I: The Microscope

II: The Specimen

III: The Structure

Reading assignment: Lecture notes pp.1-38

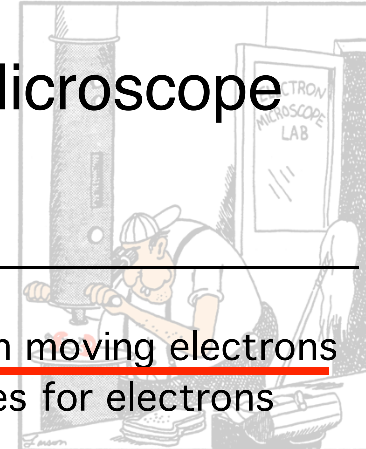
§ I: The Microscope

I.A Principles of TEM

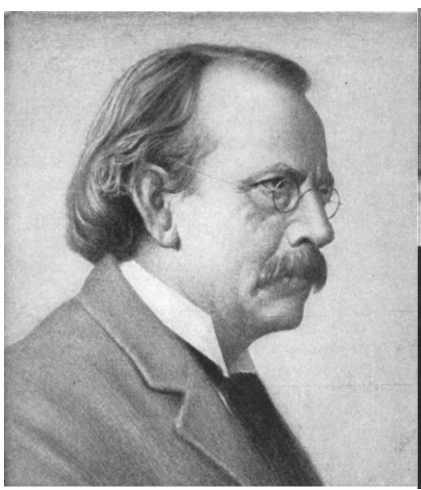
I.A.1 Origin of the Electron Microscope

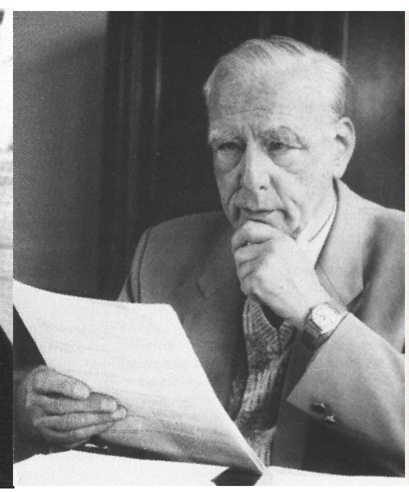
(page 1 of lecture notes)

I.A.1 Brief History of the Transmission Electron Microscope



DATE	NAME/COMPANY	EVENT
★1897	J. J. Thompson	Discovered the electron
★1924	Louis deBroglie (as grad student)	Identifies wavelengths associated with moving electrons
1926	H. Busch	Magnetic or electric fields act as lenses for electrons
★1929	E. Ruska	Ph. D thesis on magnetic lenses
1931	Davisson & Calbrick	Properties of electrostatic lenses
★1932	M. Knoll & E. Ruska	First electron microscope built (prototype of modern microscopes)
★1935	E. Driest & H. Muller	Surpass resolution of the LM
1938	B. von Borries & E. Ruska	Constructed TEM capable of resolving 10 nm (= 100 Å)
1939	Siemens	First practical TEM
★1941	RCA	Commercial TEM with 2.5 nm resolution
1946	J. Hillier	1.0 nm resolution achieved





CHEM 165 Winter 2013

A Few Ground Rules

- TEM is not simply "knob twiddling"

- To be "good", need to understand basic principles

- TEM relies on **many** basic principles (mostly physics)

- Some concepts may not make much sense at first…but
  HANG IN THERE! (review and re-review the concepts so they become 2nd nature to you)

Goal: Even if you don't aspire to be a practicing electron microscopist, at least you can view published work with a critical 'eye'

KEY CONCEPT:

Electrons and photons have common properties

For example, they are both used to form images

§ I: The Microscope

I.A Principles of TEM

I.A.2 Comparison of Light and Electron Microscopes

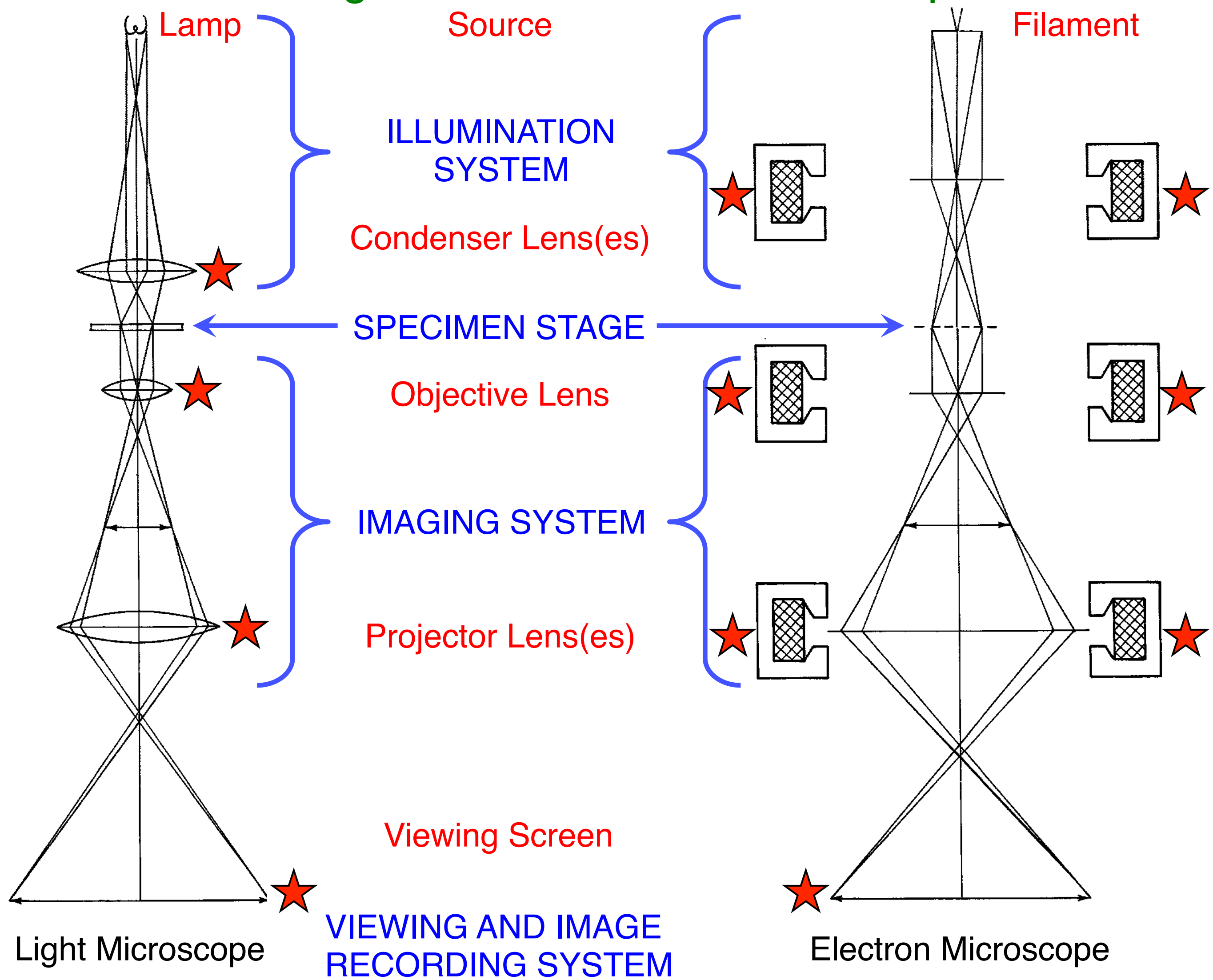
(pp.1-7 of lecture notes)

I.A.2 Comparison of Light and Electron Microscope

I.A.2 Comparison of Light and Electron Microscope

I.A.2 Comparison of Light and Electron Microscope

Similar arrangement and function of components



From Agar, Fig. 1.6, p.8

I.A.2 Comparison of Light and Electron Microscope

SIMILARITIES

Similar arrangement and function of components

ILLUMINATION SYSTEM: Radiation source & condenser lens

- Source produces illumination beam
- Condenser focuses beam on specimen

SPECIMEN STAGE:

- Hold specimen between illumination & imaging systems

IMAGING SYSTEM: Objective and projector lenses

- Objective produces first (intermediate) image
- Projector(s) magnifies a portion of the intermediate image to form final image

