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

Lecture Slides

Jan 15, 2013

Fill In Blank (XXX)

According to Abbe's simple criterion for estimating the resolving power of an optical instrument, the smallest object spacings (or details) one can expect to resolve with the instrument are about **XXX** the wavelength of the radiation used to form images.

A. one tenth the size of

B. one half the size of

C. the same size as

D. two times the size of

E. ten times the size of

Multiple Choice Question

Which dimension in the following list is largest?

A. 0.0191 μm

B. 19.0 nm

C. 190 Å

D. 1.91 nm

E. 1.92×10^{-10} m

True / False

The angular aperture typically used in electron optics is much smaller than what is used in light optics.

A. True

B. False

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

Announcements for Jan 15, 2013

Reading assignment for Thursday: Lecture notes pp.65-72

'Virtual homework': always check web site for new updates

Recitation session: Friday Jan 18; York 4080A; 5-6:00 pm

TEM facility tour: Jan 28,29 (check web site)

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

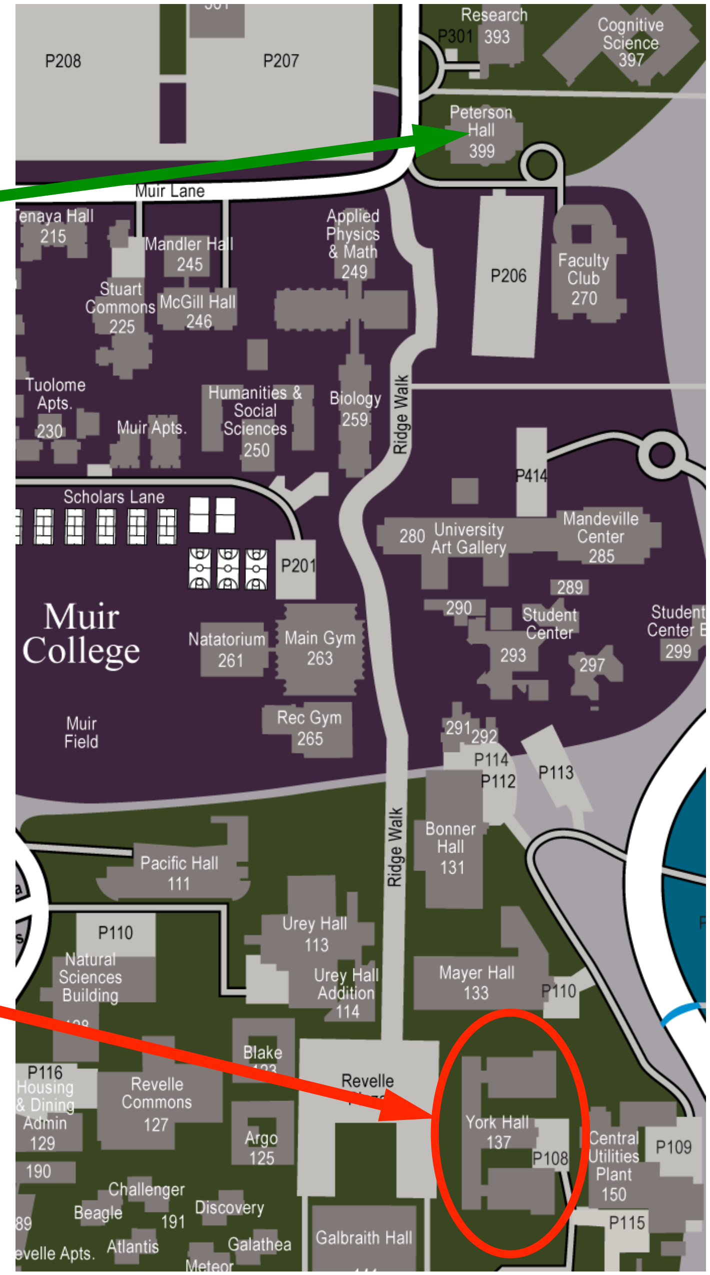
CHM 165,265 / BIMM 162 / BGGN 262 Winter 2013

Peterson Hall, Room 103; Muir Campus

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

Will include a laser diffraction demo, showing the relationship between simple objects and their diffraction patterns

York Hall 4080-A Revelle Campus



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

3D Electron Microscopy of Macromolecules

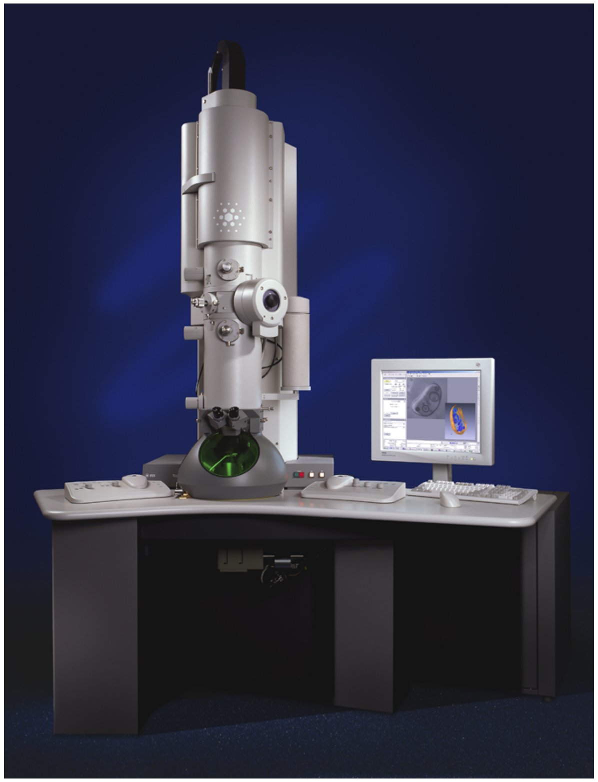
TEM Facility Tour

Where: 1510 Bonner Hall basement

When: Aiming for Jan 28, 29th

Check class web site for details on dates, times, and directions to facility

Attendance is optional but 5 pts extra credit towards final grade will be awarded



FEI Technai Sphera
(200keV; LaB_6; LN_2)

To reserve and guarantee a time slot, email **nholson@ucsd.edu**
First come, first served.

Class Web Page: Jan 14, 2013

UCSD
UNIVERSITY OF CALIFORNIA, SAN DIEGO

Dr. Timothy S. Baker

Intro | Members | Courses | Images | Publications | Software | Documentation and Procedures | Microscope Access | Microscope Facilities

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 10, 2013

Virtual Homework - Practice Questions for Section I (PDF) Updated January 10, 2013 (Password protected)

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)
- Lecture #2 January 10, 2013 (4.3 MB)

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I.A PRINCIPLES OF TRANSMISSION EM

KEY CONCEPTS FROM LECTURE #2

- **Coherence:** defines variance in λ and phase of component waves

- **Instrument resolving power:** limited by λ of radiation; at best = 1/2 λ

- **Image resolution:** always $\leq$ resolving power of instrument

- **Electron waves:** potential to resolve finer object details than can photons

- **Rayleigh Criterion:** gives more realistic estimate of instrument resolving power for TEM (compared to Abbe's simple 1/2 wavelength rule) primarily because it accounts for effects of lens aperture.

- **Geometrical (Ideal) Optics: Ray paths** through lenses and apertures

- **Physical (Real) Optics:** Accounts for diffraction and interference effects

I.A PRINCIPLES OF TRANSMISSION EM

MORE KEY CONCEPTS FROM LECTURE #2

- **Ideal vs. Real Lenses**

- **Ray Diagrams**

- **Converging / Diverging Lenses; Real / 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

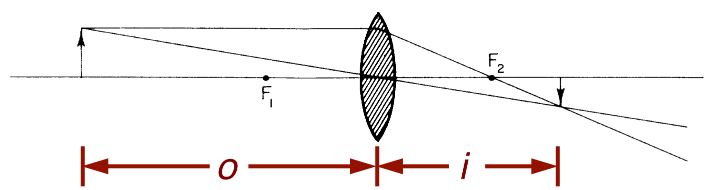
- **High Magnification Imaging:** generally requires 3-4 lenses

Review

I.A.4 Optics (Lens Theory)

I.A.4.h Magnification

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



For a converging lens:

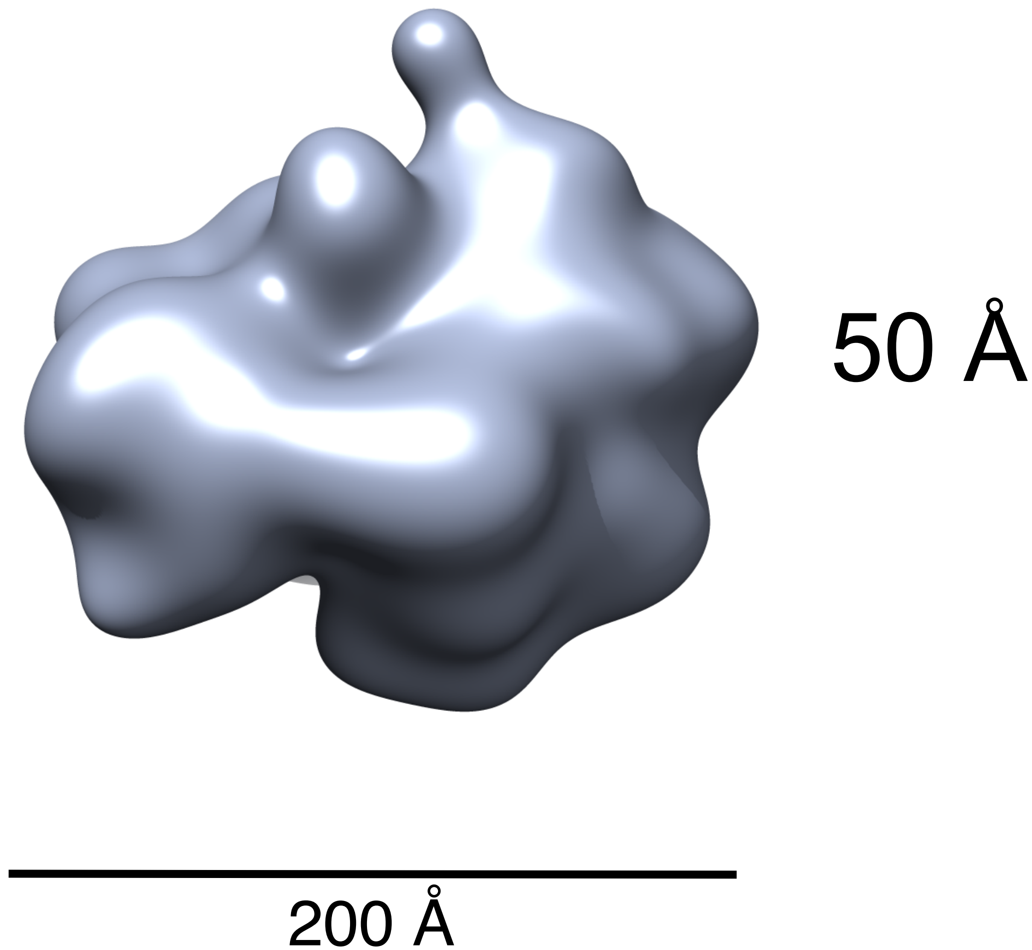
- If object is **> 2f** in front of the lens, the image formed is **real**, **inverted**, and **smaller** than the object (***M*** **< 1**)
- If object is **exactly 2*f*** in front of the lens, image is **real**, **inverted**, and **the same size** as the object (***M*** **= 1**)
- If object is **between *f* and 2*f***, image is **real**, **inverted**, and **larger** than the object (***M*** **> 1**)
- If object is **< *f***, image is **virtual**, **erect**, and **larger** than the object (***M*** **> 1**)

Slide not shown in class lecture

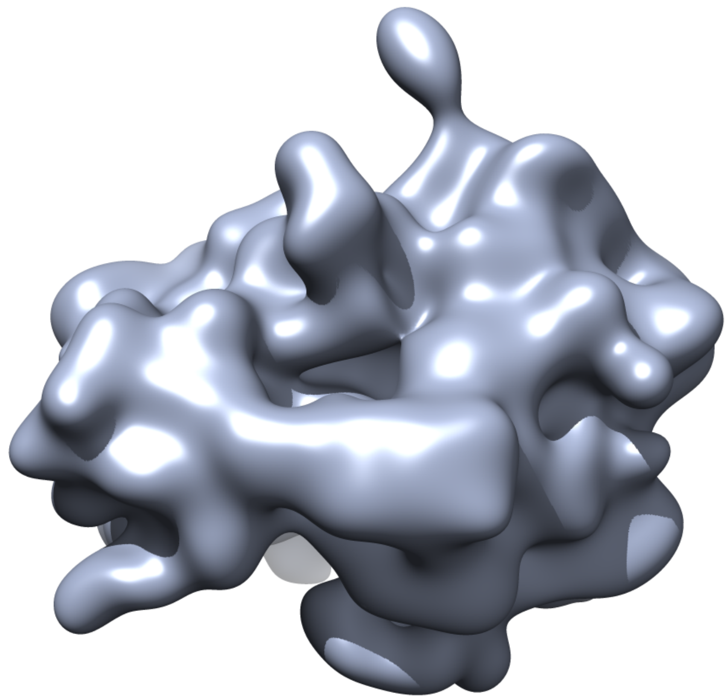
Resolution (d)

Low	↔	High
Poor	↔	Good
Coarse detail	↔	Fine detail
Large number	↔	Small number

Resolution (d)



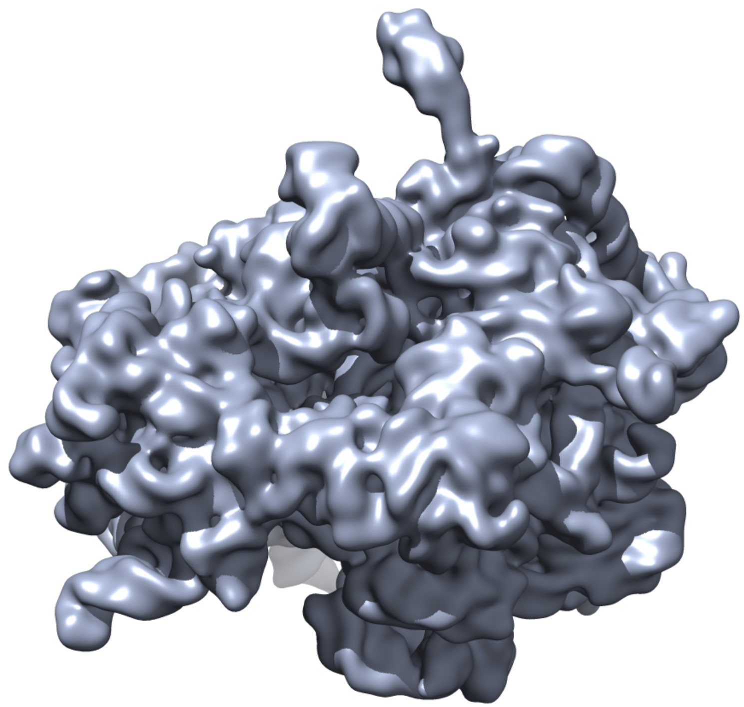
Resolution (d)



25 Å

200 Å

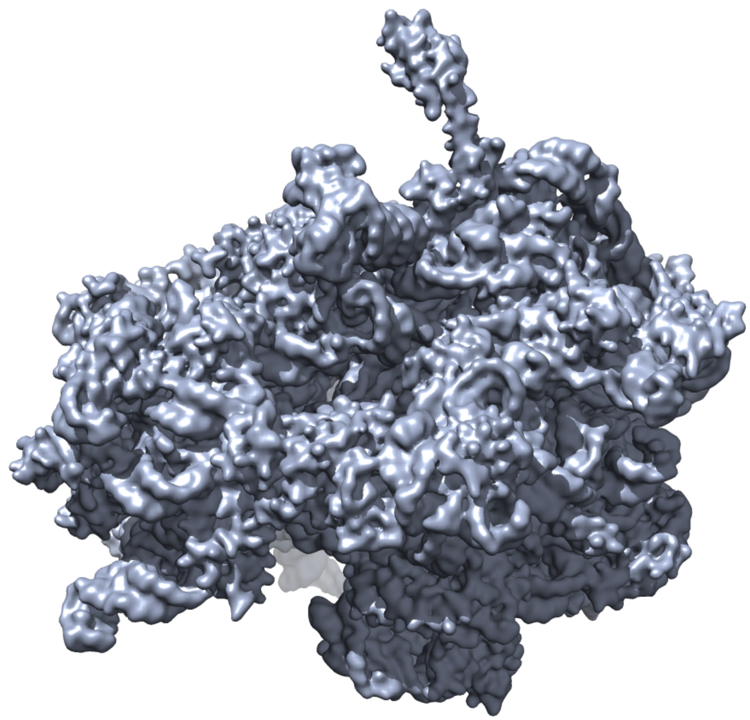
Resolution (d)



10 Å

200 Å

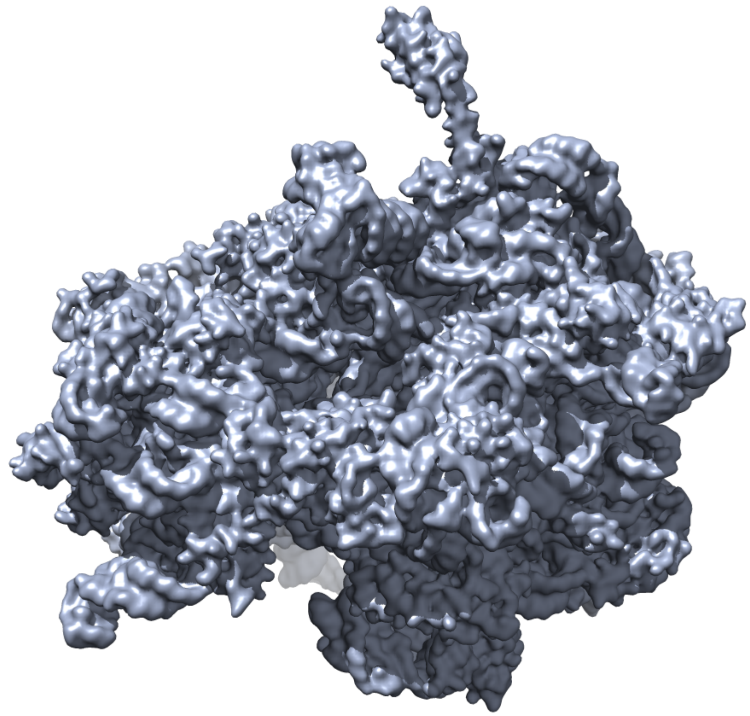
Resolution (d)



5 Å

200 Å

Resolution (d)

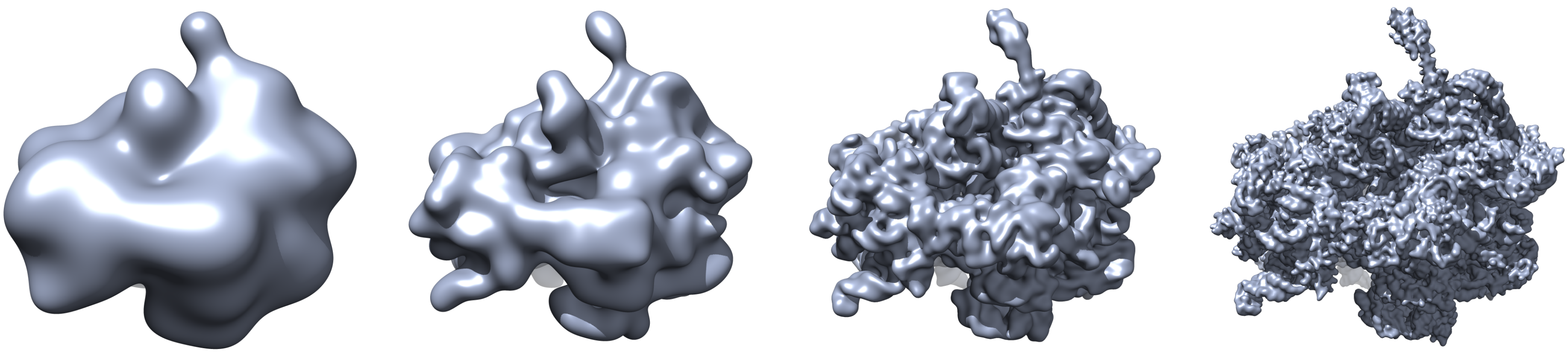


5 Å

Thermus thermophilus 70S ribosome

Resolution (d)

Low ⟷ High

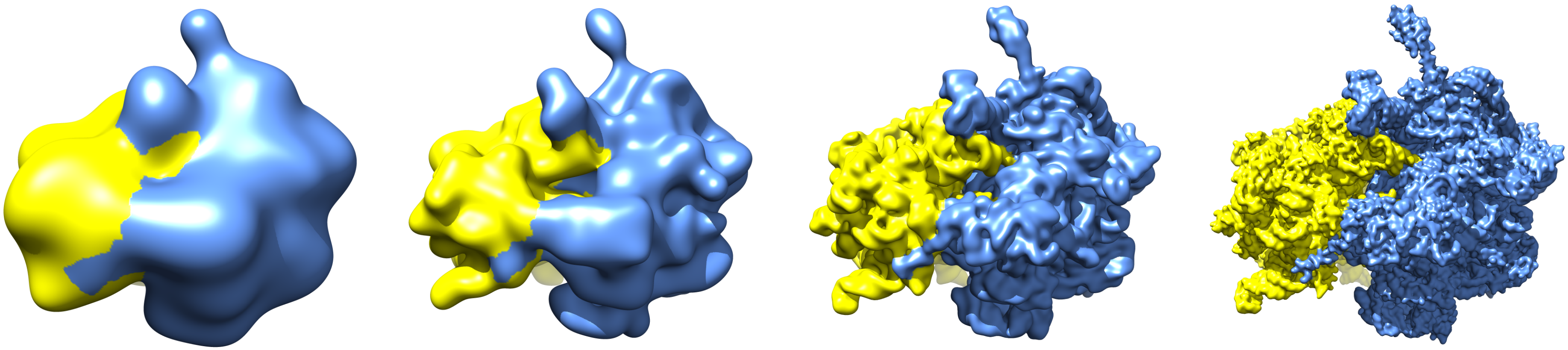


50 Å | 25 Å | 10 Å | 5 Å

Thermus thermophilus 70S ribosome

Resolution (d)

Low ⟷ High



50 Å 25 Å 10 Å 5 Å

Thermus thermophilus 70S ribosome

§ 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

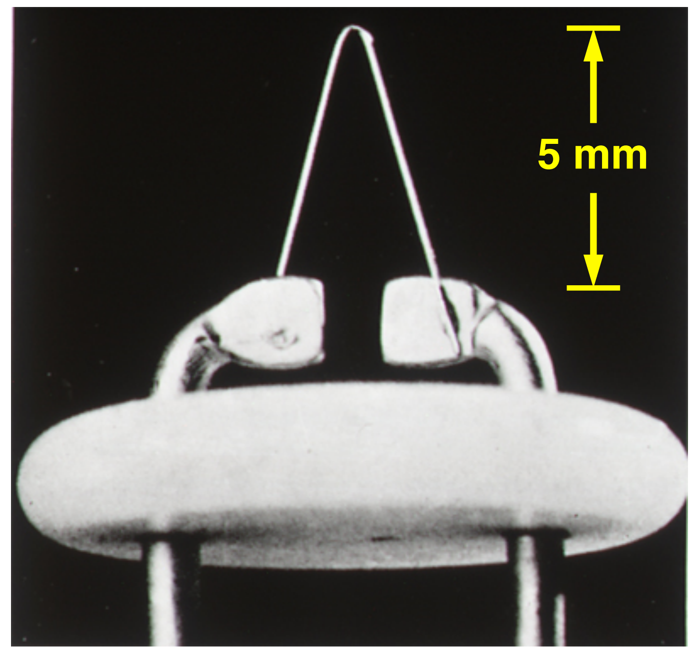
I.A.5.a Electron Emission

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:

