ELECTRON MICROSCOPY

14:10 – 17:00, Mar. 8, 2018
14:10 – 17:00, Mar. 15, 2018
P101, Institute of Physics, Academia Sinica

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References:

Optics, in any standard freshman or high school physics course.

"Transmission Electron Microscopy" D.B. Williams and C. B. Carter, 1996, Plenum.

"Scanning Electron Microscopy and X-ray Microanalysis" J.I. Goldstein, D.E. Newbury, P. Echin, D.C. Joy, C.E. Lyman, E. Lifshin, L. Sawyer, and J.R. Michael, 3rd ed, 2003, Kluwer/Plenum.

"Diffraction Physics" J.M. Cowley, 3rd ed, 1995, North-Holland.

"Electron Microscopy of Thin Crystals" P. Hirsch, A. Howie, R.B. Nicholson, D.W. Pashley, and M.J. Whelan; 2nd ed., 1977, Robert E. Krieger.

"Practical Electron Microscopy in Materials Science" J. W. Edington, l976, Van Nostrand Reinhold.

"Procedures in Electron Microscopy", eds. A.W. Robards and A.J. Wilson, 1996 (or later), Wiley.

"Atlas of Optical Transforms" G. Harburn, C.A. Taylor, and T. R. Welberry; 1967, Cornell University.

“DigitalMicrograph”, Gatan, Inc.

Outline:

Introduction

The Electron microscope

Principle of image formation

Diffraction

Specimen preparation

Contrast/Applications

Scanning electron microscopy

Electron microprobe / Analytical electron microscopy

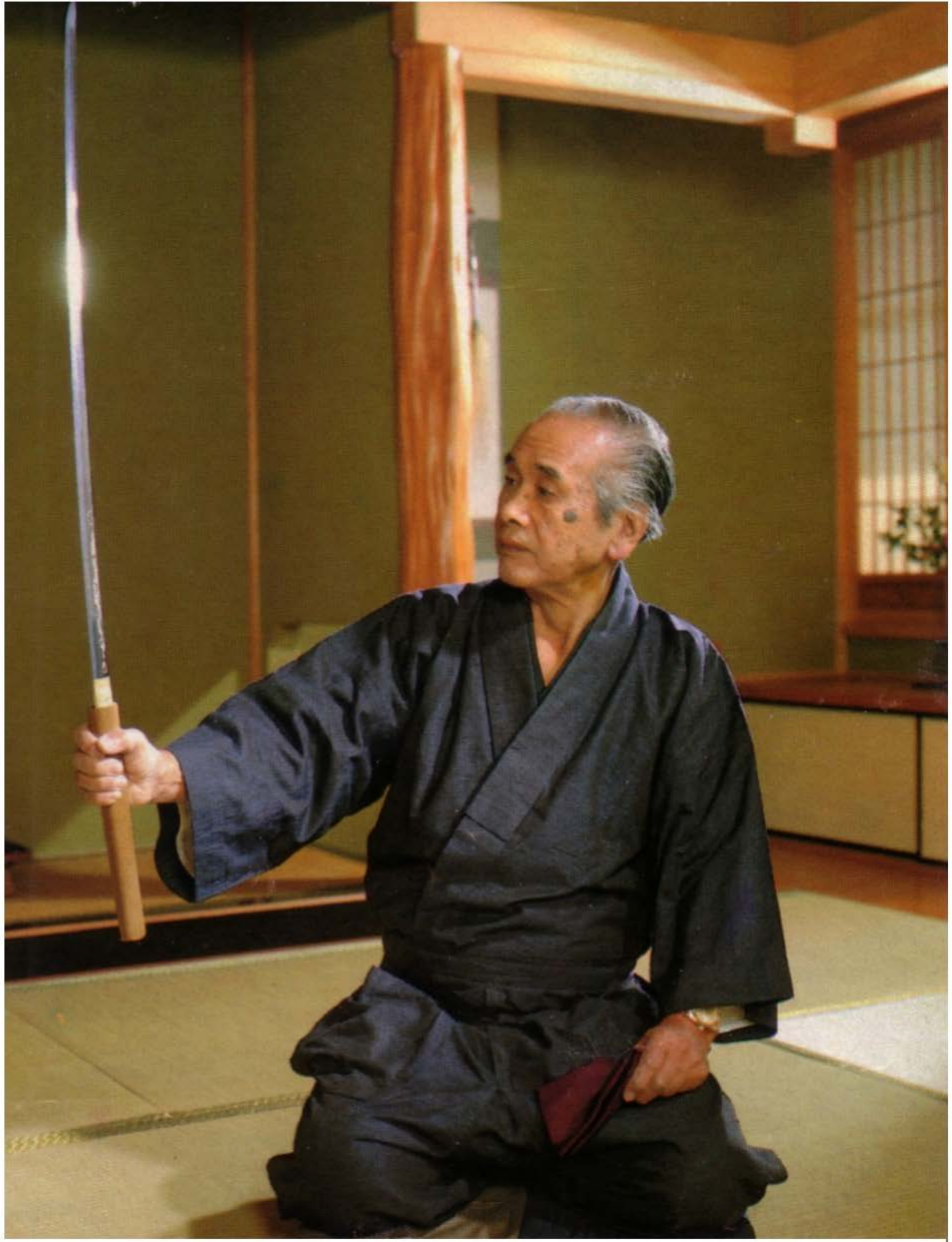
Introduction:

Why electron microscopy?

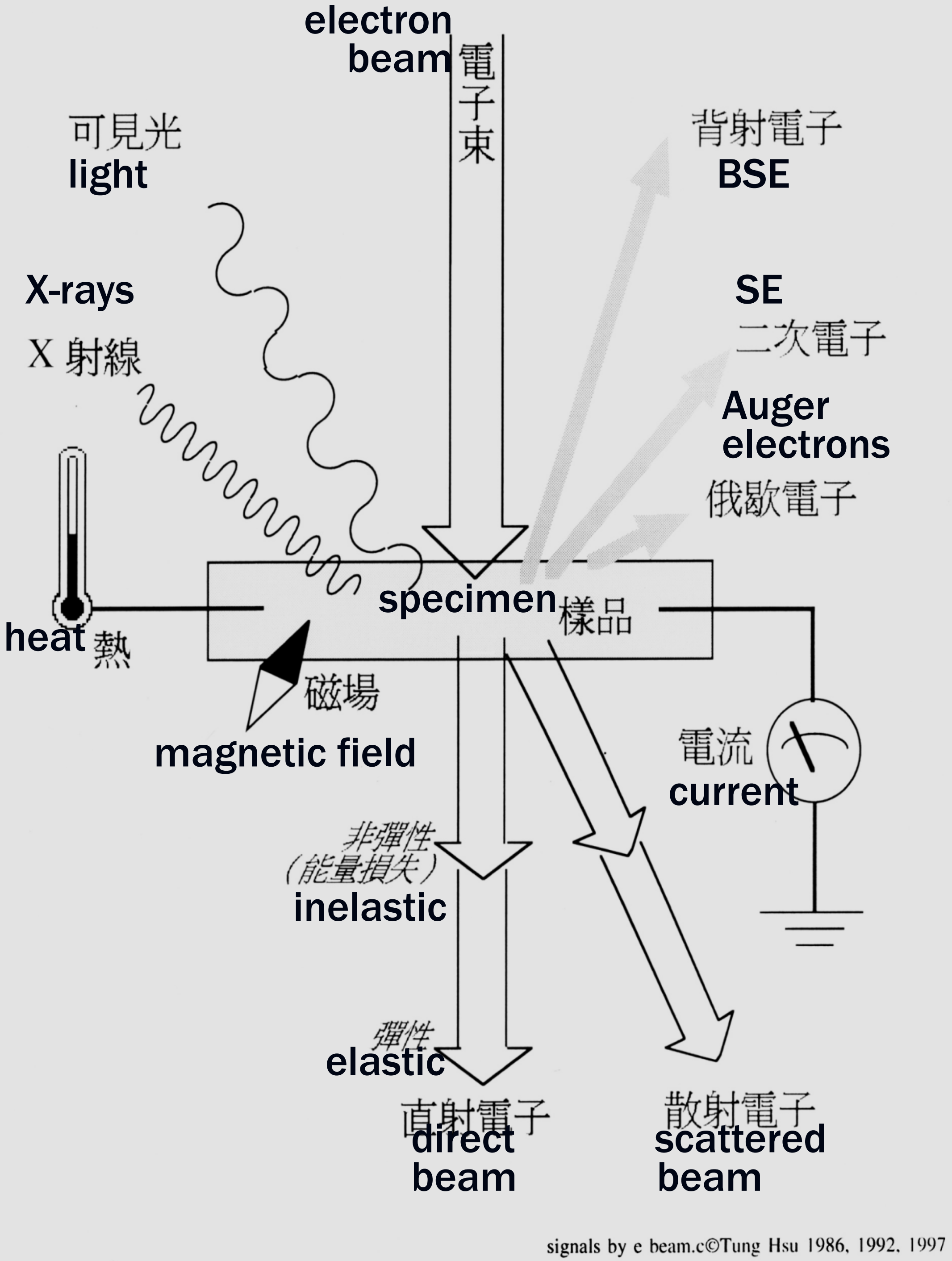
- Sensitivity:
  - Beam/solid (specimen) interaction
- (Spatial) Resolution:
  - Microscopy vs. microprobe
  - Wavelength, properties of lens

Information other than the image

A brief history of electron microscopy



Traditional materials characterization:
incidence beam (probe): photon
exit beam (signal): photon
detector: eye
processor/storage: brain
(ref. Taiyo)



Why electron microscopy (EM)?

Information obtainable from EM

Beam/solid interaction

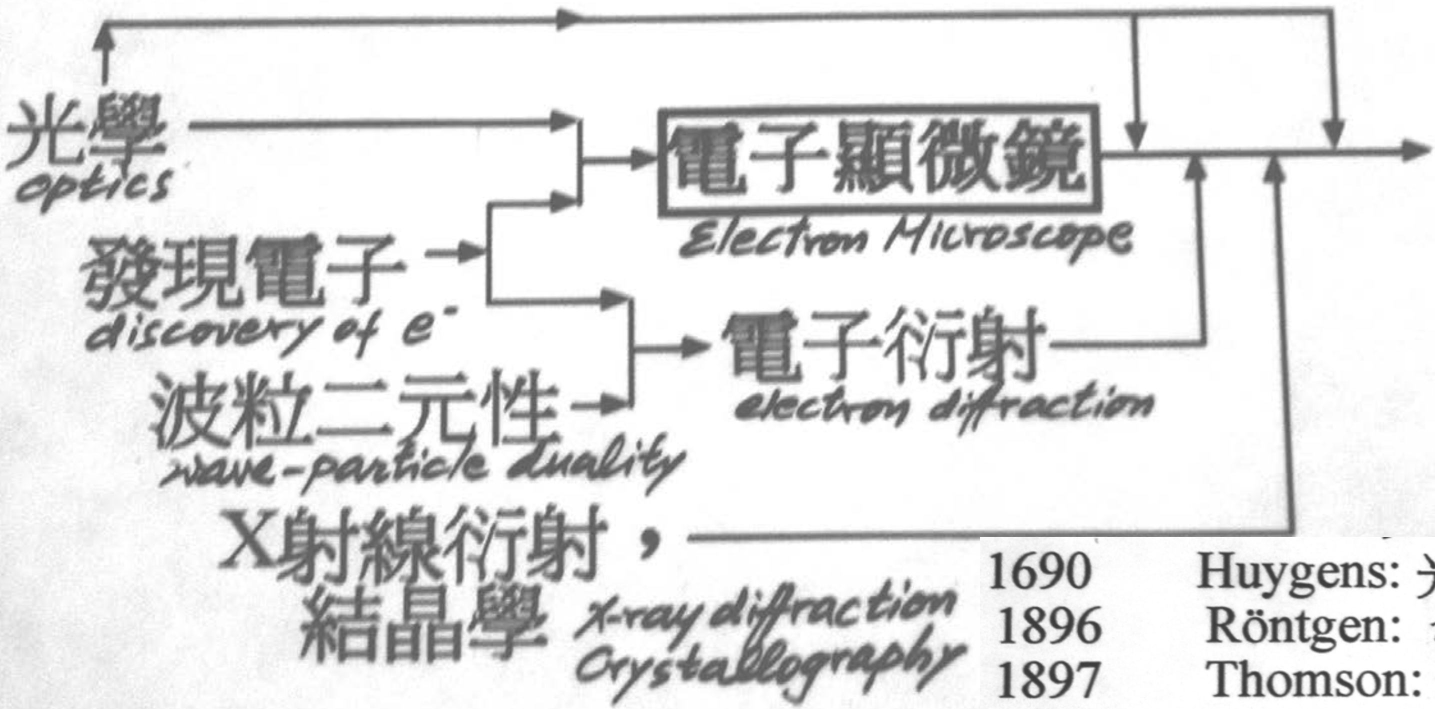
- image: morphology
  - scattering power
  - crystal structure
  - crystal defects
  - atomic structure
- other than the image:
  - (chemical) elemental composition
  - electronic structure

(Spatial) Resolution:

