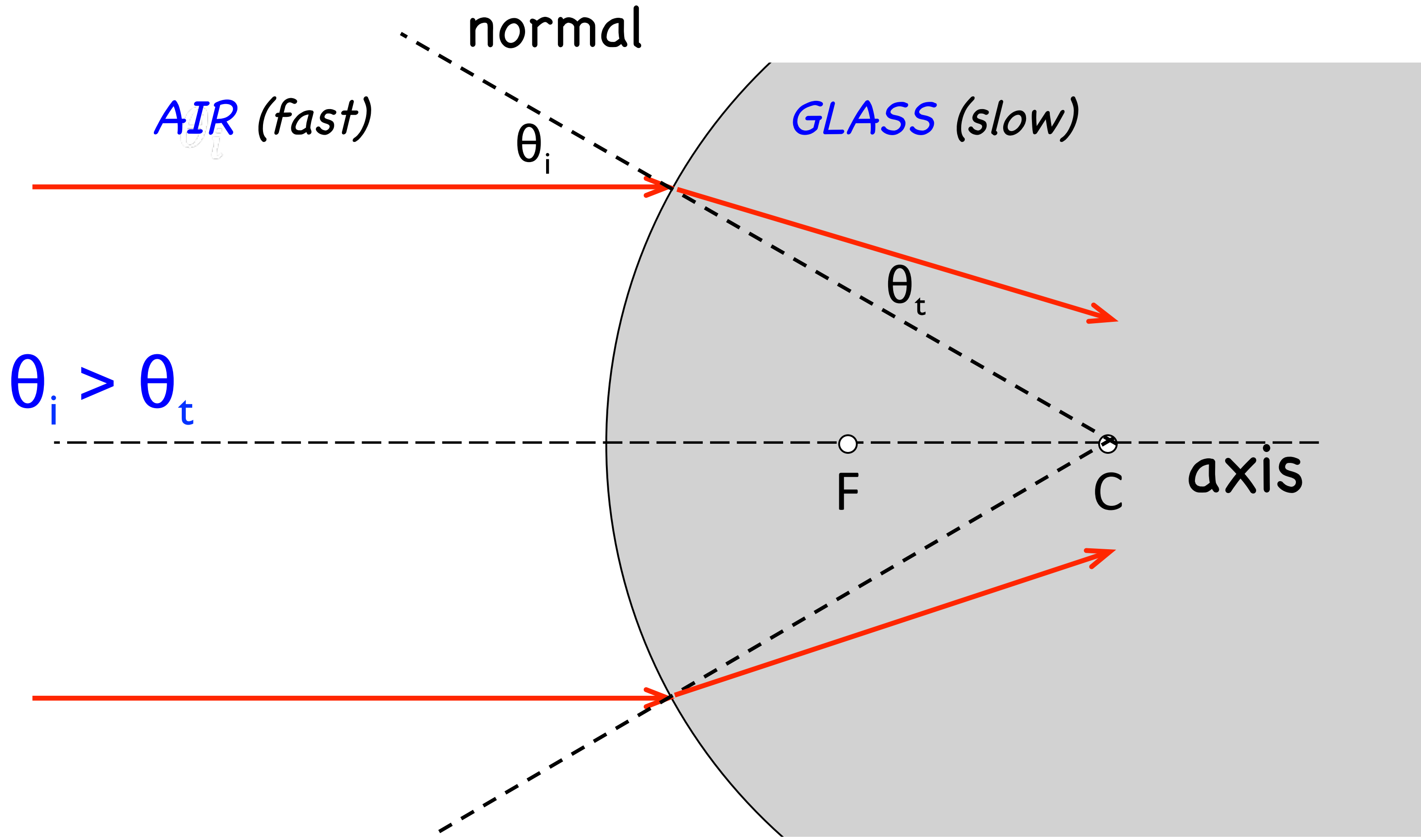
Refraction review



- rays bend *toward* normal when entering *slower* medium (larger n)
- *away* from normal when entering *faster* medium (smaller n)
- do not bend if enter perpendicularly

Convex glass surface refraction: *air to glass*

utilize refraction by shaping glass to focus light -> lens

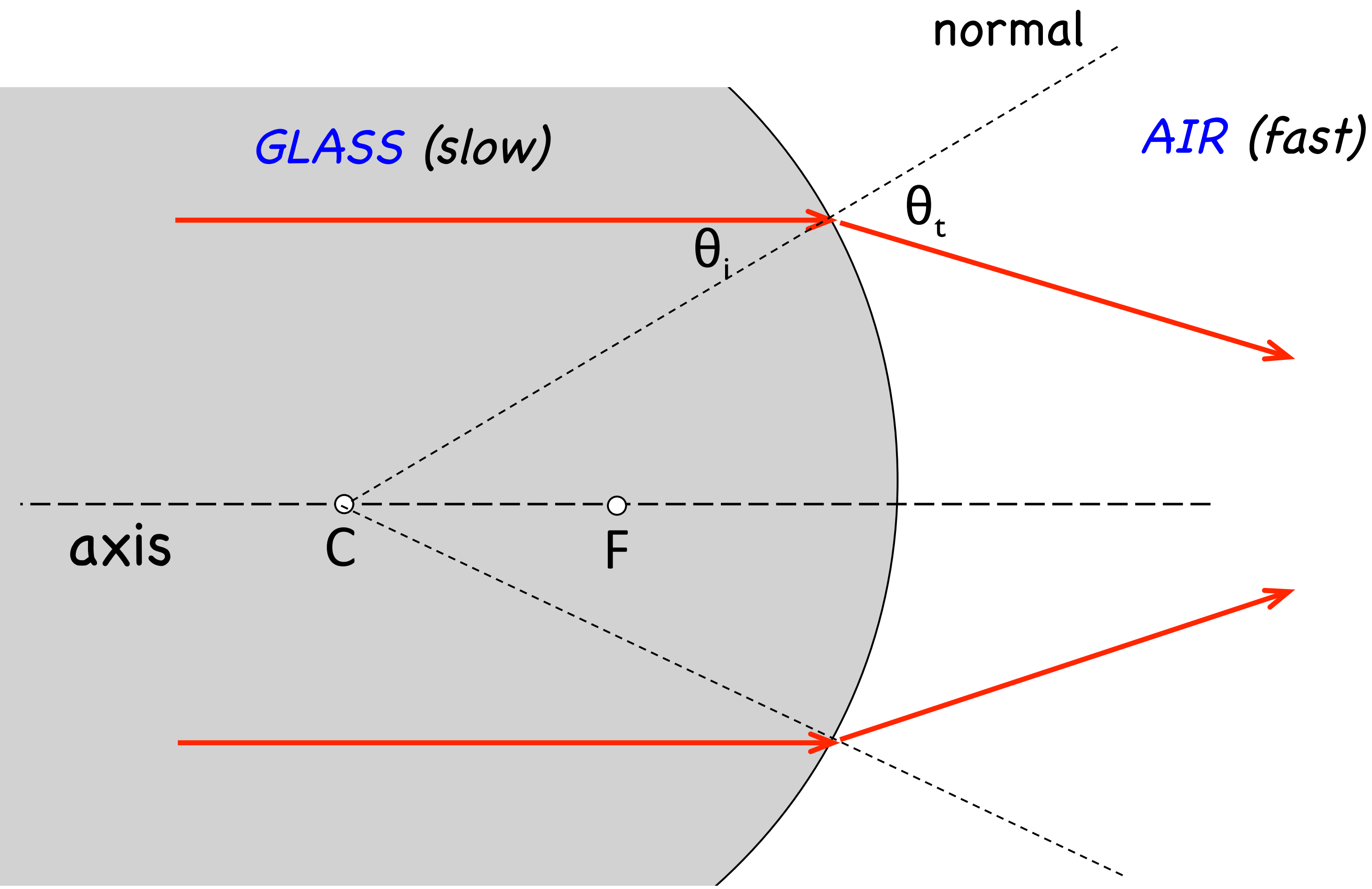


fast to slow bends towards the normal

A *convex* surface is called "*converging*" because parallel rays converge towards one another

Convex glass surface refraction: *glass to air*

utilize refraction by shaping glass to focus light -> lens



slow to fast bends away from the normal

$\theta_i < \theta_t$

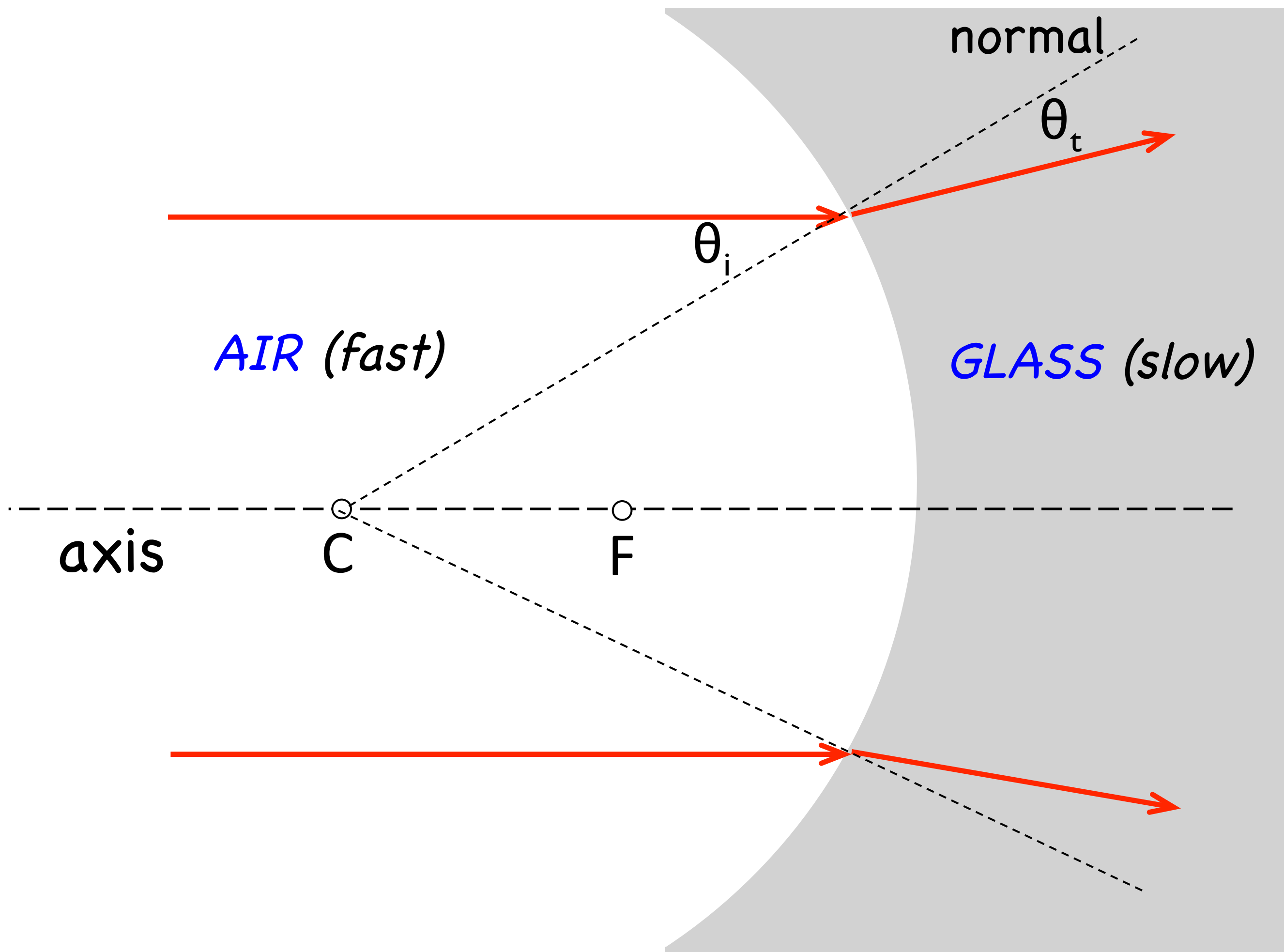
A *convex* surface is *converging* for both air to glass and glass to air rays

Concave glass surface refraction: *air to glass*

utilize refraction by shaping glass to focus light -> lens

fast to slow bends toward the normal

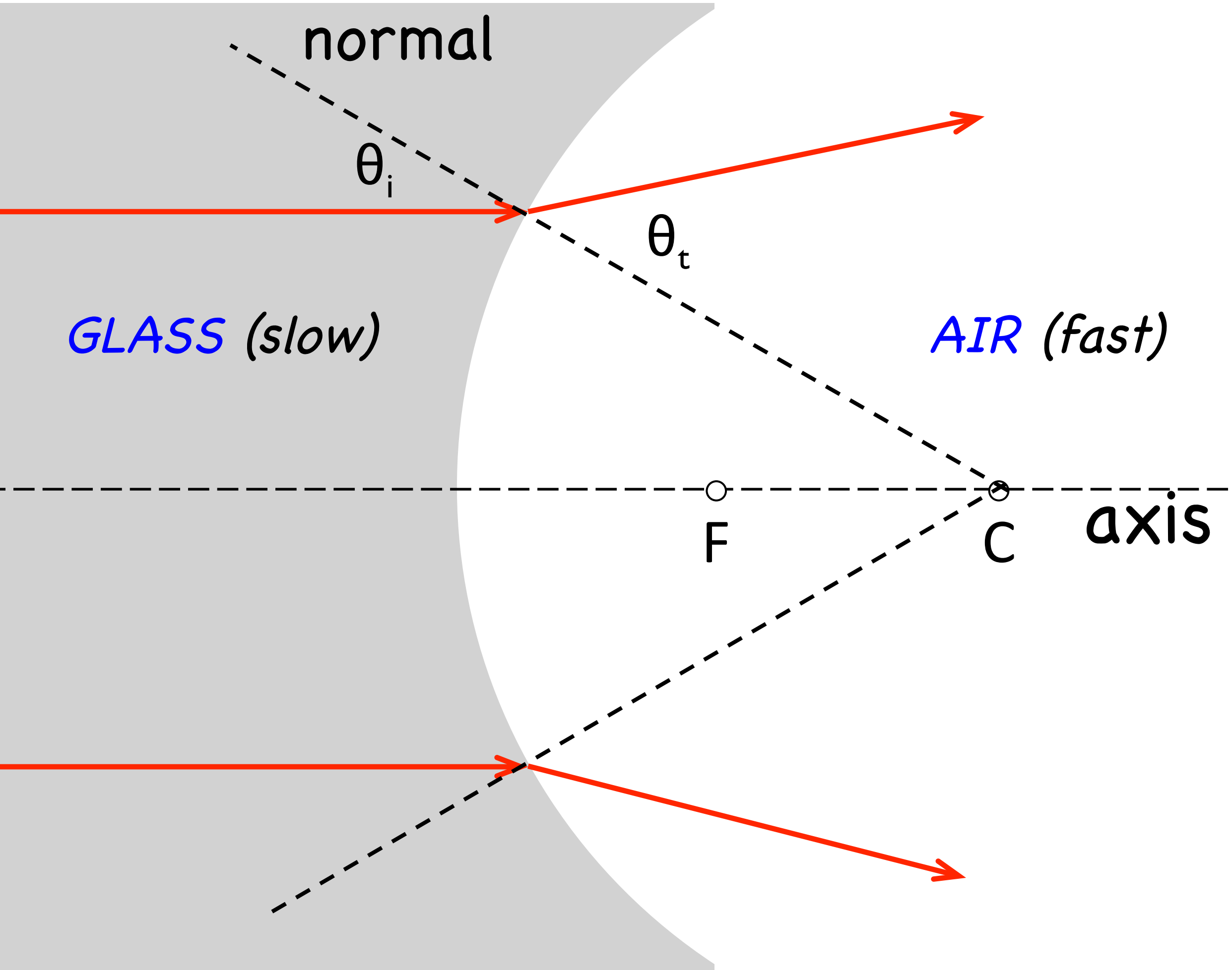
$\theta_i > \theta_t$



A *concave* surface is called "*diverging*" because parallel rays diverge away from one another

Concave glass surface refraction: *glass to air*

utilize refraction by shaping glass to focus light -> lens



slow to fast
bends away from
the normal

$\theta_i < \theta_t$

Again, the surface is divergent for both air to glass and glass to air rays

Concave and convex lenses

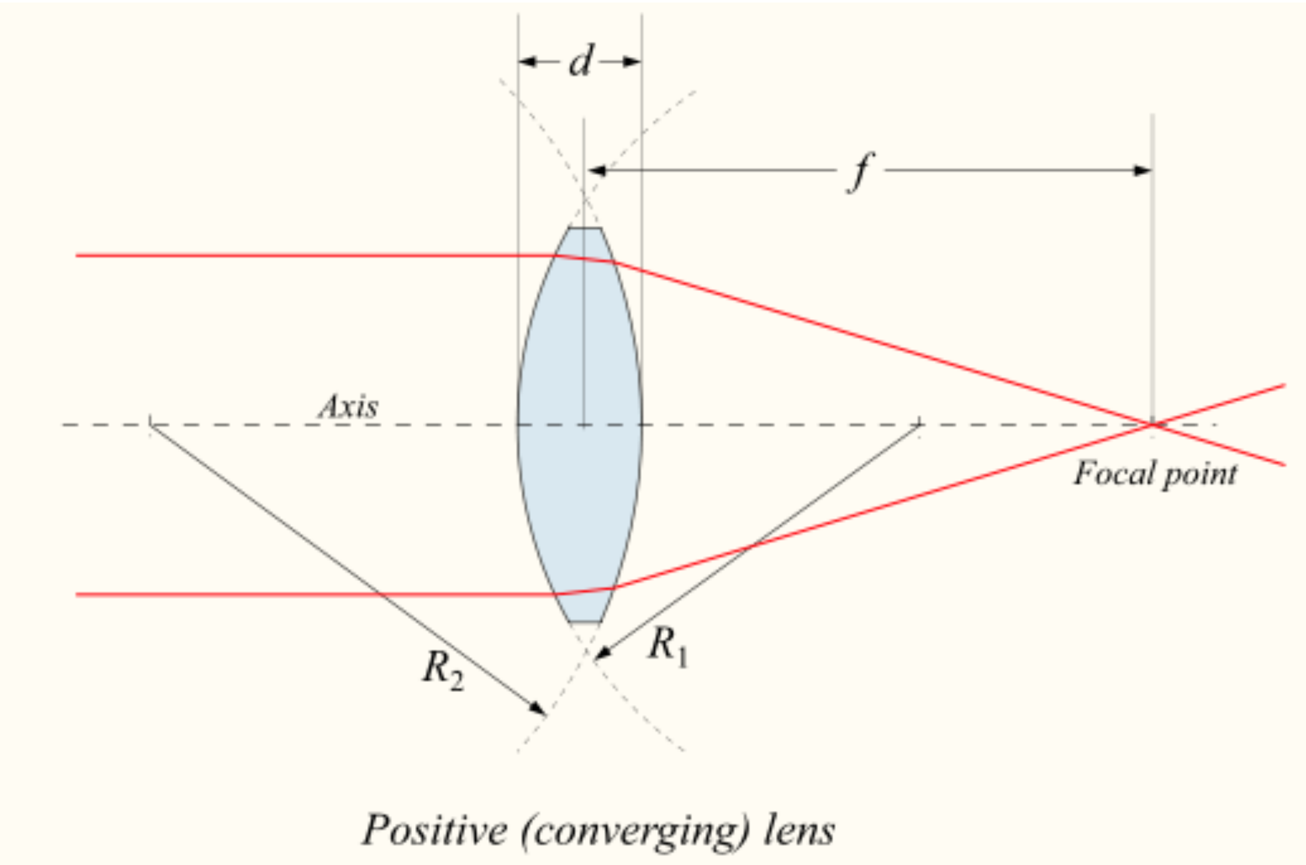
utilize refraction by shaping glass to focus light -> lens

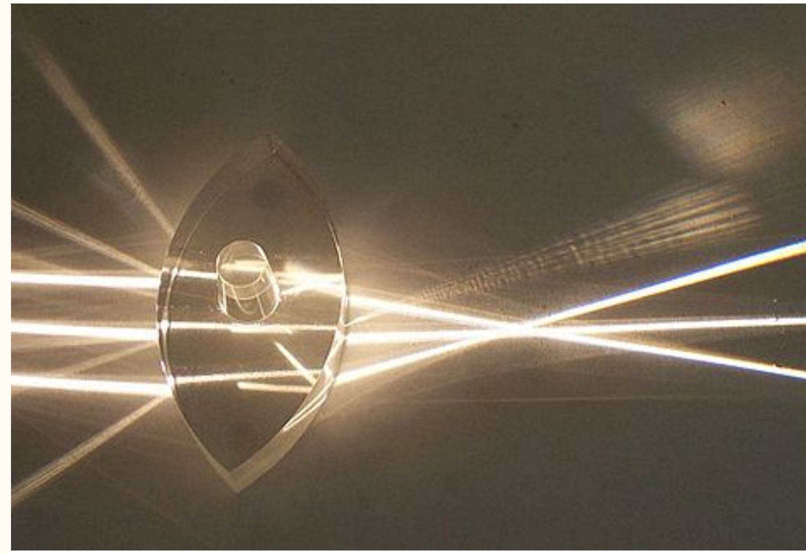
converging lens
"bi-convex"
has two convex surfaces

diverging lens
"bi-concave"
has two concave surfaces

Concave and convex lenses

utilize refraction by shaping glass to focus light -> lens

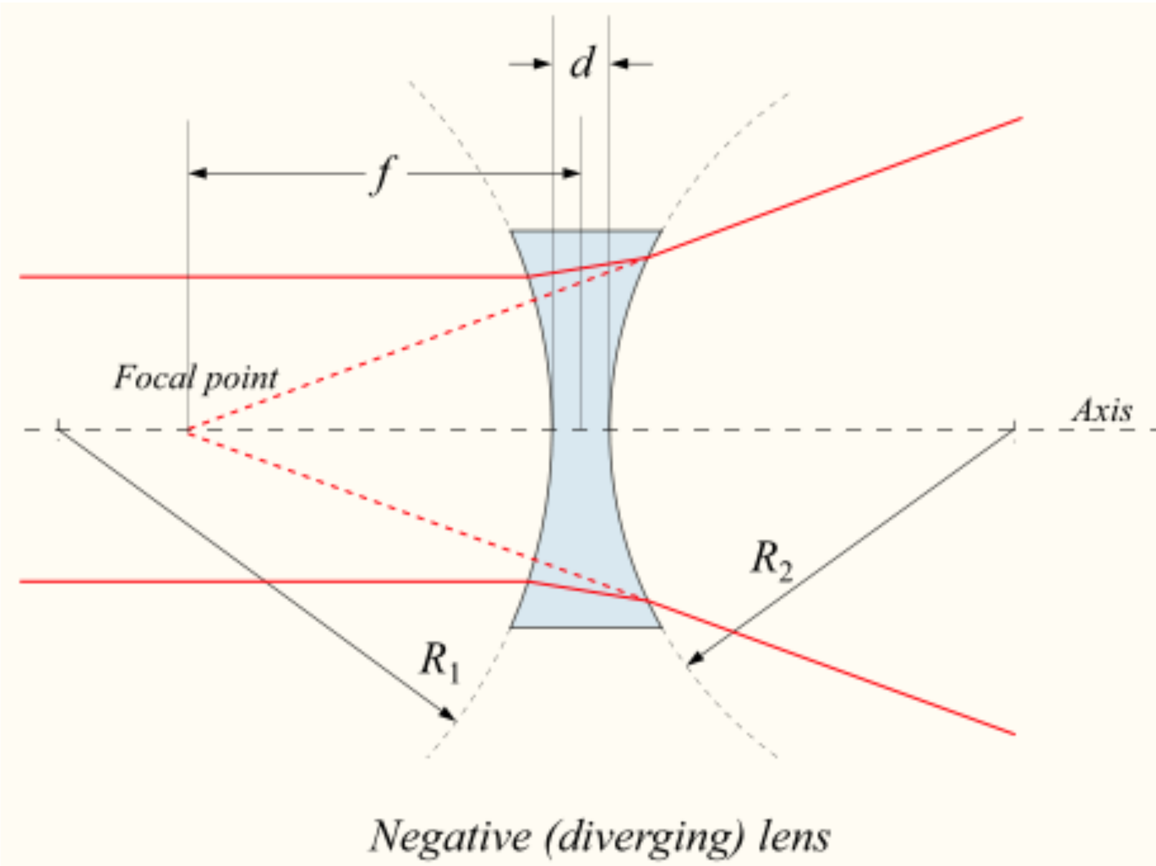


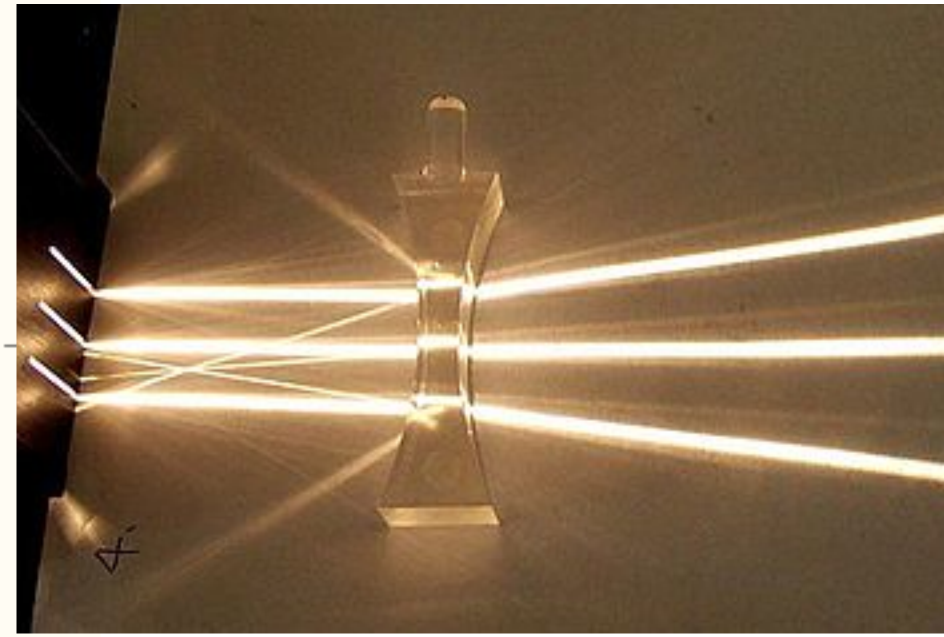


converging lens
"bi-convex"
has two convex surfaces

Concave and convex lenses

utilize refraction by shaping glass to focus light -> lens

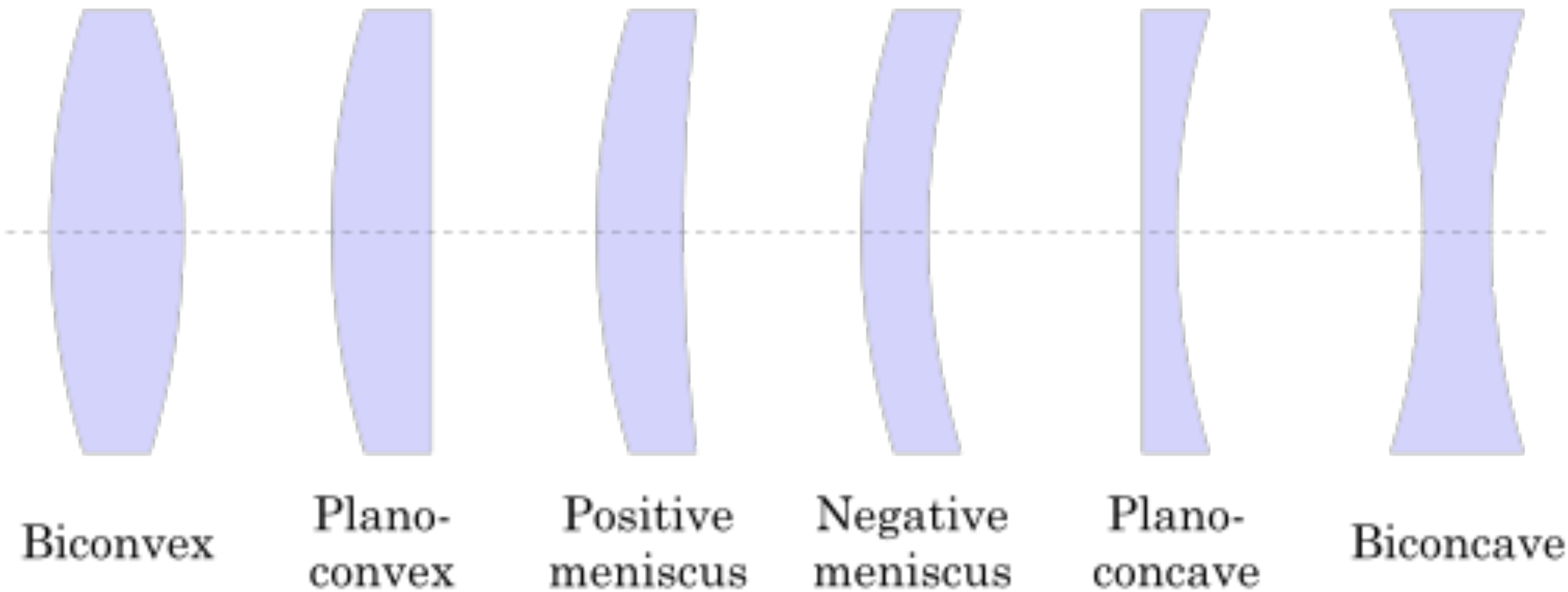




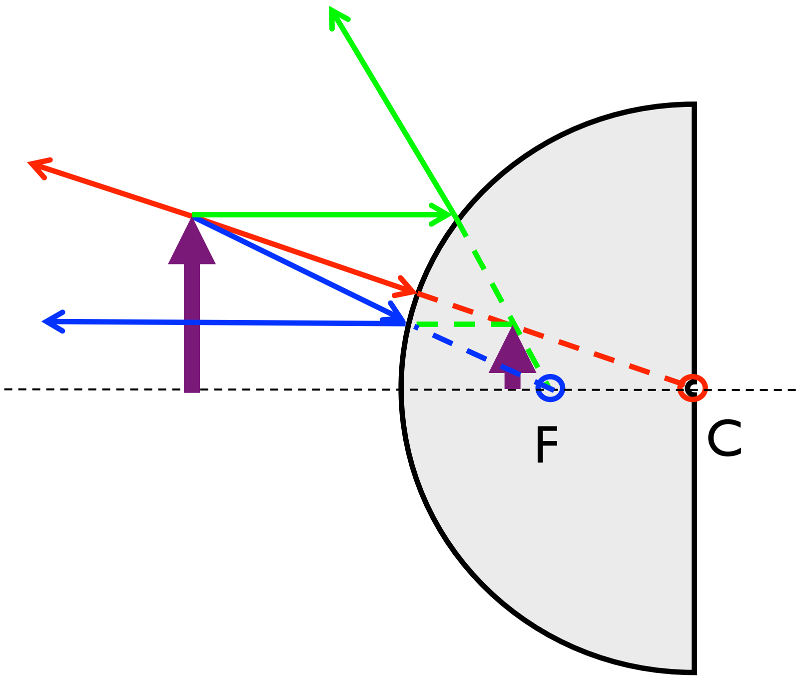
diverging lens
"bi-concave"
has two concave surfaces

