CHM 165,265 / BIMM 162 / BGGN 262 Spring 2013

Lecture Slides

Jan 10, 2013

CHM 165,265 / BIMM 162 / BGGN 262 Spring 2013

Announcements for Jan 10, 2013

Reading assignment for next Tuesday: Lecture notes pp.39-64

'Virtual homework': On class web site by tomorrow

Please fill out and turn in your class roster sheet if you haven't already done so

Reminders:

- Keep your *p-Flasher* sheets readily available during class
- Powerpoint lectures posted on Web site will include additional ('hidden') slides not shown during class

Sample Question

Rearrange the following list of dimensions according to increasing size:

0.15 μm	1 Å
0.3 mm	0.5 nm
0.5 nm	7.5 Å
1 cm	1 nm
1 μm	25 Å
1 nm	0.15 μm
1 mm	400 nm
1 Å	1 μm
7.5 Å	30 μm
10 m	65 μm
25 Å	0.3 mm
30 μm	1 mm
65 μm	1 cm
400 nm	500 mm
500 mm	10 m

Note: m = meter; cm = centimeter; mm = millimeter; μm = micron; nm = nanometer; Å = Ångstrom

Class Web Page: Jan 9, 2013

CHEM 165,265 / BIMM 162 / BGGN 262 - 3D Electron Microscopy of Macromolecules
Winter Quarter 2013

Syllabus (PDF)

Book list (PDF)

Reference list (PDF)

The Bottom Line (PDF) -- Key concepts from daily lectures through January 8, 2013

Lecture Notes

- Sec. IA. Principles of the transmission electron microscope (9.2 MB)
- Sec. IB. Design of the transmission electron microscope (3.5 MB)

Powerpoint® presentations from lecture (PDFs)

- Introduction to the course January 8, 2013 (48 MB)
- Lecture #1 January 8, 2013 (15.5 MB)

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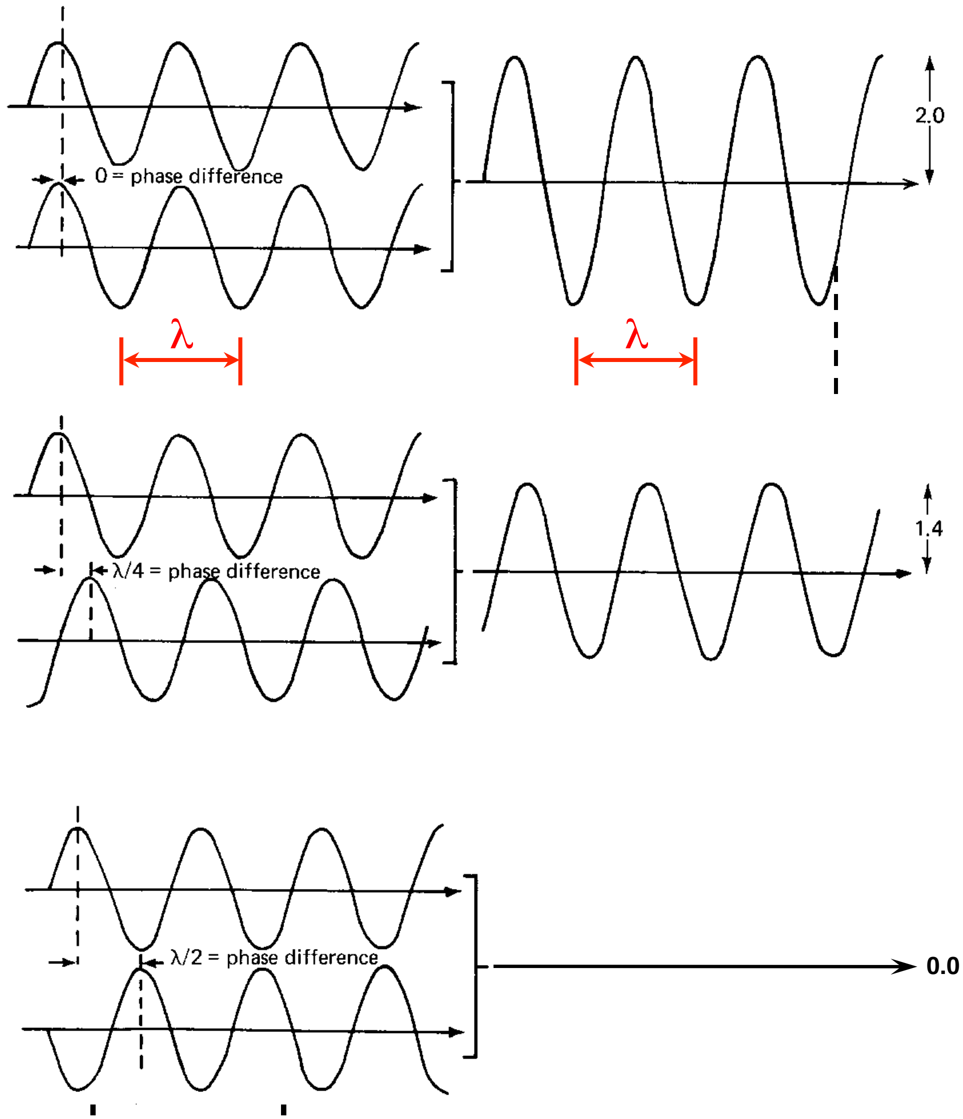
I.A PRINCIPLES OF TRANSMISSION EM

KEY CONCEPTS FROM LECTURE #1

- Arrangement and function of components in LMs and TEMs are similar
- Photons and electrons exhibit properties of particles AND waves
- Any moving particle has a wavelength associated with it (DeBroglie)
- In TEM, electrons travel *very* fast and have *very* short wavelengths
- Diffraction occurs when radiation encounters and is bent by 'obstacles'
- Interference occurs when diffracted and undiffracted waves combine
- Ideal lens: images each object point as a point in the image plane
- Real lens: images each object point as an Airy disk in the image plane

I.A.3.c Interference / Diffraction / Coherence

Effects of waves interfering (combining) with each other



Total constructive interference
"In phase"

Partial destructive interference

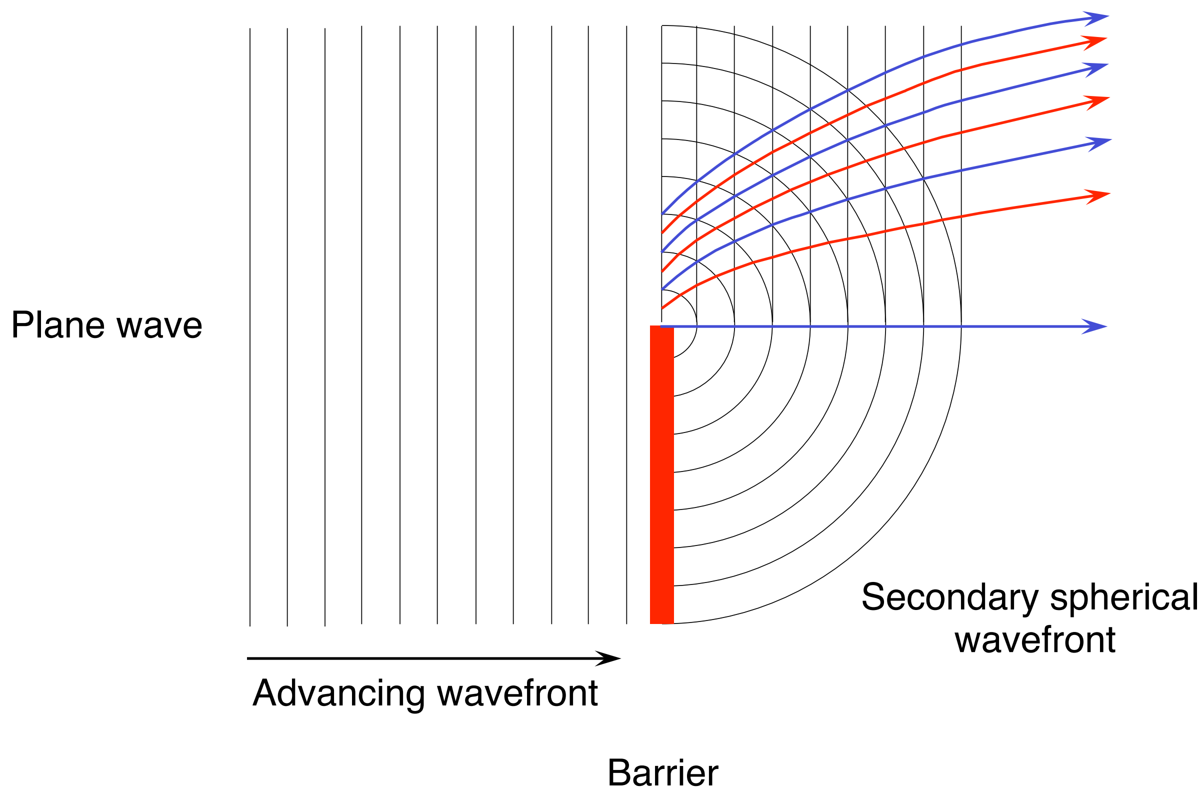
Total destructive interference
"Out of phase"

From Glusker and Trueblood., Fig. 5, p.19

I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

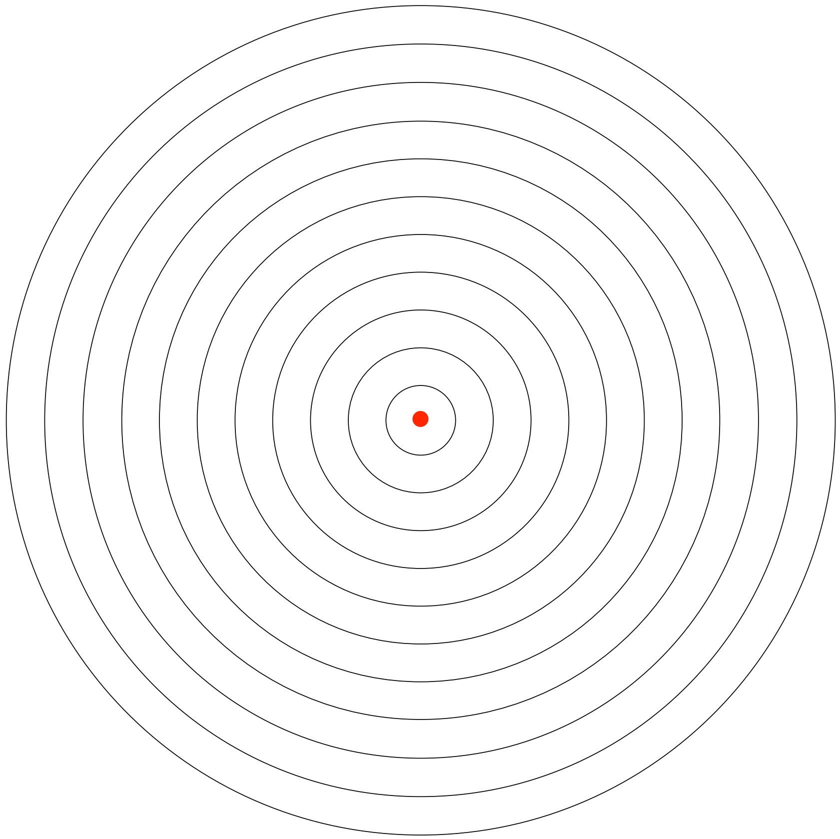
Diffraction phenomena: bending of the path of radiation passing close to an obstacle.



I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

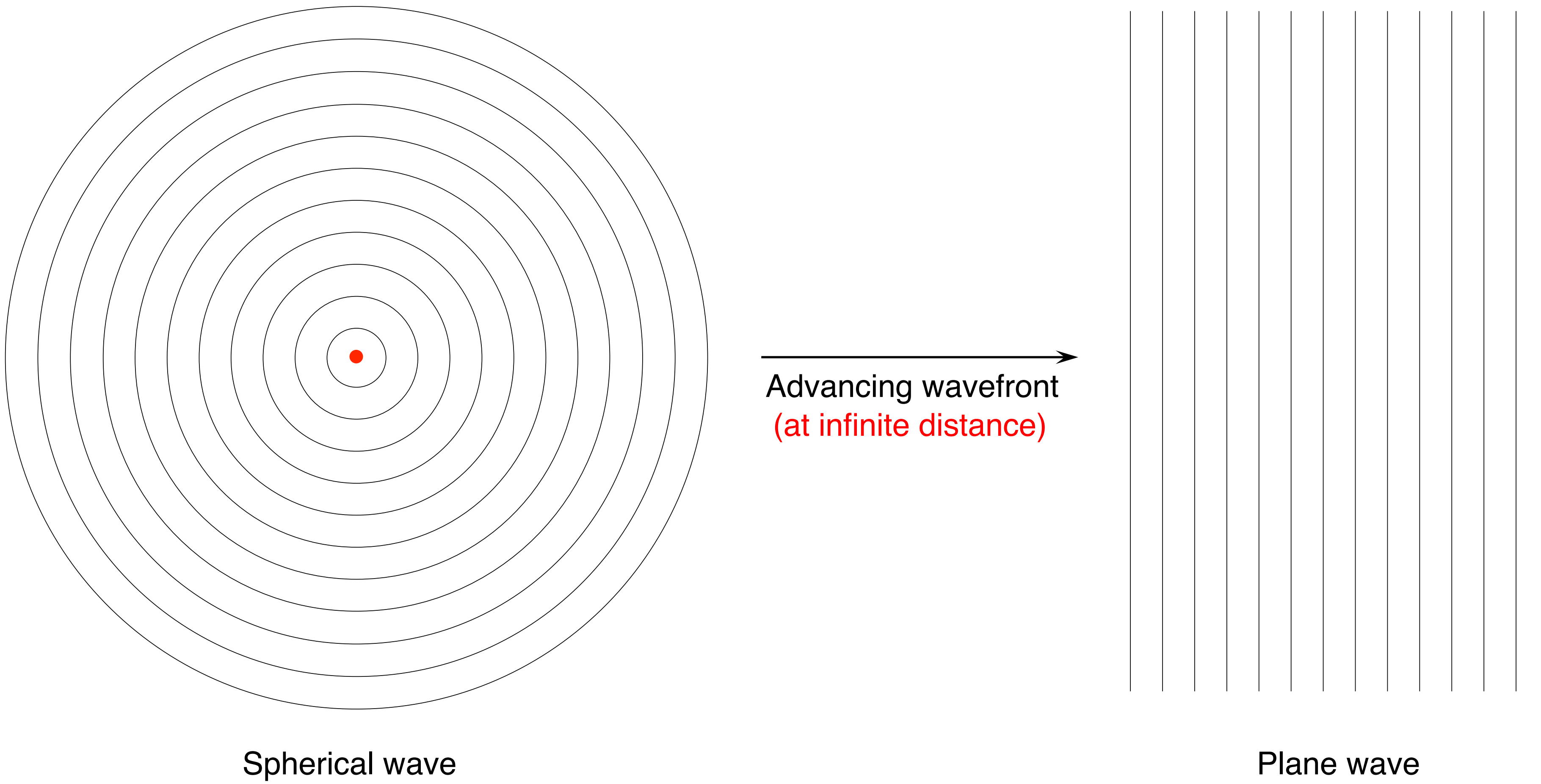
Spherical vs. Plane Wave



I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

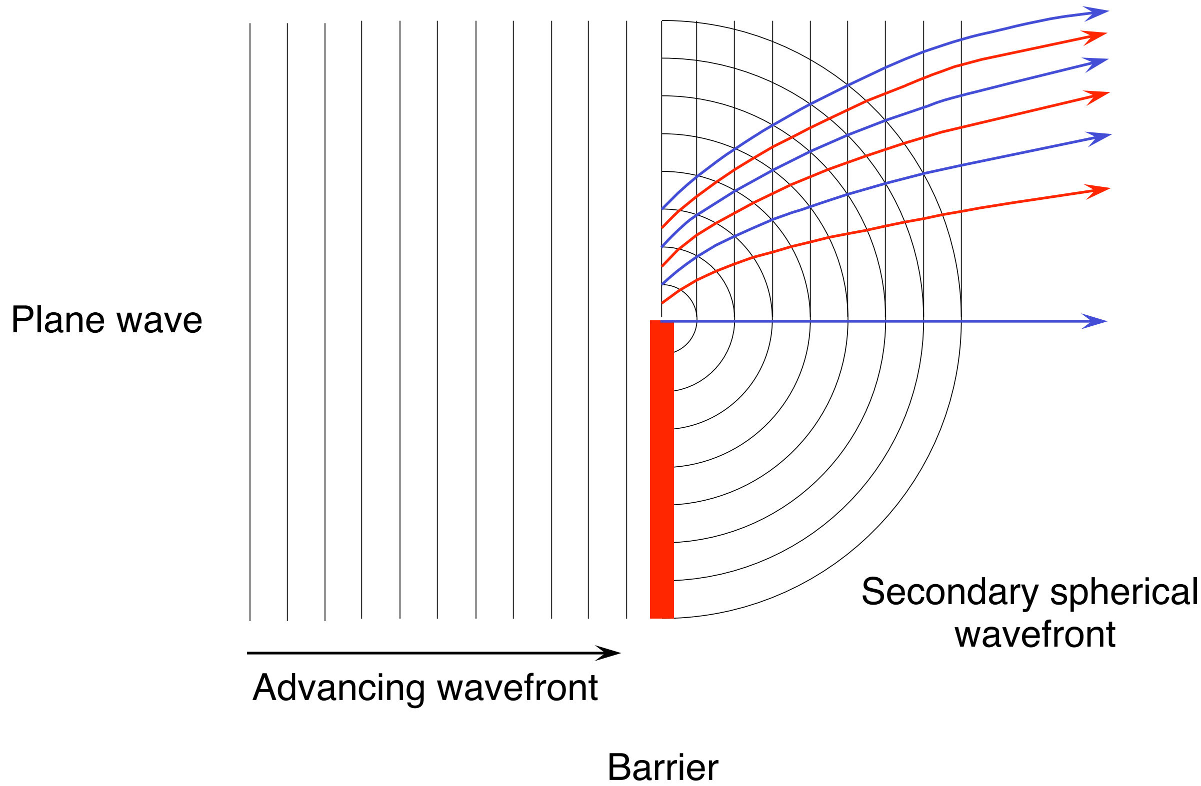
Spherical vs. Plane Wave



I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

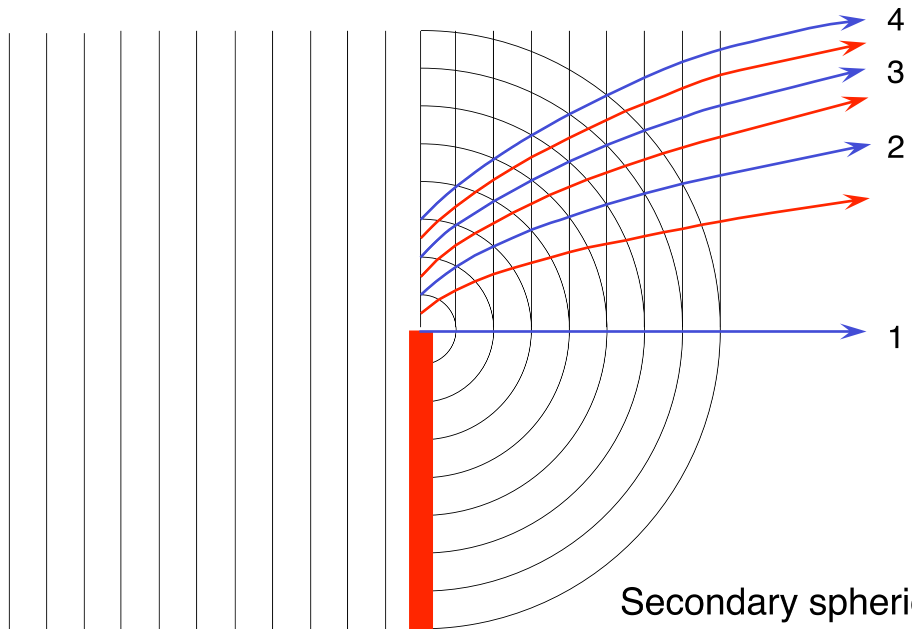
Diffraction phenomena: bending of the path of radiation passing close to an obstacle.

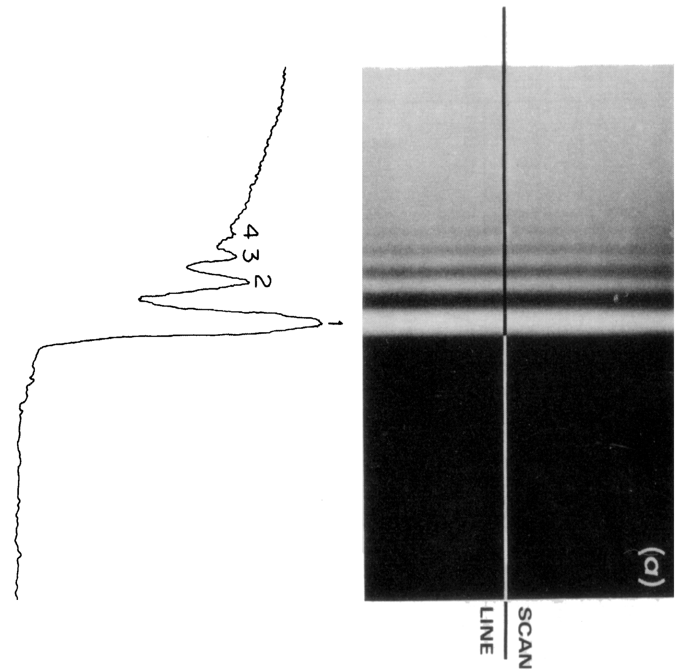


I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

Diffraction phenomena: bending of the path of radiation passing close to an obstacle.