- Microscopy vs. microprobe
- Wavelength, properties of lens

電子顯微鏡的早期歷史

The early history of electron microscopy



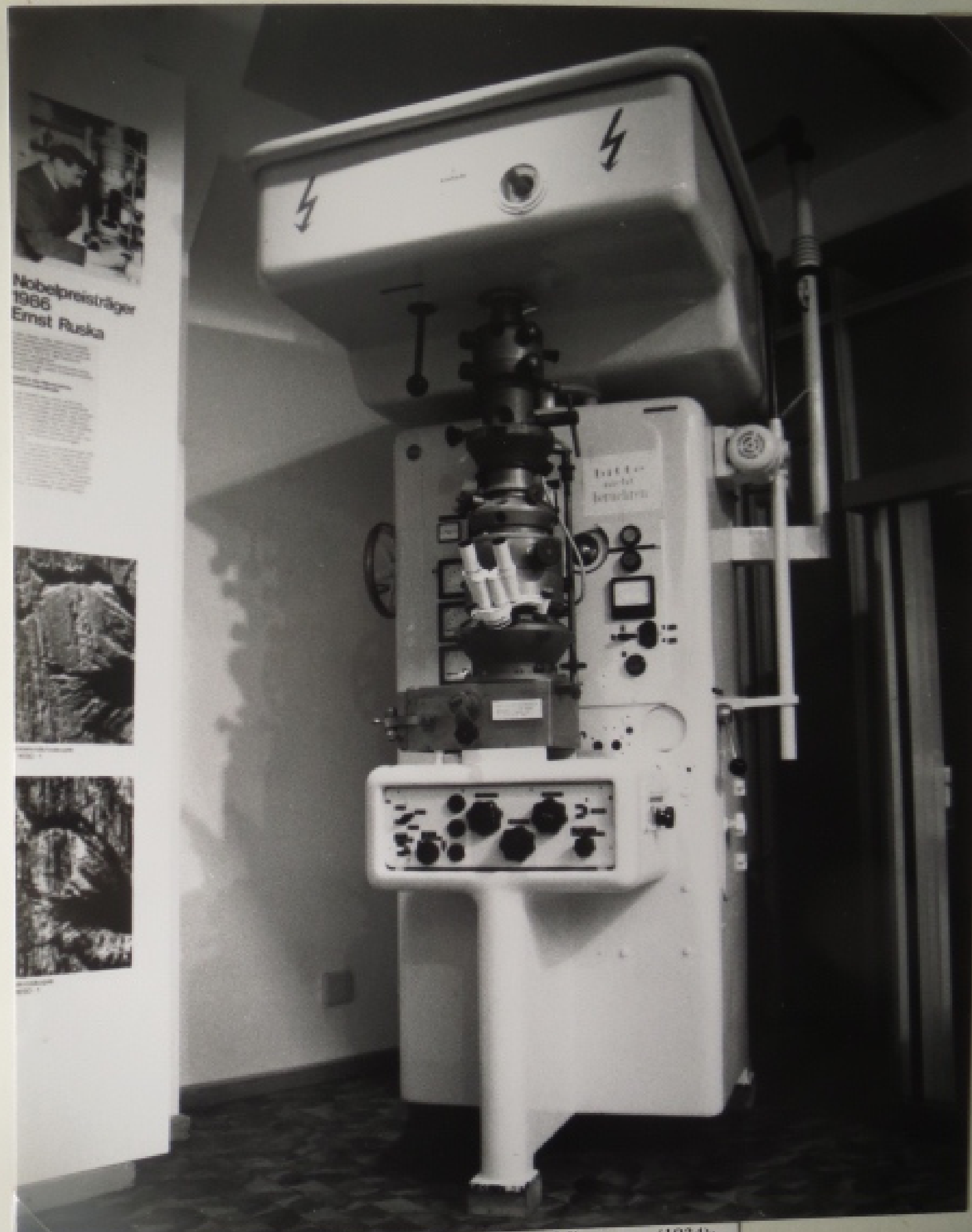
More recent:

computer
aberration correction
digital imaging
environmental
dynamic/high speed

1690	Huygens: 光波，衍射 light waves, diffraction
1896	Röntgen: 發現X射線 discovery of X-rays
1897	Thomson: 發現電子 discovery of electrons
1913	Bragg and Bragg, von Laue: X射線衍射 X-rays diffraction
1924	de Broglie 波 matter waves
1926	Schödinger 方程式 equation
	Busch: 電子束聚焦 focusing of electron beam
1927	Davisson & Germer, Thomson: 電子衍射 electron diffraction
1931	Ruska & Knoll: 鐵心磁鏡 iron core magnetic lens
1934	完成電子顯微鏡 electron microscope

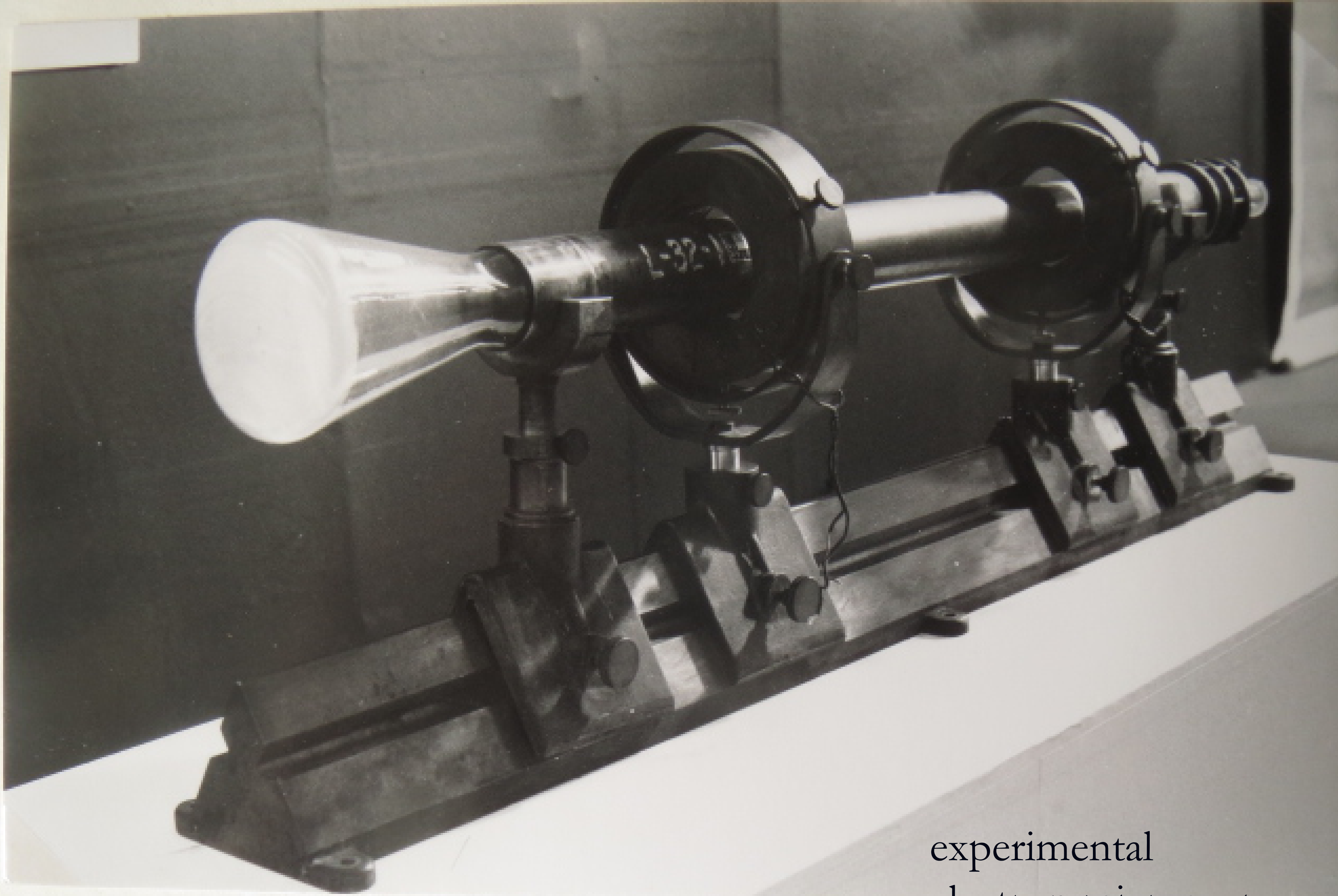
Various Electron Microscopes

first
electron microscope,
(replica)

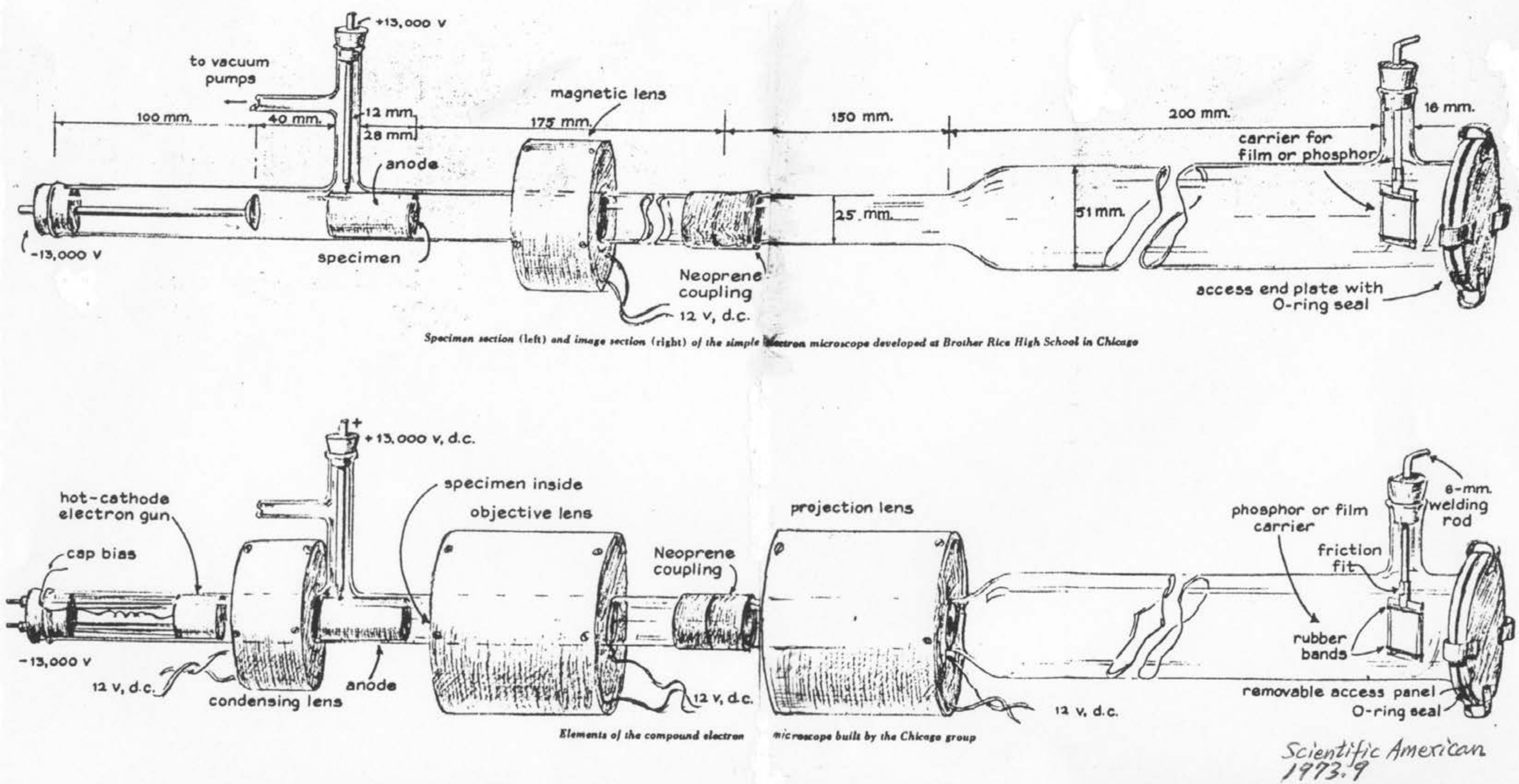


Ruska's Commercial Electron Microscope (1934);
Museum f. Verkehr u. Technik, Berlin; 1987.

