I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

1. Rectilinear propagation of light

2. Law of reflection

3. Law of refraction (Snell’s Law)

4. Independence of rays

I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

Rectilinear Propagation of Light

(when refractive index, *n*, is constant)

$$n = \frac{c}{v}$$

n = refractive index

c = speed of light in a vacuum

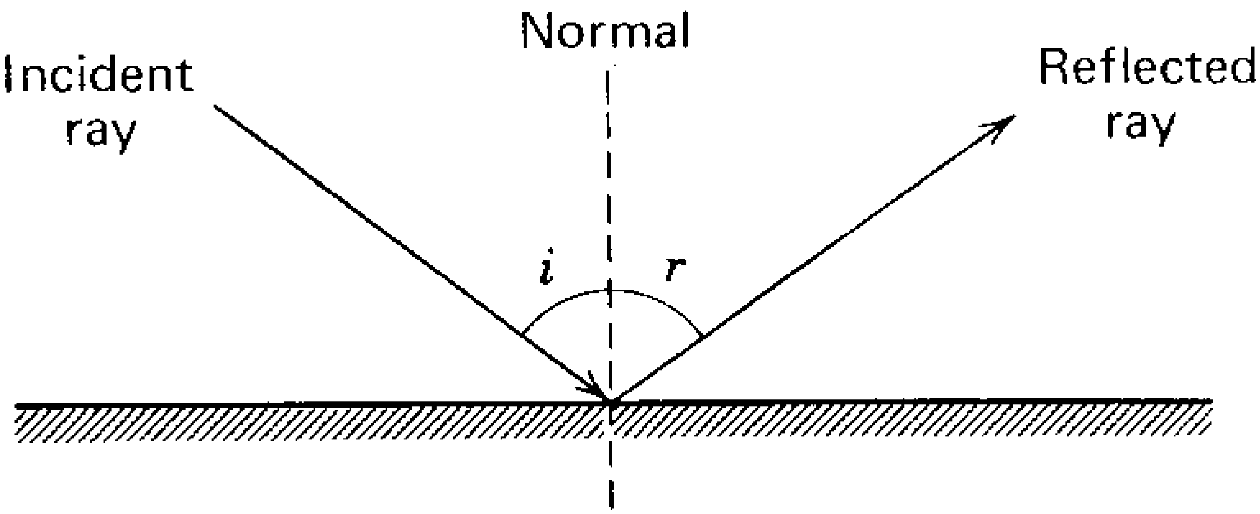
v = speed of light in the medium

I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

Law of Reflection

($i = r$)



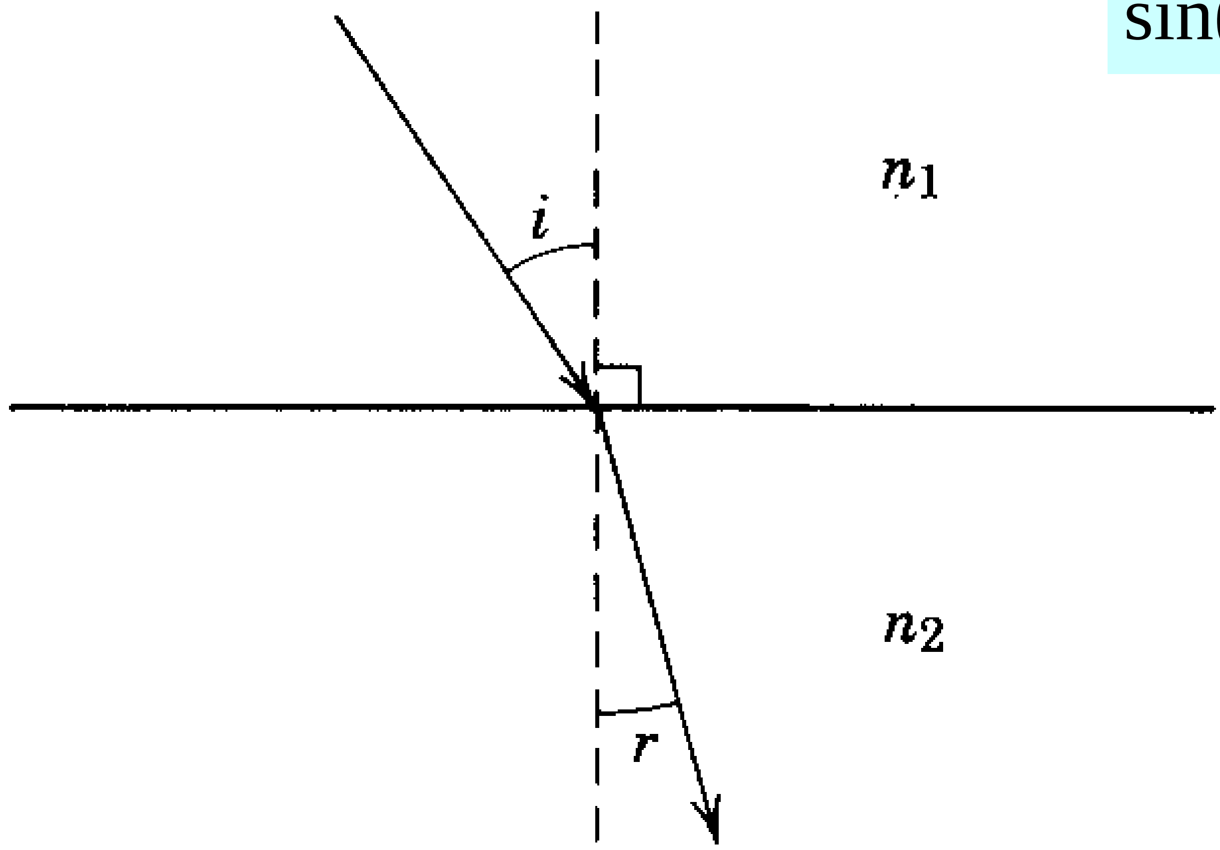
From Slayter, Fig. 1-2, p. 4

I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

Law of Refraction (Snell's Law)

$$\frac{\sin(i)}{\sin(r)} = \frac{n_2}{n_1}$$



From Slayter, Fig. 1-3, p. 6

I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

Independence of Rays

Assumption: light rays travel independently through space

I.A.4 Optics (Lens Theory)

I.A.4.a Basic Laws of Classical Geometrical Optics

What about electrons?

1. Rectilinear propagation of light

2. Law of reflection

3. Law of refraction (Snell's Law)

4. Independence of rays

Except #4, these laws hold for electrons.

When current density in an electron beam is too high, electrons can interfere with one another (charge repulsion)

I.A.4 Optics (Lens Theory)

I.A.4.b Classical vs. Electron Optics

CLASSICAL OPTICS:

- Refractive index changes abruptly at glass lens surface
- It remains constant between the surfaces
- Refraction of light at surfaces of different refractive indices makes it possible to construct imaging lenses
- Glass surfaces can be shaped

ELECTRON OPTICS:

- Changes in refractive index are gradual
- Rays follow continuous curves rather than broken straight lines
- Refraction of electrons accomplished by magnetic fields in space around charged electrodes or solenoids

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

- Fundamental principles of optics govern the **design and operation** of LMs **and** TEMs

- **Basic optical principles** involving the use of refractile elements (lenses) to form magnified images are **identical** in both the LM **and** TEM

- TEM only differs from the LM in:

Radiation used: e^- vs. photons

Radiation is bent or refracted differently

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

GEOMETRICAL OPTICS:

- Study of paths followed by 'rays' of light or electrons through lenses and apertures

- Study of geometrical constructions used to find the relative positions and sizes of objects and their images

Definition:

Ray of light or electrons is an **infinitely** thin pencil or beam

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

GEOMETRICAL OPTICS: (Ideal World)

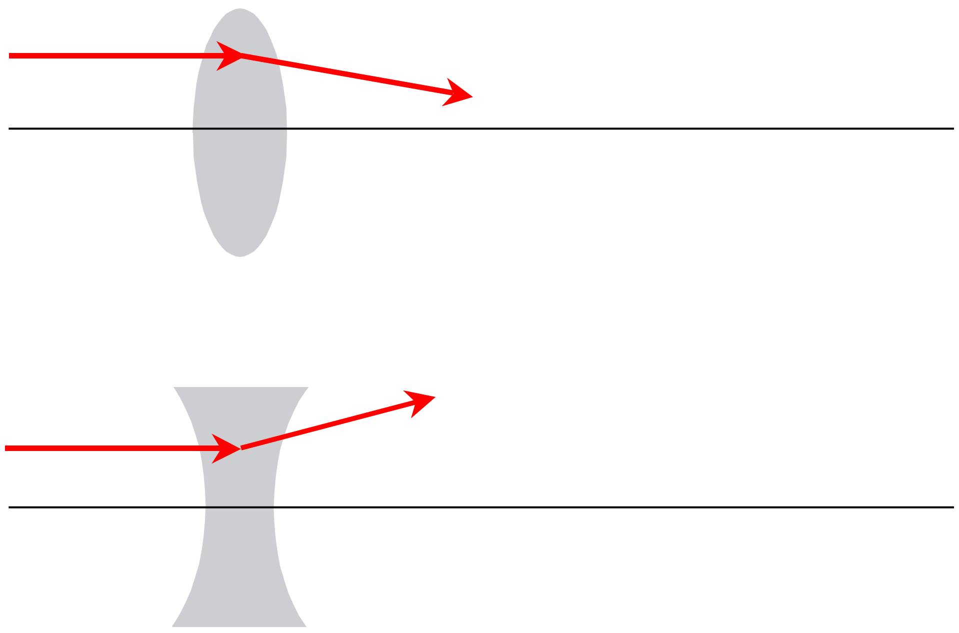
PHYSICAL OPTICS: (Real World)

- 'Rays' are really just a useful abstraction
- They do not physically exist because of diffraction, which arises owing to the wave nature of light and electrons
- Interference and diffraction phenomena can **not** be explained in simple geometrical terms but can be derived from the principles of physical optics
- **IMPORTANT: All results** obtained in geometrical optics can be derived from the principles of physical optics

I.A.4 Optics (Lens Theory)

I.A.4.d Ideal vs. Real Lenses

Lenses: used to **bend** light or electrons in a **predictable** way



I.A.4 Optics (Lens Theory)

I.A.4.d Ideal vs. Real Lenses

Lenses: used to **bend** light or electrons in a **predictable** way

Properties of an **ideal lens** with an axis of rotational symmetry:

1. Each ray of the bundle of rays which passes from an **object point** will be refracted by the **ideal** lens to meet in **one image point**

2. Rays originating from points which lie on a **plane perpen-dicular** to the axis, must be imaged in a plane which is also perpendicular to the axis

3. The **image appears like the object irrespective** of magni-fication (relative linear dimensions of object preserved in the image)

I.A.4 Optics (Lens Theory)

I.A.4.d Ideal vs. Real Lenses

OK, so what about the 'real world' (*i.e.* real lenses)?