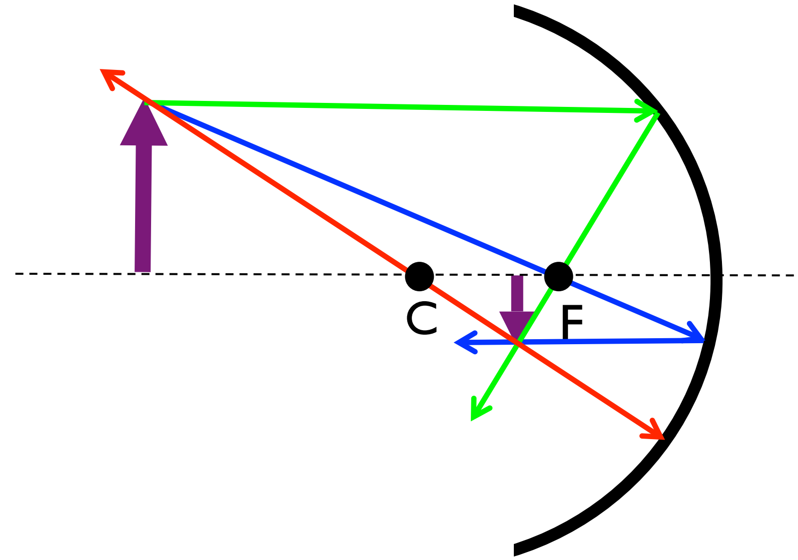
Variety of lenses

utilize refraction by shaping glass to focus light -> lens



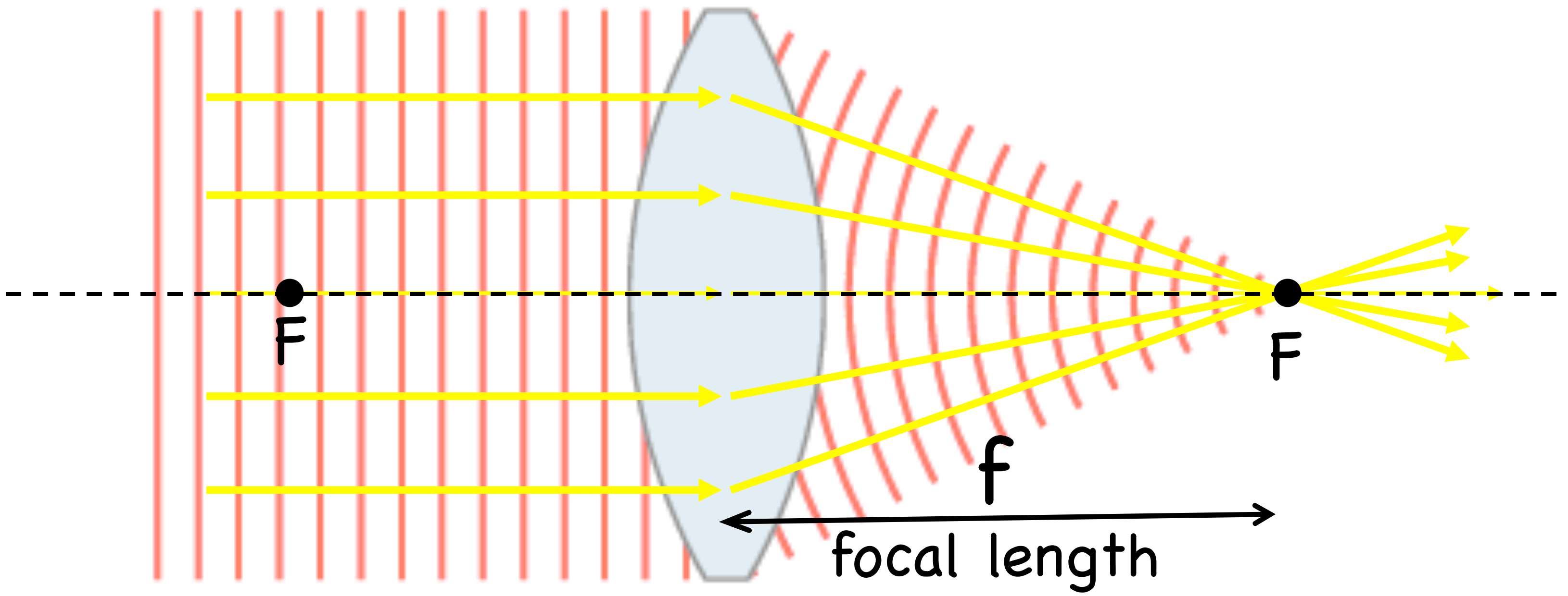
Compare to mirrors





Opposite of mirrors, where a convex surface is divergent and a concave surface is convergent

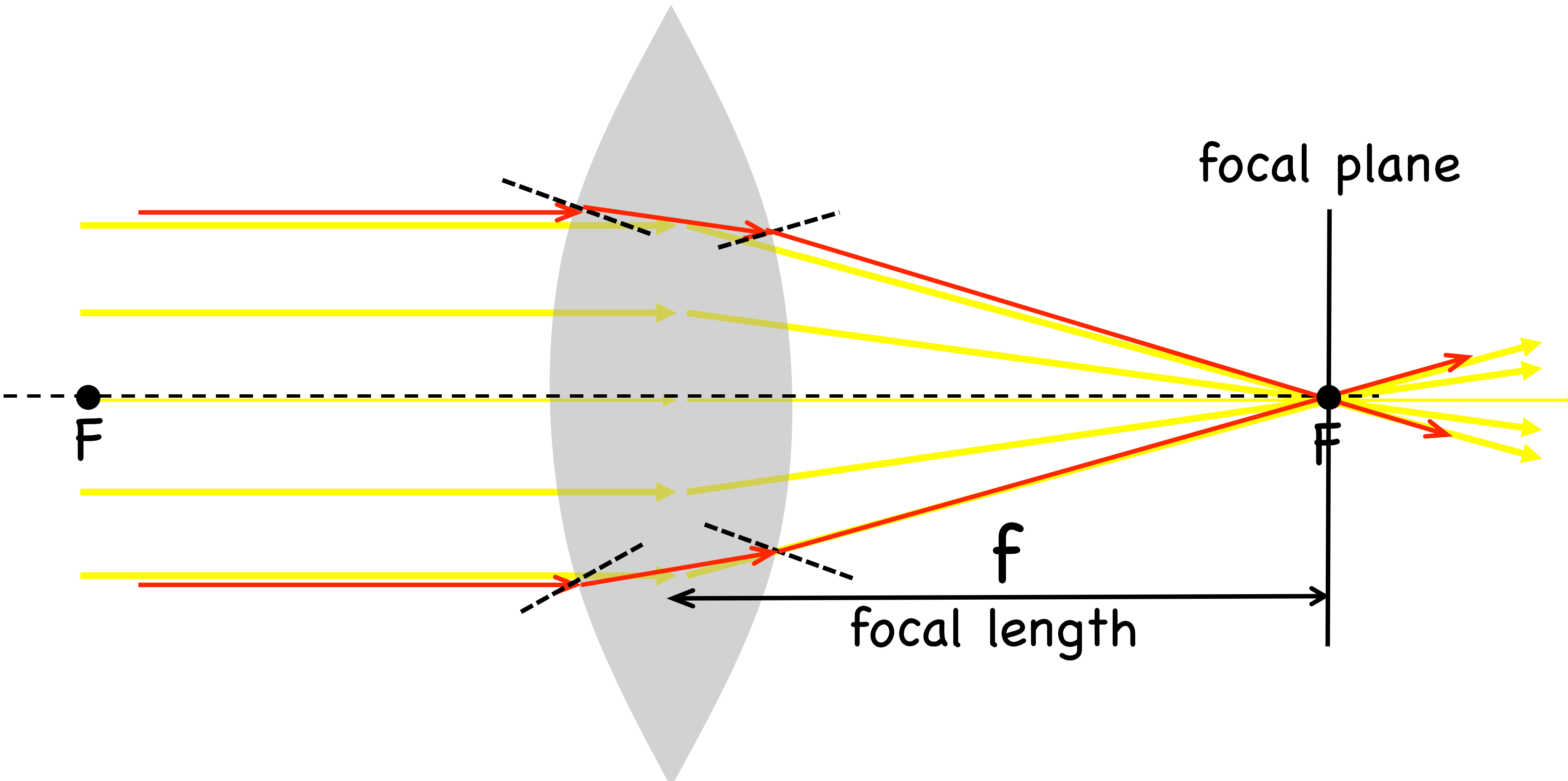
Converging lens



focal point F:

- is the image point of a distant star (as for curved mirror)
- is where all (parallel) rays from a distance star intersect
- exists on both sides of a lens

Converging lens



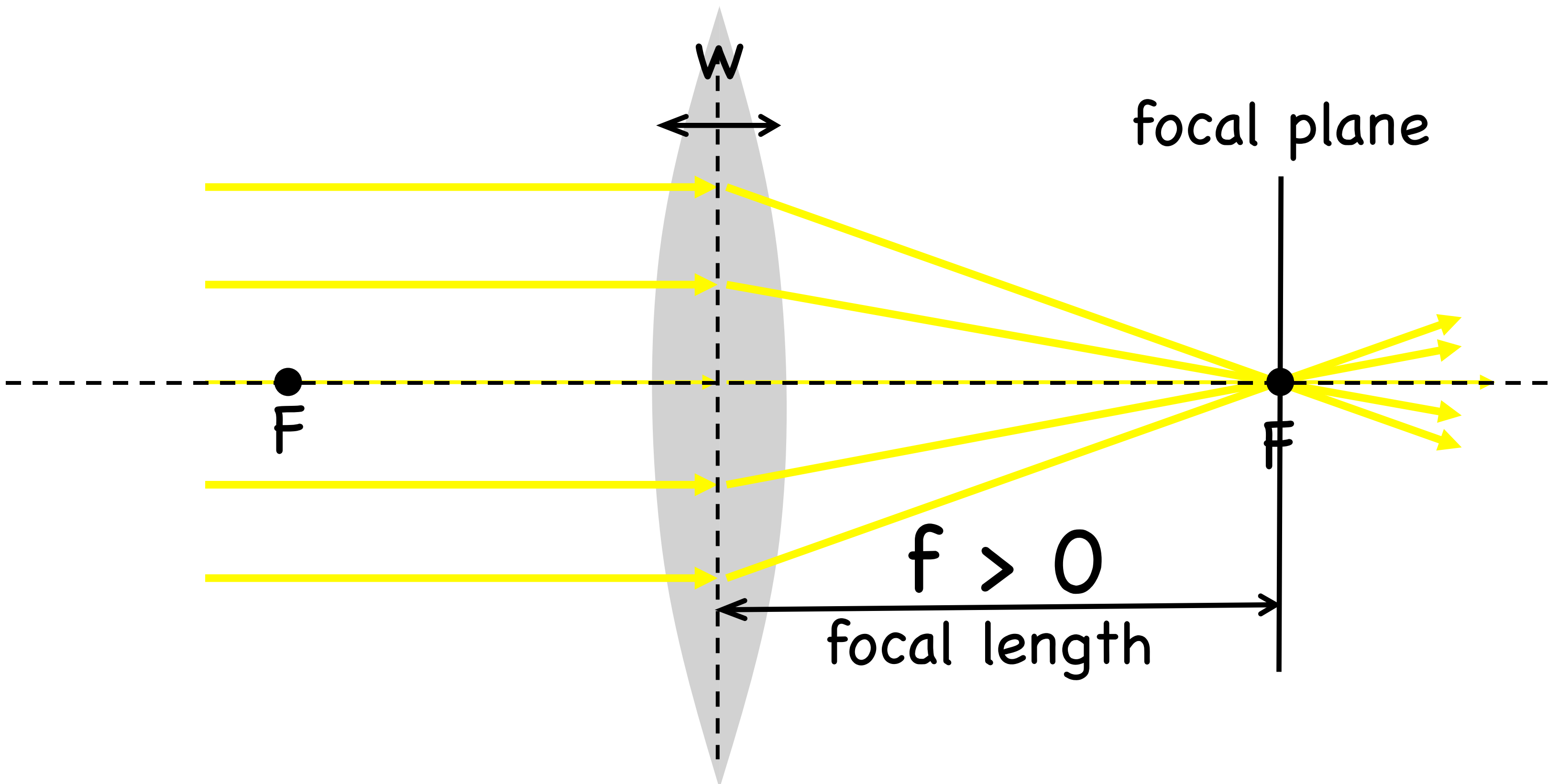
focal point F:

- is the image point of a distant star (as for curved mirror)
- is where all (parallel) rays from a distance star intersect
- exists on both sides of a lens

Converging *thin* lens

Ray tracing is accurate only for thin lenses, width w much smaller than the focal length f (cf mirrors)

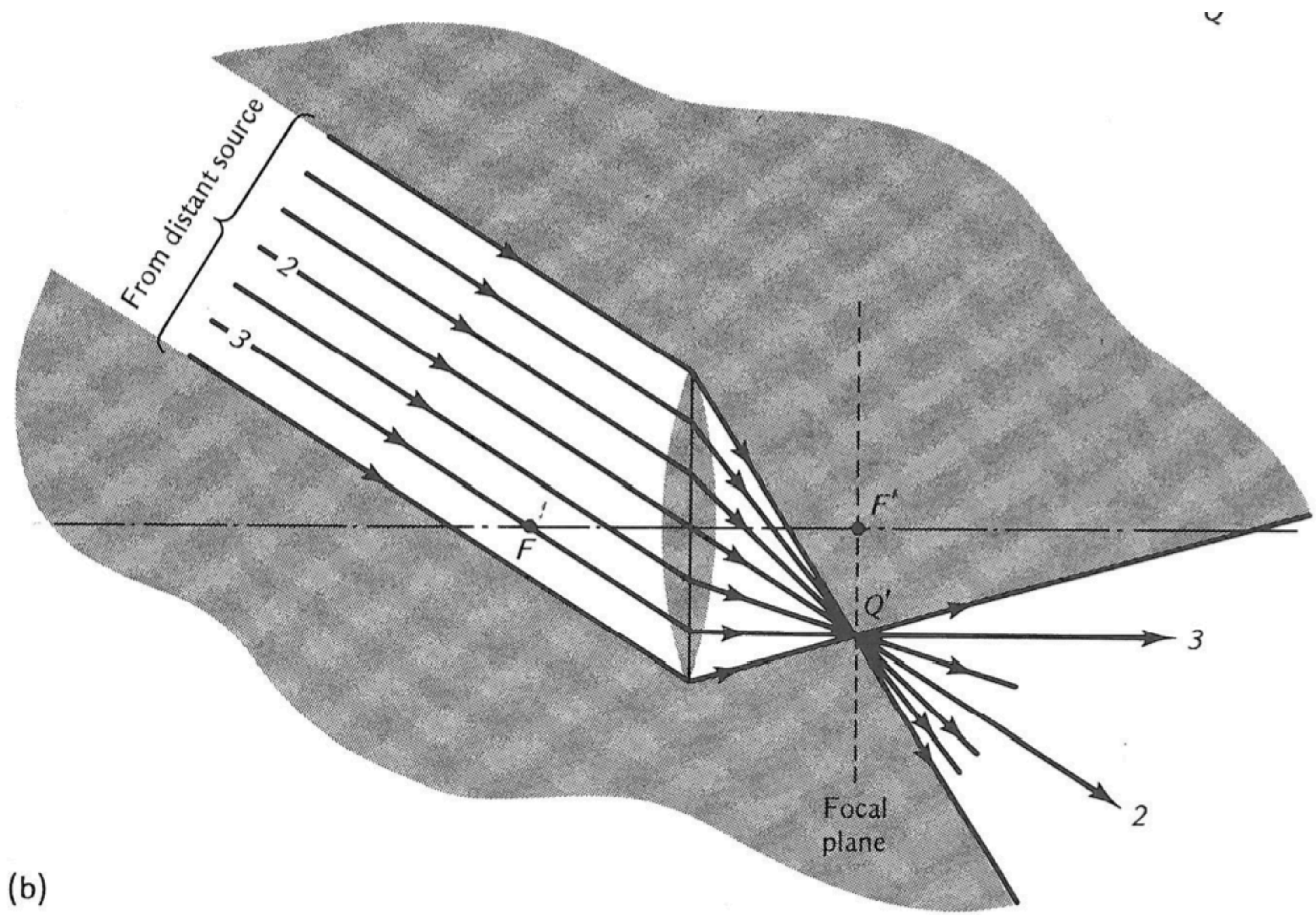
-> all of refractive focusing can be taken to take place at lens' midplane



focal point F:

- is the image point of a distant star (as for curved mirror)
- is where all (parallel) rays from a distance star intersect
- exists on both sides of a lens

View of an image

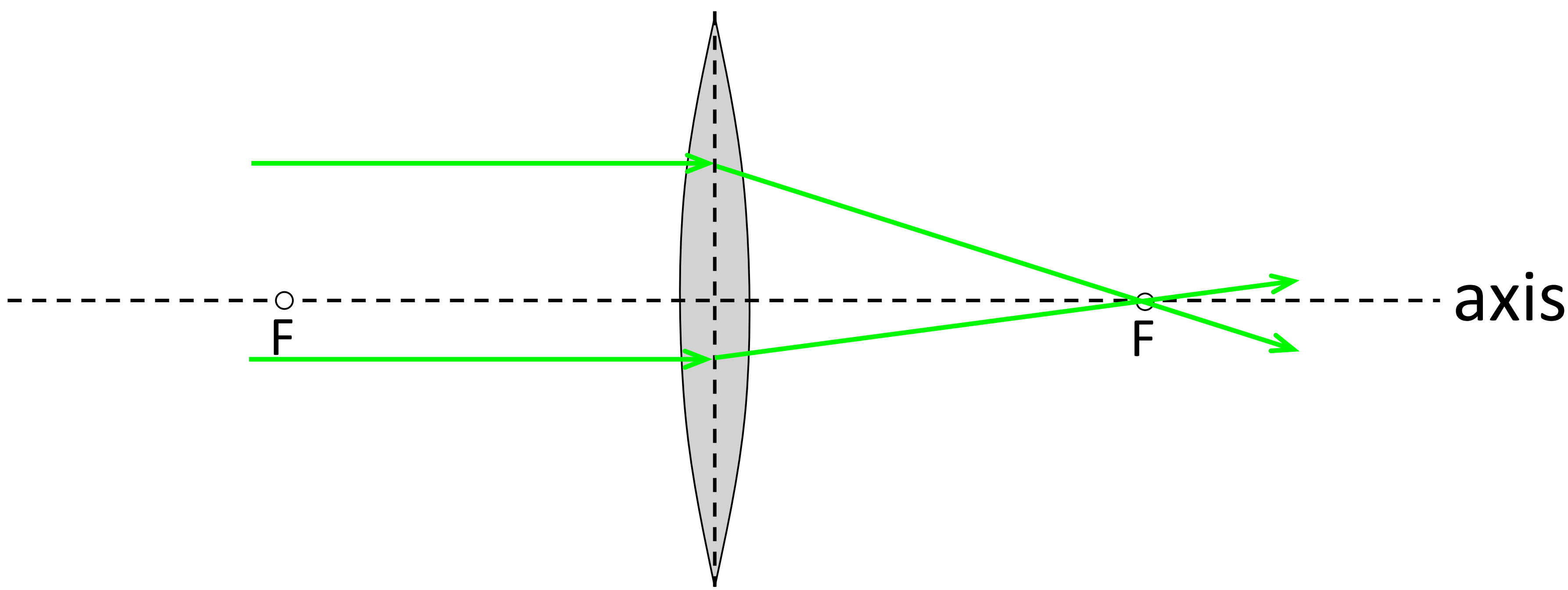


Parallel rays from a distance source (e.g. star) all focus at a focal point; the distance object is imaged in the focal plane, as in magnifying glass focusing (imaging) the sun onto a leaf to burn it

Special rays: converging lens

Rule 1:

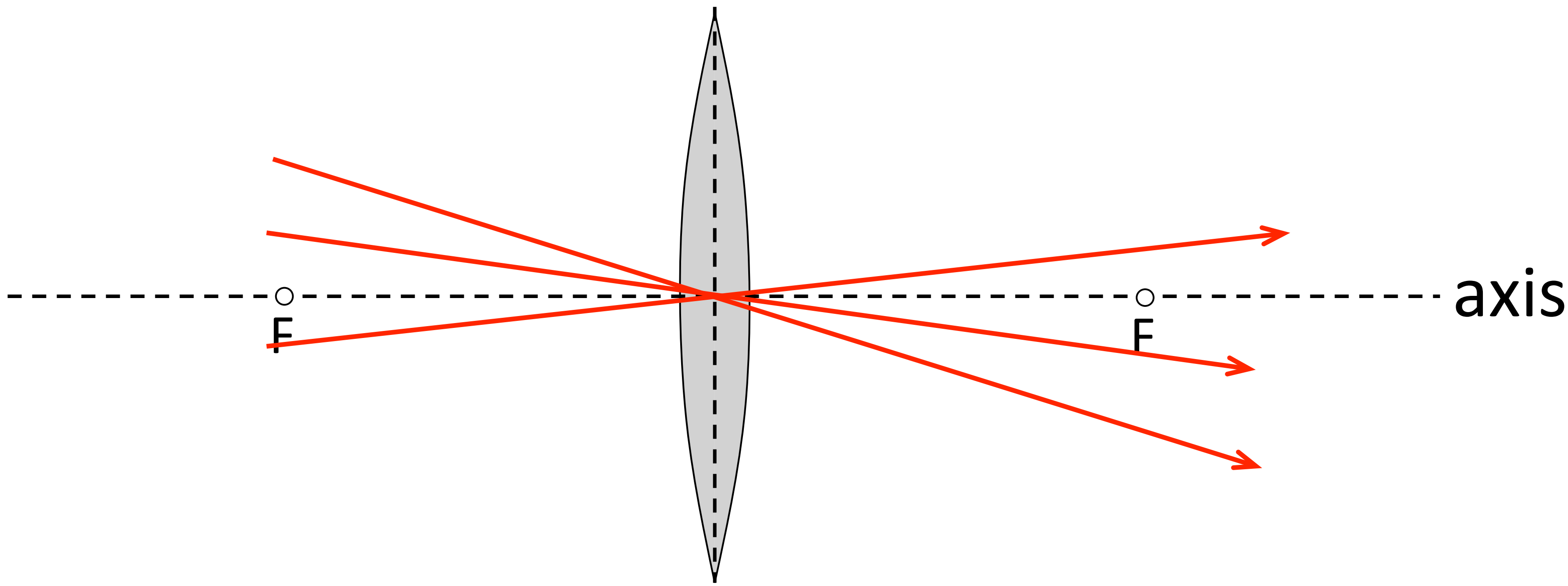
All rays incident parallel to the axis are deflected (focused) through the focal point, F.