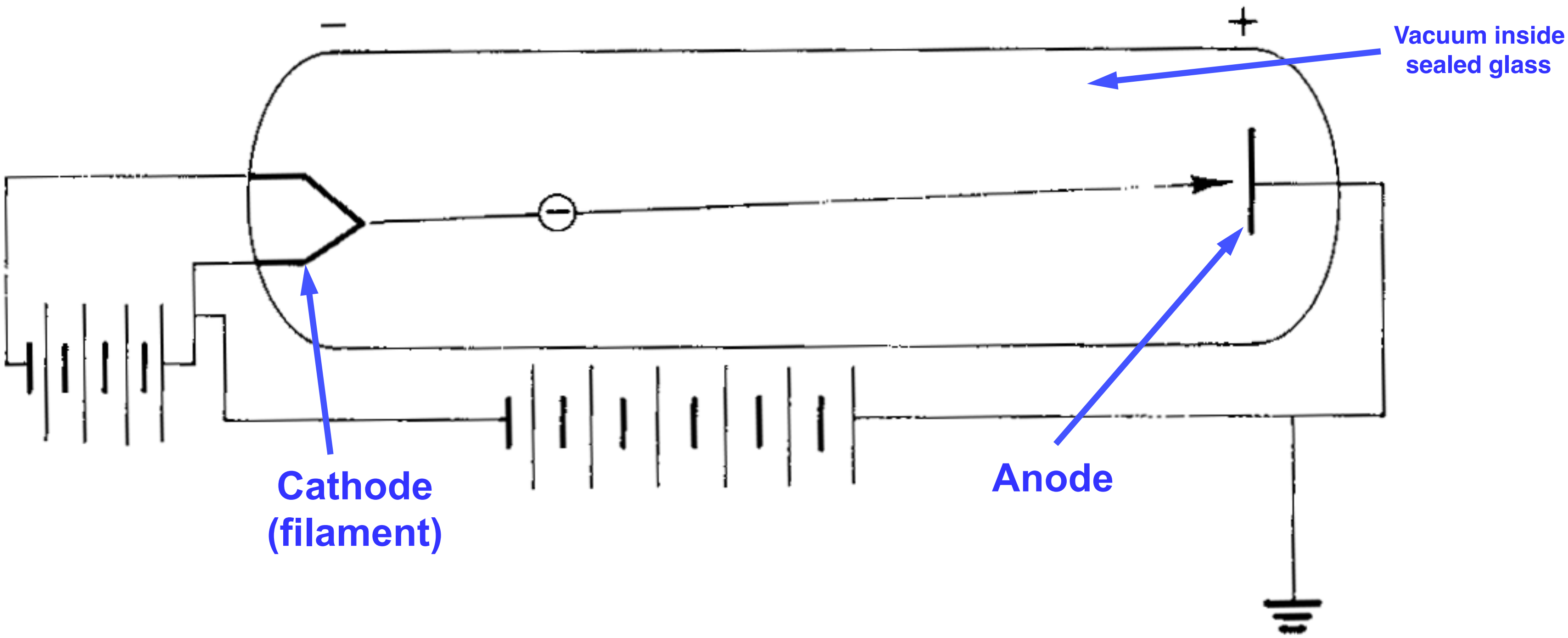
Electromagnetic lenses produce strong magnetic fields

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

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission

FACT: Electrons accelerate in an applied electric field

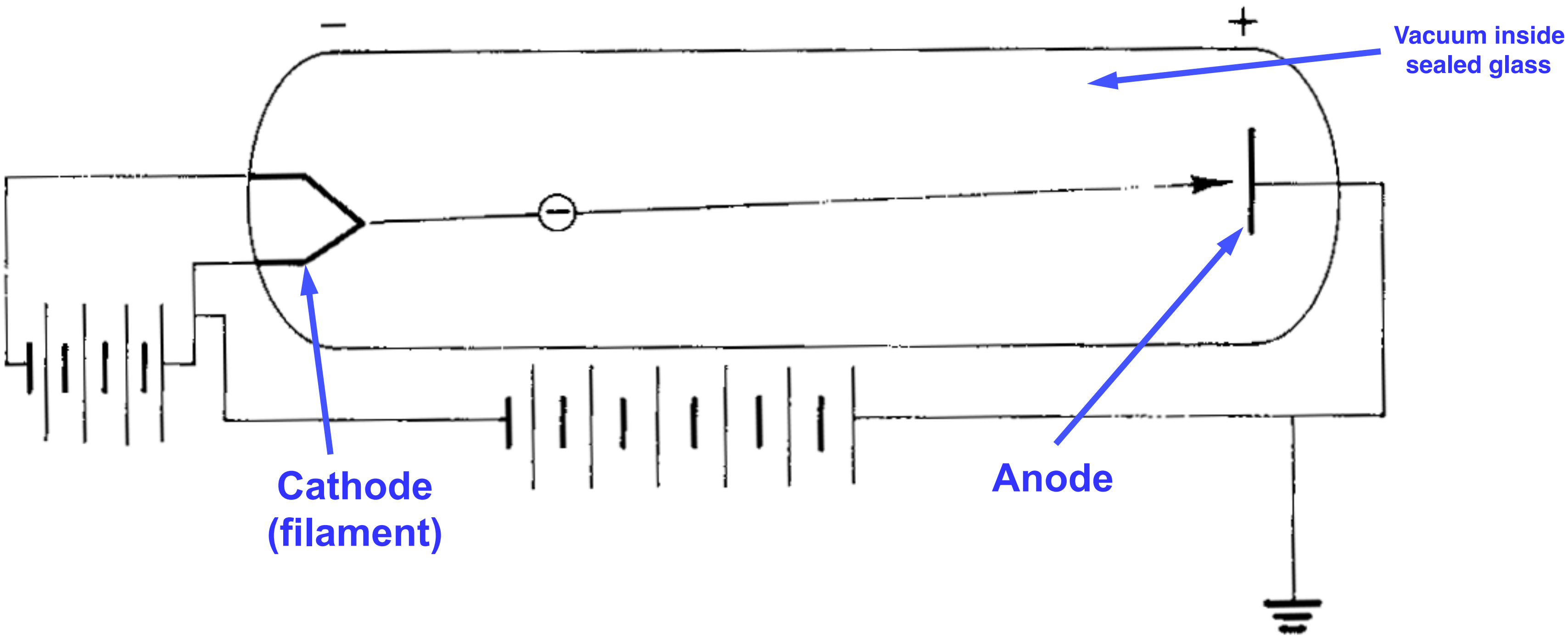


From Sjostrand, Fig. II.15, p.26

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission

FACT: Electrons accelerate in an applied electric field



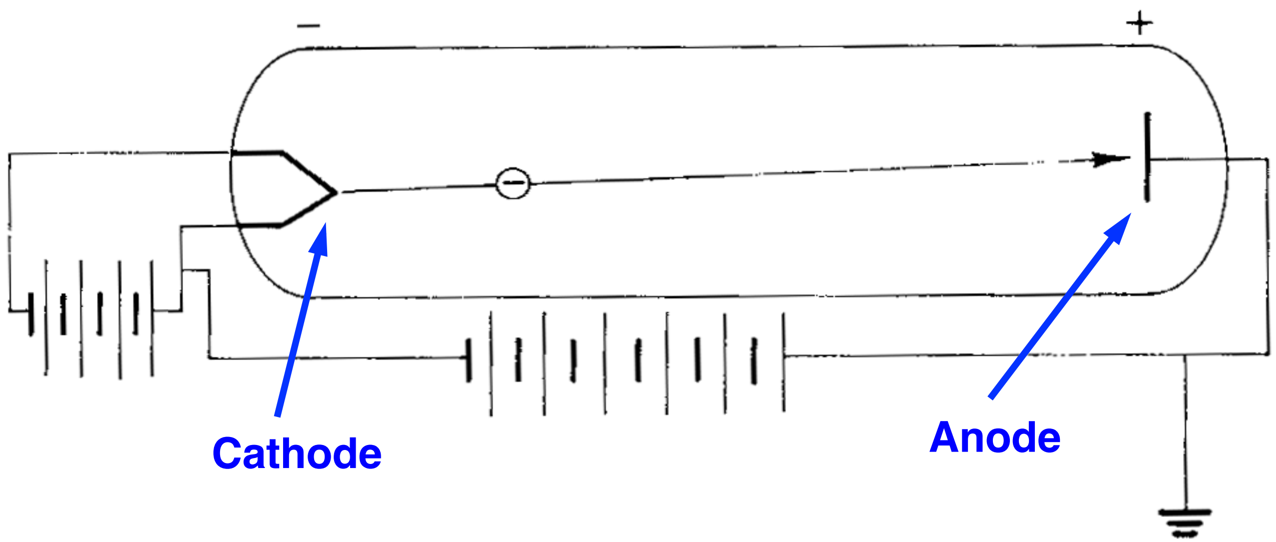
A strong electrostatic field applied in a vacuum between a wire [**cathode**], at negative potential, and an **anode**, at positive potential, causes e^- to accelerate away from the wire towards the anode

From Sjostrand, Fig. II.15, p.26

Slide not shown in class lecture

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission



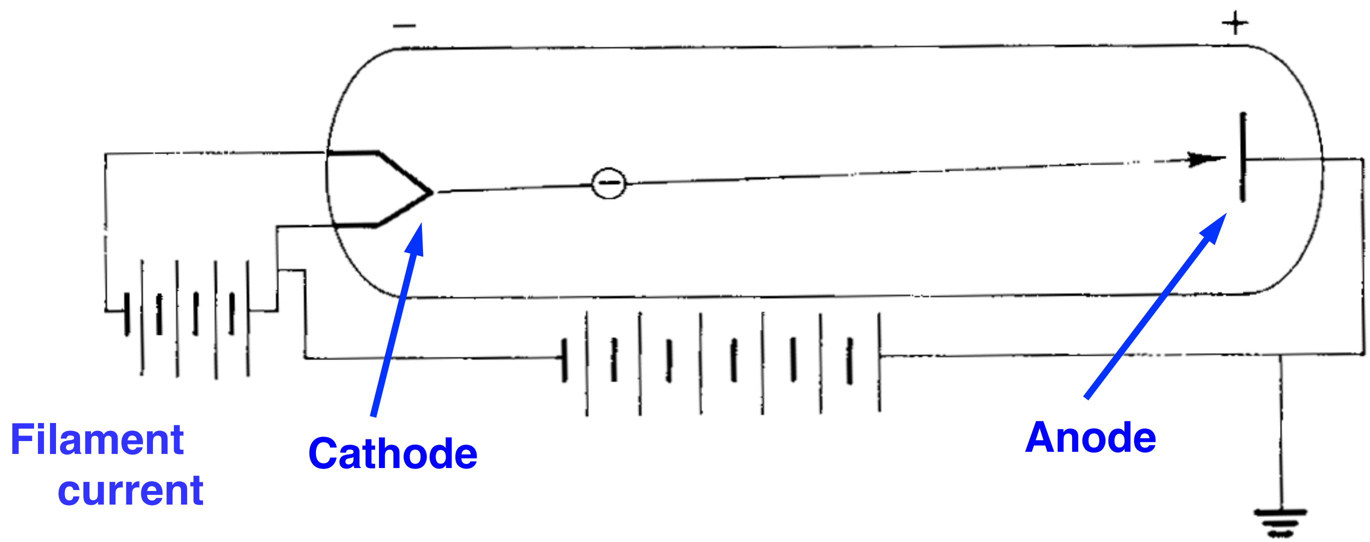
Speed of the moving e- **depends on strength** of the electrostatic field (**voltage**) between the cathode and anode.

$$v = \sqrt{\frac{2eV}{m}}$$

From Sjostrand, Fig. II.15, p.26

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission



Speed of the moving e- **depends on strength** of the electrostatic field (**voltage**) between the cathode and anode.

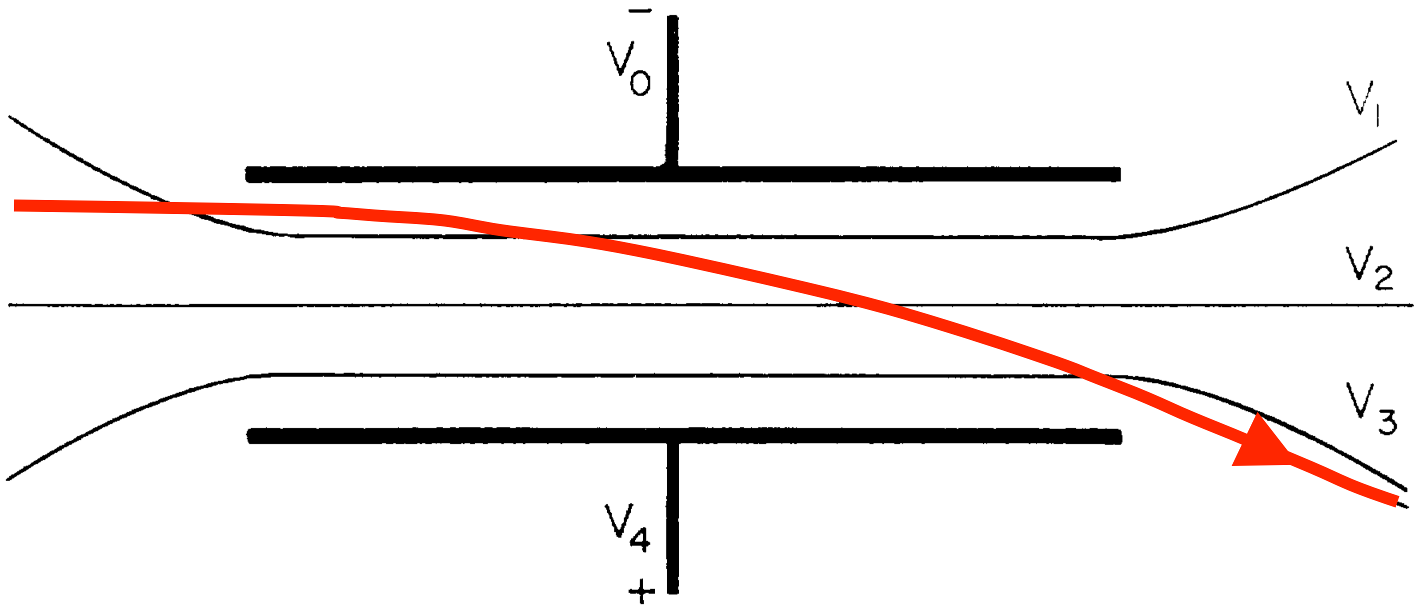
Number of e^- that leave the wire depends on the **temperature** to which the wire is heated, which depends on the **filament current**

From Sjostrand, Fig. II.15, p.26

I.A.5 Electron Optics / Electron Lenses

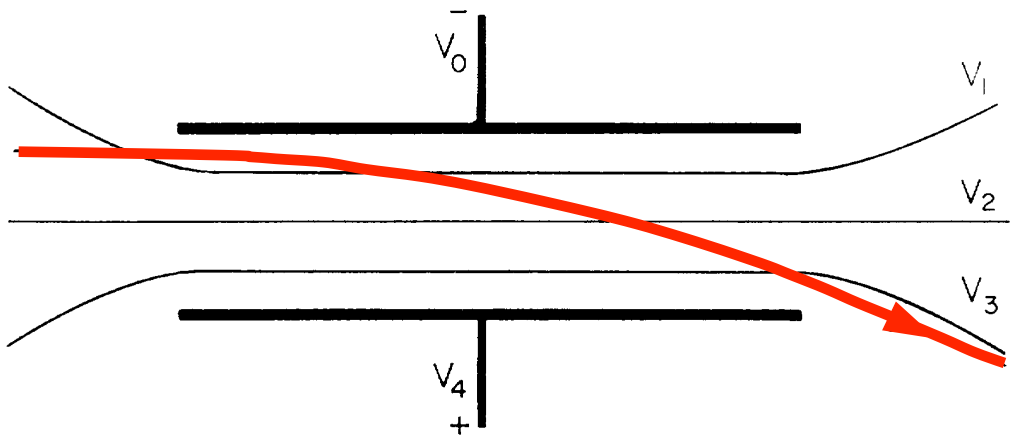
I.A.5.b Electric Field / Equipotentials

Path of an electron between two parallel plates of opposite charge



From Sjostrand, Fig. II.22, p.33

Electric Field / Equipotentials



- Electrons traveling in a direction parallel to the plates are affected by the force directed **perpendicular** to the plates

- Electrons are attracted toward the positive plate

- Path changes in a **series of gradual steps** at the equipotential surfaces

RESULT: fundamentally same as given by Snell's Law of refraction (light optics). **Curved equipotential surfaces** exhibit the **properties of a lens.**

From Sjostrand, Fig. II.22, p.33

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses

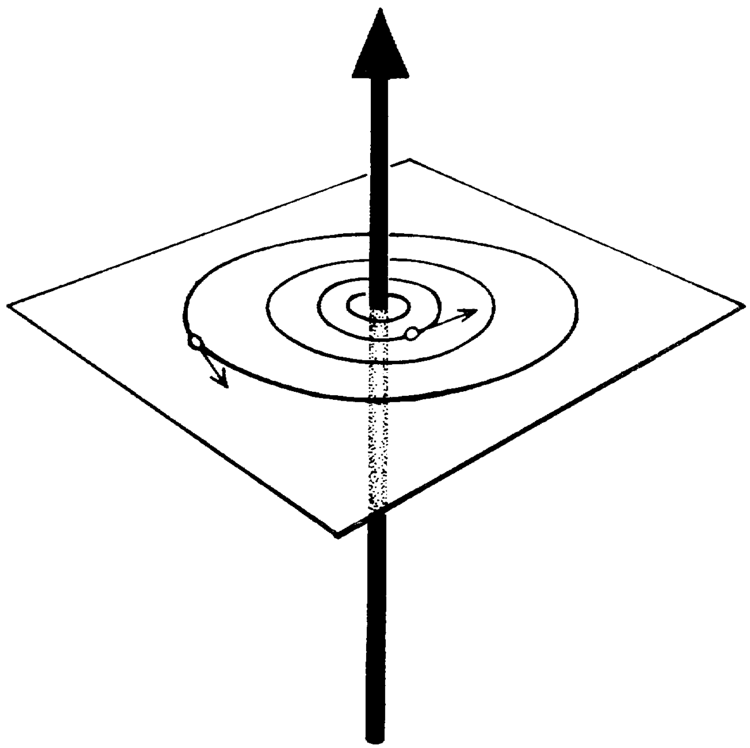
The path of a moving electron is bent when the electron encounters an **electric** field.

What happens if a moving electron encounters a **magnetic** field?

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses

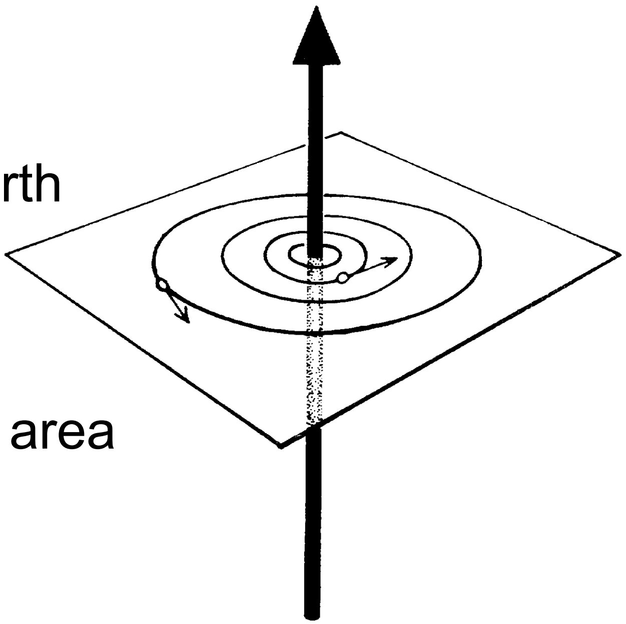
Magnetic field: An electric current passing through a conductor gives rise to a magnetic field



From Sjostrand, Fig. II.26, p.35

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses



Direction in which magnetic field lines point = North

Magnetic flux density = number of lines per unit area

Flux density depends on the properties of the material **surrounding** the conductor

Iron induces a higher flux density than air or a vacuum

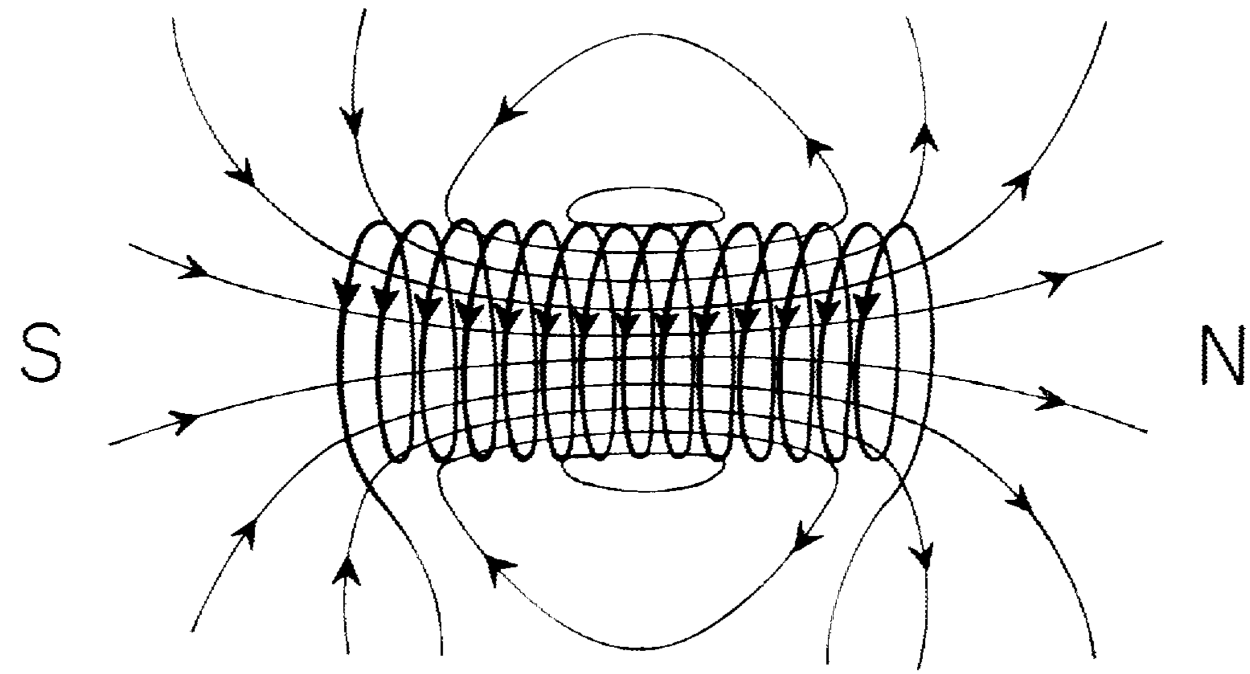
From Sjostrand, Fig. II.26, p.35

Slide not shown in class lecture

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses

Magnetic field induced by current passing through a solenoid



If conductor is in the form of a **circular loop**, the lines of force form circles around the loop

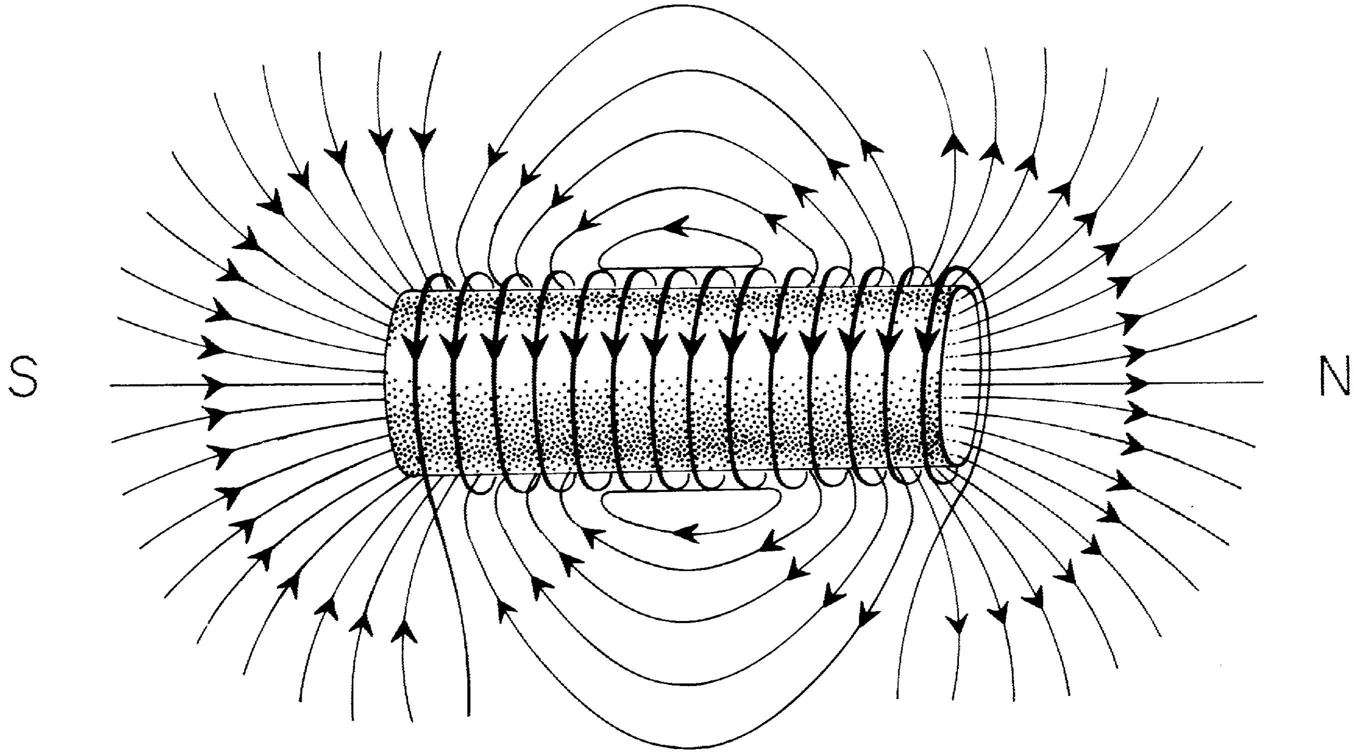
Flux density is greatest at the **center** of the loop