In practice, imaging by a real lens does **not** correspond to that of an ideal lens

- Object point represented in image plane by **Airy disc**

(Recall: caused by wave properties of light and electrons)

I.A.4 Optics (Lens Theory)

I.A.4.d Ideal vs. Real Lenses

REAL LENSES

Glass (light) verses electromagnetic (electron) lenses:

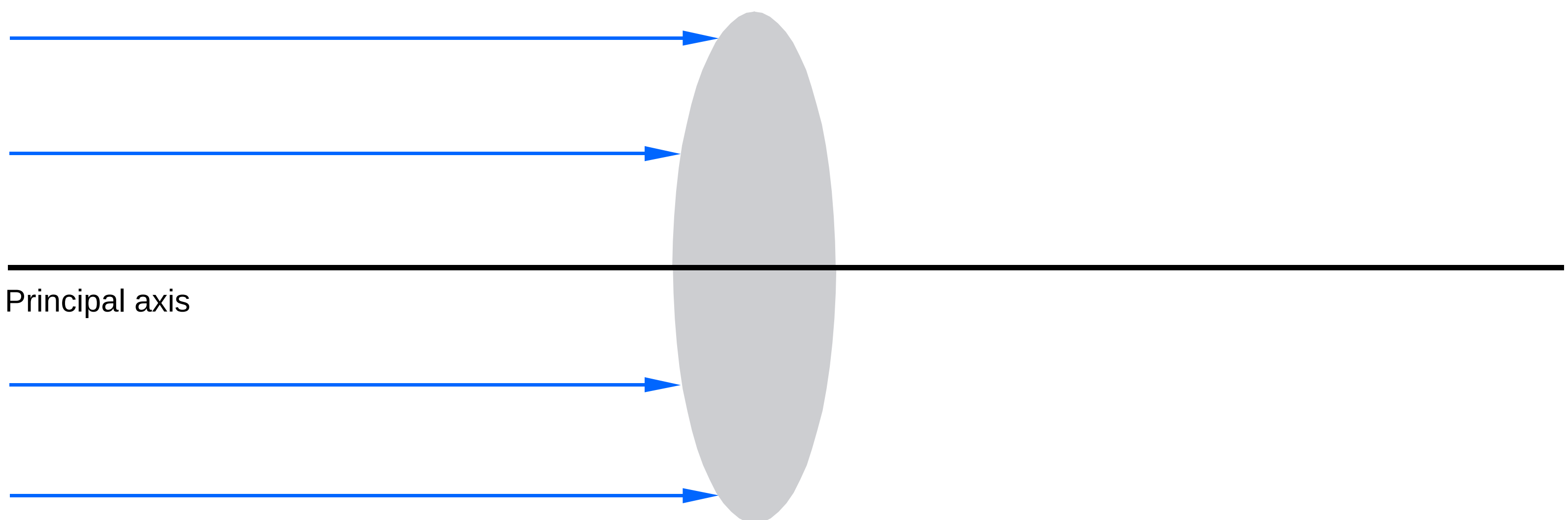
- Electron beam does not change in velocity as it passes through the magnetic field
- Light rays slow down when passing into a medium of higher refractive index
- Refraction continuous with electrons
- Light follows straight lines and bends sharply at glass surfaces
- Electrons follow spiral trajectories through magnetic fields

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Method of construction of ray diagrams based on three simple principles

1. All rays entering the lens **parallel to the axis** are brought to a common point on the axis, the **focal point**



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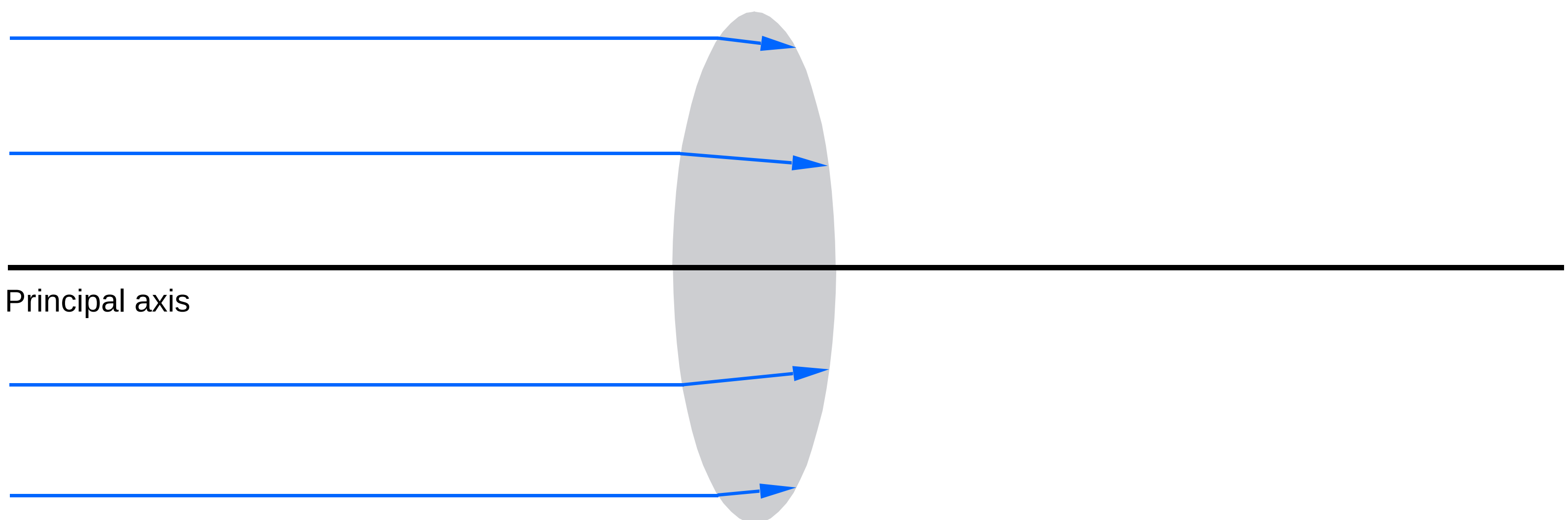

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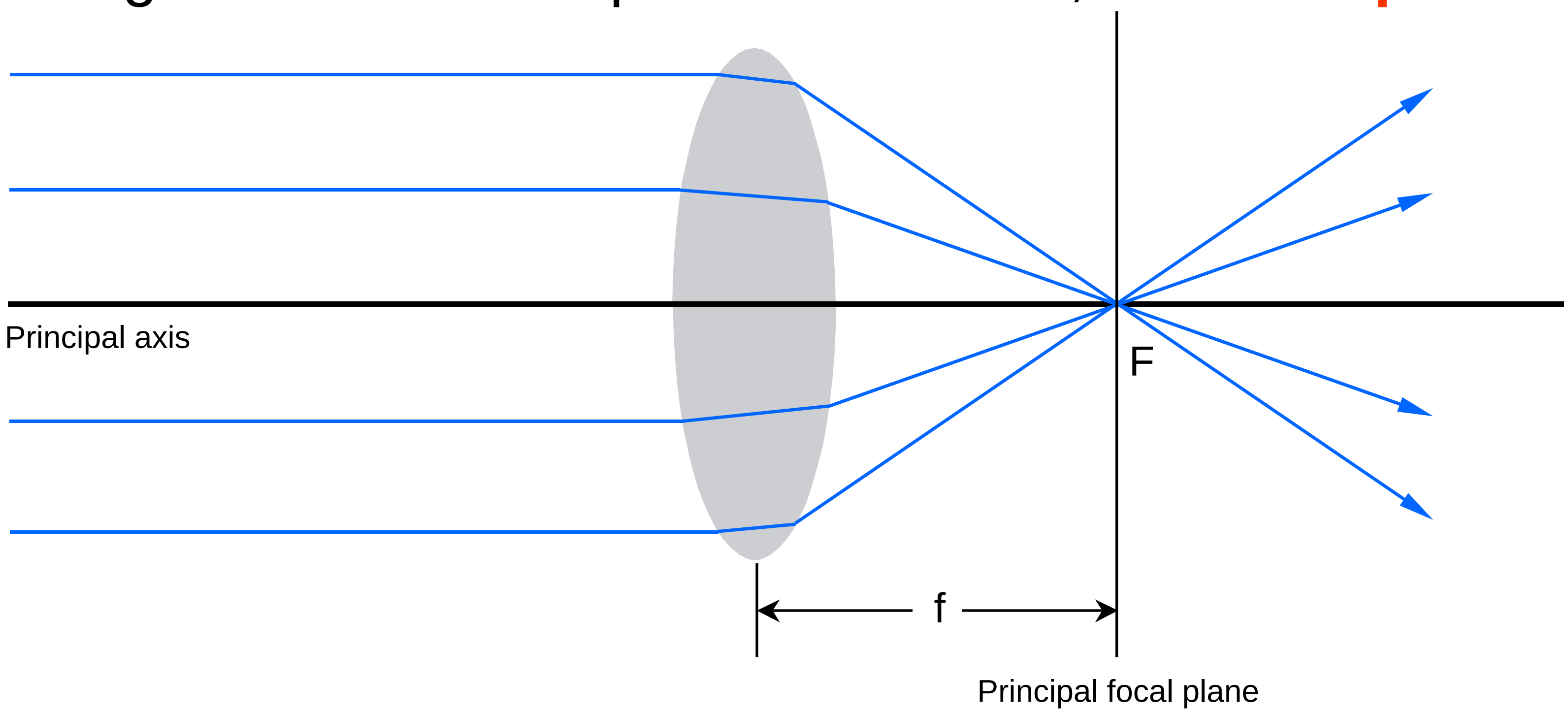

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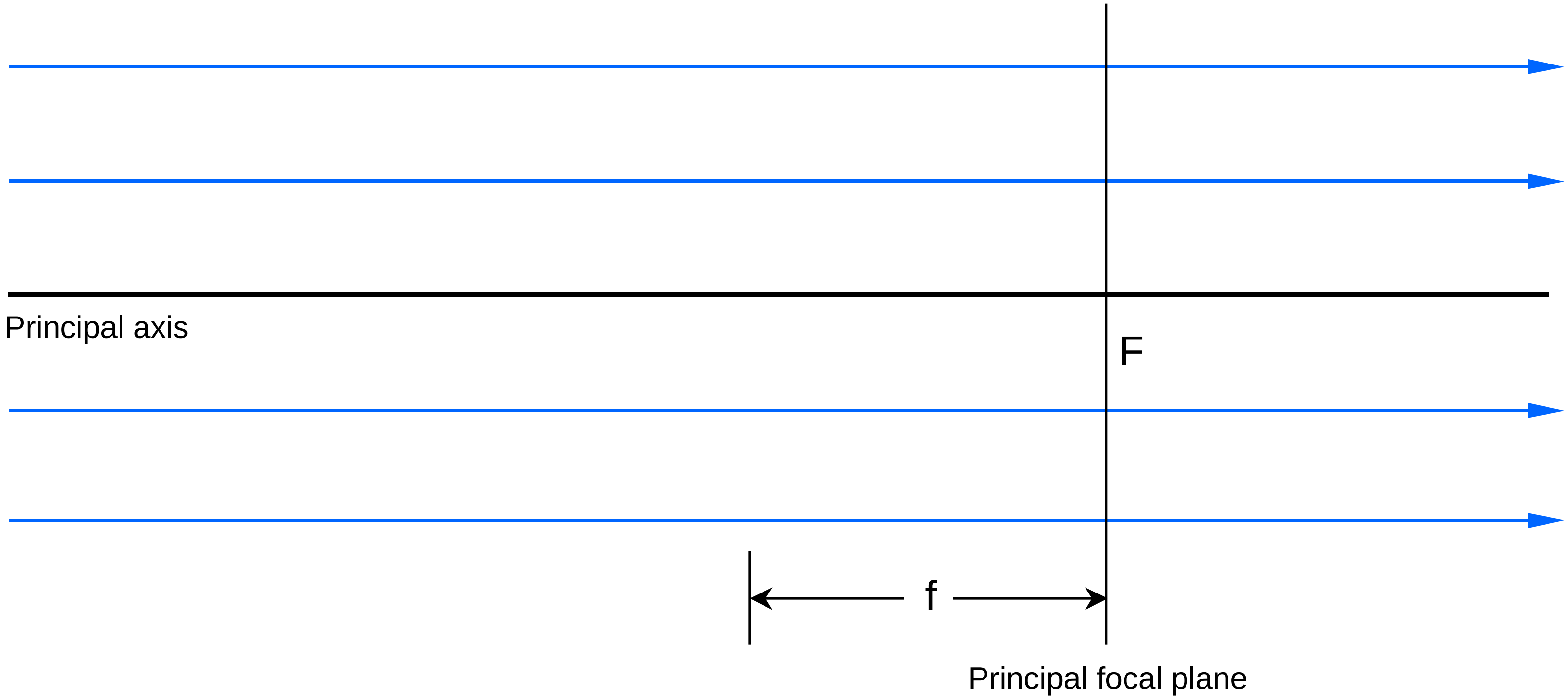