Special rays: converging lens

Rule 2:

All rays passing through the center of the lens are undeflected, continuing straight through without being bent



Special rays: converging lens

Rule 3:

All rays passing through the focal point, F are deflected to exit parallel to the axis (reverse of rule 1)

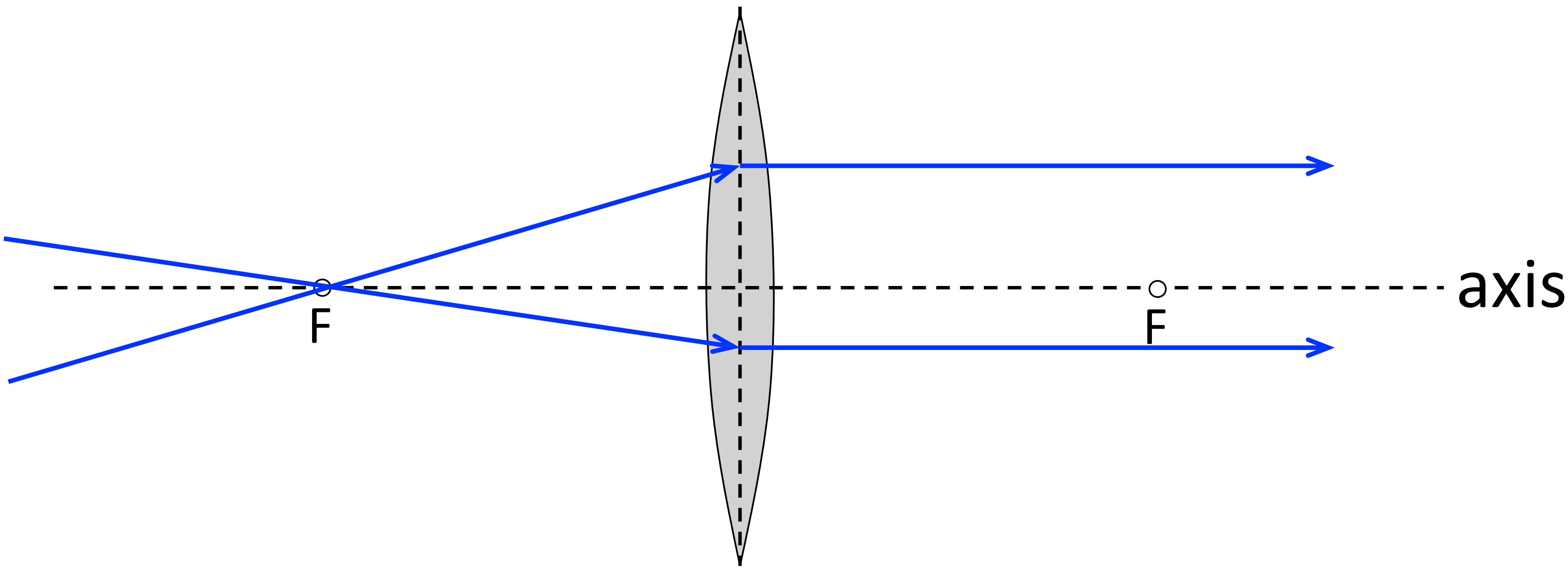
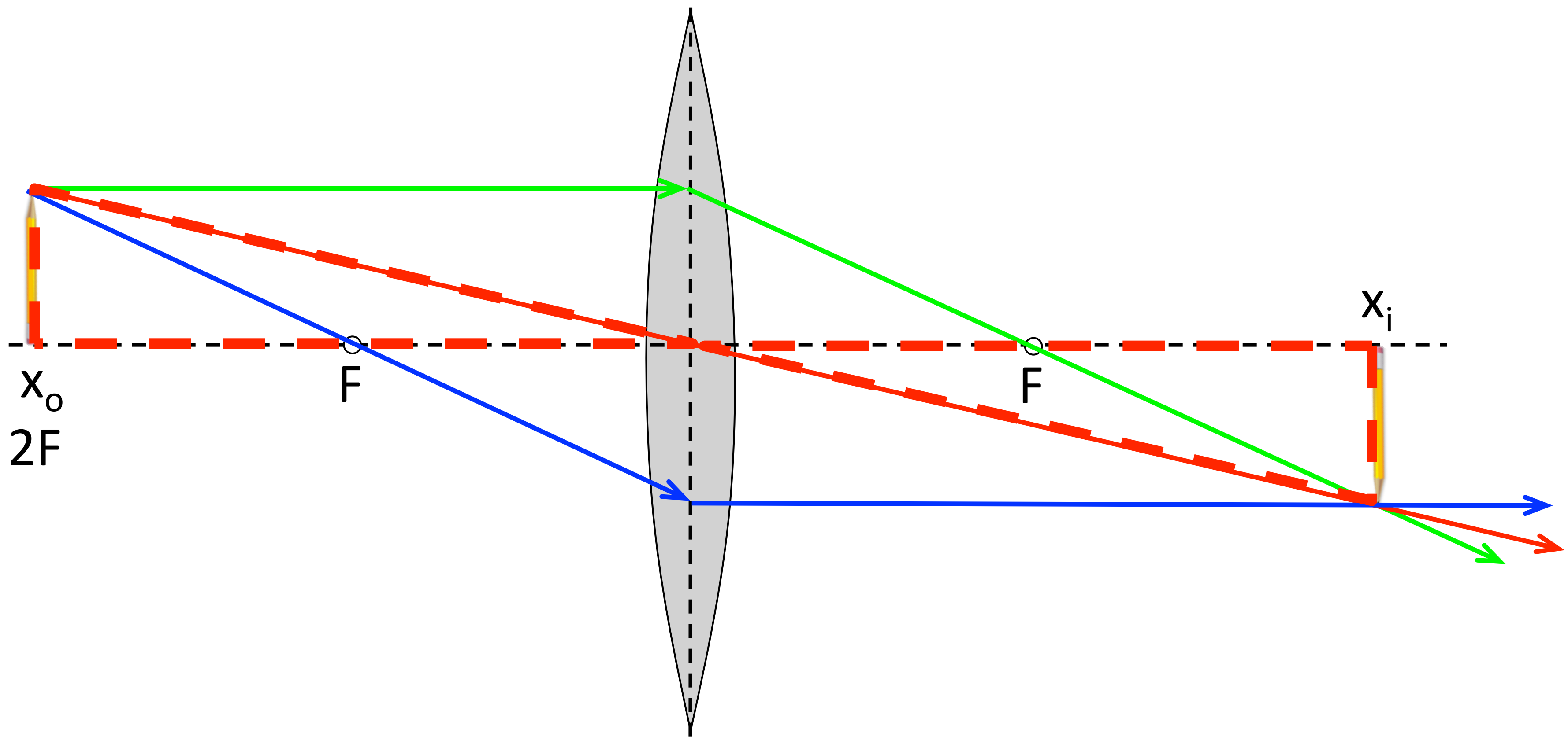


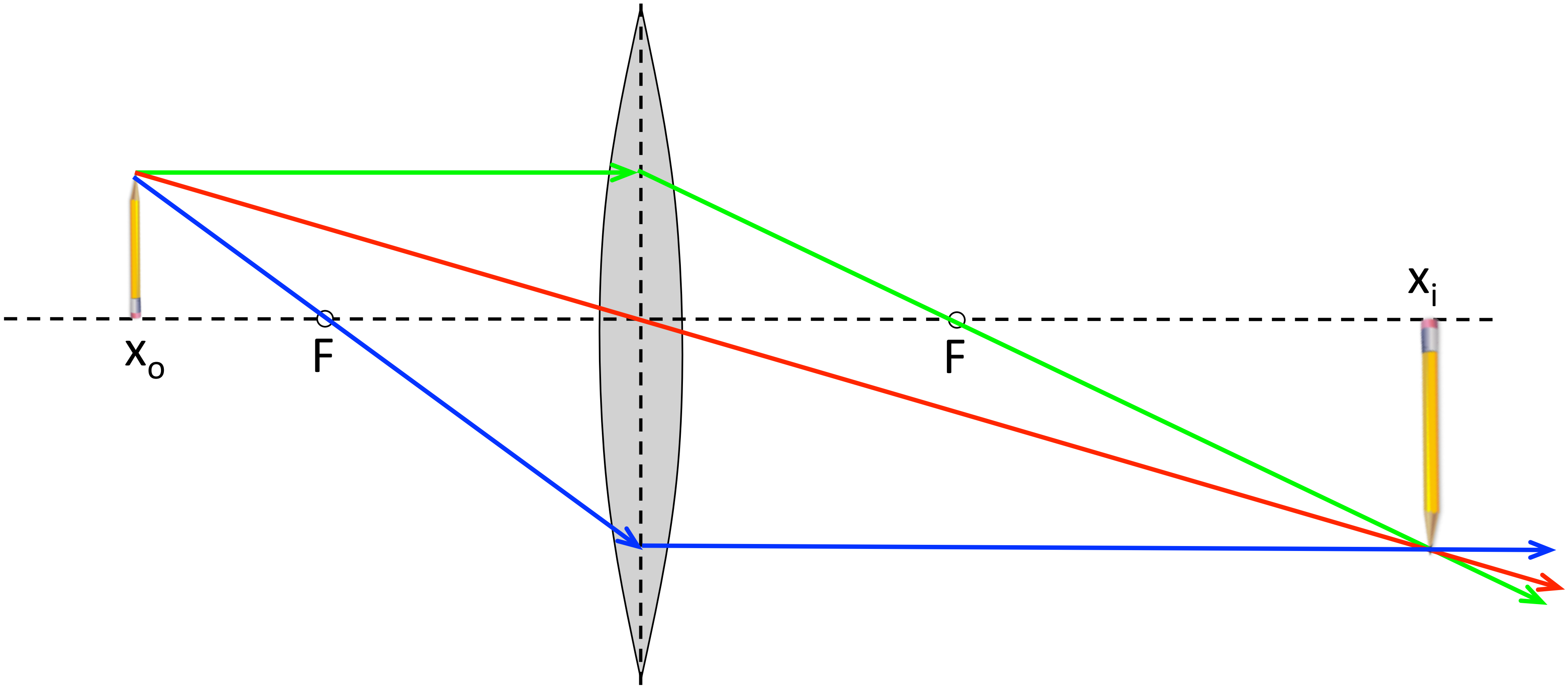
Image formation: converging lens



$x_o = 2f$ (camera image on film):

The image is *real*, *inverted* and of the *same size* as the object. More generally this will depend on the position of the object x_o relative to the focal point F of the lens. As x_o moves out to > 2f, image becomes smaller.

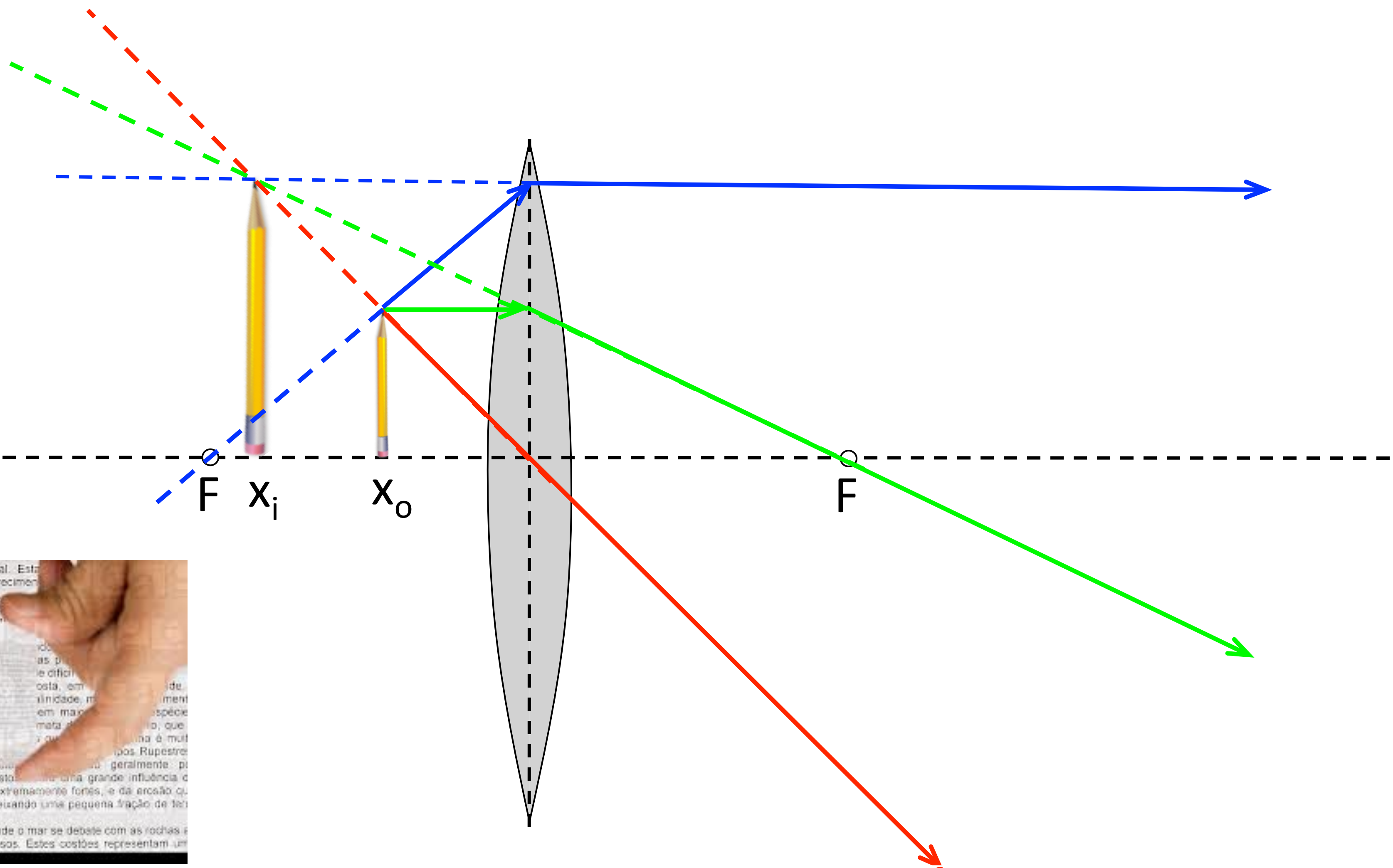
Image formation: converging lens



$f < x_o < 2f$ (overhead projector image on screen):

The image is *real*, *inverted* but is *larger* than the object. More generally this will depend on the position of the object x_o relative to the focal point F of the lens.

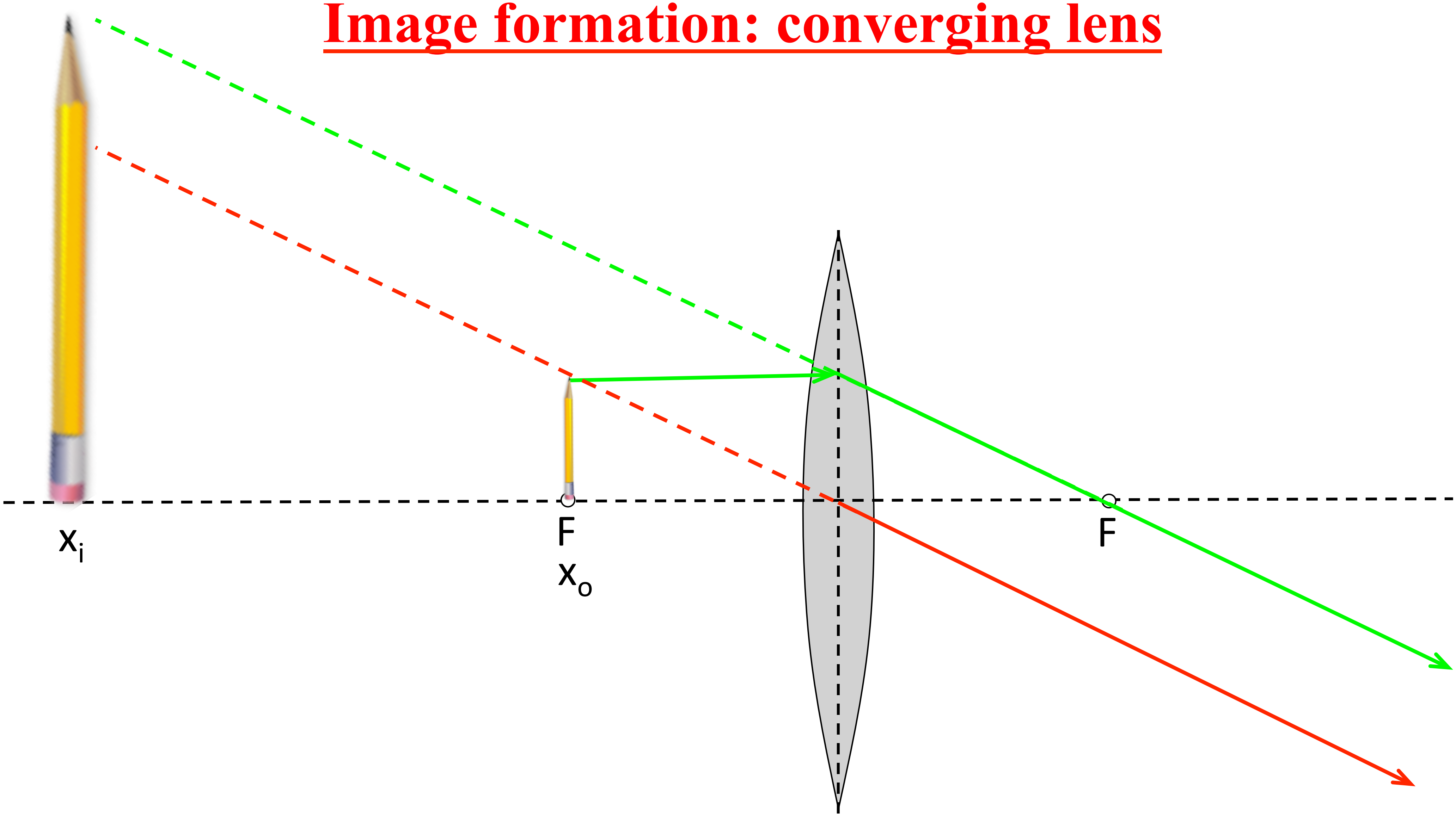
Image formation: converging lens



$x_o < f$ (magnifying glass image):

The image is *virtual*, *right side up,* and is *larger* than the object. More generally this will depend on the position of the object x_o relative to the focal point F of the lens.

Image formation: converging lens



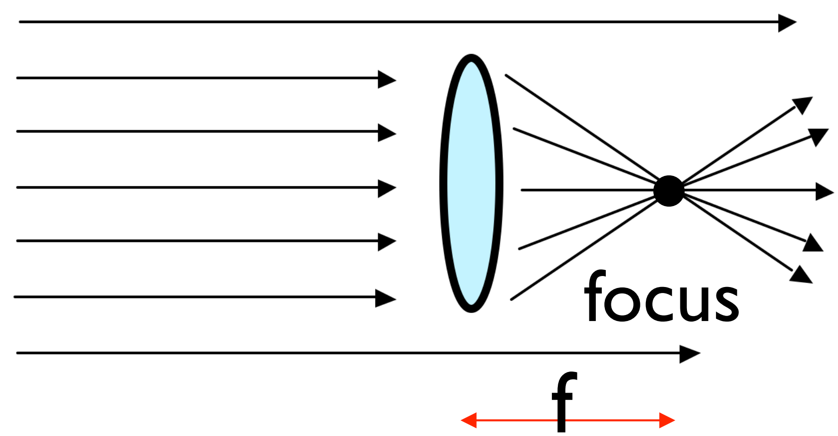
$x_o = f$ (magnifying glass image focused at infinity):

The image is *virtual*, *right side up,* and is *larger* moves out to infinity

clicker question

Focal length and index of refraction

Q: A converging lens has a focal length f=20cm when it is in air. The lens is made with index of refraction $n_{glass} = 1.6$. When the lens is placed in water ($n_{water} = 1.33$), the focal length of the lens is:



(a) unchanged
(b) longer, f > 20 cm
(c) shorter, f < 20 cm

clicker question

Focal length and index of refraction

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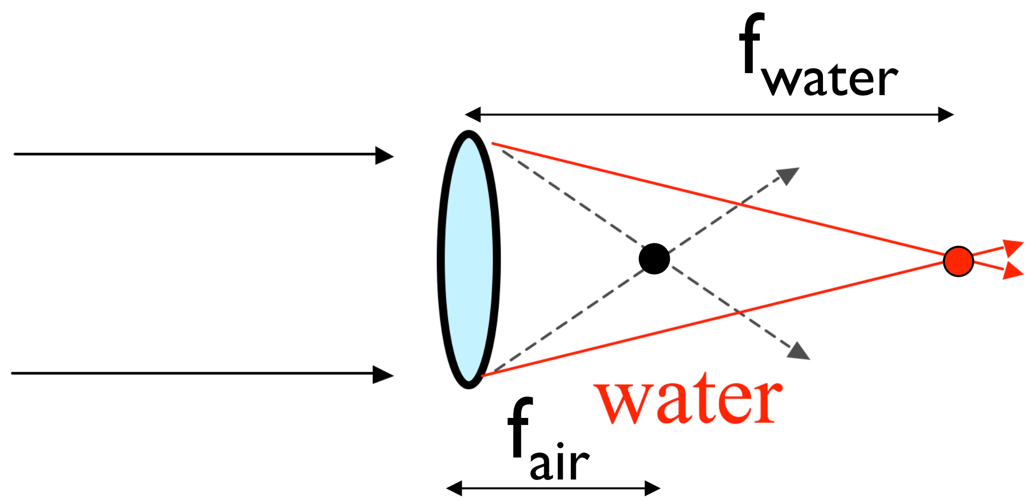
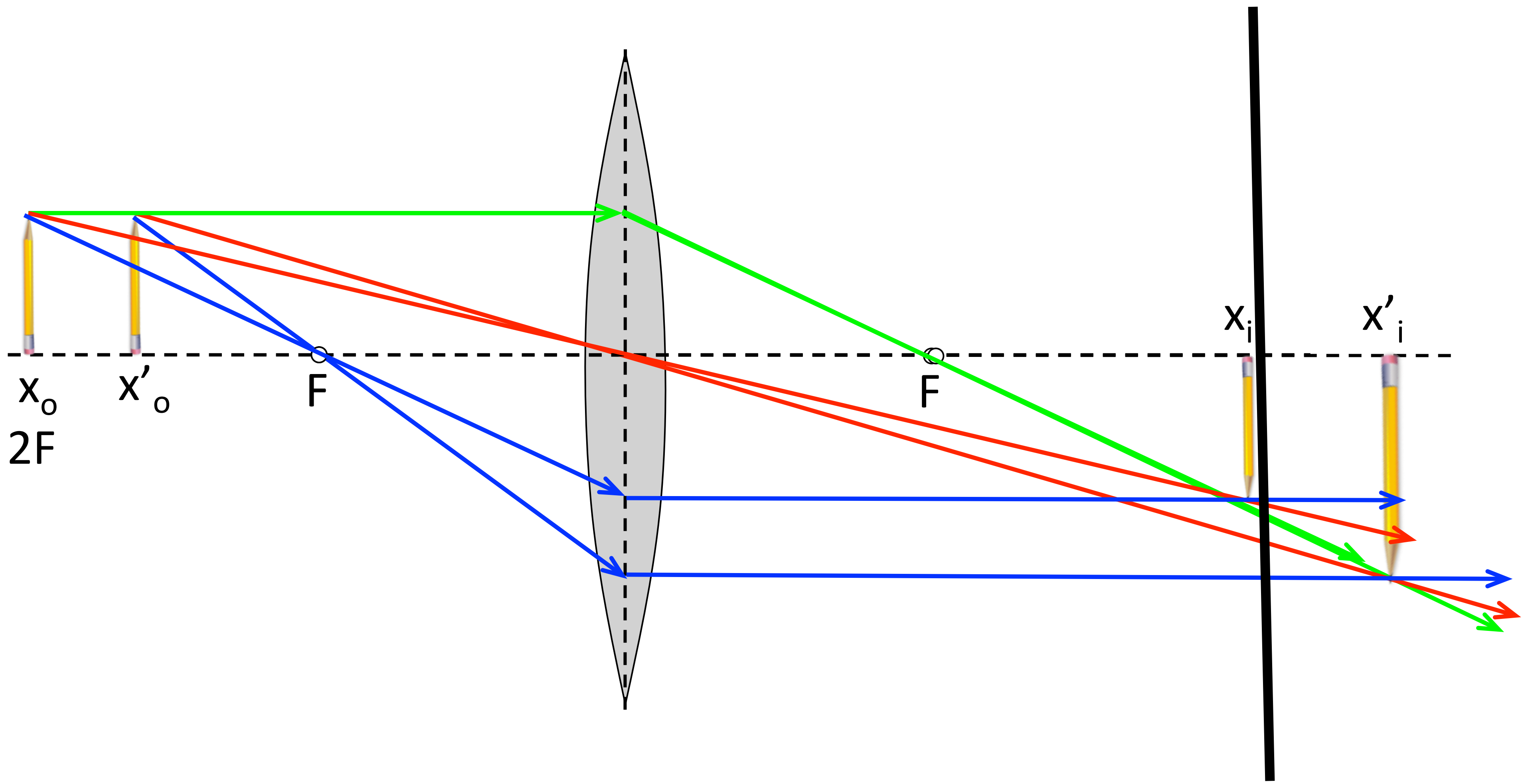


(a) unchanged
(b) longer, f > 20 cm
(c) shorter, f < 20 cm

n (glass) = 1.5
n (air) = 1.0
n (water) = 1.3

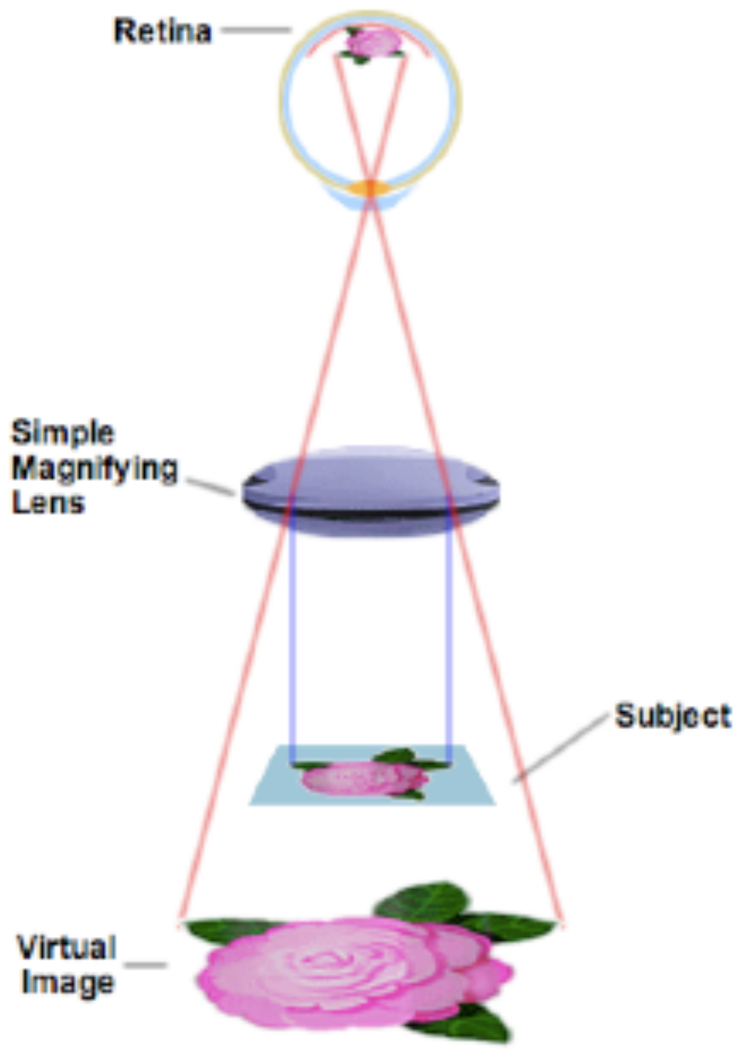
Refraction and therefore ray focusing increases with contrast (difference) of indices of refraction

Image formation: converging lens



Two objects -> two images. Image in focus depends on where you put the screen. Screen at x_i smaller image is sharp while larger image is blurry (since its rays are not focused there)

Magnifying glass applet



http://micro.magnet.fsu.edu/primer/java/lenses/simplemagnification/index.html

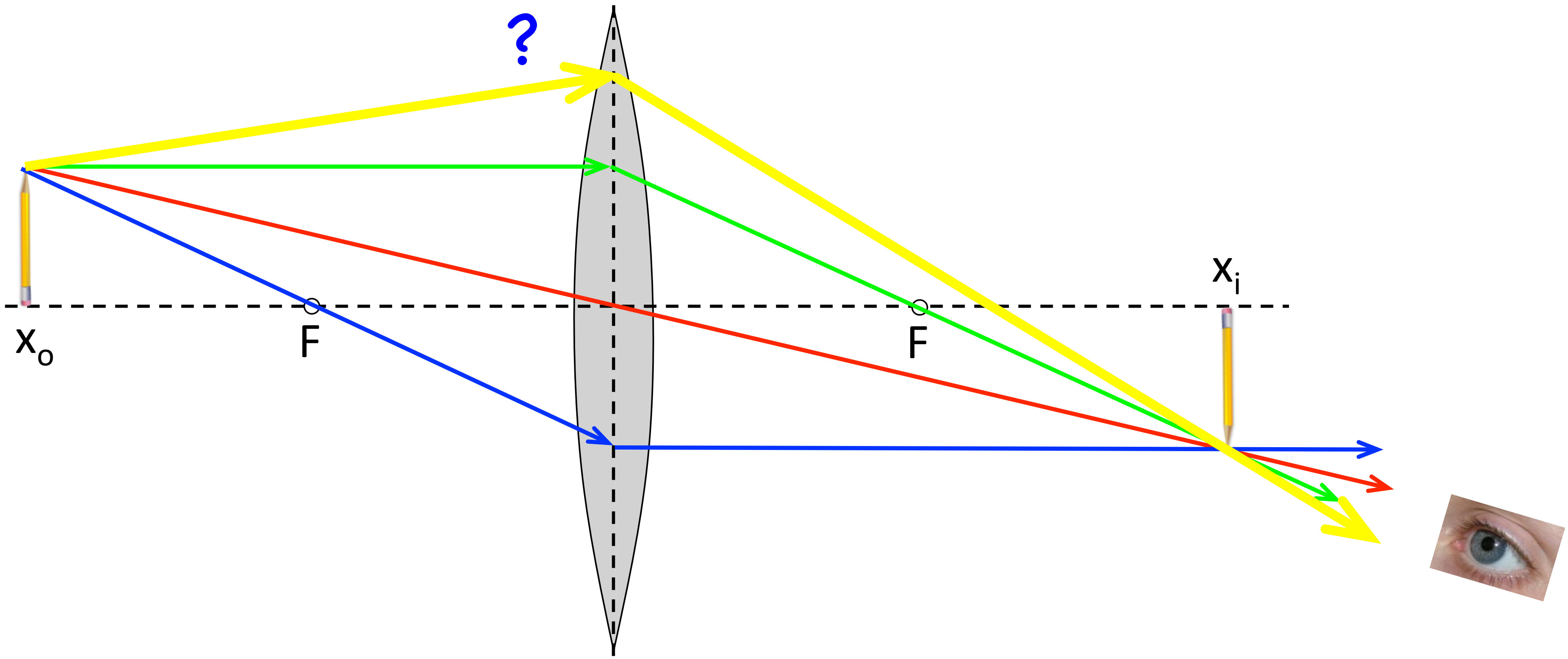
Image formation: converging lens

http://en.wikipedia.org/wiki/File:ThinLens.gif

- $x_o > 2f$: real, inverted, smaller -> camera image on film
- $2f > x_o > f$: real, inverted, larger -> overhead projector
- $x_o < f$: virtual, right side, larger -> magnifying glass

Ray tracing

Where will this ray go?