From Sjostrand, Fig. II.28, p.37

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses

Flux density even higher if solenoid has an iron core



From Sjostrand, Fig. II.31, p.40

I.A.5 Electron Optics / Electron Lenses

I.A.5.e Magnetic Fields and Magnetic Lenses

However…

Use of iron leads to a problem: **lens hysteresis**

Lens strength depends to some extent on the **magnetic history** of the lens

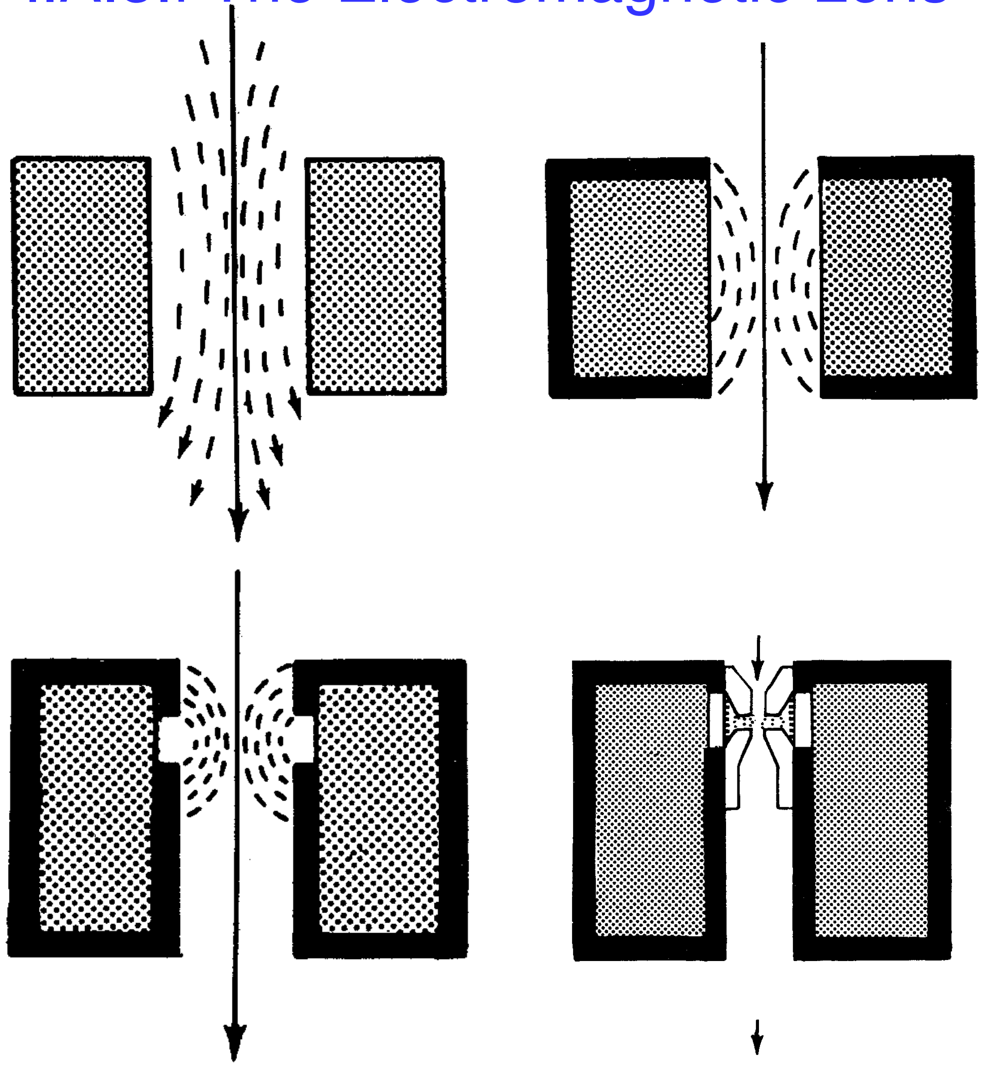
Read about lens hysteresis and lens normalization (p.32, lecture notes)

Slide not shown in class lecture

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Solenoid



Soft-iron casing encloses outer solenoid surface; concentrates the field.

Soft-iron encasing with narrow annular gap reduces magnetic field to short region along the lens axis.

Soft-iron encasing + soft-iron pole pieces concentrate field to a very small, annular gap.

From Wischnitzer, 2nd ed., Fig. 35, p.33

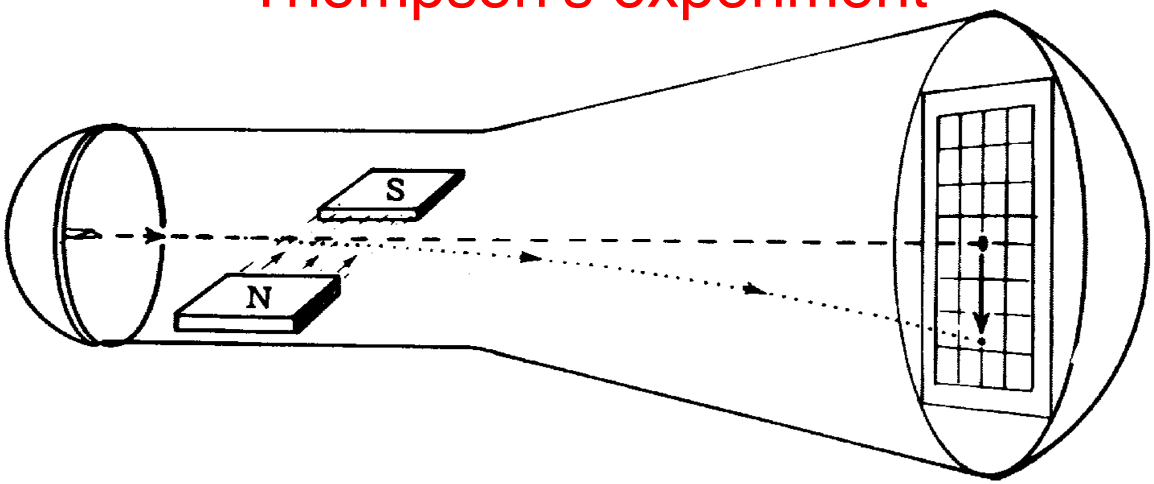
Slide not shown in class lecture

I.A.5 Electron Optics / Electron Lenses

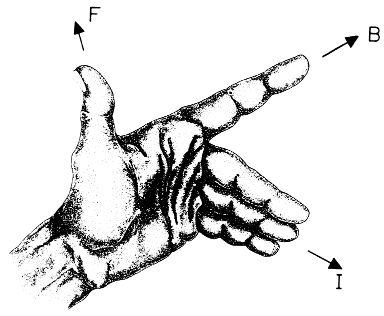
I.A.5.f The Electromagnetic Lens

Forces Acting on a Current in a Magnetic field

Thompson's experiment



From Wischnitzer, Fig. 25, p.25

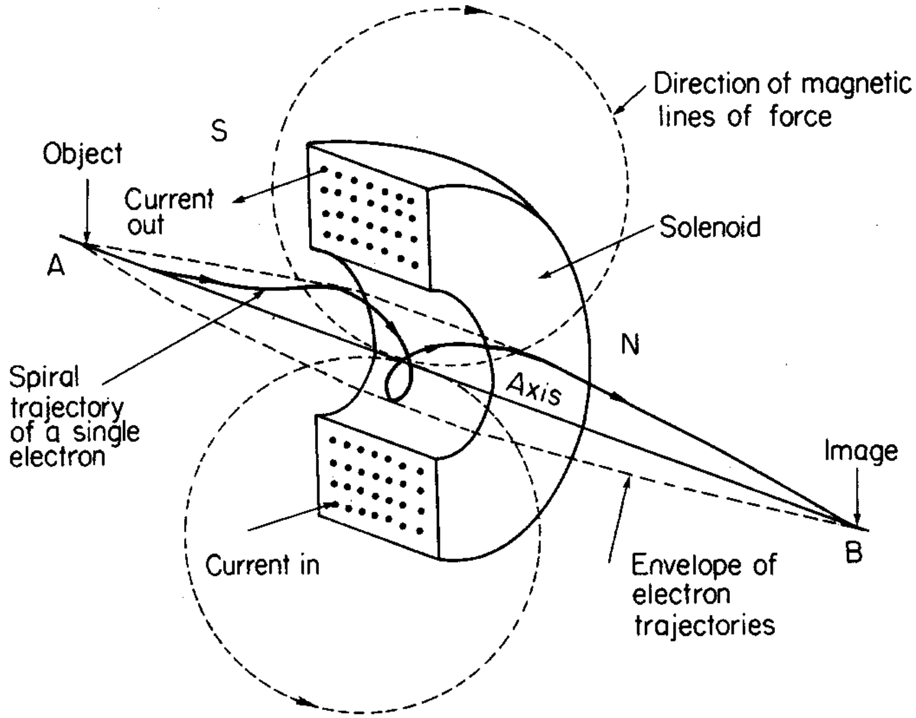


From Sjostrand, Fig. II.35-36, p.43

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Path of Electron Through an Electromagnetic Lens



Electron starting at point A on axis and **at an angle to it** follows a **spiral path**, returning to the axis at point B

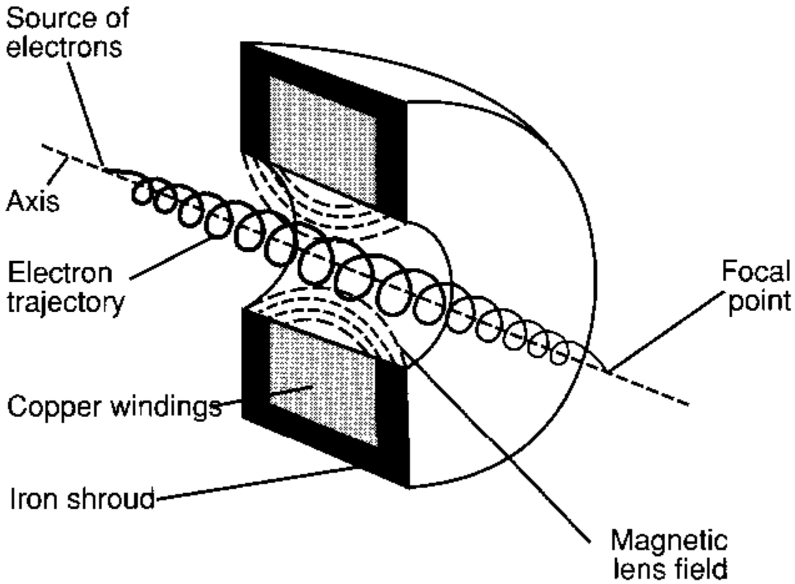
BOTTOM LINE: Action is ***similar*** to a **converging** glass lens

From Meek, 1st ed., Fig. 1.3, p.8

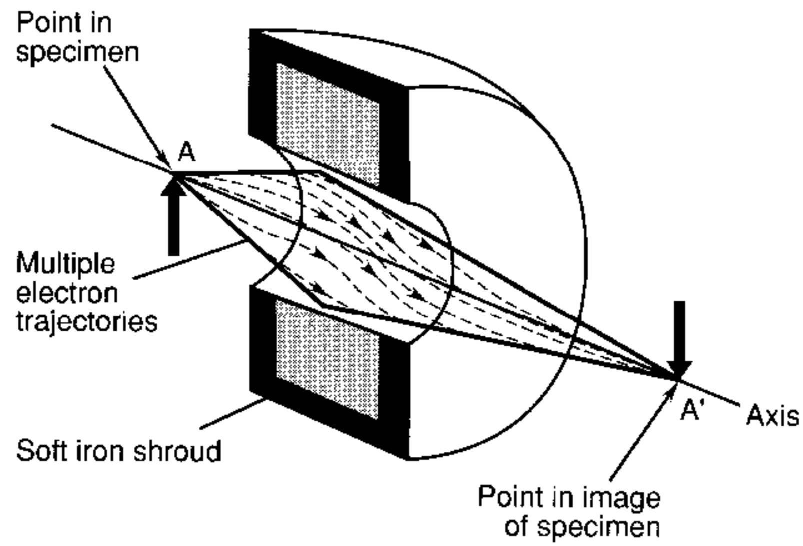
I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Path of Electron Through an Electromagnetic Lens



Spiral path of single electron through the electromagnetic lens. **Note:** this is a <u>highly exaggerated</u> schematic diagram, since the path does not include multiple, full rotations.



Schematic diagram of the paths of many different electrons through the electromagnetic lens, scattered from a single point in the specimen.

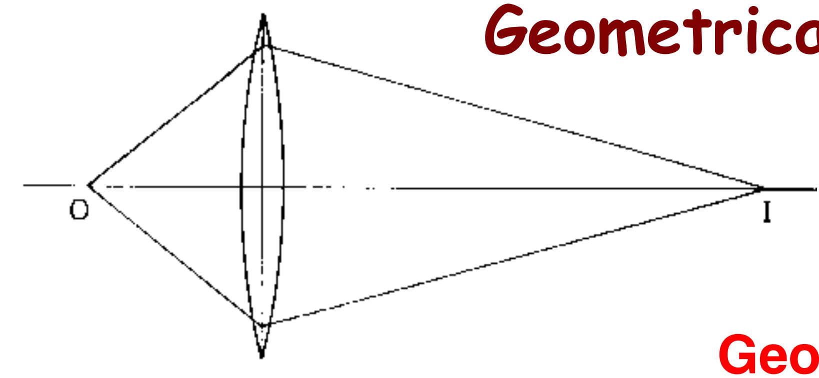
From Bozzola, 1st Ed., Figs. 6-11 and 6-12, p.142

Slide not shown in class lecture

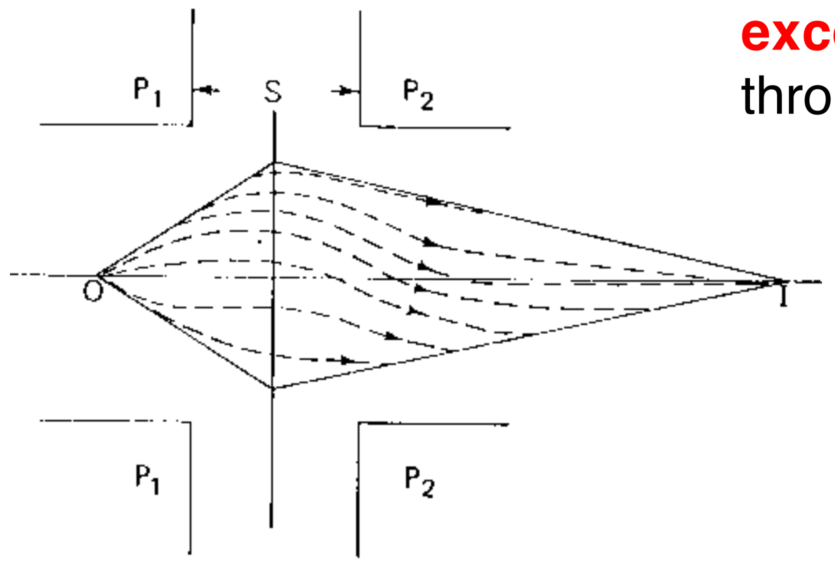
I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Geometrical Optics



Glass lens



Magnetic lens

<u>**Geometrical**</u> optics for a magnetic lens is the **SAME** as that for a glass lens, **except e^- travel in spiral paths** through a magnetic lenses

From Agar, Fig. 1.4, p.5

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Properties of a Magnetic Lens

- Any **axially-symmetric** magnetic field has the properties of an ideal lens

- **All formulas** for the **ideal lens** may be applied

- Magnetic lenses are **always convergent** (*i.e.* positive)

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Magnetic Lens Focal Length (f)

Determined by two factors:

Field strength in the lens gap **AND**

Speed of the e^- (depends on accelerating voltage)

$$f = \frac{KV_r}{(N \cdot I)^2}$$

f = focal length of the lens
K = a constant
V_r = accelerating voltage (relativistically corrected)
N = # of turns in the excitation coils
I = current (in amps)

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Magnetic Lens Focal Length (*f*)

$$f = \frac{KV_r}{(N \cdot I)^2}$$

How does one focus an electron image in the TEM?

Varying the **current** in the **OBJECTIVE** lens of the TEM

- Changes magnetic field strength and alters lens focal length

I.A.5 Electron Optics / Electron Lenses

I.A.5.f The Electromagnetic Lens

Magnetic Lens Focal Length (*f*)

$$f = \frac{KV_r}{(N \cdot I)^2}$$

How does one focus an electron image in the TEM?

Varying the **current** in the **OBJECTIVE** lens of the TEM

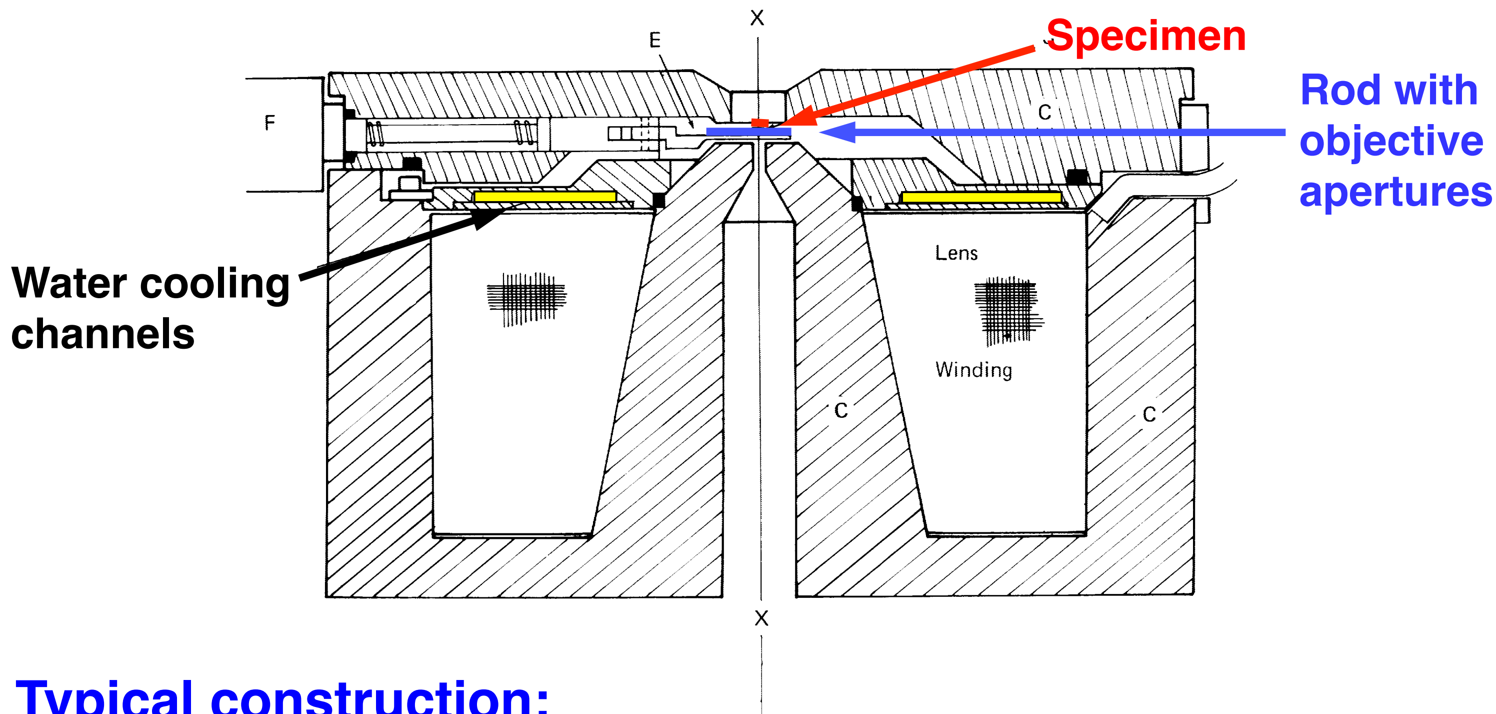
- Changes magnetic field strength and alters lens focal length

- If TEM voltage is *increased* (e^- velocity increases), lens current must be increased to keep the focal length constant

Slide not shown in class lecture

I.A.5.f The Electromagnetic Lens

Objective Lens Design



- **Typical construction:**

  Strong field of **short axial extent** (f = 1.5-3 mm) needed to form images at **high magnification**

- **Specimen** sits **inside** the magnetic field of the **objective** lens

From Agar, Fig. 2.11, p.51

A few take home messages:

- "Refractive index" changes gradually in electro-magnetic lenses

- Electrons travel spiral paths through electro-magnetic lenses

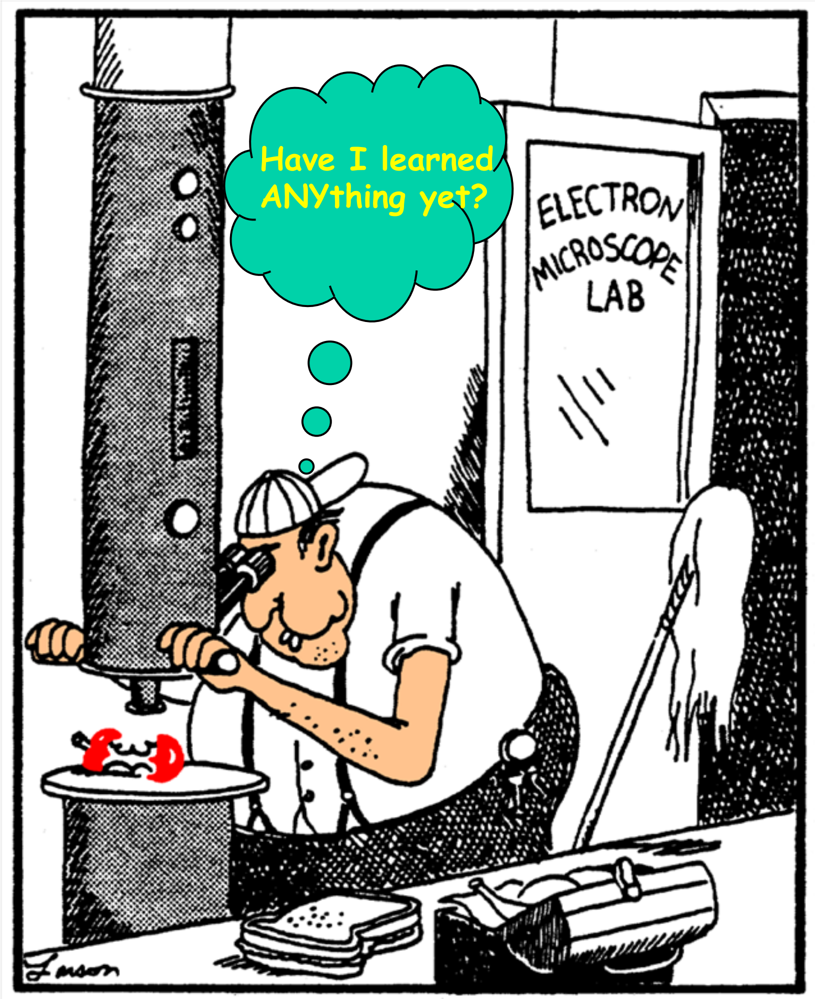
- Magnetic lens focal length determined by field strength of the lens <u>**AND**</u> by speed of electrons in the imaging beam

$$f = \frac{KV_r}{(N \cdot I)^2}$$

§ I: The Microscope

- I.A Principles of TEM
- I.B Design of the TEM

(pp.39-72 of lecture notes)



TOPICS

- Principles of TEM

  Electrons, lenses and optics

- Design of TEM

  Components top to bottom

- Contrast and image formation

  Electron scattering from object

- Optimizing TEM performance

  Alignment assures 'best' images

- Operation of TEM

  "What do all these buttons do?"