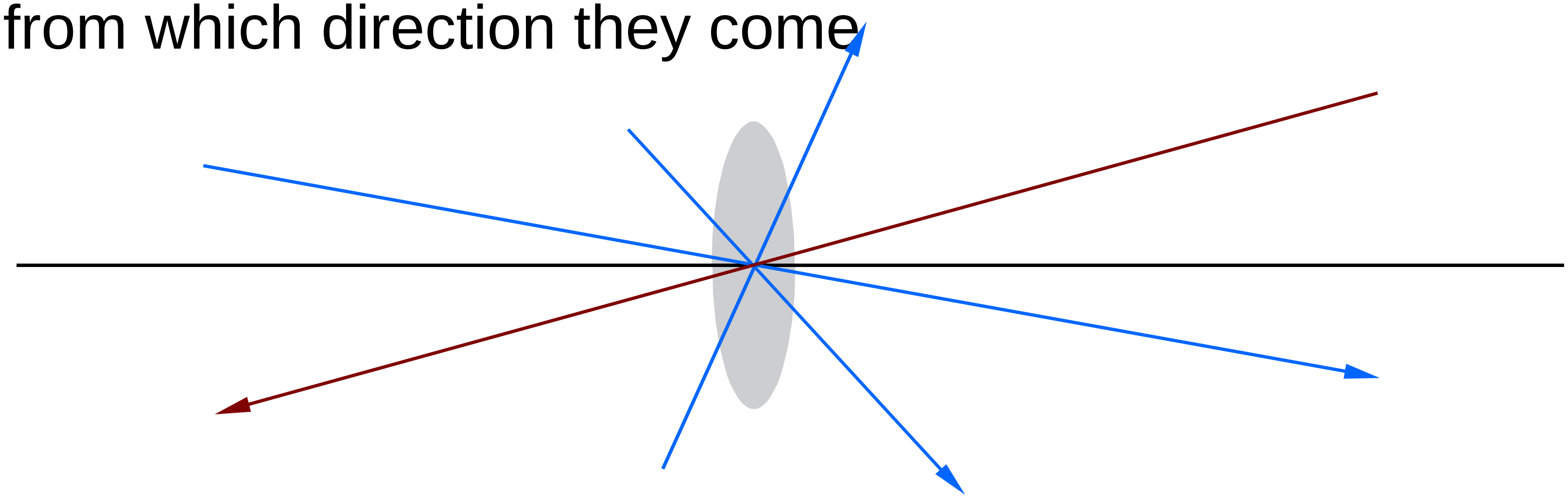
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Method of construction of ray diagrams based on three simple principles

1. All rays entering the lens **parallel to the axis** are brought to a common point on the axis, the **focal point**

2. All rays passing through the **geometrical center** of the lens are **undeviated** and pass straight on, no matter from which direction they come



I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

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2. All rays passing through the **geometrical center** of the lens are **undeviated** and pass straight on, no matter from which direction they come

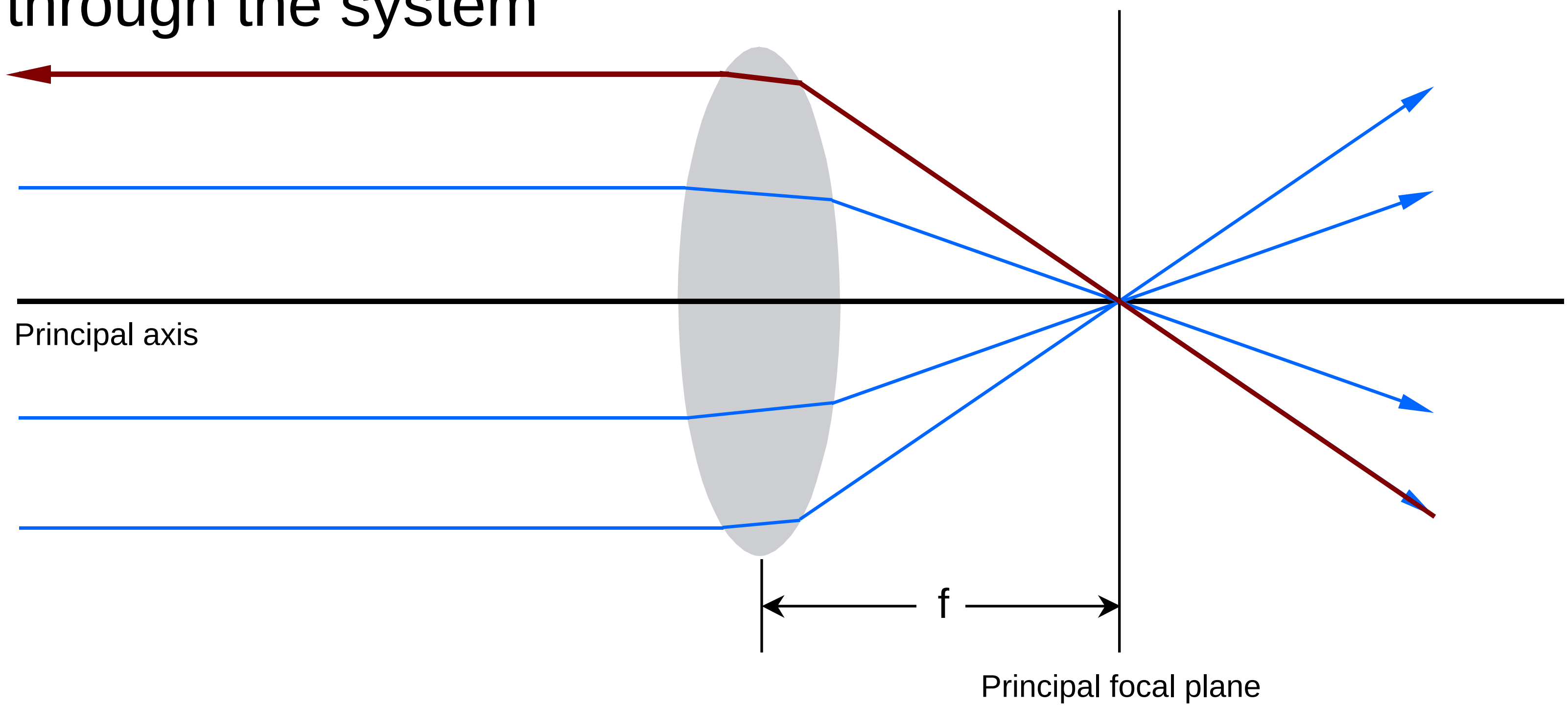
3. **Principle of reversibility:** if the direction of a ray is reversed in any system the ray **exactly retraces** its path through the system

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Method of construction of ray diagrams based on three simple principles

3. Principle of reversibility: if the direction of a ray is reversed in any system the ray **exactly retraces** its path through the system



I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

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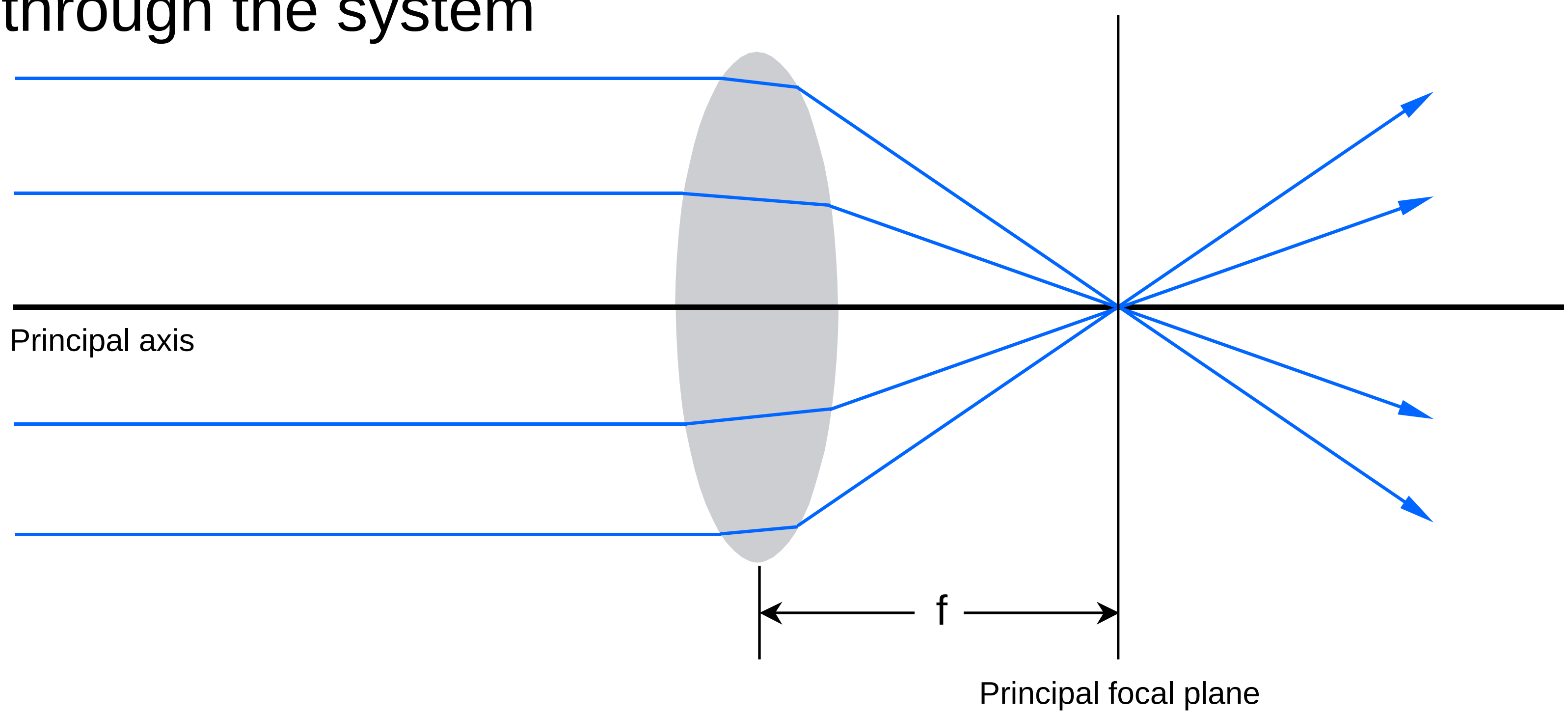

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Method of construction of ray diagrams based on three simple principles