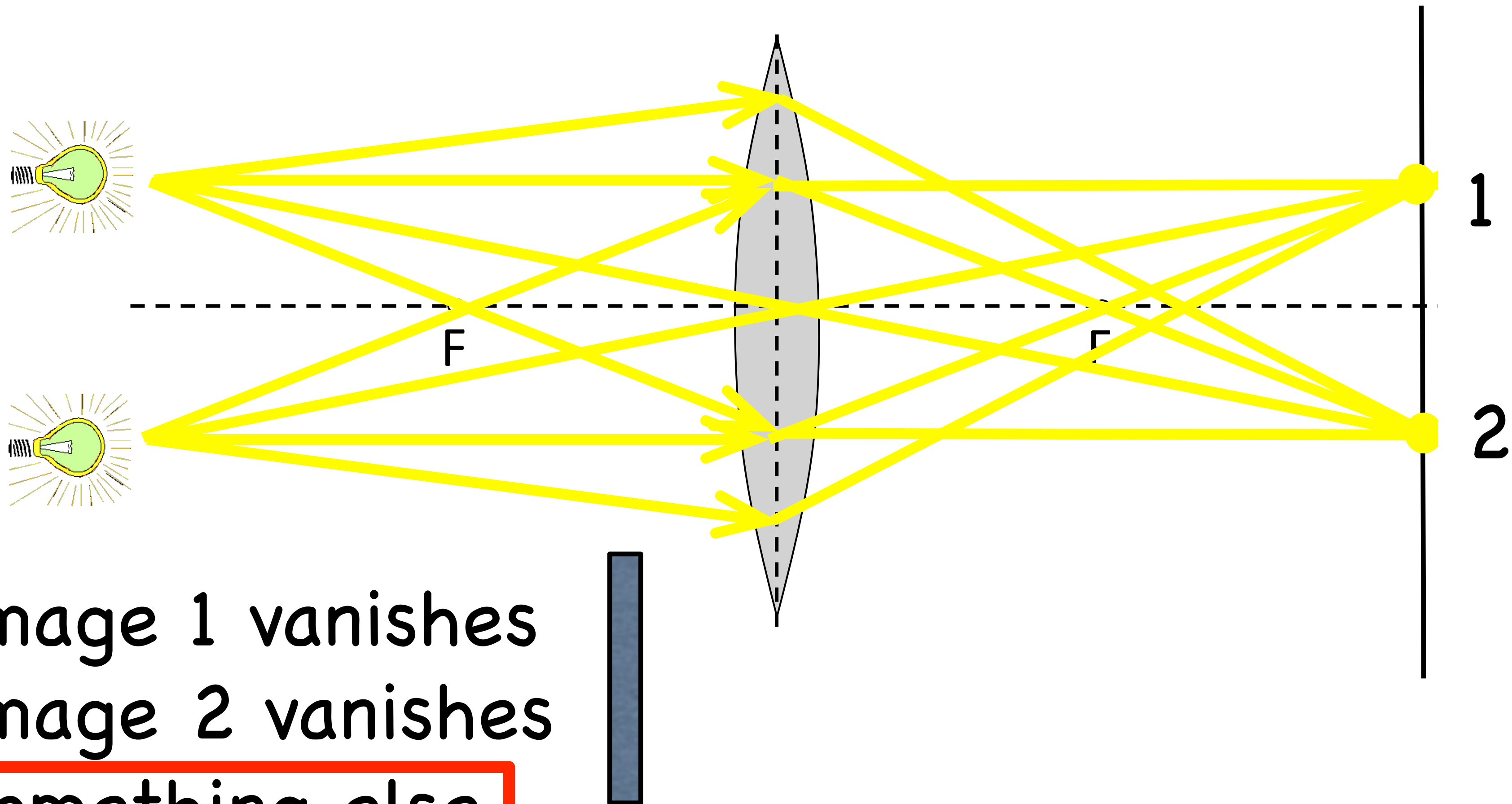


- suppose it is emitted from an object
- draw in three special rays whose tracing is simple, you know where they go
- all rays from an object will converge to the same point
- eye sees all the rays emerge from the point at x_i interprets as image

clicker question

Lens imaging

Q: Two point sources of light are imaged onto a screen by a converging lens. You slide a mask over the left half of the lens. What happens to the image?



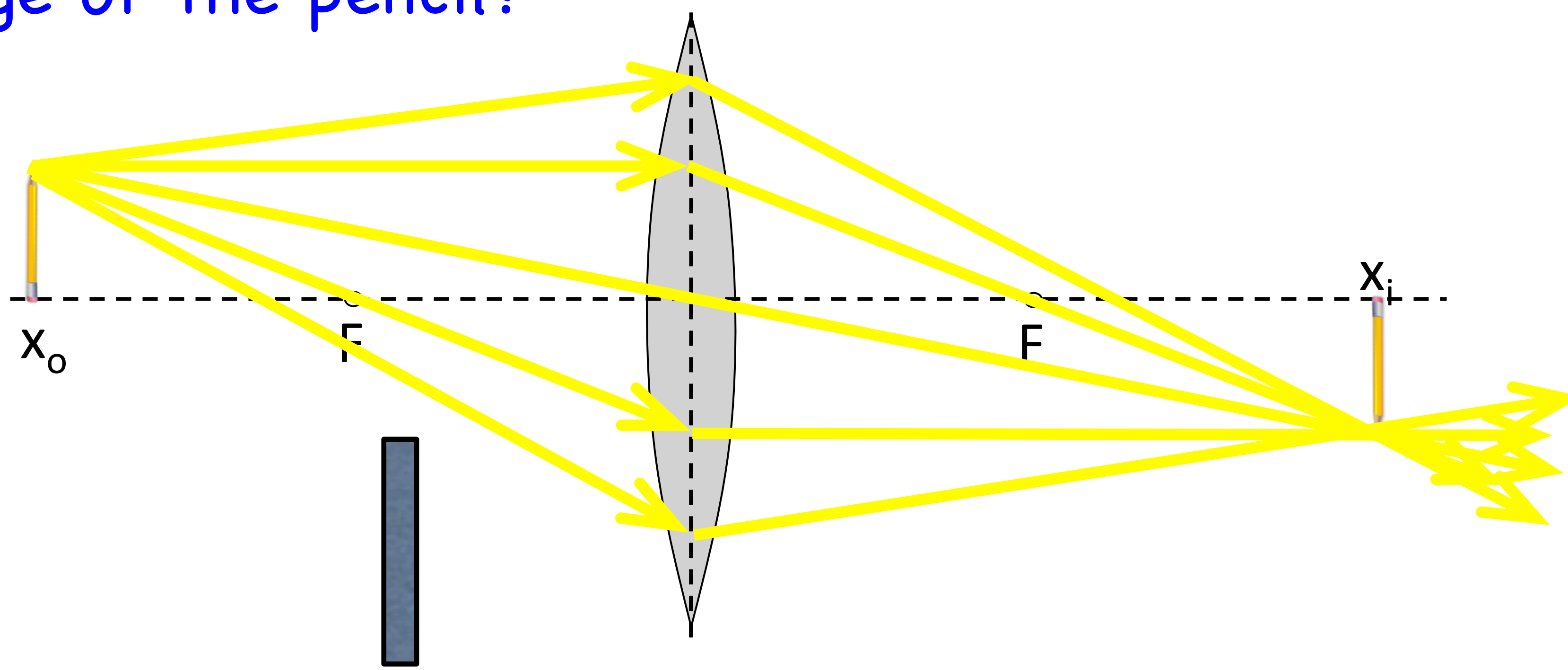
(a) image 1 vanishes
(b) image 2 vanishes
(c) something else

A: *The image gets dimmer since fewer rays reach the screen, but half the lens is still a lens, producing both images (cf pinhole camera)*

clicker question

Lens imaging

Q: A pencil is imaged using a converging lens. You slide a mask over the bottom half of the lens. What happens to the image of the pencil?



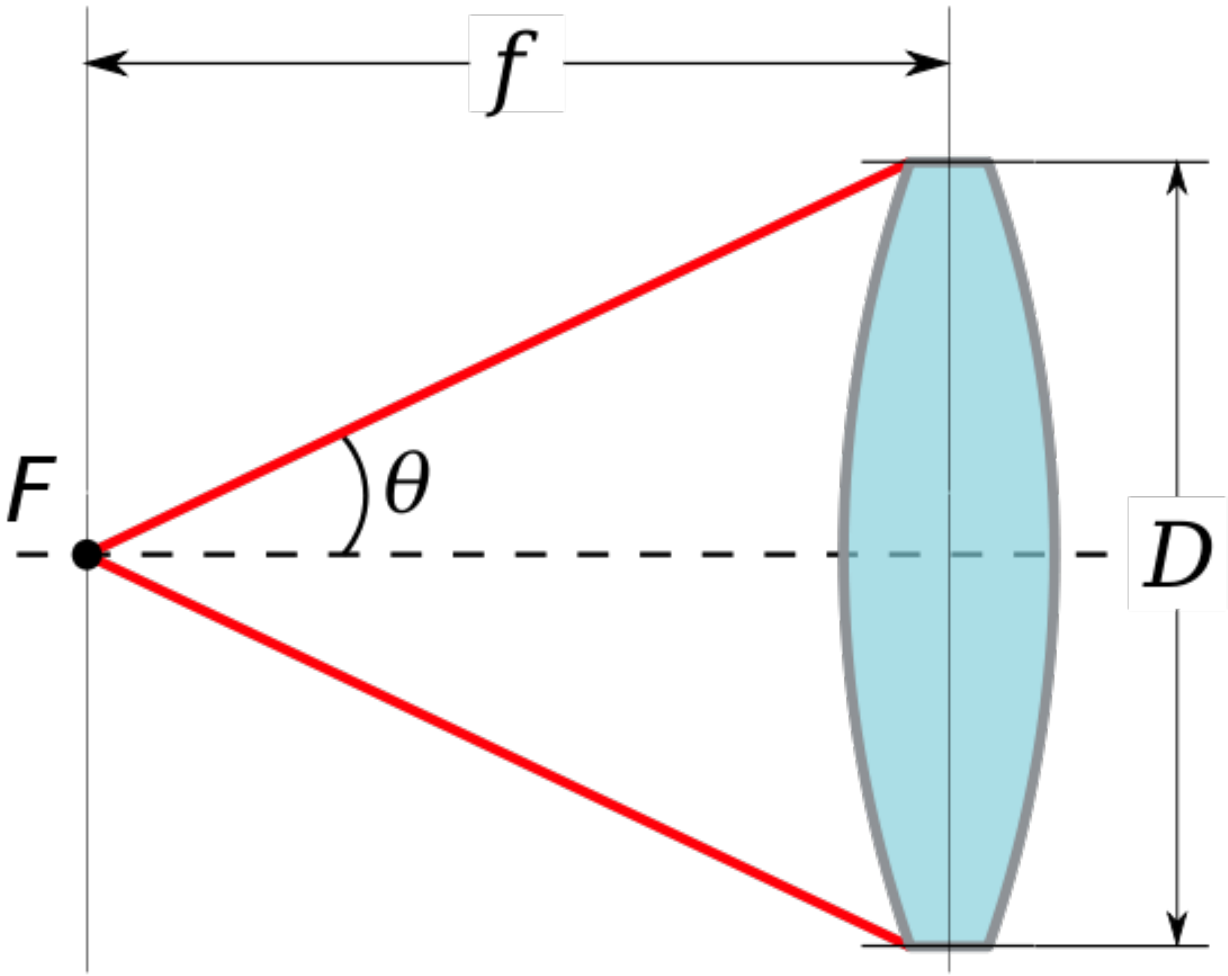
(a) image disappears due shadow of the mask

(b) half the image disappears due to mask shadow

(c) something else

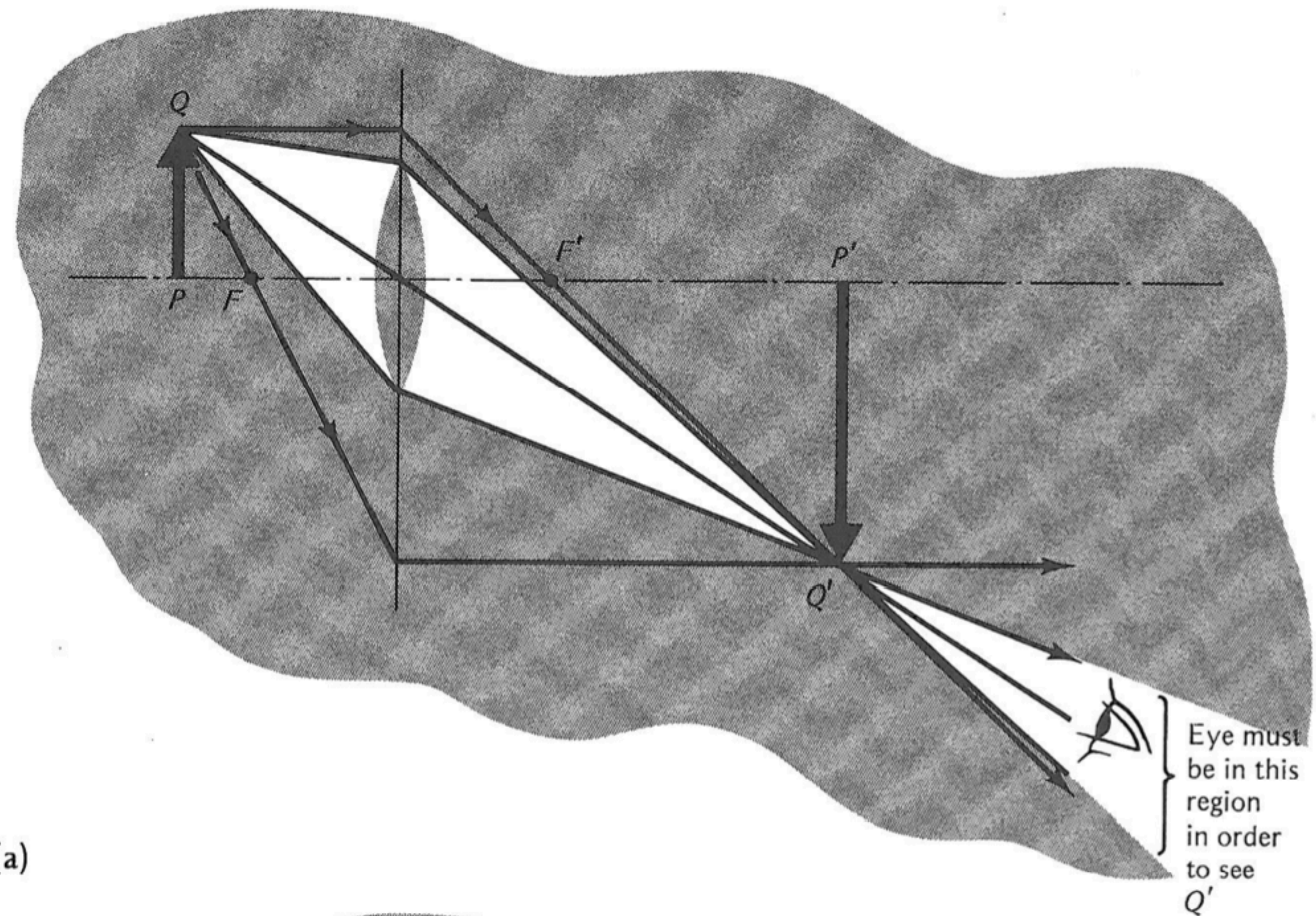
A: *The image gets dimmer since fewer rays reach the screen, but half the lens is still a lens, producing both images (cf pinhole camera)*

Numerical aperture vs f-number of a lens



- NA numerical aperture = n sinθ ≈ D/2f (optics)
- f−number = f/D ≈ 1/(2NA) (photography)

View of an image



(a)

Angle of view is limited by size, numerical aperture, NA of the lens of the eye

Focus on the image plane

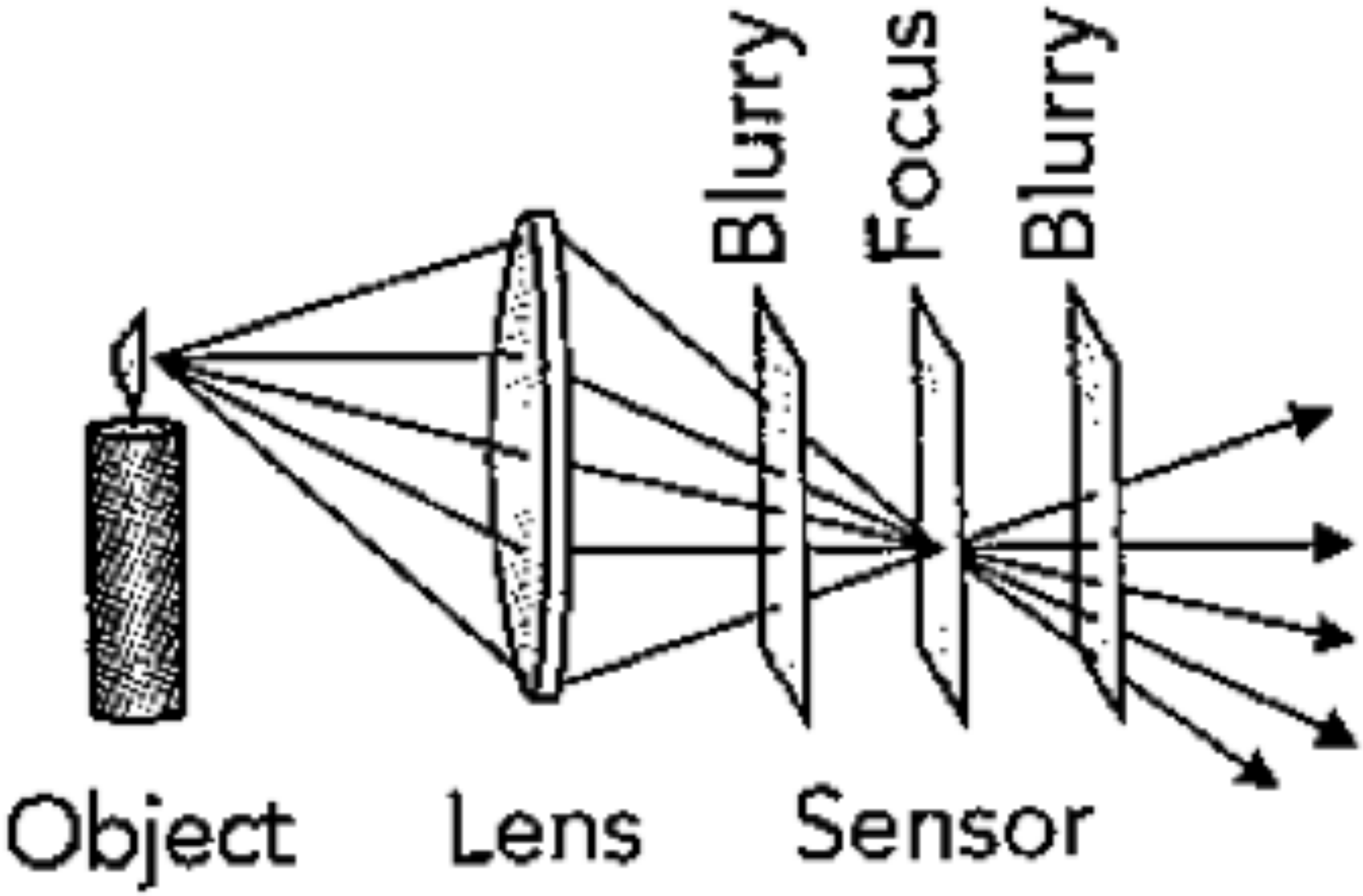
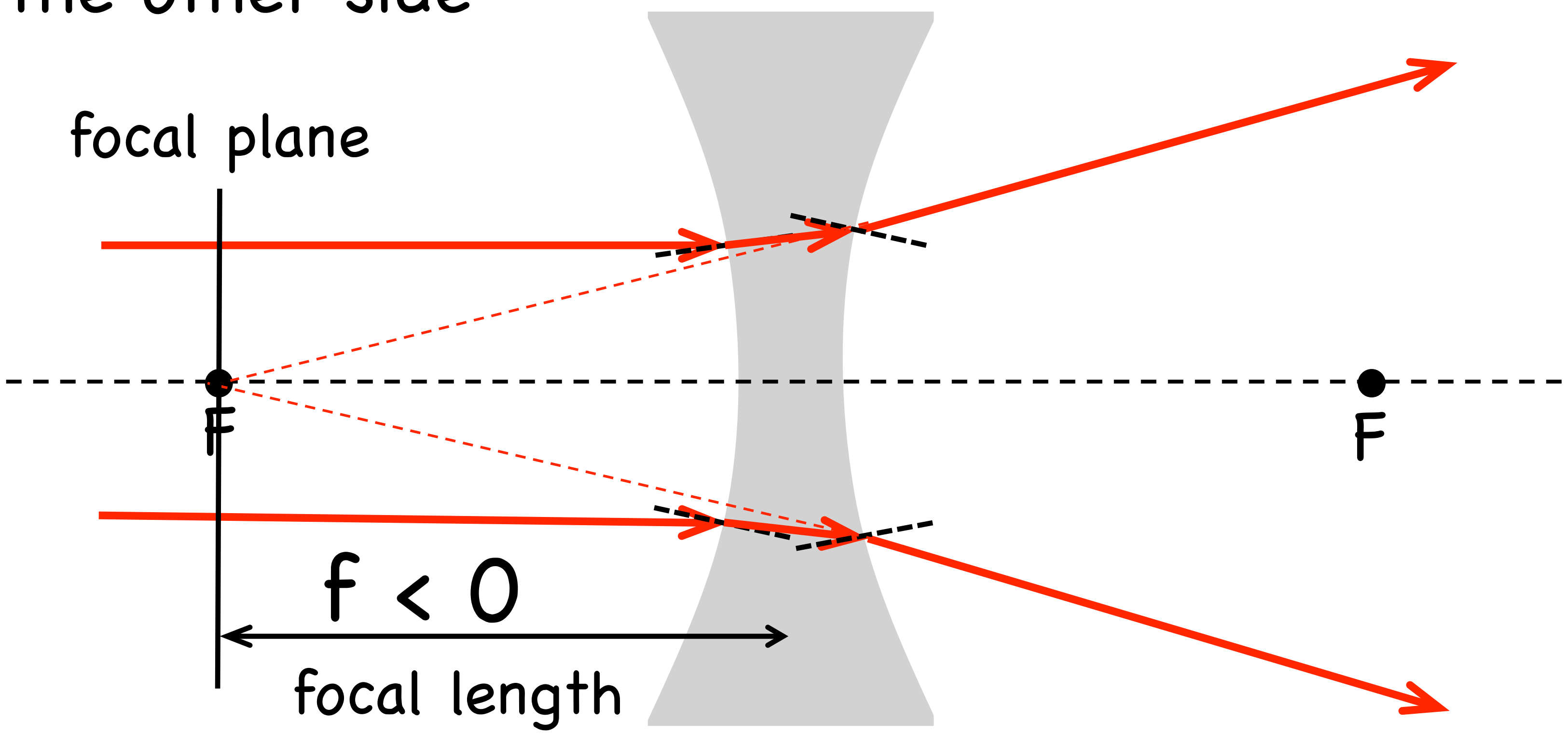


Image is only in focus at a single plane. In all other planes the image is blurry. In a camera move the lens *not* the sensor (film)

Diverging lens

Parallel rays are deflected such that when extended backwards, they appear to be coming from the focal point on the other side