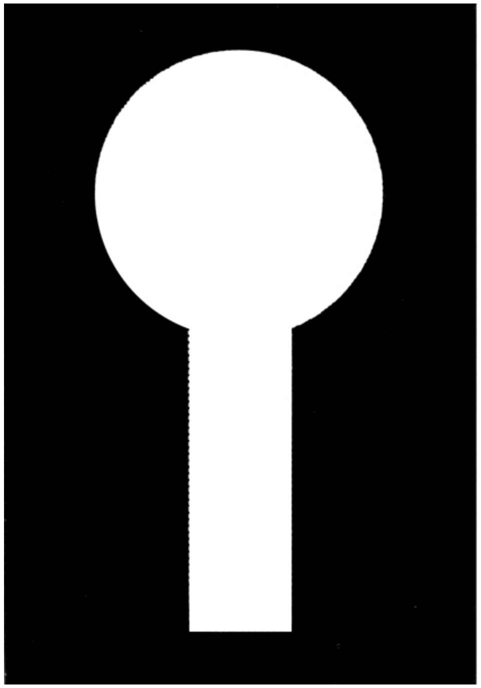


From Meek, 1st ed., Fig. 1.18, p.27

I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

Fresnel diffraction pattern formed by an irregularly shaped aperture



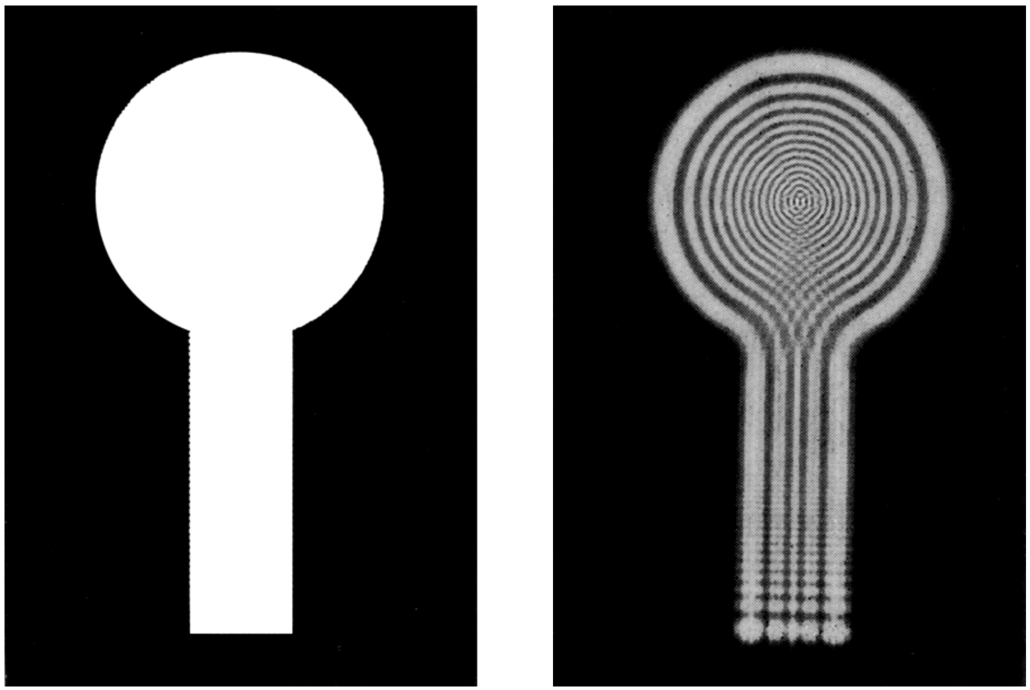
Object

From Young., Fig. 3-24, p.95

I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

Fresnel diffraction pattern formed by an irregularly shaped aperture



Object

Fresnel Diffraction Pattern

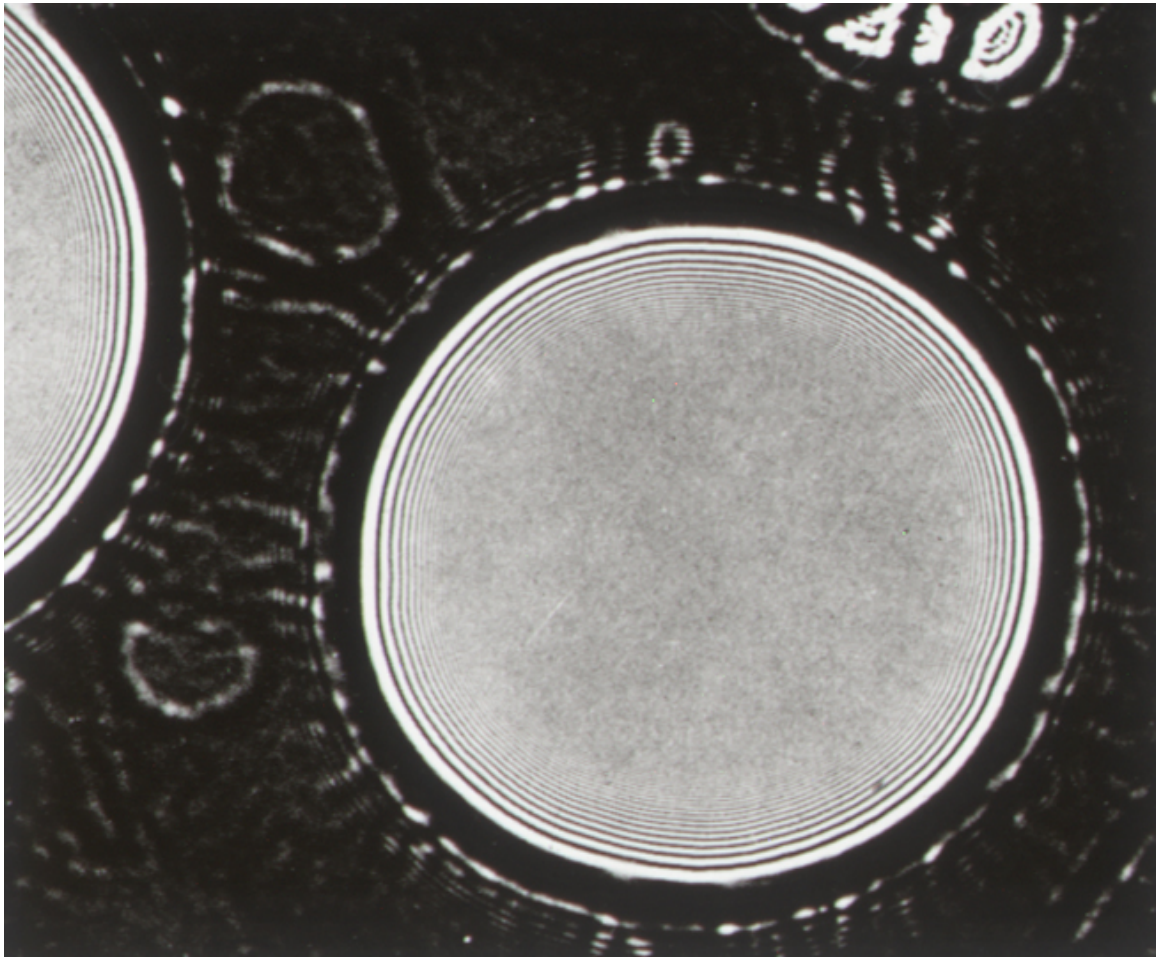
Fresnel pattern (on right) results from interference between non-diffracted light and all the light diffracted at the edges

From Young., Fig. 3-24, p.95

I.A.3 Photons/Electrons

I.A.3.c Interference / Diffraction / Coherence

Fresnel fringes in holey film imaged with a high coherence electron beam



From Agar, Fig. 3.9, p.98

Announcement

A laser diffraction demo, showing the relationship between objects and their diffraction patterns, will be presented at the start of the first recitation section on Jan 18th.

Time: 5:00 – 6:00 pm

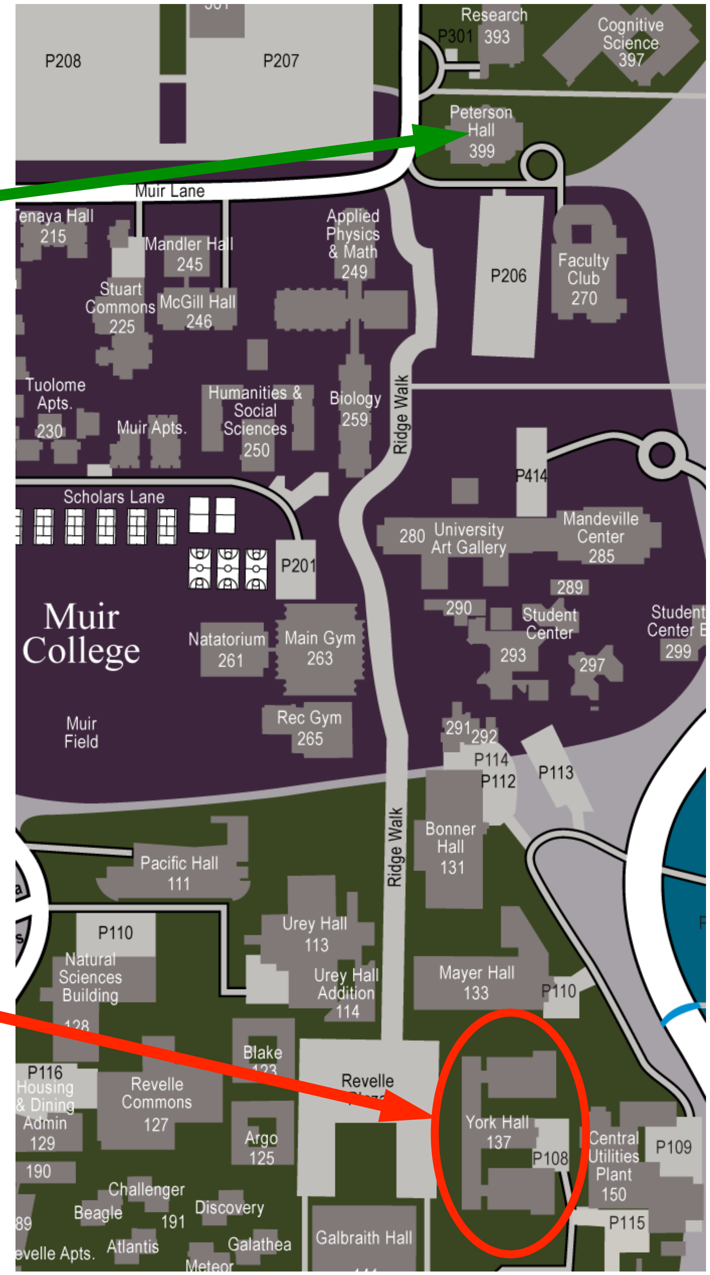
Place: York Hall 4080A

CHM 165,265 / BIMM 162 / BGGN 262 Winter 2013

Peterson Hall, Room 103; Muir Campus

Recitation session ***NEXT***
Friday, Jan 18, 2013
5:00 – 6:00 PM

York Hall 4080-A Revelle Campus



I.A.3 Photons/Electrons

I.A.3.d Resolution

Definitions

- RESOLUTION:

Ability to distinguish closely spaced points as separate points

- RESOLUTION LIMIT:

Smallest separation of points that can be recognized as distinct

- RESOLVING POWER:

Resolution achieved by a particular instrument under optimum viewing conditions

I.A.3 Photons/Electrons

I.A.3.d Resolution

Distinction between Resolution and Resolving Power

Resolving power: Property of the **instrument**

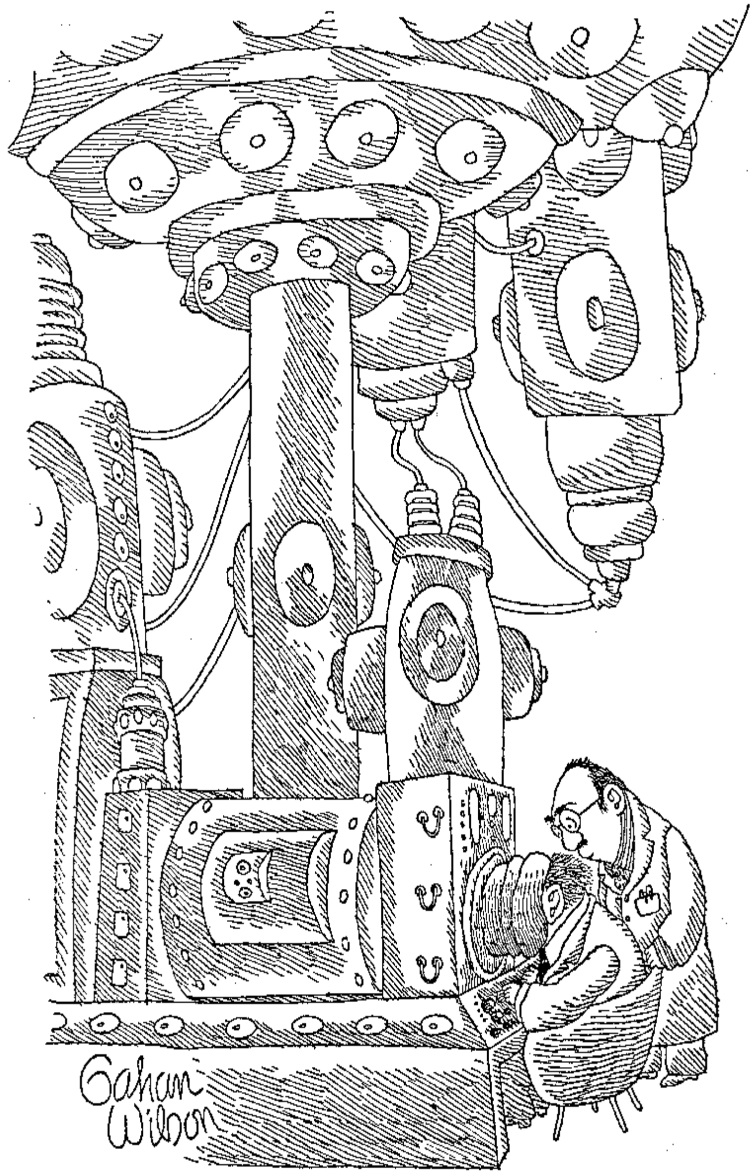
May be estimated on theoretical principles

Resolution: always **≤** resolving power

Quantity observed under any given set of experimental conditions

In the TEM, resolution achieved with **biological samples** is nearly always **considerably WORSE** than the **theoretical** instrument resolving power

Microscopy: The science of seeing the very small

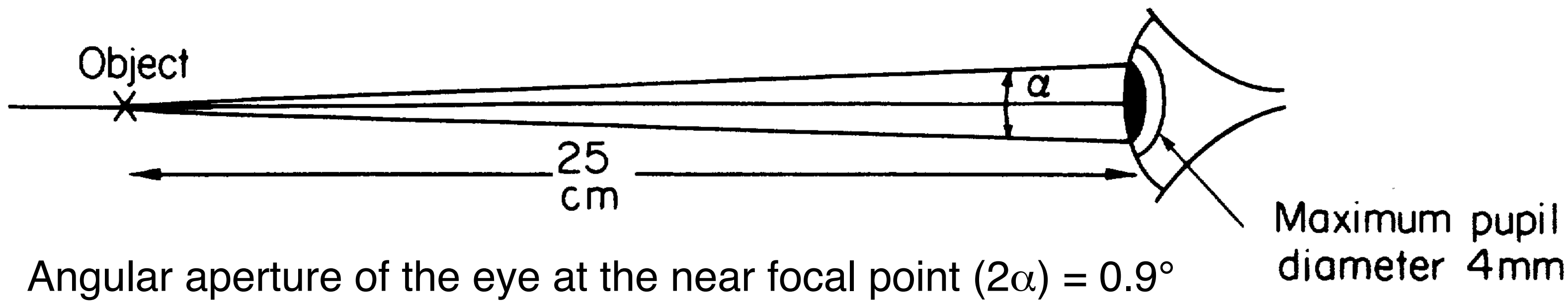


"I think I may have spotted something!"

I.A.3 Photons/Electrons

I.A.3.d Resolution

Microscopy: The science of seeing the very small



Angular aperture of the eye at the near focal point (2α) = 0.9°

Under <u>ideal</u> conditions:

Eye can focus on objects as close as ~ 250 mm

Smallest object or detail we can resolve is about 0.07 mm (70 μm)

What causes this limitation?

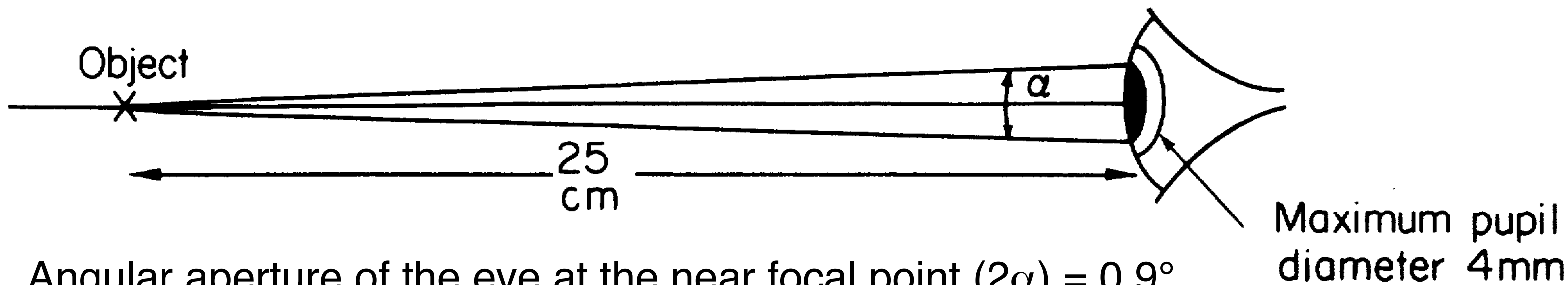
- Size of receptors in the retina
- Small angular aperture of eye
- How close the object can be placed to the eye

From Meek, 1st ed., Fig. 1.8, p.13

I.A.3 Photons/Electrons

I.A.3.d Resolution

Tennis Ball Analogy (an aside)



Angular aperture of the eye at the near focal point (2α) = 0.9°

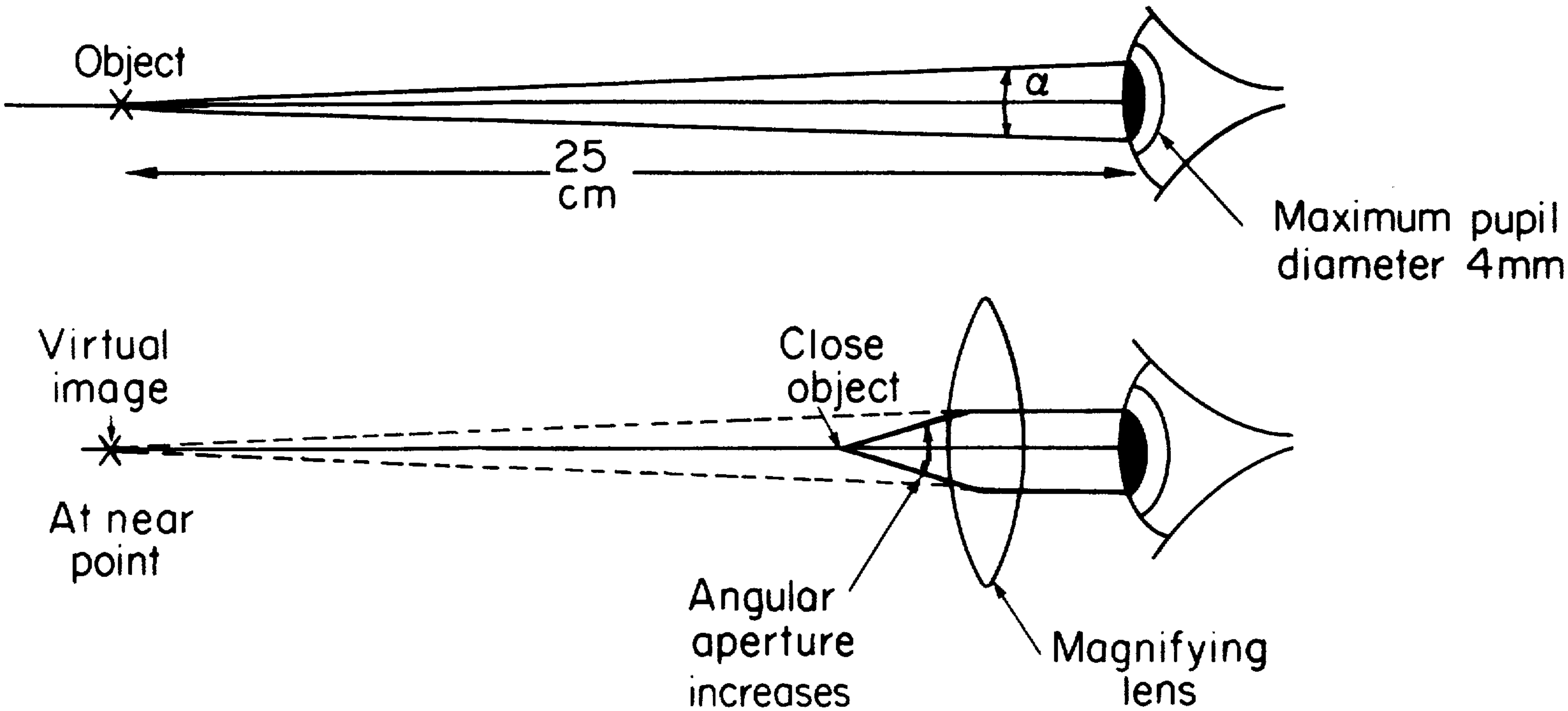
- Eye can resolve a 3 cm size object at a distance of 100 meters
- Thus, a tennis ball (~6 cm diameter) is clearly visible (*i.e.* resolvable) at that distance

But.........it's not **JUST** a question of resolution...

From Meek, 1st ed., Fig. 1.8, p.13

I.A.3 Photons/Electrons

I.A.3.d Resolution



A single biconvex lens (a very simple "microscope"):

Allows us to bring objects closer to the eye

Increases the angular aperture of the eye+lens (gather more info)

Magnifies the image falling on the retina

From Meek, 1st ed., Figs. 1.8-1.9, pp.13-14

I.A.3 Photons/Electrons

I.A.3.d Resolution

Abbe Simple Criteria of Resolution


Ernst Abbe (1840-1905)

- **Wave nature** of radiation (photons or electrons) poses ultimate limits on the size of details that can be resolved

- **Theory:** smallest resolvable object feature has a dimension **~1/2 the wavelength** of radiation used

- **Abbe Rule:** 1/2 the wavelength of the radiation used determines the **ultimate resolving power** of **any** instrument

This theory applies for **photon and electron** waves

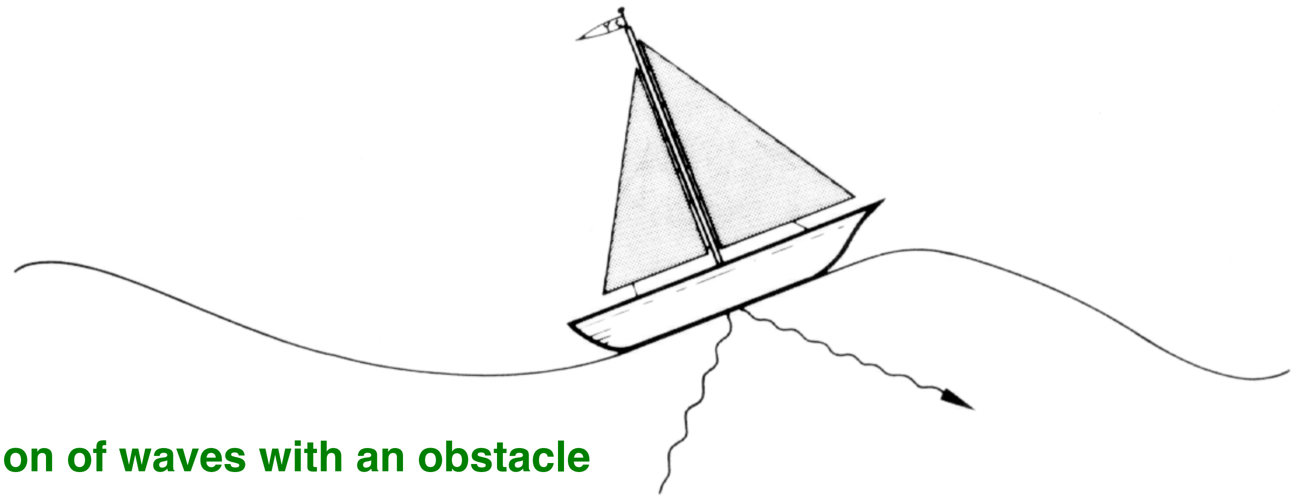
I.A.3 Photons/Electrons

I.A.3.d Resolution

Abbe Simple Criteria of Resolution

Ernst Abbe (1840-1905)

Abbe Rule: 1/2 the wavelength of the radiation used is the **ultimate resolving power** of any instrument



Interaction of waves with an obstacle

An object (or detail in an object) can only be detected ("seen") with radiation whose wavelength is comparable to or **smaller** than the size of the object

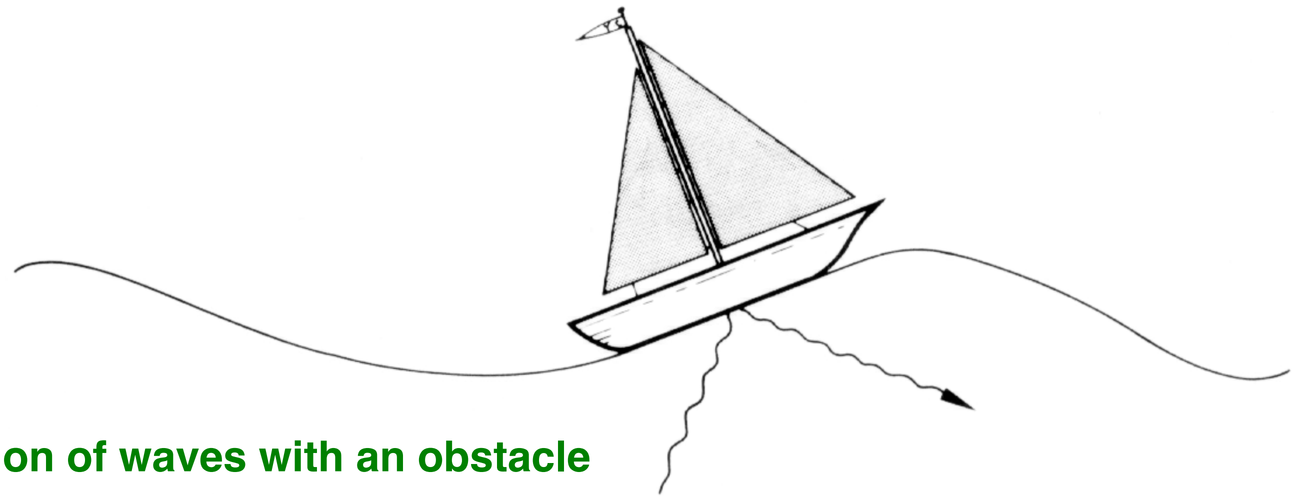
From Sherwood, Fig. 1.9, p.19

I.A.3 Photons/Electrons

I.A.3.d Resolution

Abbe Simple Criteria of Resolution

Abbe Rule: 1/2 the wavelength of the radiation used is the **ultimate resolving power** of any instrument



Interaction of waves with an obstacle

Observer who wishes to detect the presence of an object without actually seeing it directly (*e.g.* at night or beyond the horizon) can do so only by sending out waves with wavelengths comparable to or **smaller** than the size of the object, which will be reflected back to and detected by the observer.