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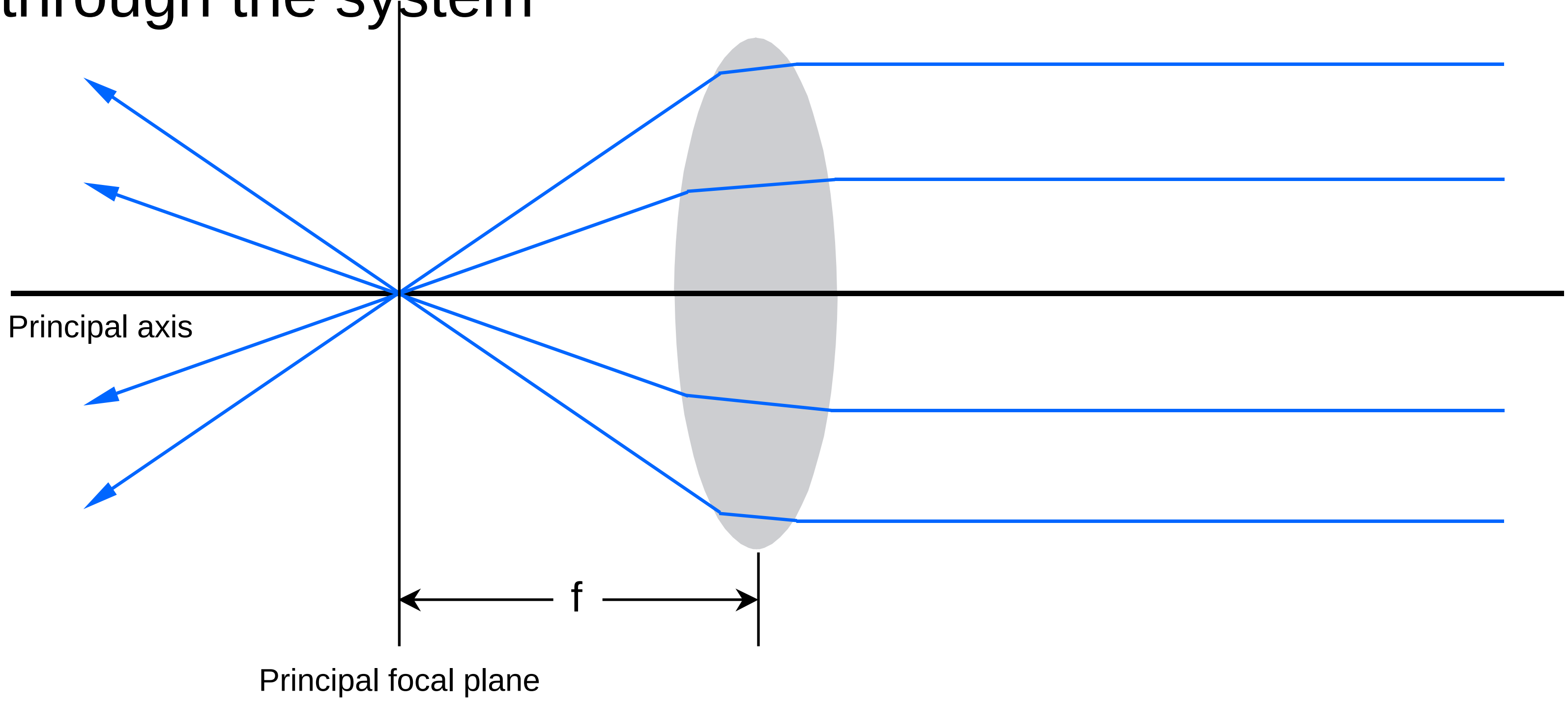
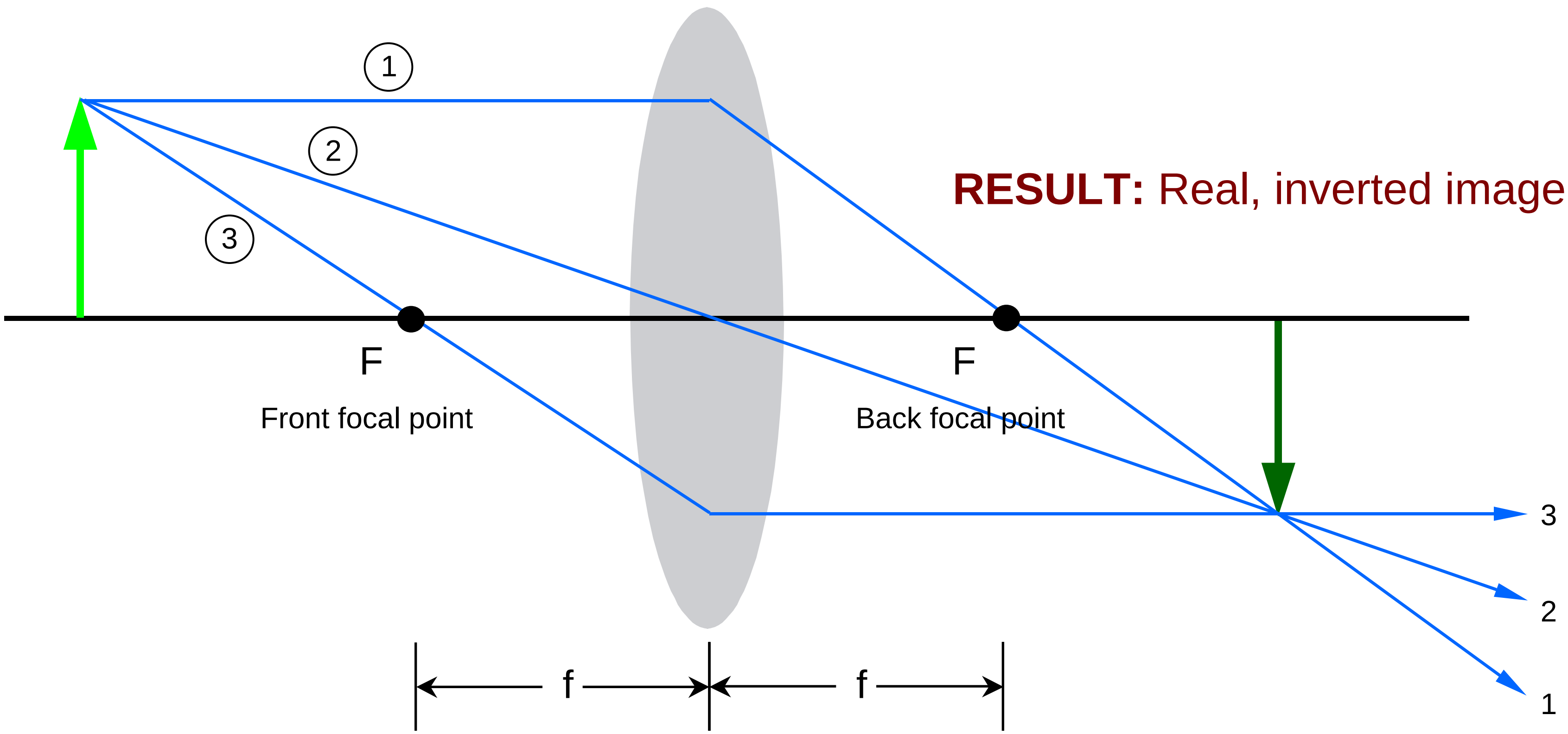


I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #1: Object distance > focal length



I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

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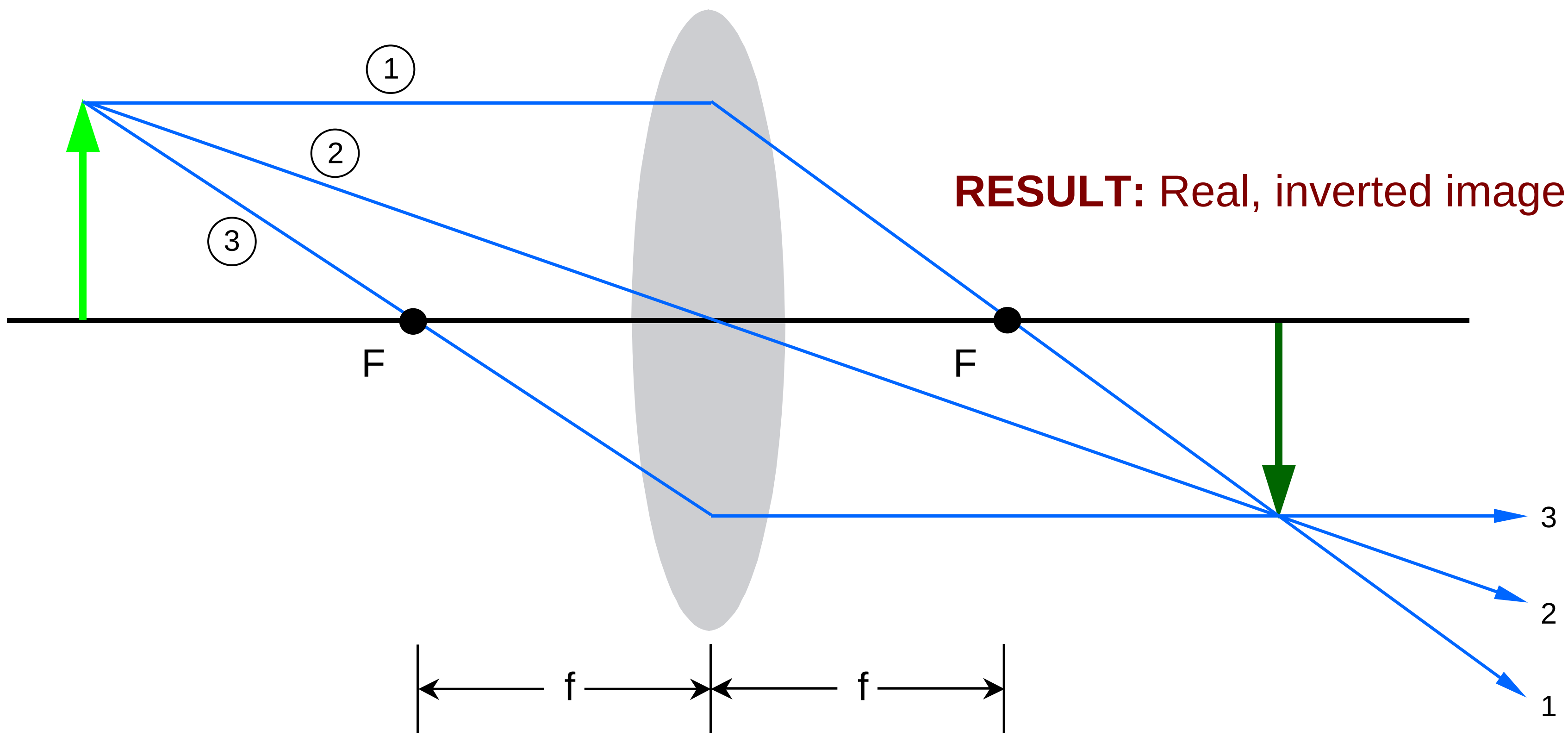

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

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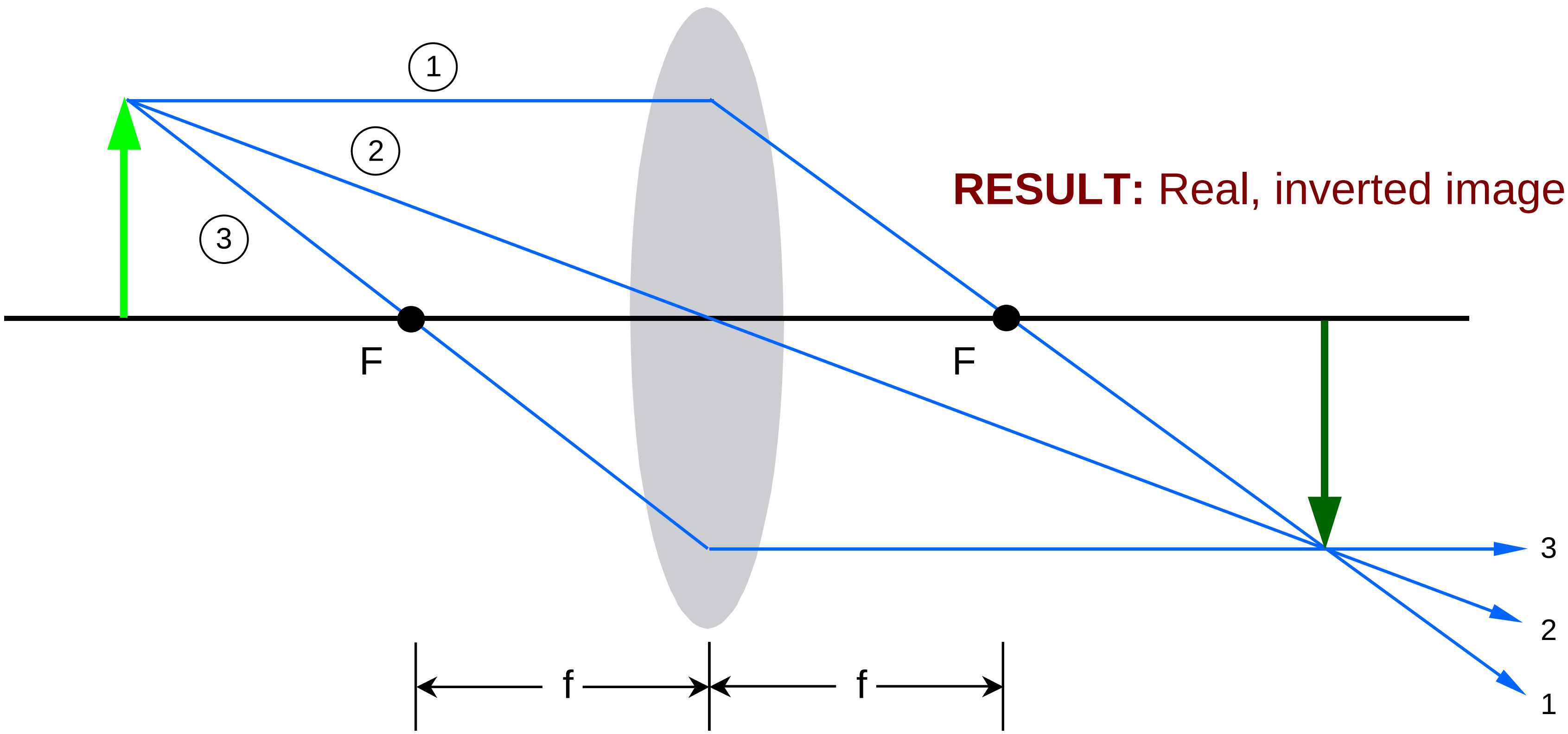


I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #1: Object distance > focal length