- Other modes of TEM

  Many ways to 'observe' specimens

- Specimen preparation for TEM

  Getting specimen ready

- Radiation damage

  Less is better

- 3D reconstruction

  Specimen 3D structure from 2D images

I.B DESIGN OF THE TEM

The TEM Top to Bottom:

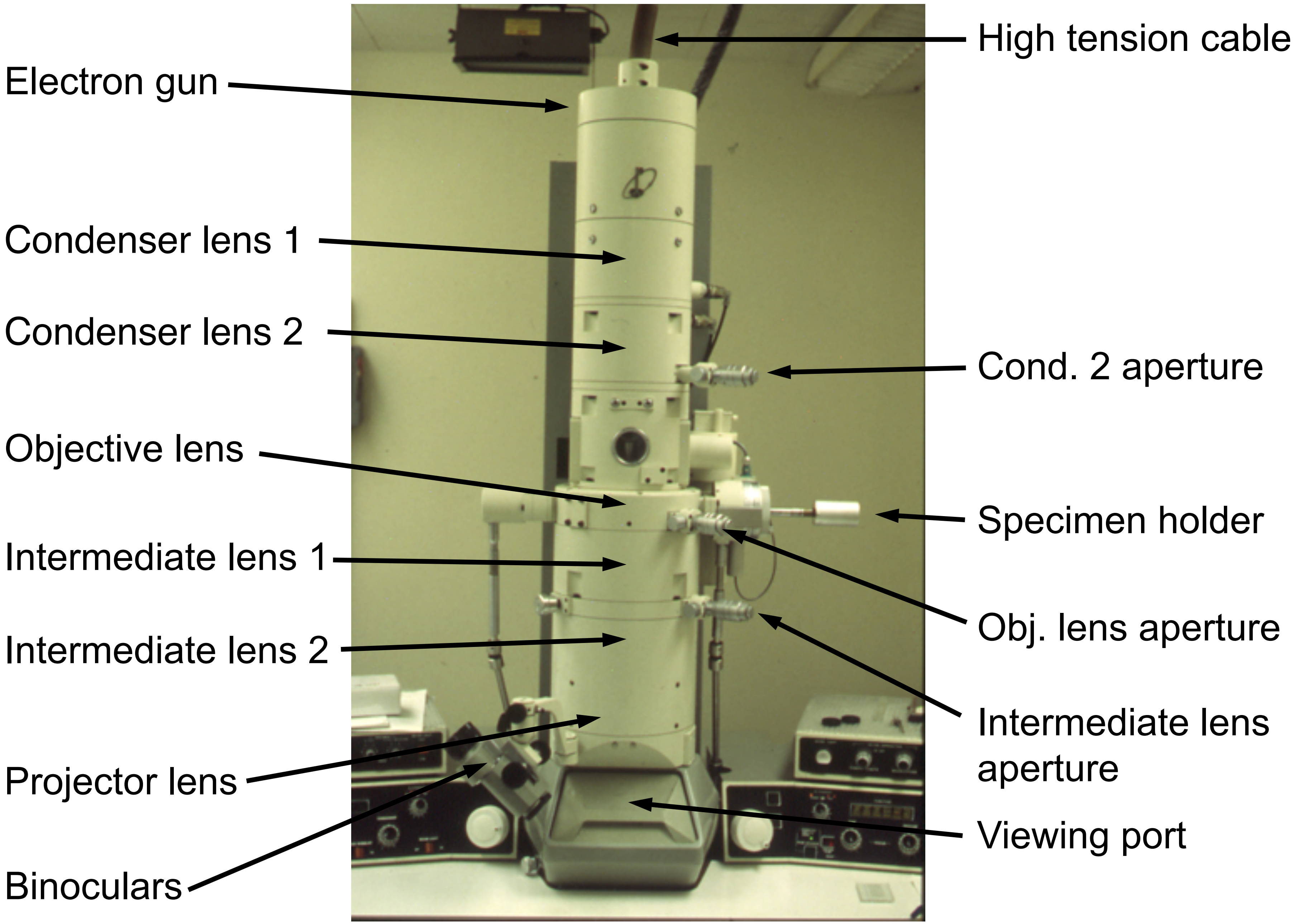
- Electron gun
- Condenser lens(es)
- Lens aberrations
- Objective lens and specimen stage
- Projector lenses
- Camera and viewing system
- Vacuum system
- Electrical system

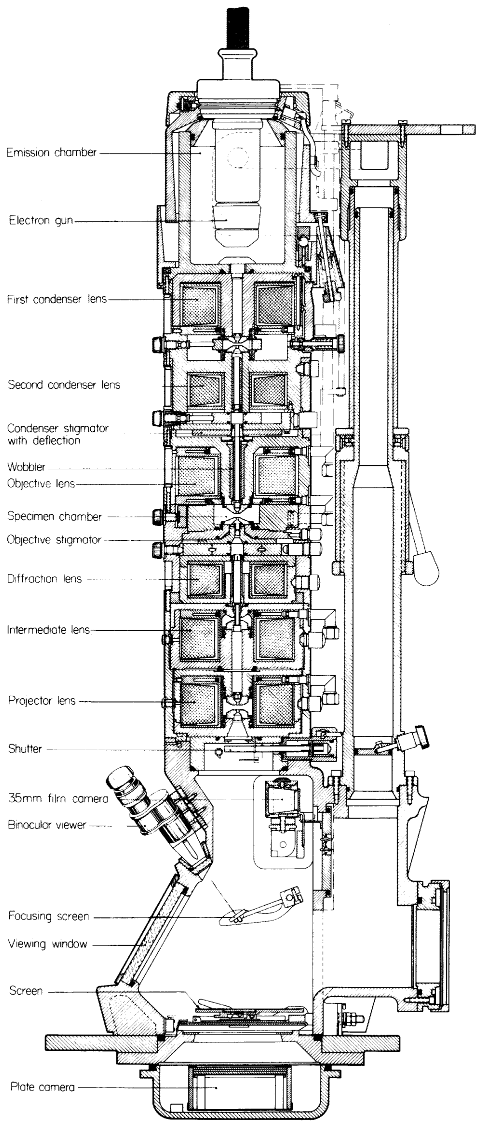
I.B DESIGN OF THE TEM

KEY CONCEPTS

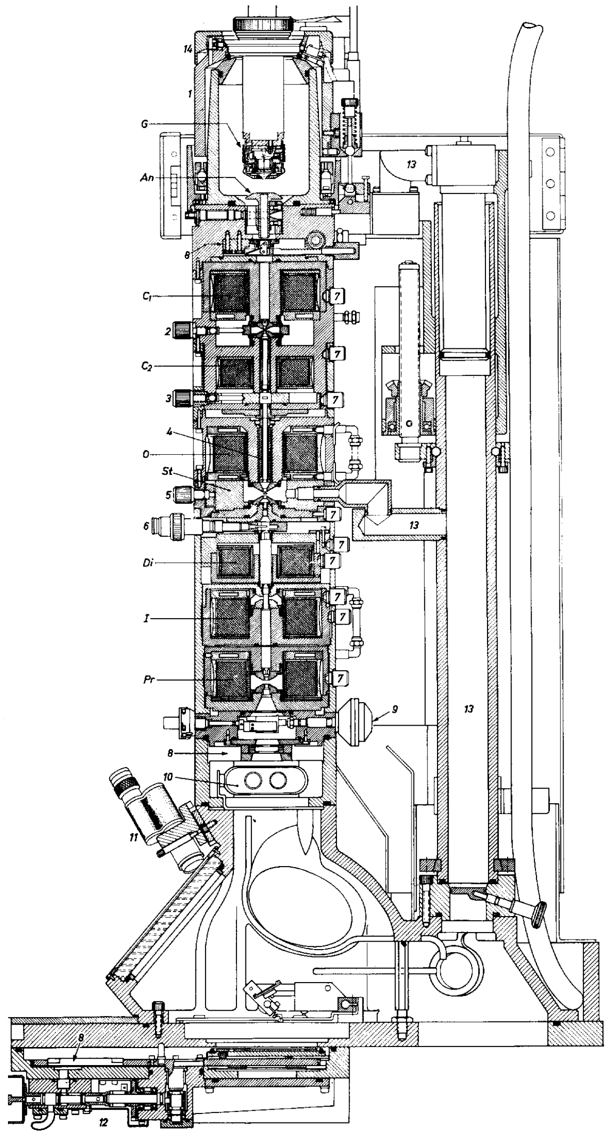
The TEM Top to Bottom:

- Electron gun: Produces beam of electrons
- Condenser lens(es): Focuses e^- beam onto specimen
- Lens aberrations: Electromagnetic lenses stink!
- Objective lens and specimen stage: Objective is most important lens
- Projector lenses: Magnify image formed by objective
- Camera and viewing system: View and record electron image
- Vacuum system: Enables beam to travel length of TEM
- Electrical system: Needed for virtually every part of the TEM

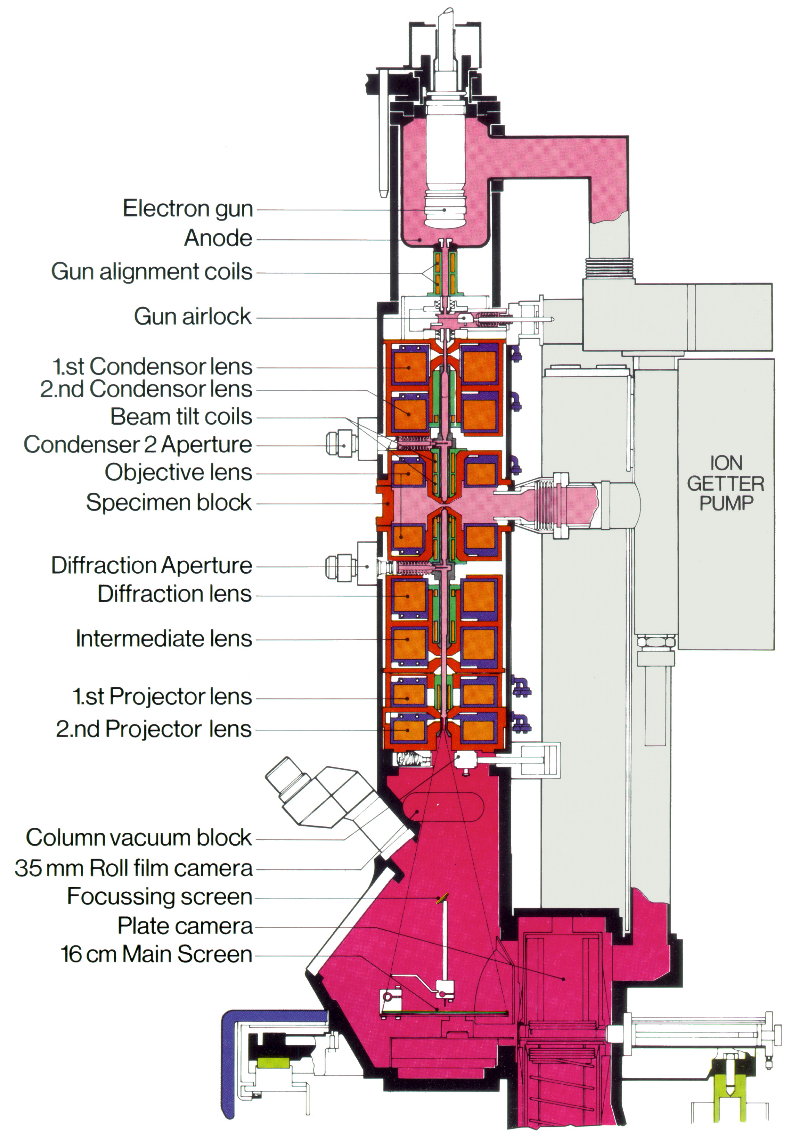

High tension cable
Electron gun
Condenser lens 1
Condenser lens 2
Cond. 2 aperture
Objective lens
Specimen holder
Intermediate lens 1
Obj. lens aperture
Intermediate lens 2
Intermediate lens aperture
Projector lens
Viewing port
Binoculars



Philips EM 200



Philips EM 300



Philips EM 400

From Meek, Fig. 5.4b, p.99

From Agar, Fig. 2.2, p.40

From Philips brochure

§ I: The Microscope

I.B Design of the TEM

(pp.39-72 of lecture notes)

§ I: The Microscope

I.B Design of the TEM

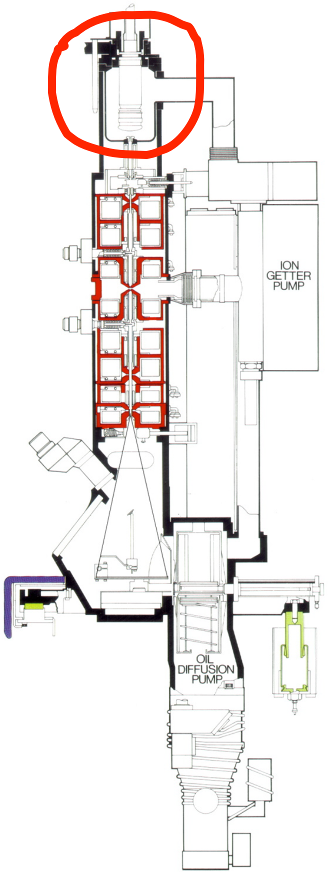
I.B.1 Electron Gun

(pp.39-42 of lecture notes)

I.B DESIGN OF THE TEM

The TEM Top to Bottom:

- Electron gun
- Condenser lens(es)
- Lens aberrations
- Objective lens and specimen stage
- Projector lenses
- Camera and viewing system
- Vacuum system
- Electrical system



I.B.1 The Electron Gun

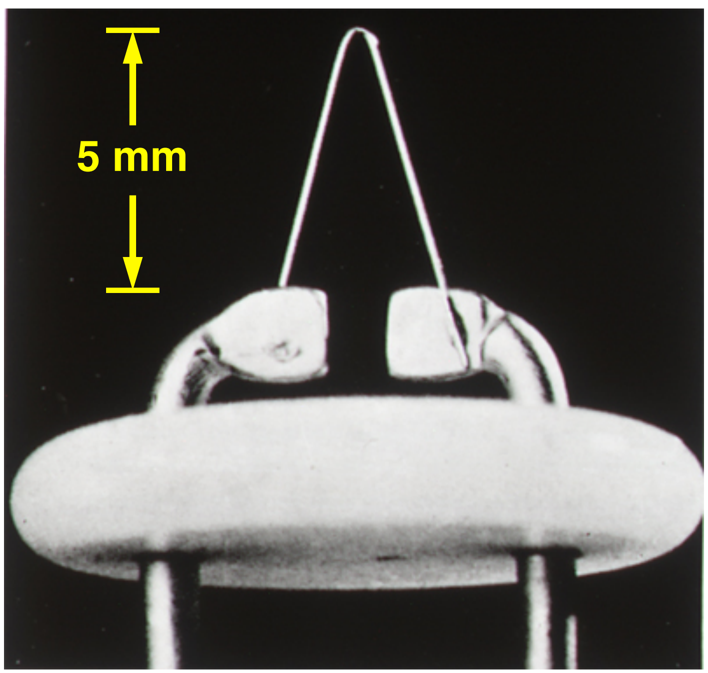
KEY CONCEPT

Gun creates source of high voltage electrons

I.B.1 The Electron Gun

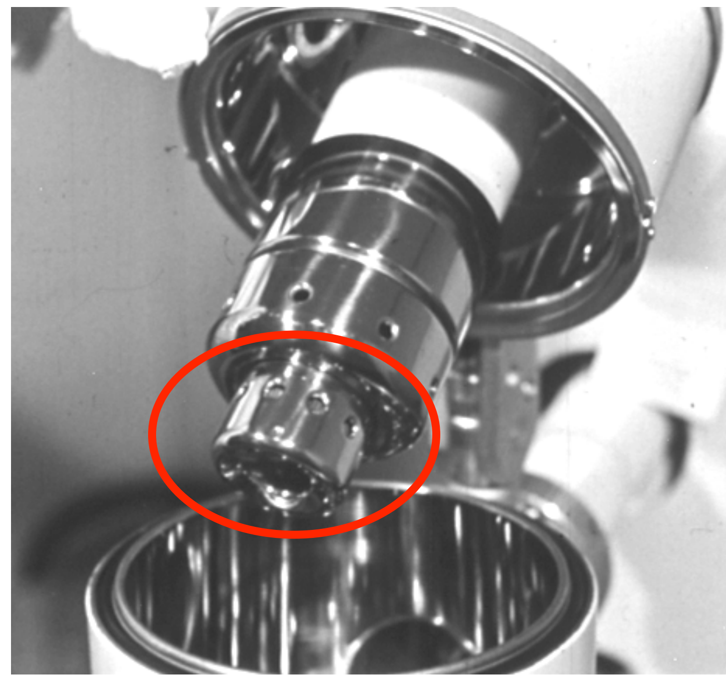
I.B.1.a Gun Design

Gun in most TEMs consists of a tungsten wire (**filament-cathode**), bent into a hairpin ("V") shape and surrounded by a **shield** (gun cap, **wehnelt cylinder**) with a circular aperture (1-3 mm diameter) centered just below the filament tip



Electron gun tungsten filament (cathode)

From Agar, Fig. 2.5, p.45



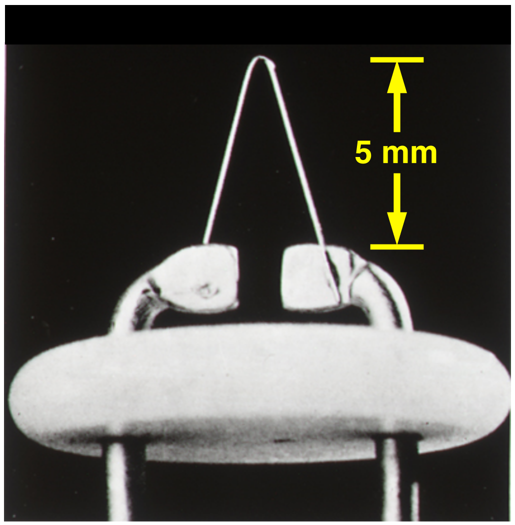
Wehnelt cylinder

From Crang and Ward

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission

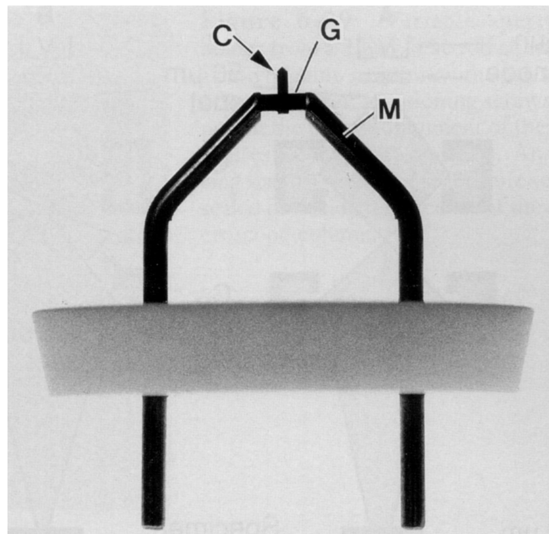
TEM Filaments



Tungsten filament

From Agar, Fig. 2.5, p.45

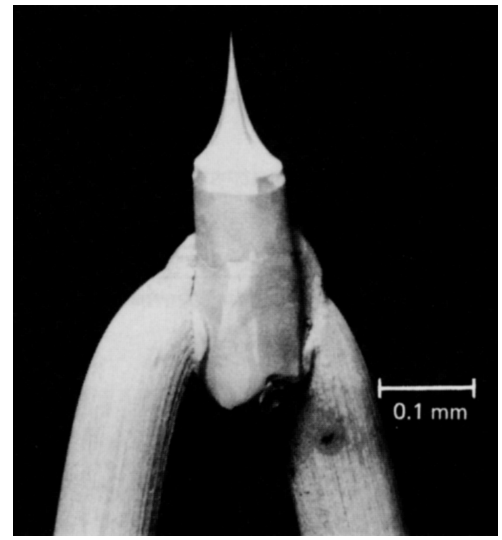
$3



LaB_6 filament

From Bozzola, 1st Ed., Fig. 6-26, p.155

$1000



Tungsten, cold field-emitting tip

From Watt, Fig. A4.8, p.444

$18,000

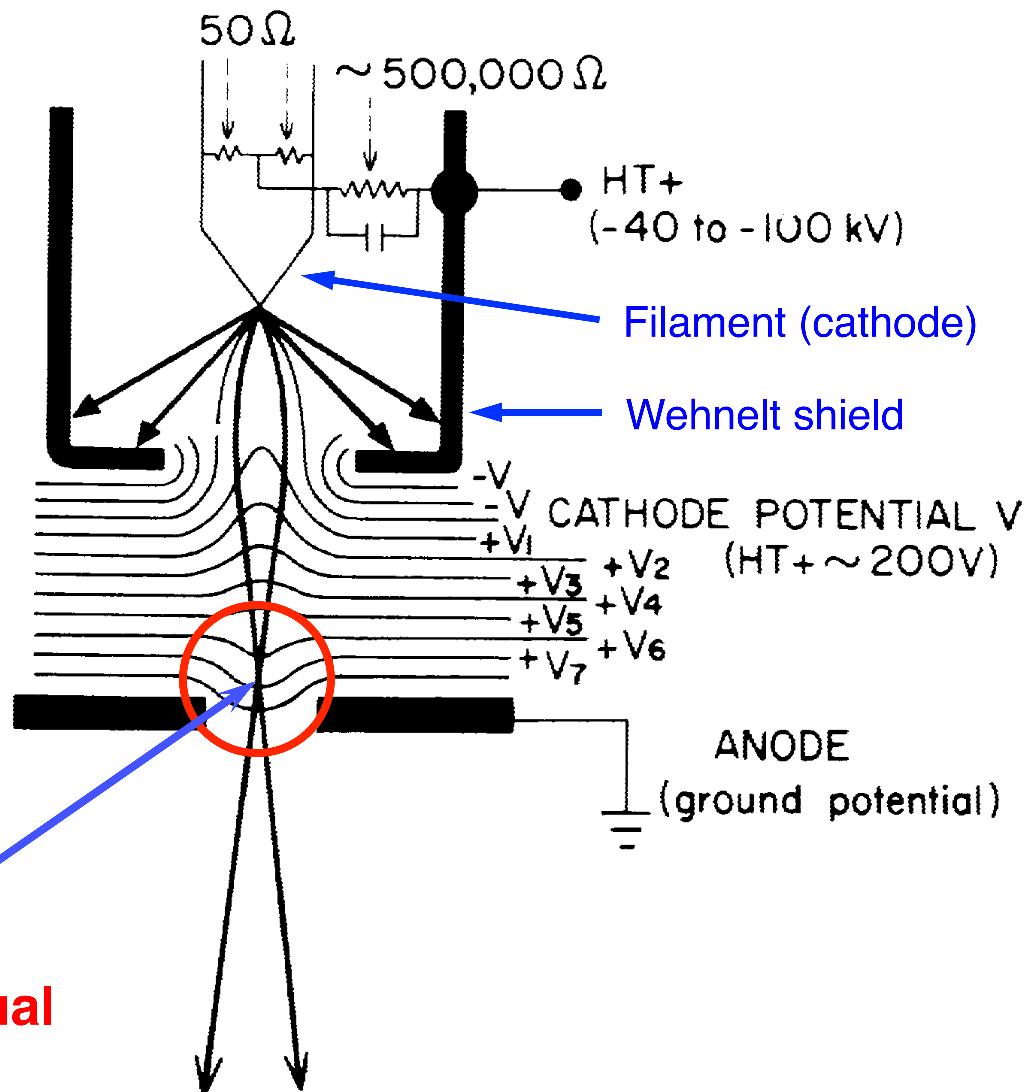
I.B.1 The Electron Gun

I.B.1.a Gun Design

Electrons accelerated across large potential difference (~100,000 volts) between **cathode** and **anode**

Wehnelt shield controls **beam shape and emission**

Anode controls **acceleration**



Crossover considered the **actual source** of e^- for the TEM

From Sjostrand, Fig. III.6, p.74

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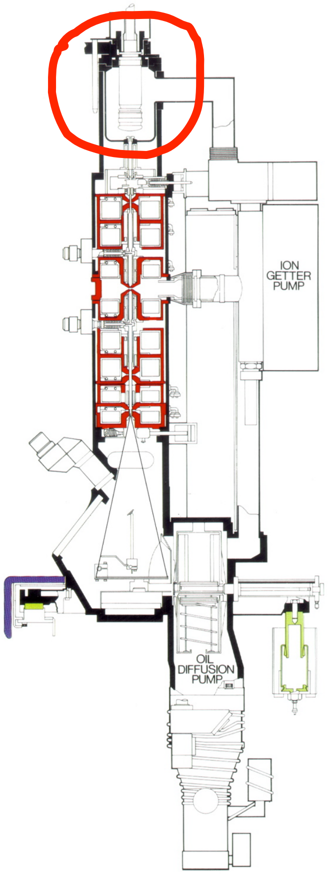