Slide not shown in class lecture

From Sherwood, Fig. 1.9, p.19

I.A.3 Photons/Electrons

I.A.3.d Resolution

Magnification Limits

Maximum **useful** magnification of an instrument is limited by the wavelength of the radiation used for imaging

"***In theory***" (always suspicious words - see lecture notes for details)**:**

LM: 1000X **TEM: 100,000,000X**

In reality:

LM: 1000X **TEM: <1,000,000X**

I.A.3 Photons/Electrons

I.A.3.d Resolution

Magnification Limits

Good News / Bad News:

LM nearly perfectly obeys Abbe's Simple Rule

TEM falls *way way way* short

"Why is this?"

Main limitation in achieving the <u>theoretical</u> resolving power in a TEM concerns the:

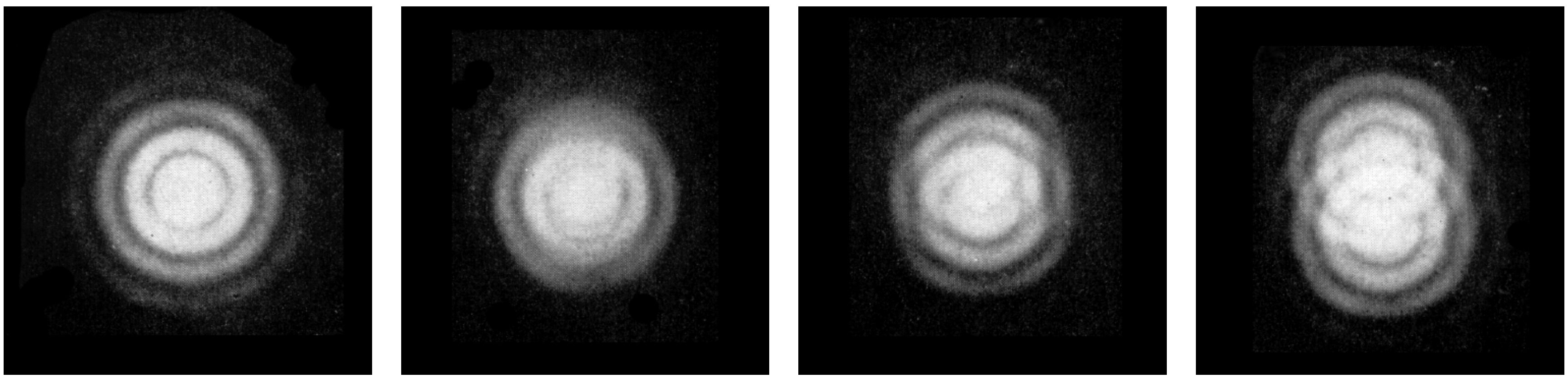
- **Nature of the imaging lenses**
- **Nature of the image formation process**

I.A.3 Photons/Electrons

I.A.3.d Resolution

Rayleigh Criterion

Lord Rayleigh
1842-1919



The shortest distance between 2 Airy disks at which the two disks appear partially separated corresponds to about 1/2 the width of the disks

From Sjostrand, Fig. IV.18, p.115

I.A.3 Photons/Electrons

I.A.3.d Resolution

Rayleigh Criterion

Lord Rayleigh
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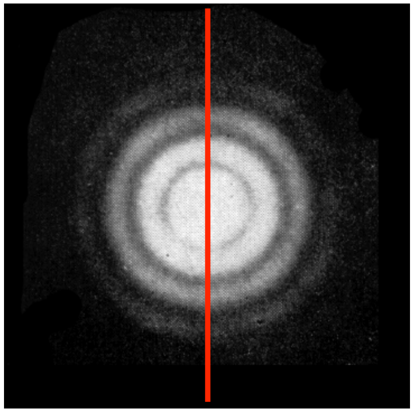
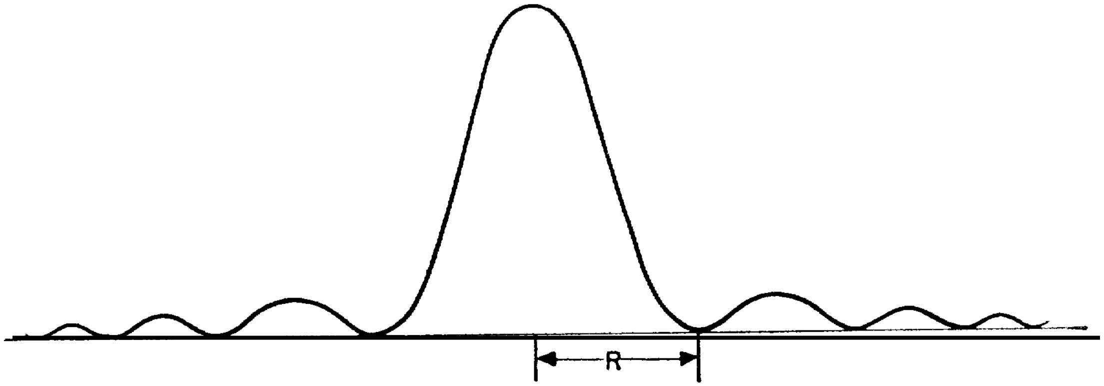
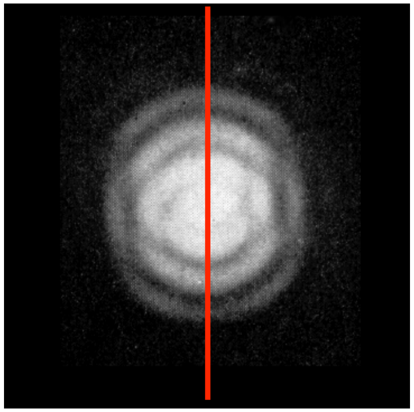
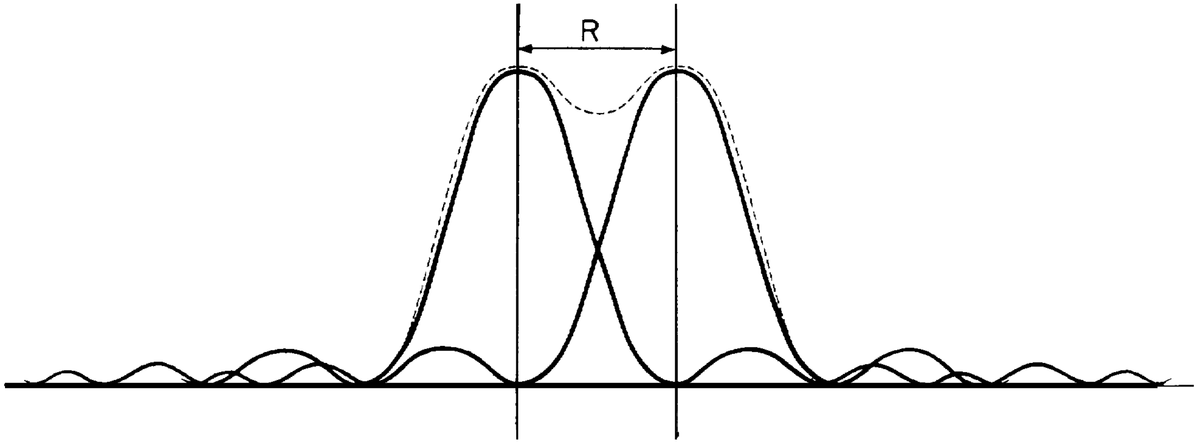








From Sjostrand, Fig. IV.18, p.115

I.A.3 Photons/Electrons

I.A.3.d Resolution

Rayleigh Criterion

Lord Rayleigh
1842-1919

The **shortest distance** between two Airy disks at which they appear partially separated corresponds to about 1/2 the width of the disks

The distance, *d*, in **object space** is given by the **Abbe Equation**:

$$d = \frac{0.612\lambda}{n \cdot \sin\alpha}$$

λ = wavelength of the radiation
n = refractive index of the media
α = lens semi-angular aperture

Note: $n \sin\alpha$ = lens numerical aperture (N.A.)

I.A.3 Photons/Electrons

I.A.3.d Resolution

Rayleigh Criterion

Lord Rayleigh
1842-1919

$$d = \frac{0.612\lambda}{n \cdot \sin\alpha}$$

To maximize resolving power (*i.e.* aim to get d as small as possible), λ must be decreased, *n* increased, or α increased

	n	*sin* α	λ*	*d*
LM	1.5	0.87	400 nm	~ 0.2 μm
TEM				

* λ = 400 nm for violet light

I.A.3 Photons/Electrons

I.A.3.d Resolution

Rayleigh Criterion

Lord Rayleigh
1842-1919

$$d = \frac{0.612\lambda}{n \cdot \sin\alpha}$$

To maximize resolving power (*i.e.* aim to get d as small as possible), λ must be decreased, *n* increased, or α increased

	n	*sin* α	λ*	*d*
LM	1.5	0.87	400 nm	~ 0.2 μm
TEM	1.0	0.01	0.0037 nm	0.23 nm

* λ = 400 nm for violet light

= 0.0037 nm for 100kV electrons

Take home message:

Resolving power in a TEM falls far short of the theoretical limit imposed by the wavelength of the moving electrons…….

…….*mainly because*, the semi-angular aperture (α) in a TEM is very small

Take home message:

Resolving power in a TEM falls far short of the theoretical limit imposed by the wavelength of the moving electrons…….

Nonetheless, the TEM still **far outperforms** the light microscope

§ I: The Microscope

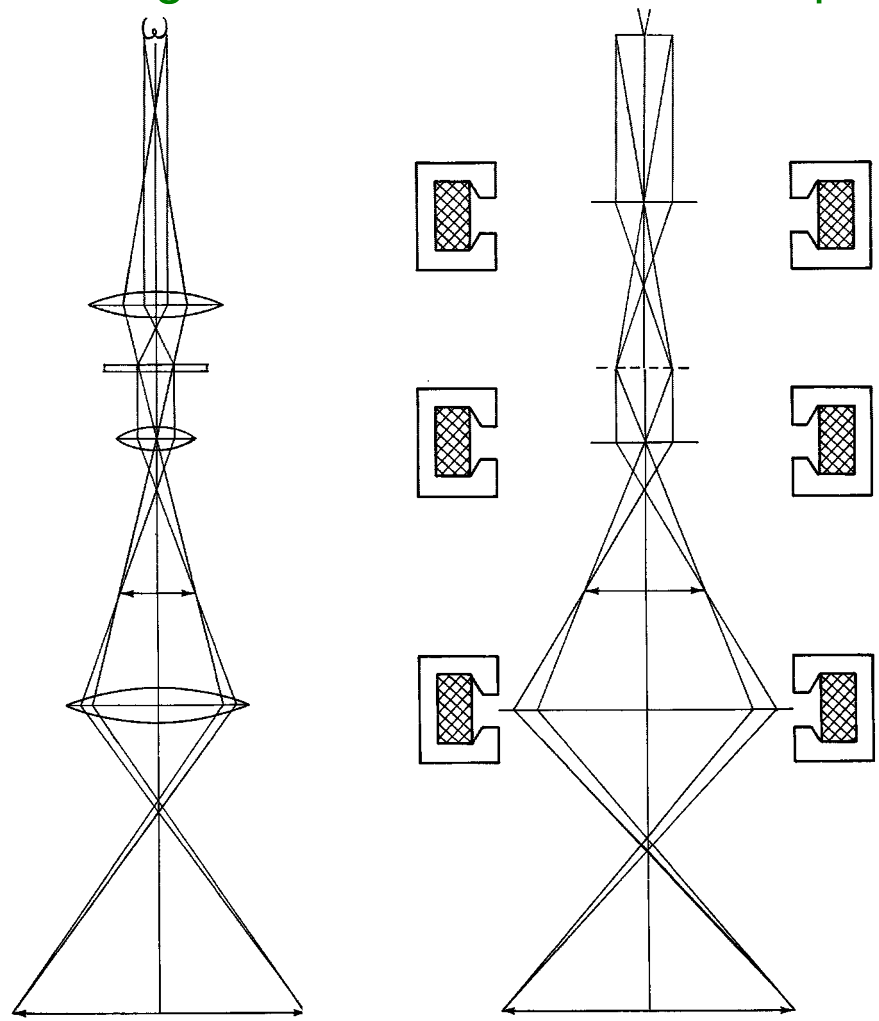
I.A Principles of TEM

I.A.4 Optics (Lens Theory)

(pp.17-25 of lecture notes)

I.A.2 Comparison of Light and Electron Microscope

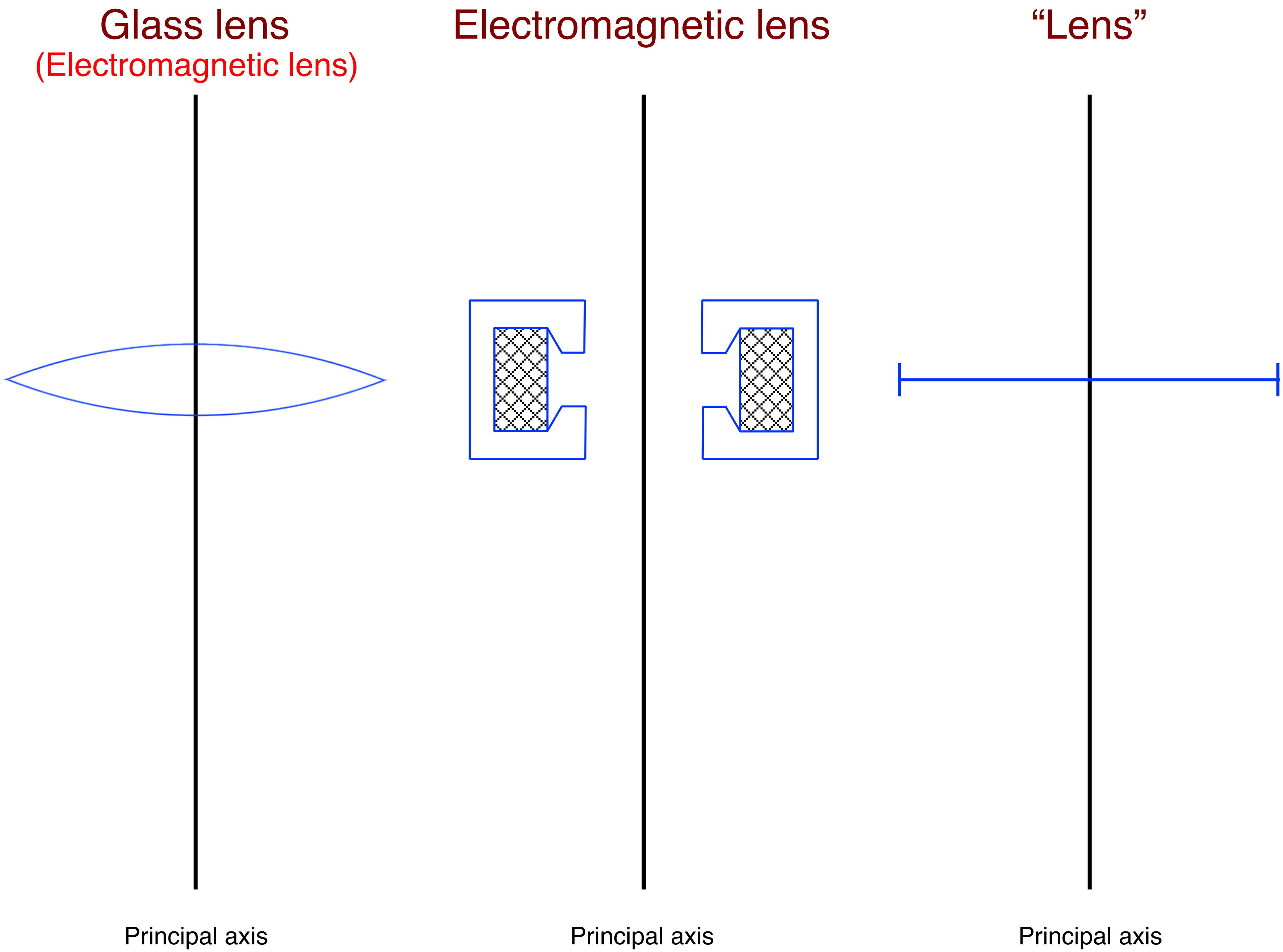
Similar arrangement and function of components

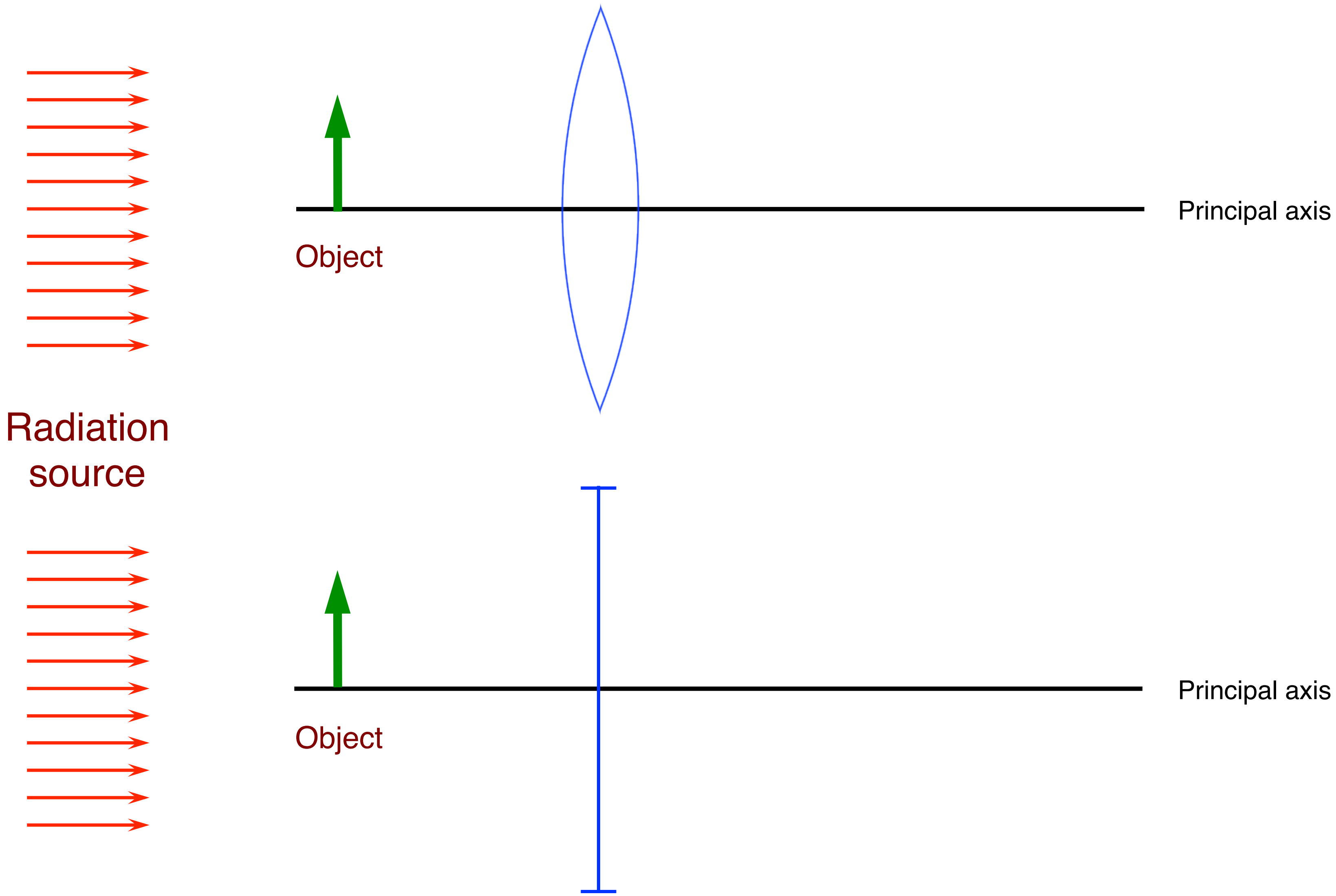


Light Microscope

Electron Microscope

From Agar, Fig. 1.6, p.8


Glass lens
(Electromagnetic lens)
Electromagnetic lens
“Lens”
Principal axis
Principal axis
Principal axis


Radiation
source
Object
Principal axis
Object
Principal axis

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

Note: "Geometrical Optics" ignore the wave properties of the radiation.