IMAGE RECORDING SYSTEM: Photographic emulsion (film) or CCD or DDD camera

- Converts radiation into a 'permanent' image

Slide not shown in class lecture

I.A.2 Comparison of Light and Electron Microscope

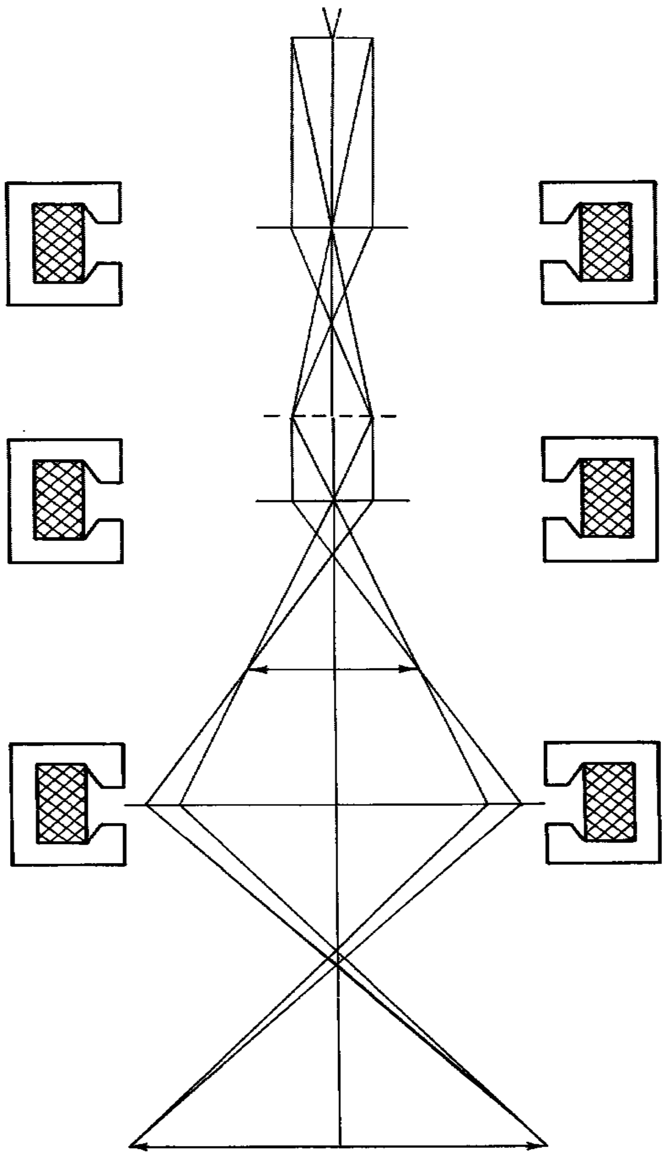
DIFFERENCES

Light Microscope	Electron Microscope
- Optical lenses **Glass**; **fixed** focal length	- Magnetic lenses **Ferromagnetic** materials & windings of copper wire **Variable** focal length (vary current)
- Magnification changes Switch objective lens or ocular (eyepiece)	- Magnification changes Objective lens focal length 'fixed' Projector focal length varied
- Depth of field small **Different** focal levels in specimen	- Depth of field large **Entire** (thin) specimen is **in focus**
- Mechanism of image formation Mainly **amplitude** (scattering) contrast	- Mechanism of image formation Mainly **phase** (interference) contrast

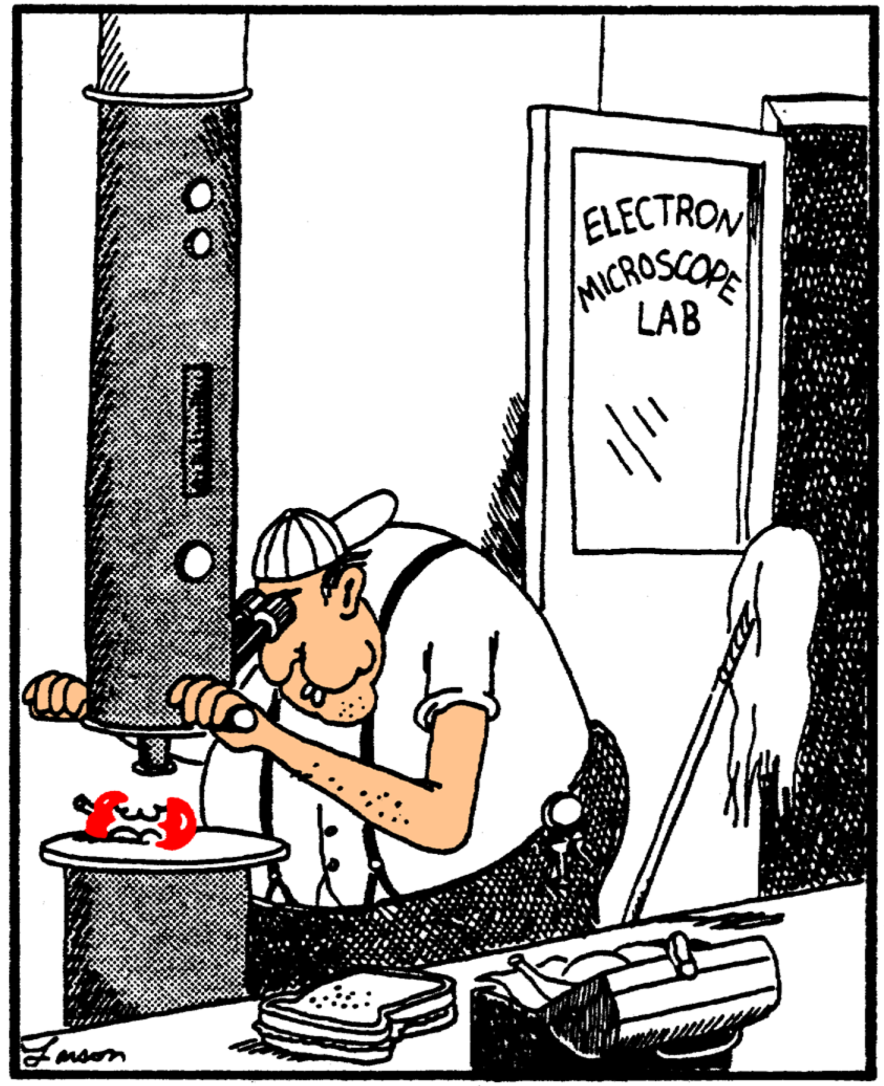
I.A.2 Comparison of Light and Electron Microscope

MORE DIFFERENCES

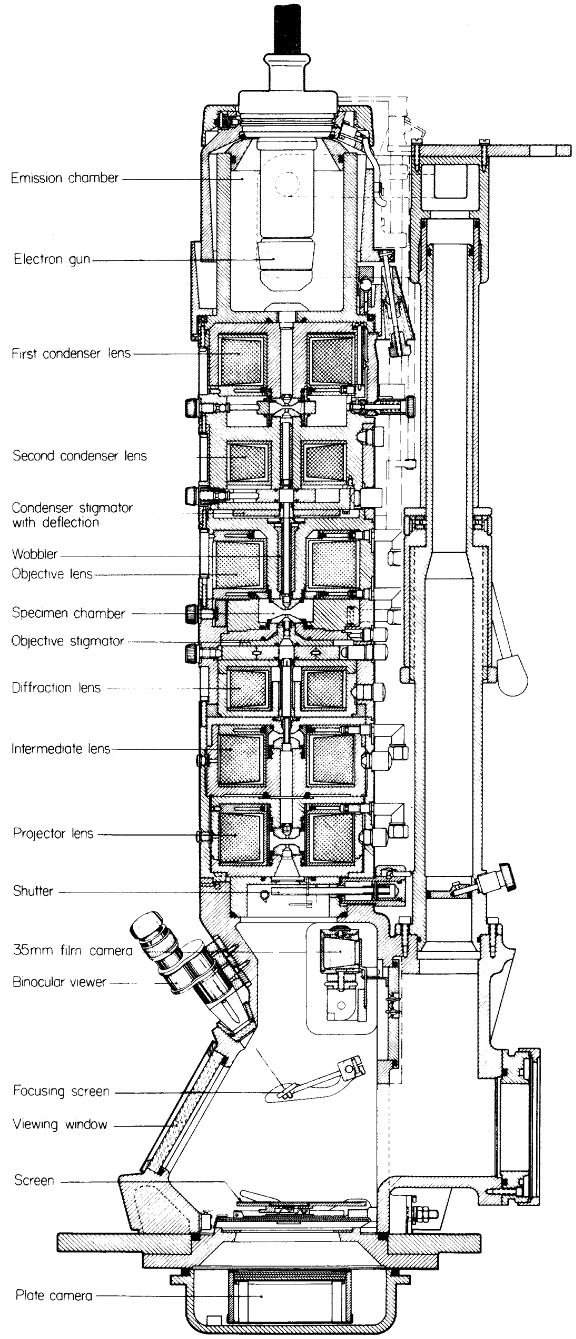
Light Microscope	Electron Microscope
- Specimen Environment -	
Nothing unusual	**High vacuum** (10^{-6} - 10^{-7} Torr) Specimen *usually* **dehydrated** (dead!)
- Beam Effects -	
None	Biological specimens **rapidly damaged**
- Magnification/Resolution -	
~1000X or less	~ 10,000 to 100,000X or more
~0.1 μm or worse	~ 0.3 nm (0.003 μm) or better
- Orientation of Components -	
Radiation source generally at **bottom**	Radiation source at **top**
- Price Tag -	
$1000s (not confocal)	$400,000 -> $5,000,000 or more!!!