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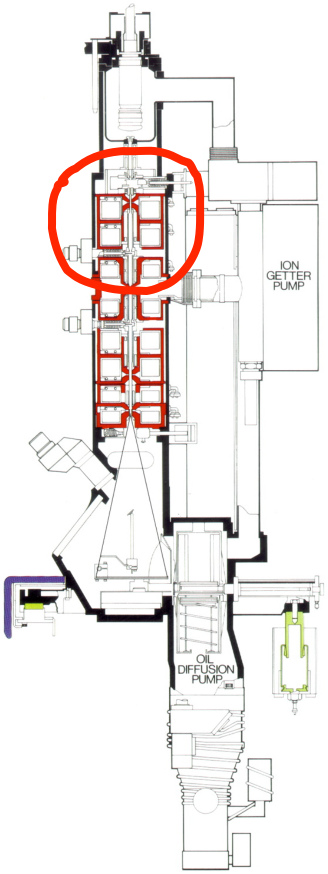


§ I: The Microscope

I.B Design of the TEM

I.B.2 Condenser Lens(es)

(pp.42-46 of lecture notes)

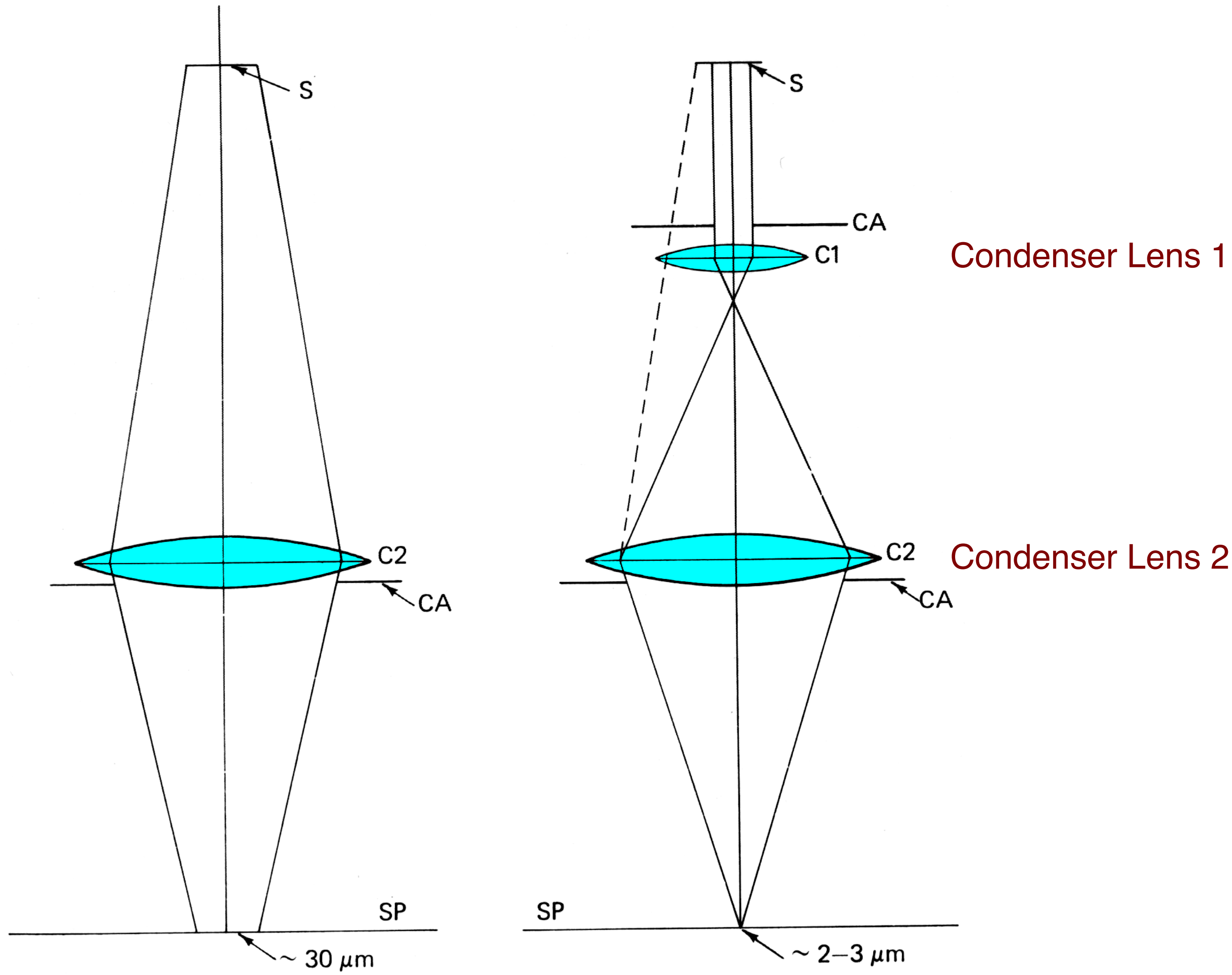
I.B.2 Condenser Lens(es)

Bottom Line:

Condenser lens system **focuses / concentrates** the electron beam onto the specimen to give optimal **illumination** for viewing and recording the image

I.B.2 Condenser Lens(es)

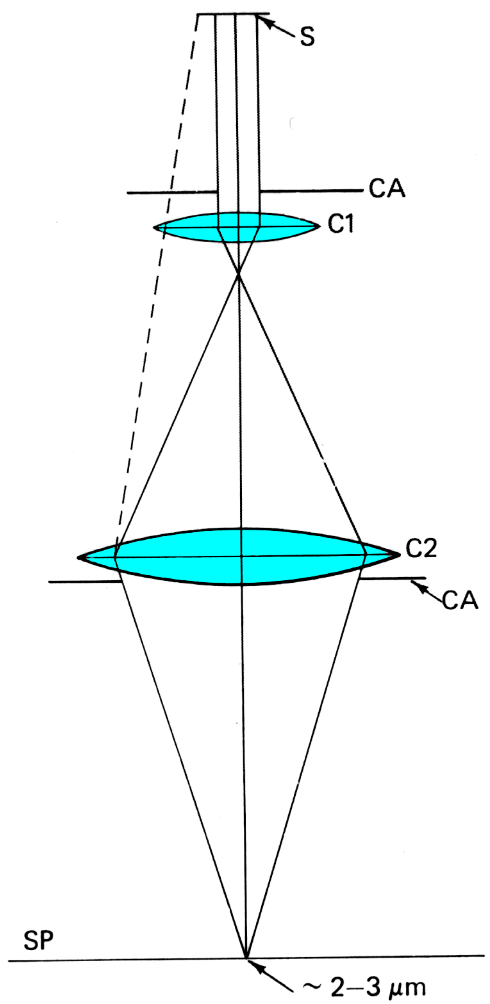
I.B.2.a,b Single and Double Condenser Systems



From Agar, Fig. 1.16, p.22

I.B.2 Condenser Lens(es)

I.B.2.b Double Condenser System



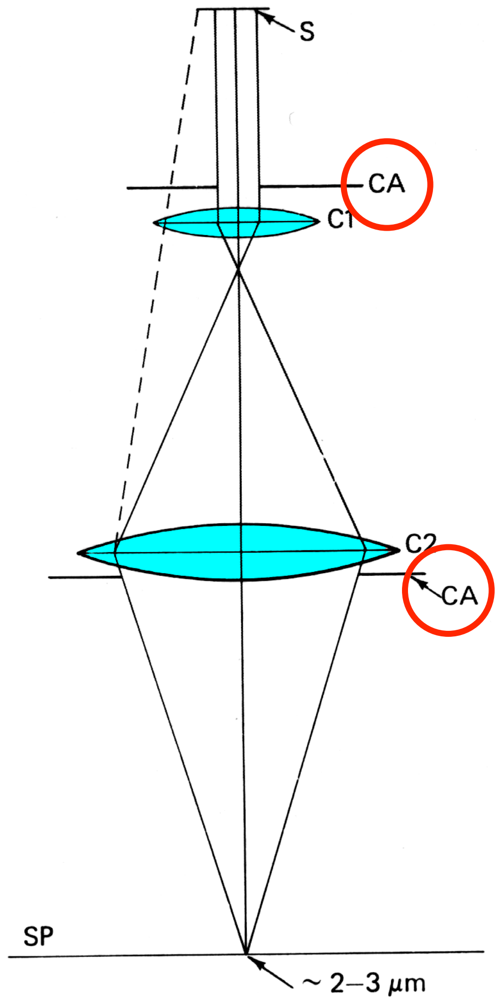
From Agar, Fig. 1.16, p.22

ADVANTAGES (lots of them!):

- More flexible control of illumination
- Wider range of intensities
- Reduces area of object irradiated
- Reduces specimen contamination
- Improves image contrast (smaller e^- source produces a higher coherence beam)
- Higher efficiency of double condenser ==> gun brightness can be reduced (increases filament life)

I.B.2 Condenser Lens(es)

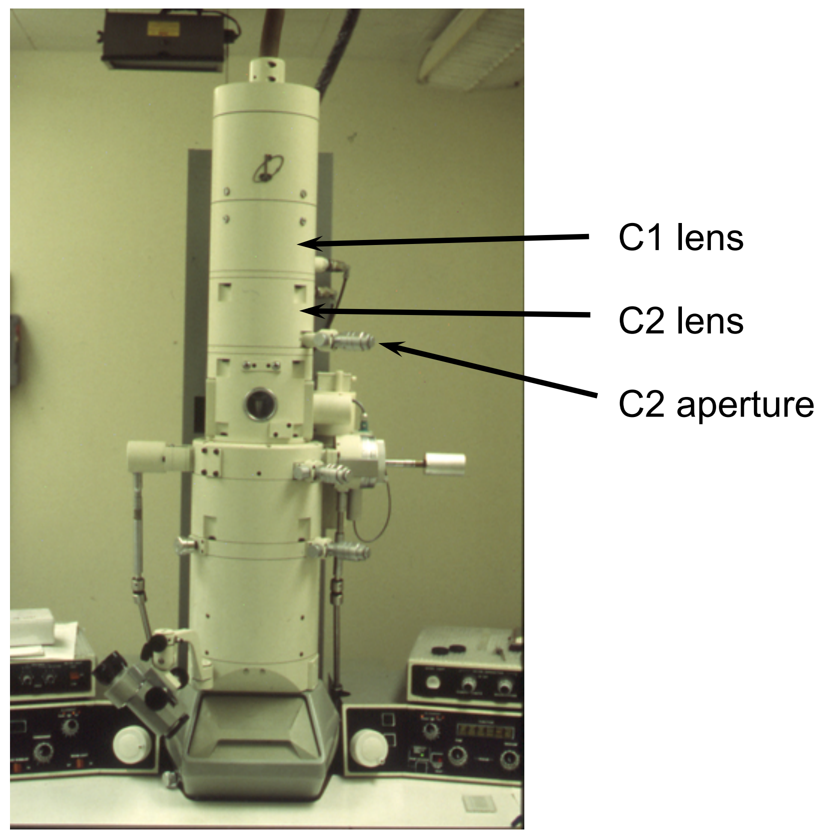
I.B.2.c Condenser Apertures



From Agar, Fig. 1.16, p.22

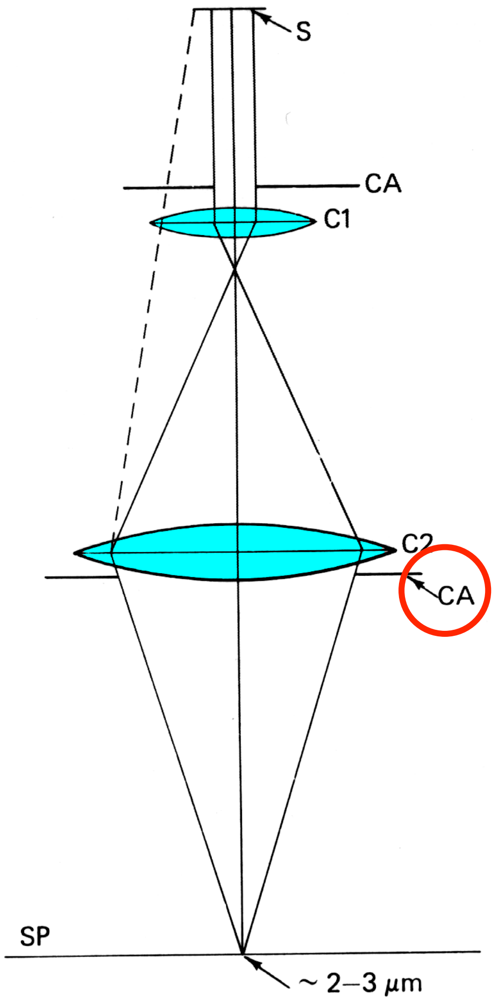
- **CA1** is often a **fixed** aperture

- **CA2** is generally **adjustable** with centering controls
  (aperture holder allows rapid exchange of 3 different size apertures).



I.B.2 Condenser Lens(es)

I.B.2.c Condenser Apertures



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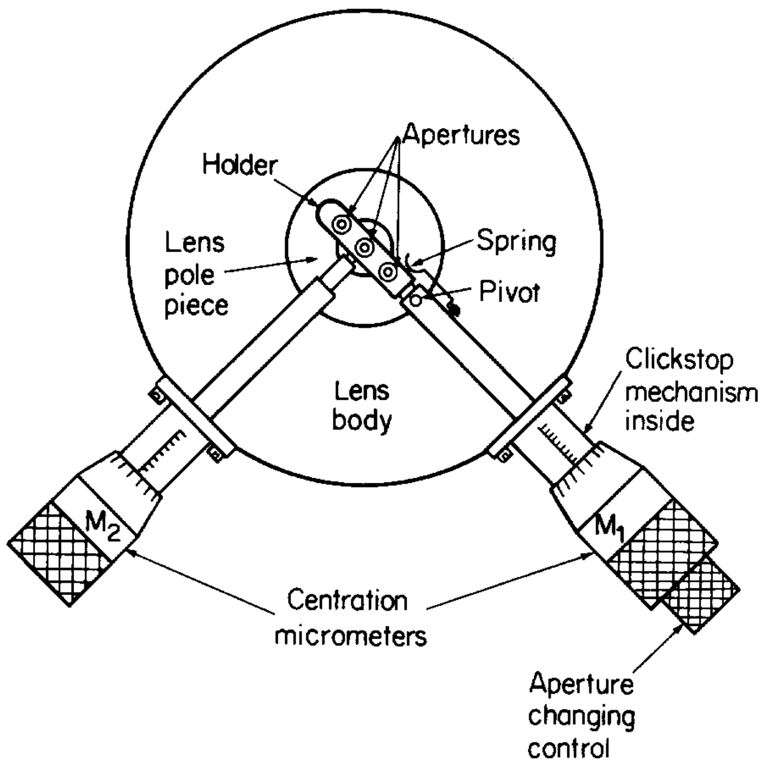

From Meek, 1st ed., Fig. 5.2, p.95

I.B DESIGN OF THE TEM

The TEM Top to Bottom:

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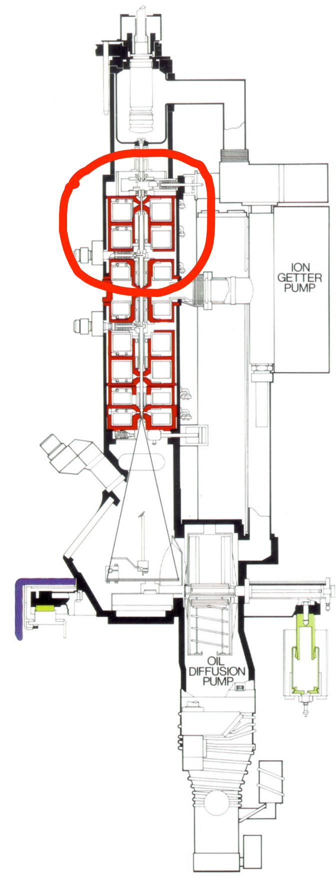
- Electrical system



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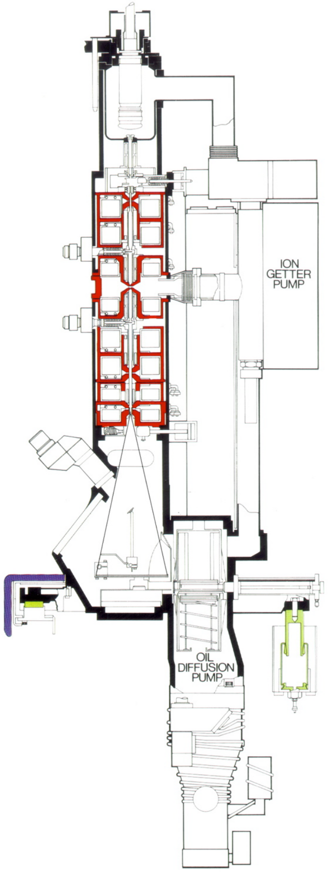

§ I: The Microscope

I.B Design of the TEM

I.B.3 Lens Aberrations

(pp.47-54 of lecture notes)

I.B DESIGN OF THE TEM

I.B.3 Lens Aberrations

Lots and lots of them:

- Spherical aberration
- Distortion
- Chromatic aberration
- Lens asymmetry
- Lens current fluctuations
- Curvature of field
- Coma and anisotropic coma
- Space charge distortion

I.B DESIGN OF THE TEM

I.B.3 Lens Aberrations

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- **Spherical aberration**
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- Curvature of field
- Coma and anisotropic coma
- Space charge distortion

Bottom Line:

Electromagnetic lenses are 'crummy'

They are the reason why resolving power in TEM is **much worse** than estimated by the simple Abbe 1/2 λ criterion

To reduce aberrations, the **semi-angular aperture** (α) of the **objective** lens is made **VERY small** (recall Abbe's equation?)

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

I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration

Bottom Line:

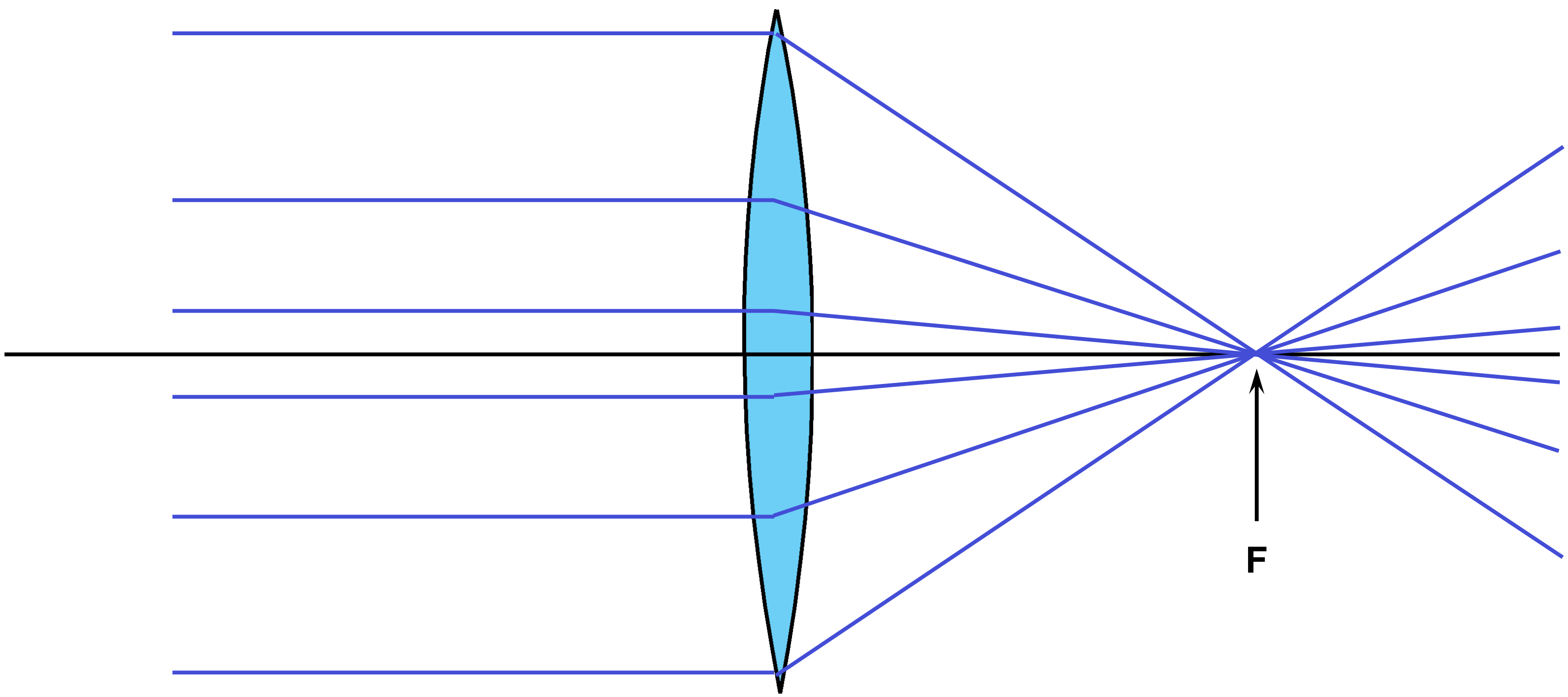
Spherical aberration is main culprit

Spherical aberration in TEM electromagnetic lenses is the **principal factor** that **limits TEM resolving power**

I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration

Recall: For an **IDEAL** lens, all rays entering lens parallel to the optic axis are focused behind the lens on the axis at a **single point**, the focal point

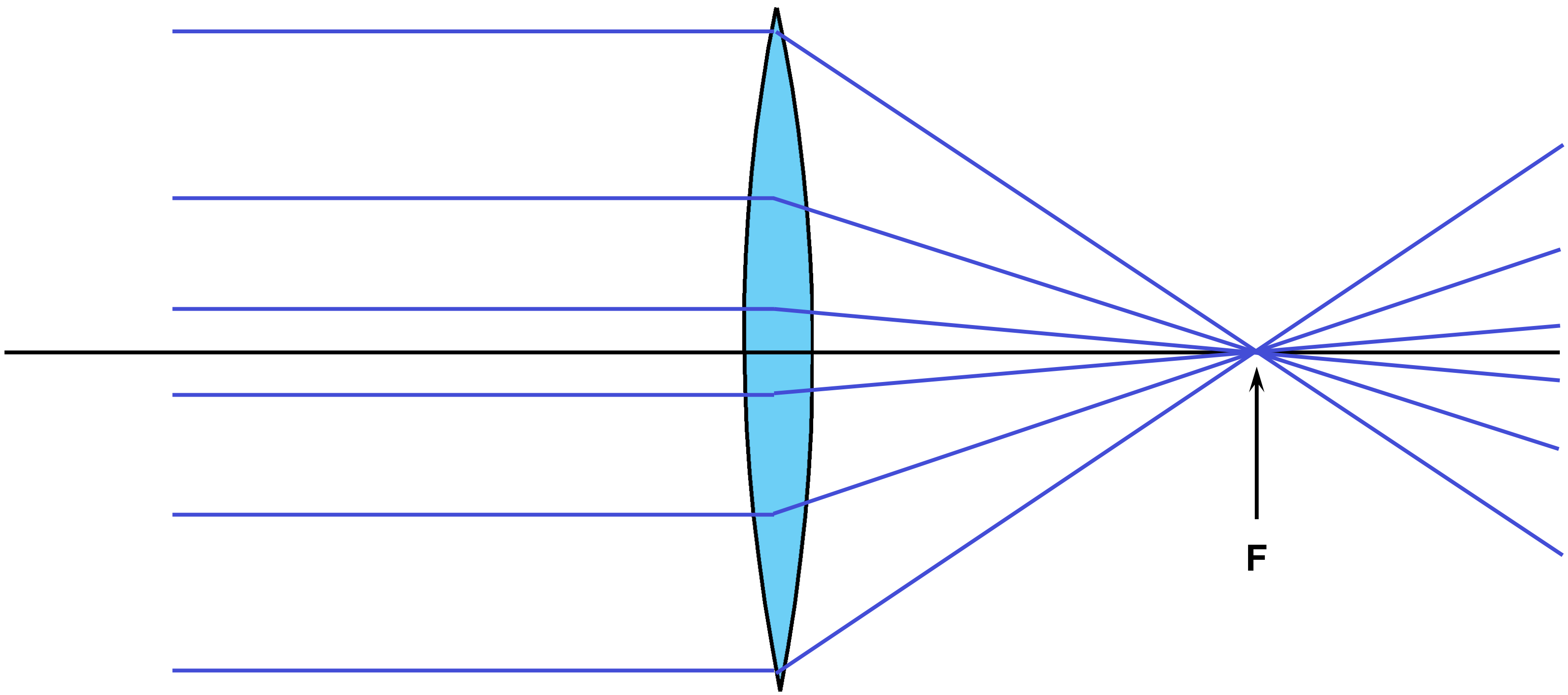


I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration

For a **REAL** lens (esp. electromagnetic), rays entering different parts of the lens experience different lens (or field) strength and hence are not focused at a single point on the optic axis