first commercial electron microscope, 1934

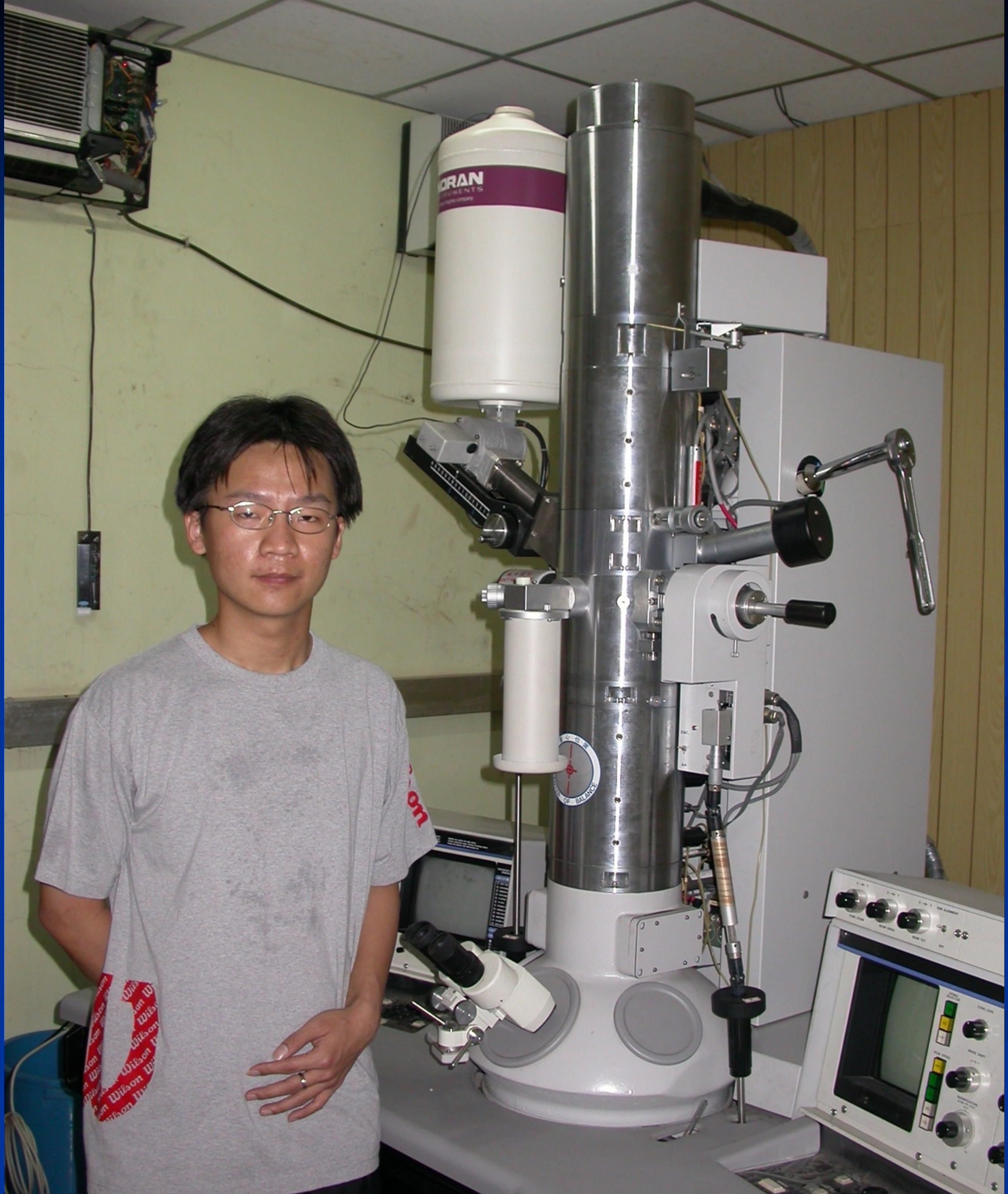


experimental
electron microscope,
1940s, Japan



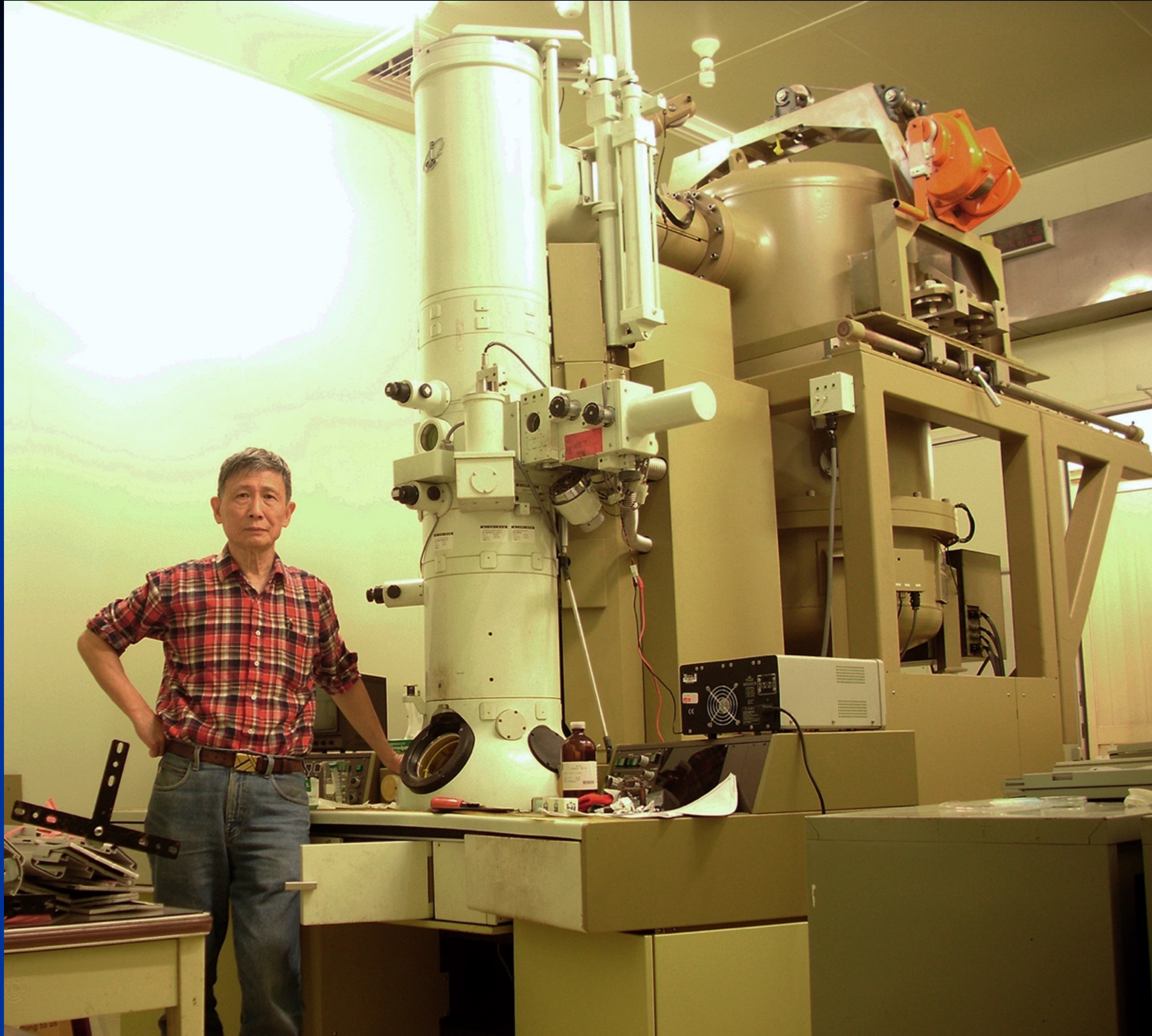
Experimental electron microscope,
Loyola High School, Chicago

Hitachi H-600
NTHU, 2008



JEOL
JEM-4000EX

NTHU, 2016
After retirement of machine and man



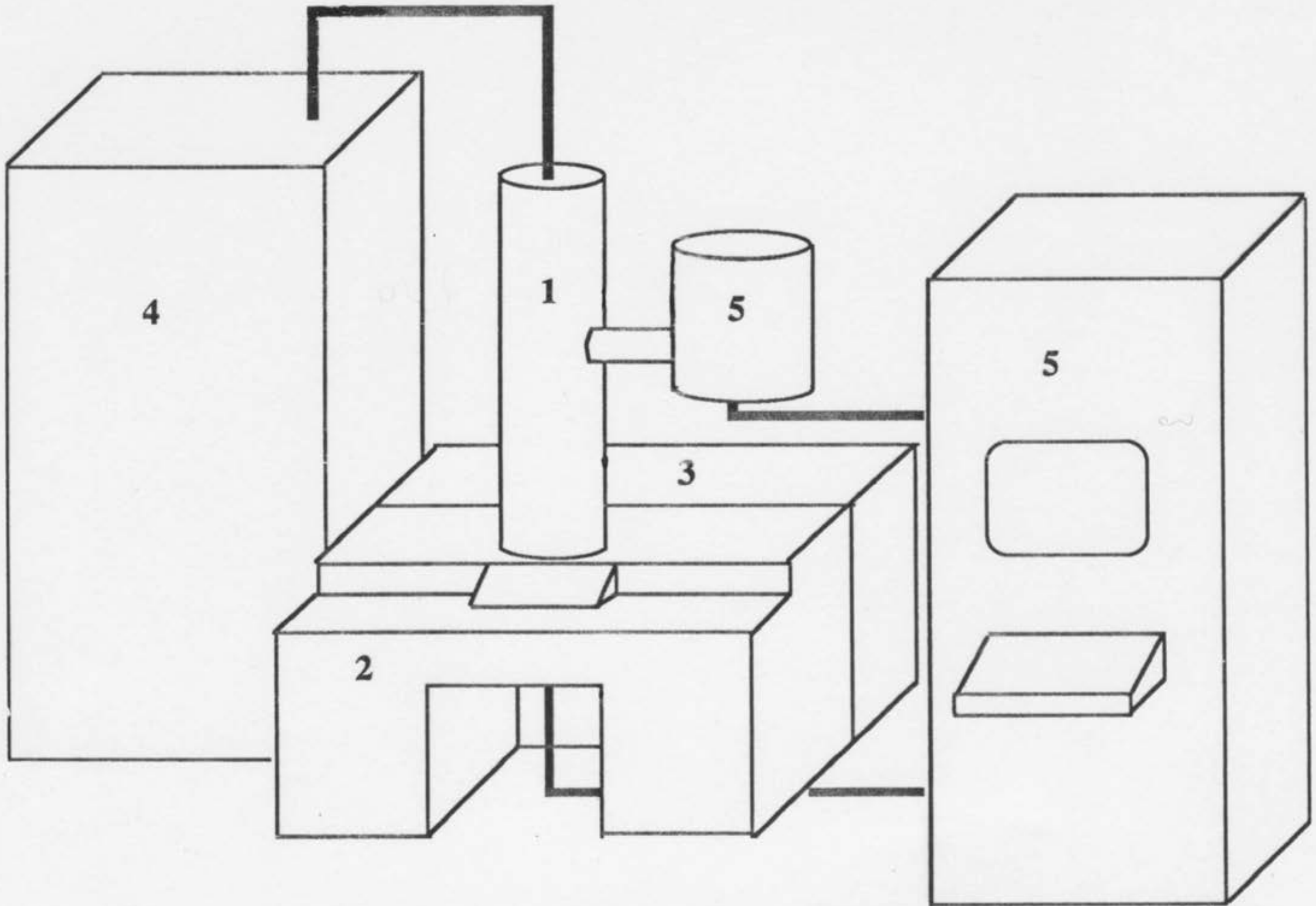
JEOL
JEM-ARM1250/1000

scanning
electron
microscope

UC Berkele
ca. 1973

the electron microscope

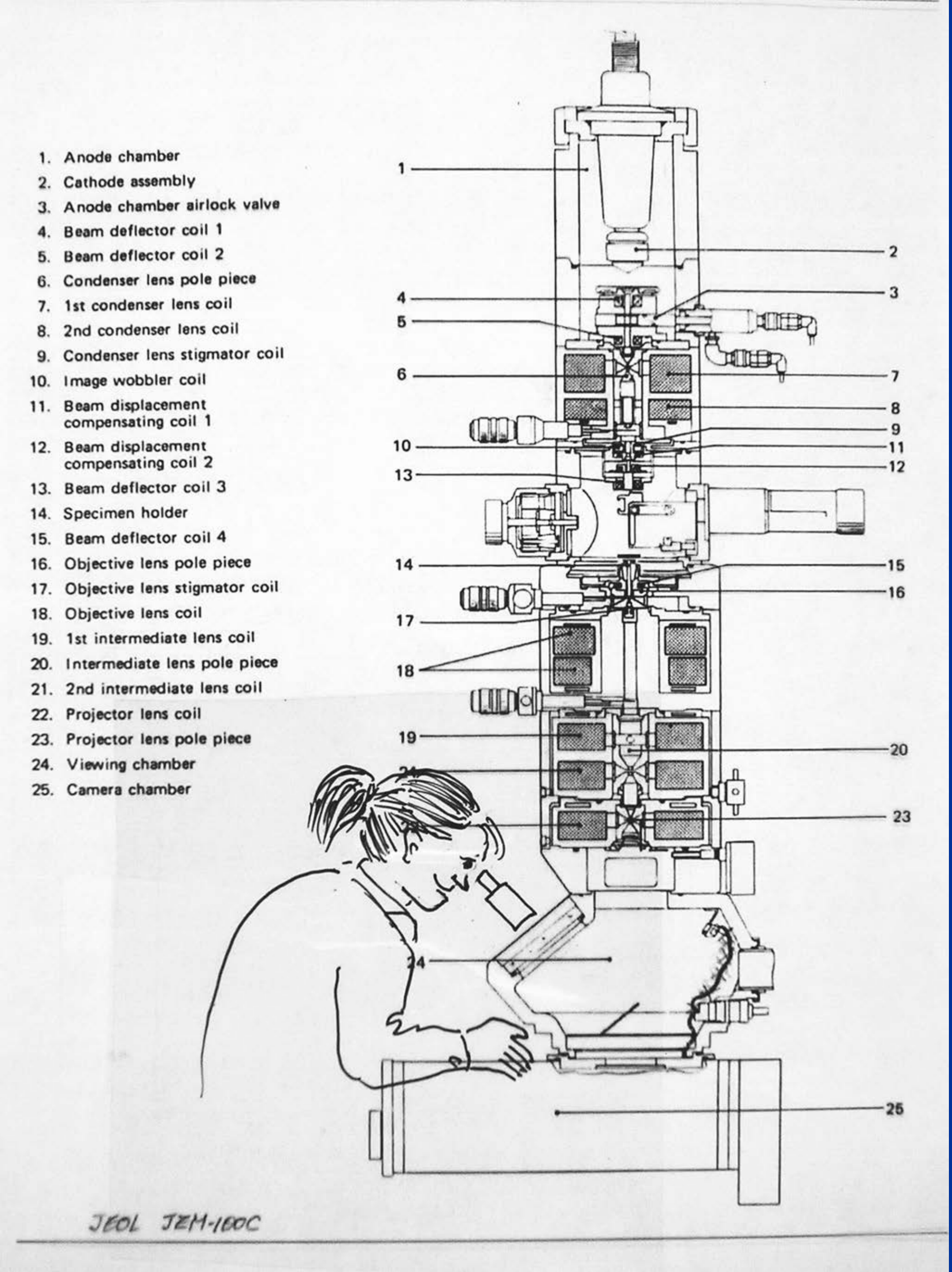
structure and major components



穿透式电子显微镜的主要部件

MAJOR COMPONENTS OF A TEM

1. electron optics column 镜筒
2. electronics and controls 电子系统
3. vacuum system 真空系统
4. high voltage power supply 高压电源
5. accessories 附件



The Electron Optics Column of JEOL JEM-100C

The Lens System:

Condenser Lens:

Controls beam intensity, density, convergence, coherence.

Objective Lens:

Magnification, introducing contrast.

Intermediate Lens:

Further magnification, imaging or diffraction.

Projector Lens:

Final magnification

Apertures

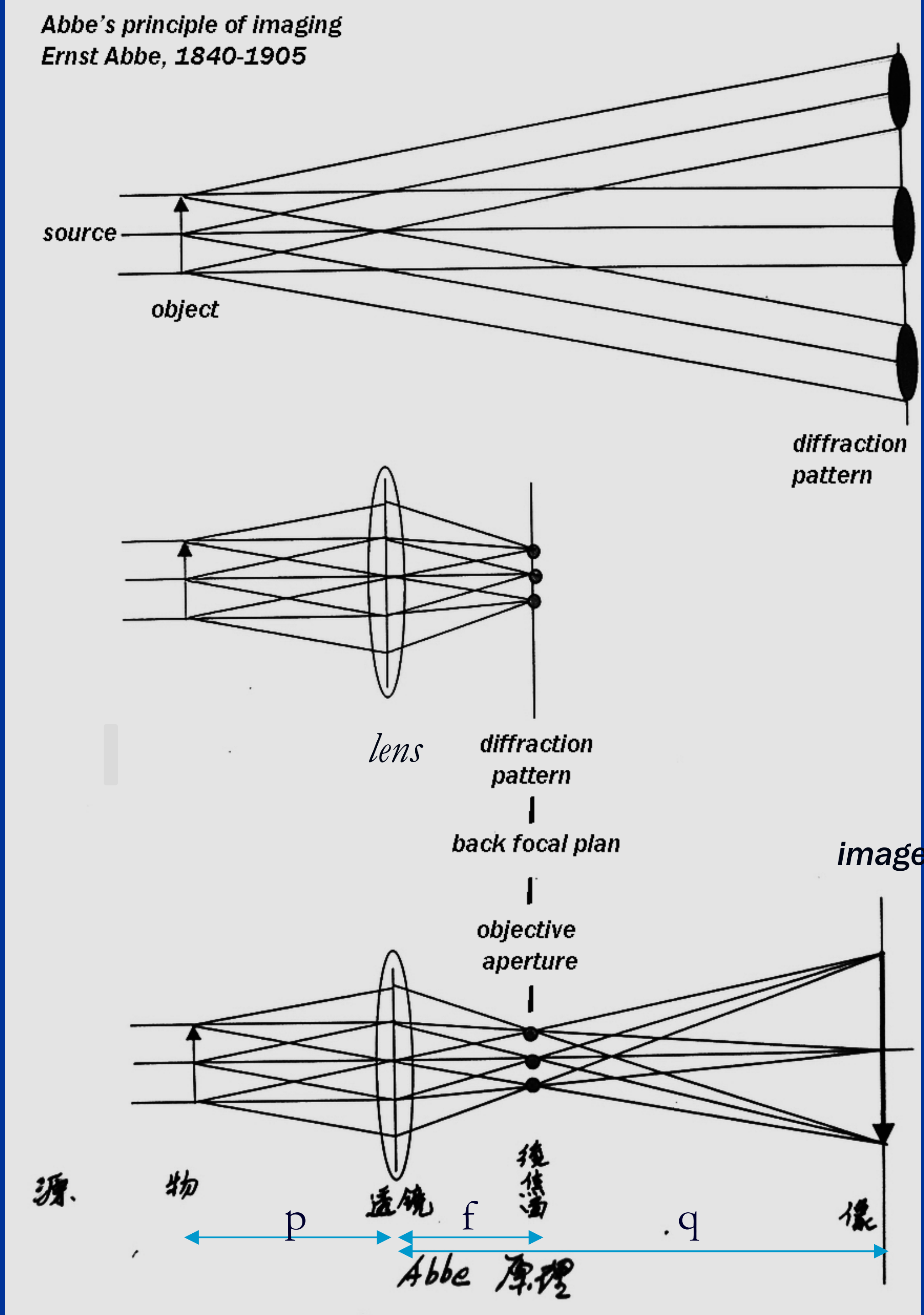
Specimen chamber

Camera

Objective lens,
JEOL JEM-100C

OPTICAL MICROSCOPY

ABBE'S PRINCIPLE



Abbe's Principle of image formation

scanning electron microscope
scanning electron microscope

Principle of Fundamental geometrical and physical optics

Abbe's principle and the back focal plan (BFP)