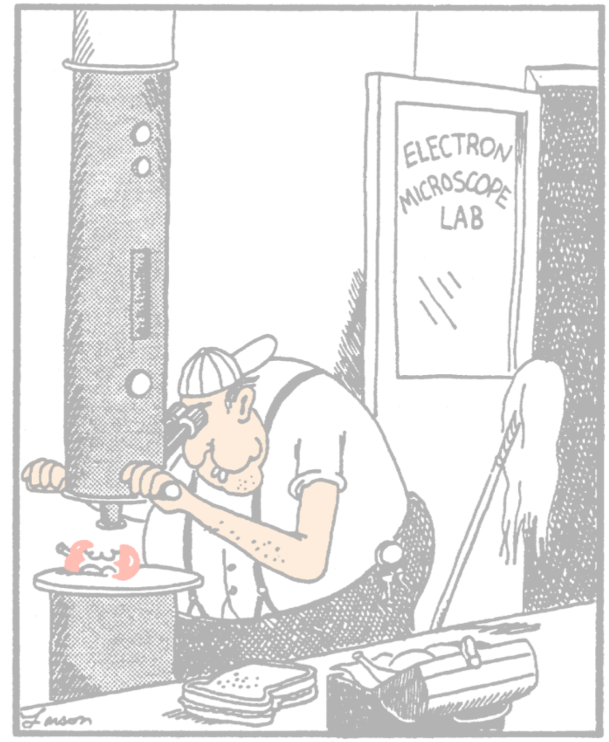


Electron Microscope



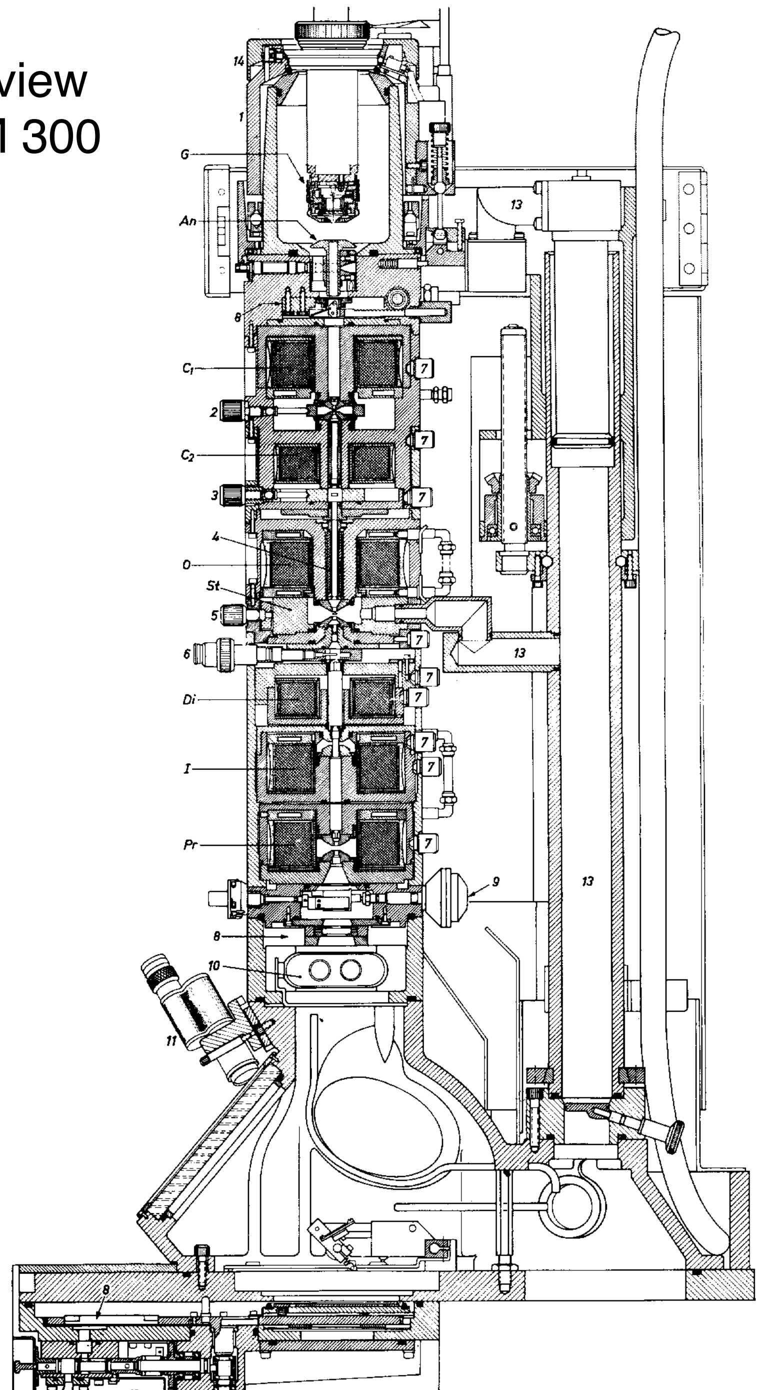
Cross-sectional view of the Philips EM 200

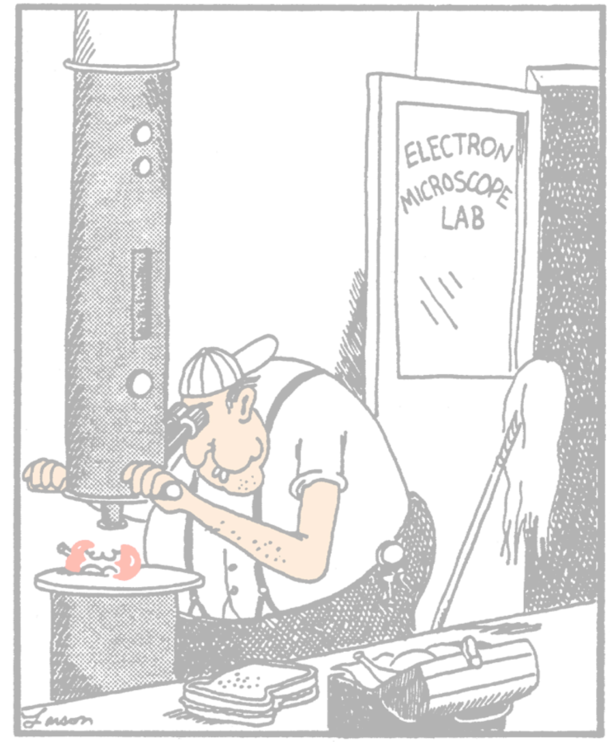




From Meek, Fig. 5.4b, p.99

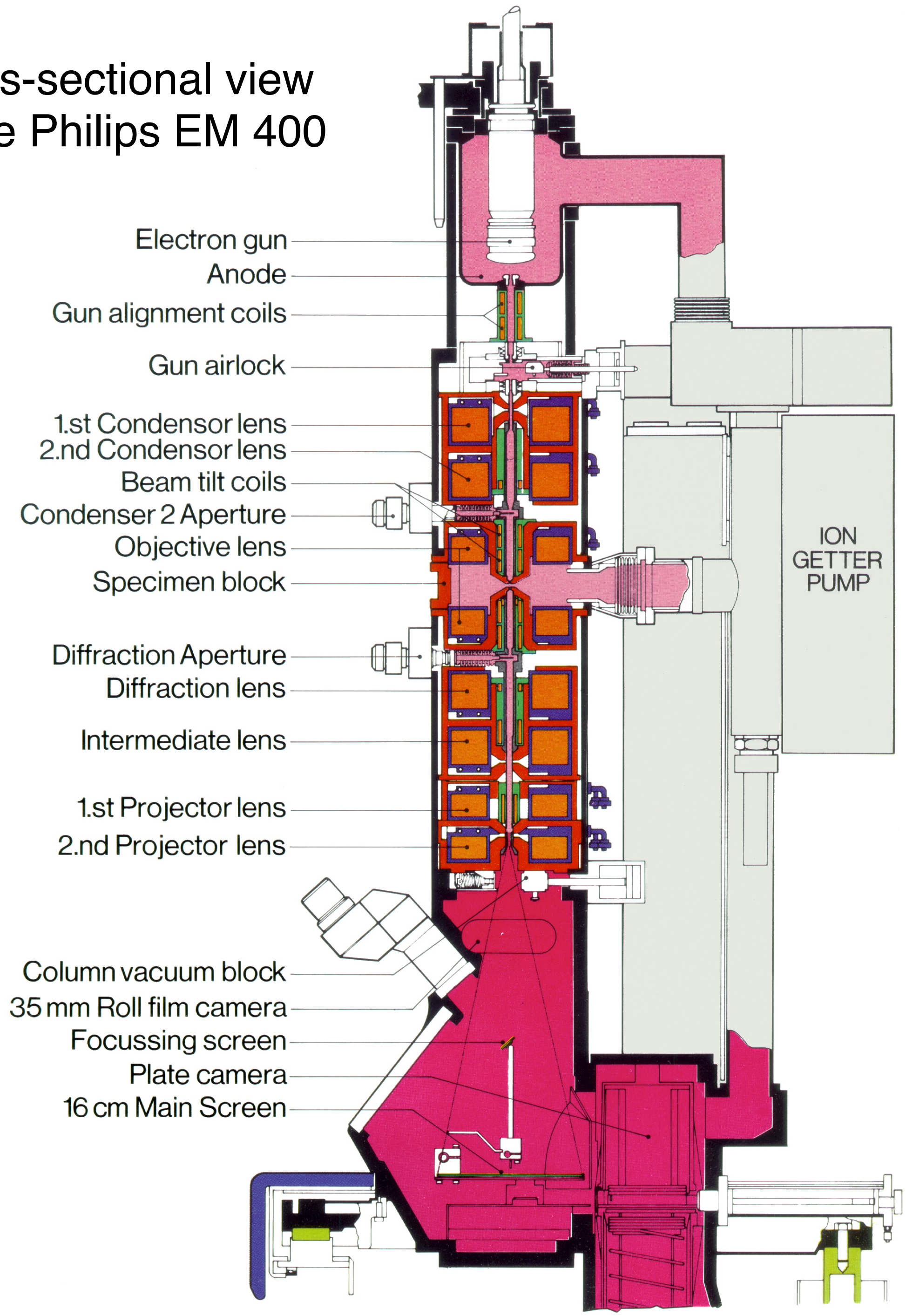
Cross-sectional view of the Philips EM 300