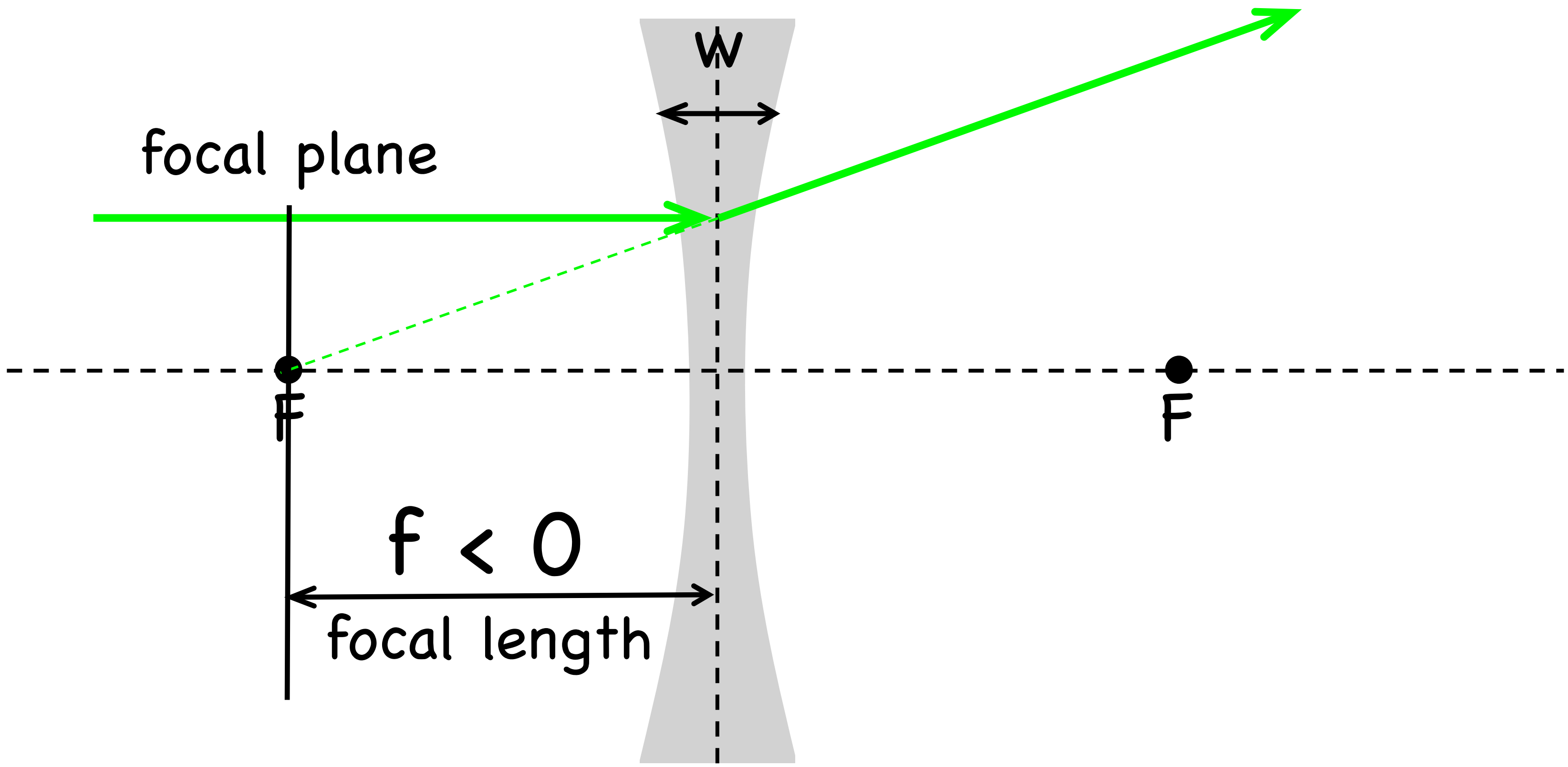
focal point F:

- is the image point of a distant star (as for curved mirror)
- is where all (parallel) rays from a distance star intersect
- exists on both sides of a lens

Diverging *thin* lens

Ray tracing is accurate only for thin lenses, width w much smaller than the focal length f (cf mirrors)

-> all of refraction focusing can be taken place at lens' midplane



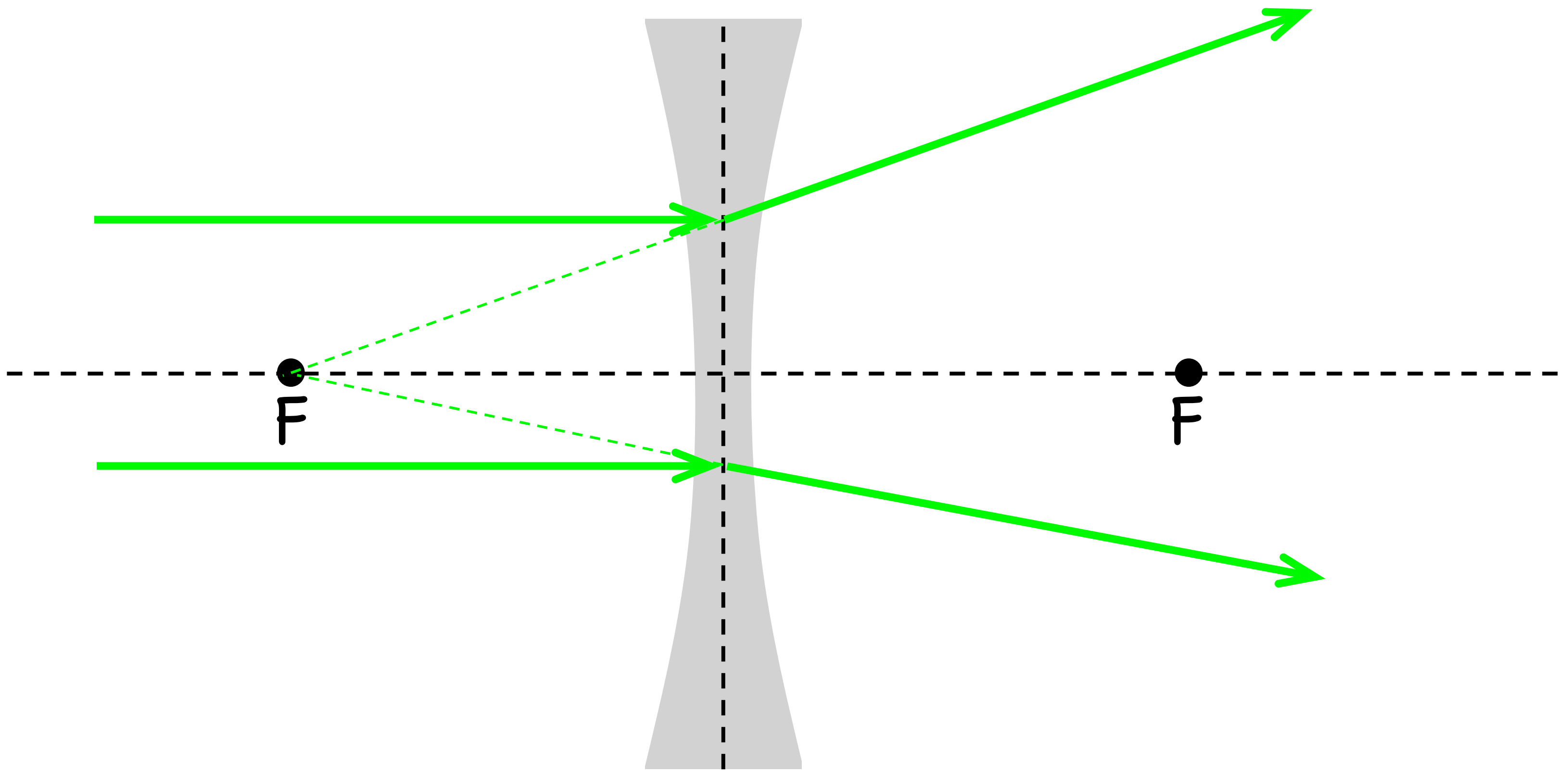
focal point F (f < 0):

- is the image point of a distant star (as for curved mirror)
- is where all (parallel) rays from a distance star intersect
- exists on both sides of a lens

Special rays: diverging lens

Rule 1:

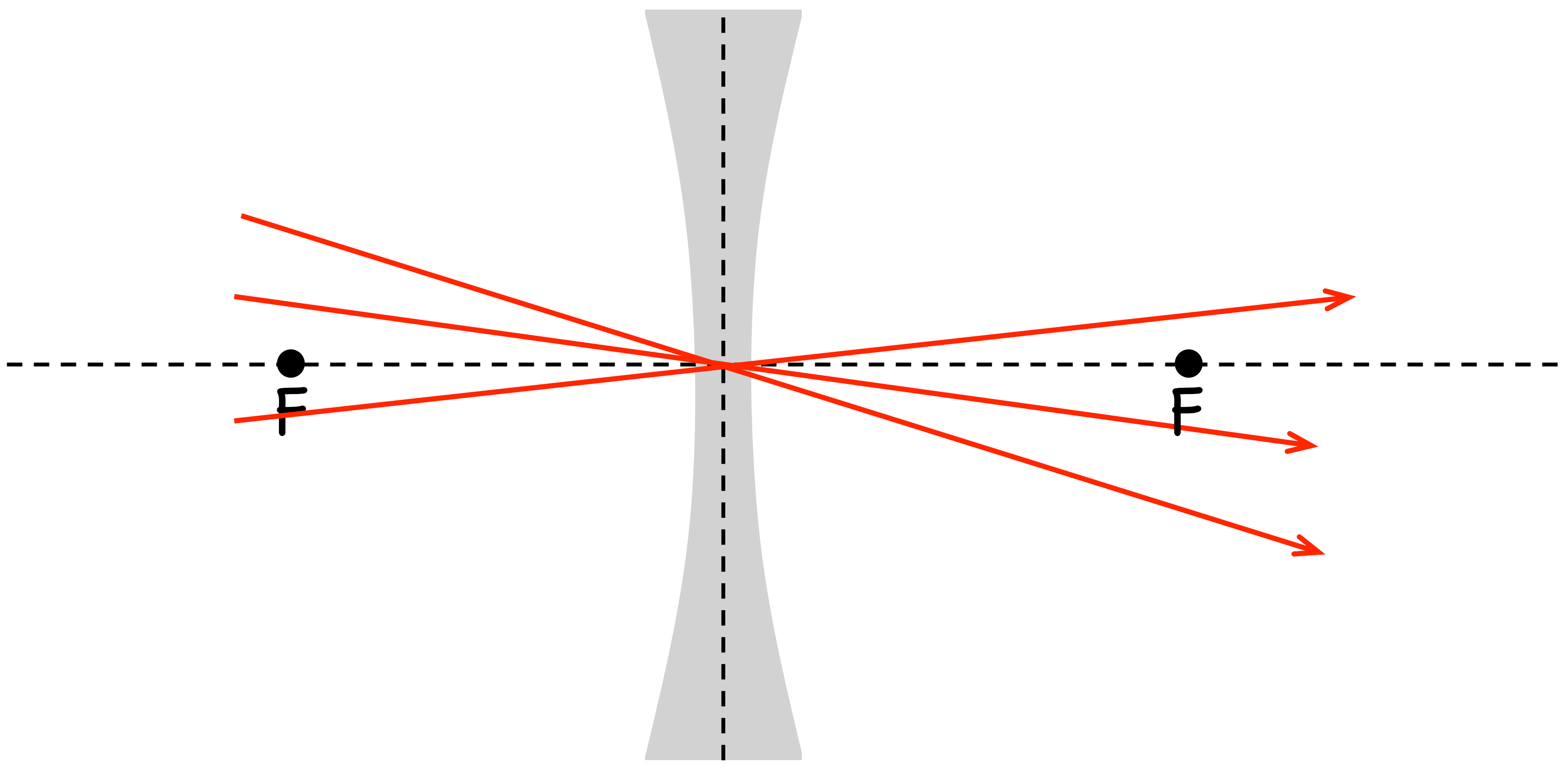
All rays incident parallel to the axis are deflected so that they appear to be coming from the focal point, F in front of the lens



Special rays: diverging lens

Rule 2:

All rays that pass through the center of the lens continue un-deflected (straight) through the lens



Special rays: diverging lens

Rule 3:

All rays whose extension passes through the focal point on the other side of the lens, are deflected to be parallel to the axis (reverse of rule 1)

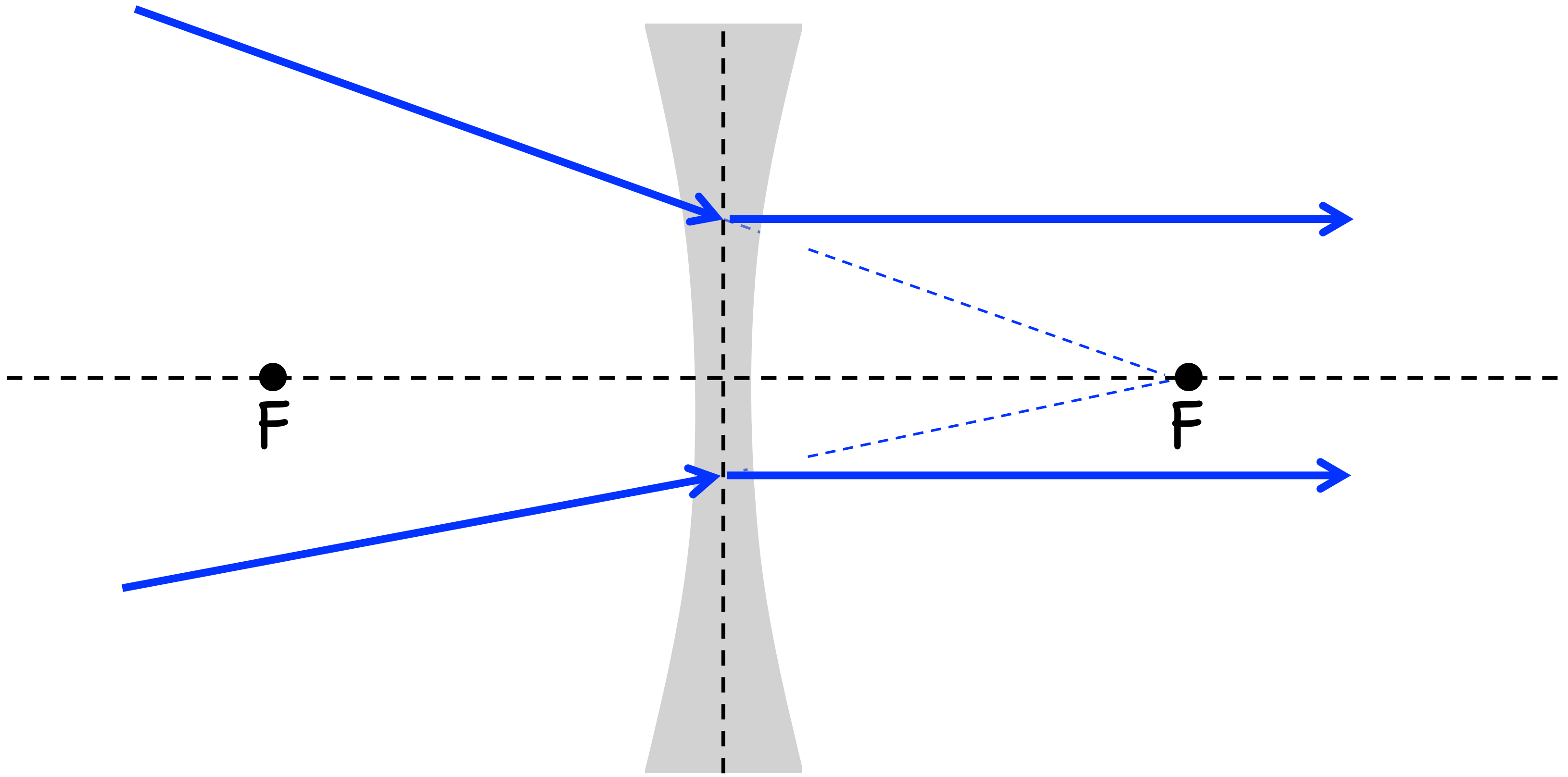
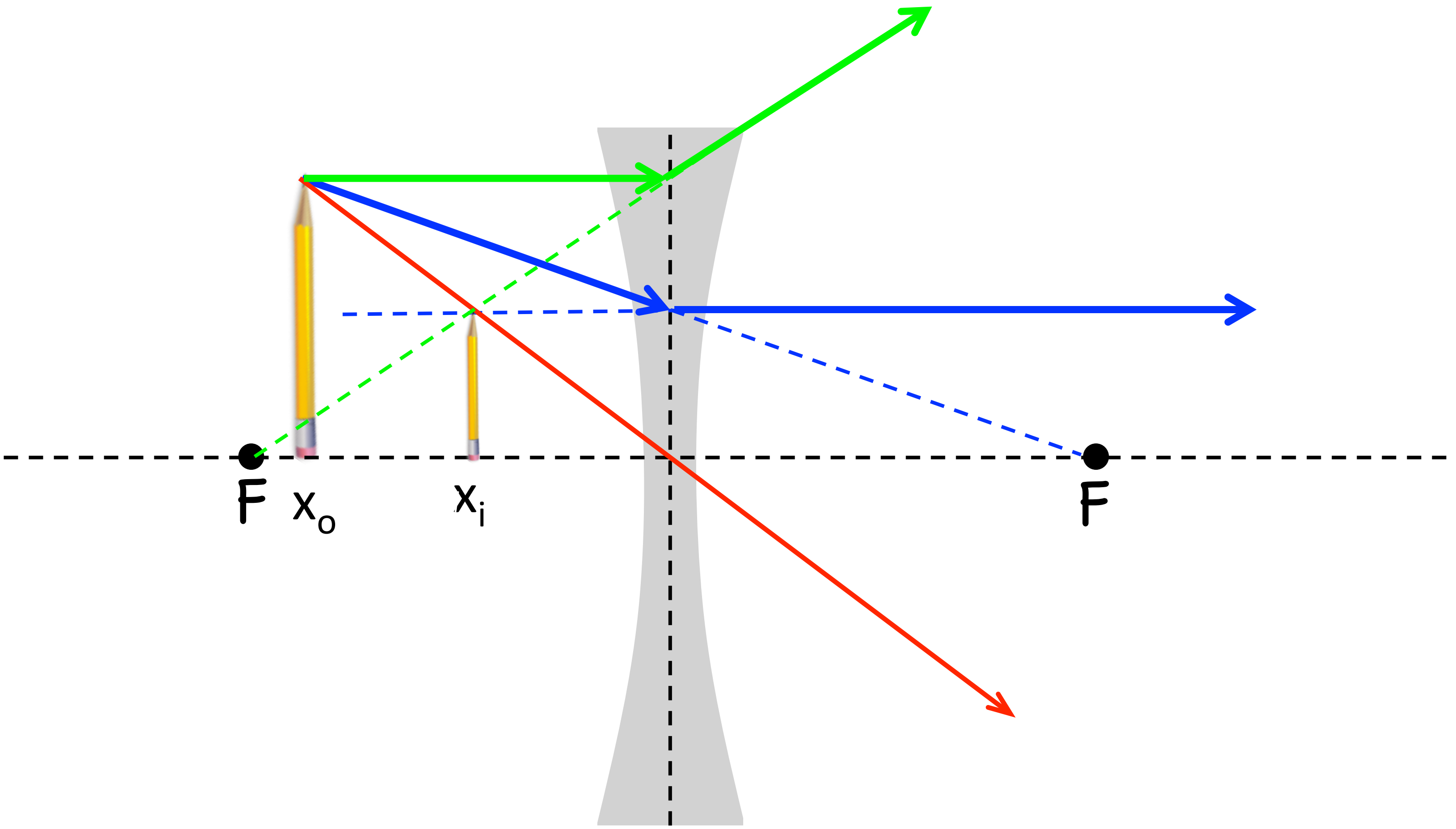


Image formation: diverging lens

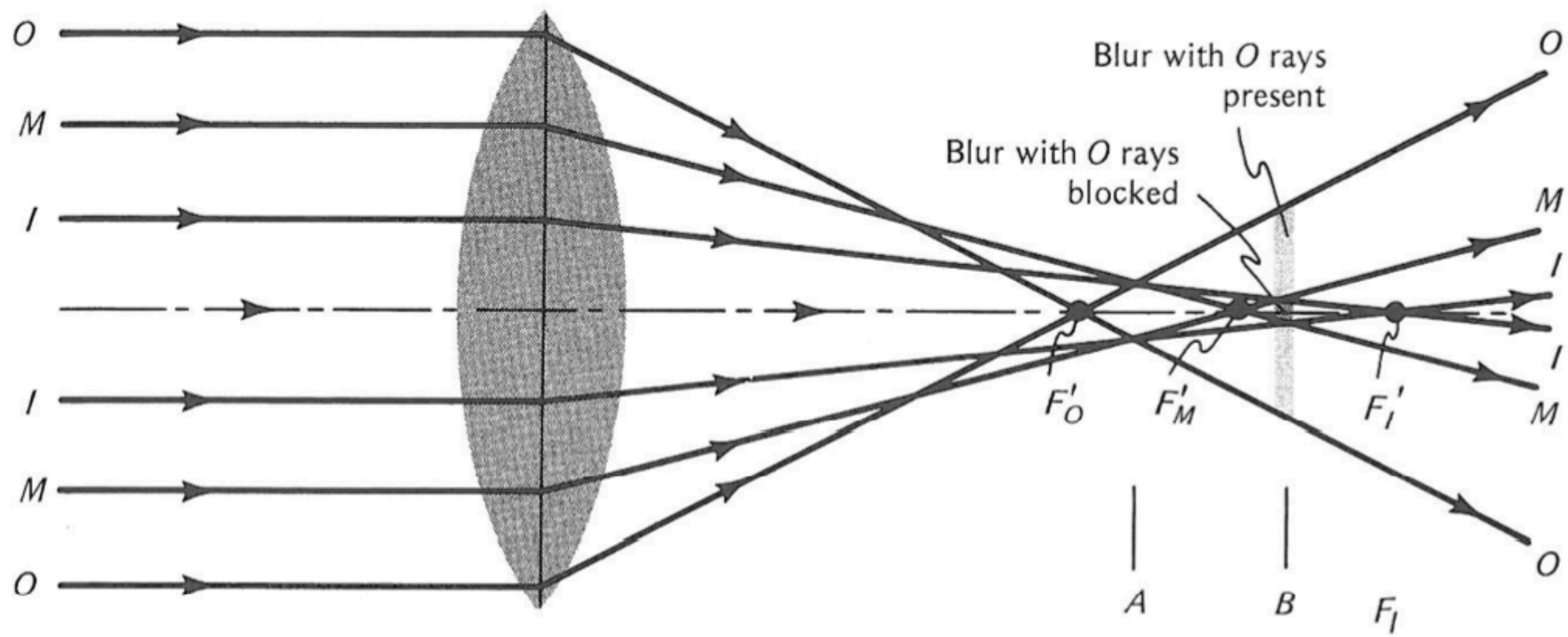


$x_i < 0,\ f < 0$:

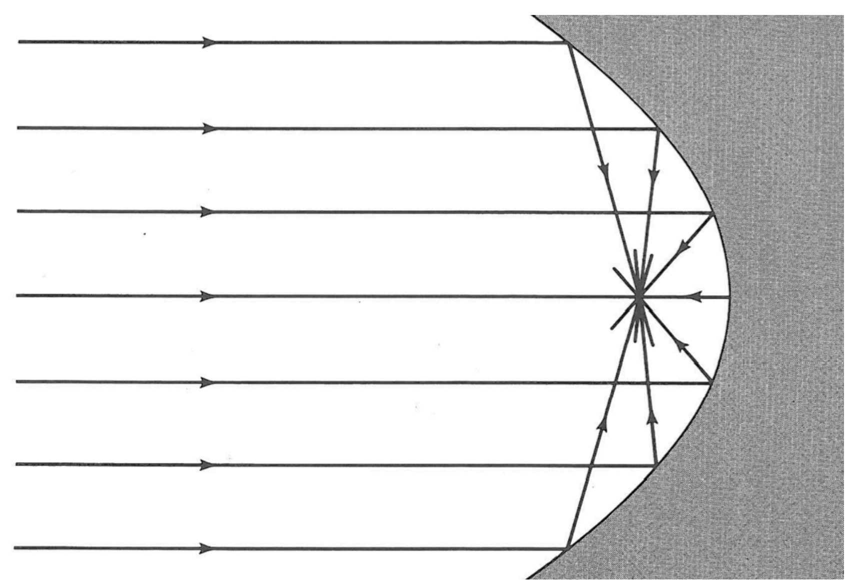
The image is *virtual*, *right side up* and is smaller than the object. More generally this will depend on the position of the object x_o relative to the focal point F of the lens.