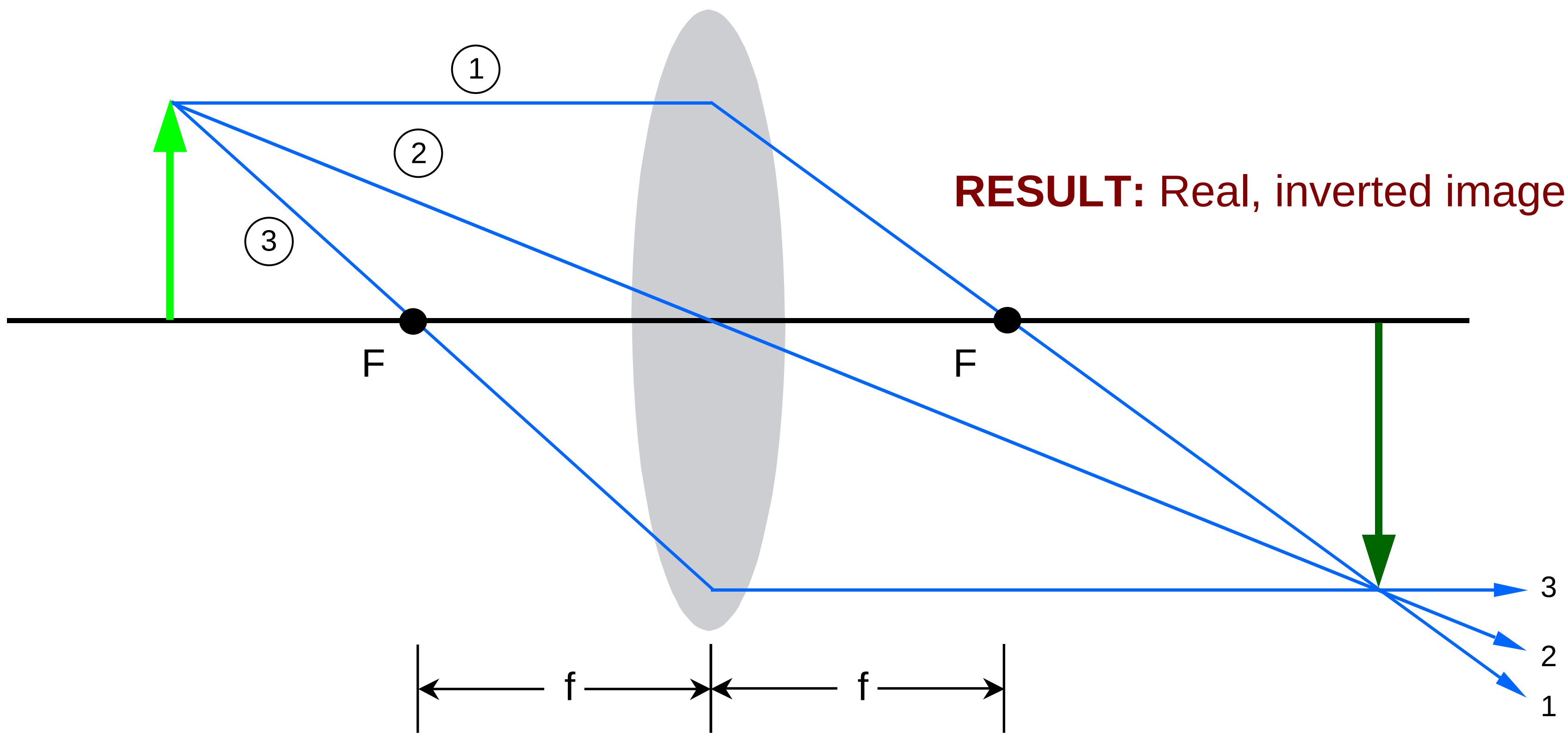
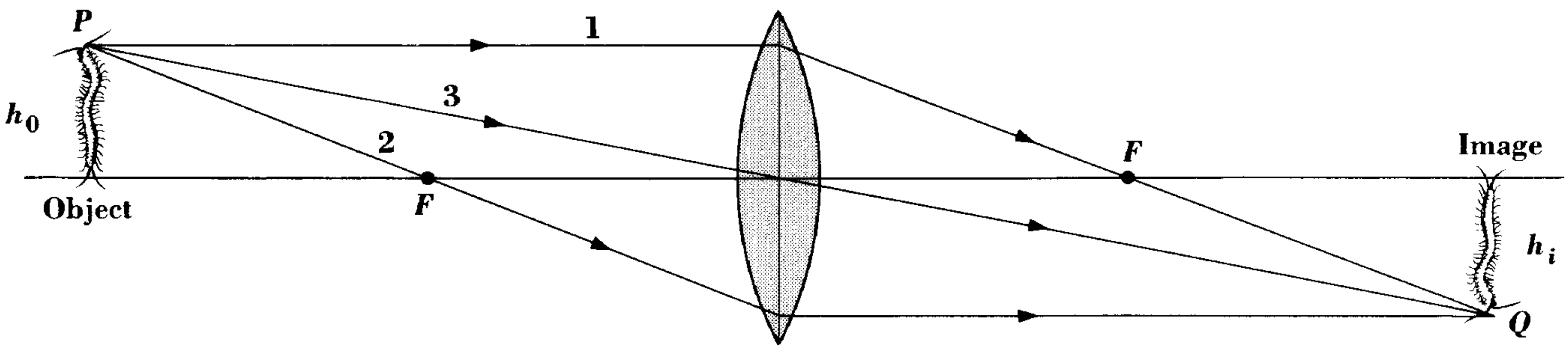


Image Formation by a Thin Convex Lens

CASE #1: Object distance > focal length

RESULT: Real, inverted image



From Young, Fig. 4-10, p. 127

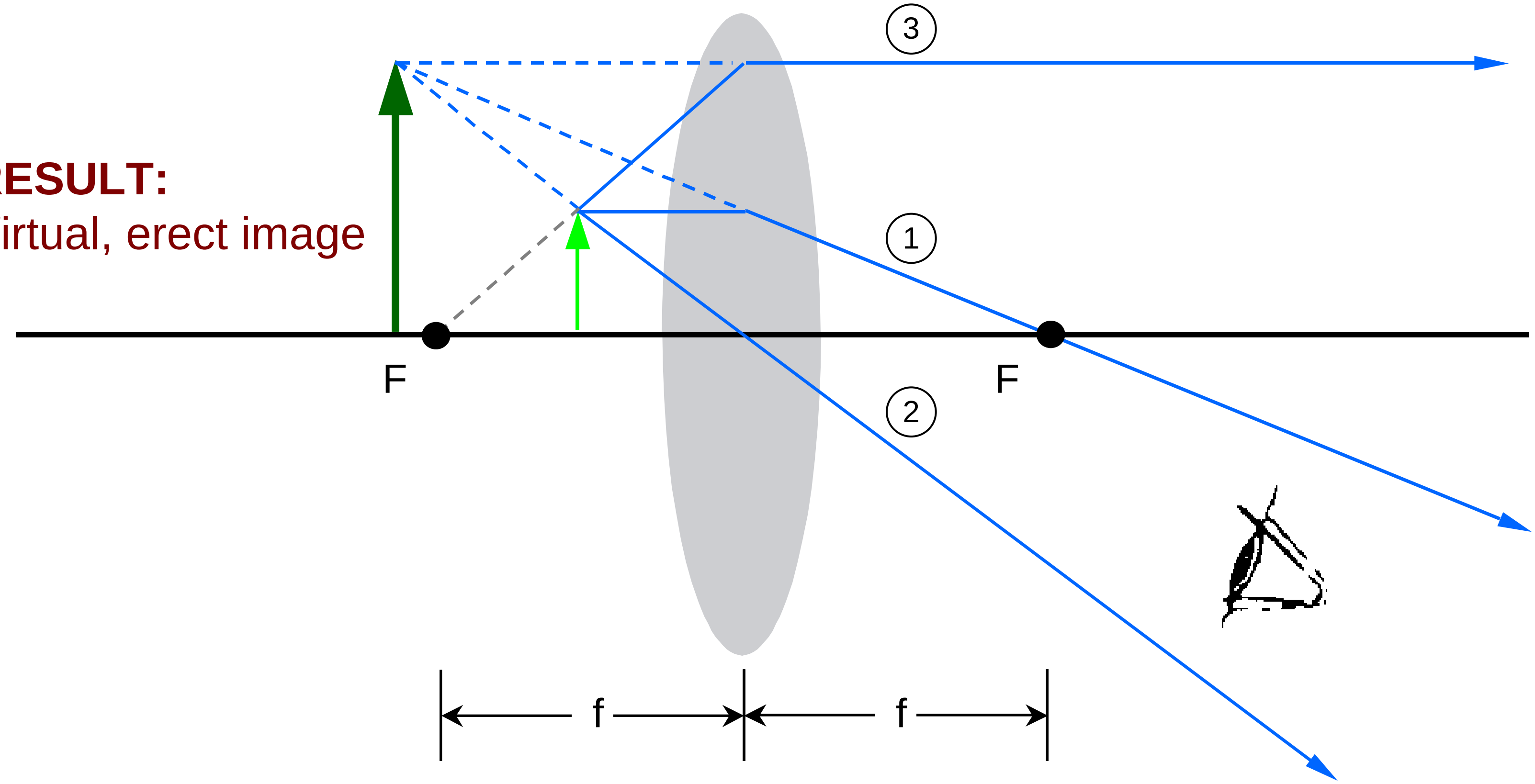
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #2: Object distance < focal length

RESULT:
Virtual, erect image



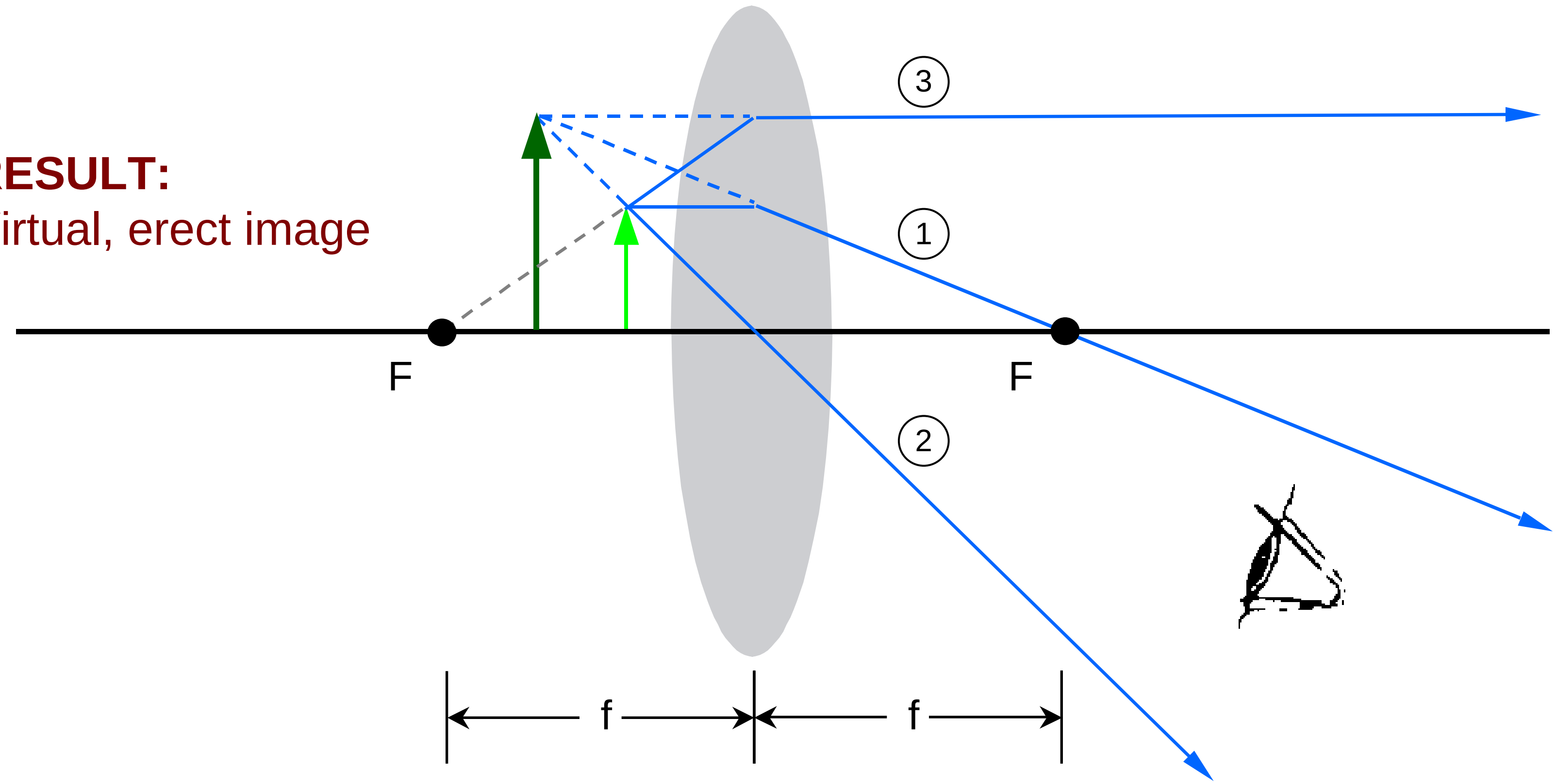
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #2: Object distance < focal length