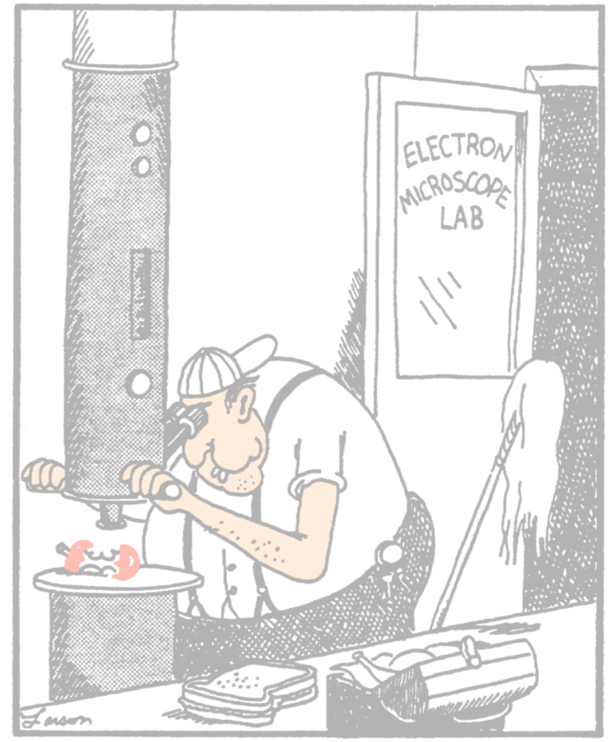




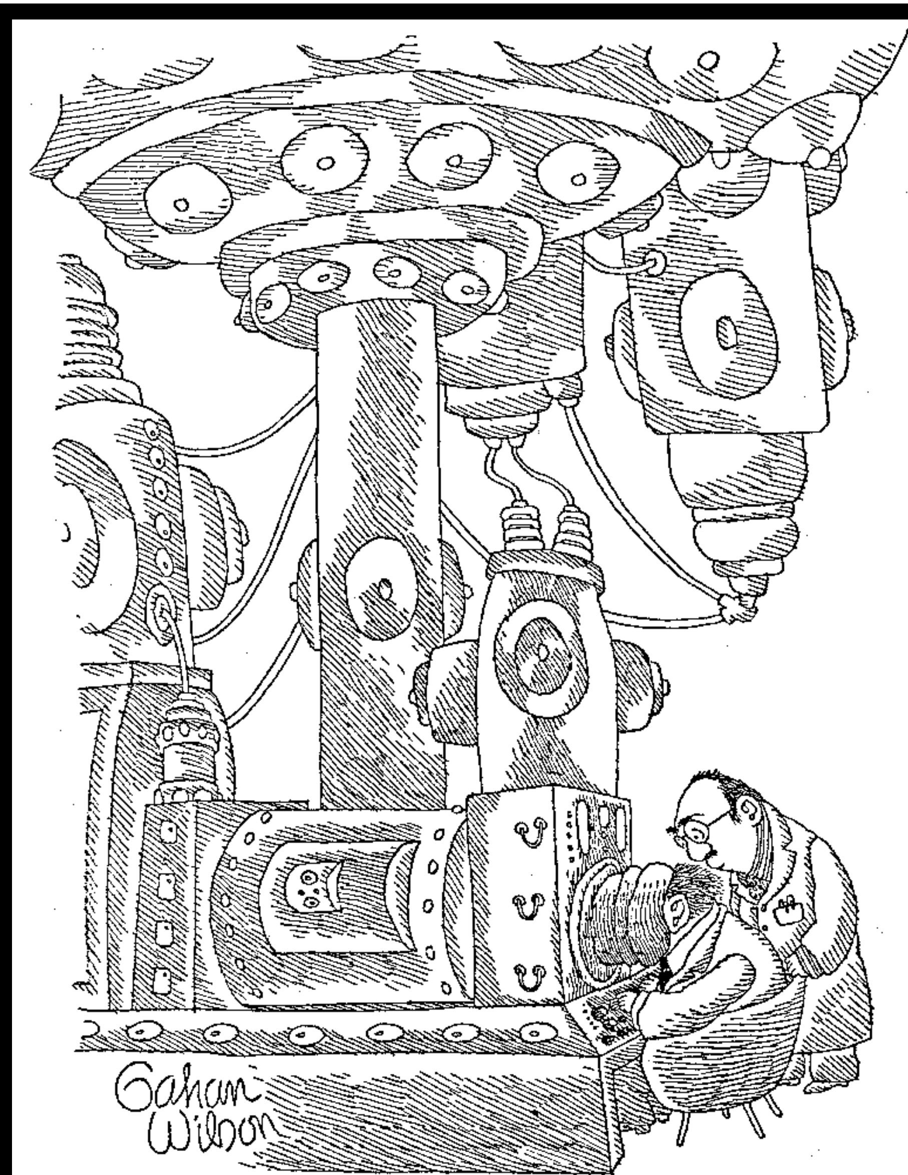
From Agar, Fig. 2.2, p.40

Cross-sectional view of the Philips EM 400



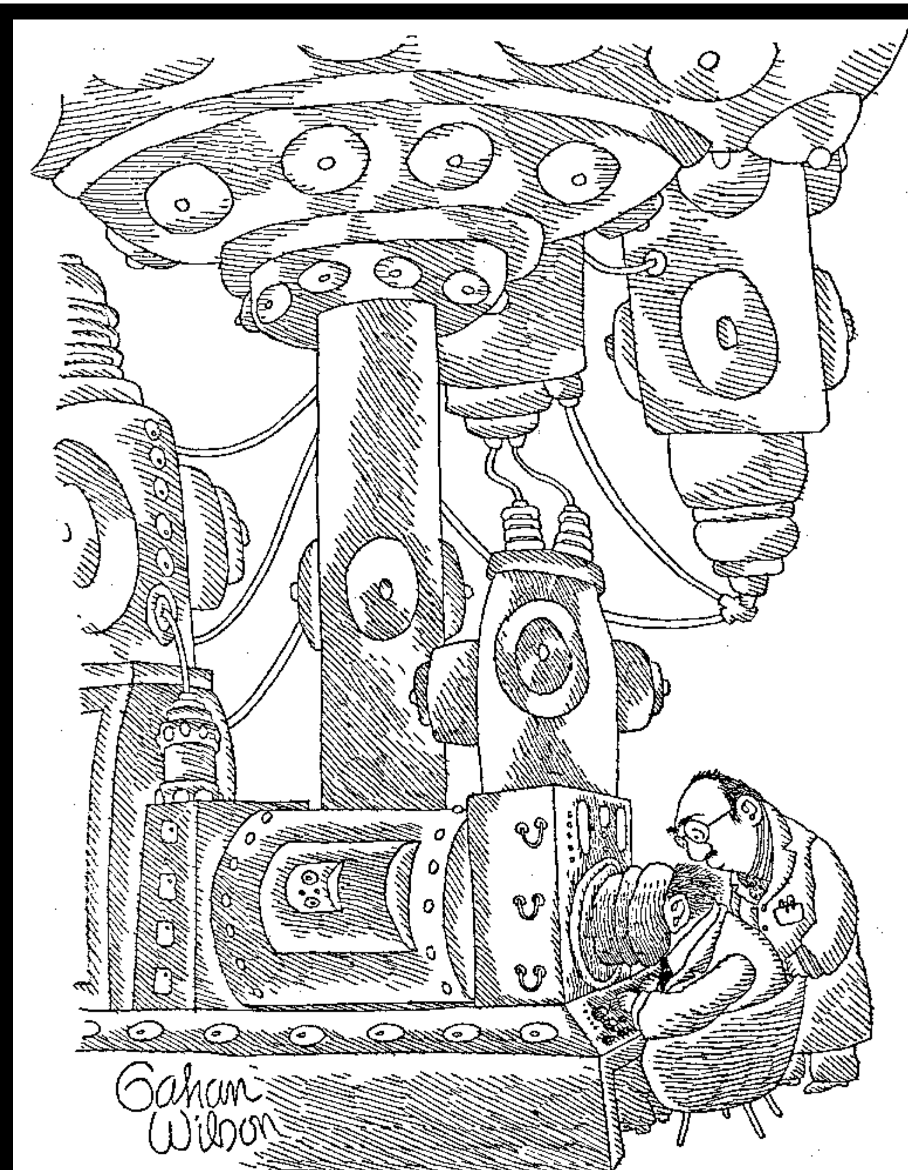


FEI Tecnai Polara 300kV, Helium stage



"I think I may have spotted something!"

FEI Titan 80-300kV



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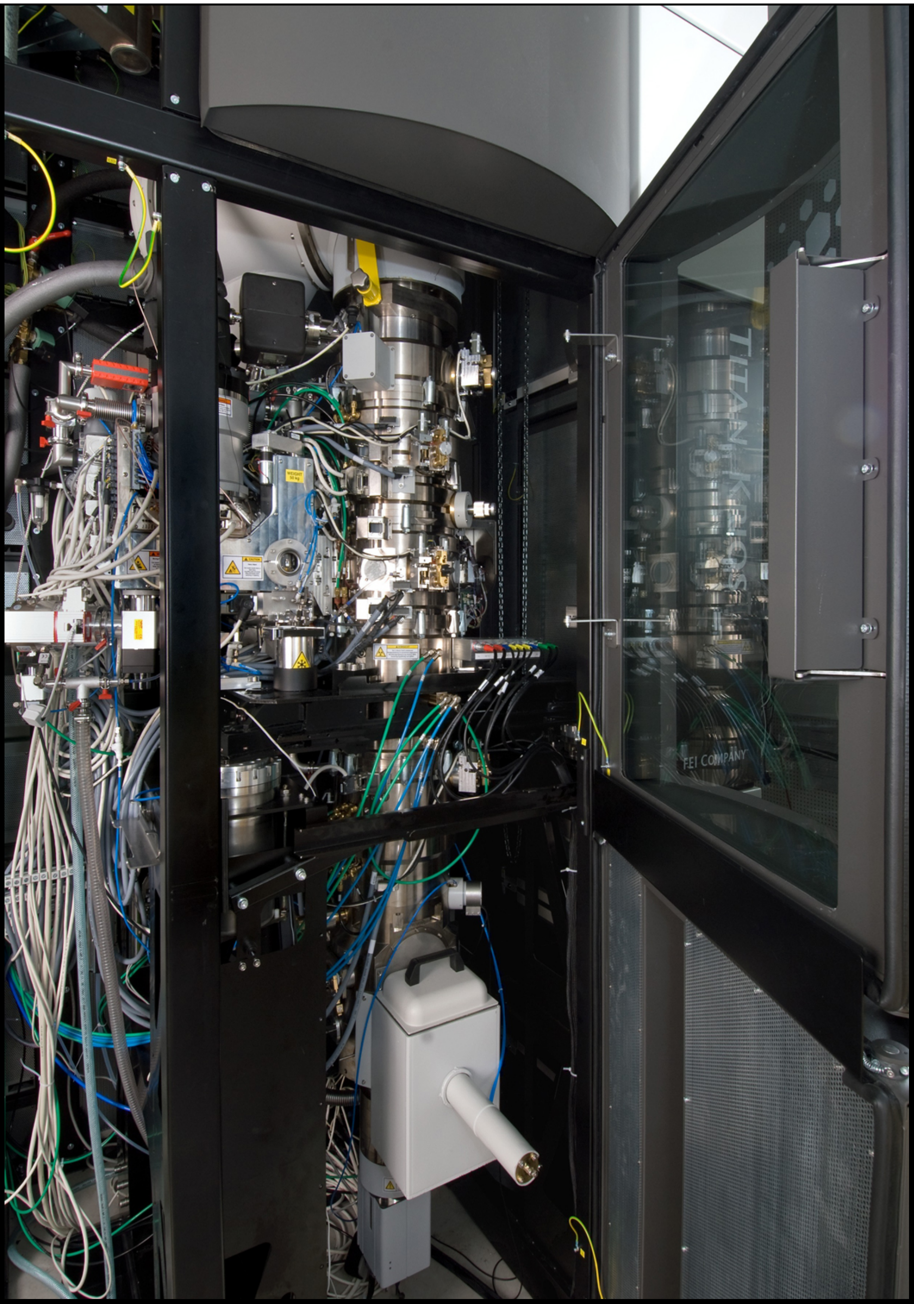