Spherical aberration

- The nonparaxial (outer) rays have a different focal point F_o than the paraxial (inner) rays, F_i ,leading to a blurry image

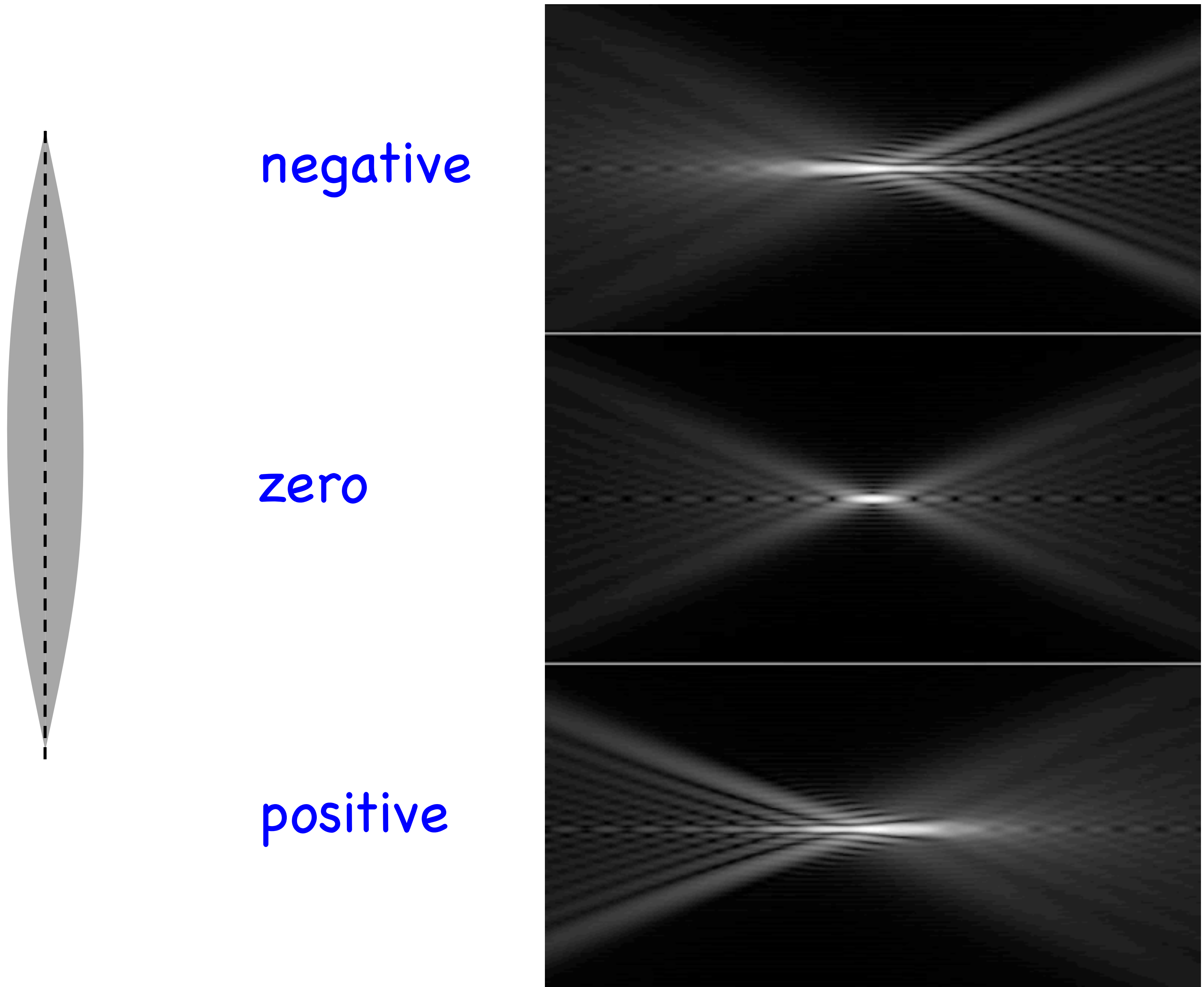


- *Parabolic* reflector has no spherical aberration



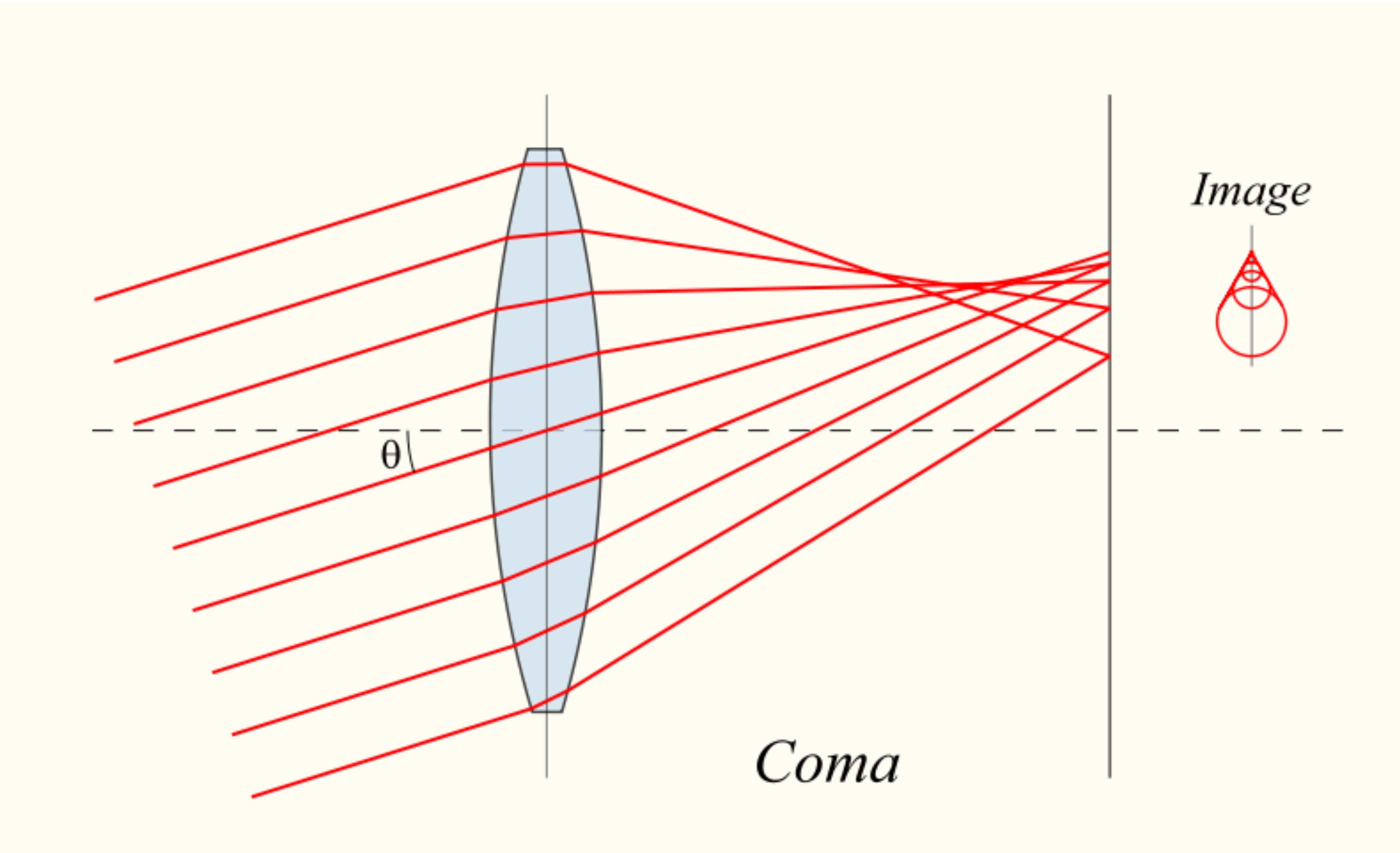
Spherical aberration

- The nonparaxial (outer) rays have a different focal point F_o than the paraxial (inner) rays, F_i , leading to a blurry image



Coma aberrations

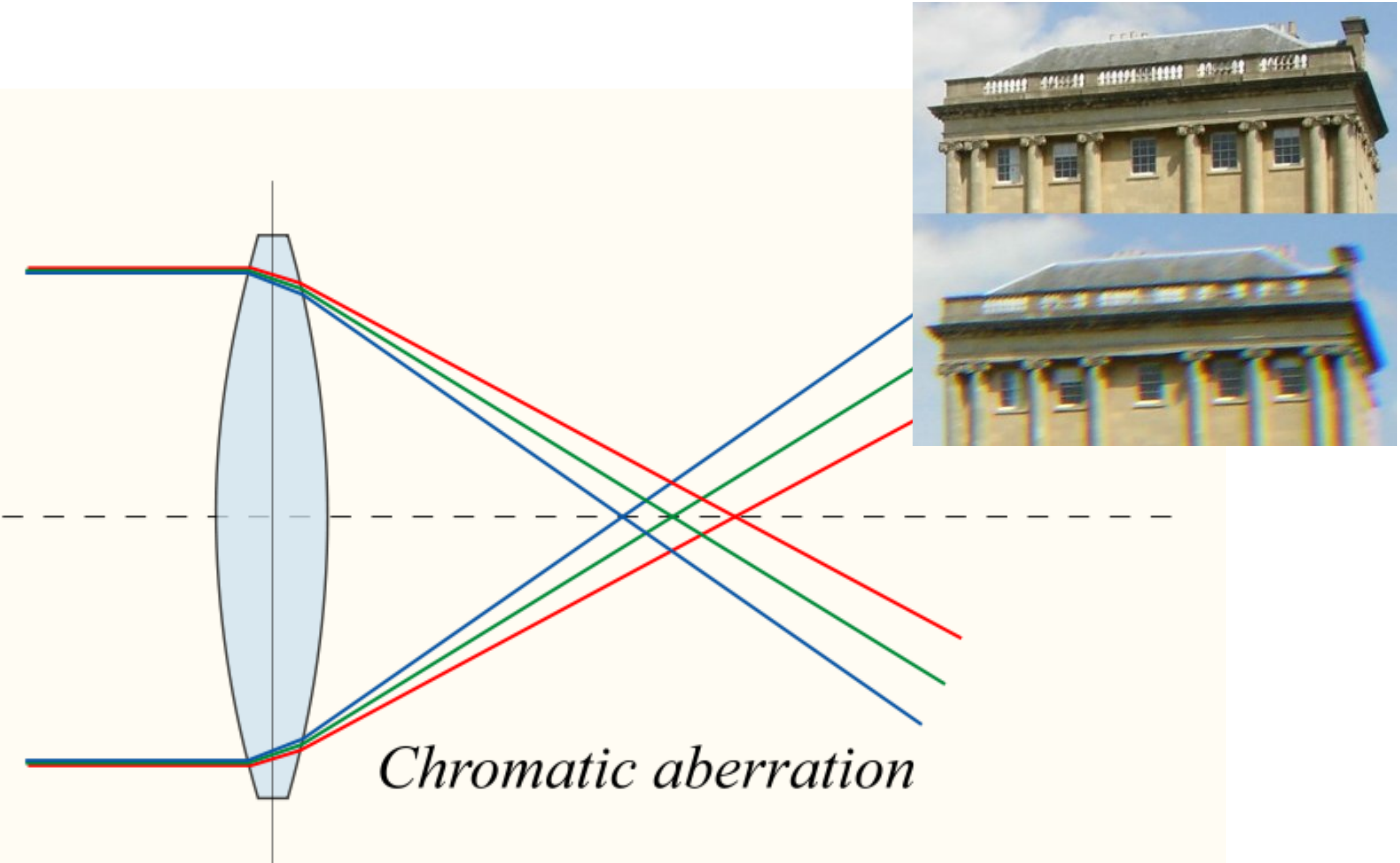
- Rays passing through a lens at an angle have different focal points



Chromatic aberrations

- Different colors have different focal points

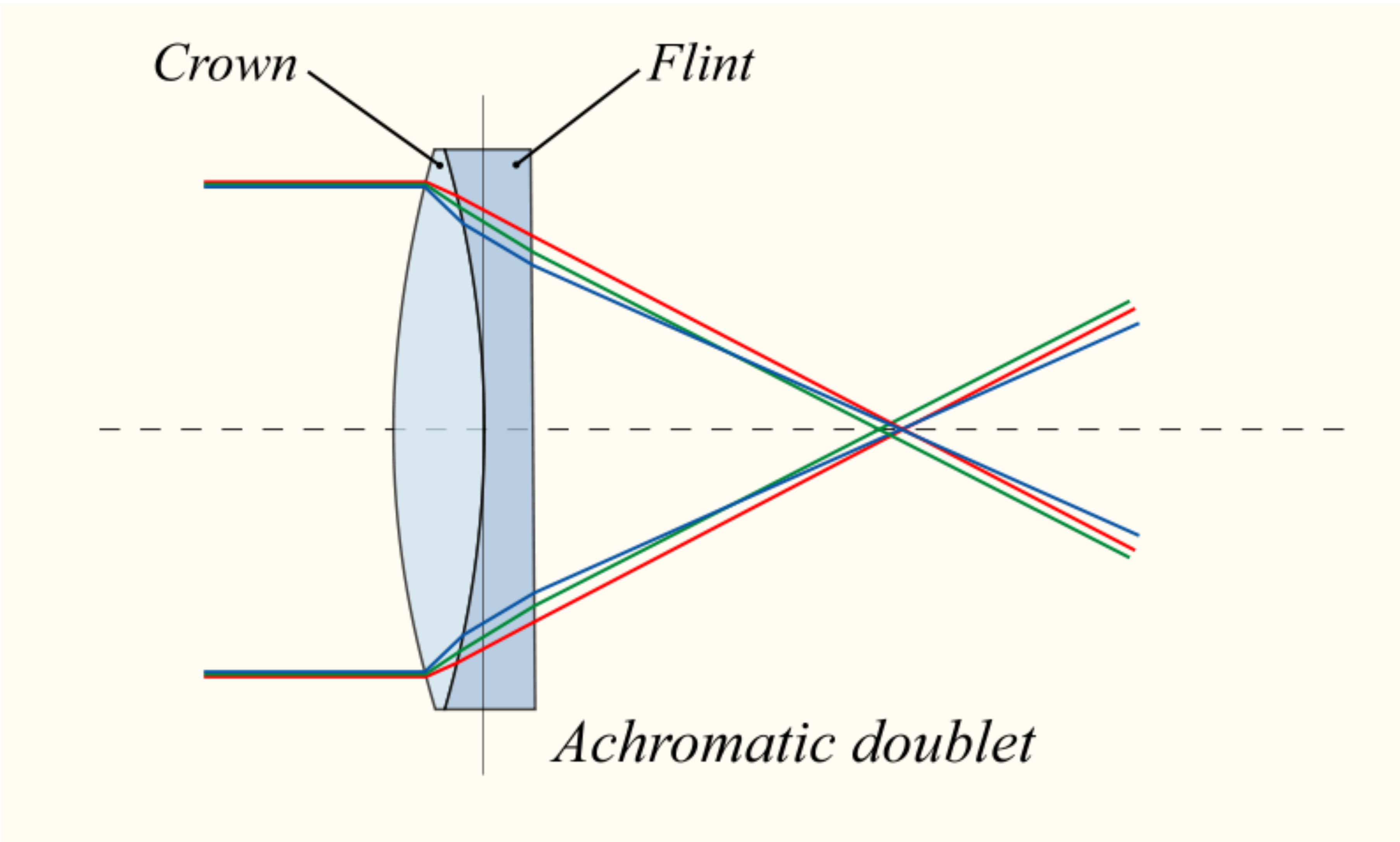
(due to dispersion of glass; index of refraction depends on frequency)



Chromatic aberrations

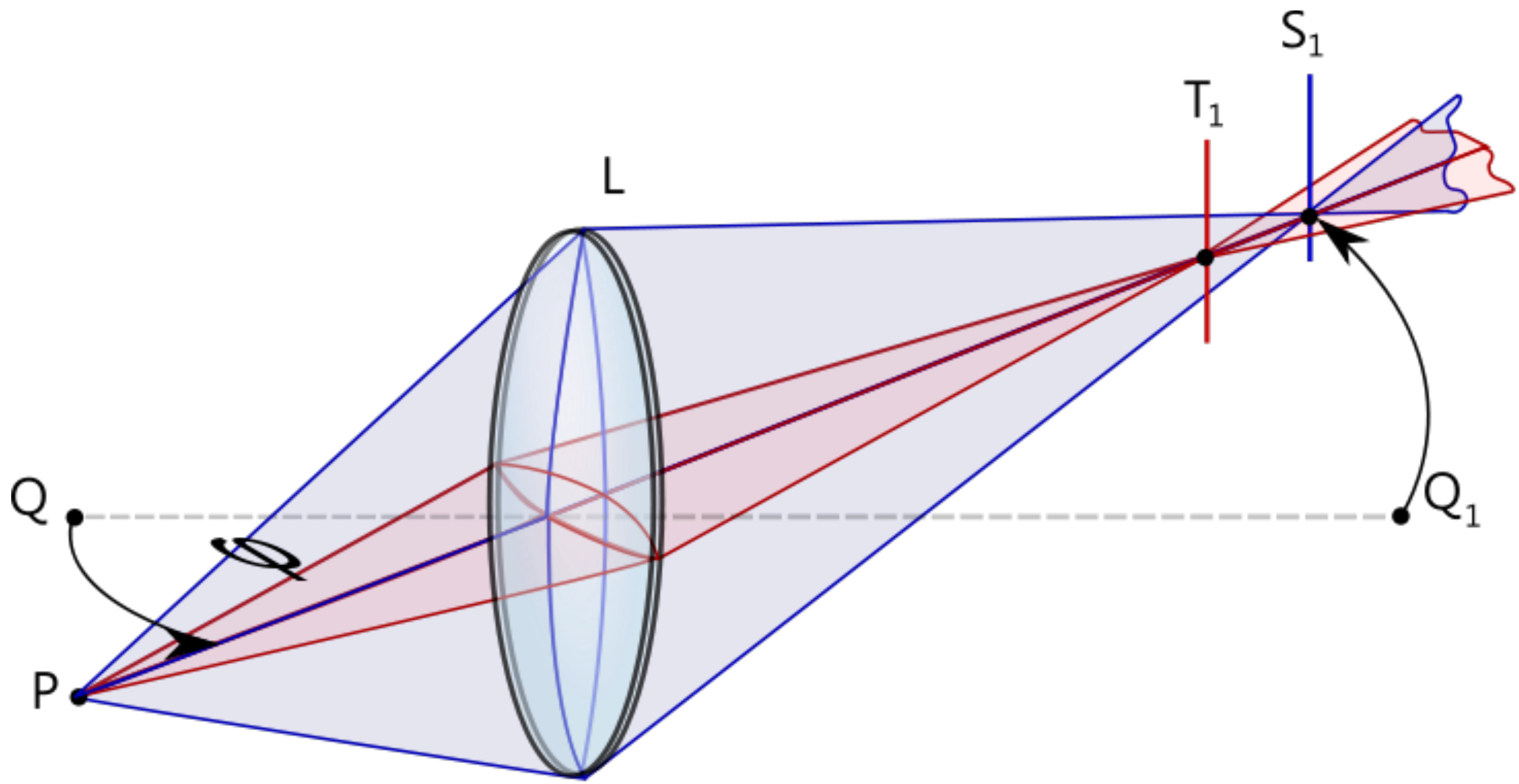
- Different colors have a different focal point
  (due to dispersion of glass)

correction:

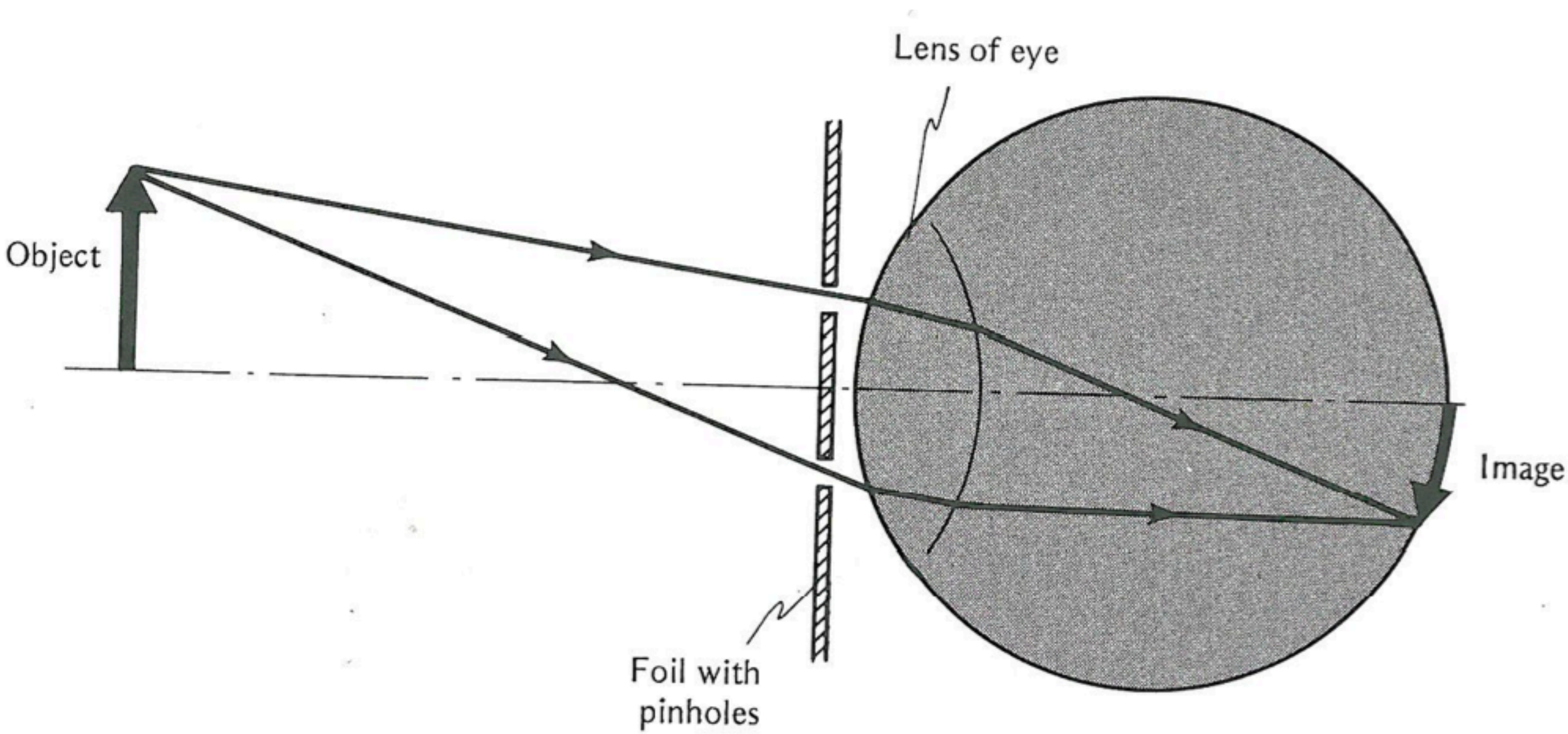


Astigmatic aberrations

- Rays in different planes (vertical and horizontal) have different focal points



Optics of an eye lens



The lens of the eye creates one image from rays that passed through different pinholes. Compare to a pinhole camera.

The lens equation

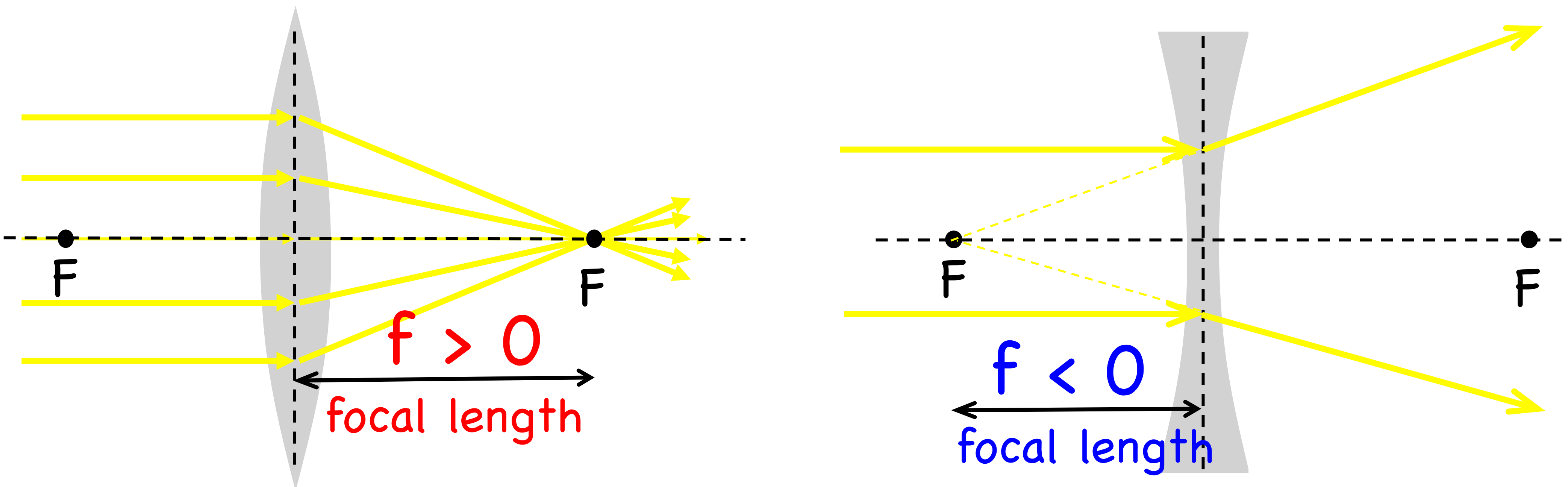
- Ray tracing is useful, but tedious for all the different cases, and accuracy requires very precise drawings

- We can avoid ray tracing by using *the lens equation*

- This will require some *algebra* and *arithmetic*

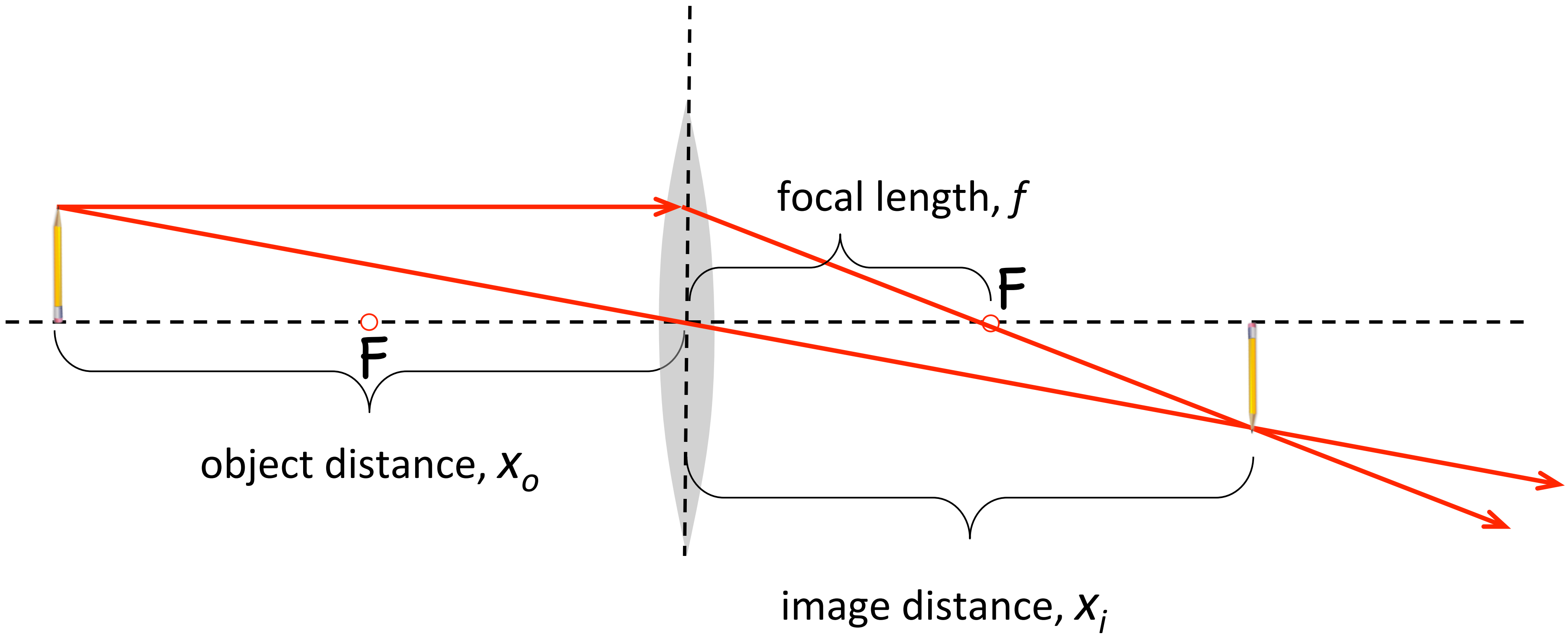
Focal length

- Recall, we defined the focal length f of a lens



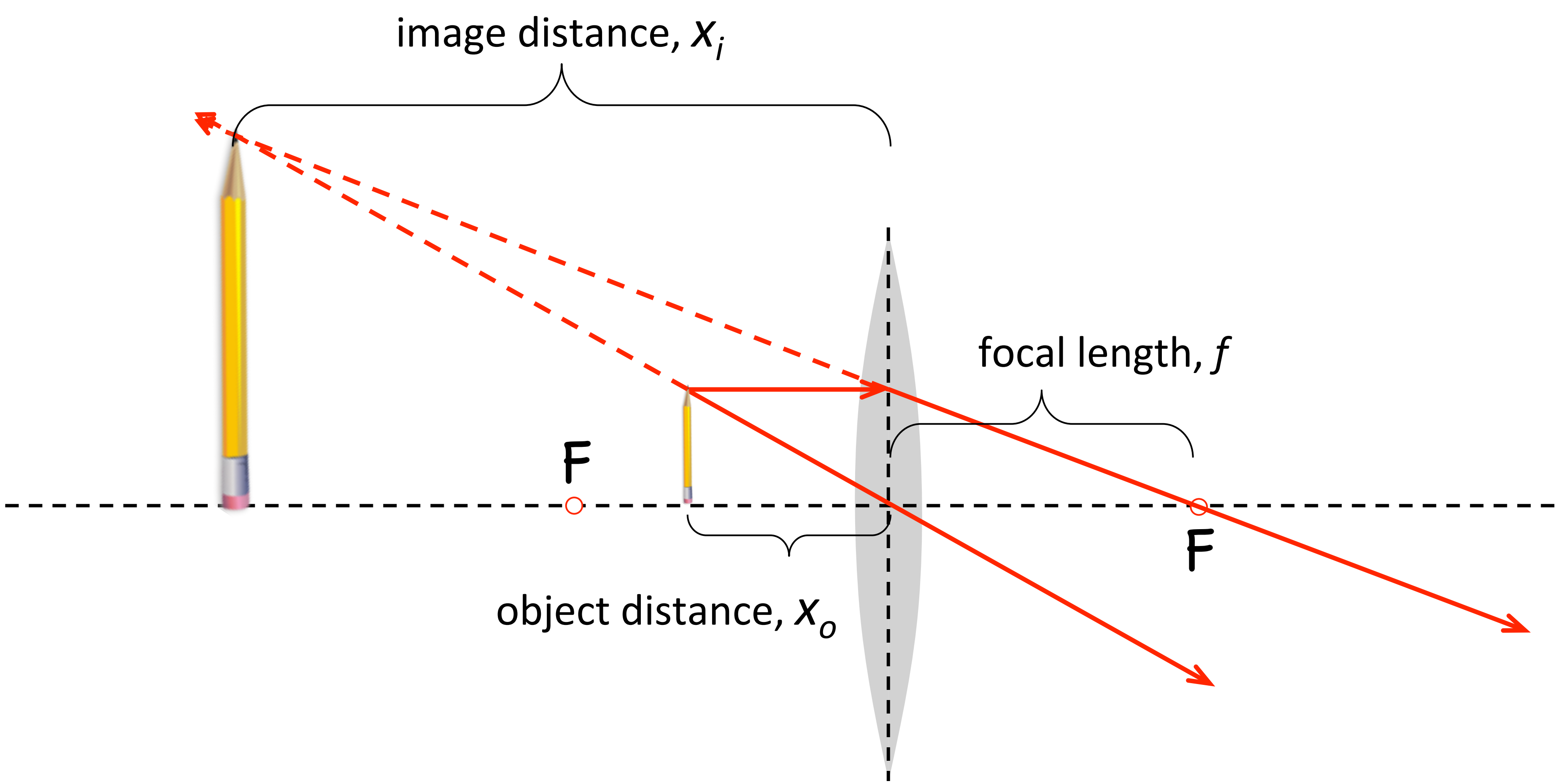
- The focal length, f is defined as positive for converging lenses and negative for diverging lenses

Lens equation terminology



The object distance is positive for an object to the left of the lens. The image distance is positive for a (real) image on the right of the lens. These quantities are negative for the reverse situation. Be careful with this.