RESULT:
Virtual, erect image



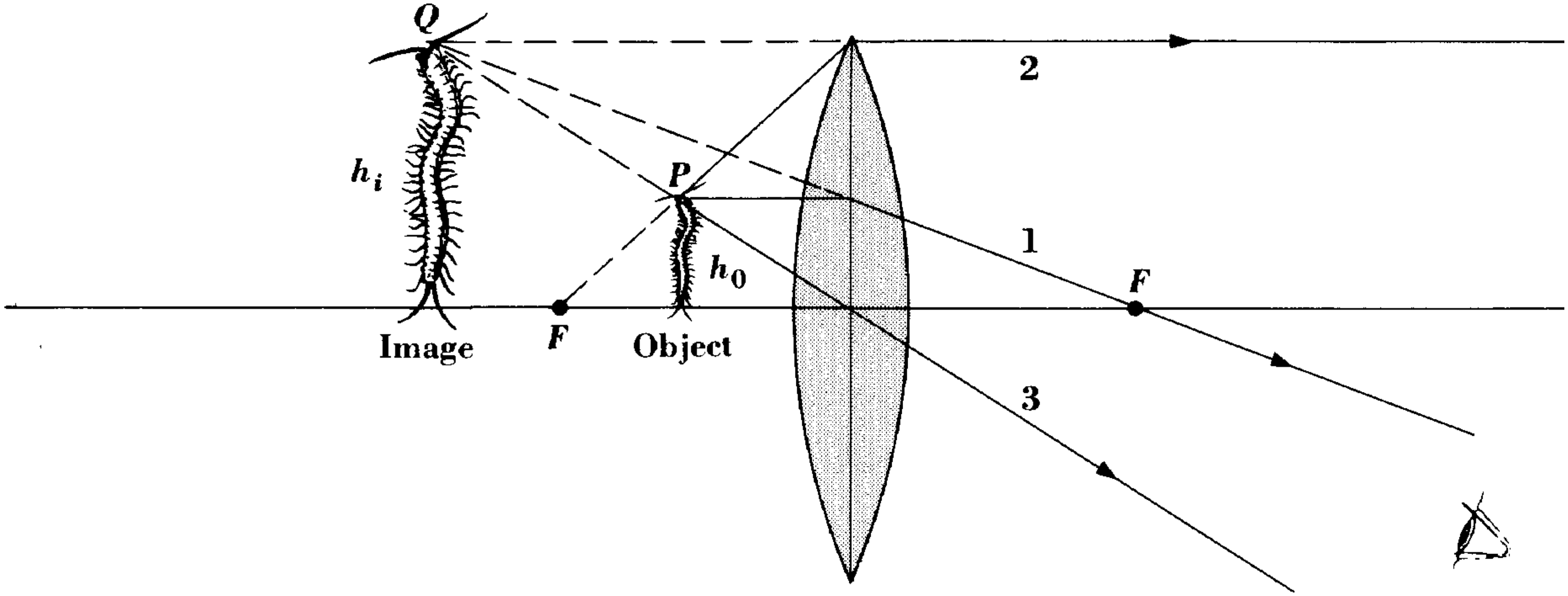
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #2: Object distance < focal length

RESULT: Virtual, erect image



From Young, Fig. 4-10, p. 127

I.A.4 Optics (Lens Theory)

I.A.4.f Definitions

Real vs. Virtual Images

REAL IMAGE:

- Rays physically reunite
- Can expose a photographic plate

VIRTUAL IMAGE:

- Rays appear to diverge
- Rays not concentrated at the position of a virtual image
- Cannot expose a photographic plate
- But can place an optical system (*e.g.* eye) behind the lens

Enables divergent rays to be focused to form a real image

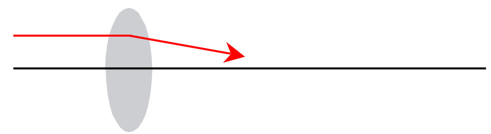
Intermediate lens of TEM sometimes used this way in order to reduce the final size of the real image formed by the projector lenses

I.A.4 Optics (Lens Theory)

I.A.4.f Definitions

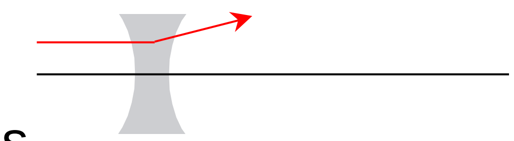
Converging and Diverging Lenses

Converging (positive) lens:



- Bends rays toward the axis
- Positive focal length
- Forms real inverted image of object placed to the left of the first focal point
- Forms erect virtual image of object placed between the first focal point and the lens.

Diverging (negative) lens:



- Bends rays away from the axis
- Negative focal length
- Object placed anywhere to the left results in an erect virtual image
- Not possible to construct a negative magnetic lens although negative electrostatic lenses can be made.

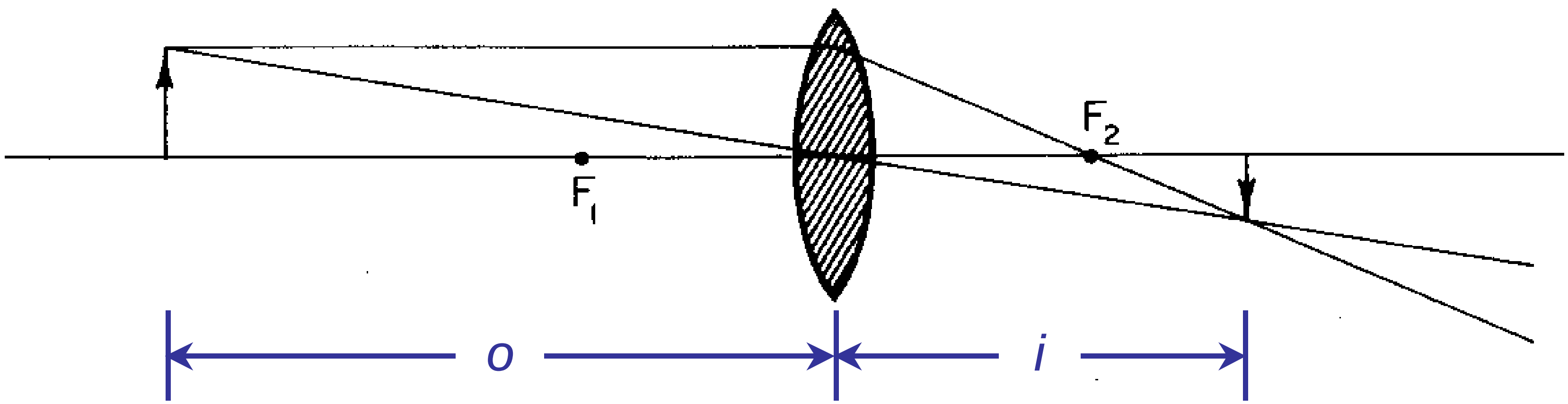
I.A.4 Optics (Lens Theory)

I.A.4.g Lens Formula

THIN LENS EQUATION

$$\frac{1}{f} = \left(\frac{1}{o}\right) + \left(\frac{1}{i}\right)$$

f = focal length of thin lens
o = distance of object in front of lens
i = distance of image behind lens



From Sjostrand, Fig. II.11, p. 22

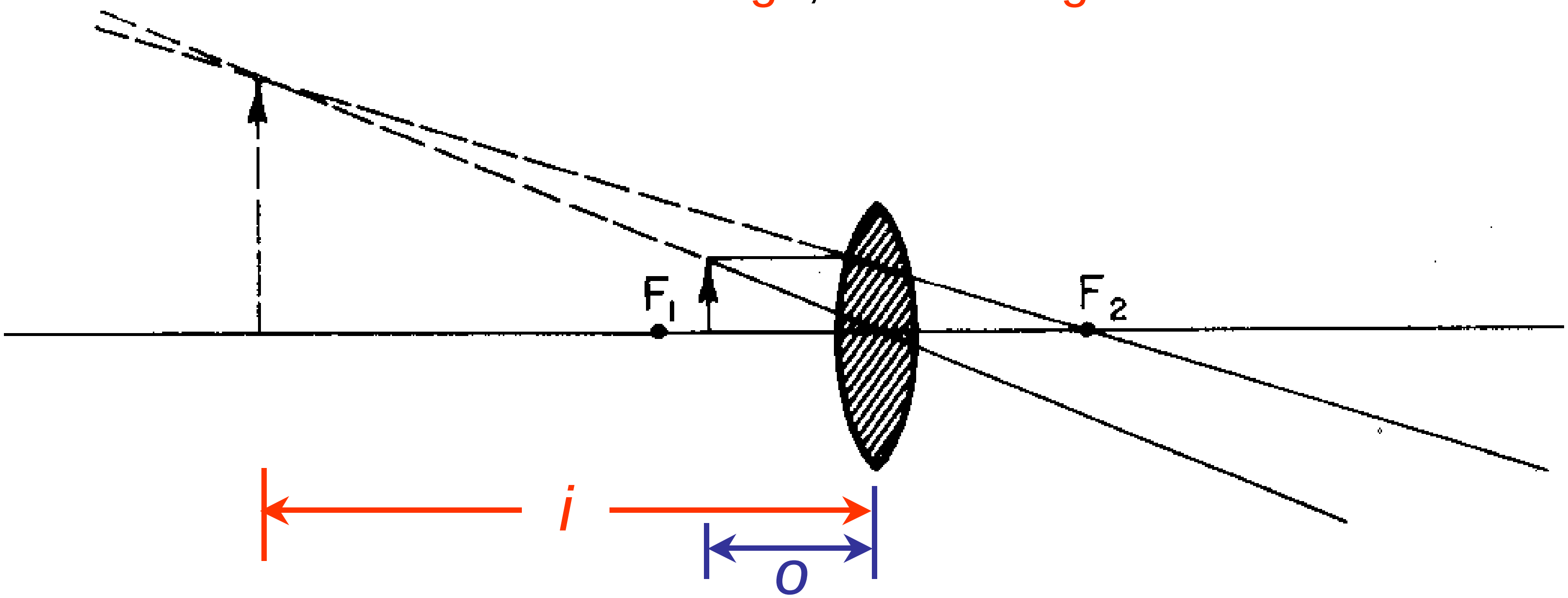
I.A.4 Optics (Lens Theory)

I.A.4.g Lens Formula

THIN LENS EQUATION

$$\frac{1}{f} = \left(\frac{1}{o}\right) + \left(\frac{1}{i}\right)$$

NOTE: For a virtual image, *i* has a negative value



From Sjostrand, Fig. II.13, p. 22

I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$M = \left| \frac{i}{o} \right|$$

It doesn't get any easier than this folks!