§ I: The Microscope

I.A Principles of TEM

I.A.3 Photons/Electrons

(pp.7-16 of lecture notes)

I.A.3 Photons/Electrons

KEY CONCEPTS

- Photons **and** electrons behave as particles **AND** waves

- **Any** moving particle has a **wavelength** associated with it

- **TEM: electrons** travel **very fast** (near speed of light) and have **very short** wavelengths

- **Diffraction:** path of radiation is bent by 'obstacles'

I.A.3 Photons/Electrons

I.A.3.a Dual Concept of Wave and Particle

Light (photons) has both particle **and** wave properties

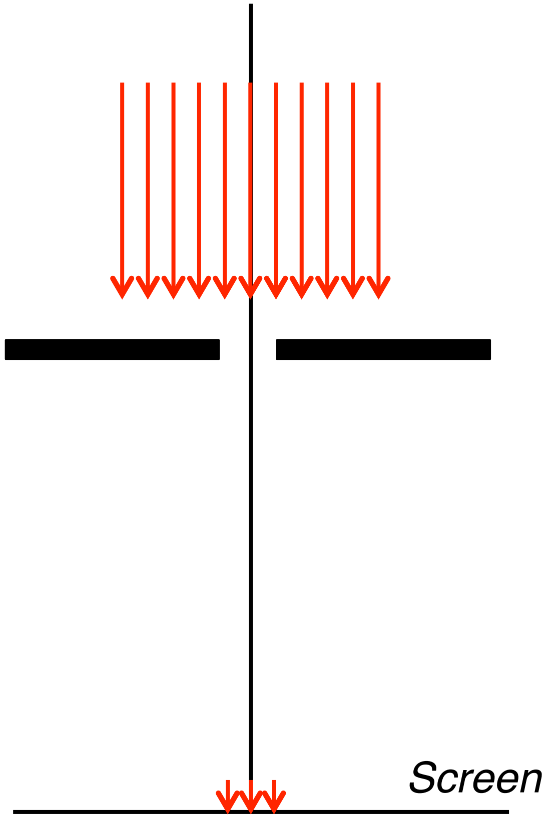
Electrons also exhibit particle **and** wave properties

Diffraction of light and electrons illustrates their wave nature

Diffraction refers to the **bending** of the path of radiation by 'obstacles'

I.A.3 Photons/Electrons

I.A.3.a Dual Concept of Wave and Particle

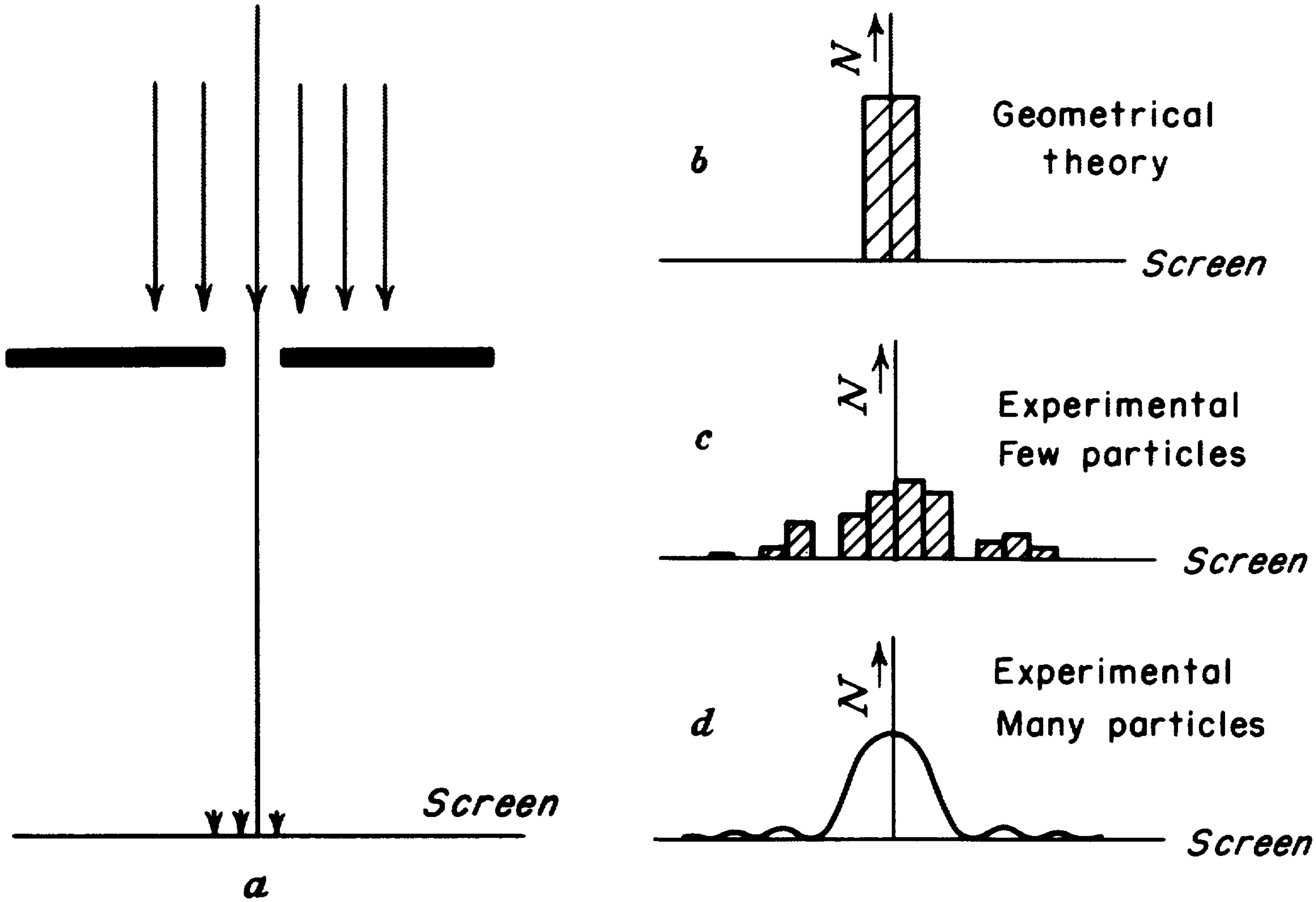


Adapted from Hall, Fig. 1.8, p.13

I.A.3 Photons/Electrons

I.A.3.a Dual Concept of Wave and Particle

Statistical Nature of Diffraction Patterns



From Hall, Fig. 1.8, p.13

I.A.3 Photons/Electrons

I.A.3.b Electron Velocity and Wavelength

DeBroglie (1924):

A particle of mass, *m*, moving at a velocity, v, has a wavelength (λ) given by:

$$\lambda = \frac{h}{mv}$$

DeBroglie wave equation
(h = Planck's constant)

Wavelength decreases as velocity increases

I.A.3 Photons/Electrons

I.A.3.b Electron Velocity and Wavelength

$$\lambda = \frac{h}{mv}$$

DeBroglie wave equation
(*h* = Planck's constant)

$$\frac{1}{2}mv^2 = eV$$

Kinetic energy of moving electron
(e = electron charge; V = voltage)

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

Solve above for velocity of electron

$$\lambda = \left(\frac{h}{m}\right) * \frac{1}{\sqrt{\frac{2eV}{m}}} = \sqrt{\frac{h^2}{2meV}}$$

λ inversely related to 1/*V*

$$\lambda = \sqrt{\frac{150}{V}} * 10^{-8}\, cm = \frac{1.23}{\sqrt{V}}\, nm$$

Plug in known constants
(lecture notes pp.8-9)

$$\lambda = \frac{1.23}{\sqrt{V + 10^{-6} V^2}}\, nm$$

Make Einstein happy

I.A.3 Photons/Electrons

I.A.3.b Electron Velocity and Wavelength

$$\lambda = \frac{1.23}{\sqrt{V + 10^{-6} V^2}} \, nm$$

(includes relativistic effects)

V	λ (nm)	*v* (x10^{-10} cm/sec)	*v/c*
10,000	0.0122	0.585	0.195
50,000	0.0054	1.237	0.414
100,000	0.0037	1.644	0.548
1,000,000	0.0009	2.822	0.941

TO SUMMARIZE THUS FAR:

Moving electrons behave as particles and waves (somewhat analogous to photons)

High voltage electrons move fast and have very short wavelengths

p-Flasher Question

Which of the following ***best*** describes an electron that has been accelerated through a voltage difference of 100,000 volts?