I.A.4 Optics (Lens Theory)

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

1. Rectilinear Propagation of Light

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

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

n = refractive index

c = speed of light in a vacuum (3×10^{10} cm/sec)

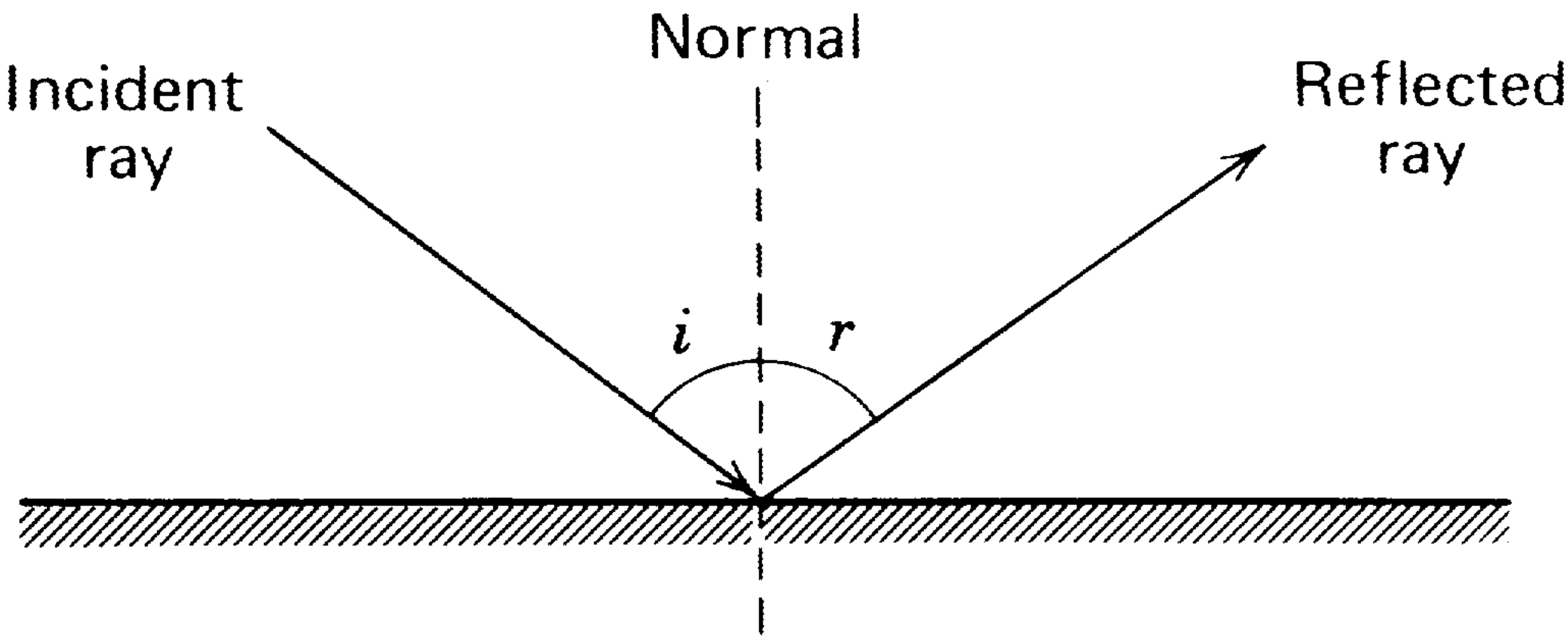
v = speed of light in the medium

I.A.4 Optics (Lens Theory)

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

2. Law of Reflection

($i = r$)



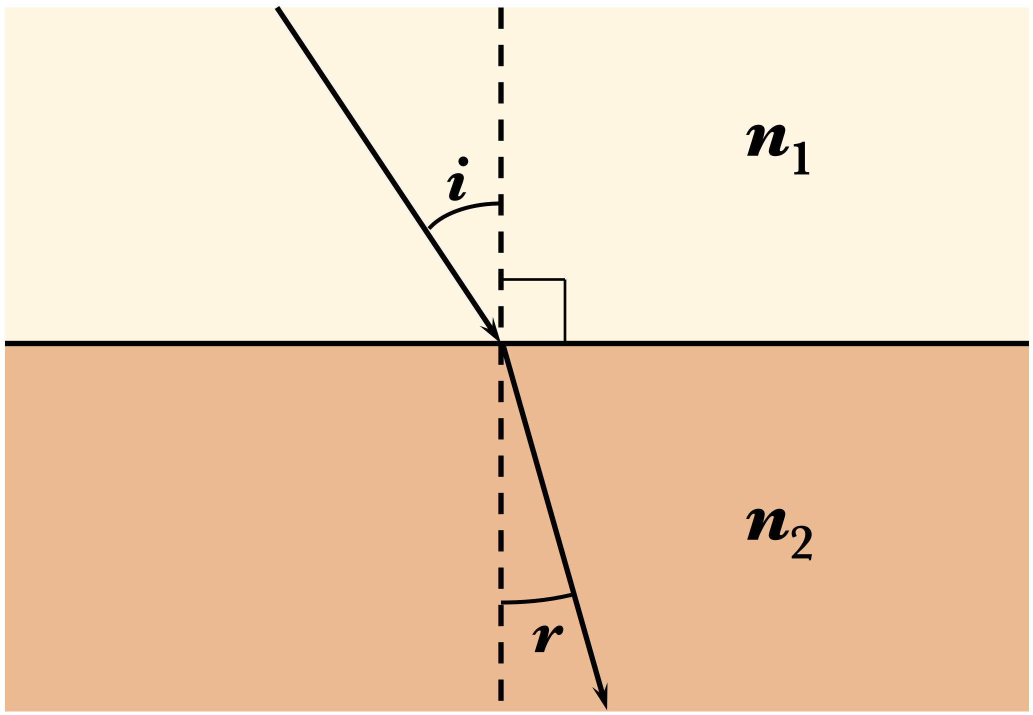
From Slayter, Fig. 1-2, p. 4

I.A.4 Optics (Lens Theory)

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

Willebrord Snell
1580-1626

3. Law of Refraction (Snell's Law)



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

I.A.4 Optics (Lens Theory)

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

4. 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 for #4, these laws hold for electrons

However, even #4 holds for electrons (except under extreme conditions: see p.17 of lecture notes).

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

Design and operation of LMs **and** TEMs governed by fundamental principles of optics (**identical** in LM **and** TEM)

Both use "refractile elements" (lenses) to form magnified images

Optics in TEM and LM differ in two ways:

- Radiation used (electrons vs. photons)
- Radiation is bent or refracted differently

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

GEOMETRICAL OPTICS: **Ideal World**

PHYSICAL OPTICS: **Real World**

p-Flasher Question

Which of these gives the most realistic estimate of the resolving power of an optical instrument?

A. Size of rod and cone receptors in the retina

B. Abbe Simple Rule: ½ the wavelength of the radiation being used

C. Rayleigh Criterion: depends on wavelength of radiation and numerical aperture of the lens

D. Distance between object and lens

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

GEOMETRICAL OPTICS: Ideal World

PHYSICAL OPTICS: Real World

I.A.4 Optics (Lens Theory)

I.A.4.c Geometrical and Physical Optics

GEOMETRICAL OPTICS: Ideal World

- Studies the **paths** followed by **rays** of light or electrons through lenses and apertures

Definition of 'ray': Infinitely thin beam

- Uses **geometrical** constructions to find the relative positions and sizes of objects and their images

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

  Rays don't physically exist

  Diffraction occurs instead (due to wave nature of light and electrons)

- Interference and diffraction phenomena:

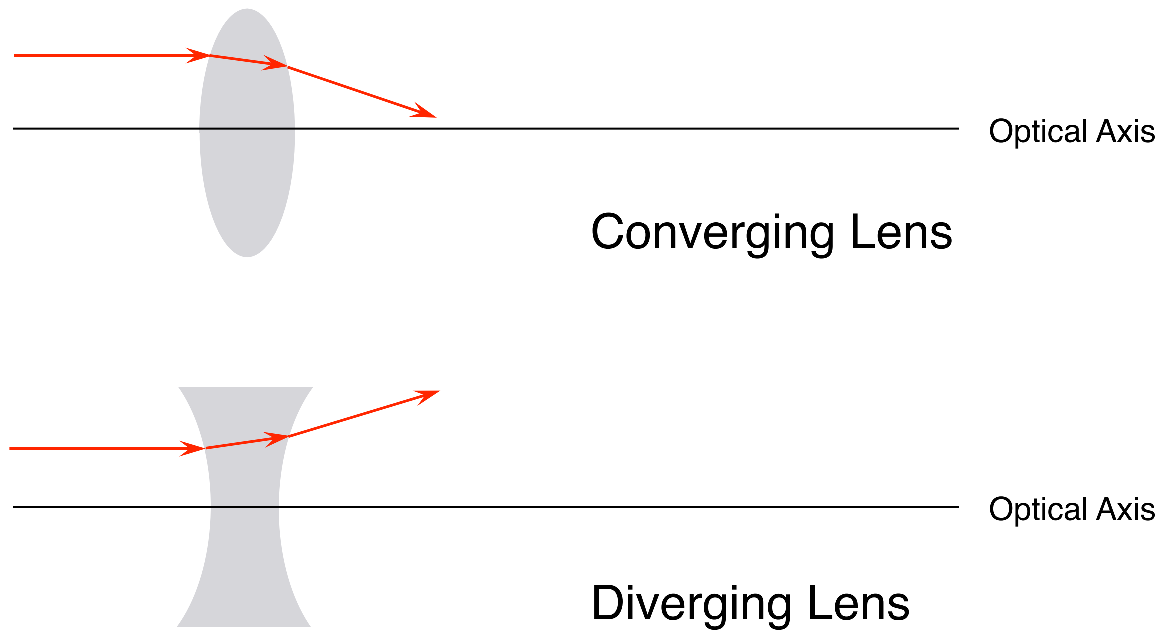
  Can't be explained in simple geometrical terms

  Can be derived from 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 that passes from an object point is refracted by an ideal lens to meet in one image point

2. Rays originating from points that lie on a plane perpendicular to the axis, must be imaged in a plane that is also perpendicular to the axis

3. The image appears like the object irrespective of magnification (relative linear dimensions of object preserved in the image)

See p.18 of the lecture notes

I.A.4 Optics (Lens Theory)

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

What about the "**real world**" (*i.e.* real lenses)?

Imaging by a **real** lens differs from that of an **ideal** lens

Each object point is represented in the **image plane** by an **Airy disc**

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

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

REAL LENSES

Glass (light) verses electromagnetic (electron) lenses:

- **Photons** follow **straight line** trajectories and **bend sharply** at glass surfaces

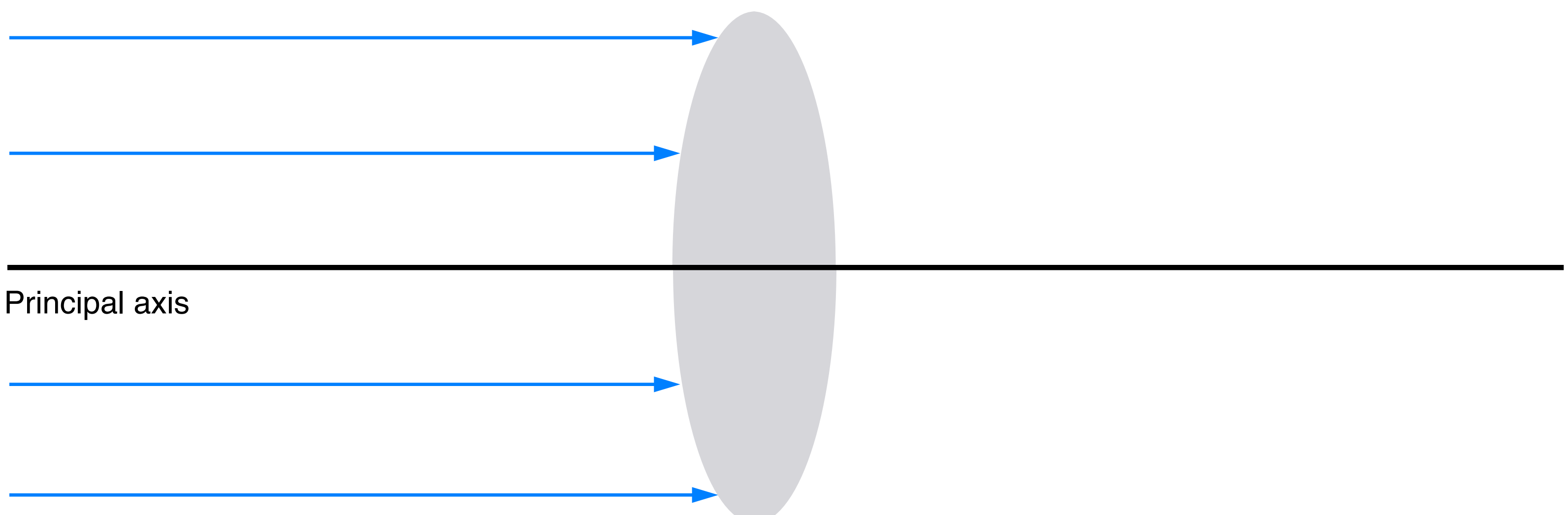
- **Electrons** follow **spiral** trajectories through magnetic fields, where refraction is **continuous**

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
Three Simple Principles

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

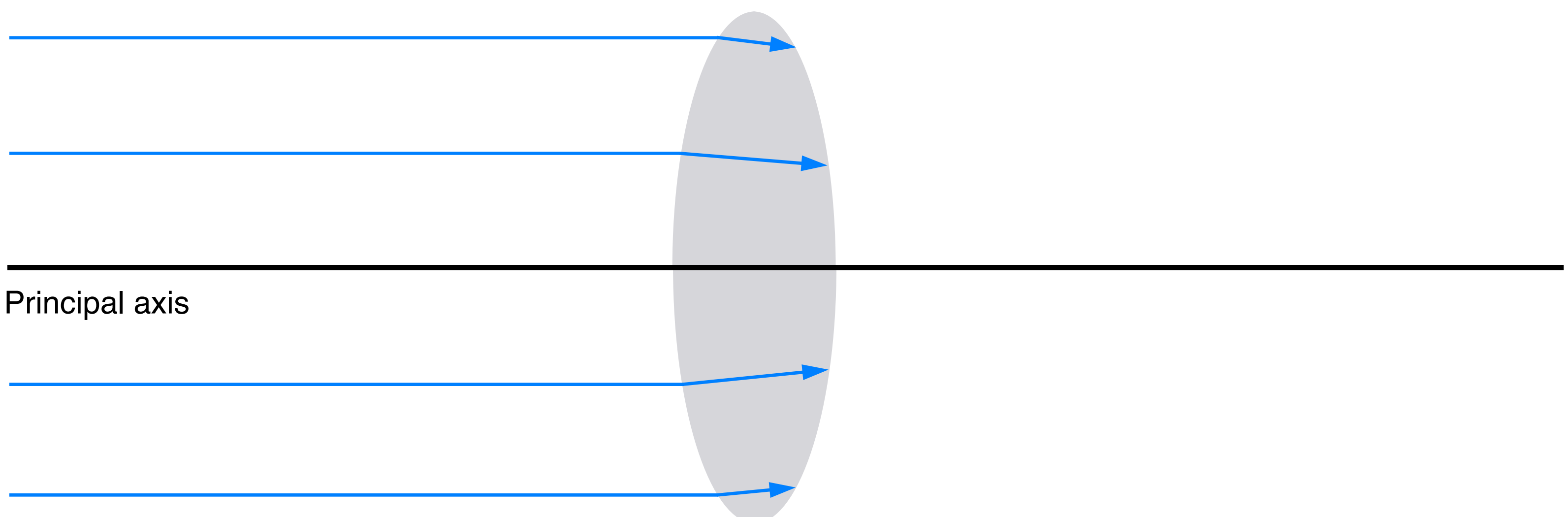


I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
Three Simple Principles

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

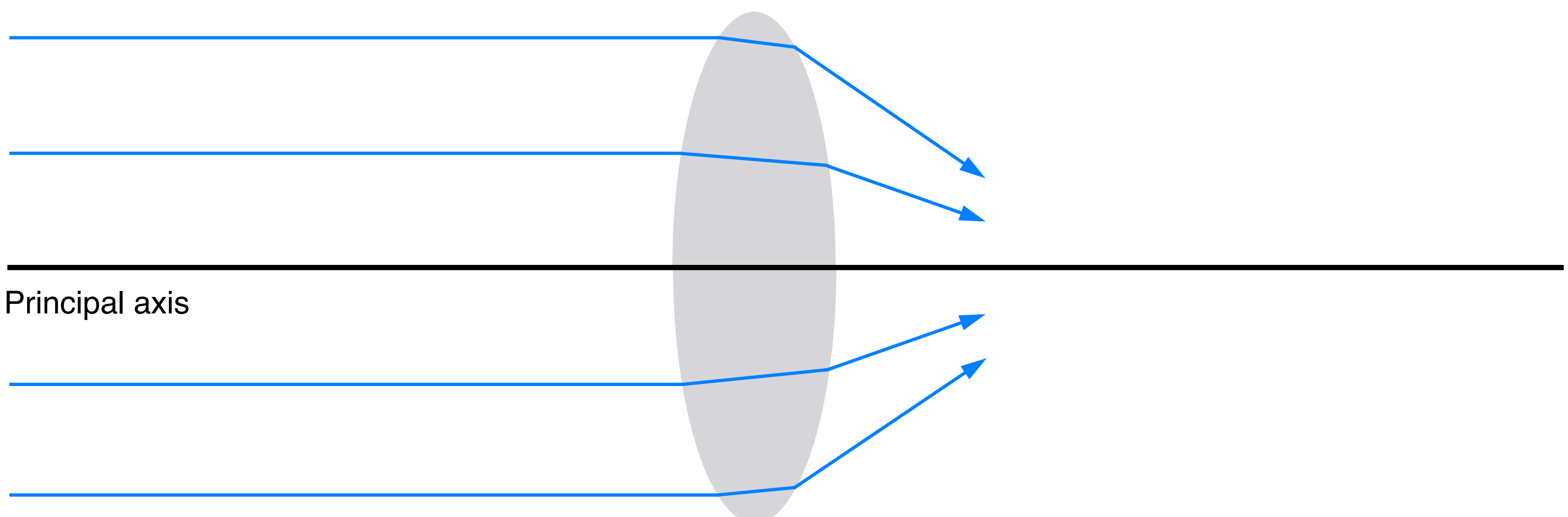


I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
Three Simple Principles

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



I.A.4 Optics (Lens Theory)

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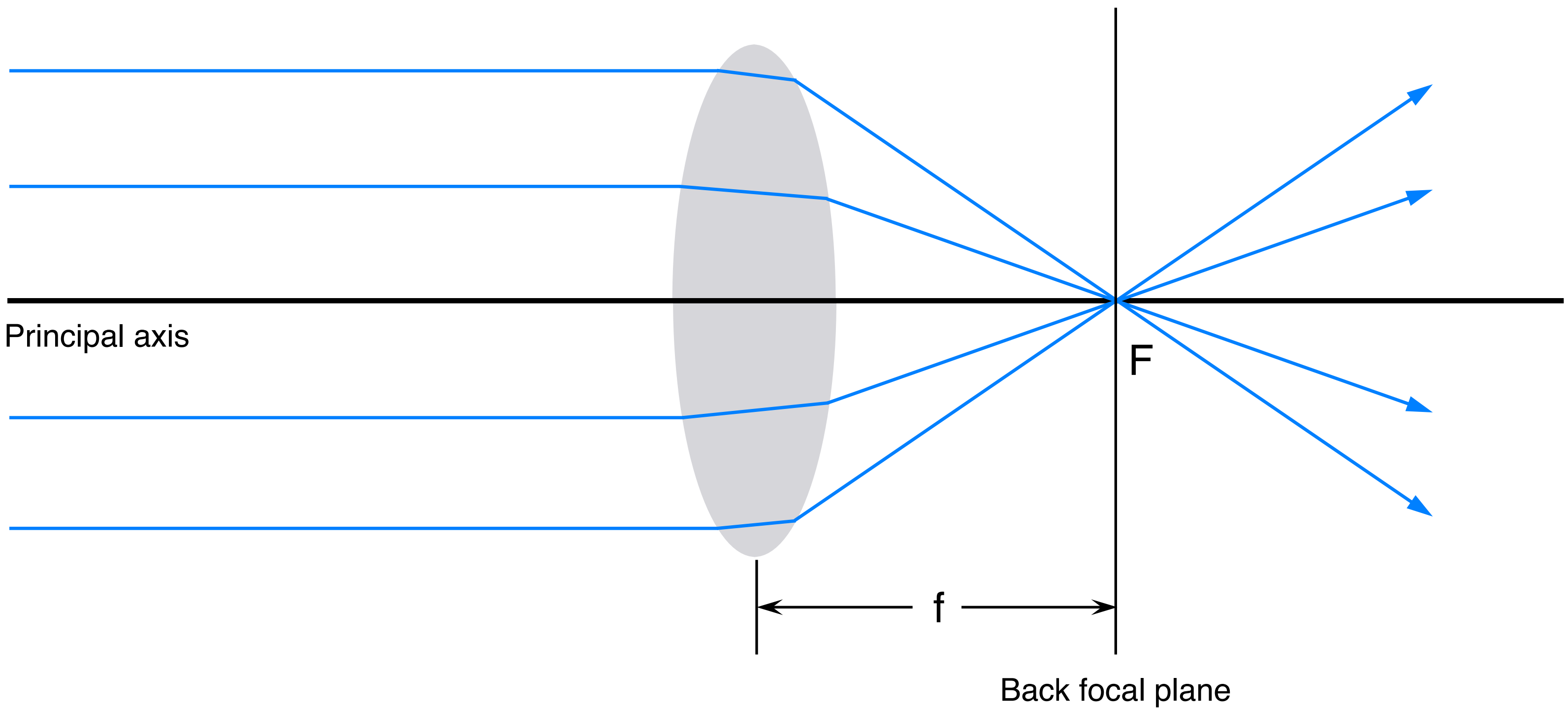

I.A.4 Optics (Lens Theory)

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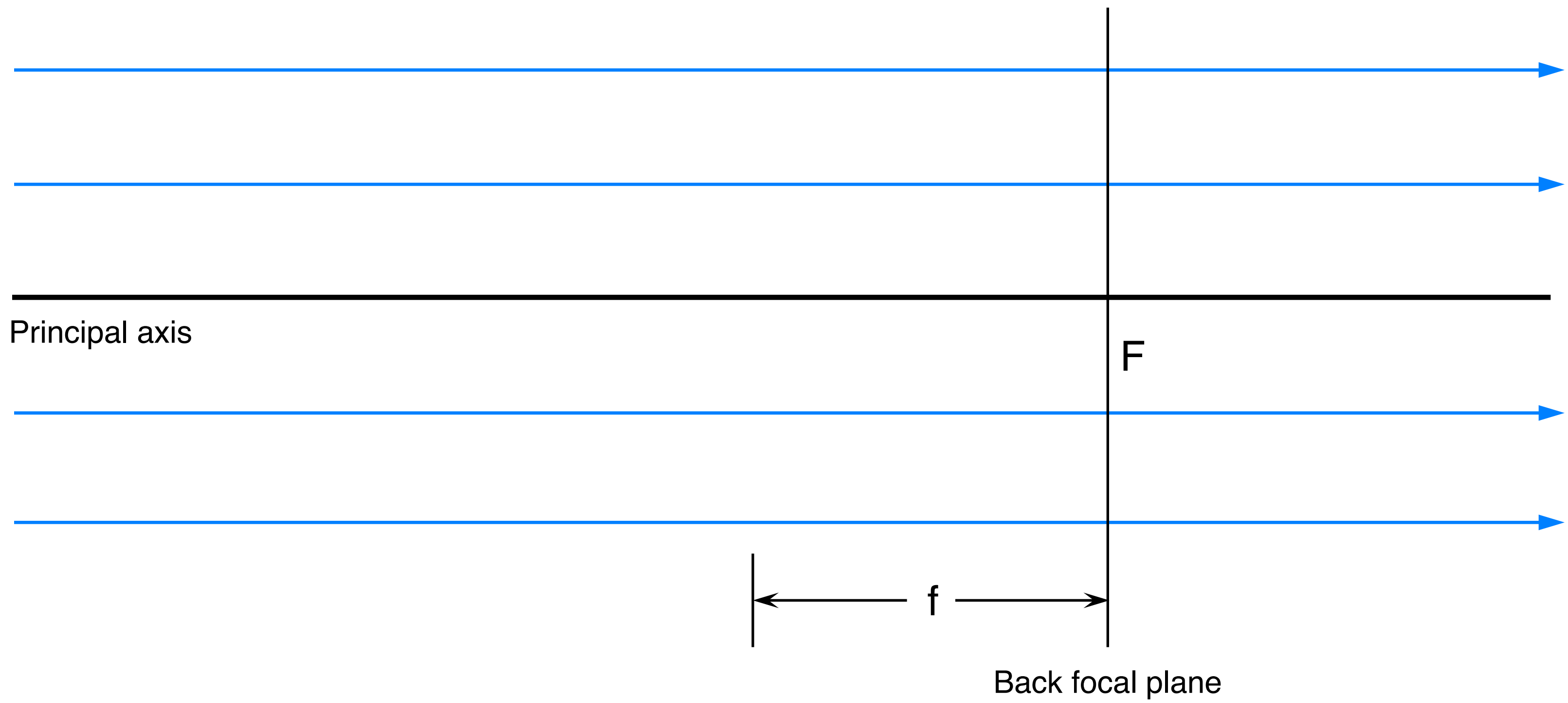