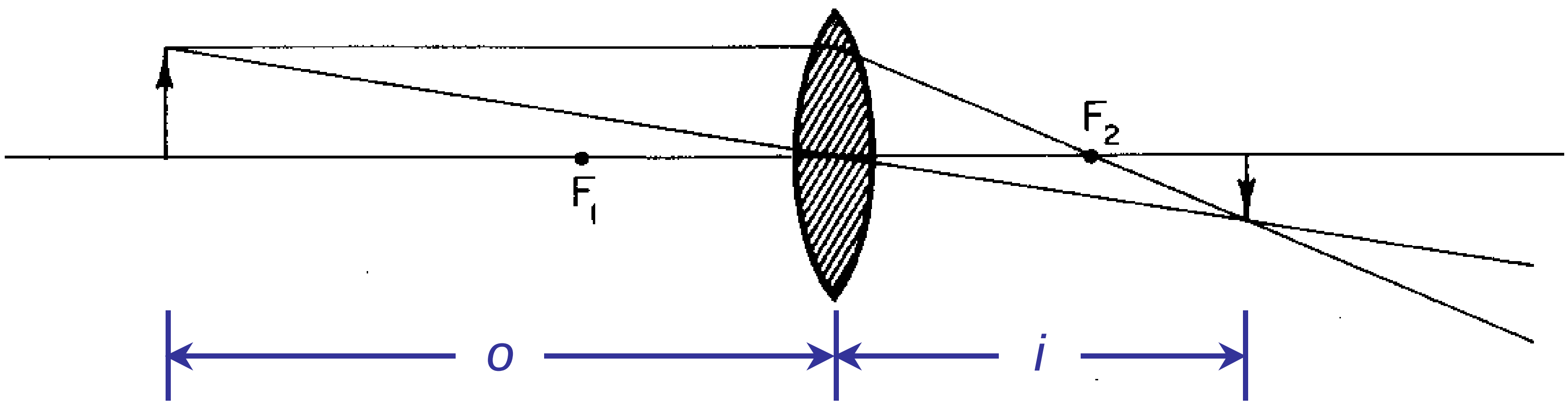
I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$M = \left| \frac{i}{o} \right|$$

For converging lens:

When object is **> 2f** in front of the lens, image is **real**, **inverted**, and **smaller** than the object ($M < 1$).



From Sjostrand, Fig. II.11, p. 22

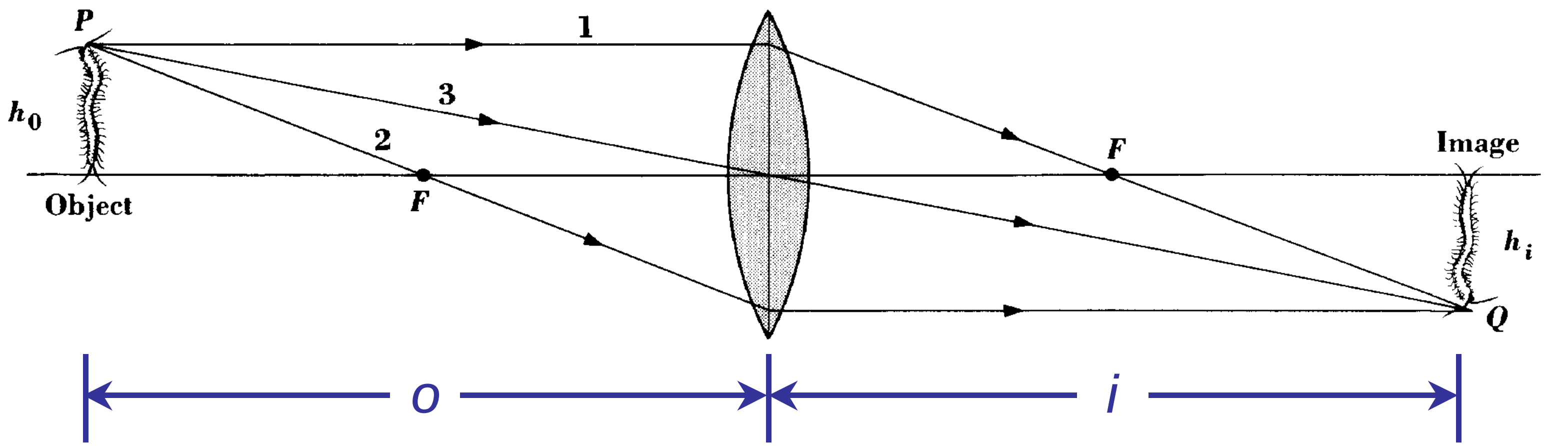
I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$M = \left| \frac{i}{o} \right|$$

For converging lens:

When object is ***2f*** in front of the lens, the image is **real, inverted,** and **the same size** as the object ($M = 1$).



From Young, Fig. 4-10, p. 127

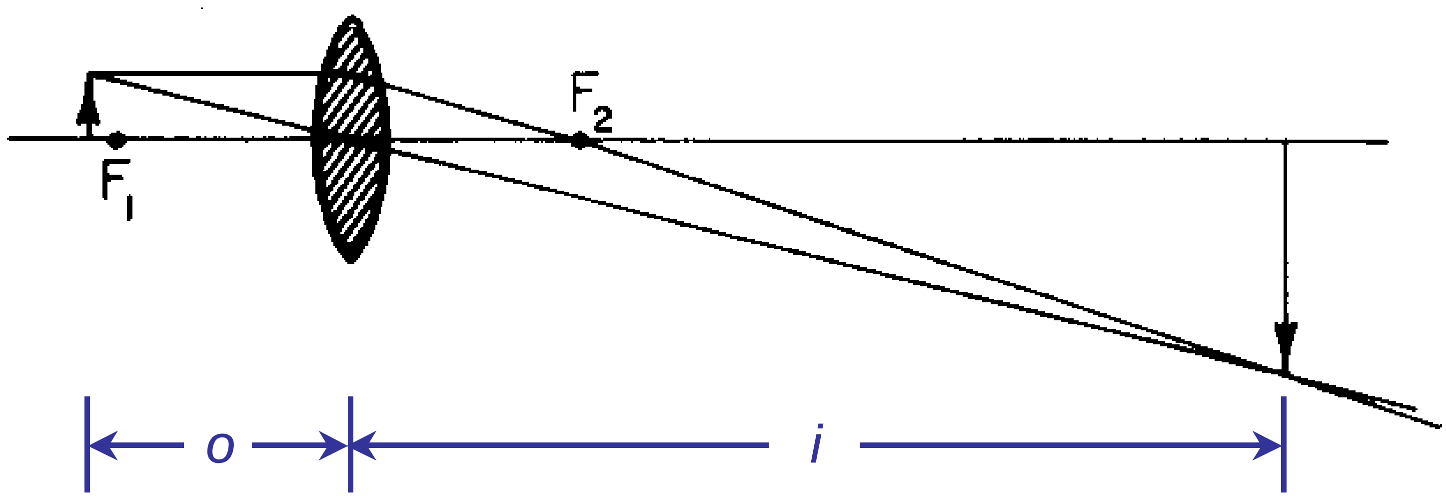
I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$M = \left| \frac{i}{o} \right|$$

For converging lens:

When object is **between *f* and 2*f***, the image is **real**, **inverted**, and **larger** than the object ($M > 1$).



From Sjostrand, Fig. II.12, p. 22

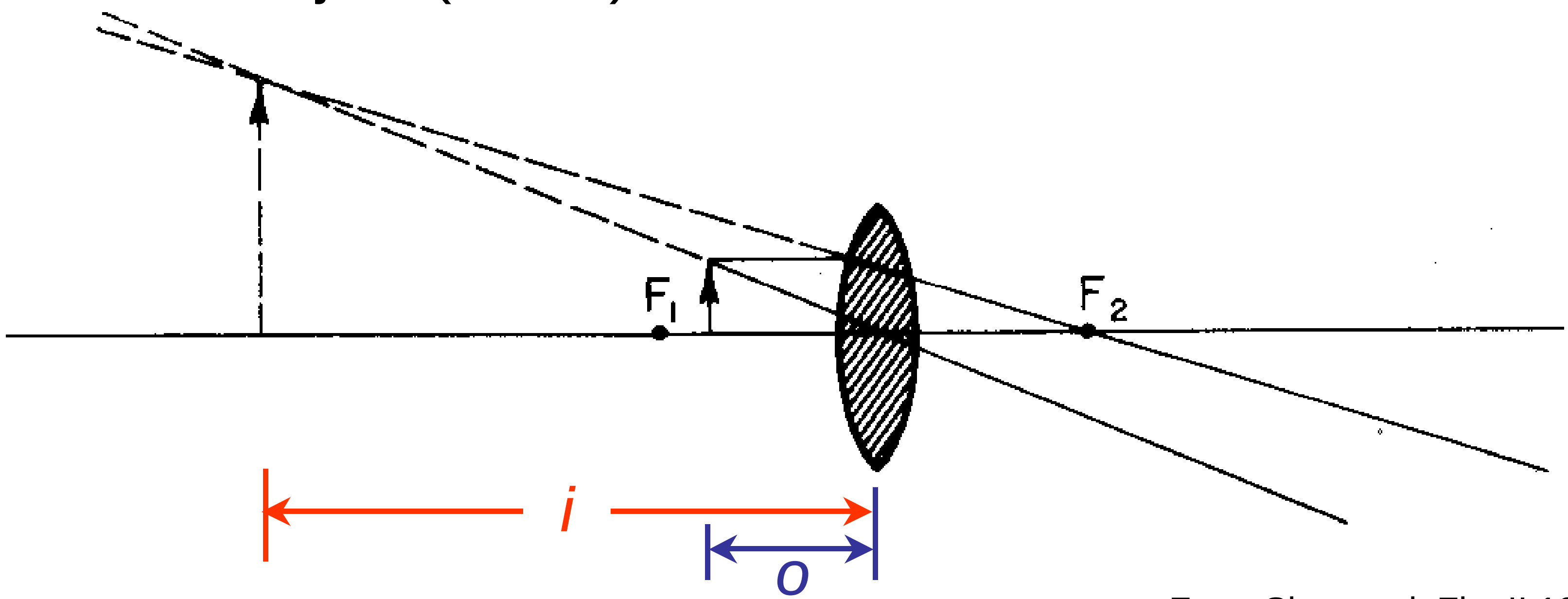
I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$M = \left| \frac{i}{o} \right|$$

For converging lens:

When object is **< *f***, the image is **virtual**, **erect**, and **larger** than the object ($M > 1$).

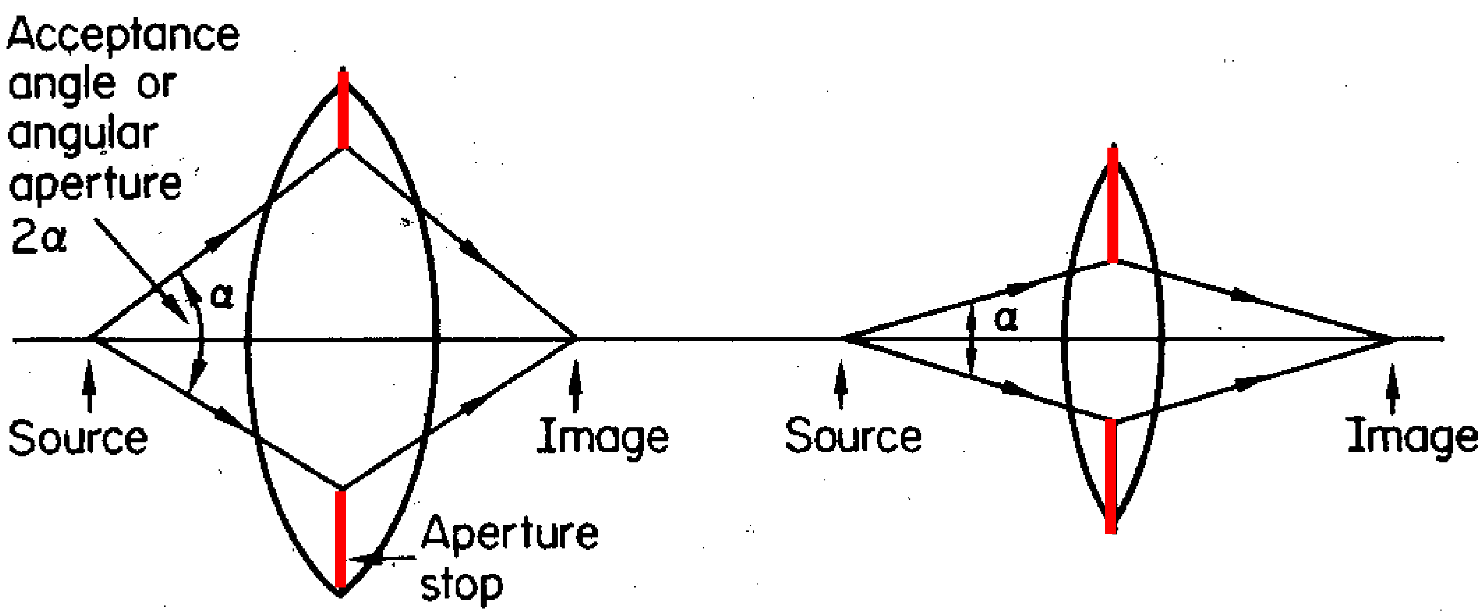


From Sjostrand, Fig. II.13, p. 22

I.A.4 Optics (Lens Theory)

I.A.4.i Angular aperture of the lens (2α)

Lens Aperture: determines the amount of radiation arriving from the object which can be focused to form an image.