A) It moves faster than a speeding bullet (or superman)

B) It moves slower than a speeding bullet (or superman)

C) It moves a significant fraction of the speed of light

D) It moves 1.6 times the speed of light

I.A.3 Photons/Electrons

KEY CONCEPTS

- Photons **and** electrons behave as particles **AND** waves

- **Any** moving particle has a **wavelength** associated with it

- **TEM:** **electrons** travel **very fast** (near speed of light) and have **very short** wavelengths

- **Diffraction:** path of radiation is bent by 'obstacles'

- **Interference:** combination of diffracted and undiffracted waves

- **Resolution:** ability to distinguish objects or object details

- **Instrument resolution:** limited by wavelength of radiation

Ideal vs. Real Lenses

Ideal lens: images each point in an object as a point in the image plane

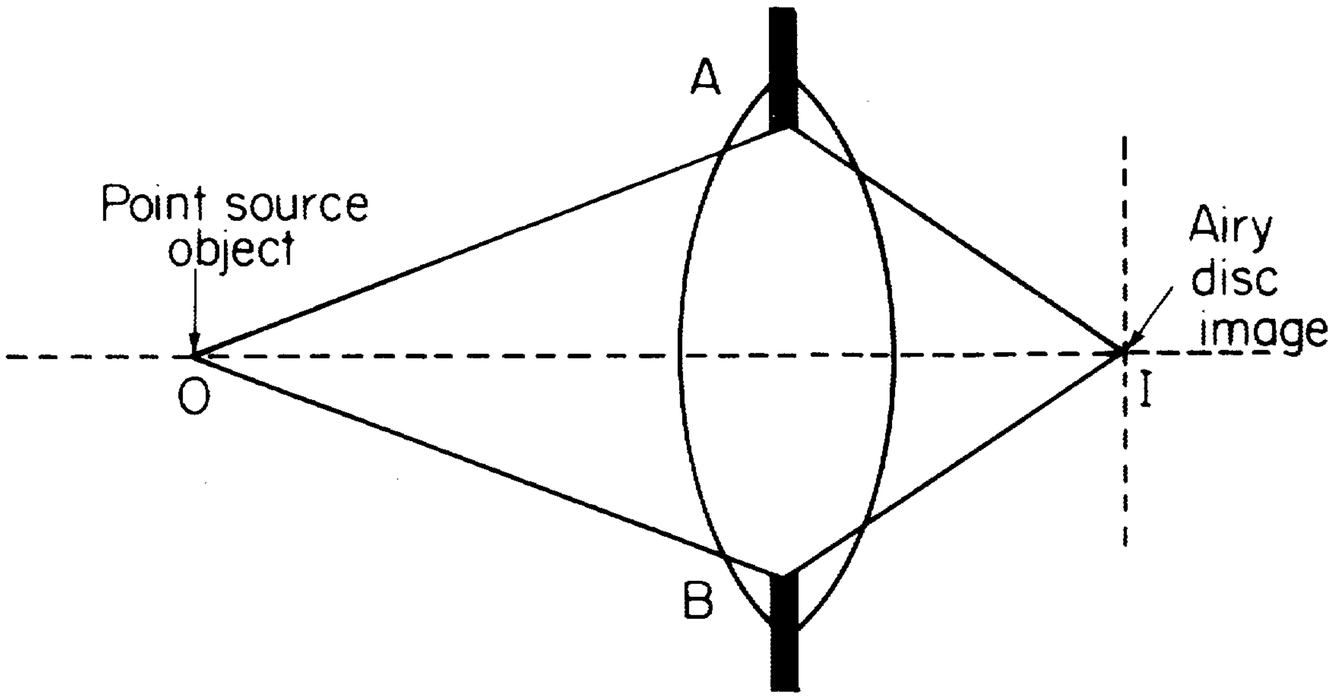
Real lens: images each point in an object as an Airy disk in the image plane

I.A.3 Photons/Electrons

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

IDEAL LENS: takes each point in an object and represents it **exactly** as a point in the image.

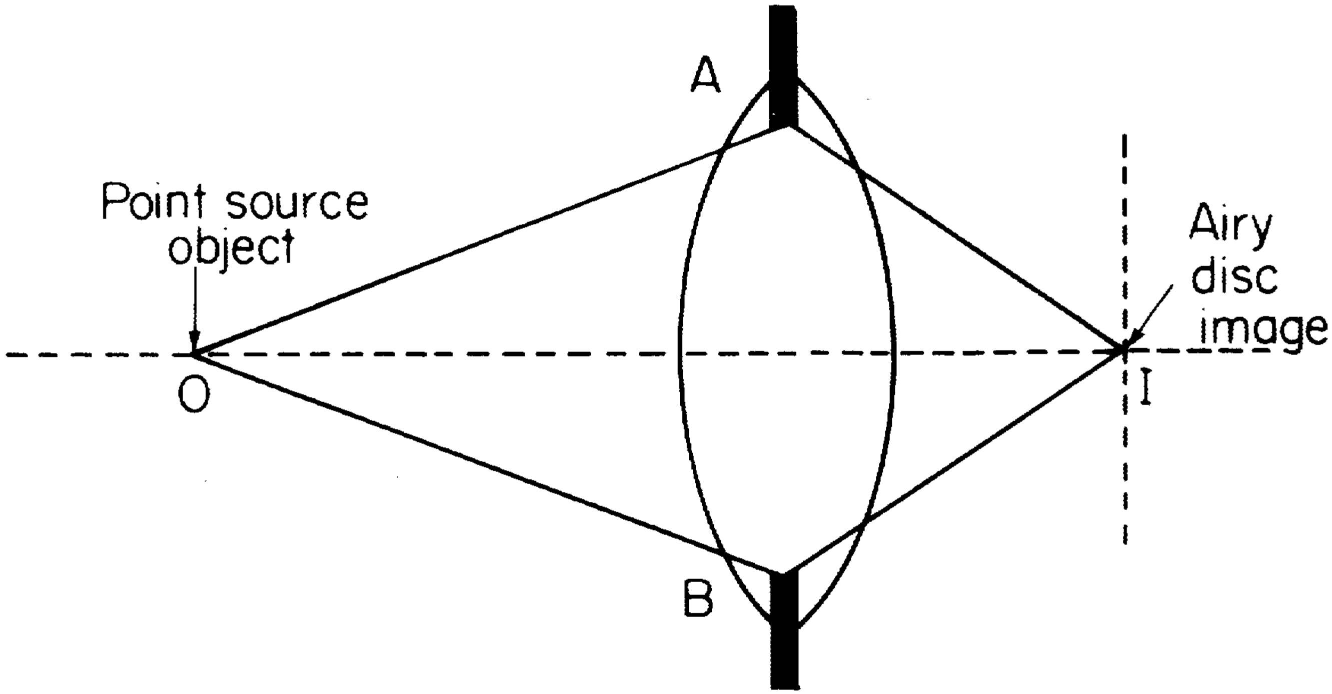
REAL LENS: takes each object point and spreads it out into a circular disk (**Airy disk**) in the image plane.

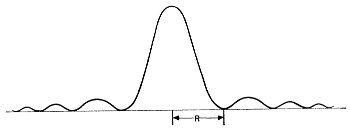


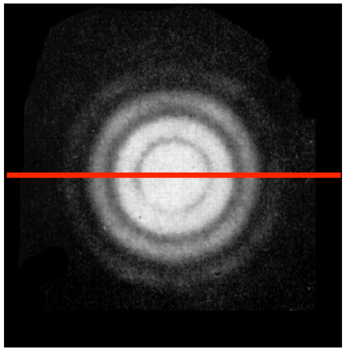
From Meek, 1st ed., Fig. 1.22, p.35

I.A.3 Photons/Electrons

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







Airy disk image is caused by interference of radiation diffracted by the lens aperture.

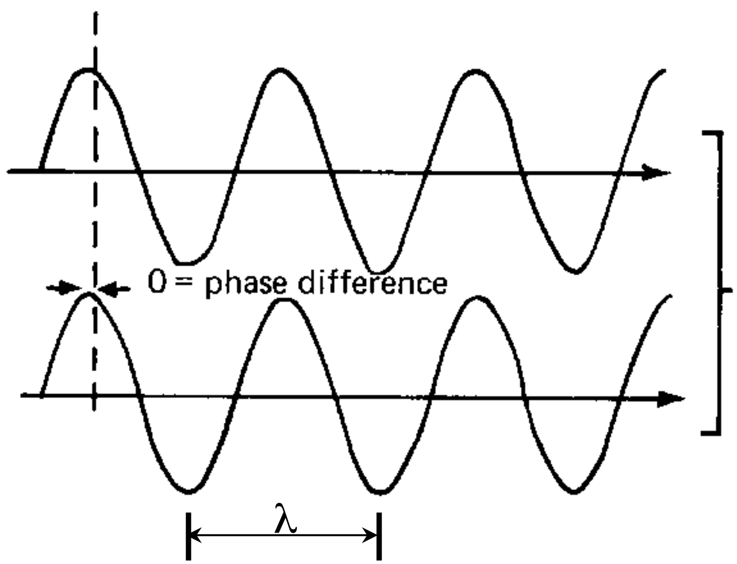
Size (diameter) of Airy disk depends on the size of the aperture.