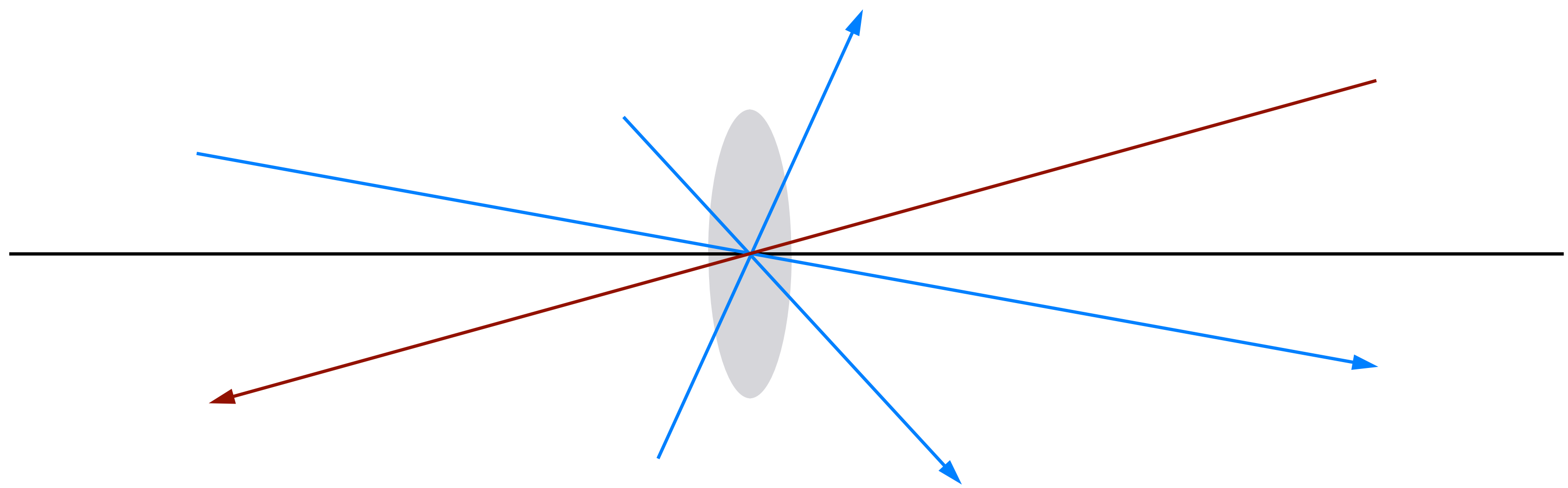
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
Three Simple Principles

1. All rays entering a converging lens **parallel to the lens 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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Three Simple Principles

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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

Construction of Ray Diagrams:

Three Simple Principles

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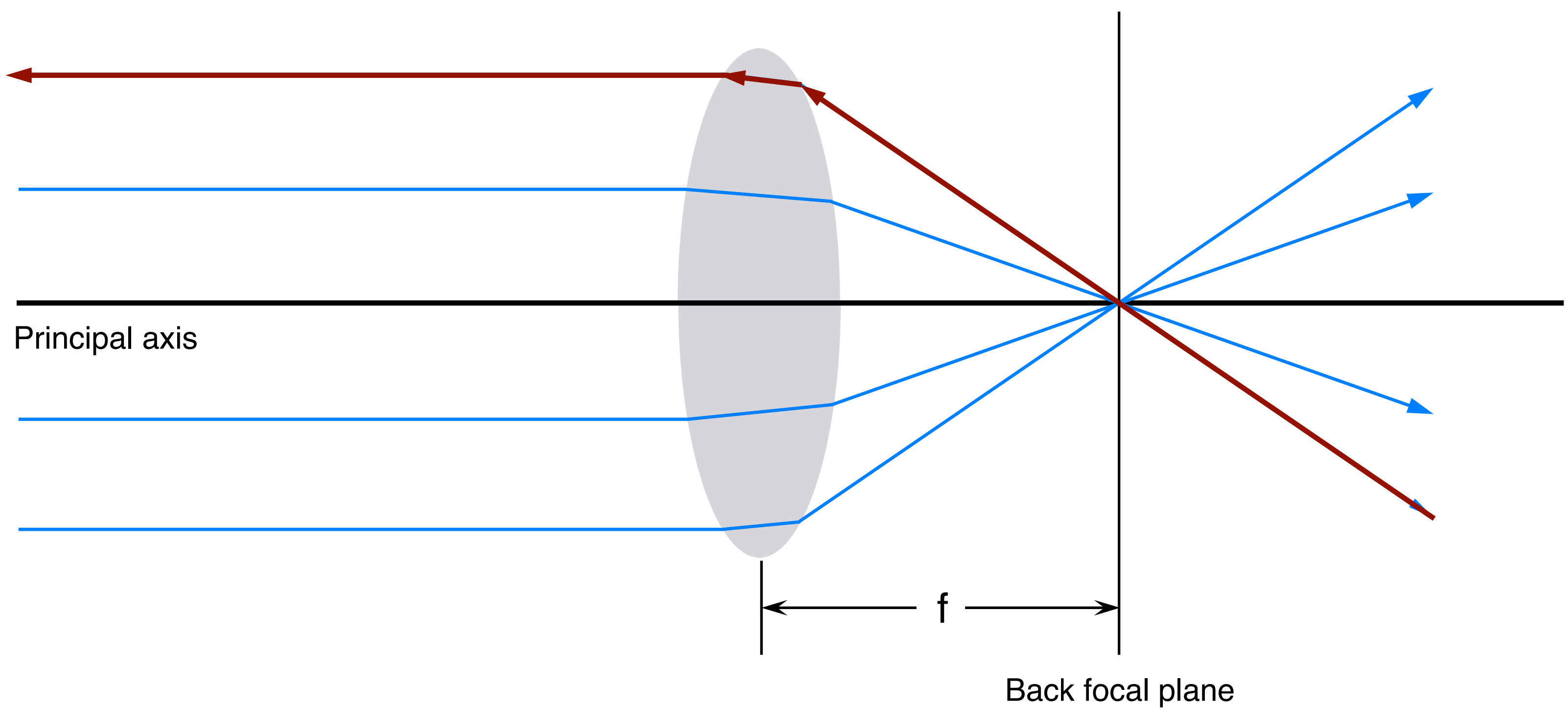

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
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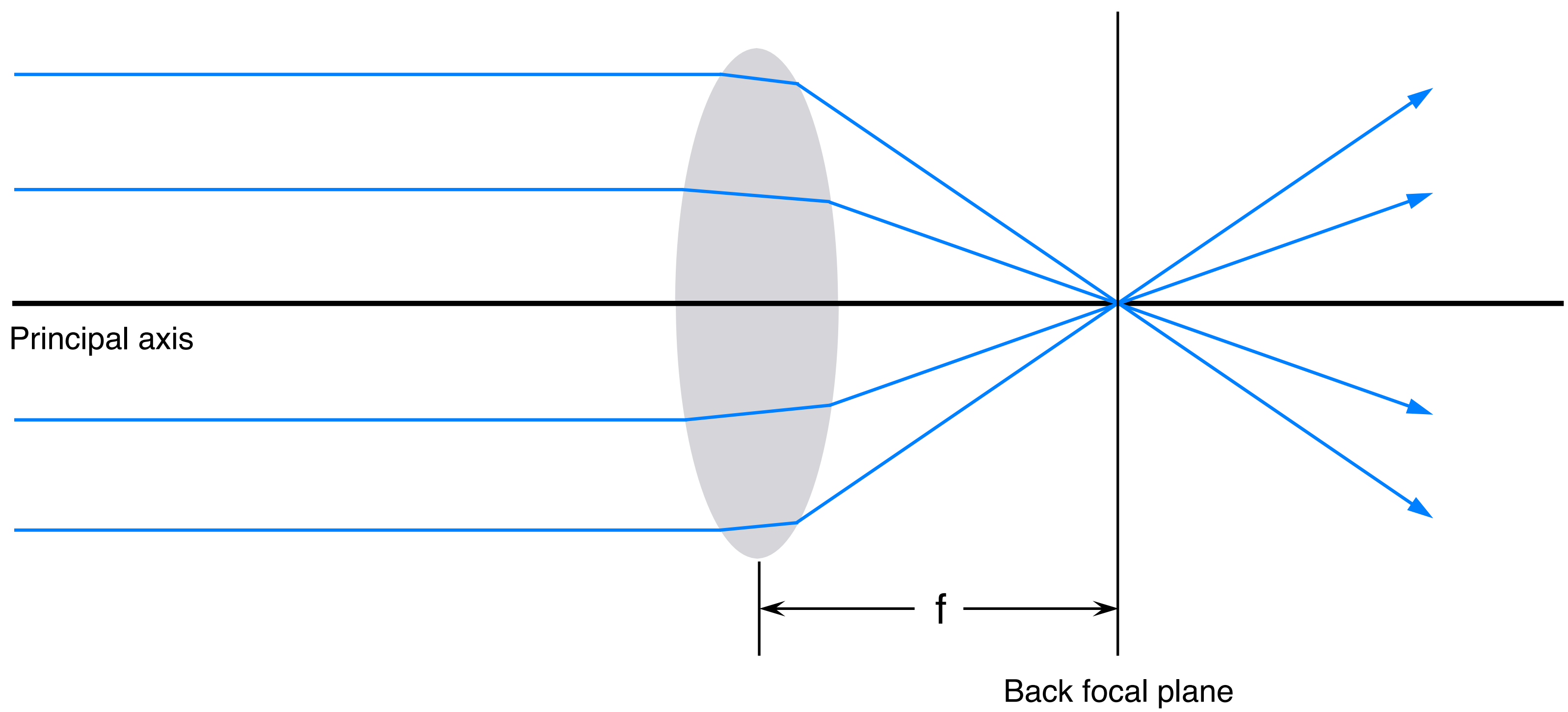

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Construction of Ray Diagrams:
Three Simple Principles

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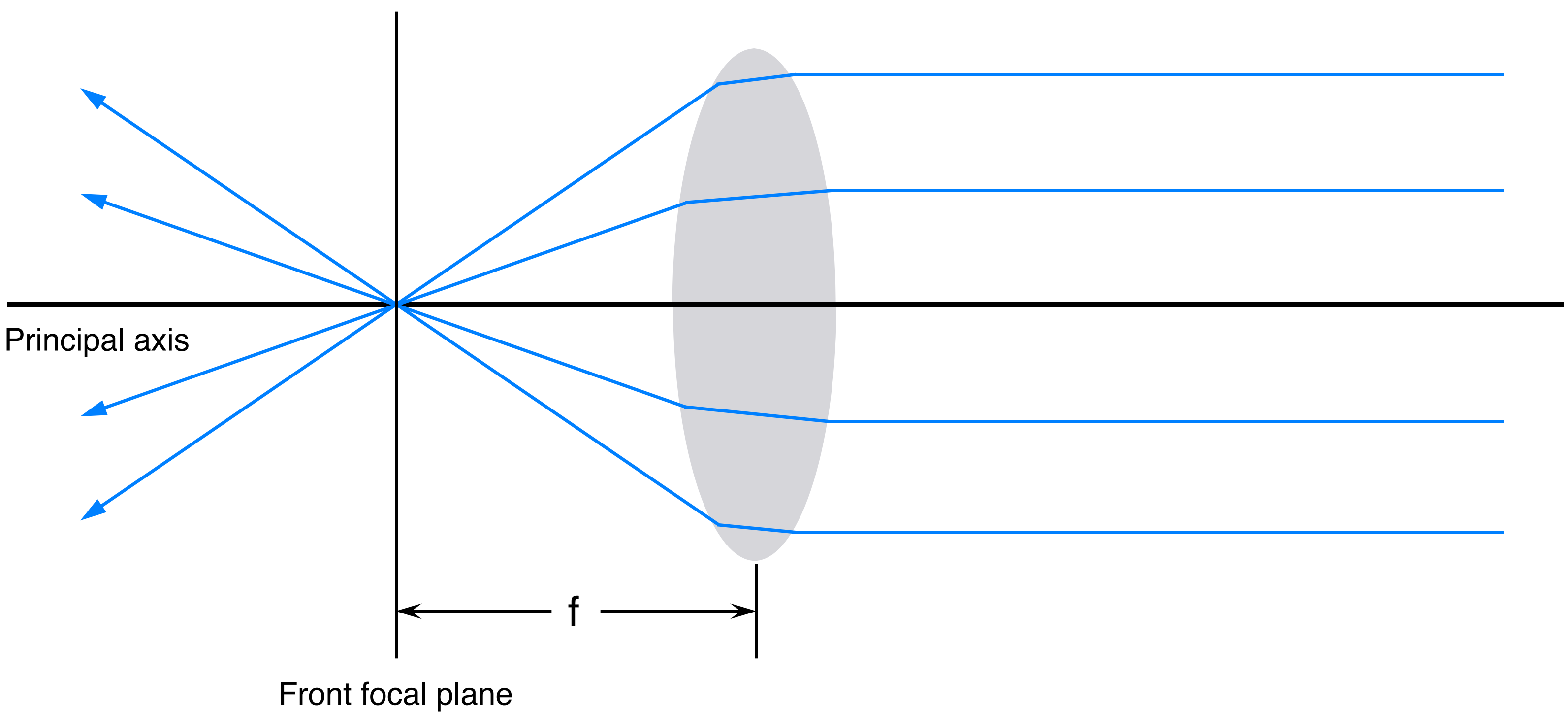


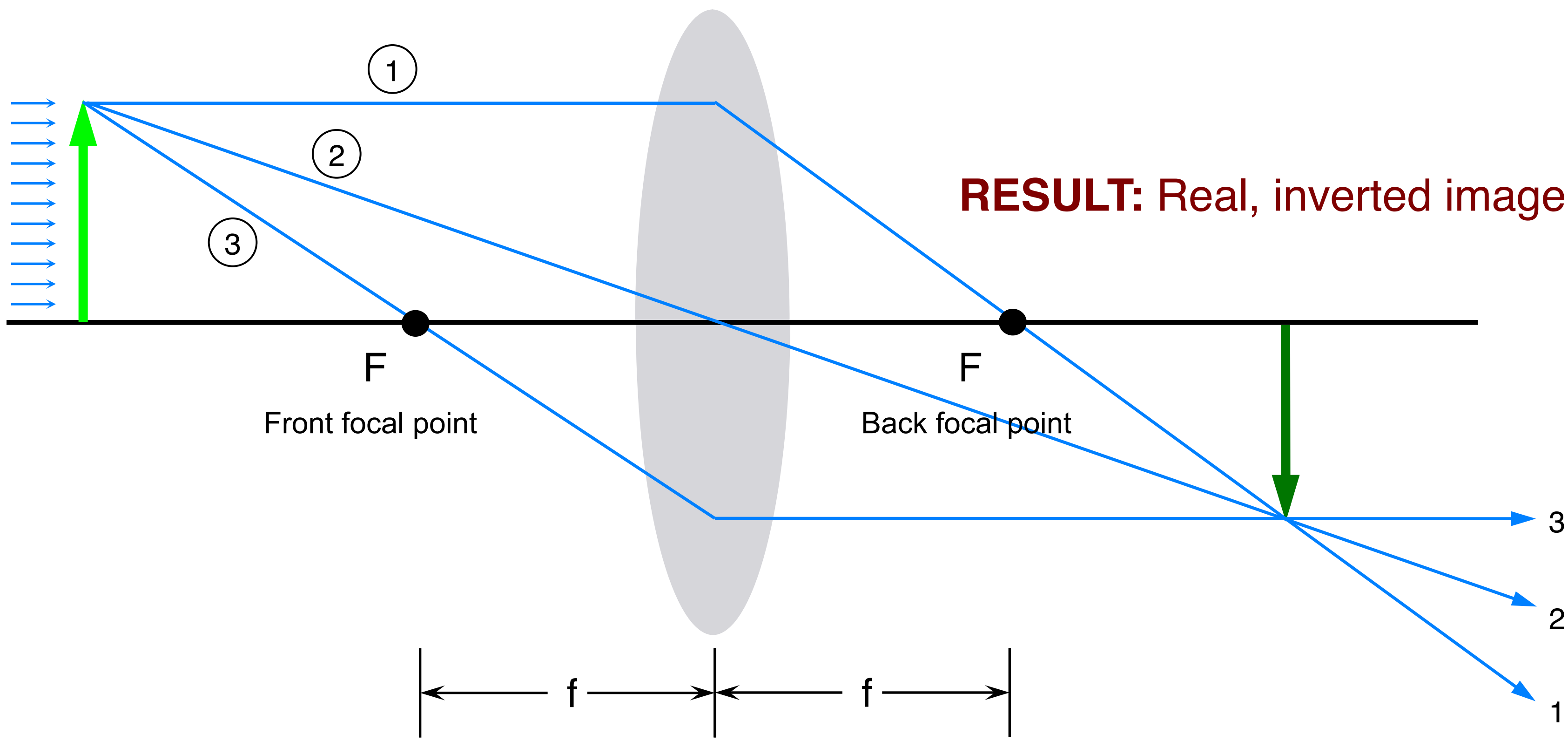
OK, so how might one put all these wonderful facts to good use?

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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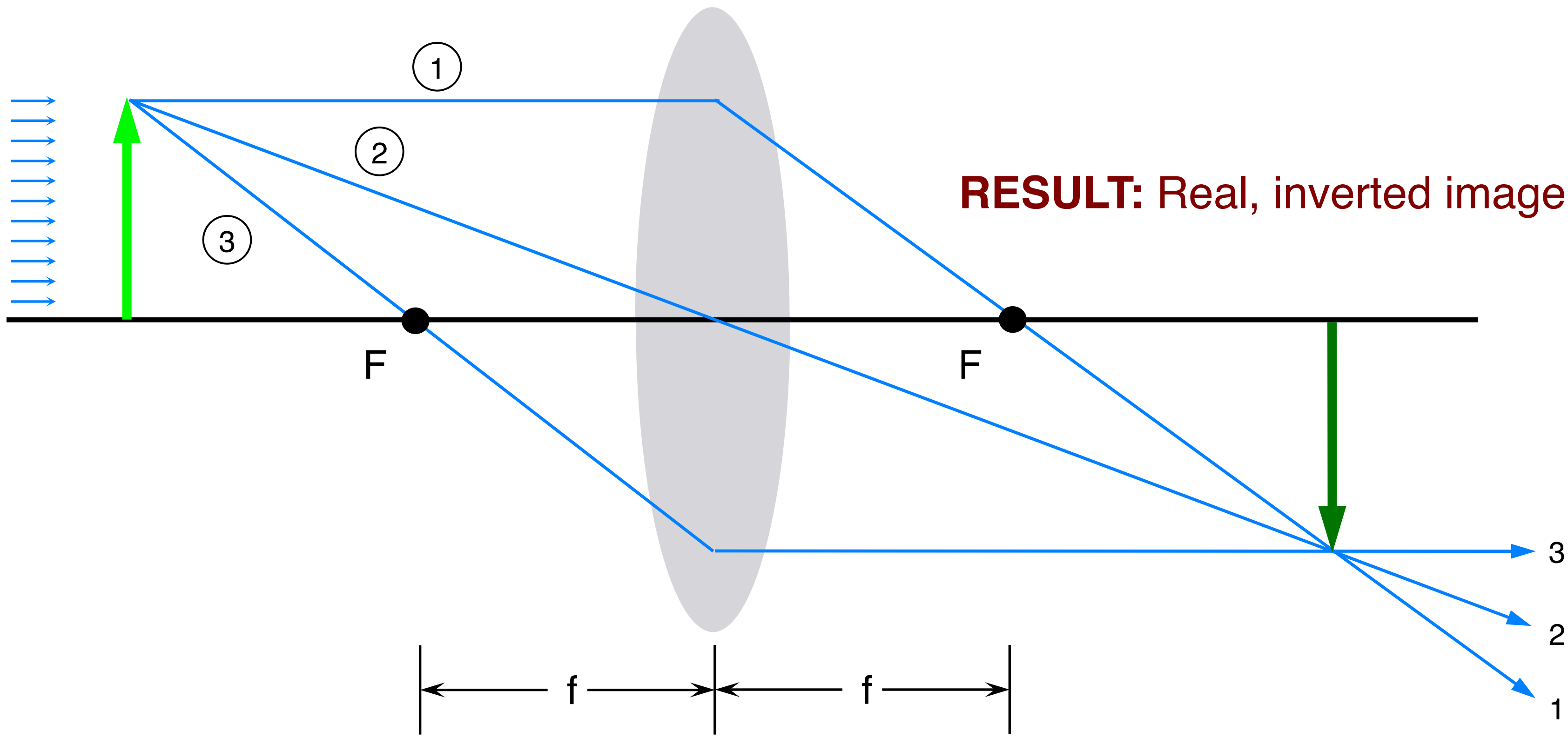

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

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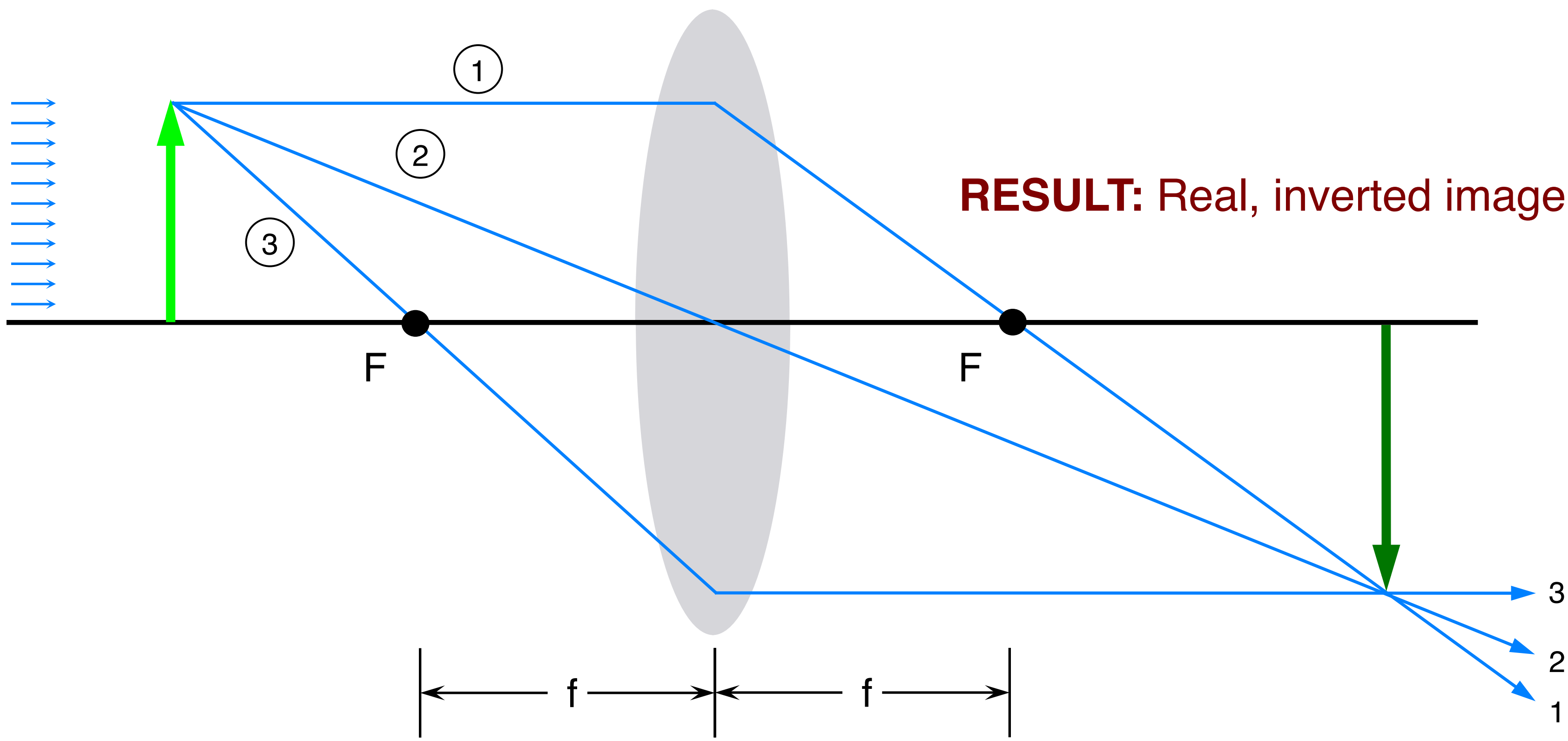