Contrast: Beam/solid interaction

BFP and the objective aperture:

- Bright field (BF)
- Dark field (DF) images.

$$1/p + 1/q = 1/f$$

Principle of image formation

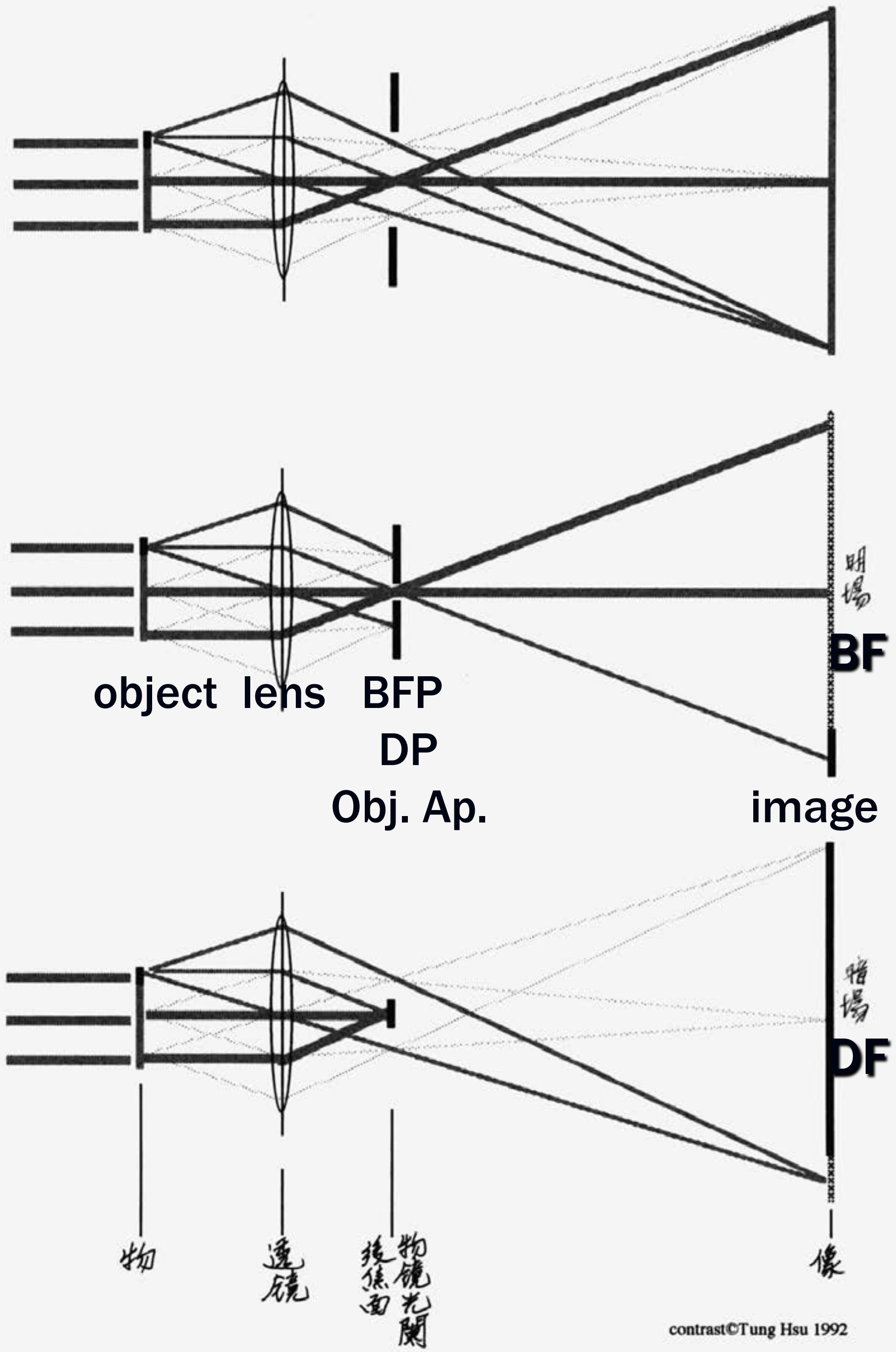
Fundamental geometrical and physical optics

Abbe's principle and the back focal plan (BFP)

Contrast: Beam/solid interaction

BFP and the objective aperture:

Bright field (BF) and dark field (DF) images.



Contrast: Beam/solid interaction

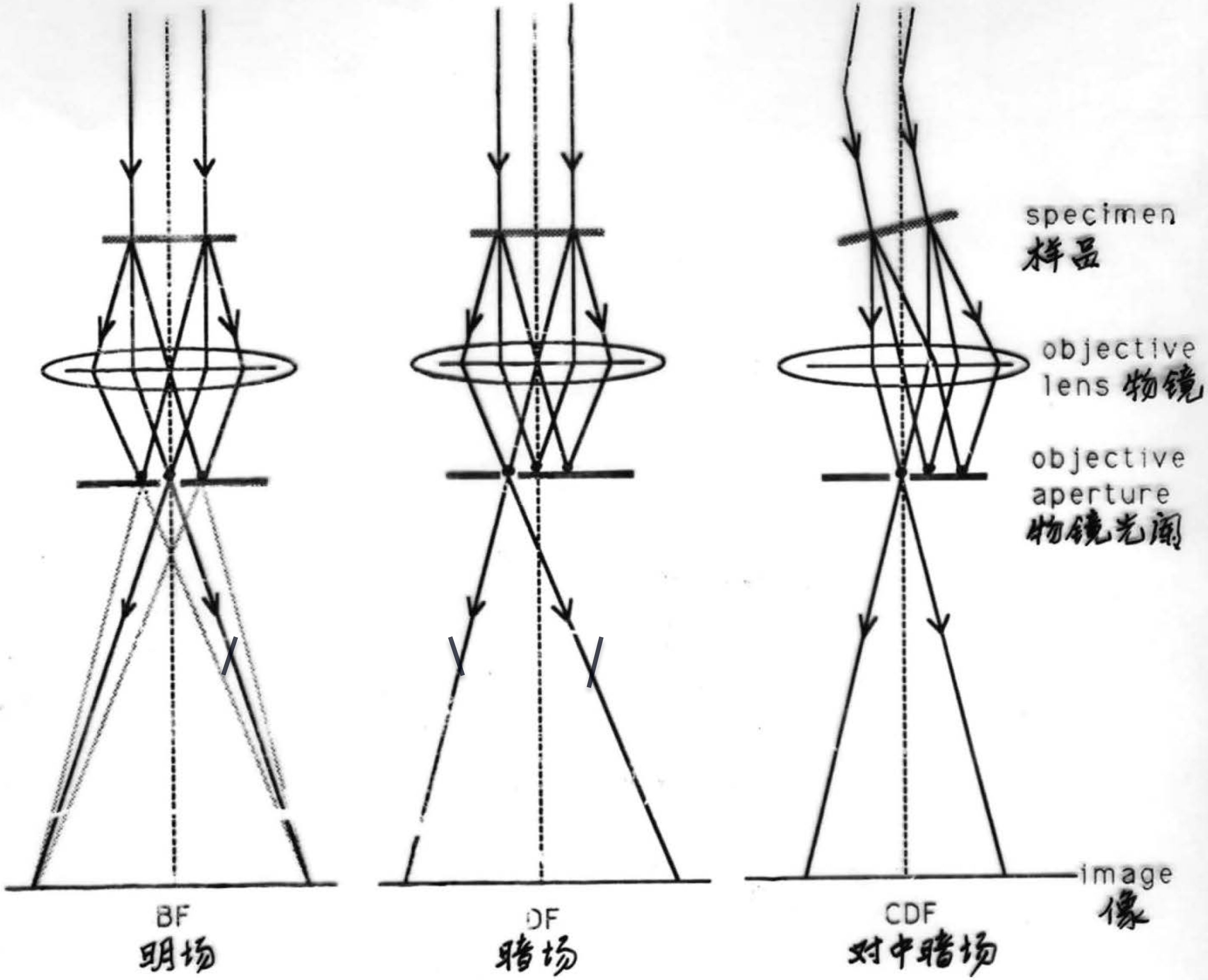
Back focal plane,

objective aperture,

diffraction pattern

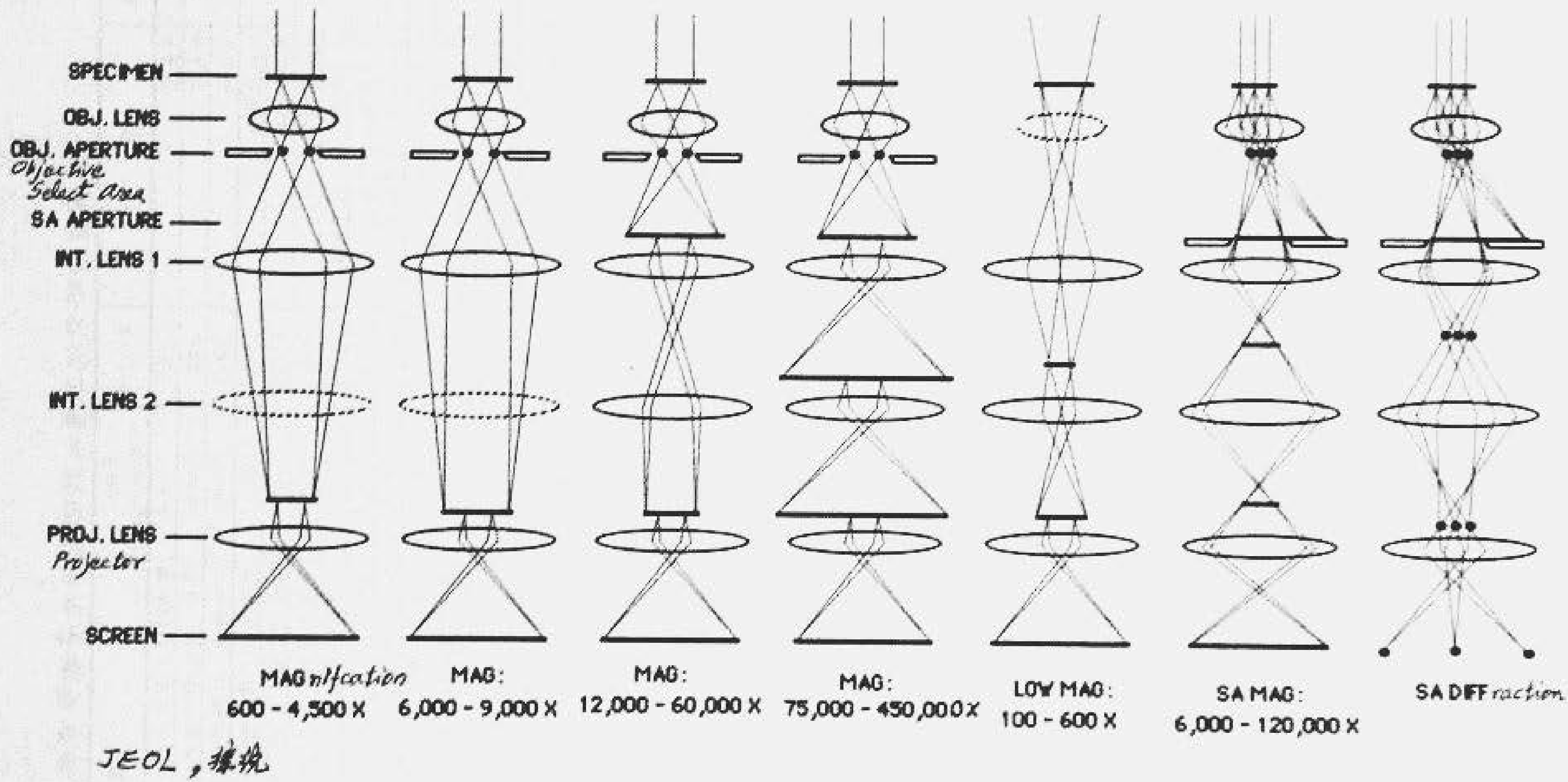
Bright field (BF) and dark field (DF)

images.



DIFFRACTION CONTRAST

繞射襯度 (衍衬)


SPECIMEN
OBJ. LENS
OBJ. APERTURE
Objective
Select area
SA APERTURE
INT. LENS 1
INT. LENS 2
PROJ. LENS
Projector
SCREEN
MAGnification 600 - 4,500 X
MAG: 6,000 - 9,000 X
MAG: 12,000 - 60,000 X
MAG: 75,000 - 450,000 X
LOW MAG: 100 - 600 X
SA MAG: 6,000 - 120,000 X
SA DIFFraction
JEOL ,

The electron gun:

An electrostatic lens +
an electron accelerator

Filament: Tungsten
LaB_6
Field emission

Acceleration voltage:
(HV or HT)
100kV – 1MV

$$\nabla^2 \Phi = 0$$
$$\mathbf{F} = -q \nabla \Phi = q\mathbf{E}$$

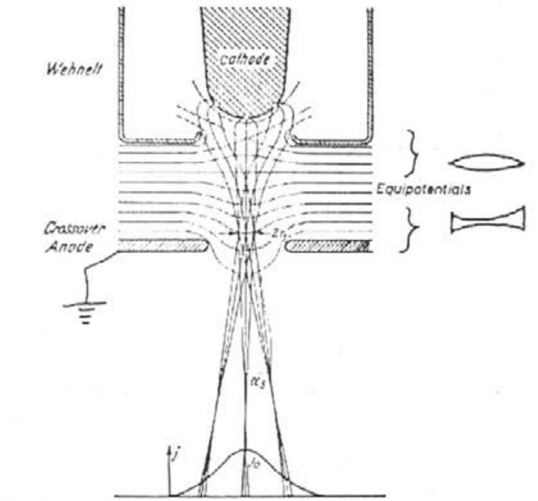


Fig. 3.2. The terminology associated with the electron gun.

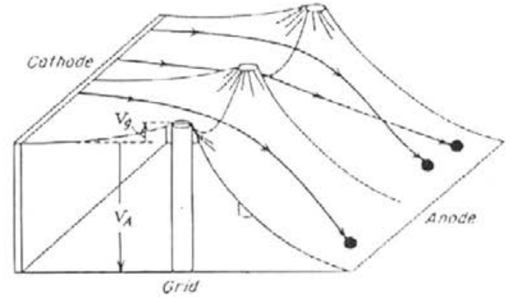


FIG. 2.9. The rubber-membrane model for experimental determination of elect
paths (exaggerated vertical scale).