From Meek, 1st ed., Fig. 1.22, p.35
and Sjostrand, Fig. IV.18, p.115

I.A.3 Photons/Electrons

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

Effects of waves interfering (combining) with each other

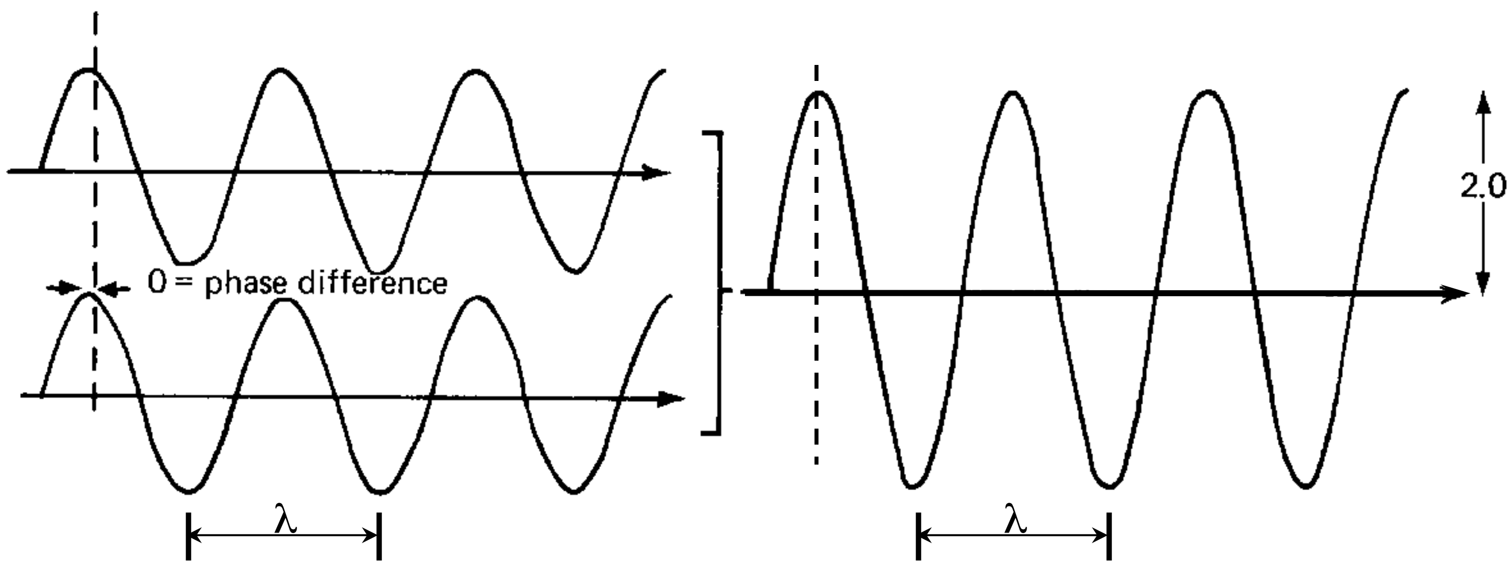


From Glusker and Trueblood., Fig. 5, p.19

I.A.3 Photons/Electrons

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

Effects of waves interfering (combining) with each other



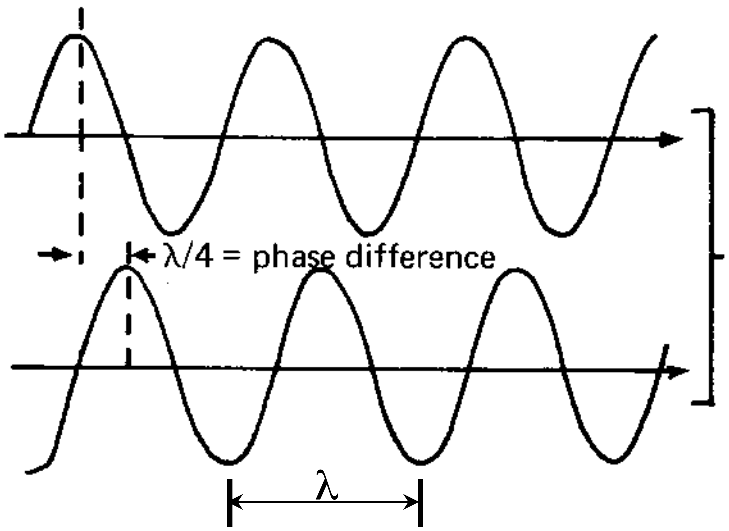
Total constructive interference
"In phase"

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

I.A.3 Photons/Electrons

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

Effects of waves interfering (combining) with each other



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

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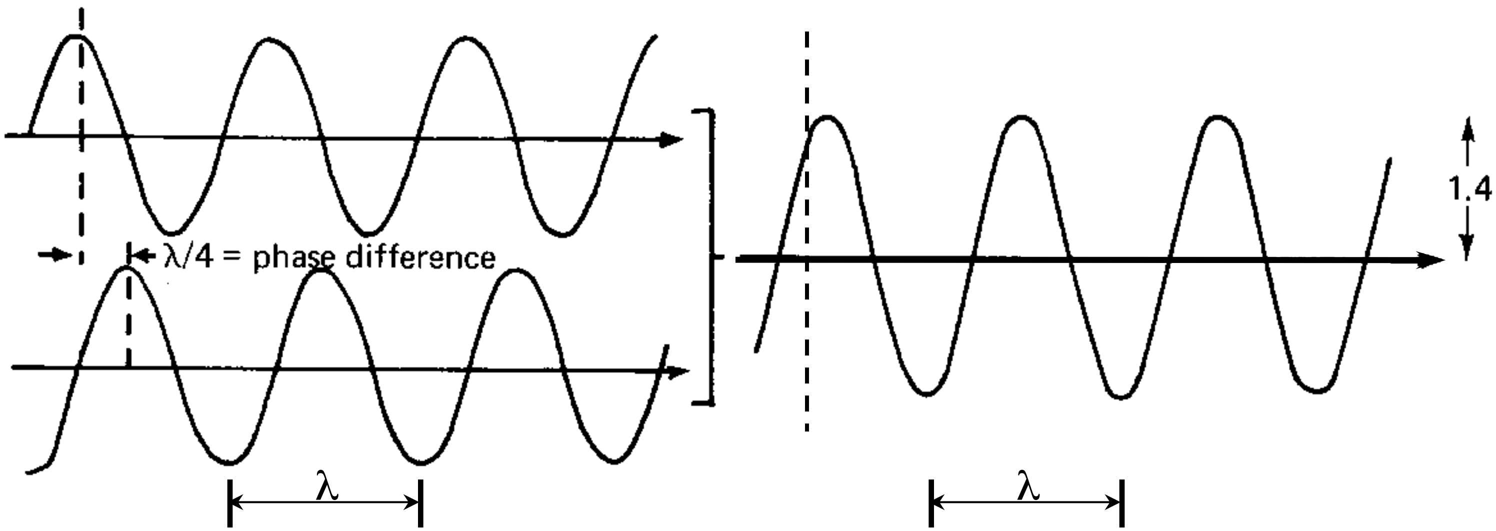


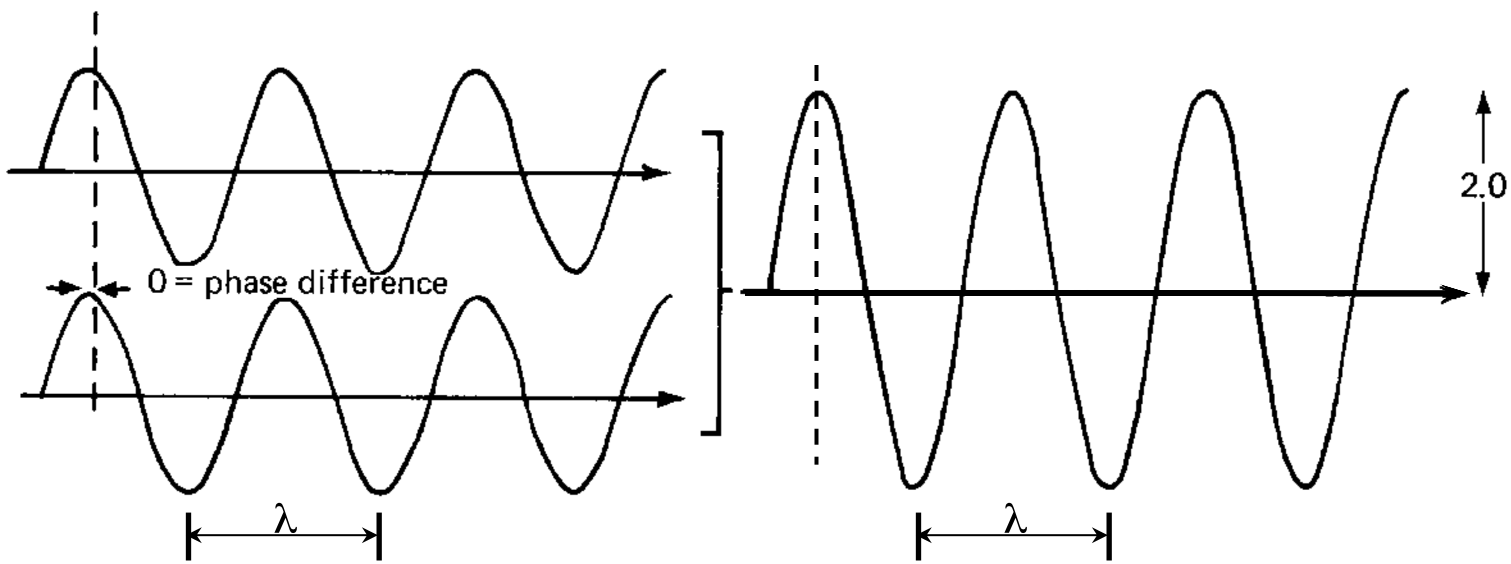
Partial destructive interference

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

I.A.3 Photons/Electrons

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

Effects of waves interfering (combining) with each other



Total constructive interference
"In phase"