Marginal rays are focused more strongly than the paraxial rays



I.B.3 Lens Aberrations

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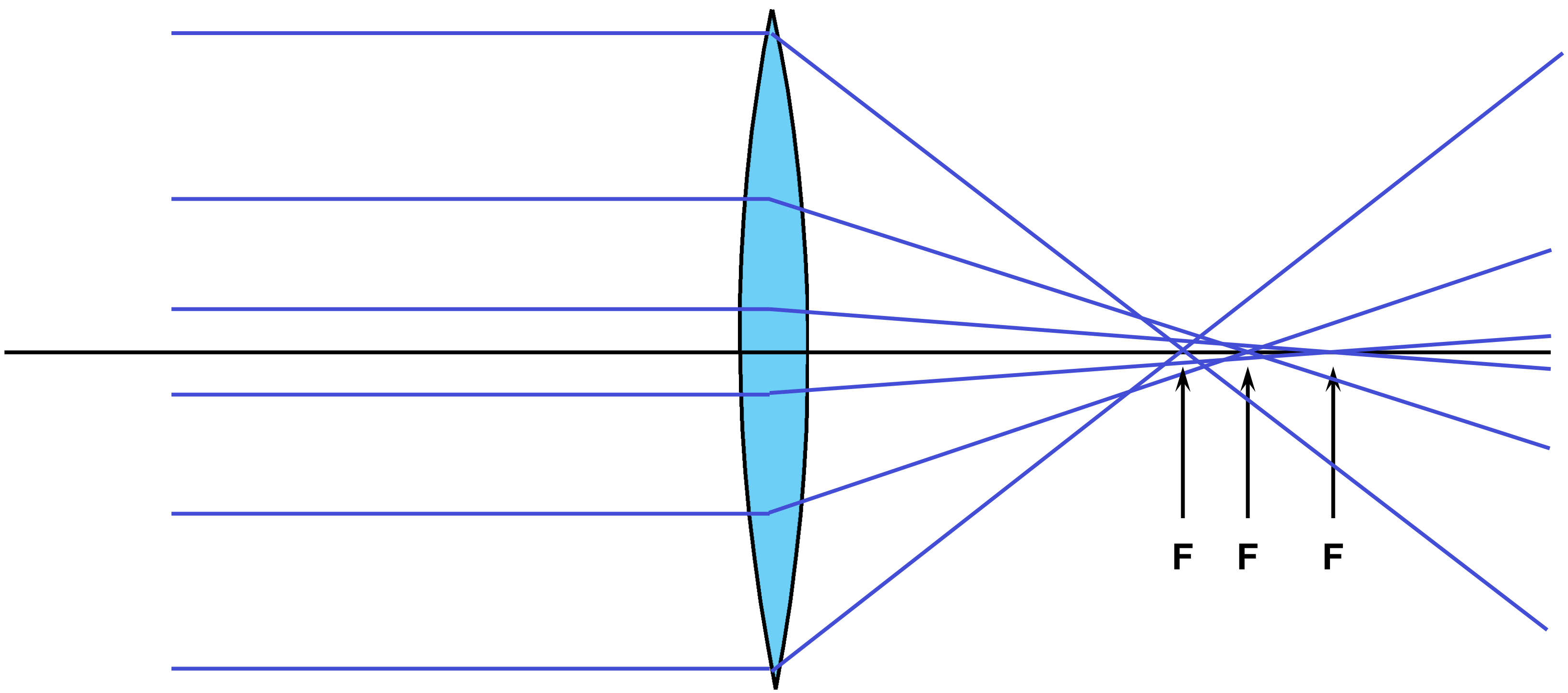

I.B.3 Lens Aberrations

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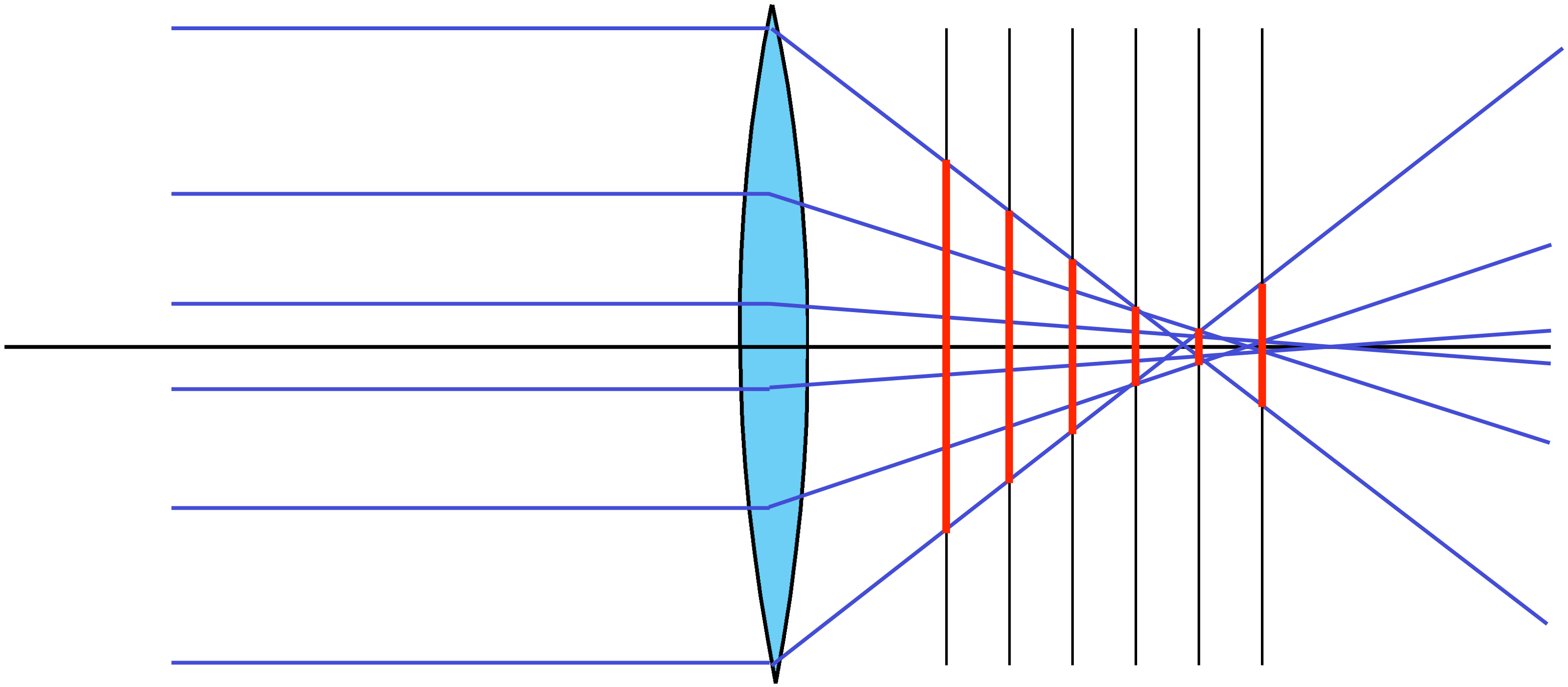

I.B.3 Lens Aberrations

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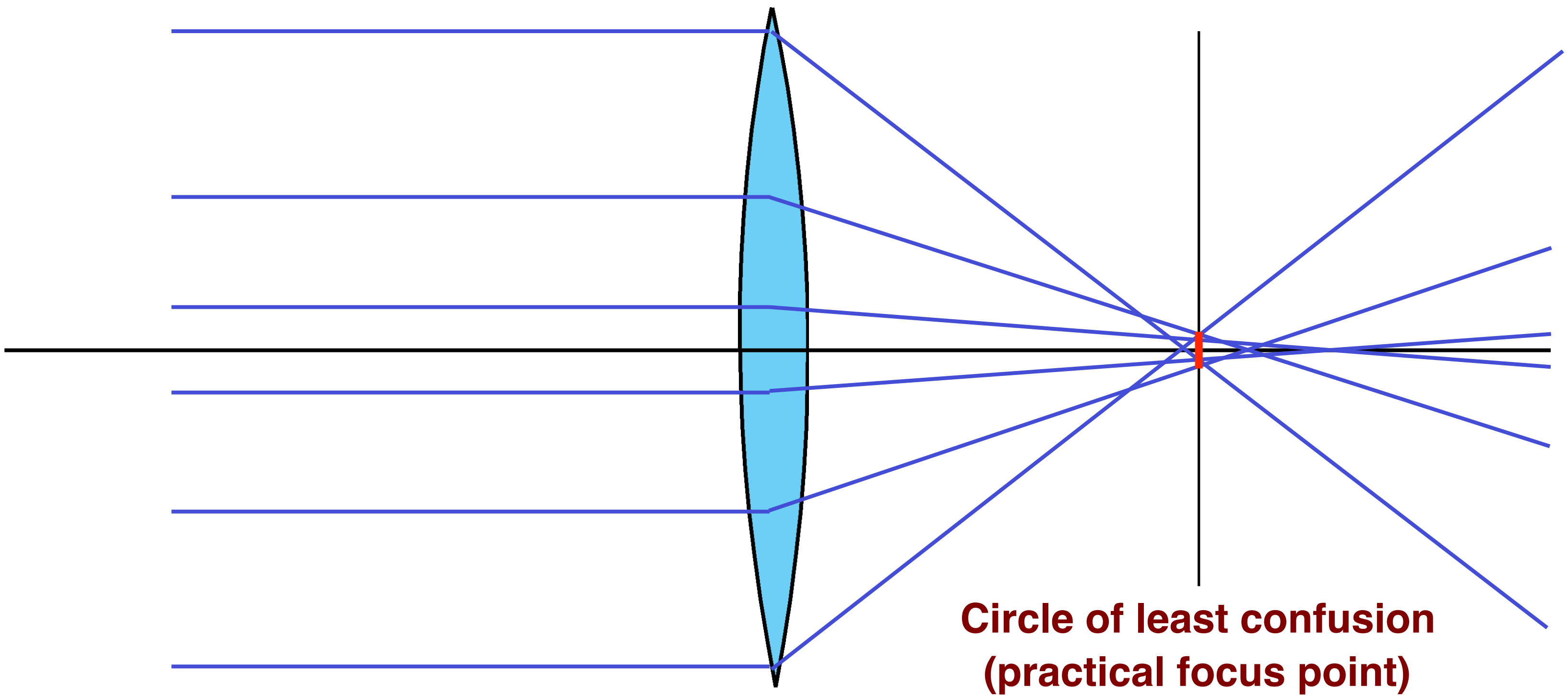
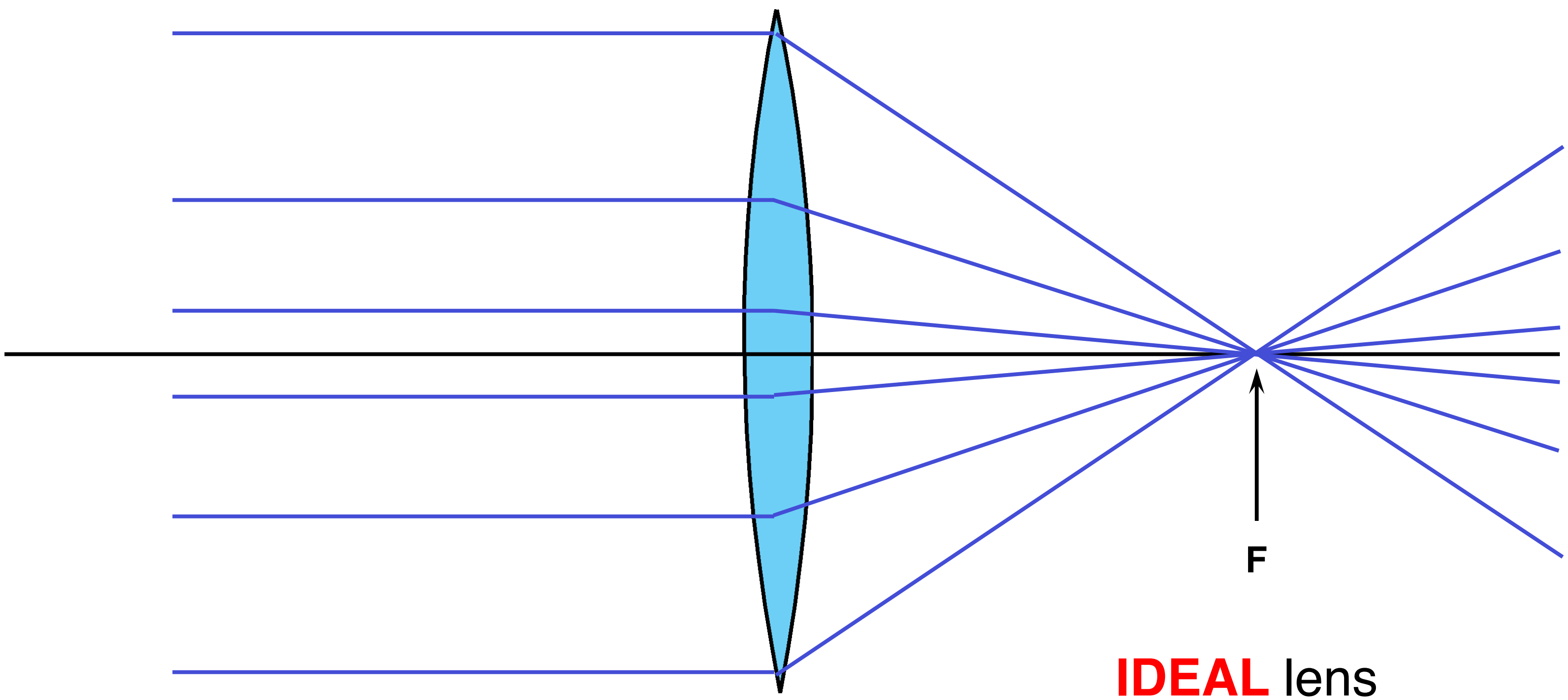


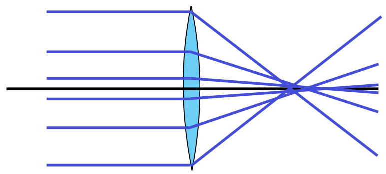
I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration



I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration



Region of focus where the marginal and paraxial rays is smallest is the ***disc of least confusion*** with diameter of disc, d_{sa}, given by:

$$d_{sa} = \frac{C_s \alpha^3}{2}$$

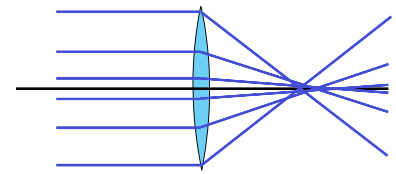
α = semi-angle of illumination

C_s = spherical aberration coefficient of objective lens

So, to **improve resolution** (*i.e.* get smaller d_{sa}), all one has to do is **reduce** the lens aperture (*i.e.* reduce α)…….all the way to zero???

I.B.3 Lens Aberrations

I.B.3.b Spherical Aberration



Life should be so simple…

SA can be minimized by 'stopping down' the lens with an aperture, but only so far because this **worsens** diffraction-limited resolution

HENCE: Decreasing α to reduce spherical aberration must be **balanced** against **loss** of resolution caused by **diffraction effects**

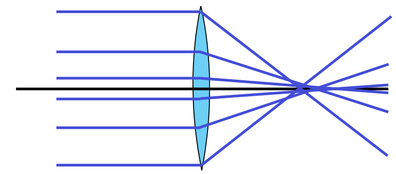
$$d_{sa} = \frac{C_s \alpha^3}{2}$$

Resolution limit due to spherical aberration

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

Resolution limit due to diffraction (Abbe equation)

See Tables (p.48, lecture notes) listing values of α (for different C_S values) that give 'optimum' resolution.



More thoughts about spherical aberration…

Glass optics:

Effects of SA **CAN be corrected** by judicious combination of converging (positive) and diverging (negative) lenses [SA of one lens counteracts the SA of the other lens]

Electron Optics:

NOT generally possible since electromagnetic lenses only work as converging (positive) lenses

Slide not shown in class lecture

I.B DESIGN OF THE TEM

I.B.3 Lens Aberrations

Lots and lots of them:

- **Spherical aberration**
- Distortion
- Chromatic aberration
- Lens asymmetry
- Lens current fluctuations
- Curvature of field
- Coma and anisotropic coma
- Space charge distortion

I.B DESIGN OF THE TEM

I.B.3 Lens Aberrations

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- **Distortion** (lecture notes, pp.49-50)
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I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration

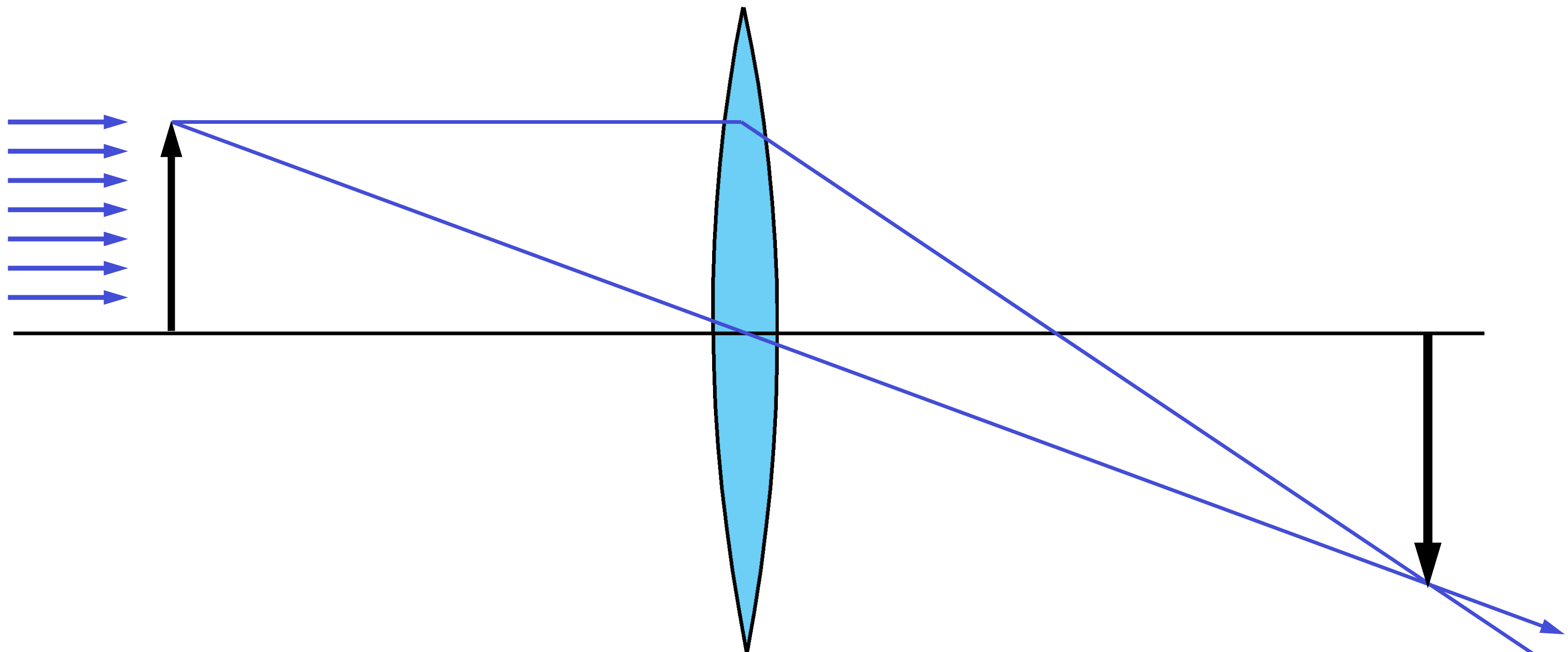
OK, what is chromatic aberration?

khroma: Greek for *"color"*

I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration

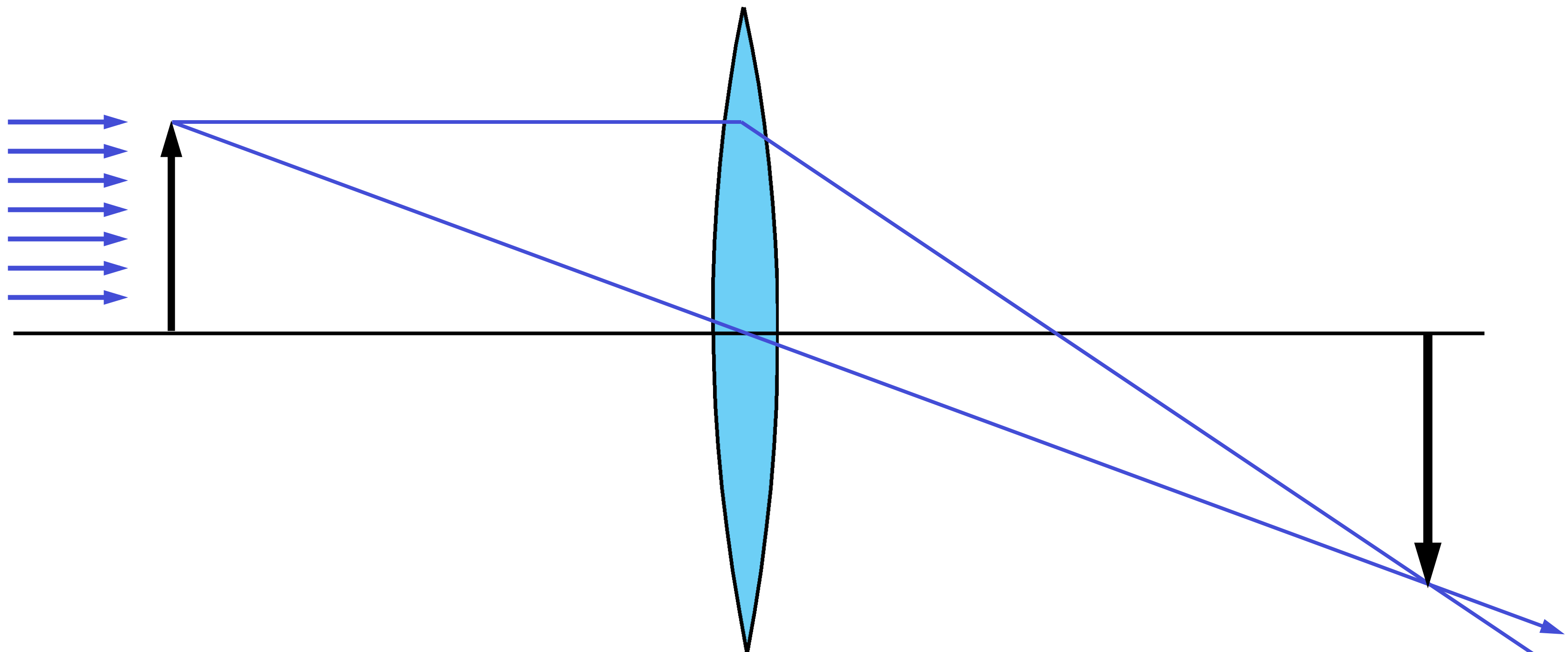
Recall: For an **IDEAL** lens, all **rays** from an object point will be focused by the lens at a point in the image plane



I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration

REAL lens: **Electrons** of **different wavelength** (velocity) leaving a point in object space are not brought to the same point in image space



I.B.3 Lens Aberrations

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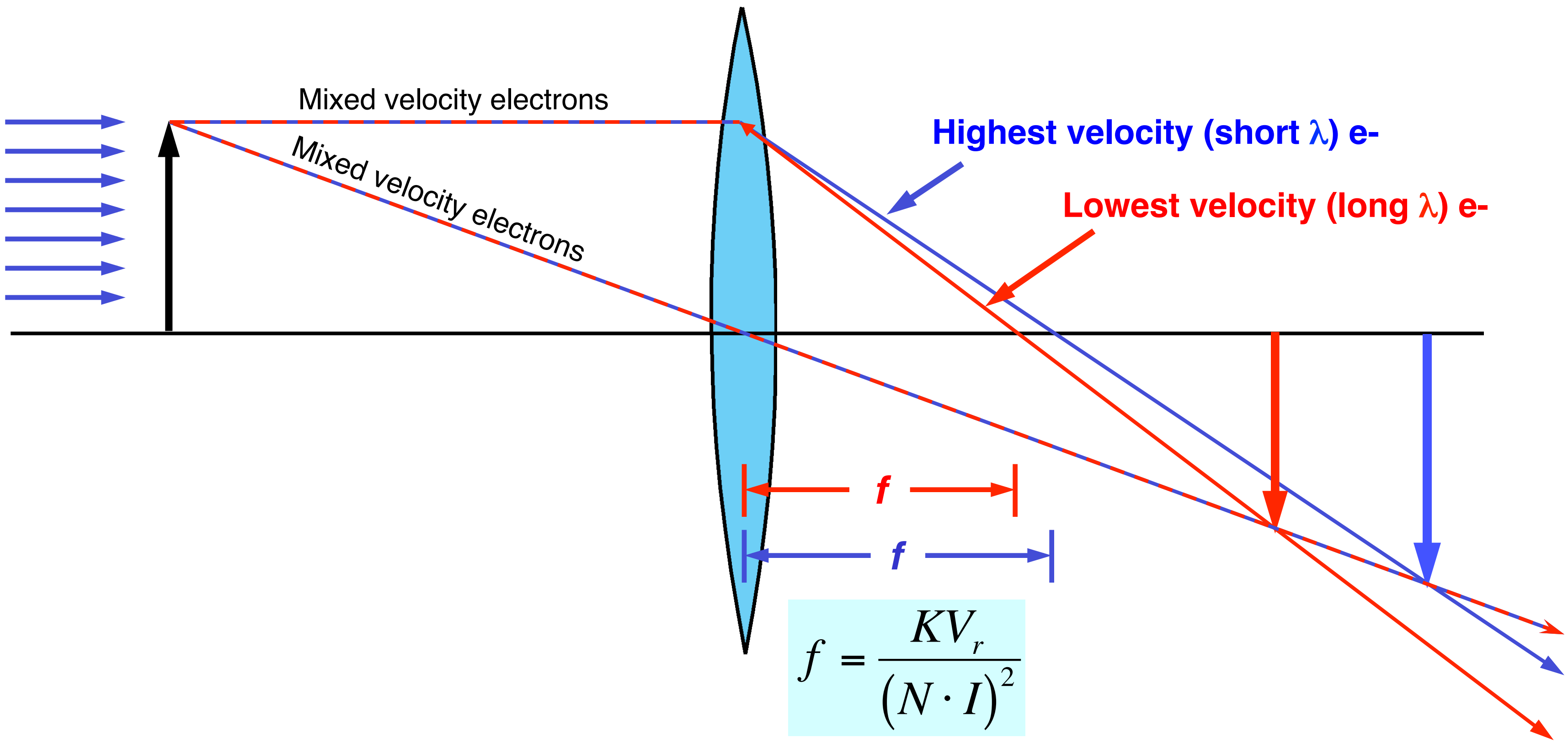
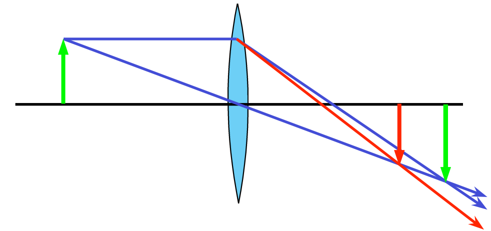


$$f = \frac{KV_r}{(N \cdot I)^2}$$

I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration



What is the nature of an image with CA?