(a) High aperture lens
2α is large

(b) Low aperture lens
2α is small

From Meek (1st ed.), Fig. 1.7, p. 12

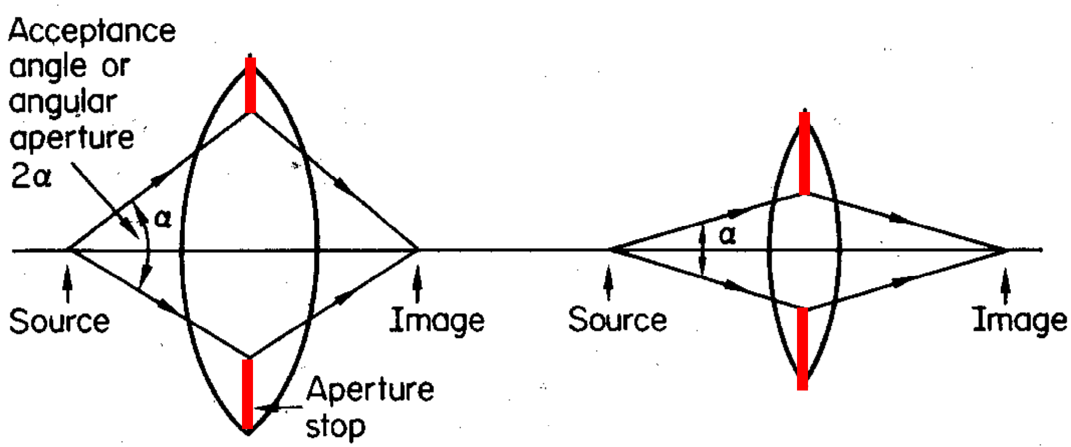
I.A.4 Optics (Lens Theory)

I.A.4.i Angular aperture of the lens (2α)

Angle **2α** is the **acceptance angle** of the lens

The **larger** it can be made, the **more information** the lens can gather and transmit into the image

A large lens of high aperture can therefore tell us more about an object than a small lens of low aperture



(a) High aperture lens 2α is large

(b) Low aperture lens 2α is small

From Meek (1st ed.), Fig. 1.7, p. 12

I.A.4 Optics (Lens Theory)

I.A.4.i Angular aperture of the lens (2α)

Important distinction between light and electron imaging lenses:

A typical LM with an oil immersion objective lens has 2α of **~175°**

In TEM, 2α is generally **< 0.01°** !!!

I.A.4.j Simple vs. Compound Microscope

KEY CONCEPT

Impractical to form high magnification images with just one lens

… or even two lenses

I.A.4 Optics (Lens Theory)

I.A.4.j Simple vs. Compound Microscope

In principle: (some ideal world)

Real image of any desired magnification can be obtained from a **single** positive lens

In practice: (the real world)

Cumbersome because of long lens-image distance

Solution:

Use two or more lenses to magnify the image in stages

Total magnification = product of mags of the lenses

Image formed by one lens constitutes the **object** for the subsequent lens, **whether or not** a real intermediate image is formed

I.A.4.j Simple vs. Compound Microscope

Example: 1- verses 2-stage magnification

Problem:

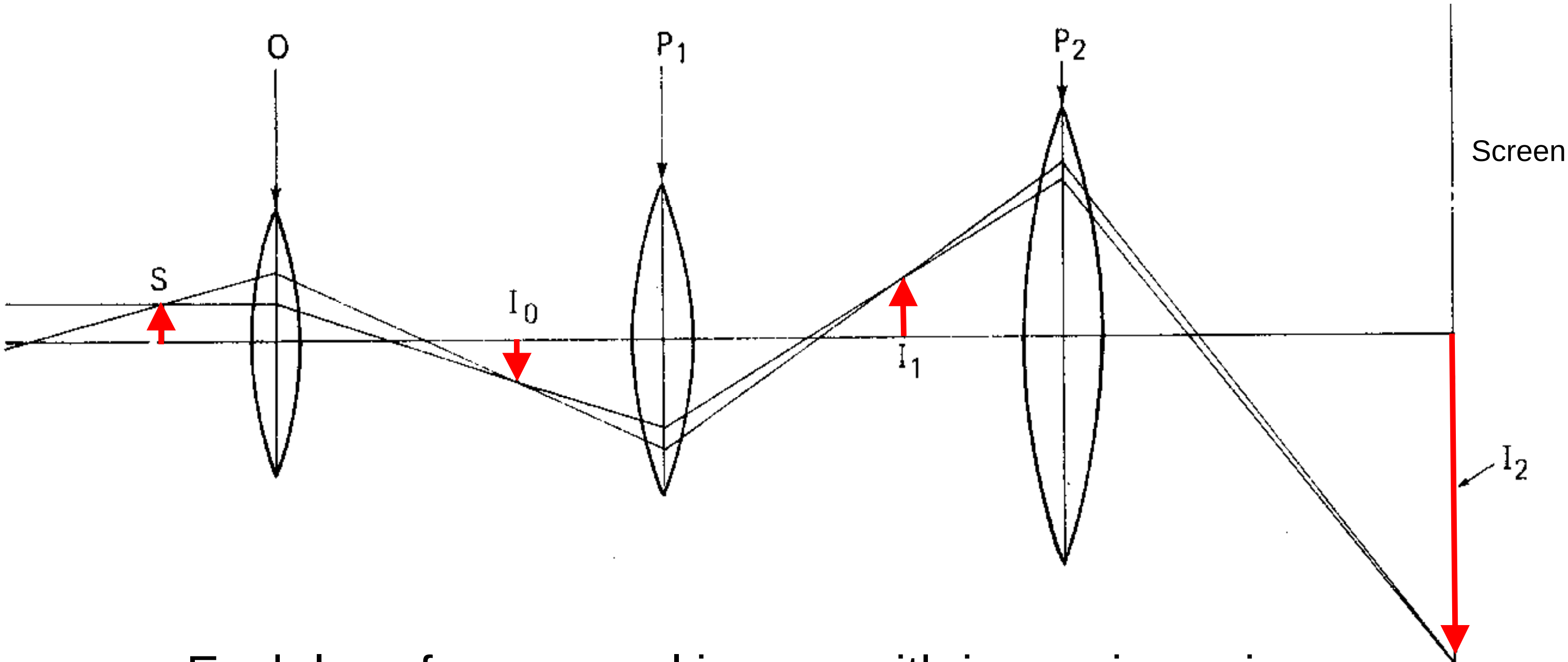
Achieve 10,000X image magnification using either 1 or 2 lenses with f = 2.0 cm for all lenses

Try to solve this on your own. See lecture notes pp.16-17.

I.A.4 Optics (Lens Theory)

I.A.4.j Simple vs. Compound Microscope

Ray diagram for high magnification mode of operation



Each lens forms a real image, with image inversion.

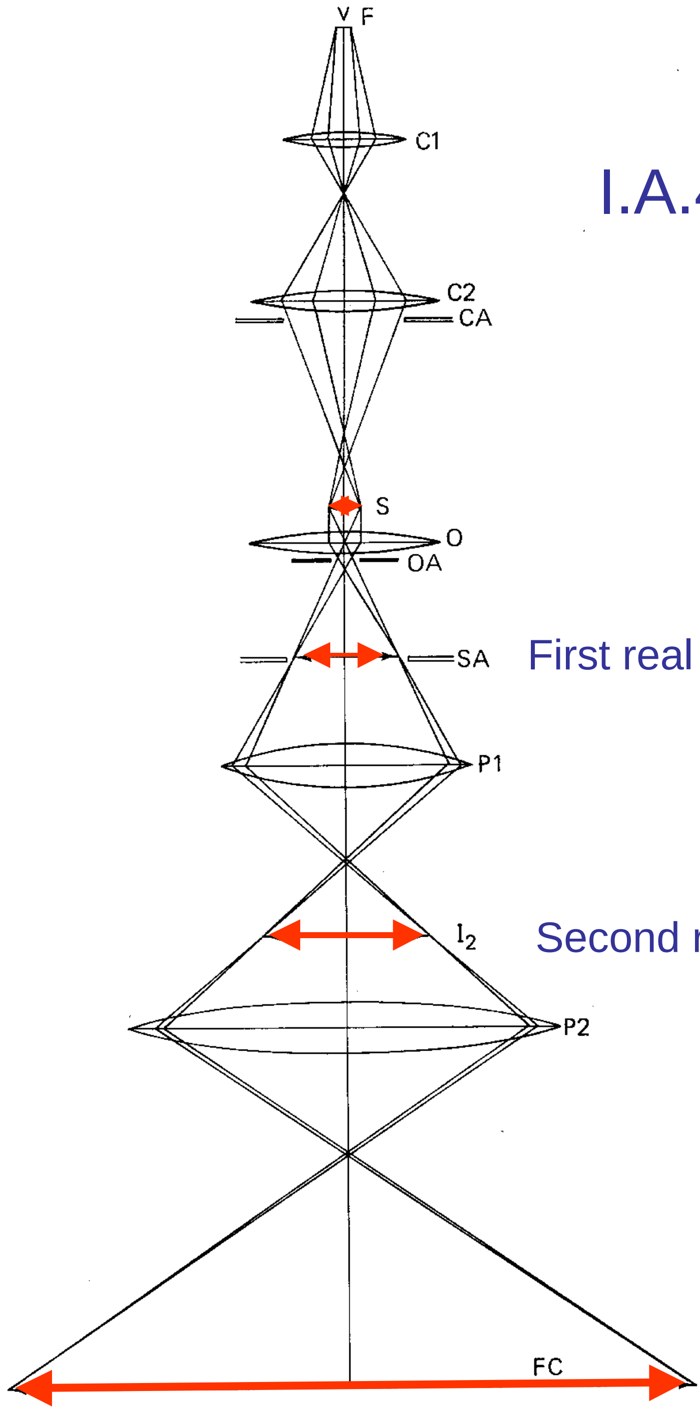
Highly schematic drawing!!!

From Agar, Fig. 1.23, p. 30

I.A.4 Optics (Lens Theory)

I.A.4.j Simple vs. Compound Microscope

Ray diagram for a two projector electron microscope



First real image

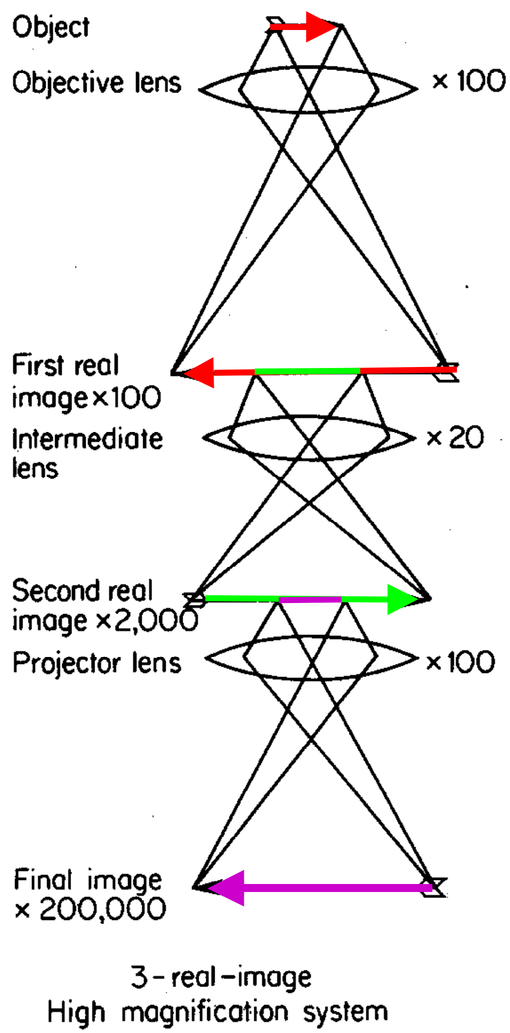
Second real image

Final real image on viewing screen

From Agar, Fig. 1.30, p. 35

I.A.4 Optics (Lens Theory)

I.A.4.j Simple vs. Compound Microscope



From Meek 1st ed., Fig. 5.16, p. 118