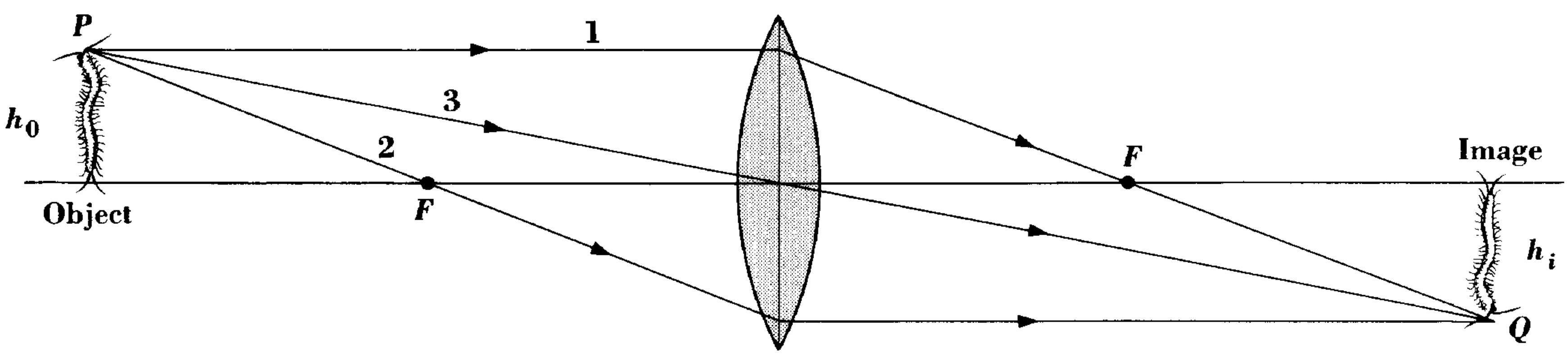
I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

CASE #1: Object distance > focal length

RESULT: Real, inverted image



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

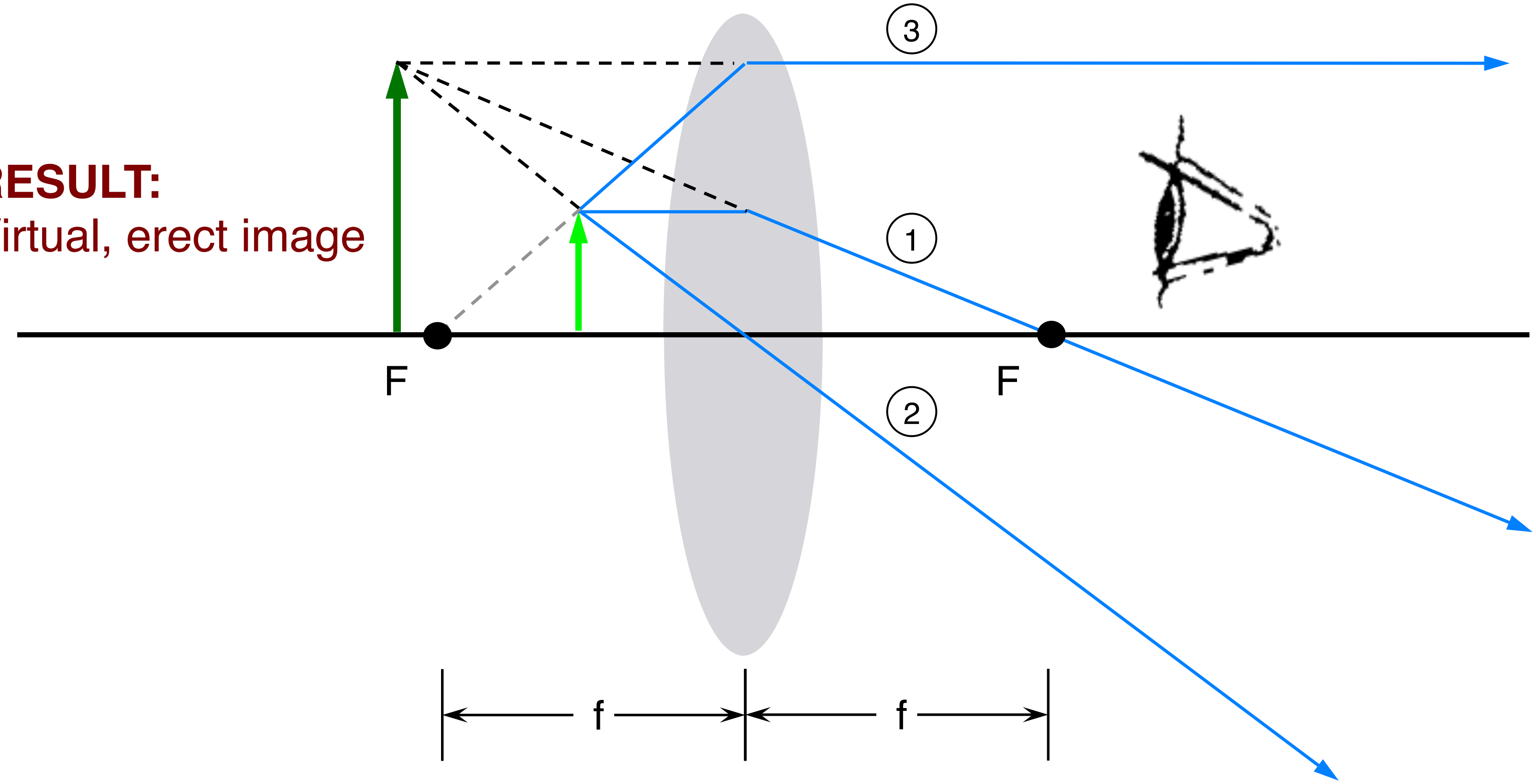
I.A.4 Optics (Lens Theory)

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

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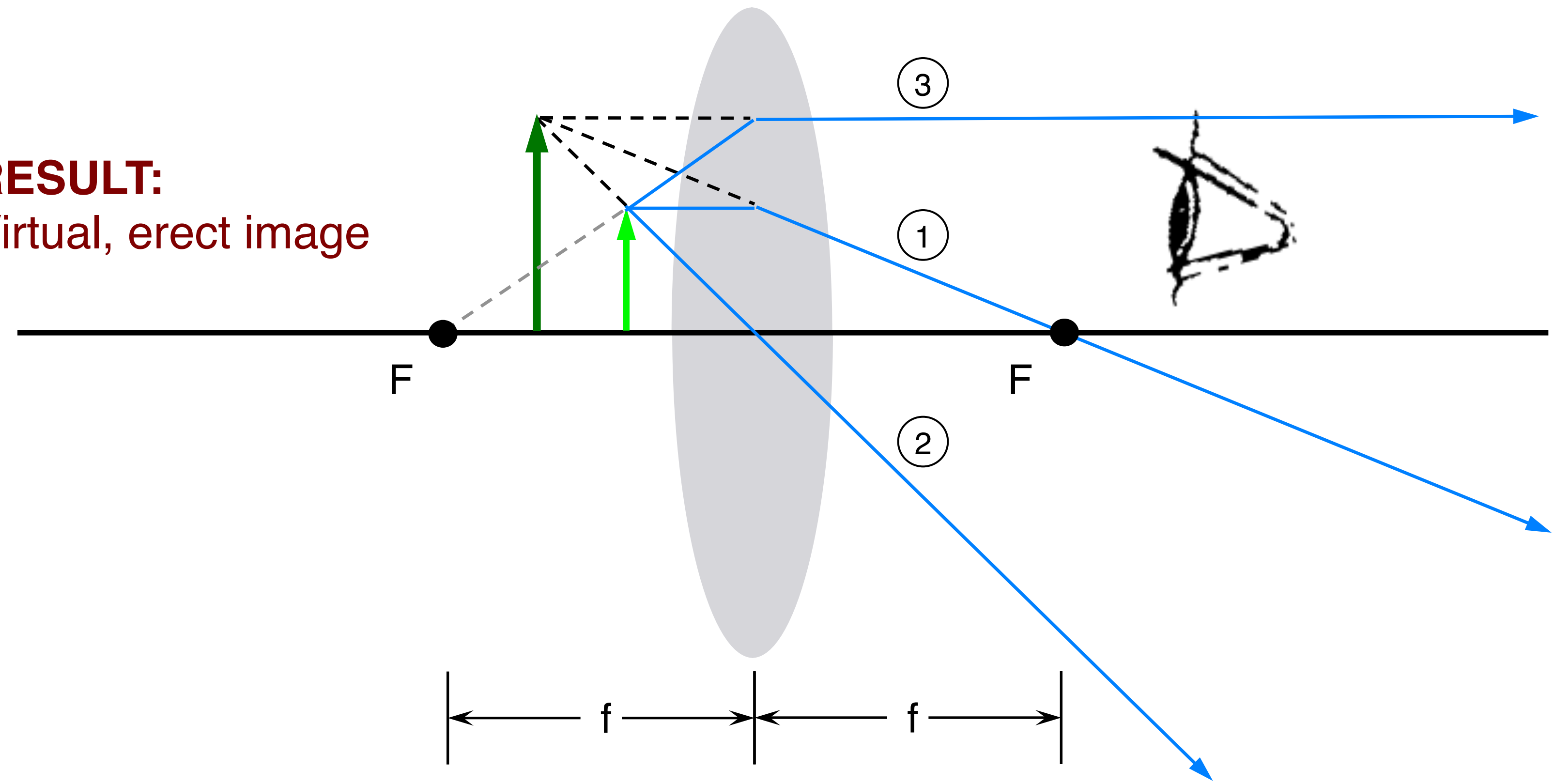

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

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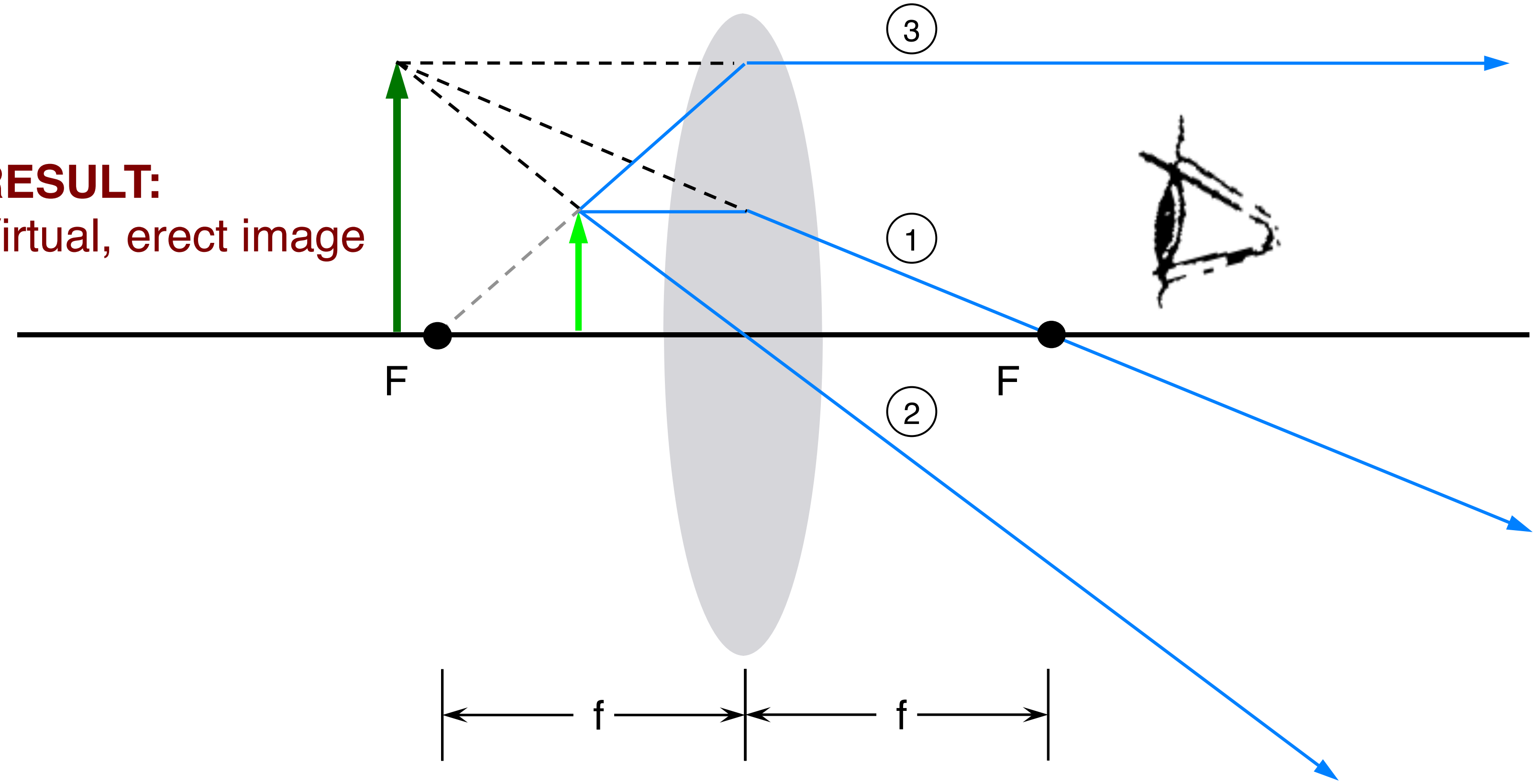

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

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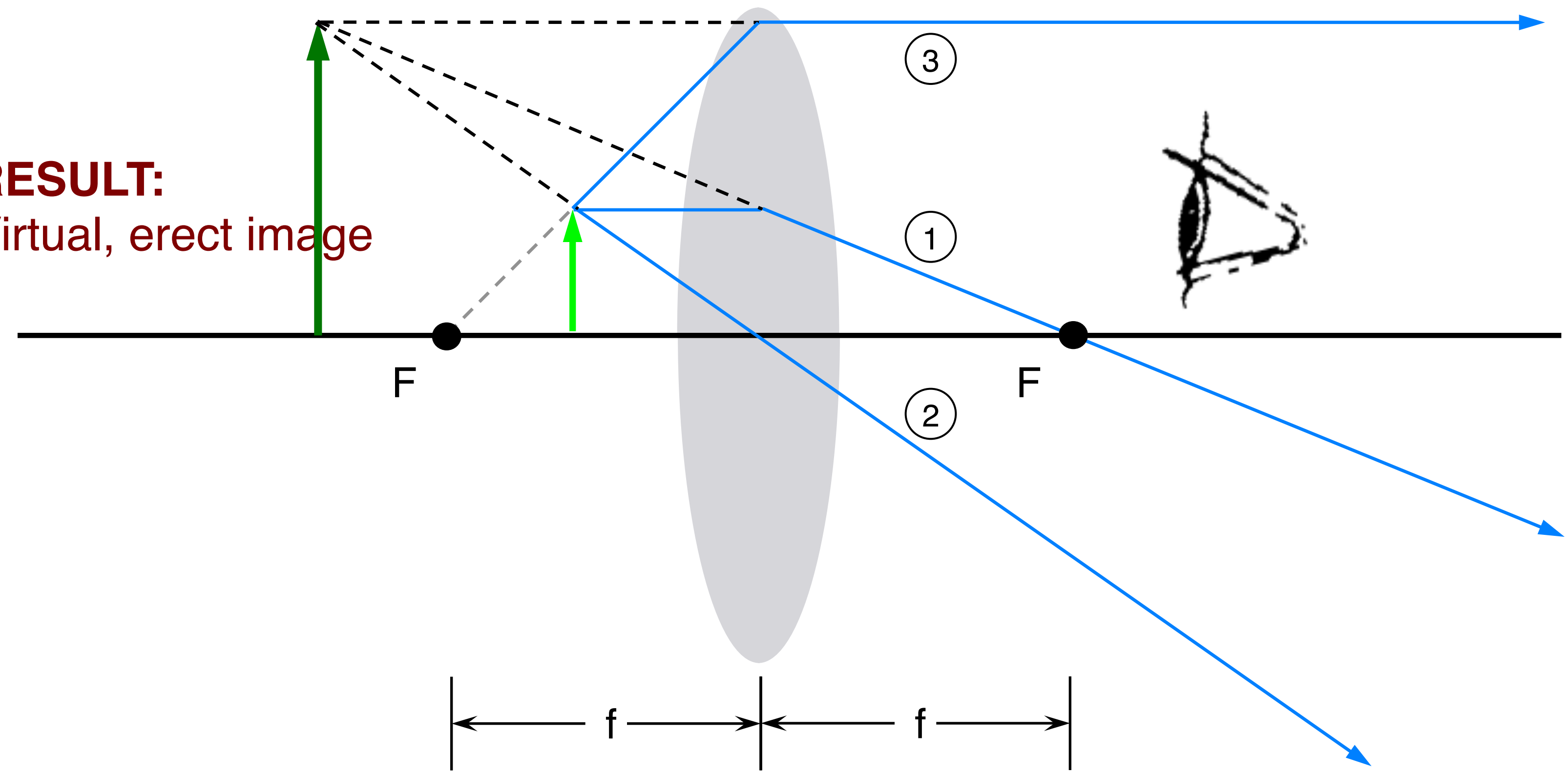

I.A.4 Optics (Lens Theory)

I.A.4.e Ray Diagrams

Image Formation by a Thin Convex Lens

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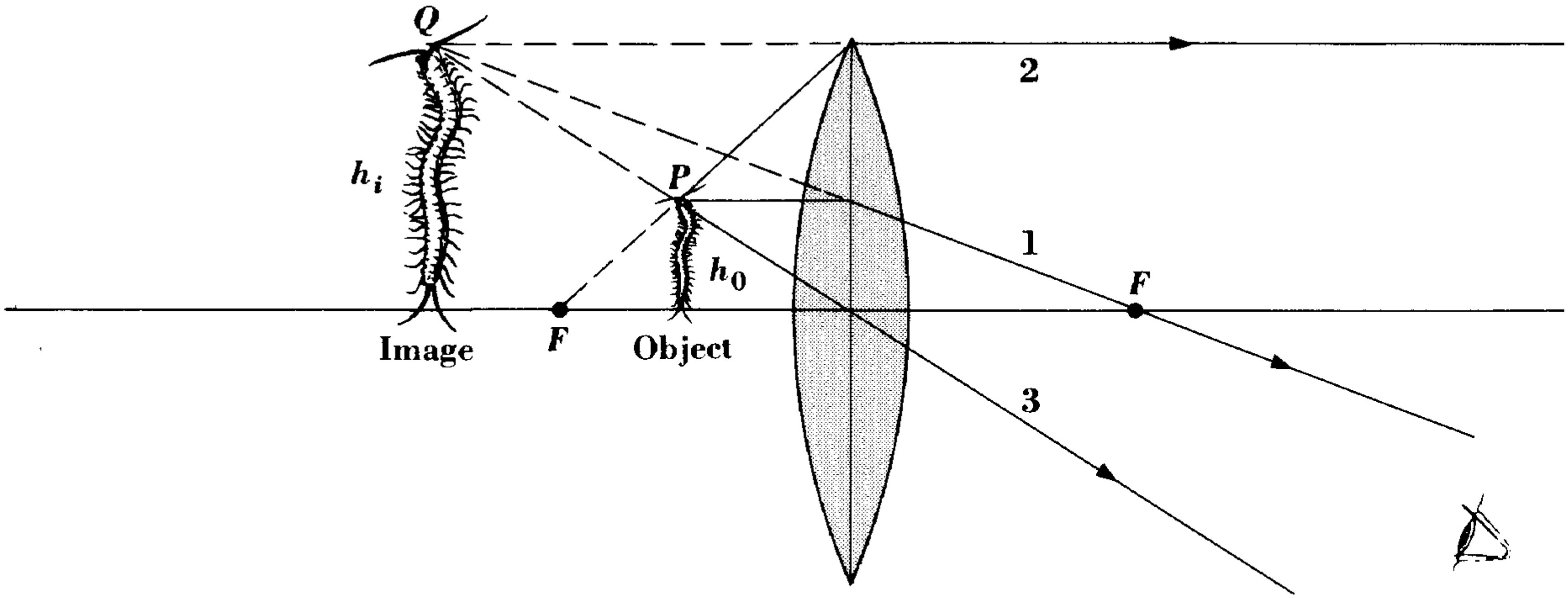


From Young, Fig. 4-10, p. 127

OK, you now know how to construct a ray diagram.

Now what?

I.A PRINCIPLES OF TRANSMISSION EM

NEW CONCEPTS

- **Real and Virtual Images**

- **Thin Lens Equation** $$\frac{1}{f} = \left(\frac{1}{o}\right) + \left(\frac{1}{i}\right)$$

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

- **Lens Aperture:** determines **amount of radiation** arriving from object that can be focused to form an image

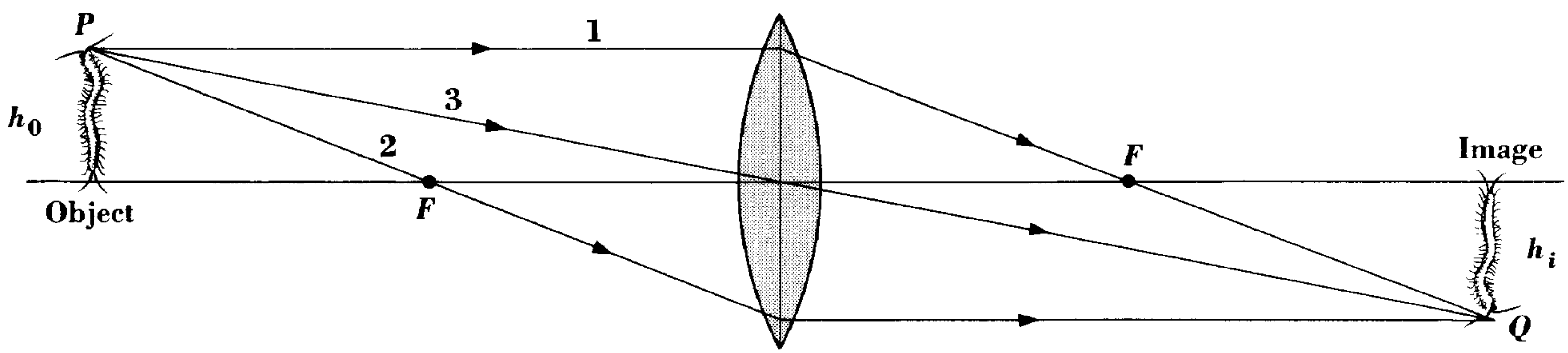
- **High Magnification Imaging:** generally requires 3-4 lenses

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

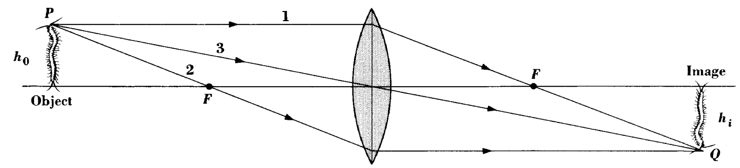
From Young, Fig. 4-10, p. 127

I.A.4 Optics (Lens Theory)

I.A.4.f Definitions

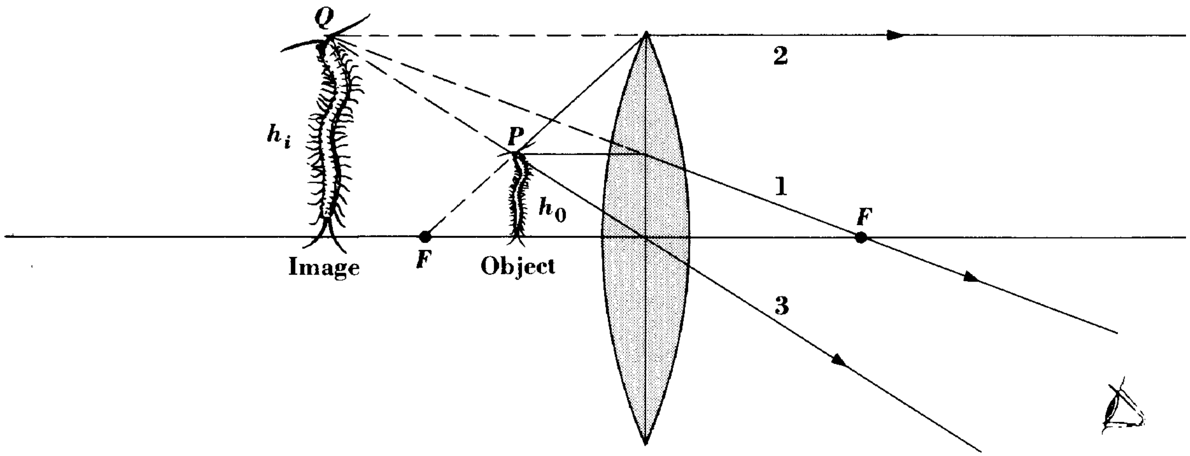
Real vs. Virtual Images

REAL IMAGE:



- Rays physically reunite
- Can expose a photographic plate with a real image

VIRTUAL IMAGE:



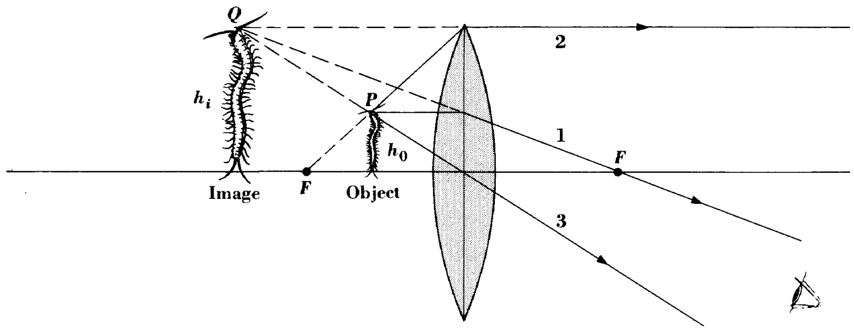
From Young, Fig. 4-10, p. 127

I.A.4 Optics (Lens Theory)

I.A.4.f Definitions

Real vs. Virtual Images

VIRTUAL IMAGE:



- Rays **diverge** and are **not physically reunited** at the position of a virtual image
- **Cannot** expose a photographic plate at the plane of a virtual image
- **Can** place an optical system (*e.g.* eye or another lens) **behind** the lens that forms the virtual image

2nd lens enables divergent rays to be focused to form a real image

Intermediate lens(es) in TEMs are sometimes used this way to **reduce** the final size of the real image formed at the view screen

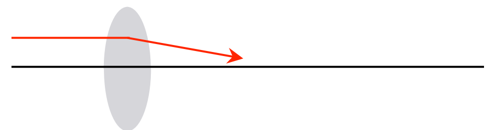
From Young, Fig. 4-10, p. 127

I.A.4 Optics (Lens Theory)

I.A.4.f Definitions

Converging and Diverging Lenses

Converging (positive) lens:



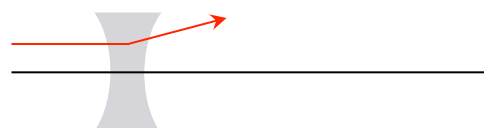
Bends rays **toward** the axis

Positive focal length

Forms real, inverted image of object placed to left of front focal point

Forms erect, virtual image of object placed between front 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

See p.21 of the lecture notes

Slide not shown in class lecture

I.A PRINCIPLES OF TRANSMISSION EM

NEW CONCEPTS

✔ - **Real and Virtual Images**

- **Thin Lens Equation** $$1/f = (1/o) + (1/i)$$

- **Magnification** $$M = \left| i/o \right|$$

- **Lens Aperture:** determines **amount of radiation** arriving from object that can be focused to form an image

- **High Magnification Imaging:** generally requires 3-4 lenses

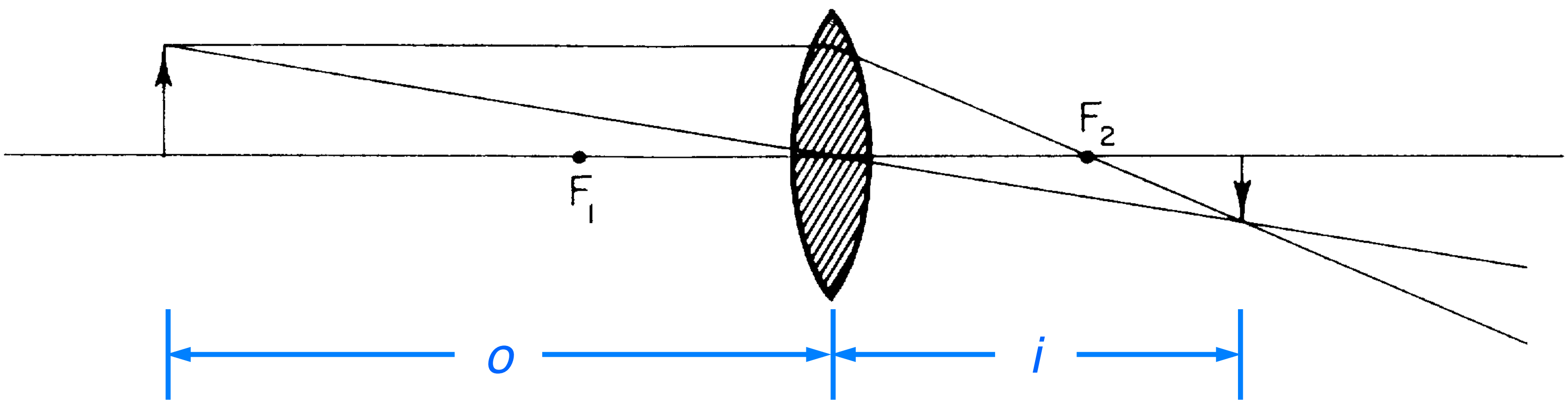
I.A.4 Optics (Lens Theory)

I.A.4.g Lens Formula

THIN LENS EQUATION

$$1/f = (1/o) + (1/i)$$

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

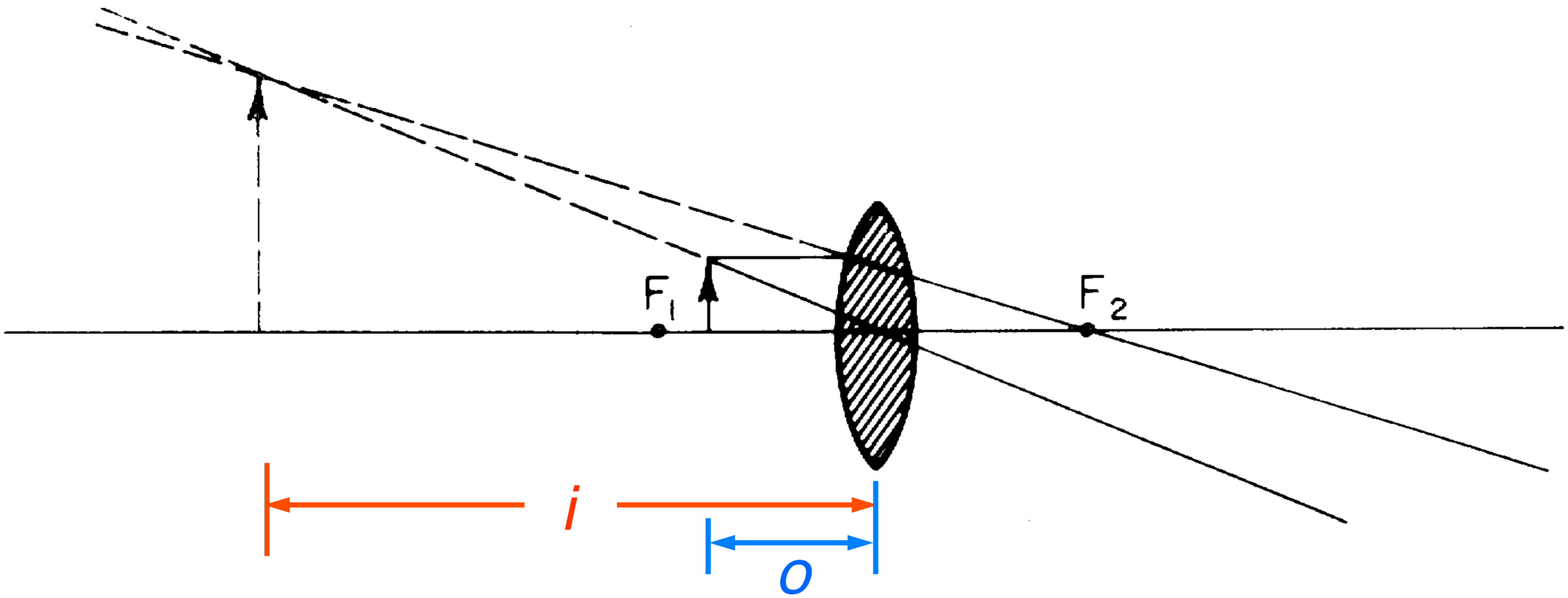
I.A.4 Optics (Lens Theory)

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 PRINCIPLES OF TRANSMISSION EM

NEW CONCEPTS

✔ - **Real and Virtual Images**

✔ - **Thin Lens Equation** $$\frac{1}{f} = \left(\frac{1}{o}\right) + \left(\frac{1}{i}\right)$$

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I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

$$\boldsymbol{M} = \left| {}^{i}\!/\!{}_{o} \right|$$

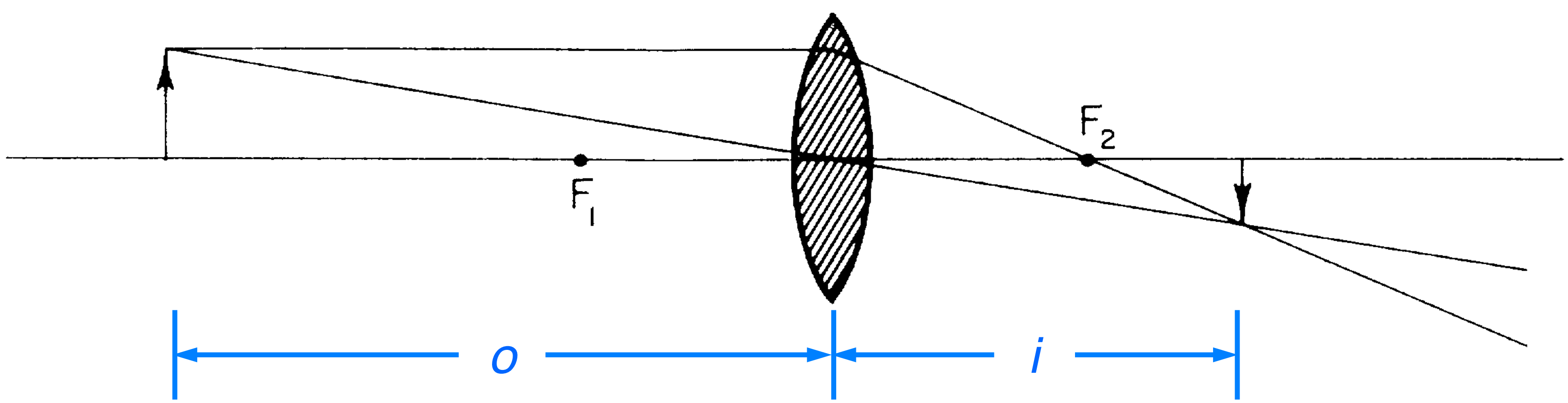
I.A.4 Optics (Lens Theory)

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

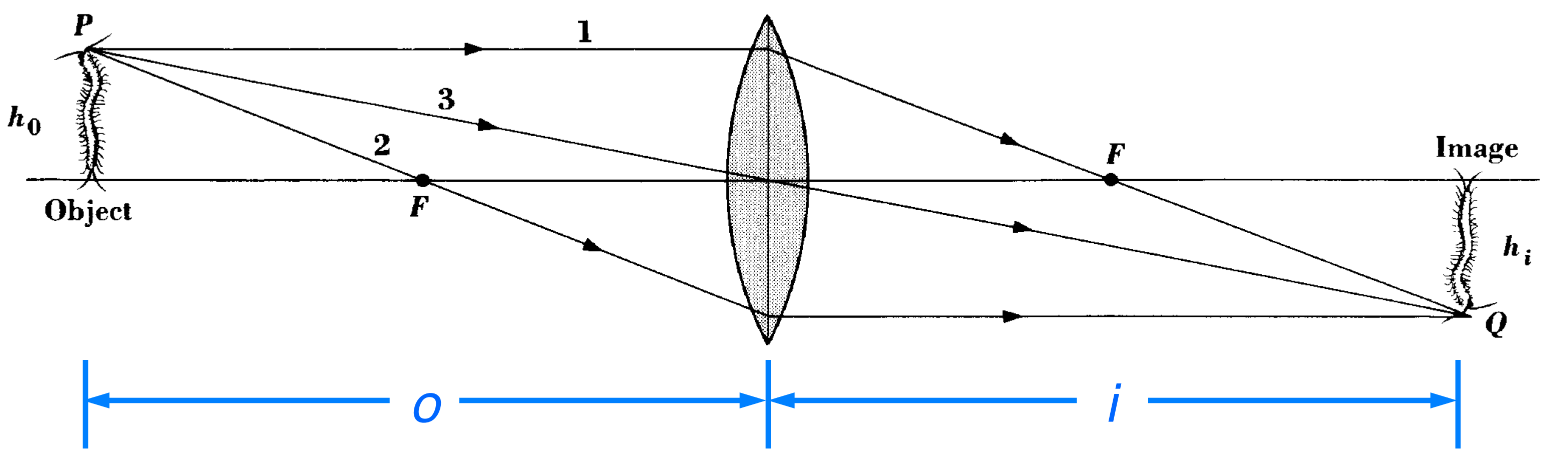
I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

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

For converging lens:

When object is **exactly 2*f*** 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

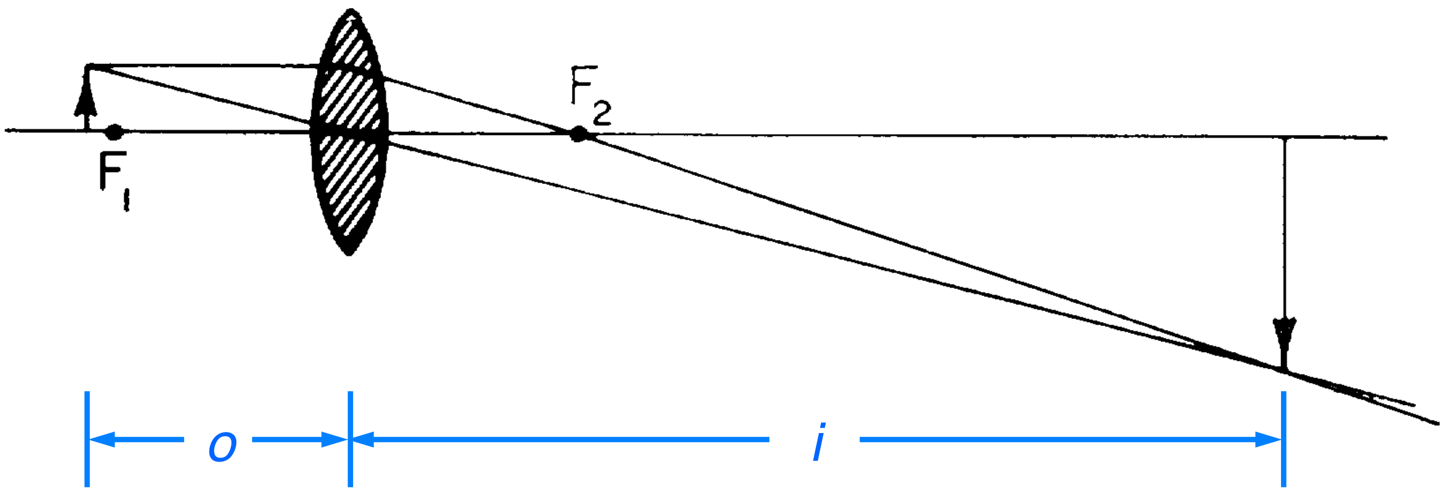
I.A.4 Optics (Lens Theory)

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

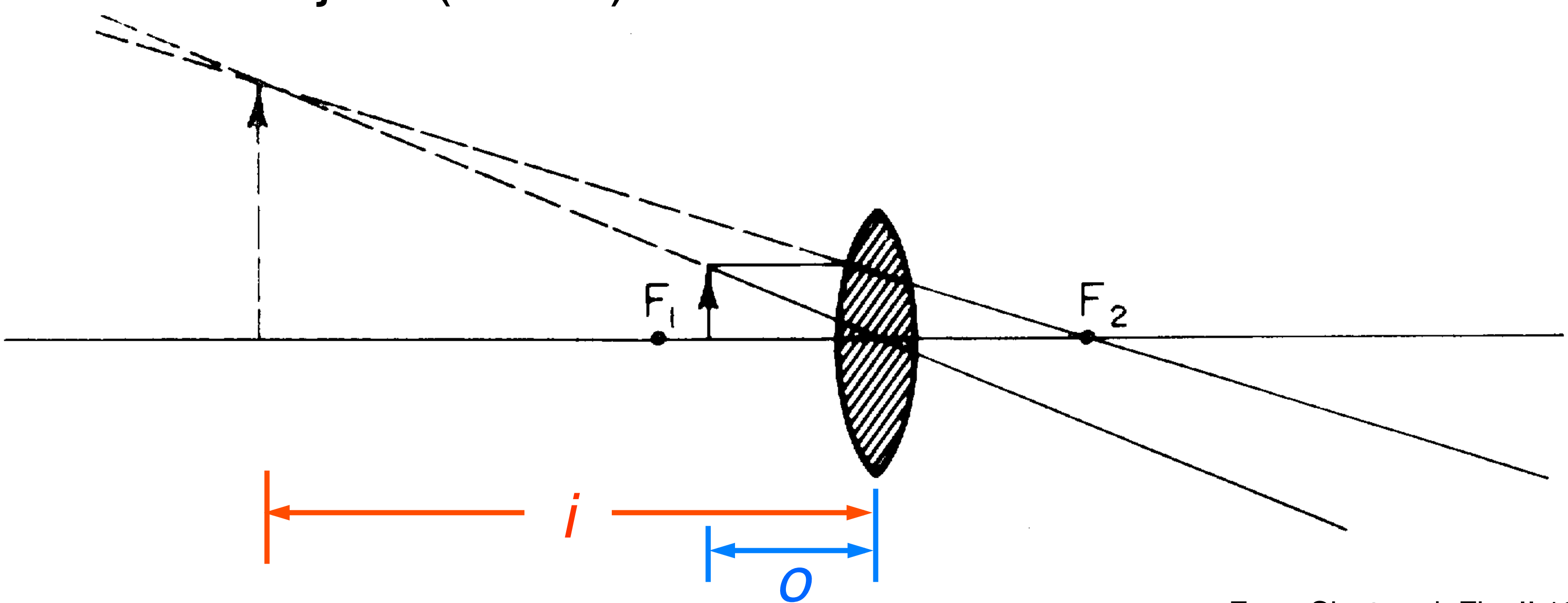
I.A.4 Optics (Lens Theory)

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 PRINCIPLES OF TRANSMISSION EM

NEW CONCEPTS

✔ - **Real and Virtual Images**

✔ - **Thin Lens Equation**

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

✔ - **Magnification**

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

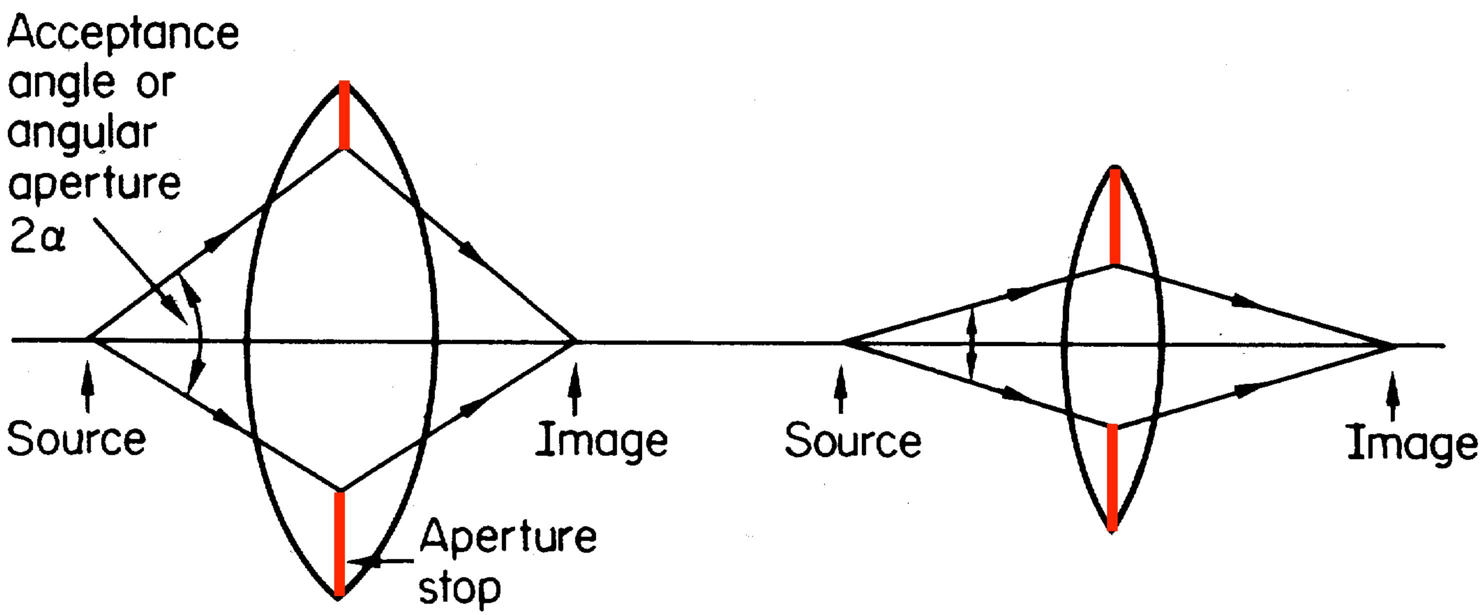
- **Lens Aperture:** determines **amount of radiation** arriving from object that can be focused to form an image

- **High Magnification Imaging:** generally requires 3-4 lenses

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 that can be focused to form an image

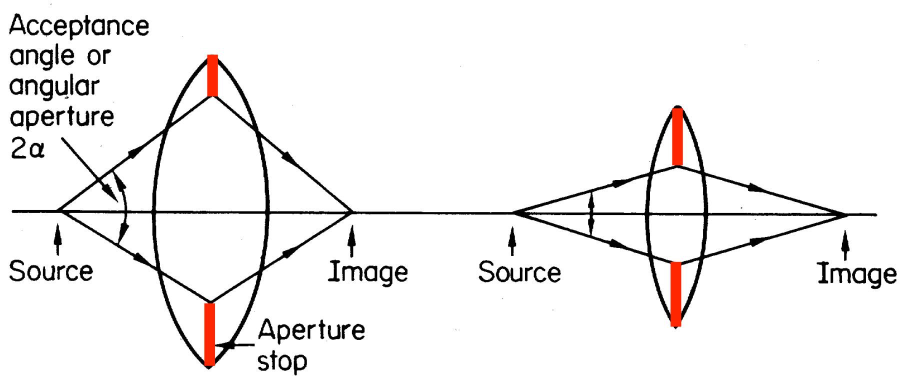


High aperture lens (2α is large)   Low aperture lens (2α is small)

Adapted 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)



High aperture lens (2α is large) Low aperture lens (2α is small)

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

As **2α increases**, the lens can gather **more information** about each object point and transmit that into the image

A lens of **high aperture** has the **potential** to **reveal more detail** (*i.e.* higher resolution) about an object than a lens of low aperture

Can you recall how this relates to our "old friend", the Airy disk?