Images with CA are the combination (superposition) of a **series** of images

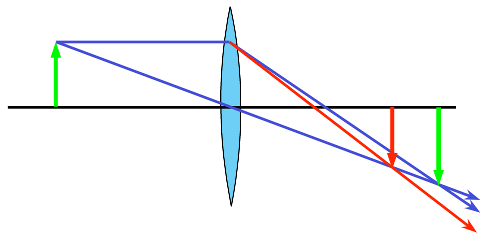
- A given lens has a **different** focal length for **each** λ electron

- For **each** λ, an **'in focus'** image forms at a specific and different image plane behind the lens and at a particular magnification

- Final image formed at **a particular** image plane is a superposition of images, each at a **different rotation and magnification**, and **only one of which is in focus**

I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration



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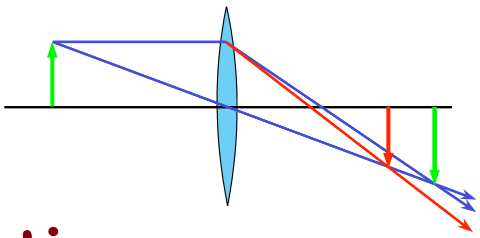
- Final image formed at **a particular** image plane is a superposition of images, each at a **different rotation and magnification**, and **only one of which is in focus**

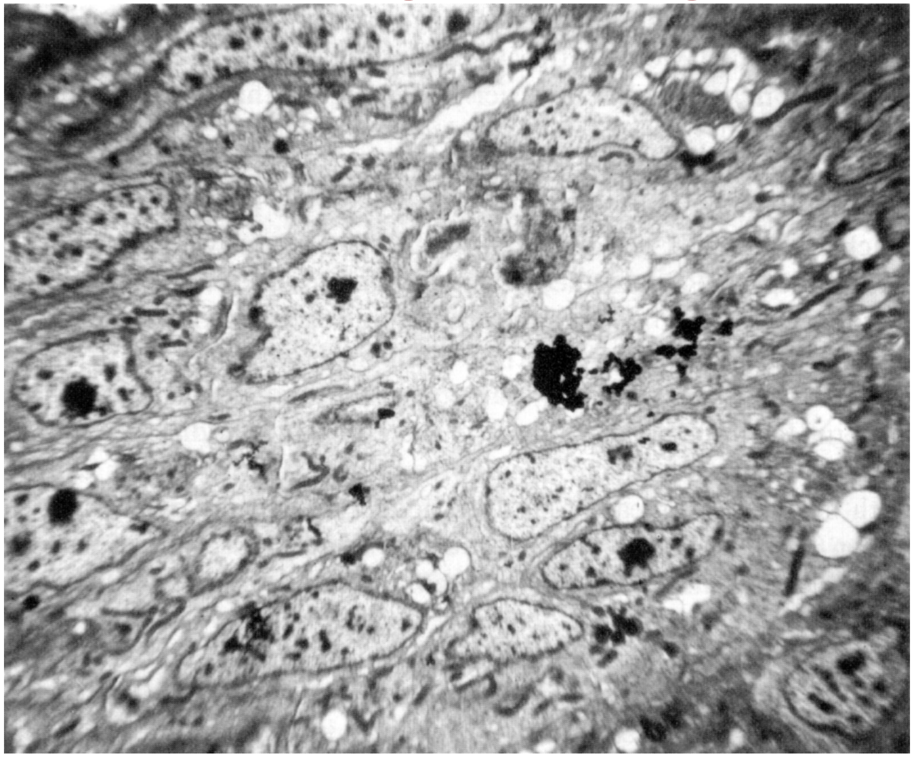
- The effects of CA in images become **progressively worse** for image points at **increasing distances from the optic axis**

I.B.3 Lens Aberrations



I.B.3.d Chromatic Aberration

Chromatic Change of Magnification



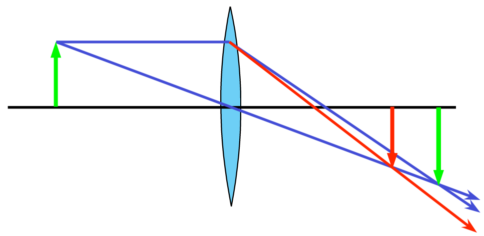
1000 Å tissue section imaged by a 30kV beam

Central part of the micrograph is the sharpest. Out-of-focus effect becomes increasingly noticeable at increasing distance from the optical axis of the TEM. Effect is more noticeable at low magnifications.

From Meek, 1st ed., Fig. 3.11, p.79

I.B.3 Lens Aberrations

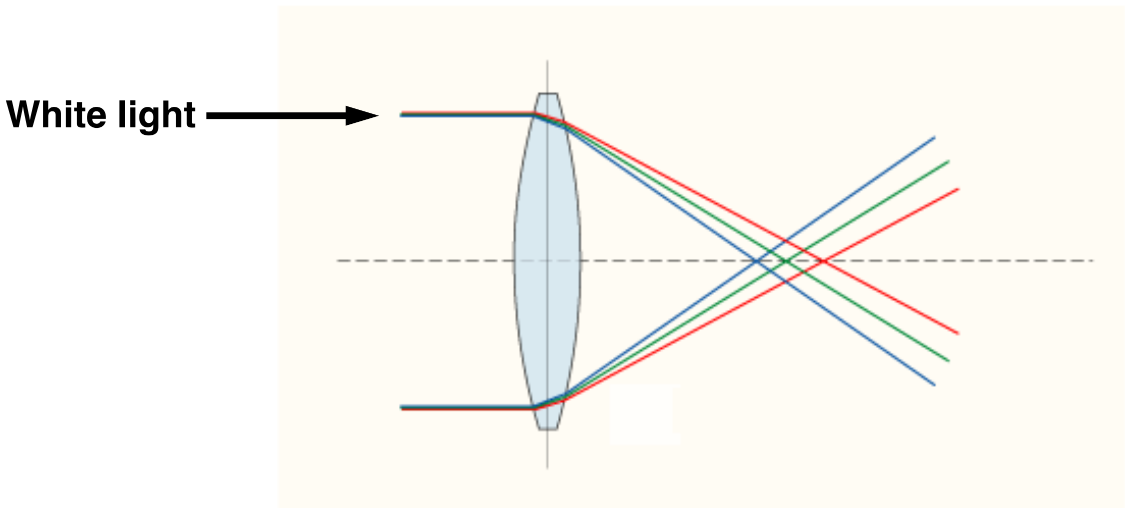
I.B.3.d Chromatic Aberration



What about photons and glass lenses?

Exactly the **opposite** occurs with glass optics

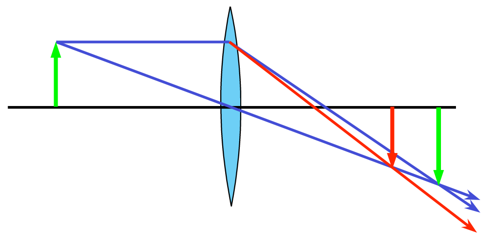
Photons of short λ (blue) are refracted **more** in glass than those of longer λ (red)



Net effect (image blurring) occurs with electrons <u>and</u> photons

I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration



What causes electrons to have different velocities?

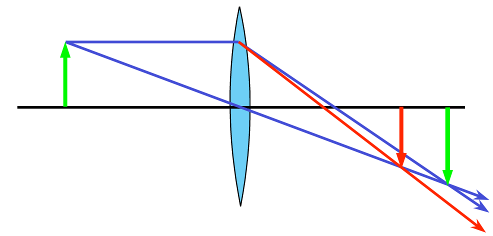
- Instabilities in high tension ($\Delta V/V < 10^{-5}$)

- Variation in velocity of e^- emitted by the cathode (± 3.5 parts/10^6)

- Energy losses when beam electrons interact with specimen atoms

I.B.3 Lens Aberrations

I.B.3.d Chromatic Aberration



Does CA limit resolution?

Of course it does……**BUT**….

… for TEM imaging of most specimens (**thin ones: ≤ 100 nm**), chromatic aberration is **NOT** a major limit to resolution in electron images.

… however, for **thick** specimens, effects of CA can be appreciable.

Limit to resolving power strictly due to CA estimated as follows (notes p.52):

$$d_{cv} = C_C \alpha_O \frac{\Delta V}{V}$$

$$d_{ci} = 2 C_C \alpha_O \frac{\Delta I}{I}$$

I.B DESIGN OF THE TEM

I.B.3 Lens Aberrations

Lots and lots of them:

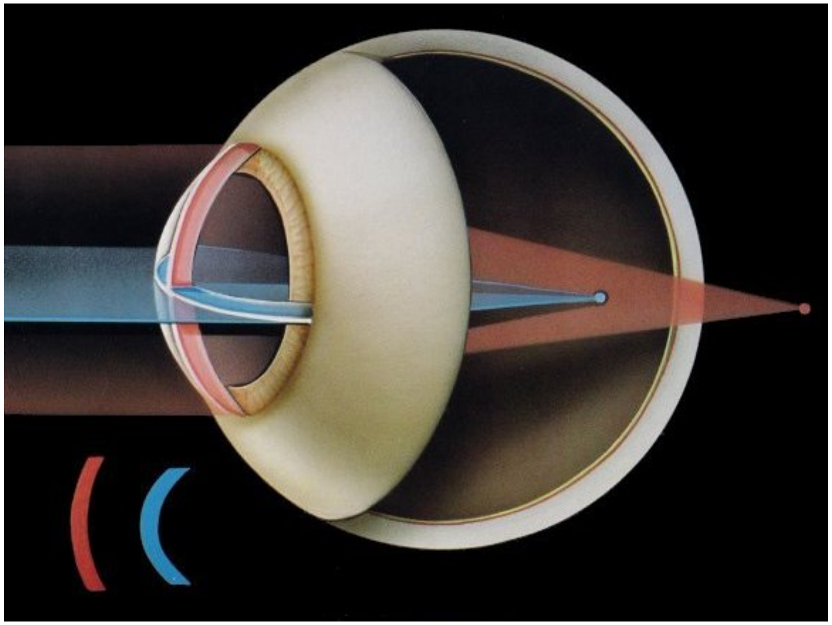
- **Spherical aberration**
- Distortion (lecture notes, pp.49-50)
- **Chromatic aberration**
- **Lens asymmetry**
- Lens current fluctuations
- Curvature of field
- Coma and anisotropic coma
- Space charge distortion

I.B.3 Lens Aberrations

I.B.3.e Lens asymmetry - Astigmatism

- Impossible to produce lens pole pieces completely free from mechanical and magnetic imperfections

- Irregularities induce an asymmetry in the magnetic field (focal length **varies** with **direction**)

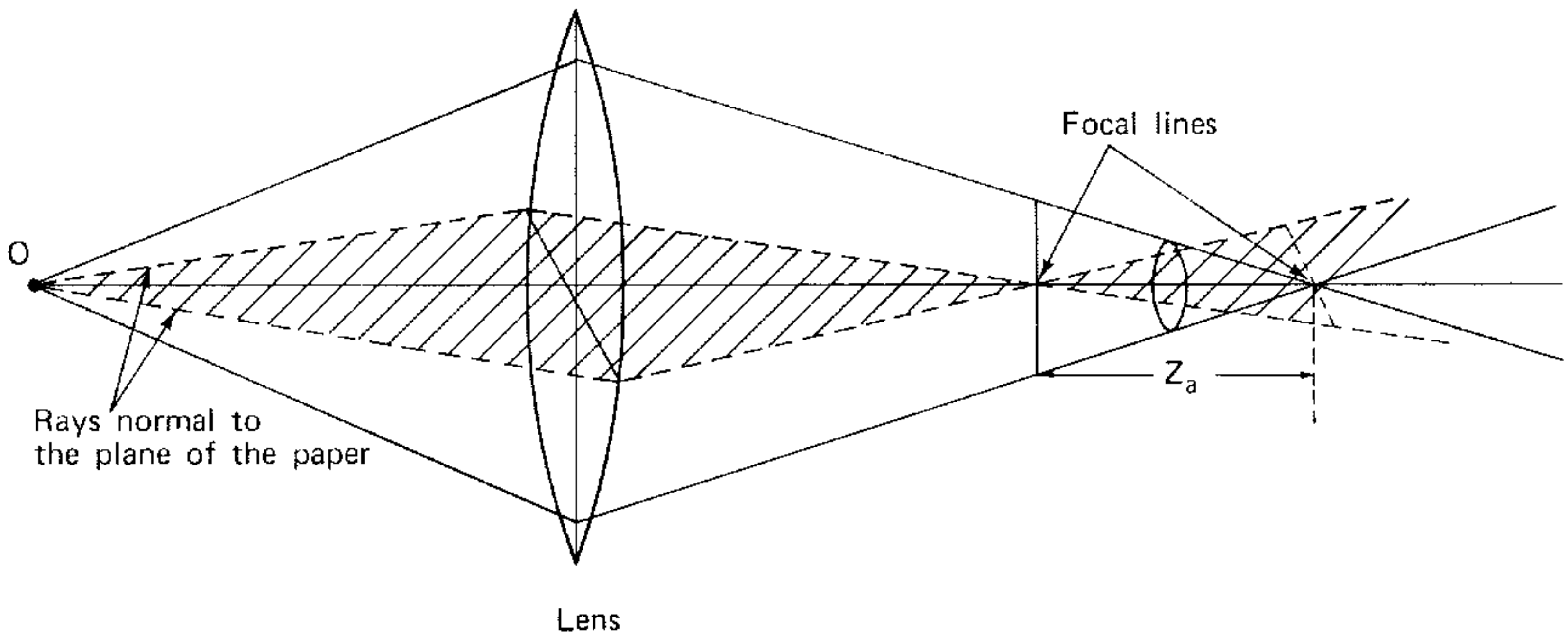


www.tedmontgomery.com/.../Astigmatism-grphc.jpg

I.B.3 Lens Aberrations

I.B.3.e Lens asymmetry - Astigmatism

Image formation with an astigmatic lens



Lens **stronger** in plane ⊥ to the screen compared to plane of screen

Point object O is imaged into **two focal lines** in ⊥ planes, Z_a apart

From Agar, Fig. 1.8, p.12

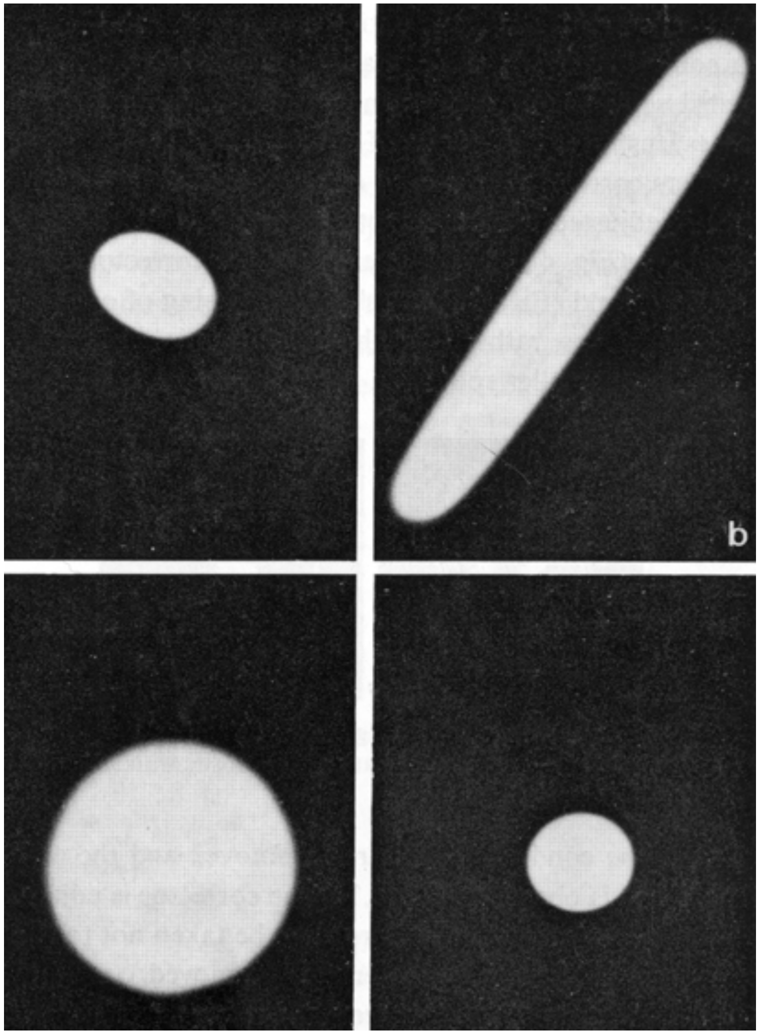
I.B.3 Lens Aberrations

I.B.3.e Lens asymmetry - Astigmatism

Condenser Lens Astigmatism

Uncorrected (astigmatic)

Corrected (stigmated)