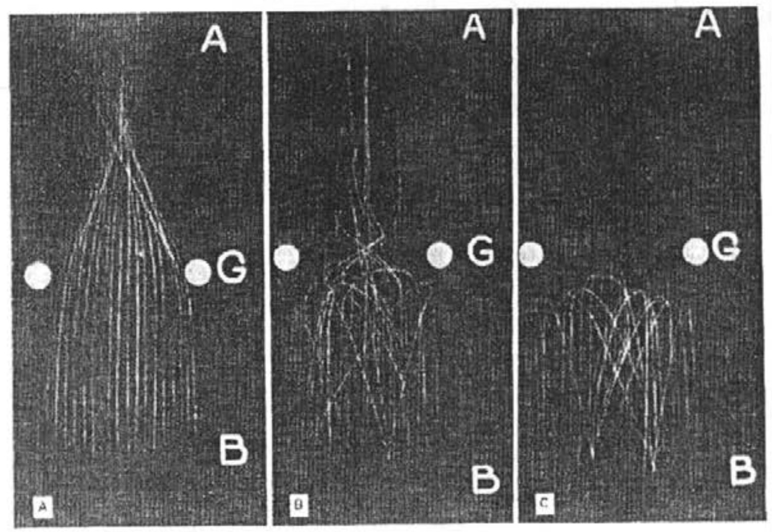
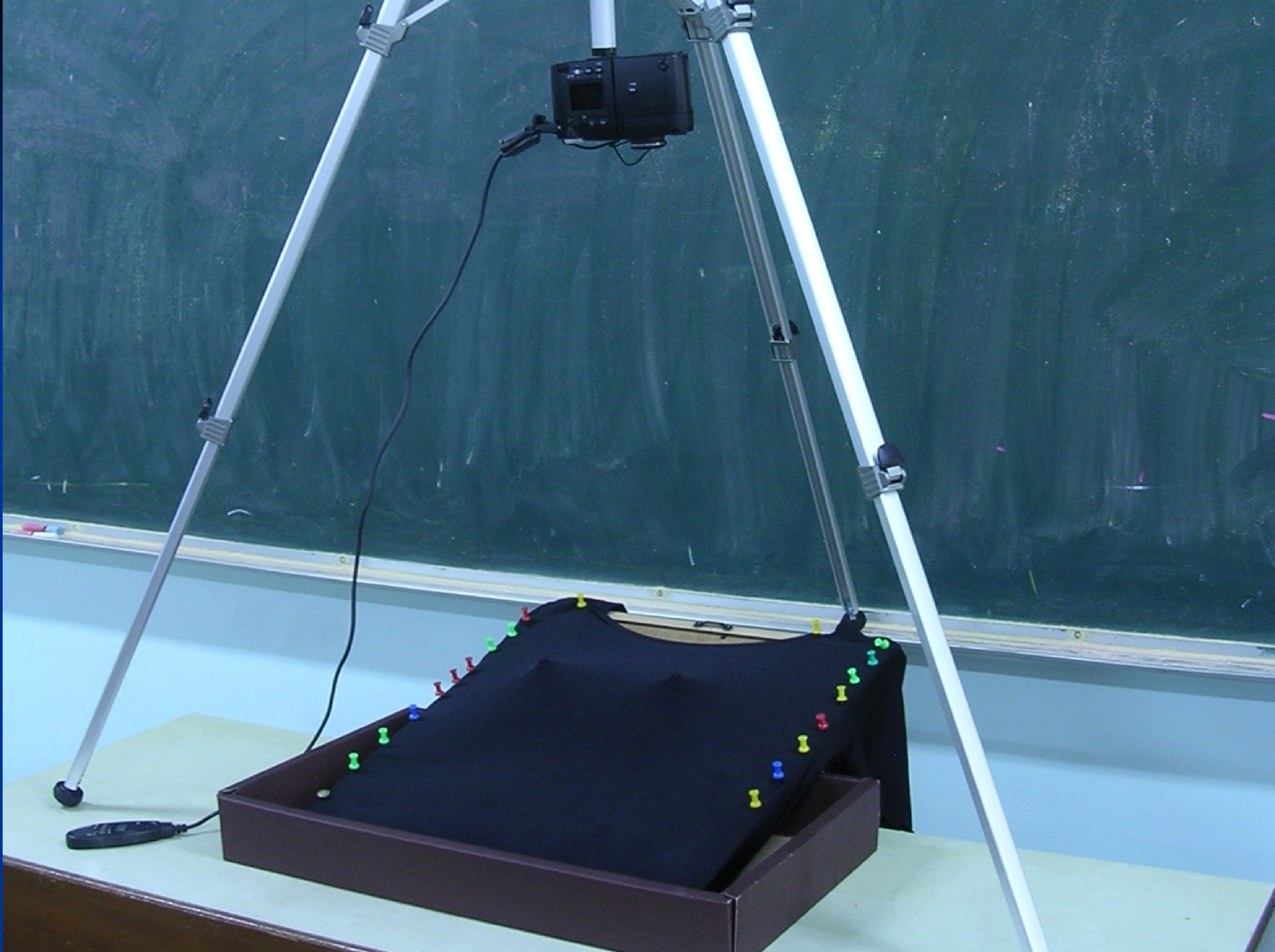
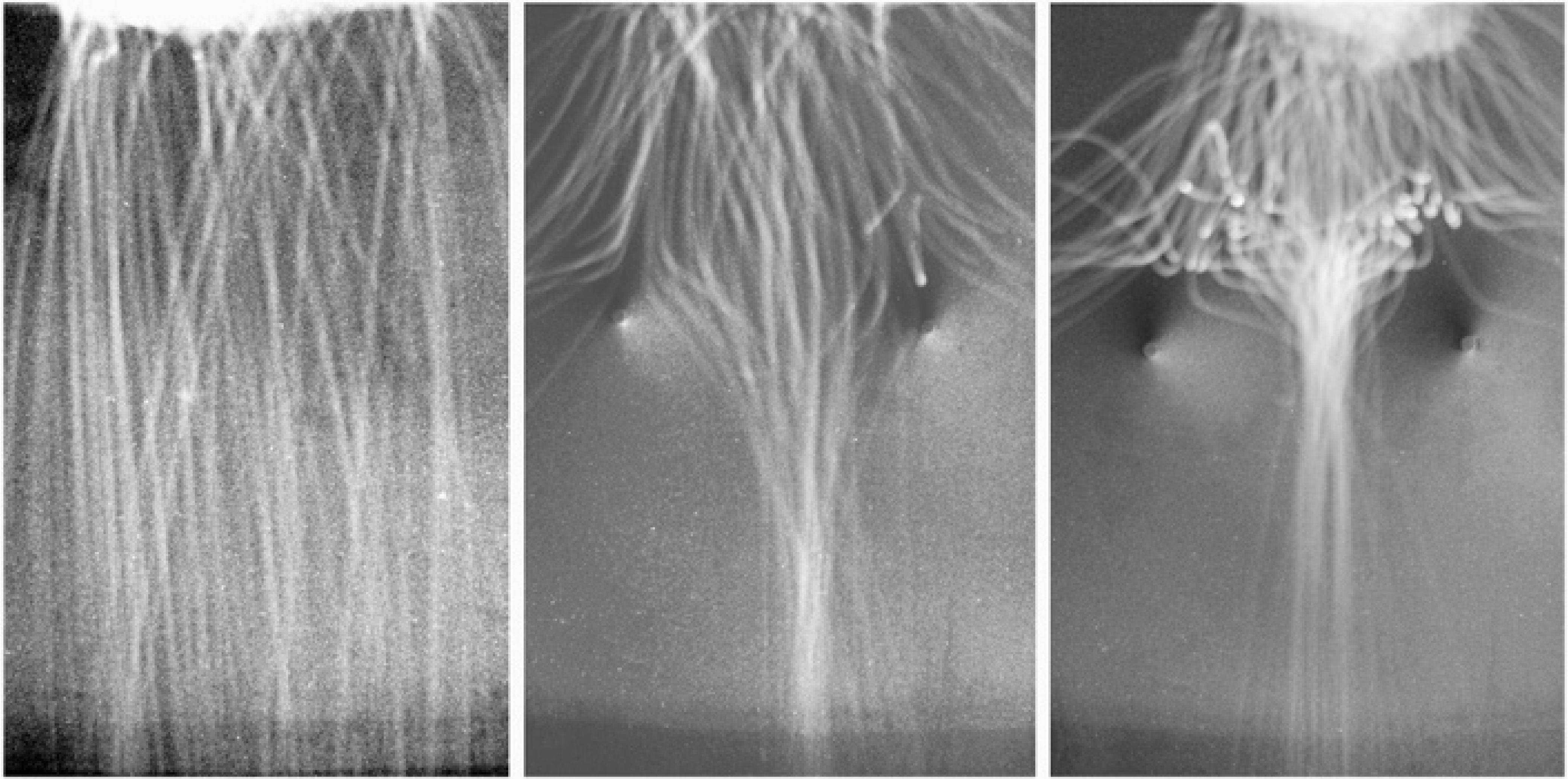


FIG. 2.10. Electron paths in a triode as determined with the rubber-membrane model. *A* is the anode, *B* the cathode, and *G* the grid. The grid potential is increasingly negative from A to C. (*Courtesy Philips Tech. Rev., Ref. 2.*)

C.E. Hall, "Introduction to Electron Microscopy", 2nd ed.
P.W. Hawkes, "Electron Optics and Electron Microscopy".