Lens equation terminology

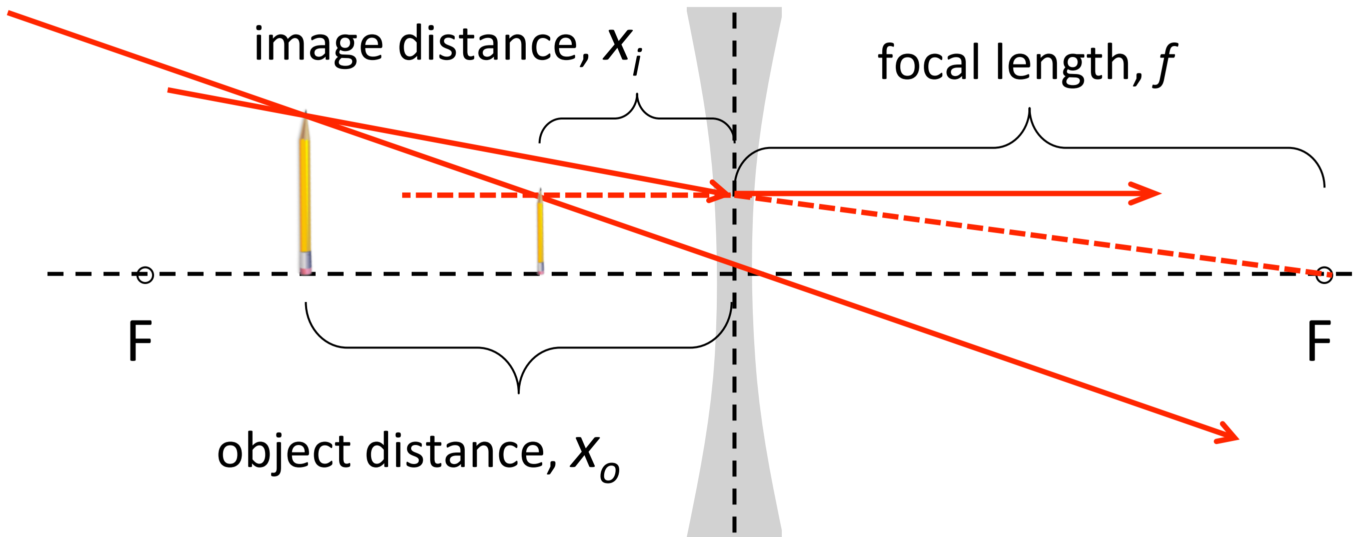


- The image distance x_i is negative for a (virtual) image on the left of the lens.

clicker question

Lens imaging

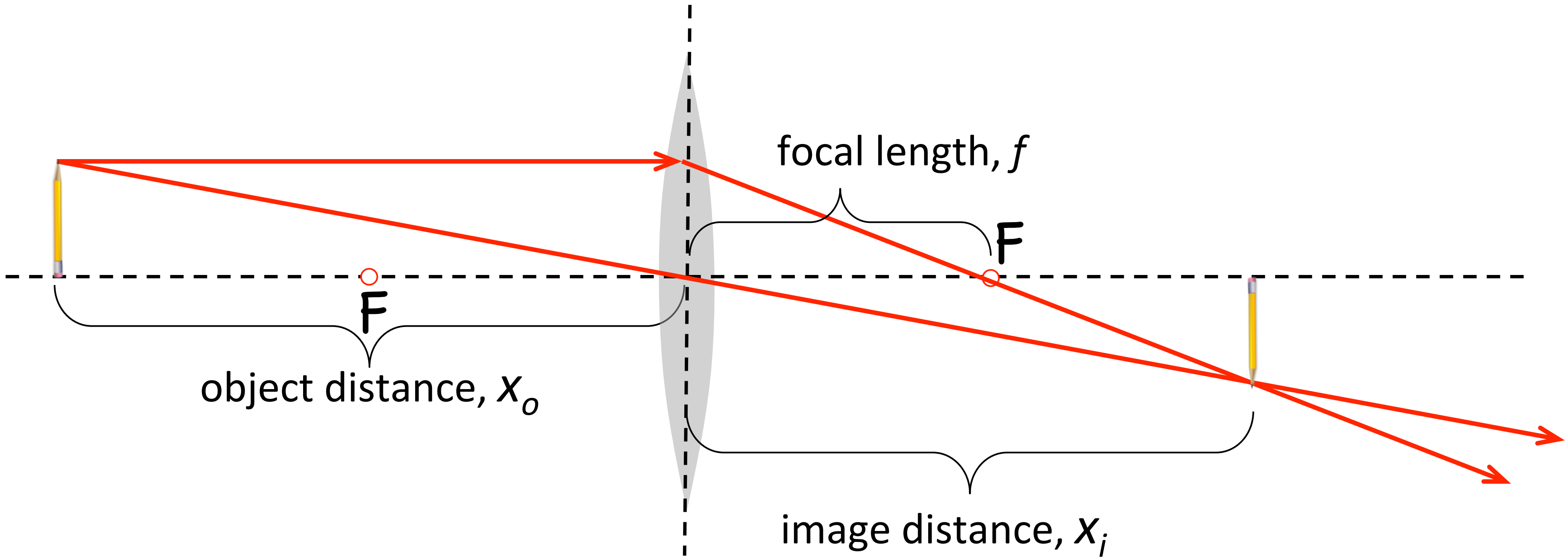
Q: Which quantities are negative in this example?



(a) image distance, x_i
(b) focal length, f
(c) object distance, x_o
(d) a and b
(e) a and c

A: *The focal length for diverging lens is negative. The image distance for a virtual image on the same side as the object is negative*

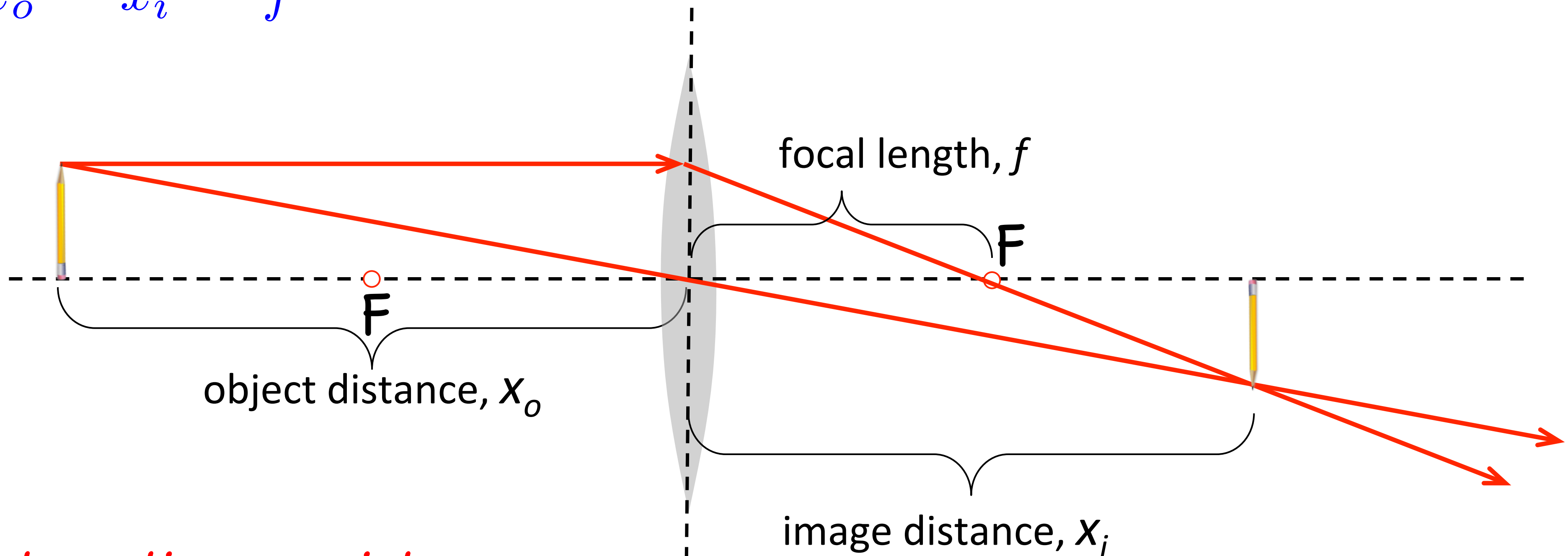
Lens equation terminology



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

Lens equation terminology

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



Interesting special cases:

1. $x_o = 2f$: $$\frac{1}{x_i} = \frac{1}{f} - \frac{1}{x_o} = \frac{1}{f} - \frac{1}{2f} = \frac{1}{2f} \quad \boxed{\rightarrow x_i = 2f}$$

2. $x_o = f$: $$\frac{1}{x_i} = \frac{1}{f} - \frac{1}{x_o} = \frac{1}{f} - \frac{1}{f} = 0 \quad \boxed{\rightarrow x_i = \infty}$$

3. $x_o = \infty$: $$\frac{1}{x_i} = \frac{1}{f} - \frac{1}{x_o} = \frac{1}{f} - \frac{1}{\infty} = \frac{1}{f} \quad \boxed{\rightarrow x_i = f}$$

Lens equation example: *image position*

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

- Given:
  - f = 10cm
  - object 15cm in front of lens, x_o = 15cm

$$\frac{1}{15} + \frac{1}{x_i} = \frac{1}{10}$$

- Find:
  - Where is the image, x_i and is it real or virtual?

$$\frac{1}{x_i} = \frac{1}{10} - \frac{1}{15}$$

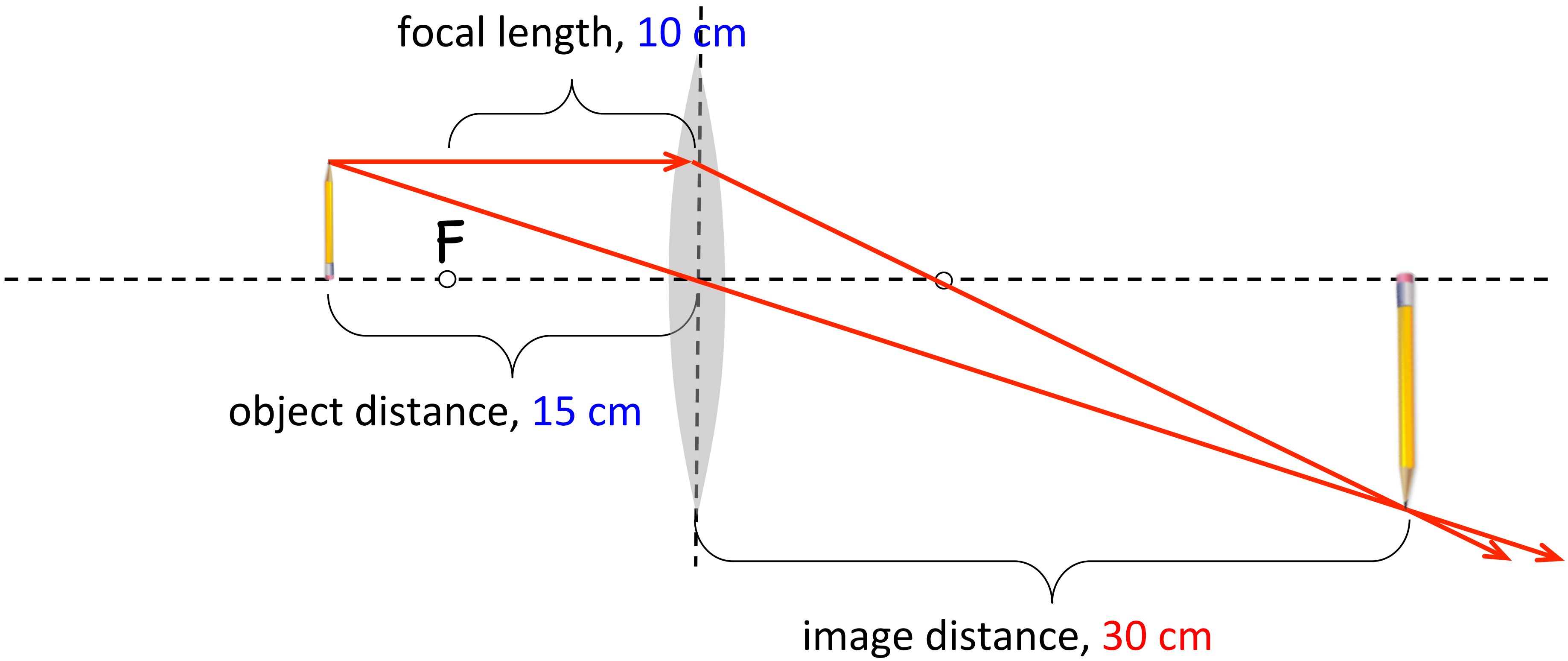
- Solve equation for x_i :
  - substitute numbers of variables
  - subtract 1/15 from both sides
  - arithmetic on calculator
  - solve for x_i

$$\frac{1}{x_i} = \frac{1}{30} = 0.033$$

$$x_i = 30\ cm$$

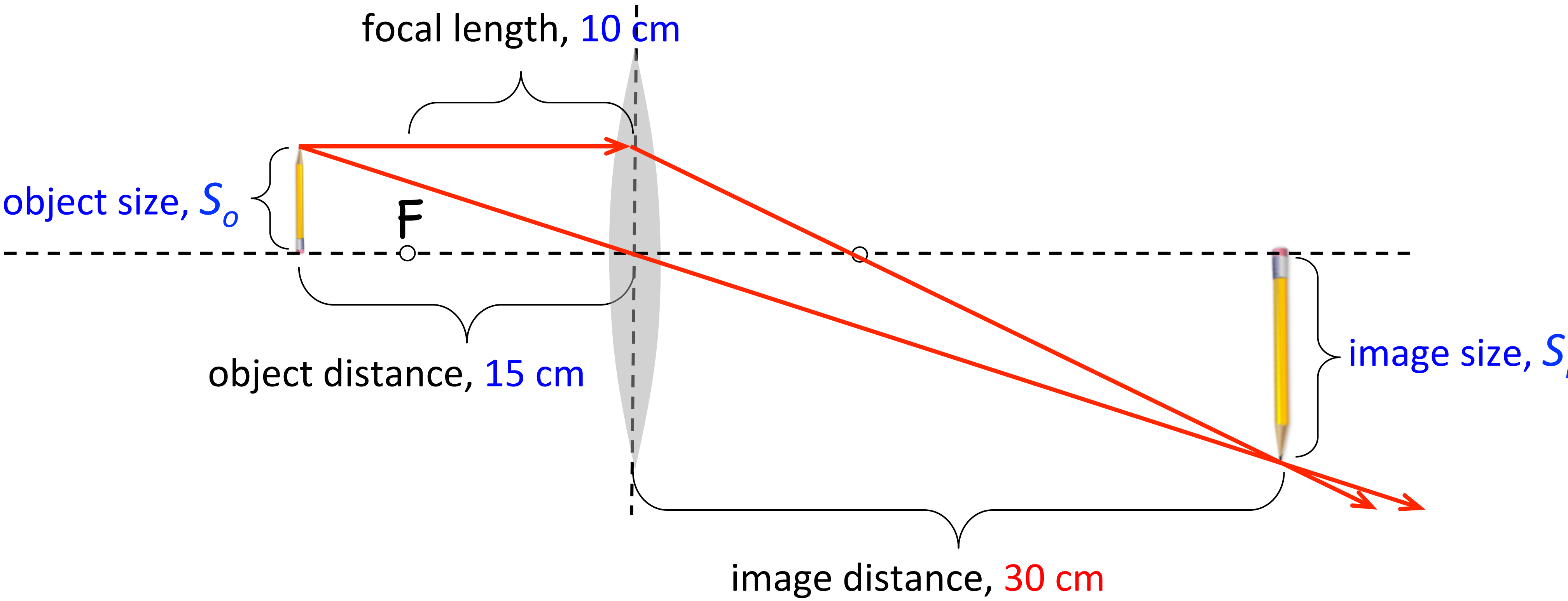
Image is 30 cm -> to the right of the lens and real

Lens equation example



We can verify our result is consistent with the result by ray tracing. Ray tracing does not give an exact numeric answer, because we cannot draw all our lines perfectly.

Lens equation example: *magnification*



- for objects and images above the axis, S is positive, below axis S is negative
- magnification $\mathbf{M = \frac{S_i}{S_o} = -\frac{x_i}{x_o} = -\frac{30\ cm}{15\ cm} = -2}$

➡ image is inverted (M negative) and double the object's size

Lens equation example: *image position*

- Given:
  - $f = 10$cm
  - object 5cm in front of lens, $x_o = 5$cm

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

$$\frac{1}{5} + \frac{1}{x_i} = \frac{1}{10}$$

- Find:
  - Where is the image, x_i and is it real or virtual?

$$\frac{1}{x_i} = \frac{1}{10} - \frac{1}{5}$$

- Solve equation for x_i :
  - substitute numbers of variables
  - subtract 1/5 from both sides
  - arithmetic on calculator
  - solve for x_i

$$\frac{1}{x_i} = -\frac{1}{10} = 0.1$$

$$x_i = -10\ cm$$

Image is -10 cm -> to the left of the lens and virtual

“Power” of a lens: *diopters*

- Definition of diopter P in terms of f:

$$P \text{ (in diopters)} = 1/f \text{ (in meters)}$$

  - positive for convergent lenses (positive f), negative for diverging lenses (negative f)

- Meaning of P:

  - P is a measure of the *ray bending power* of the lens
  - eyeglasses and contact lens prescription is given in diopters, P

clicker question

Diopters

Q: What is the *focal length* of eyeglasses with prescription of -2.0 diopters?

(a) 1 meter

(b) -1 meter

(c) 0.5 meters

(d) -0.5 meters

A: -2.0 diopters = 1/f

-> f = 1/(-2.0 diopters) -> f = -0.5 meters

Combining lenses using diopters

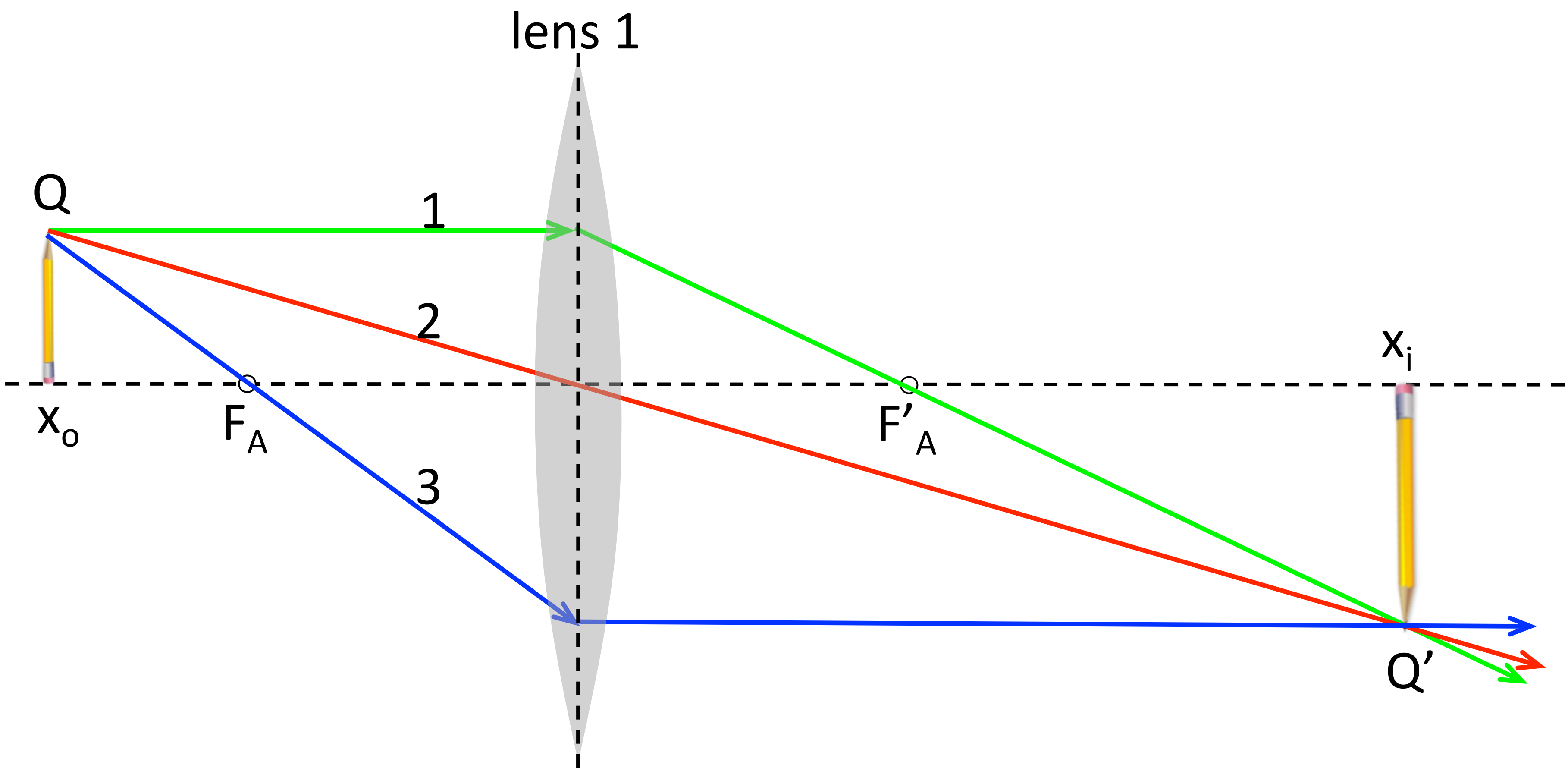
- Diopters power of a multi-lens combination?

  $P_{AB} = P_A + P_B$

- Example:
  - lens A, $f_A = 0.5$ m
  - lens B, $f_B = -1$ m
  - What is the power of combined lens?
  - What is the focal length f_{AB} of combined lens?