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

I.A.3 Photons/Electrons

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

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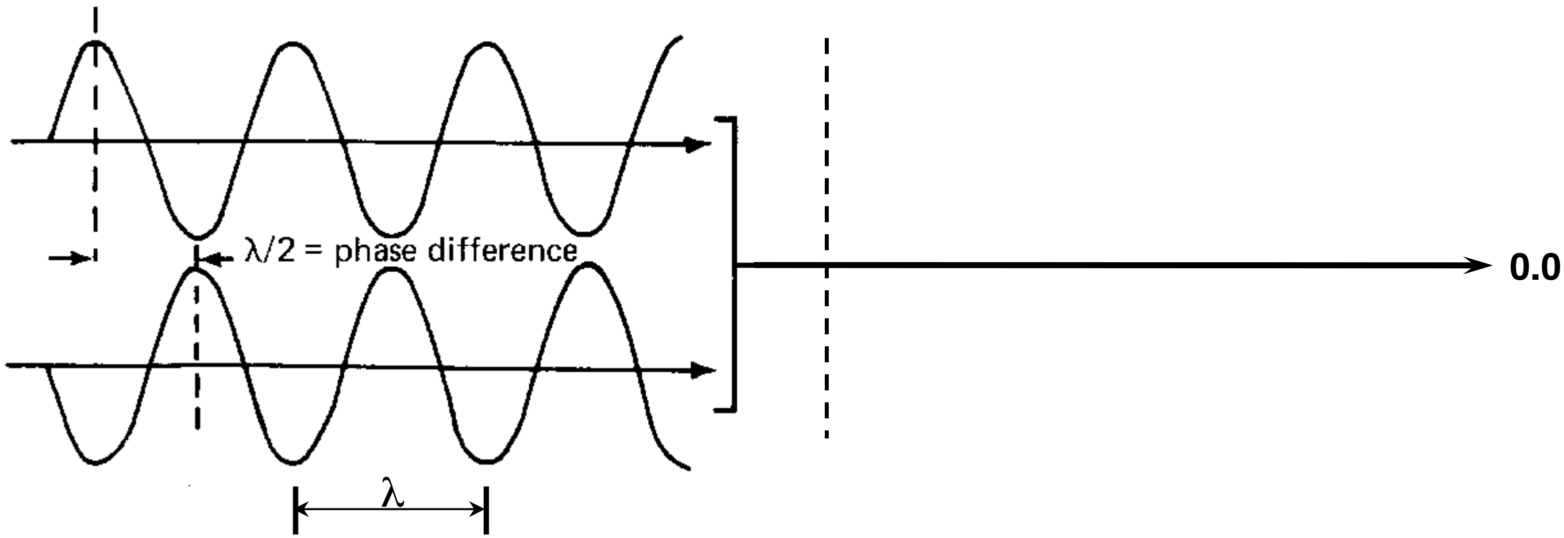
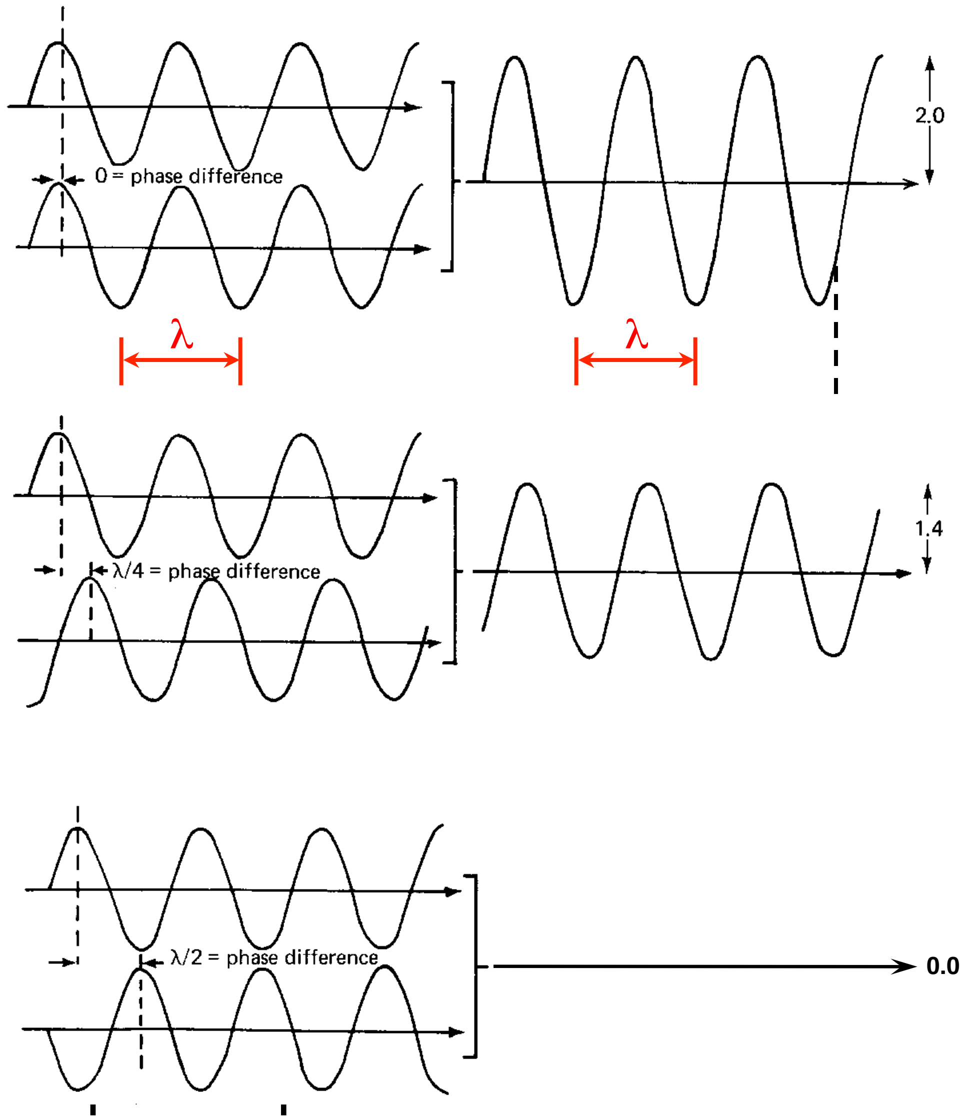


Total destructive interference
"Out of phase"

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

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

Effects of waves interfering (combining) with each other



Total constructive interference
"In phase"

Partial destructive interference

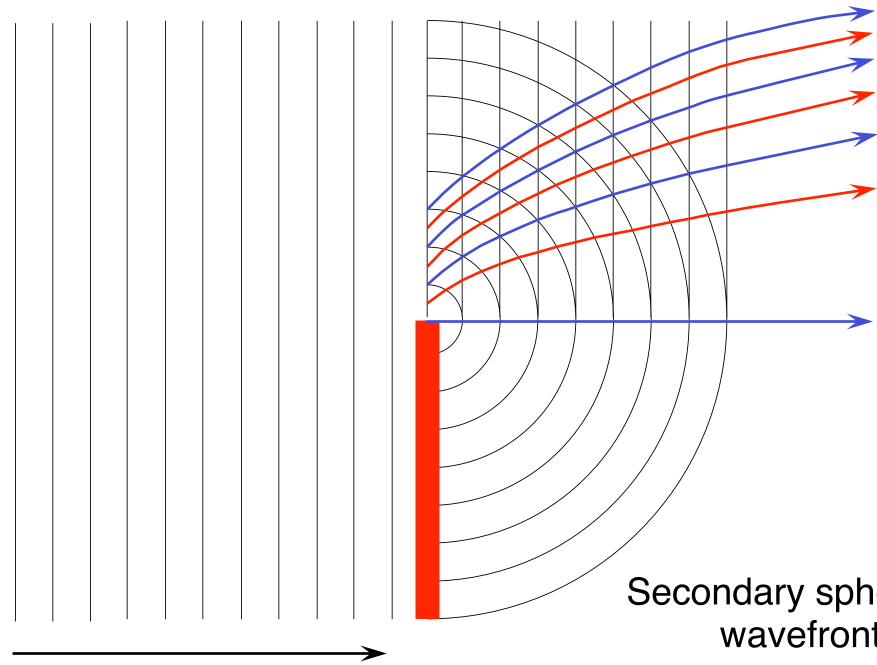
Total destructive interference
"Out of phase"

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.



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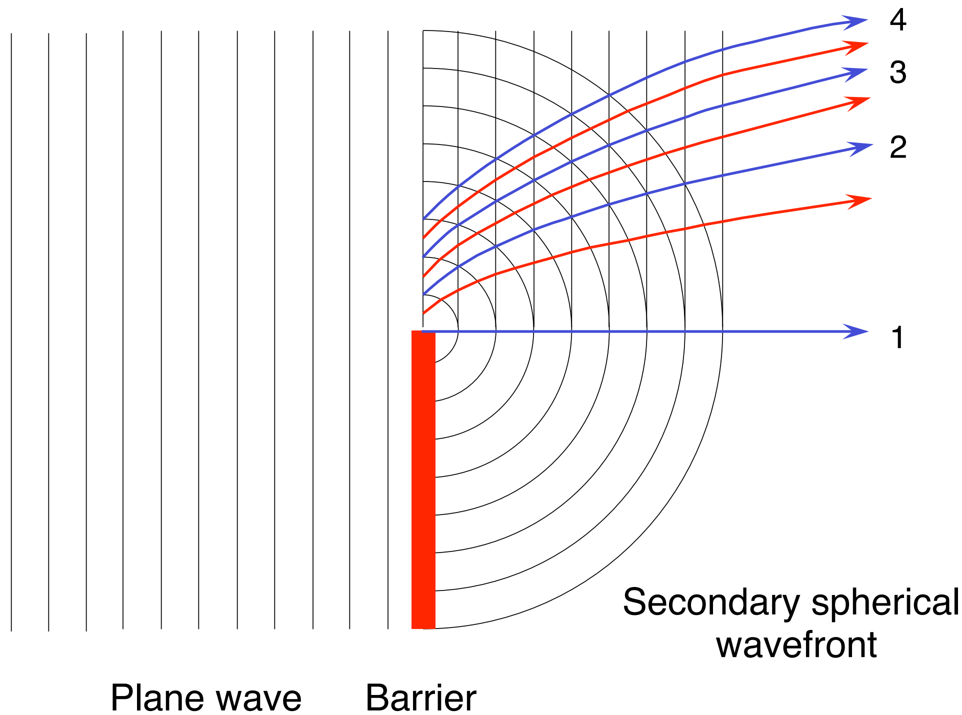

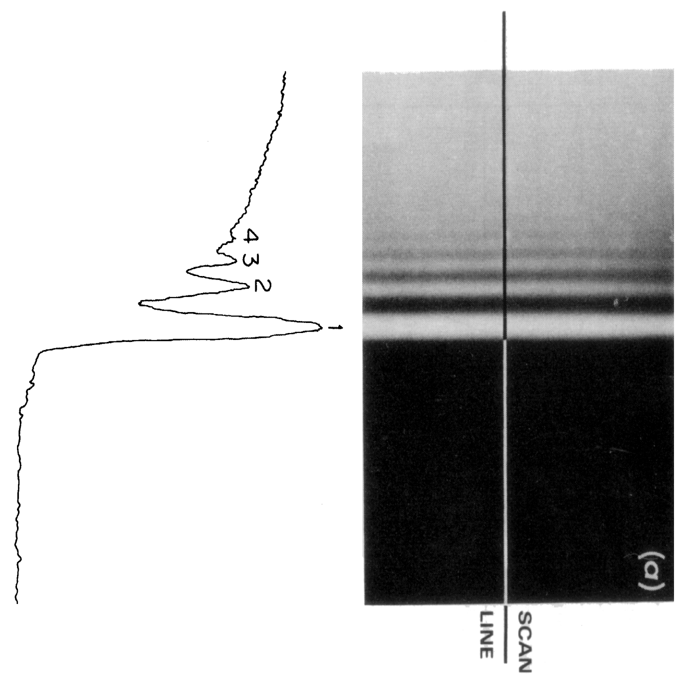

From Meek, 1st ed., Fig. 1.18, p.27