no bias   low bias   high bias   2006-0310

The electromagnetic lens

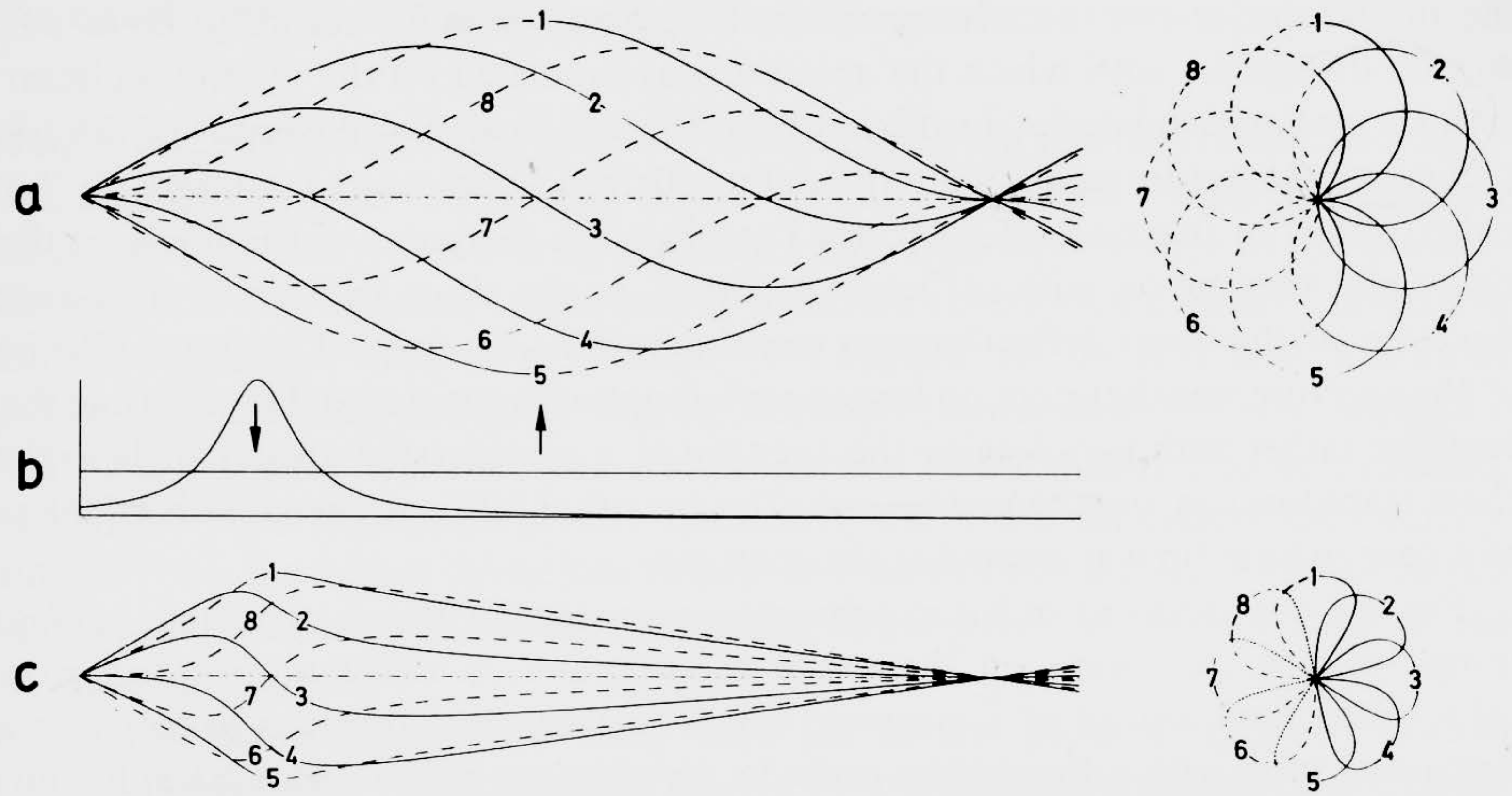


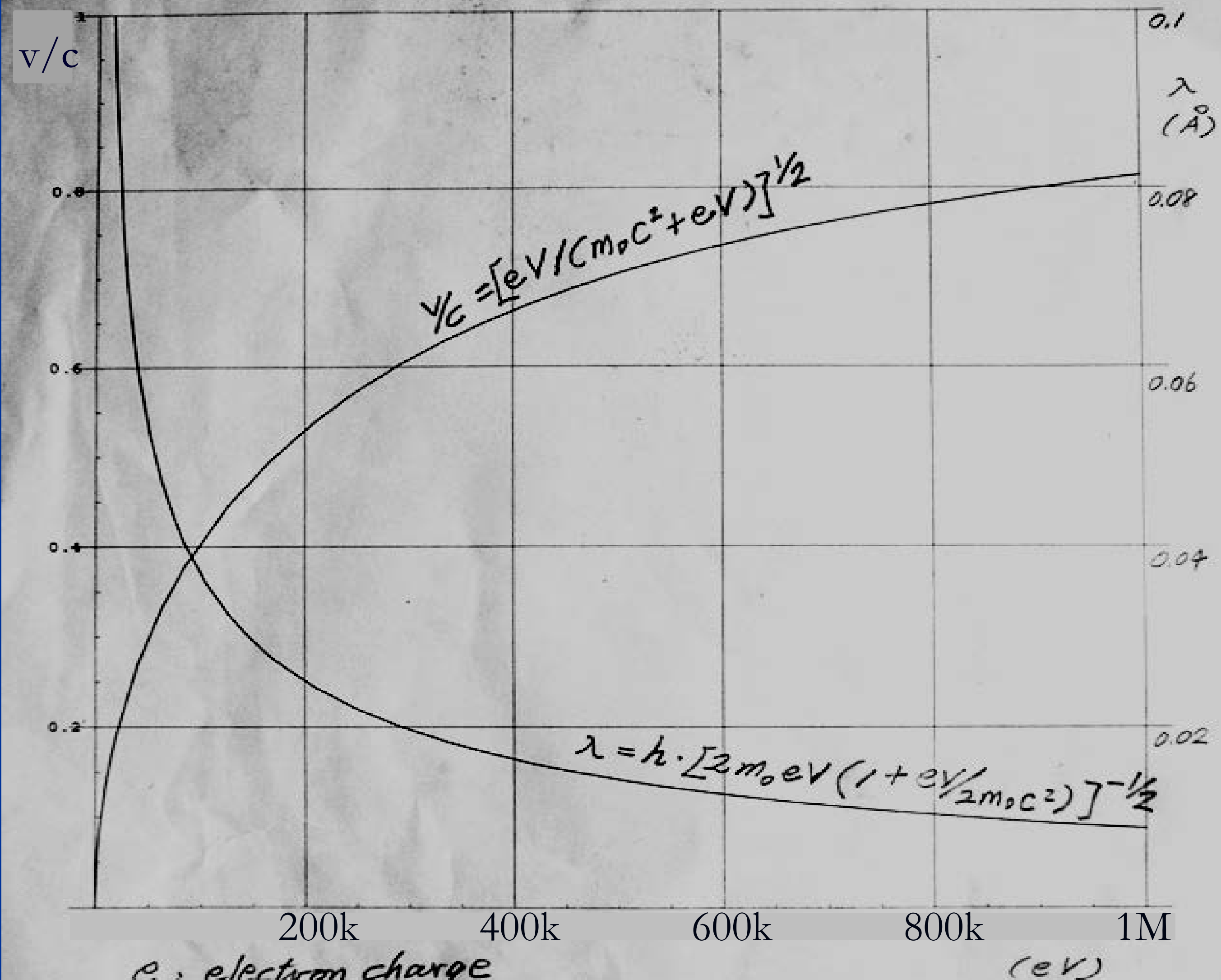
Fig. 1. Electron trajectories in a uniform (a) and in a non-uniform (c) magnetic field, issuing from an axial point of the specimen for different azimuth angles, but making the same angle with the lens axis. (b) Field distributions corresponding to (a) and (c).

"The early development of electron lenses and electron microscopy", Ernst Ruska, 1980, S. Hirzel Verlag Stuttgart

Electron micrographs
(EM, TEM images)

And

(Transmission) electron diffraction patterns
(TED patterns, DP)



e : electron charge
v : " velocity
V : acceleration voltage
m_0 : electron rest mass
c : speed of light in vacuum
h : Planck's constant
λ : electron wavelength

What is DIFFRACTION

?

Encyclopedia Britannica 1994-2002

Diffraction the spreading of waves around obstacles. Diffraction takes place with sound; with electromagnetic radiation…, and electrons, which show wavelike properties. One consequence of diffraction is that sharp shadows are not produced. The phenomenon is the result of interference…

Wikipedia 2006-2-2

Diffraction is the bending and spreading of waves when they meet an obstruction. It can occur with any type of wave…
 Diffraction also occurs when any group of waves of a finite size is propagating; for example…
Diffraction is one particular type of wave interference, caused by the partial obstruction or lateral restriction of a wave; another example…

Grant R. Fowles, “Introduction to Modern Optics”, 2nd ed., 1975, Dover, p. 106

5.1. General Description of Diffraction
If an opaque object is placed between a point source of light and a white screen, it is found that the shadow that is cast by the object departs from the perfect sharpness predicted by geometrical optics.

Born and Wolf, “Principles of Optics”, 4th ed., 1970.
Ch. VIII. Elements of the theory of diffraction

In carrying out the transition from the general electromagnetic field to the optical field, which is characterized by very high frequencies (short wavelengths), We found that in certain regions the simple geometrical model of energy propagation was inadequate. In particular, we saw that deviation from this model must be expected in the immediate neighborhood of the boundaries of shadows and in regions where a large number of rays meet. These deviations are manifested by the appearance of dark and bright bands, the diffraction fringes.

Hecht “Optics” 2nd ed, 1989

p.3. The phenomenon of diffraction, i.e., the deviation from rectilinear propagation that occurs when light advances beyond an obstruction, was first noted …

pp. 128-129. … an optical device is … unable to collect all the emitted light; the system accepts only a segment of the wavefront… there will always be an apparent deviation from rectilinear propagation even in homogeneous media – the wave will be *diffracted*.

J.M. Cowley, “Diffraction physics”

(No definitions given)

Feynman “Lectures on Physics” Ch. 30. Diffraction

This chapter is a direct continuation of the previous one, although the name has been changed from *Interference* to *Diffraction*. *No one has ever been able to define the difference between interference and diffraction satisfactorily*. It is just a question of usage, and there is no specific, important physical difference between them. The best we can do, roughly speaking, is to say that when there are only a few sources, say two, interfering, then the result is usually called interference, but if there is a large number of them, it seems that the word diffraction is more often used. So, we shall not worry about whether it is interference or diffraction, but continue directly from where we left off in the middle of the subject in the last chapter.

What else?

We don’t even need the word “diffraction”. What we observe experimentally is the result of wave propagation. When there is an object in the way of the propagating waves, a pattern associated with the shape and nature of the object and the nature of the wave is formed. This can be called the Fresnel pattern or the Fraunhofer pattern, depending upon the approximations used in describing it.

Related terms:

- Scattering (of particles)
- Reflection (by atom plans in a solid)

WAVE PROPAGATION, SCATTERING, AND SUPERPOSITION

Electrons fly through the vacuum = electron wave propagating through the vacuum.

Electrons (electron waves) can be scattered by electrostatic potential of atoms.

When two or more electron waves meet, their amplitudes are added.

How to add waves:

Direct method

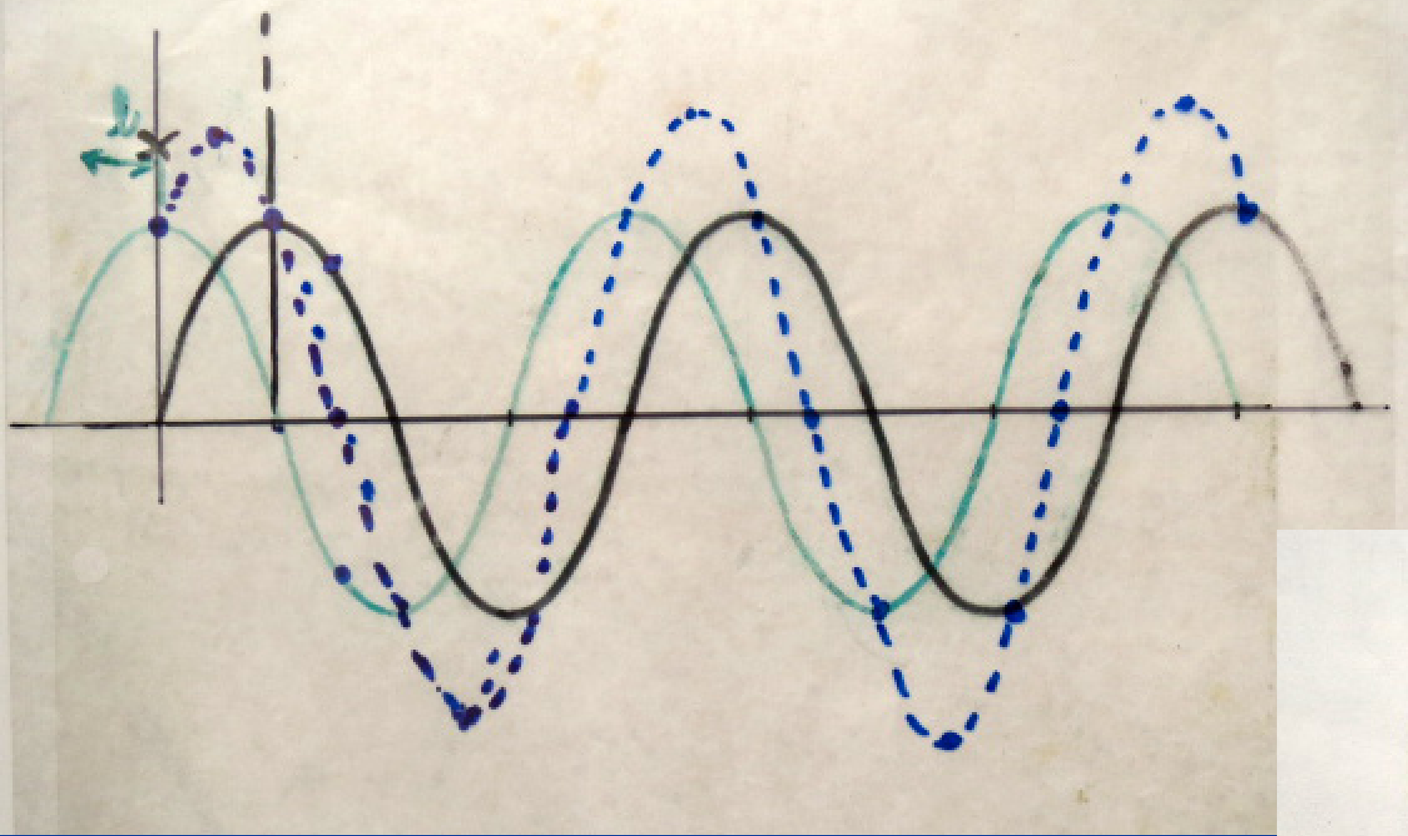
Amplitude-phase diagram (vector method)

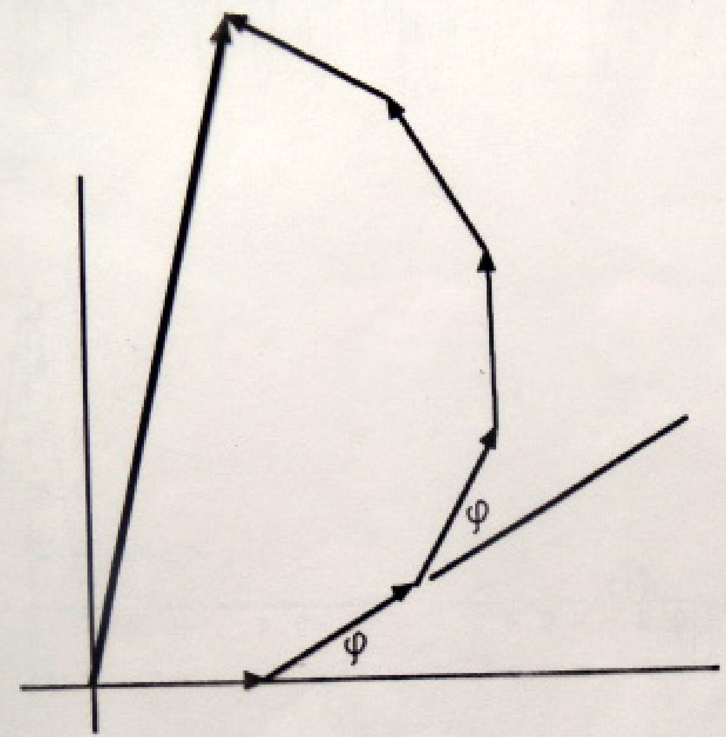
Fourier transform

- Optical bench (Atlas)
- Computer

Diffraction Patterns from 3D objects

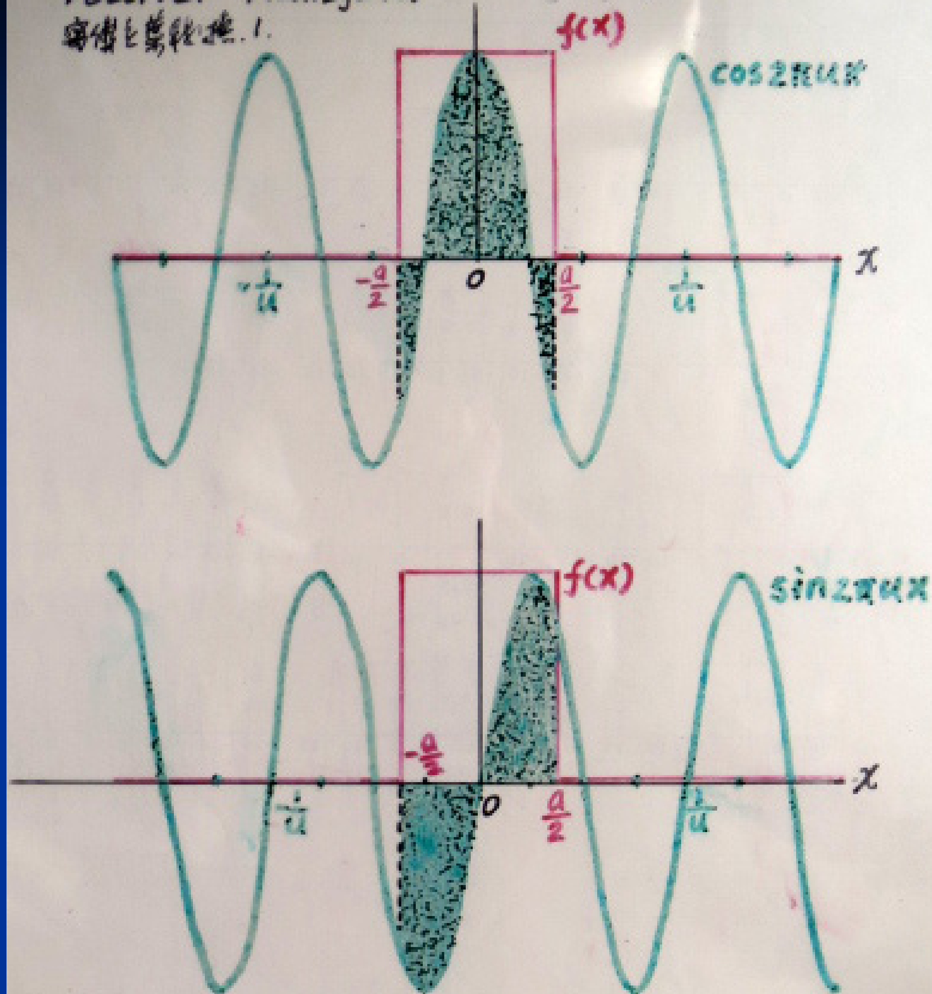
Bragg's Law $$n\lambda = 2d \sin\theta$$