- Solution:
  - power of lens A is 1/(0.5) = 2 diopters
  - power of lens B is 1/(-1) = -1 diopters
  - combined lens $P_{AB} = P_A + P_B = 2 + (-1) = 1$ diopters
  - focal length of a combined lens, $f_{AB} = 1/P_{AB} = 1$ m
  - only valid for *touching thin* lenses

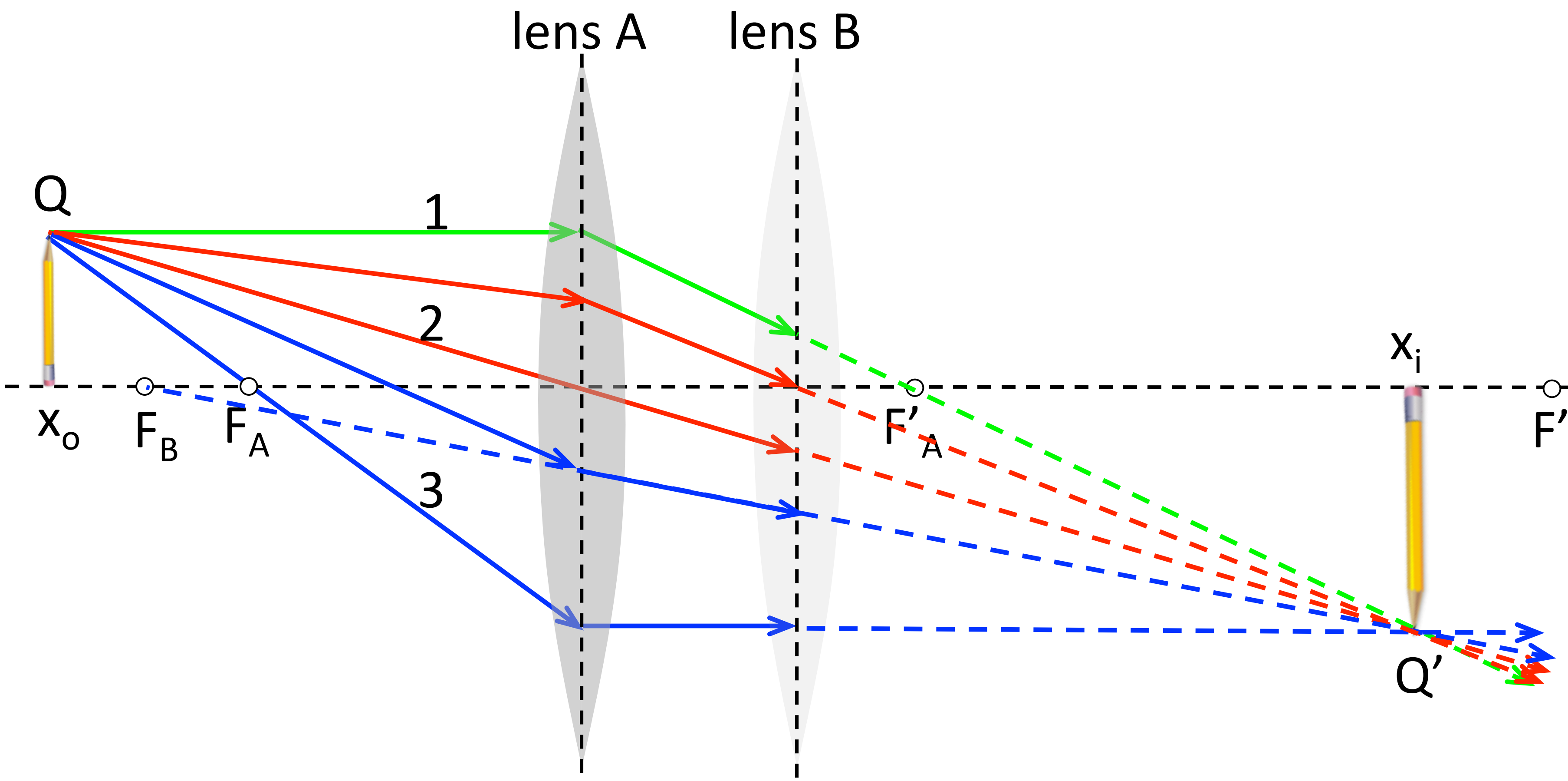
Image formation: converging lens



$f < x_o < 2f$:

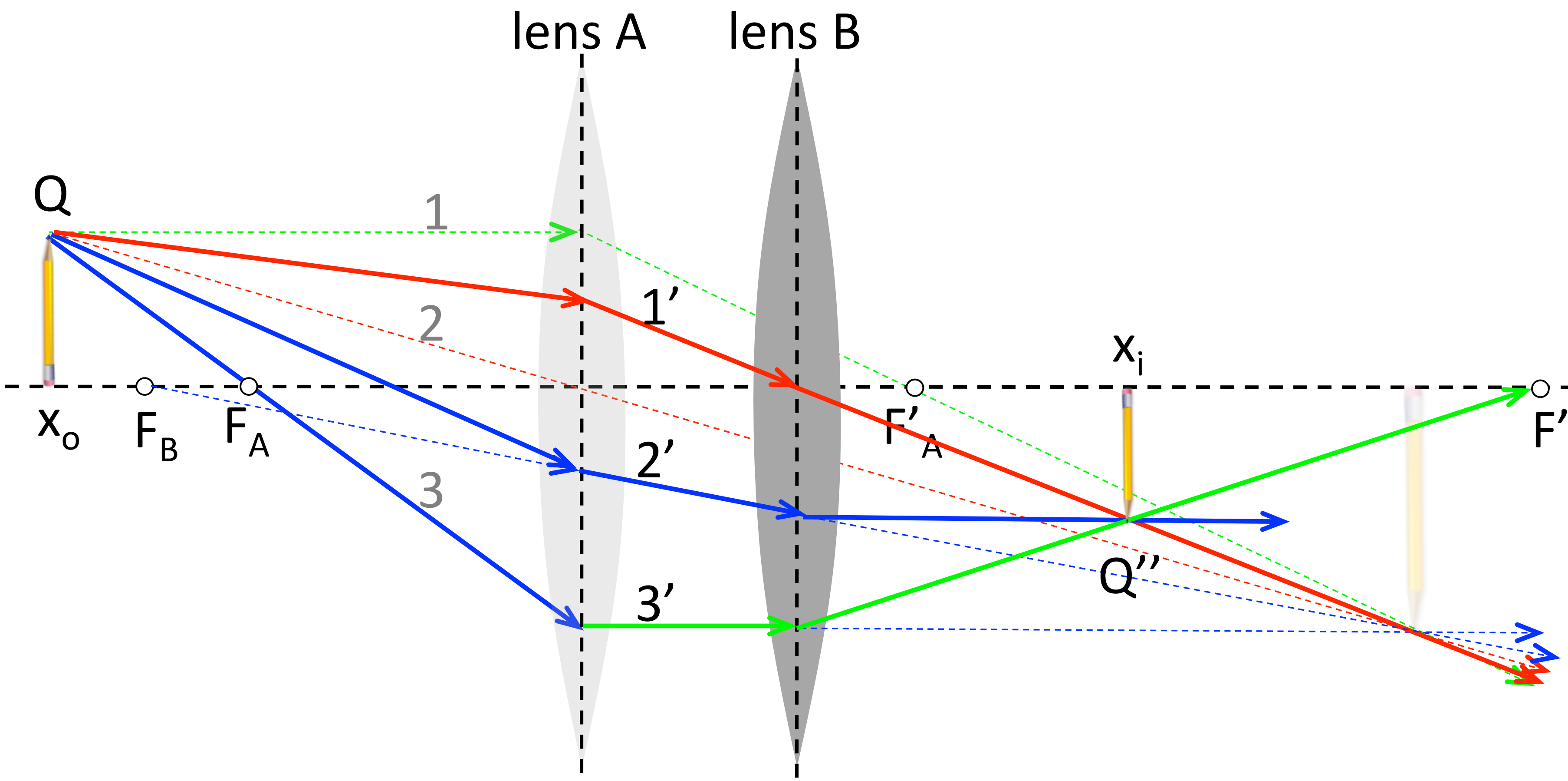
The image is *real*, *inverted,* and *larger* than the object

Image formation: converging lens



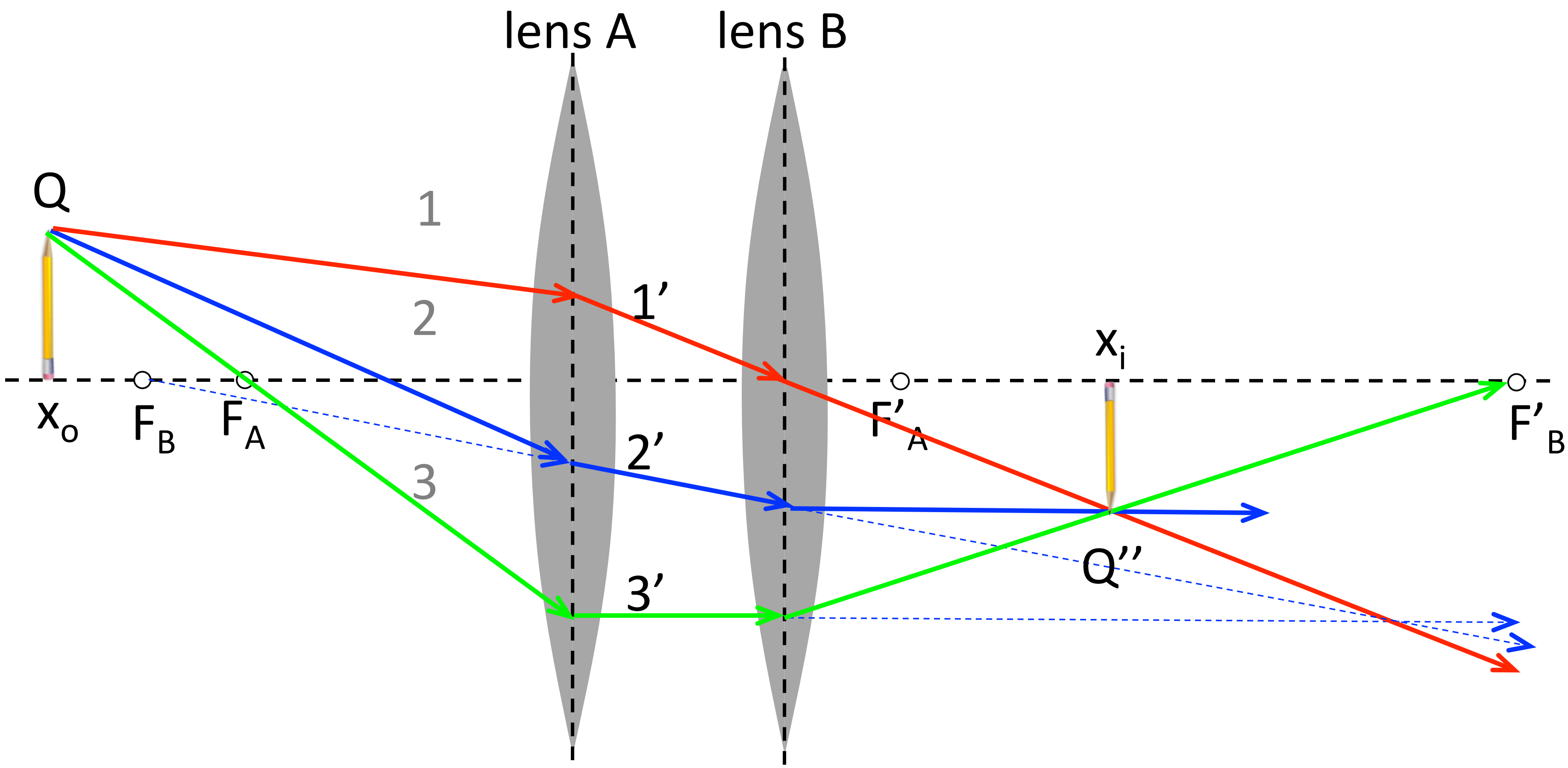
Fill additional rays (ignoring lens B) that are "special" for lens B

Image formation: converging lens



Use special rays incident on lens B to construct the image of the two-lens system at their intersection at Q'', located at x_i

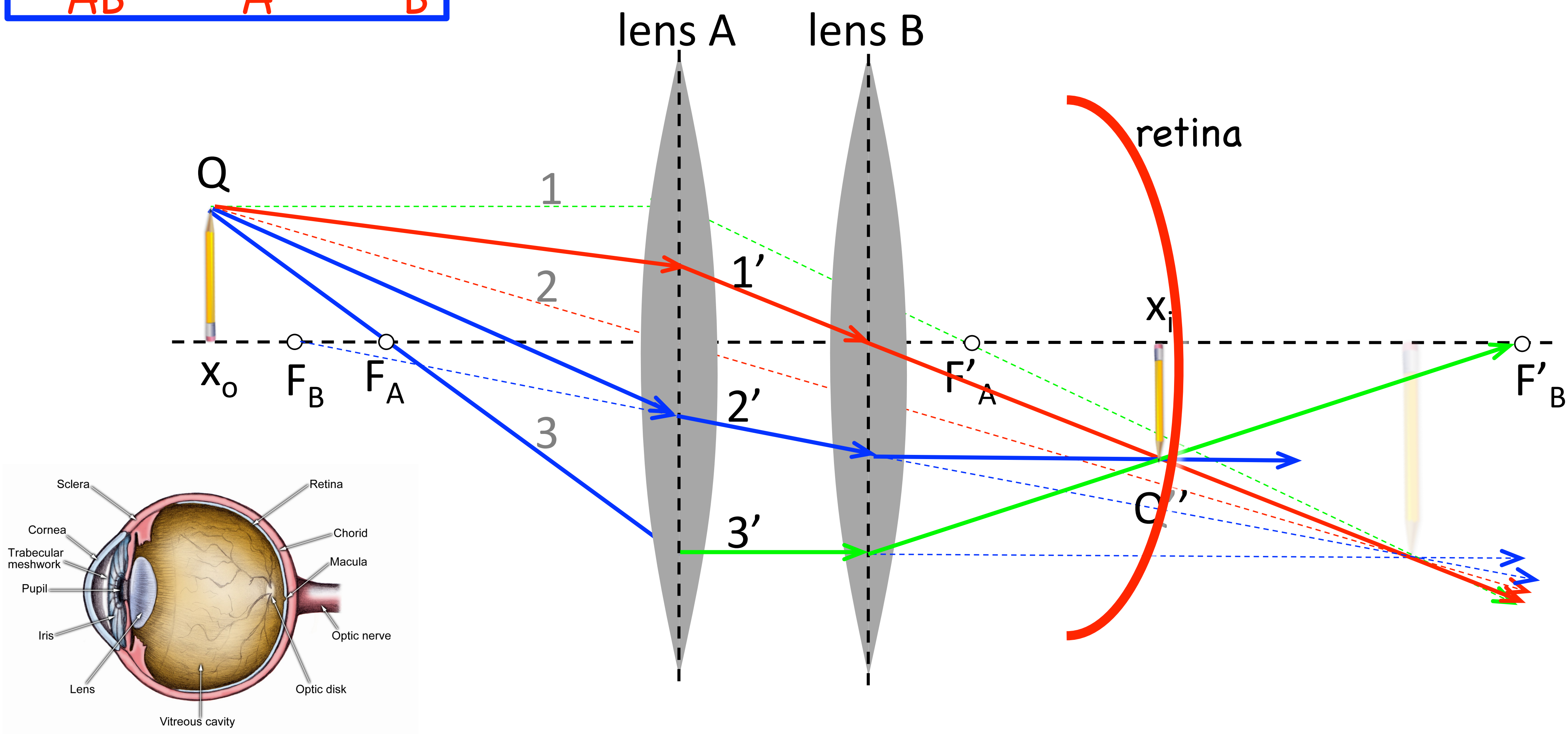
Image formation: converging lens



Ignore all the auxilary rays to obtain the final image, located at x_i

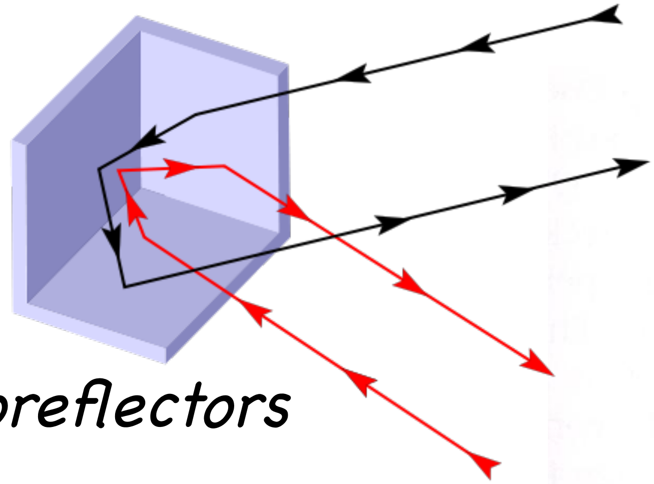
Corrective lens: *glasses*

$$P_{AB} = P_A + P_B$$



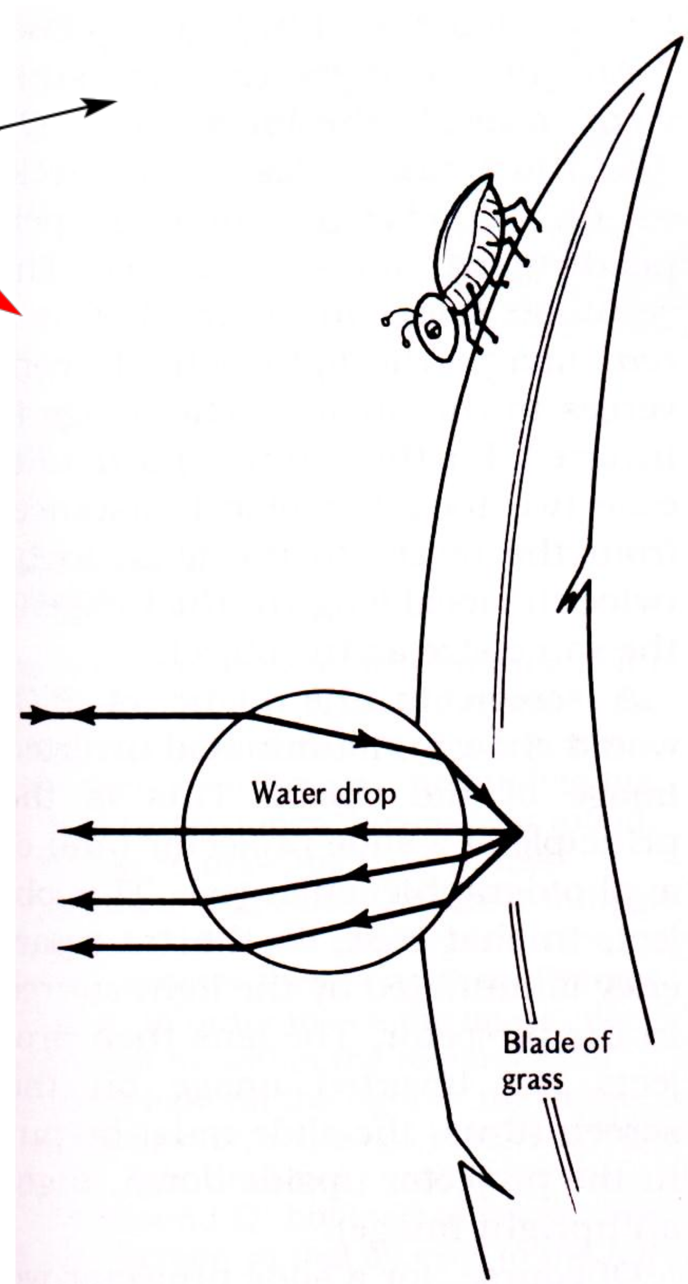
- If you have 20/20 vision, the lens of your eye (lens B) produces an image correctly on your retina. Here it produces *an image behind the retina, which looks blurry.*
- If you add a corrective lens in front, like glasses or contacts, *the combination of two lenses produces an image correctly at your retina*

Ball lens retroreflector



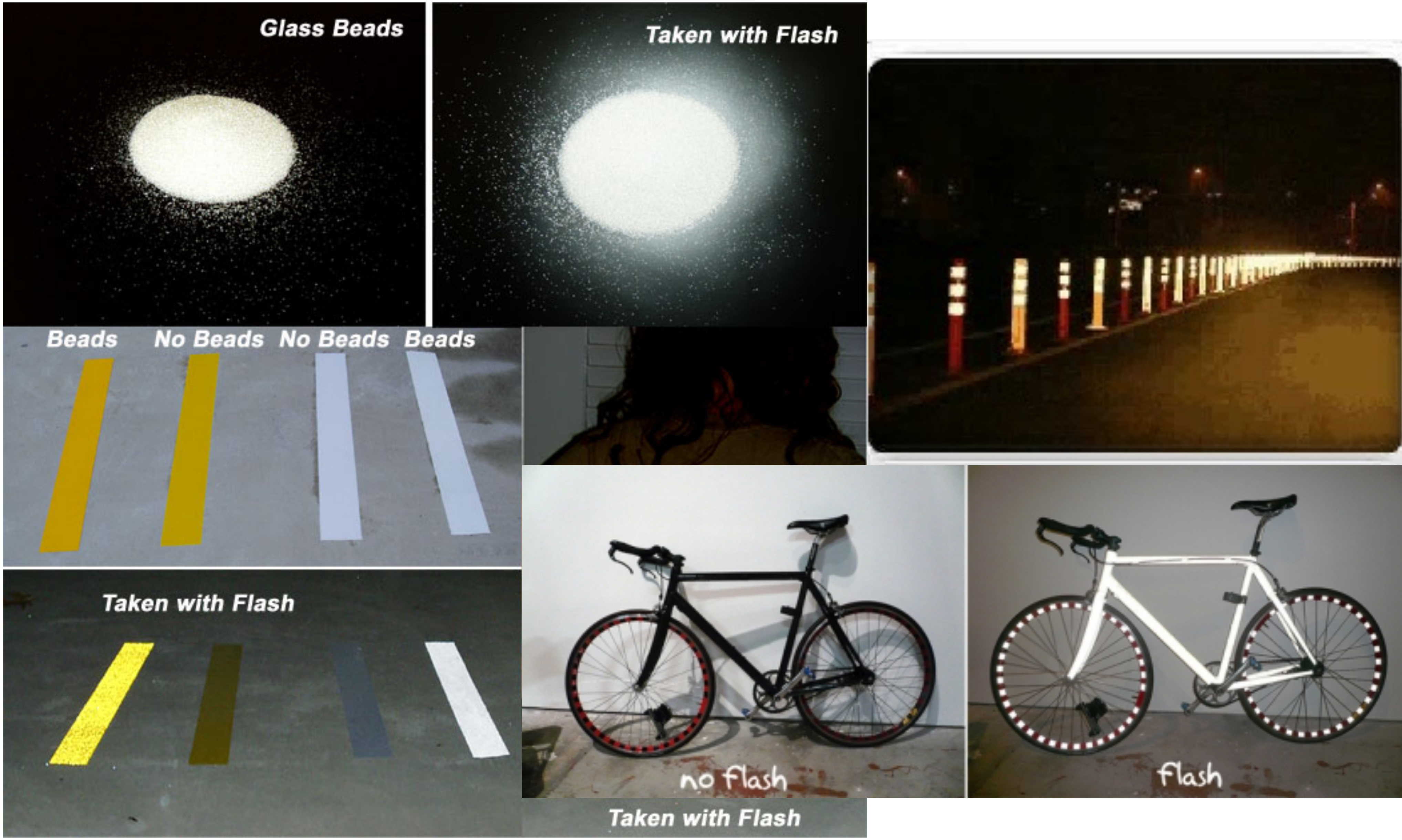
conventional retroreflectors

- A sphere of water, here a droplet on a blade of grass, acts as a converging lens
- The focal point is just past the surface of the glass, so light is reflected off the grass and returns the way it came
- A new kind of retroreflector



Ball lens retroreflector

Safety applications:



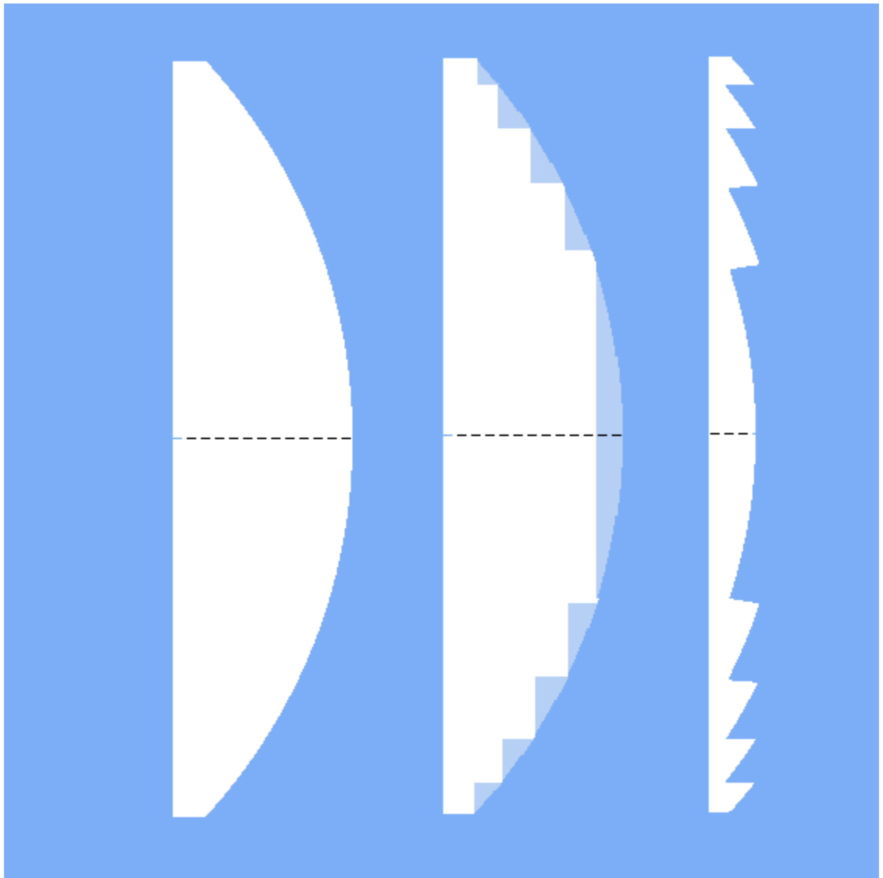
Fresnel lens

1788–1827

- high power large lens is too thick and heavy
- *A. J. Fresnel* (a French physicist):

refraction at surface -> most of the glass unnecessary

remove non-essential glass and flatten remaining segments



Fresnel lens

applications:

light house

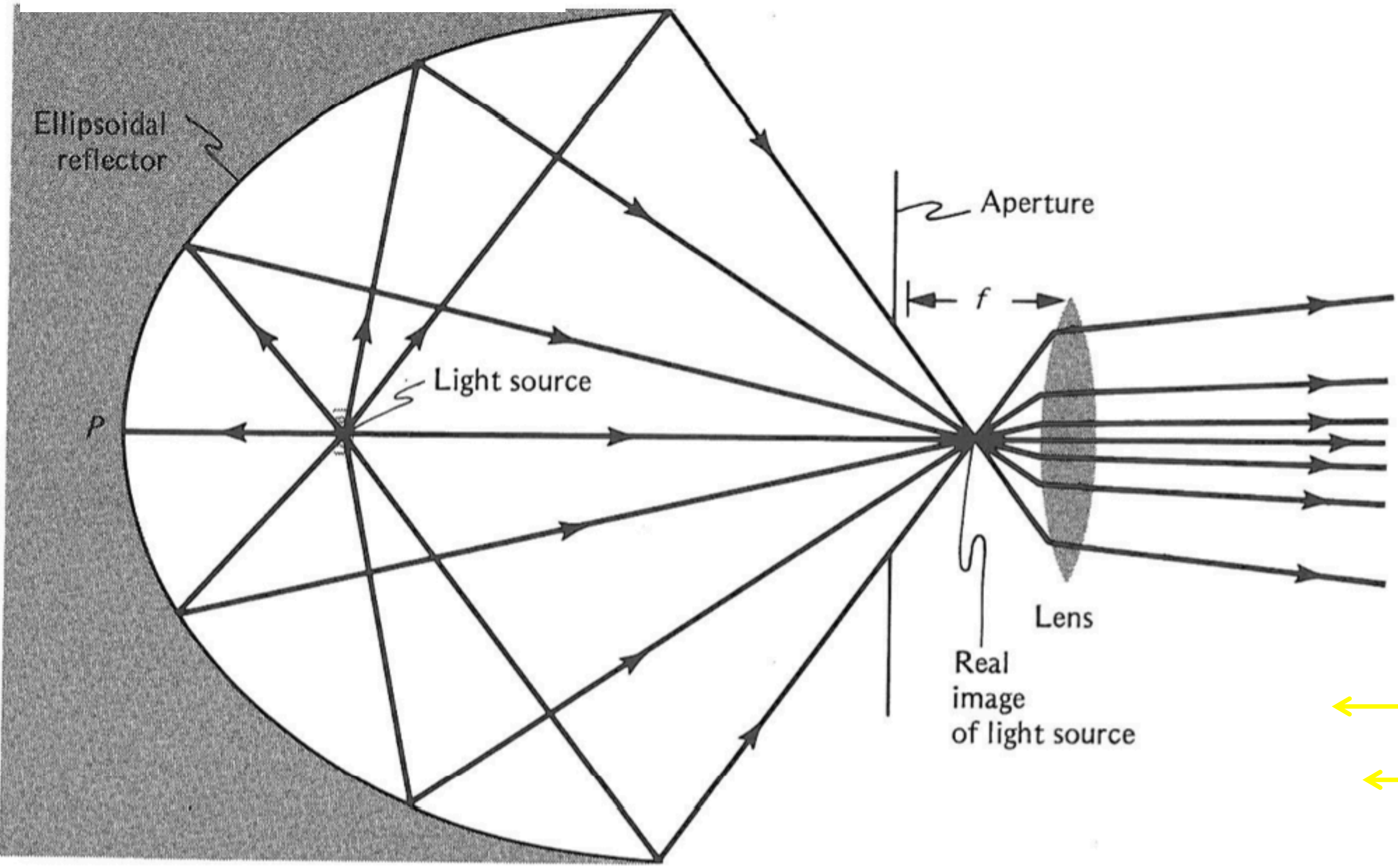
overhead projector

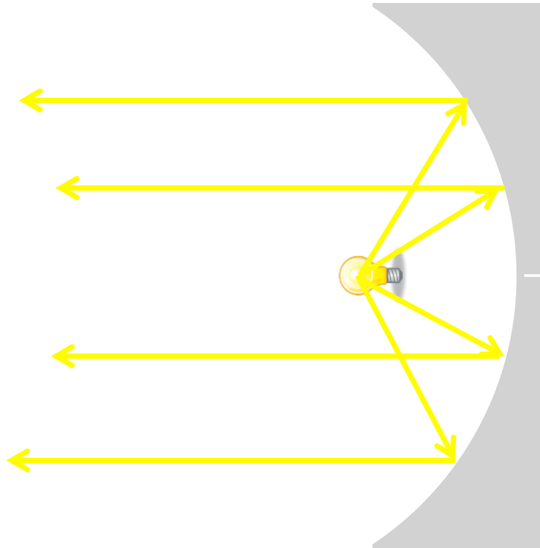
optical landing system
aircraft carrier

Ellipsoidal spotlight

applications: *beam for theater spot light*

no aberration





Contrast with spherical or parabolic mirror