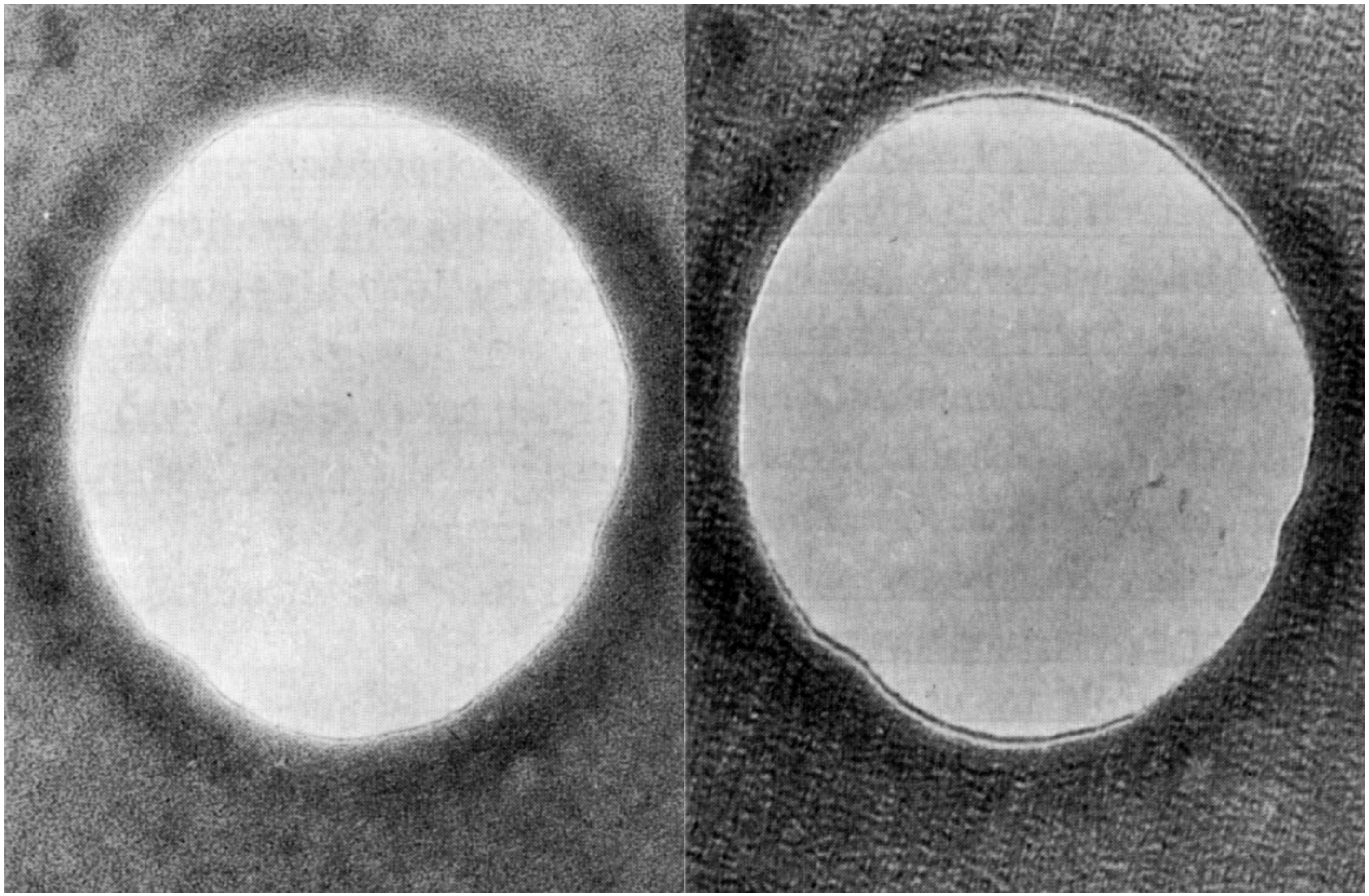
Images of focused electron beam

From Agar, Fig. 4.6, p.129

I.B.3 Lens Aberrations

I.B.3.e Lens asymmetry - Astigmatism

Objective Lens Astigmatism



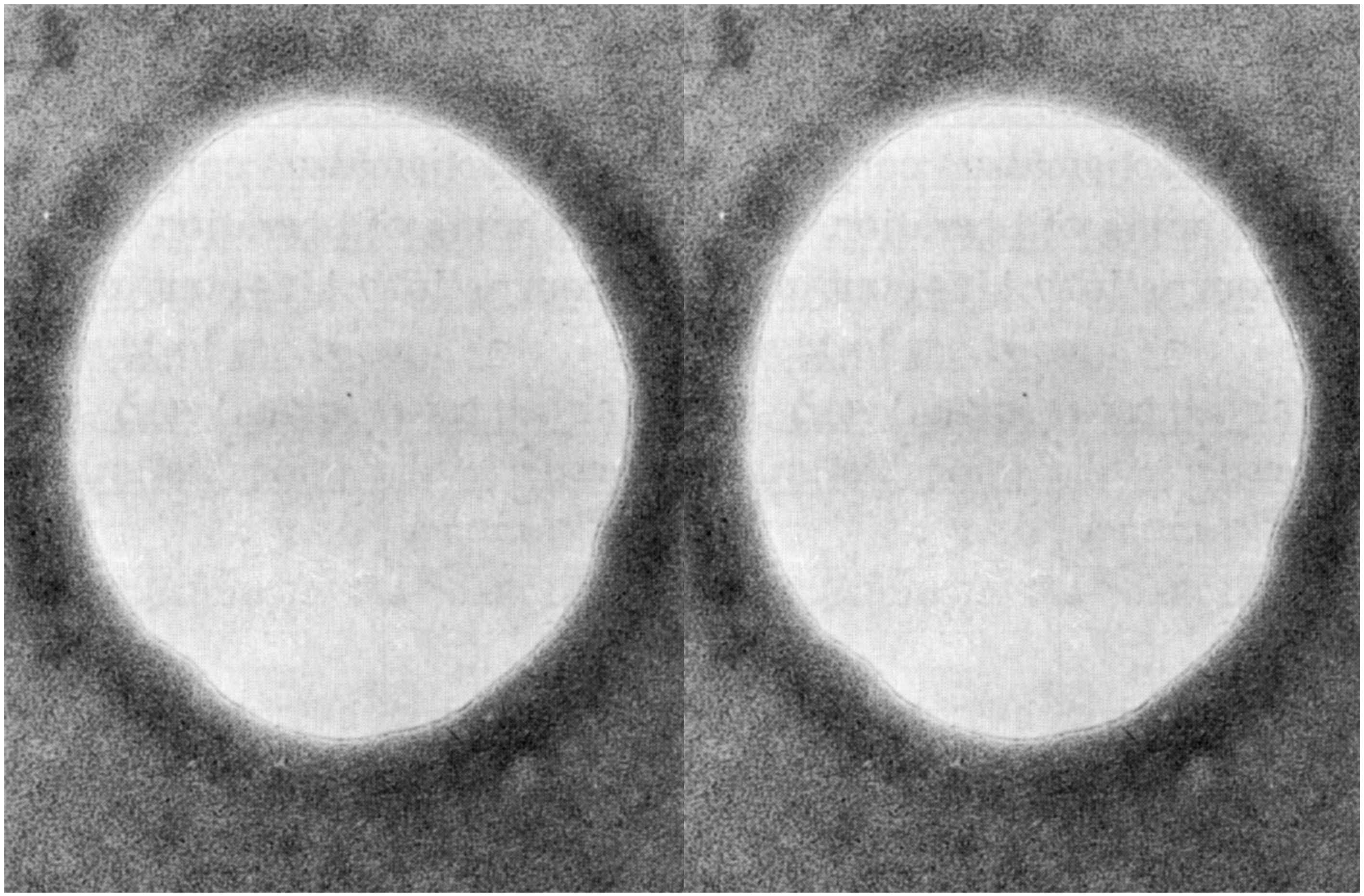
Stigmated Astigmatic

From Agar, Fig. 4.12, p.139

I.B.3 Lens Aberrations

I.B.3.e Lens asymmetry - Astigmatism

Objective Lens Astigmatism



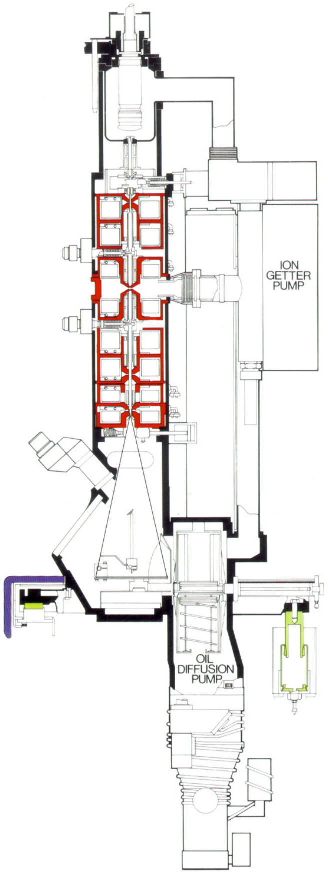
Stigmated Stigmated

From Agar, Fig. 4.12, p.139

I.B DESIGN OF THE TEM

The TEM Top to Bottom:

- Electron gun
- Condenser lens(es)
- Lens aberrations
- Objective lens and specimen stage
- Projector lenses
- Camera and viewing system
- Vacuum system
- Electrical system



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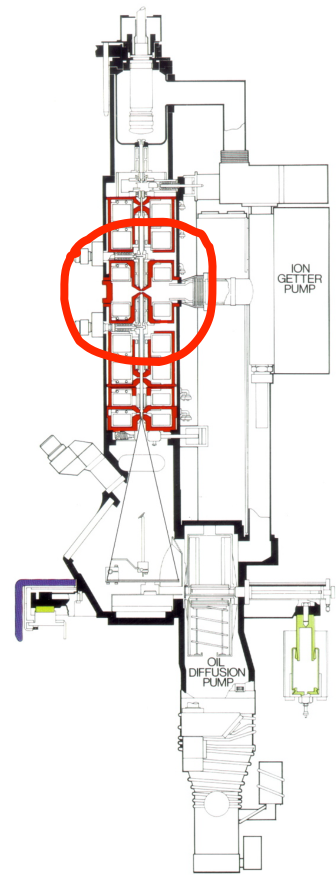
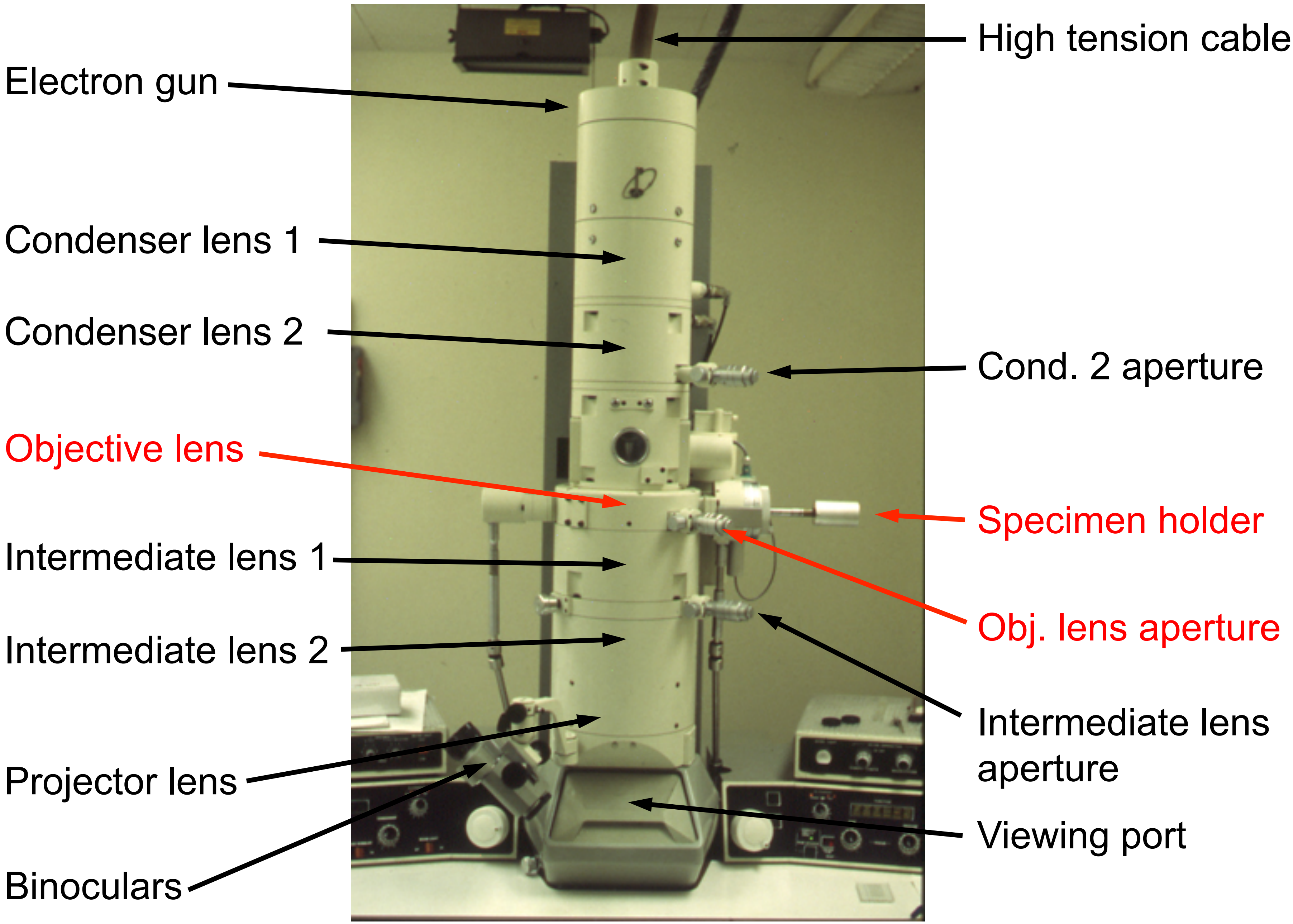


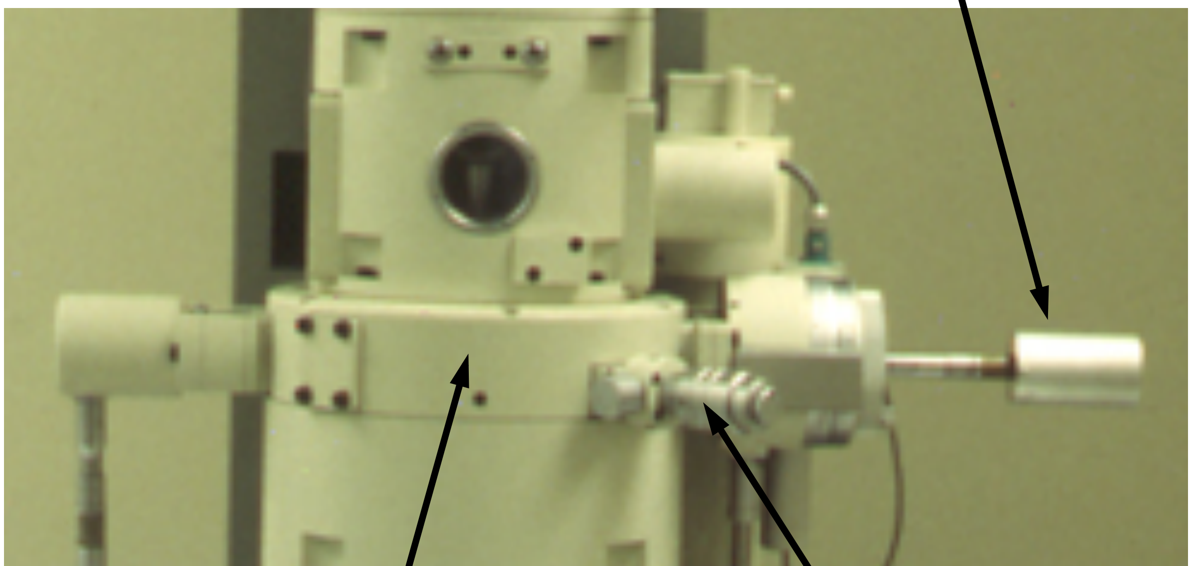
§ I: The Microscope

I.B Design of the TEM

I.B.4 Objective Lens and Specimen Stage

(pp.54-62 of lecture notes)


High tension cable
Electron gun
Condenser lens 1
Condenser lens 2
Cond. 2 aperture
Objective lens
Specimen holder
Intermediate lens 1
Obj. lens aperture
Intermediate lens 2
Intermediate lens aperture
Projector lens
Viewing port
Binoculars


Specimen holder
Objective lens
Objective lens aperture

I.B.4 Objective Lens and Specimen Stage

Bottom Line:

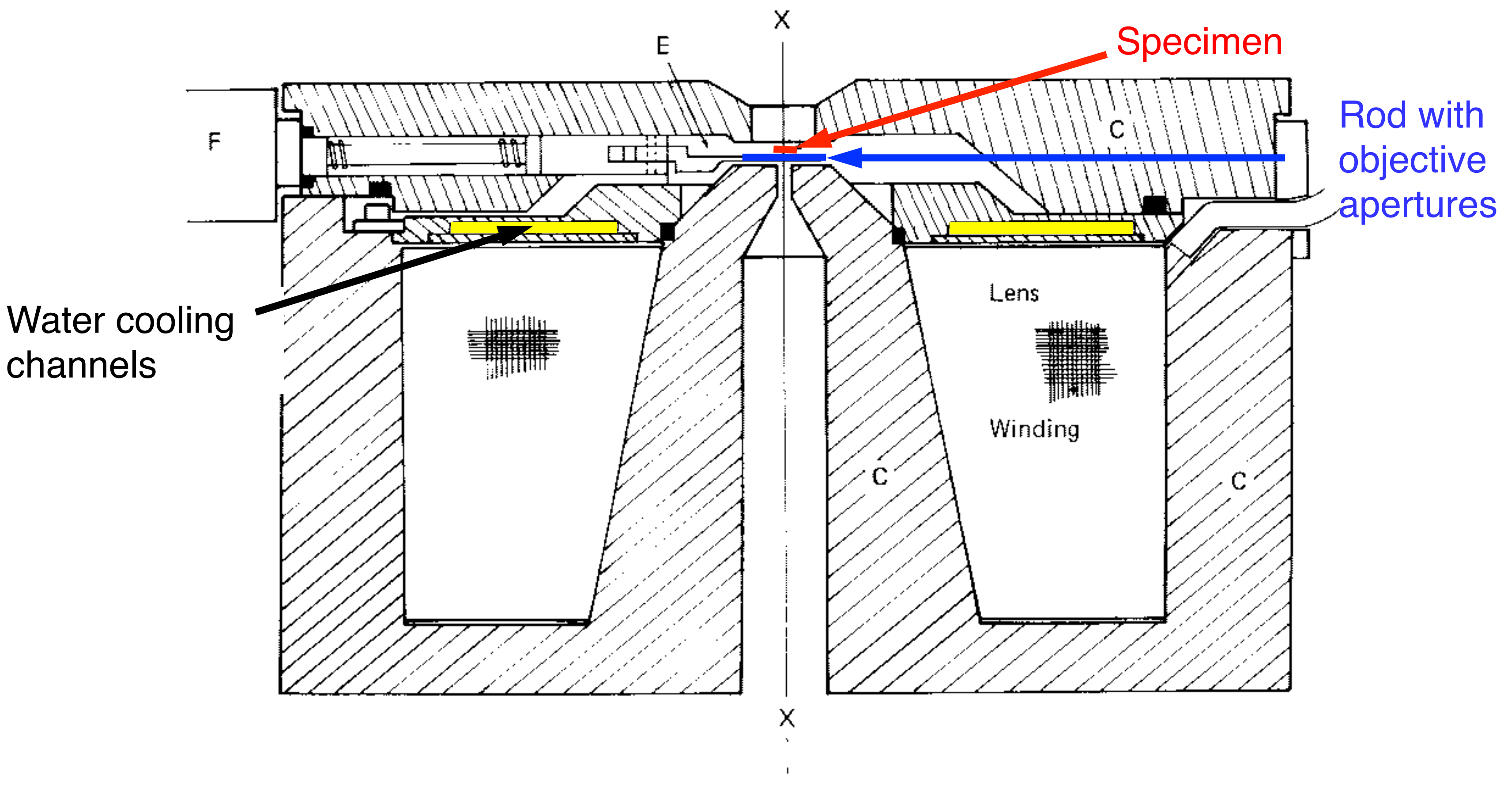
Objective lens is the **most critical** lens in the TEM

- Performs **first stage of imaging**

- Determines instrument **resolving power** and **image contrast**

I.B.4 Objective Lens and Specimen Stage

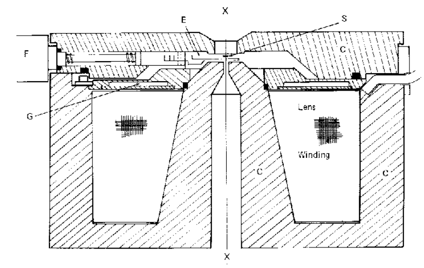
I.B.4.b Objective Lens Construction



From Agar, Fig. 2.11, p.51

I.B.4 Objective Lens and Specimen Stage

I.B.4.b Objective Lens Construction



Main Requirements

- **Specimen** situated **close to** and **before** the **front focal plane** of the objective lens

- Specimen sits ***inside*** the **lens field** (necessary to obtain short focal length)

- **Space is very cramped** (need adequate clearance for inserting several items):

  Specimen

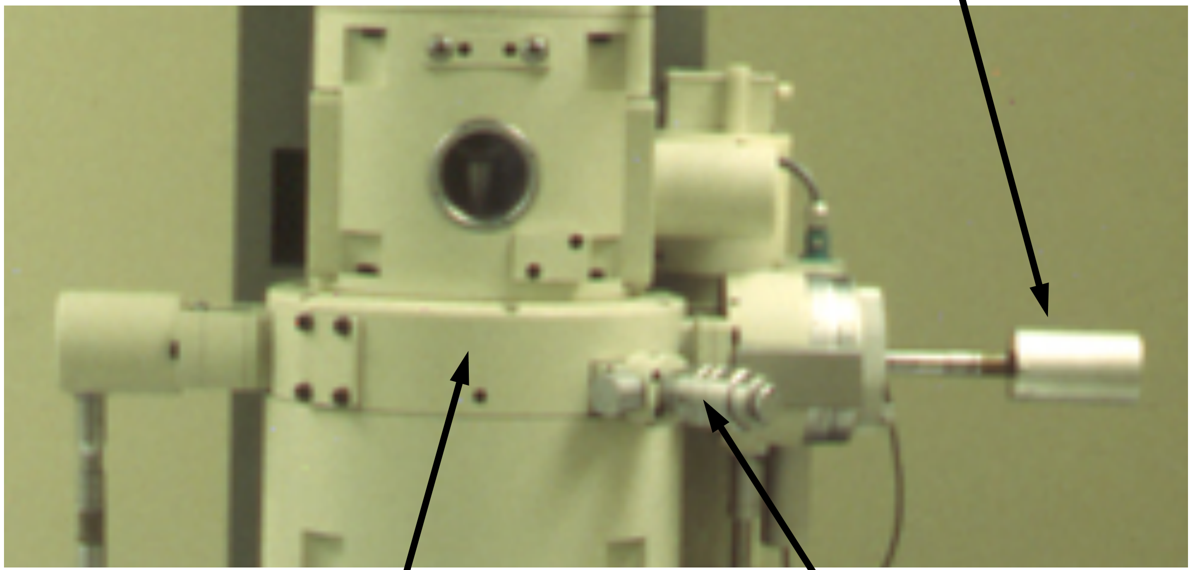
  Aperture

  Anticontaminator

  Stigmators to correct for asymmetries in the lens field

I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture (OA)



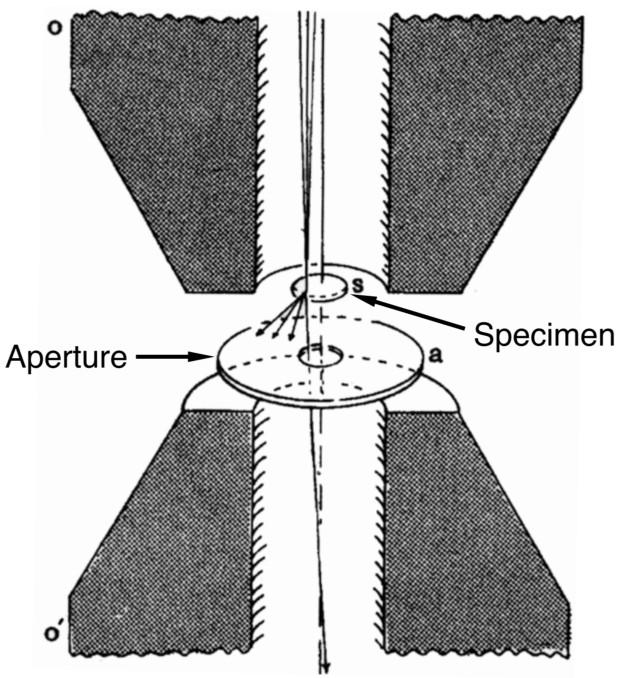
I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture (OA)

FUNCTION: Intercepts electrons **scattered** by the specimen through **large angles**

POSITION: Right at the ***back* focal plane** of the objective lens

Schematic of lengthwise section through objective lens pole pieces



From Wischnitzer 2nd ed., Fig. 51, p.60

OA does not restrict field of view

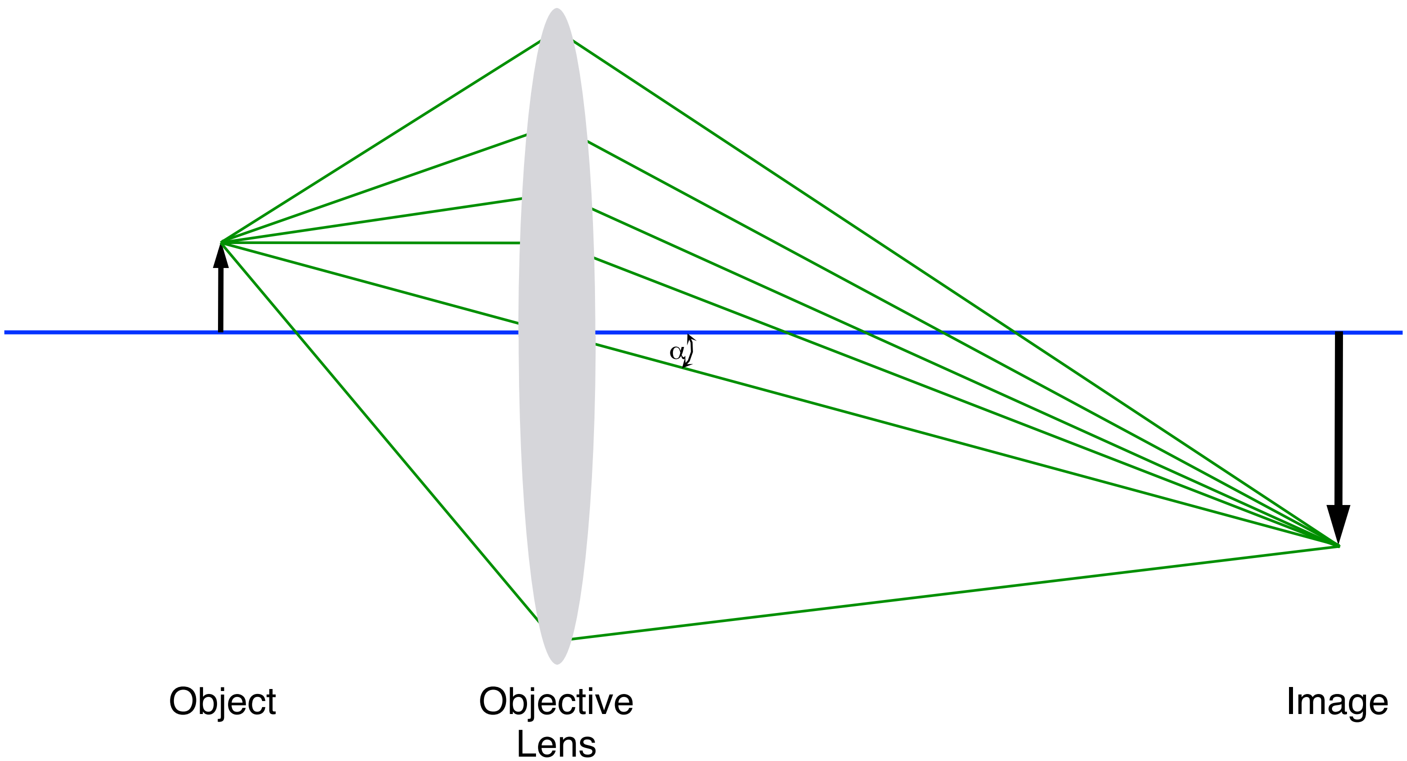
I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture (OA)

FUNCTION: Intercepts electrons **scattered** by the specimen through **large angles**

POSITION: Right at the ***back* focal plane** of the objective lens

Here, the OA screens out widely scattered electrons from being imaged



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