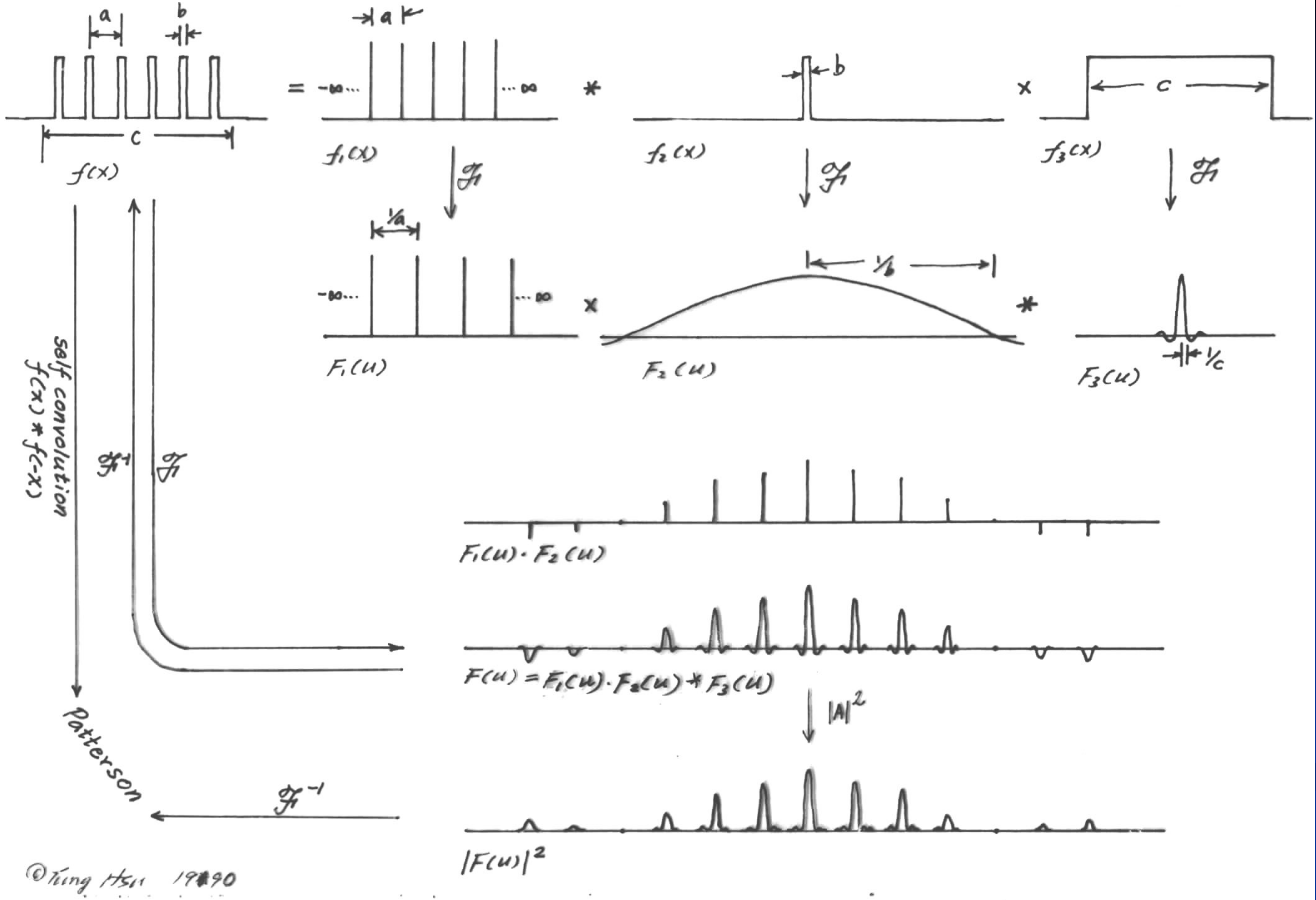


amplitude/phase diagram

Fourier Transform



$$
\begin{aligned}
\mathcal{F}[f(x)] &= \int_{-\infty}^{\infty} f(x) \exp\{2\pi i u x\}\, dx \\
&= \int_{-\infty}^{\infty} f(x) \{\cos(2\pi u x) + i \sin(2\pi u x)\}\, dx \\
&= F(u)
\end{aligned}
$$



a
b
c
f(x)
= -∞...
...∞
*
f₁(x)
b
f₂(x)
x
c
f₃(x)
𝔉
1/a
-∞...
...∞
x
1/b
*
1/c
F₁(u)
F₂(u)
F₃(u)
self convolution
f(x) * f(-x)
𝔉⁻¹
𝔉
F₁(u) · F₂(u)
F(u) = F₁(u) · F₂(u) * F₃(u)
|A|²
Patterson
𝔉⁻¹
|F(u)|²
©Ting Hsu 1990

For finding diffraction patterns:

ImageJ®:

basic image processing. Ask Ms. Chen (2789-8394) about down loading.

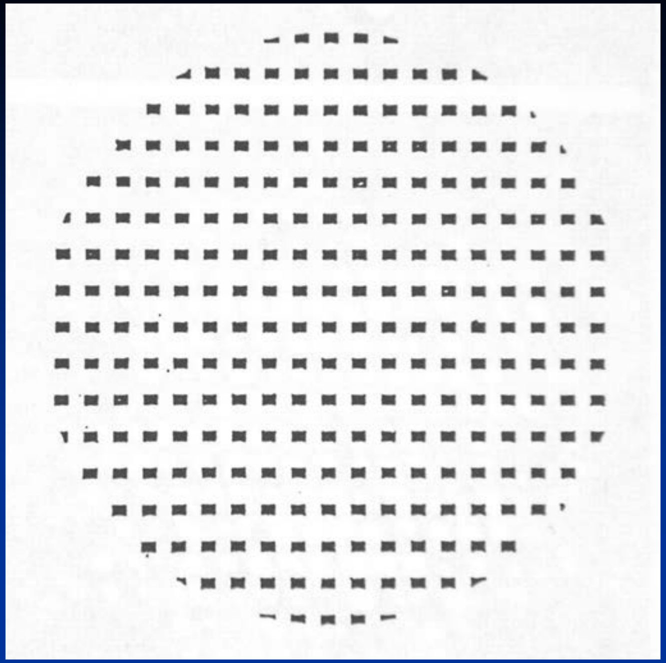
DigitalMicrograph®:

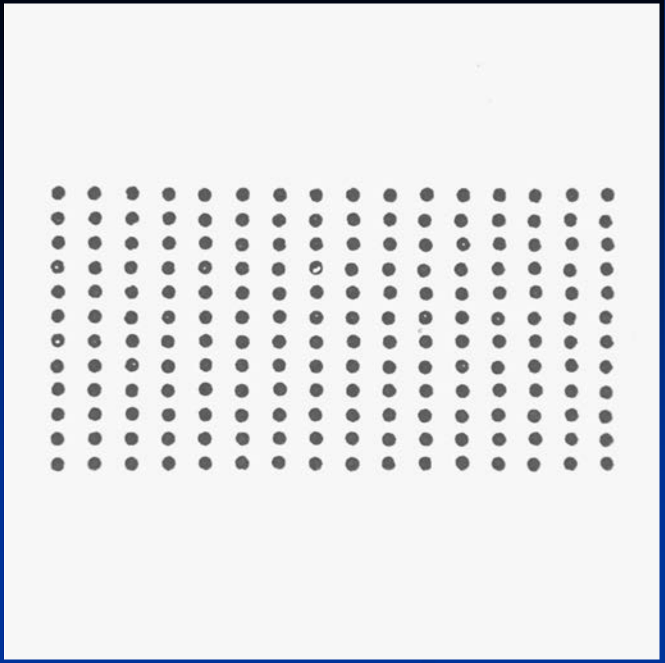
professional image processing. Ask Ms. Chen about free demo copy.

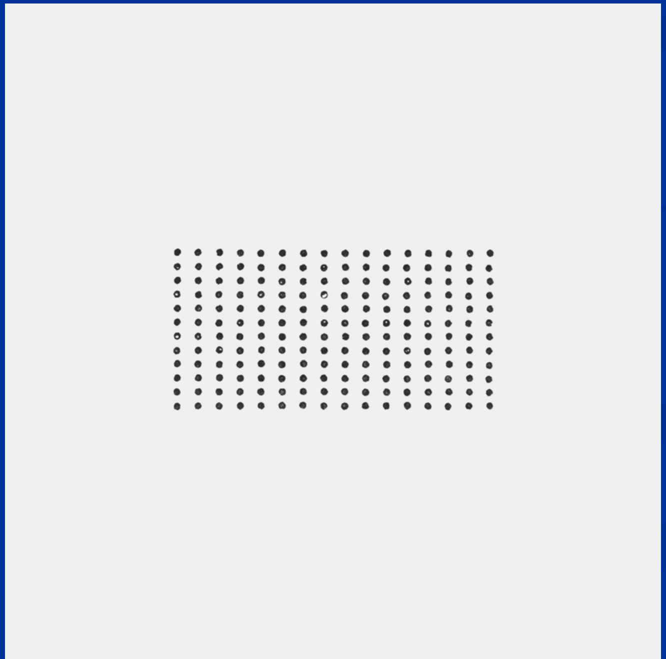
Reciprocal lattice and Ewald construction:

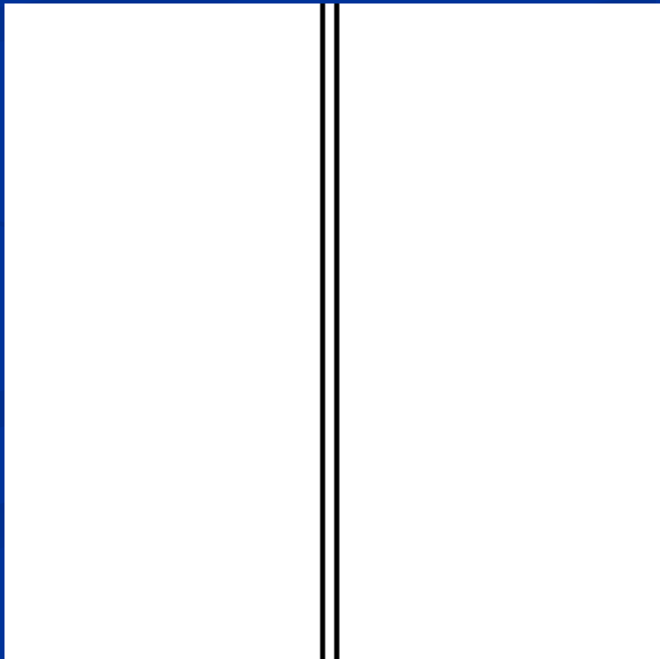
These are so cool and important. Sorry we did not have time to cover them. If you are interested, I can give a special lecture and demo on this subject. It will be free except that you have to arrange a time outside your scheduled classes.

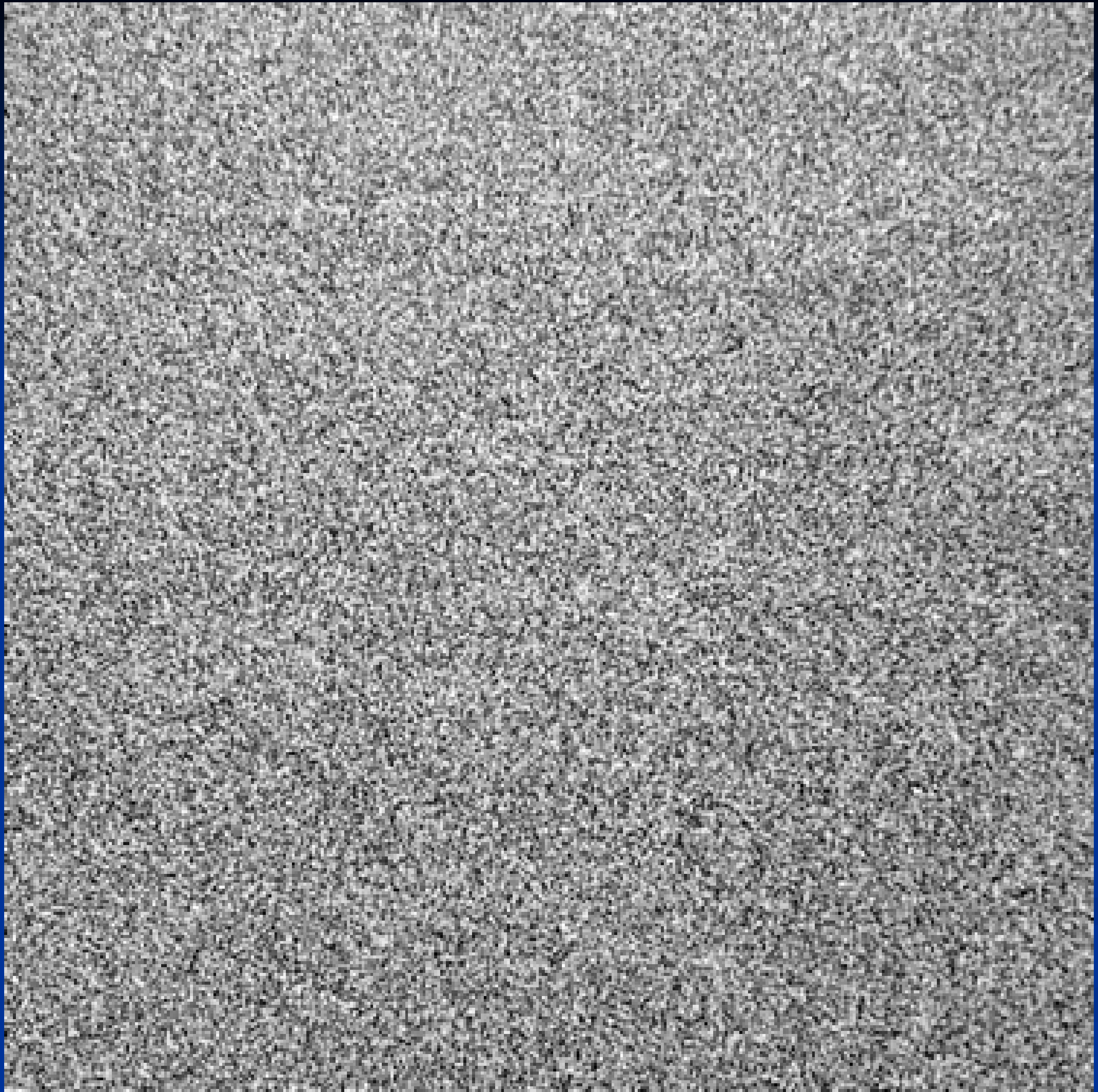
Try these on ImageJ® or DigitalMicrograph®











Try this on ImageJ®
or
DigitalMicrograph®

Examples of electron micrographs and (transmission) electron diffraction (TED) patterns