I.A.4 Optics (Lens Theory)

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

Key distinction between light and electron imaging lenses:

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

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

Recall the Abbe equation $d = \dfrac{0.612\lambda}{n \cdot \sin\alpha}$ and this table:

	n	*sin* α	λ*	*d*
LM	1.5	0.87	400 nm	~ 0.2 μm
TEM	1.0	0.01	0.0037 nm	0.23 nm

I.A PRINCIPLES OF TRANSMISSION EM

NEW CONCEPTS

✔ - **Real and Virtual Images**

✔ - **Thin Lens Equation** $$\frac{1}{f} = \left(\frac{1}{o}\right) + \left(\frac{1}{i}\right)$$

✔ - **Magnification** $$M = \left|\frac{i}{o}\right|$$

✔ - **Lens Aperture:** determines **amount of radiation** arriving from object that can be focused to form an image

- **High Magnification Imaging:** generally requires 3-4 lenses

I.A.4 Optics (Lens Theory)

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

Key Concept

It is **impractical** to form a **high** magnification image with just **one** lens

… or even two lenses

I.A.4 Optics (Lens Theory)

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

In principle: (an **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-to-image distance (*i*)**

The answer?

Use **two or more lenses** to magnify the image in **stages**

Total magnification = **product** of magnifications at all stages

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

I.A.4 Optics (Lens Theory)

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

Example: *One-stage verses two-stage magnification*

Problem (Two parts):

1. Achieve **10,000X** image magnification using only **one** lens (with ***f* = 2.0 cm**)

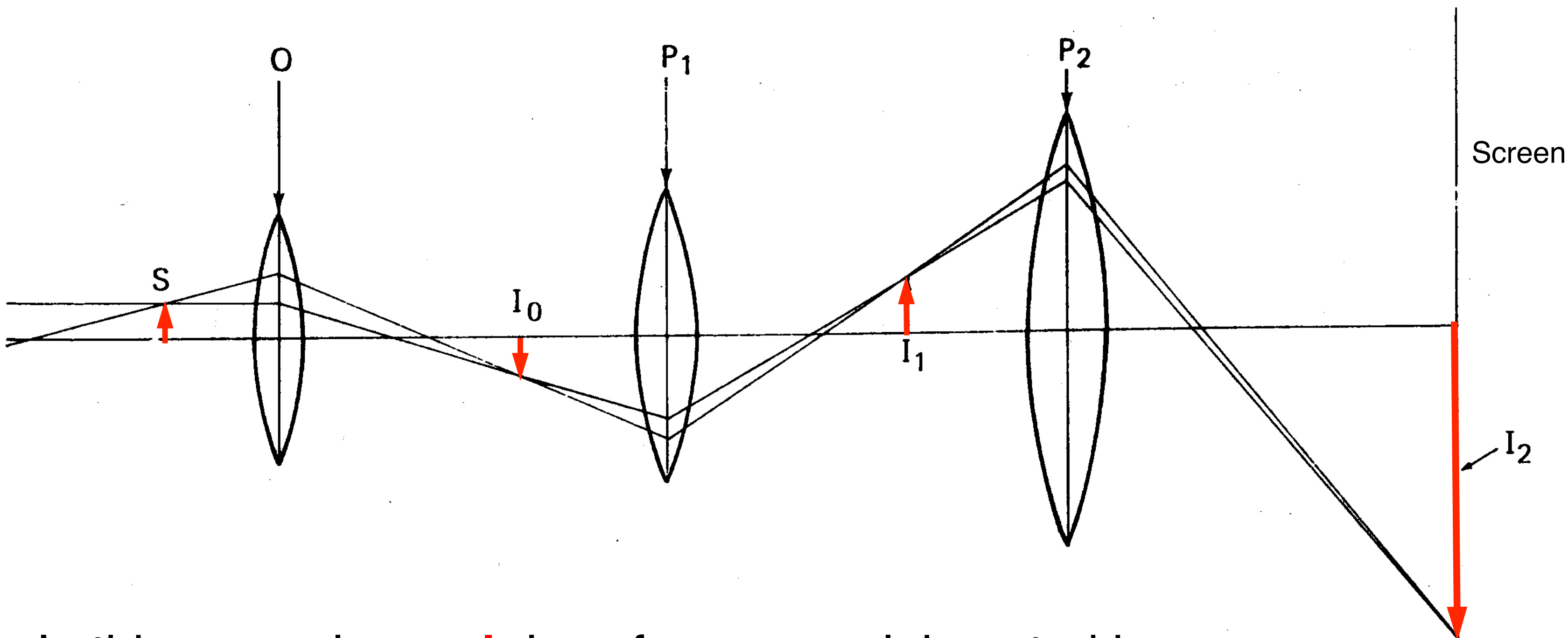
2. Achieve **10,000X** image magnification using **two** lenses (each with ***f* = 2.0 cm**)

Use the thin lens equation and try to solve this on your own (unless you have already read p.23 of the lecture notes, which gives the answer).

I.A.4 Optics (Lens Theory)

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

Ray diagram: High magnification mode of operation



In this example, **each** lens forms a real, inverted image.

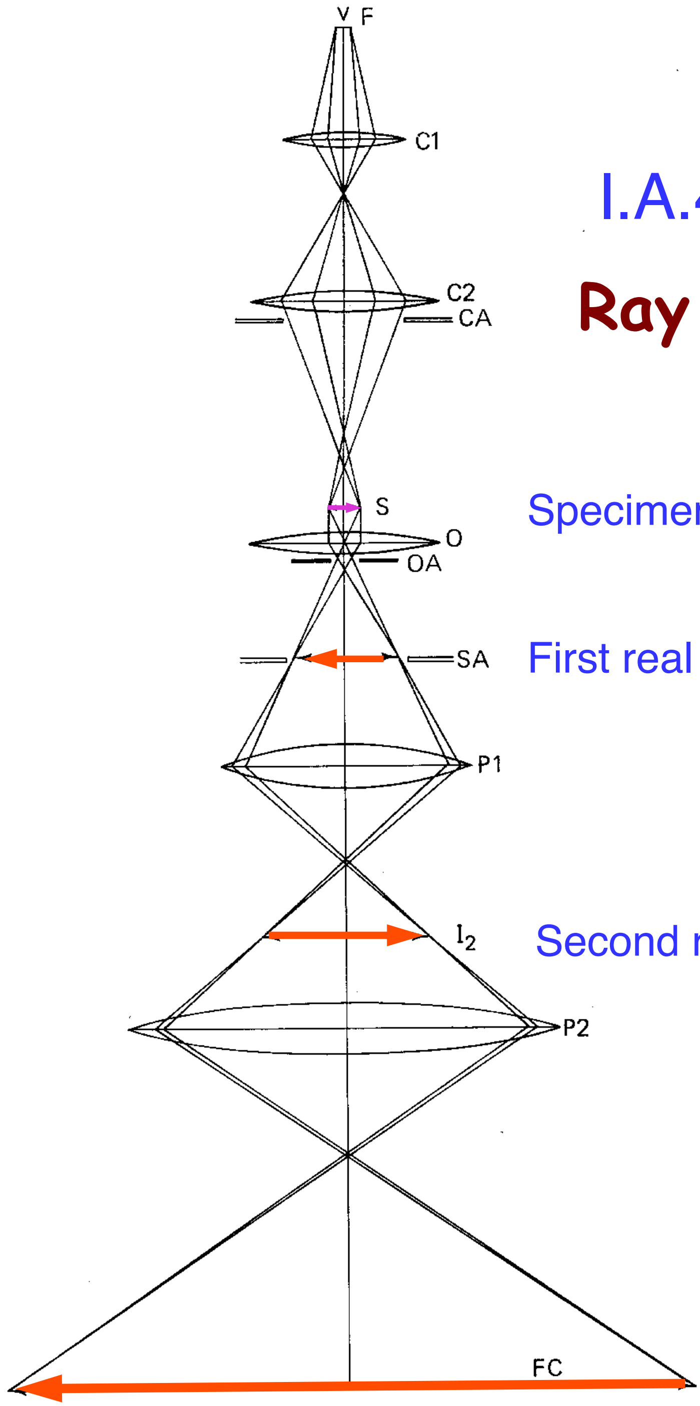
Note: Drawing is ONLY schematic!!!
(*i.e.* it is inaccurate)

From Agar, Fig. 1.23, p. 30

I.A.4 Optics (Lens Theory)

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

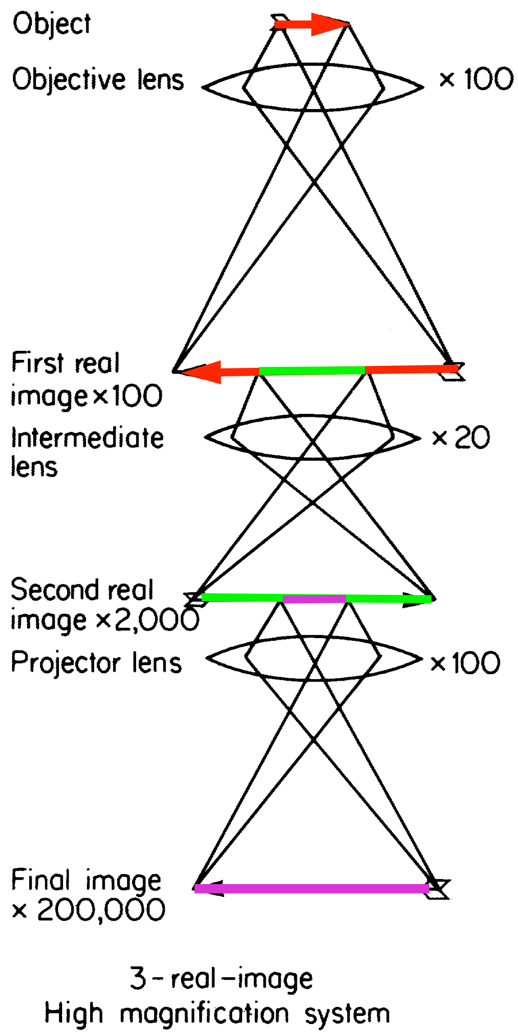
Ray diagram for a two projector TEM



From Agar, Fig. 1.30, p. 35

I.A.4 Optics (Lens Theory)

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



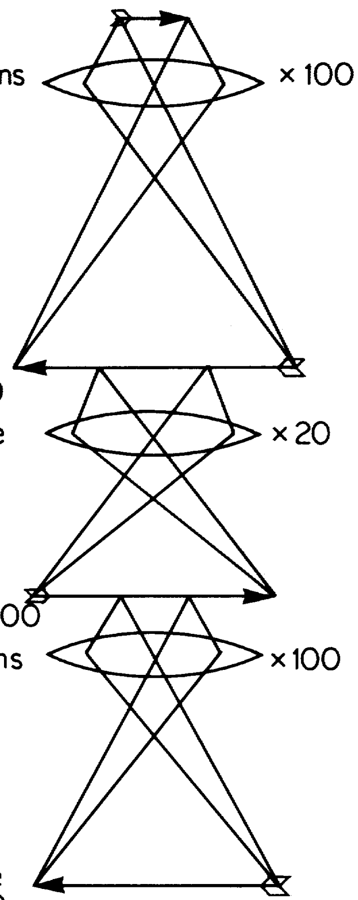
Key Concept:

Only a **portion** of each successive intermediate image is magnified by the next lens

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

I.A.4 Optics (Lens Theory)

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



3 - real - image
High magnification system

Key Concept:

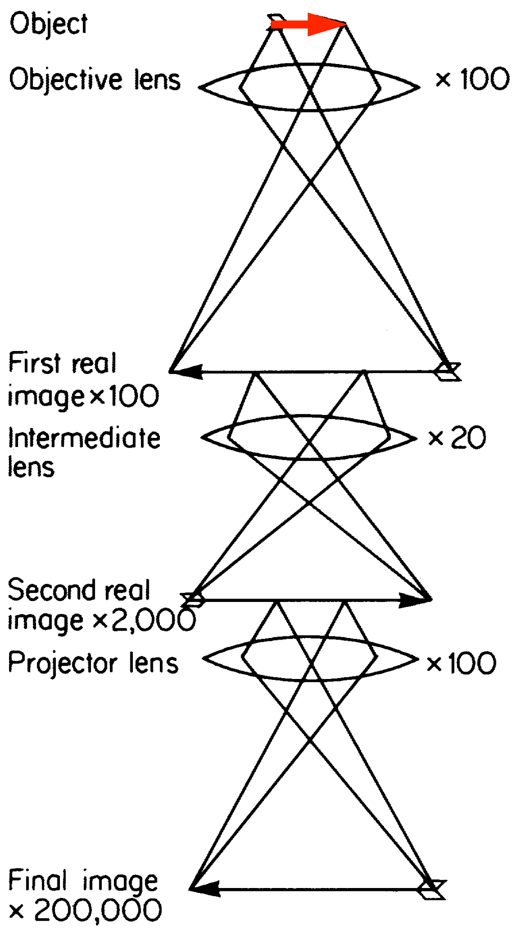
Only a **portion** of each successive intermediate image is magnified by the next lens

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

Slide not shown in class lecture

I.A.4 Optics (Lens Theory)

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



3 - real - image
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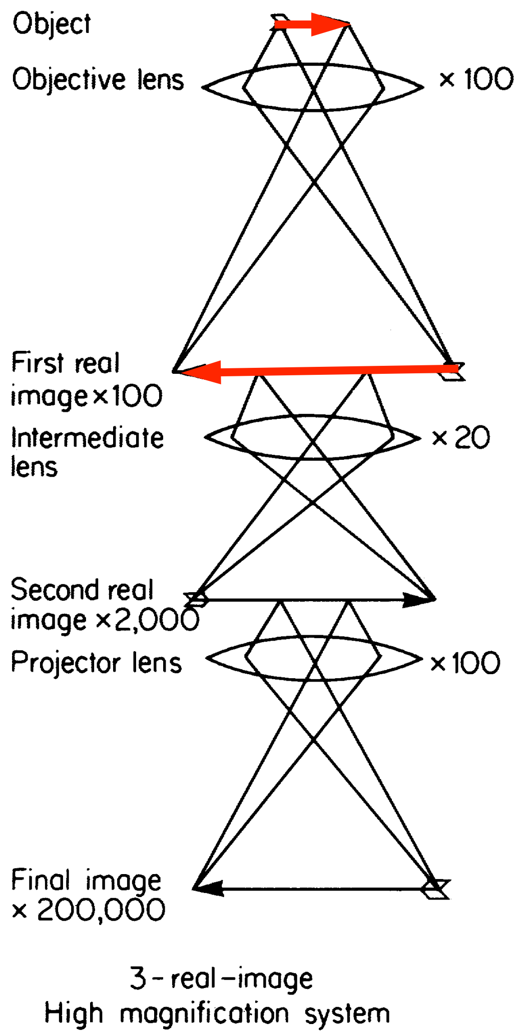
From Meek 1st ed., Fig. 5.16, p. 118

Slide not shown in class lecture

I.A.4 Optics (Lens Theory)

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



Key Concept:

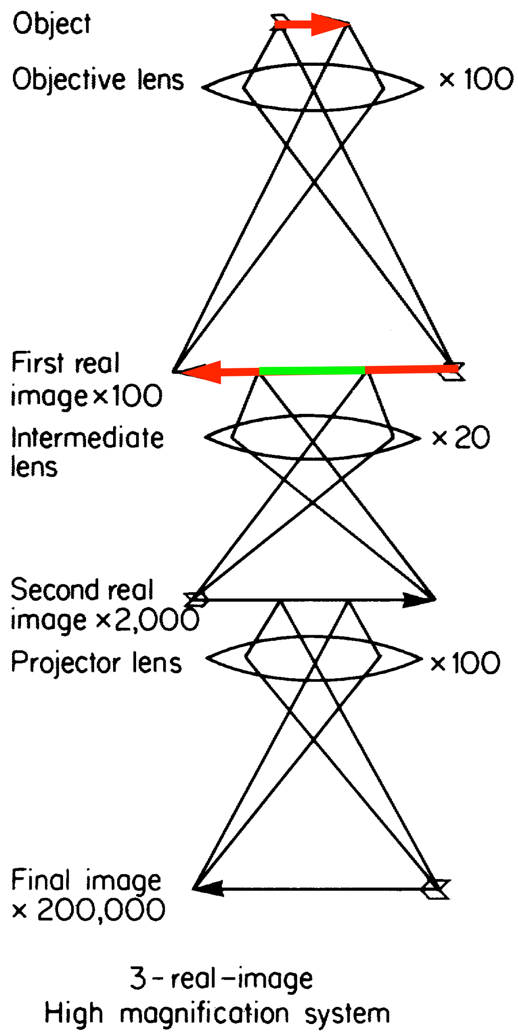
Only a **portion** of each successive intermediate image is magnified by the next lens

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

Slide not shown in class lecture

I.A.4 Optics (Lens Theory)

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



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

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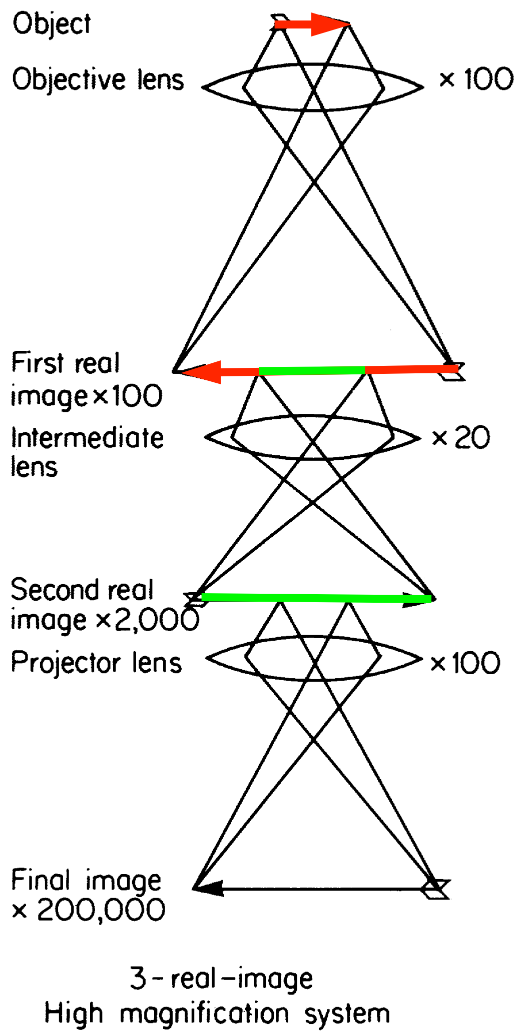
I.A.4.j Simple vs. Compound Microscope



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

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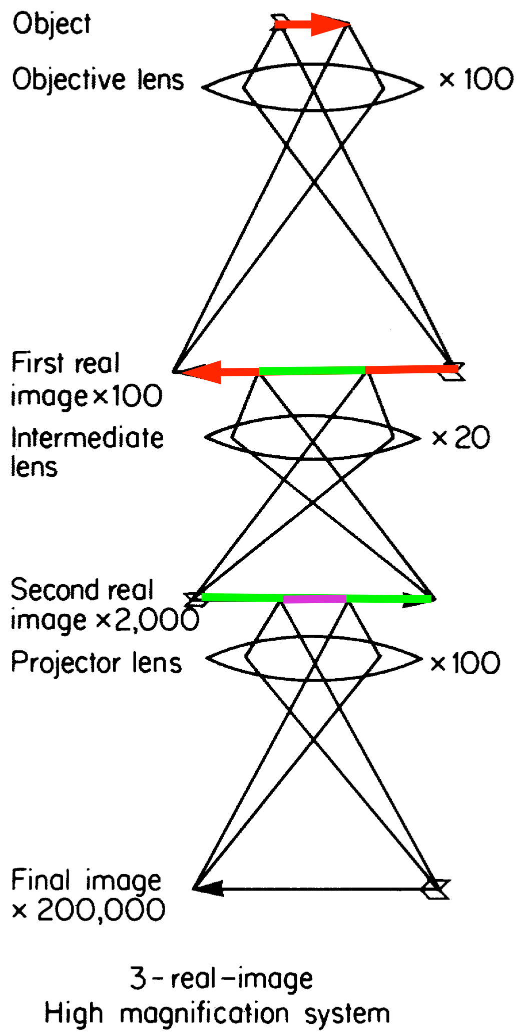
I.A.4.j Simple vs. Compound Microscope



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

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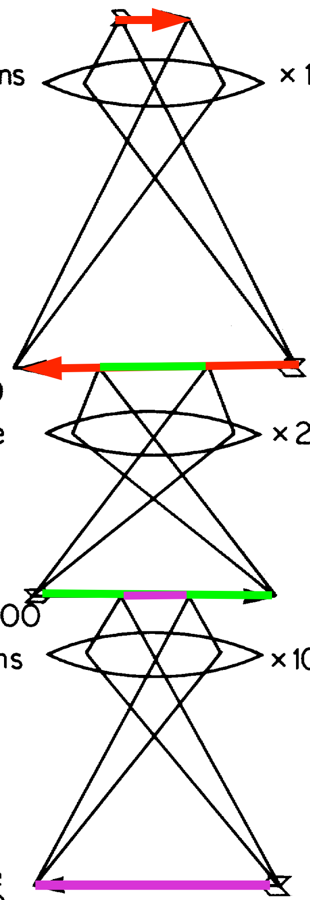
I.A.4 Optics (Lens Theory)

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



3 - real - image
High magnification system

Key Concept:

Only a **portion** of each successive intermediate image is magnified by the next lens

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

Slide not shown in class lecture

§ I: The Microscope

I.A Principles of TEM

I.A.5 Electron Optics / Electron Lenses

(pp.25-37 of lecture notes)

I.A.5 Electron Optics / Electron Lenses

NEW CONCEPTS

- **Thermionic emission** creates a source of beam electrons

- **Charged objects** produce an **electric field**

- Path of an electron passing through an **electric field** or a **magnetic field** is bent or **refracted**

- **Focal length** of electromagnetic lens determined by **field strength** and **electron speed**

I.A.5 Electron Optics / Electron Lenses

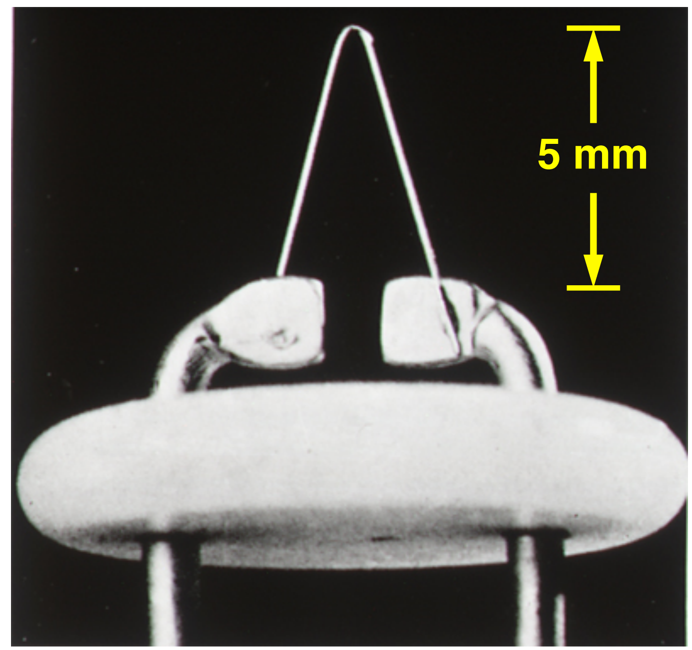
I.A.5.a Electron Emission

Thermionic Emission

Process by which **thermal energy** is supplied to loosely bound e^- in a metal to form a source of 'free' e^-

Simplest form of an electron gun filament is a **thin tungsten wire**

Wire is heated by passing an electric current through it



Electron gun tungsten filament (cathode)

From Agar, Fig. 2.5, p.45

Take home message of next several slides:

Electromagnetic lenses produce strong magnetic fields

These refract (bend) moving electrons and therefore allow them to be focused into electron images