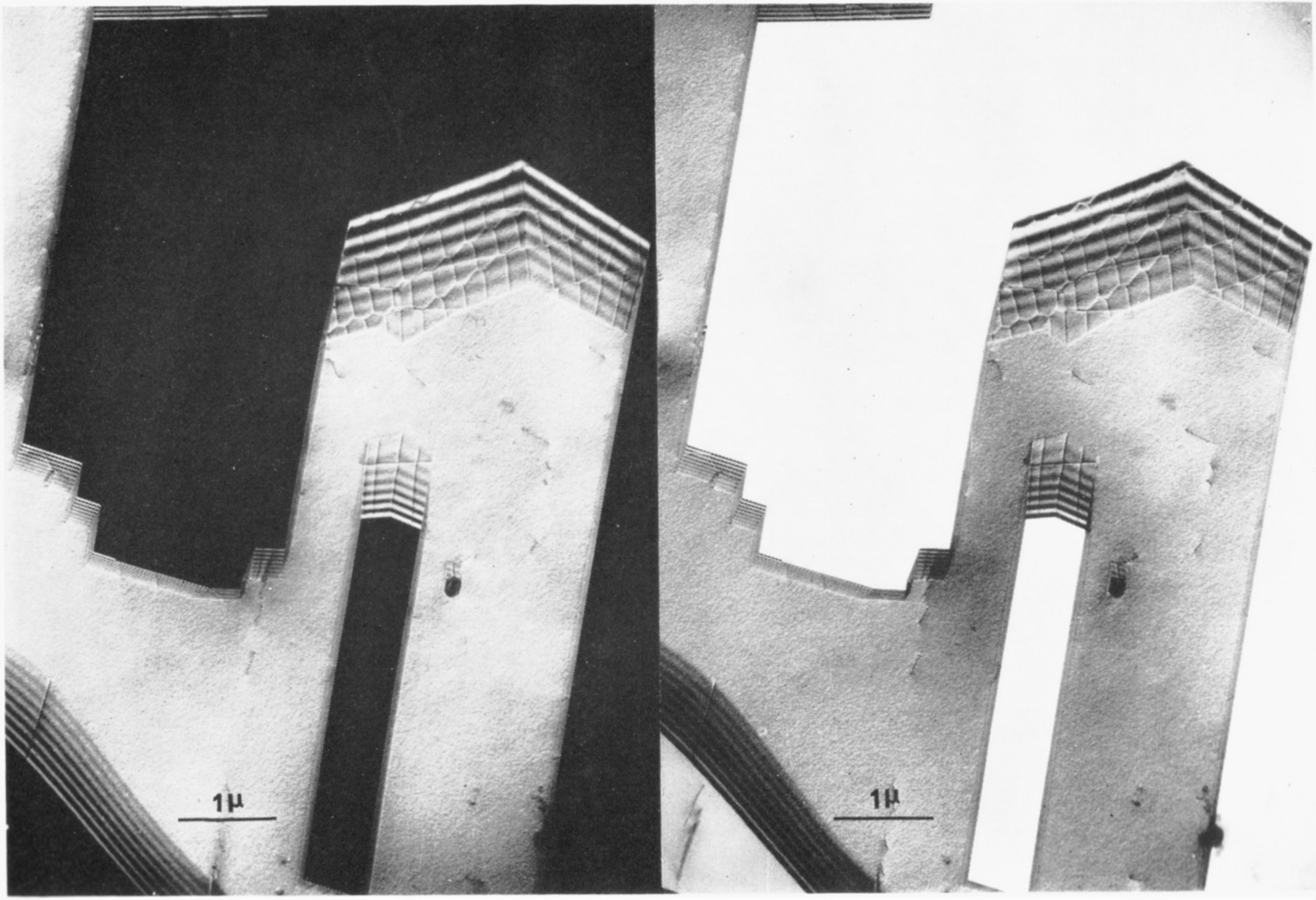
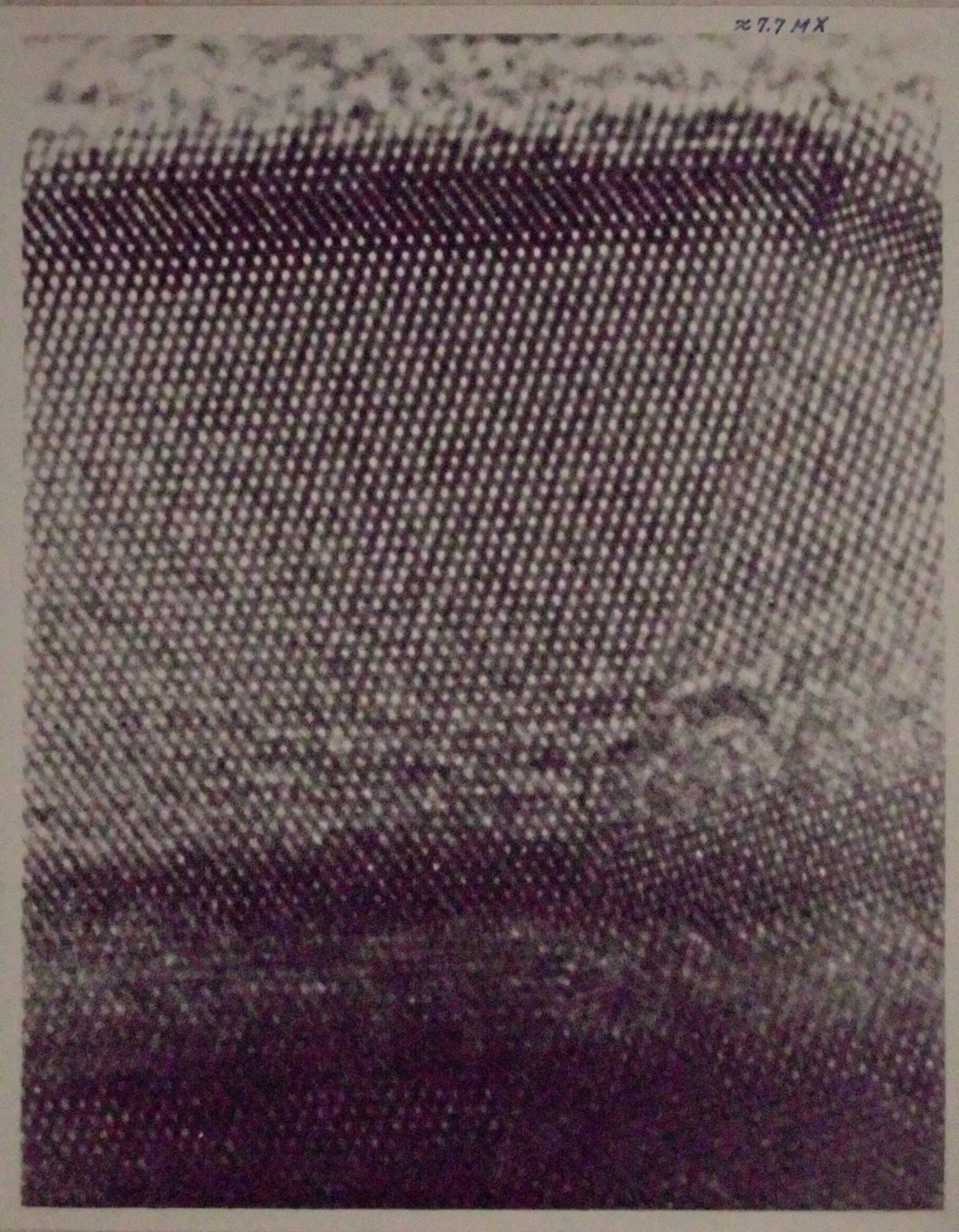
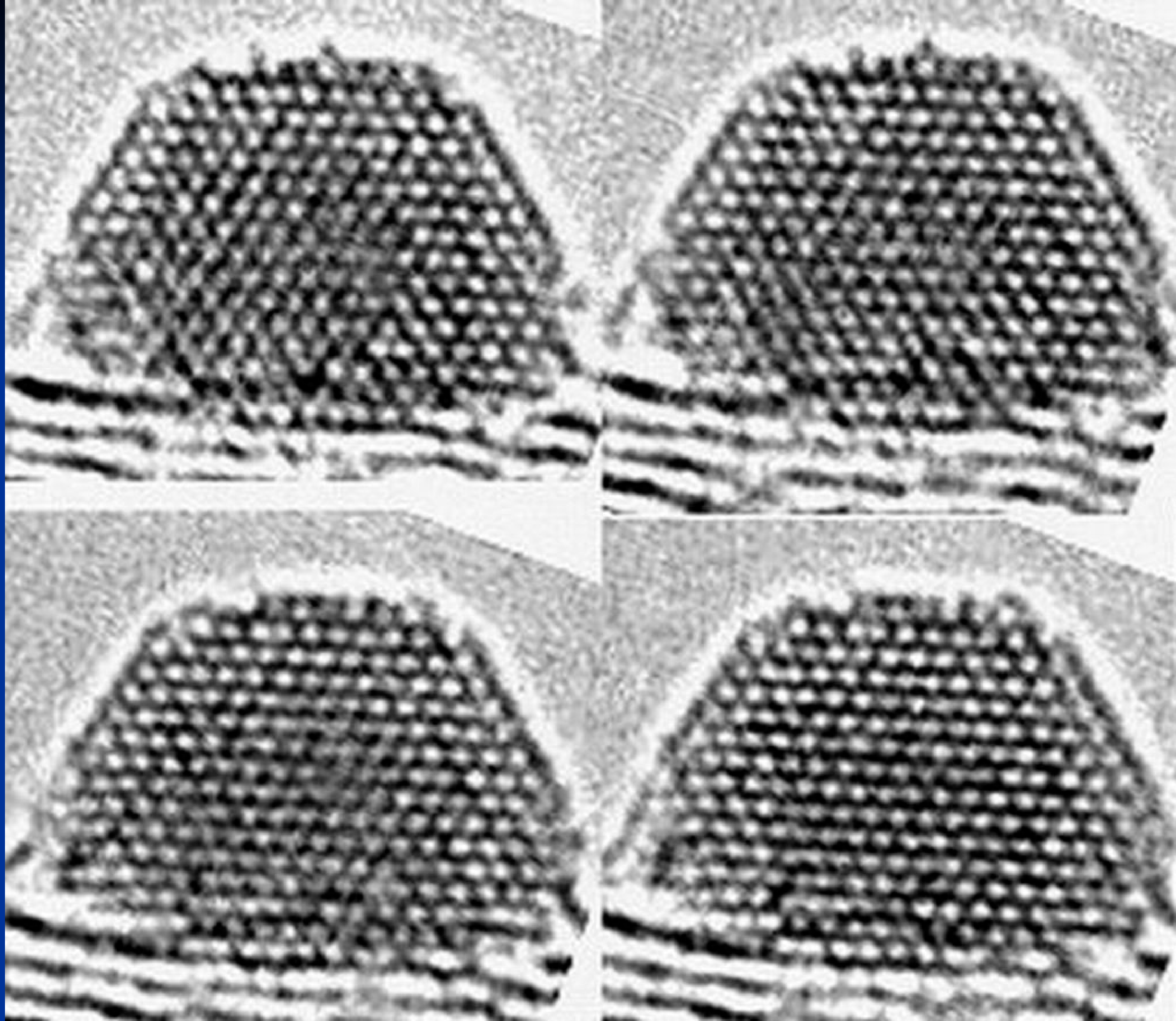


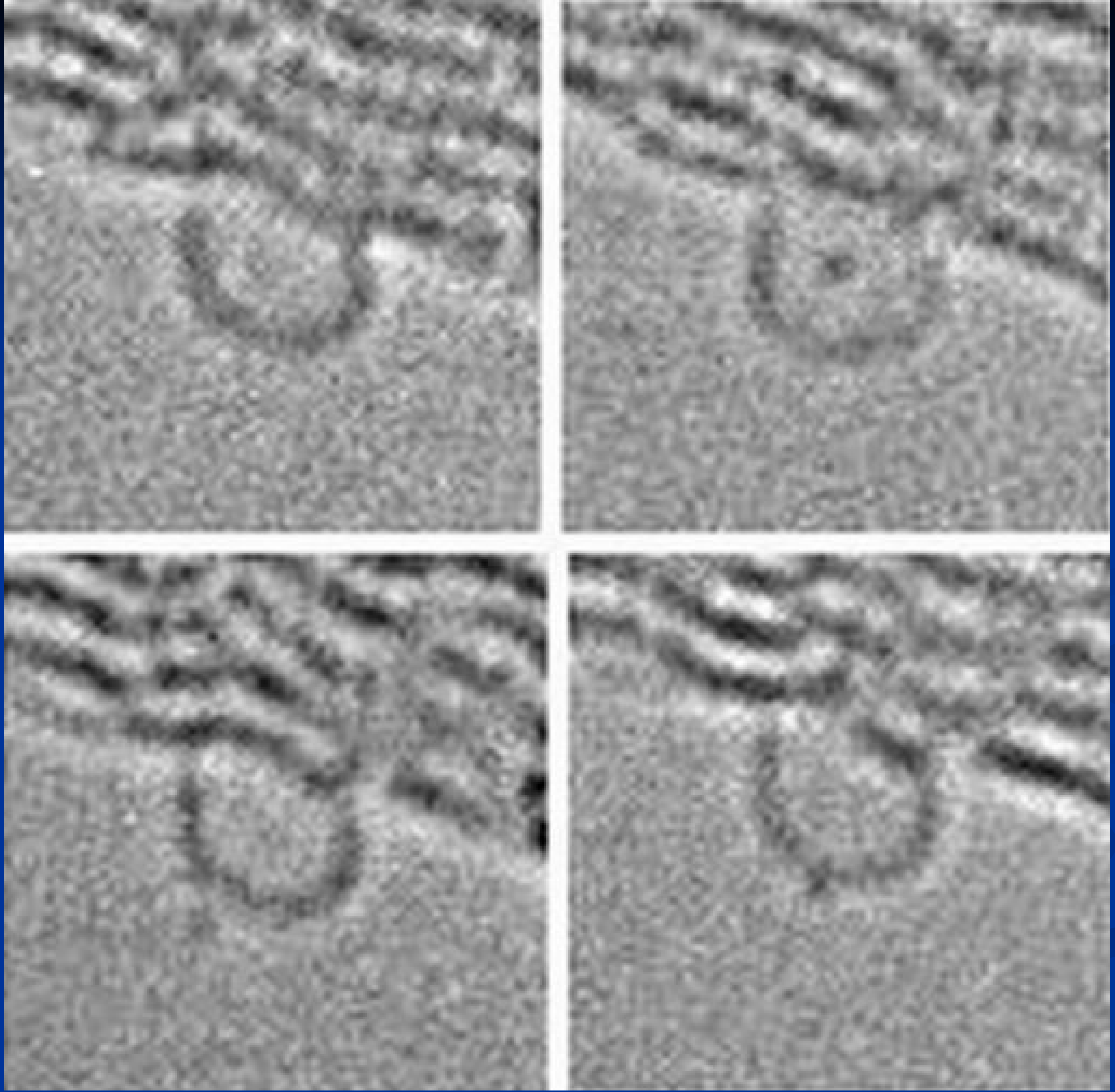
Plate X. Bright and dark-field micrographs of stainless steel, obtained with the Toulouse 1·5 MV microscope. 12 000 × ; Φ = 1 MV.

(Courtesy of Professor G. Dupouy, Laboratoire d'Optique Electronique du C.N.R.S., Toulouse)

Ref: Hawkes, P.W. (1974), Electron Optics and Electron Microscopy, Taylor & Francis, London.


≈7.7 MX





Contrast mechanism:

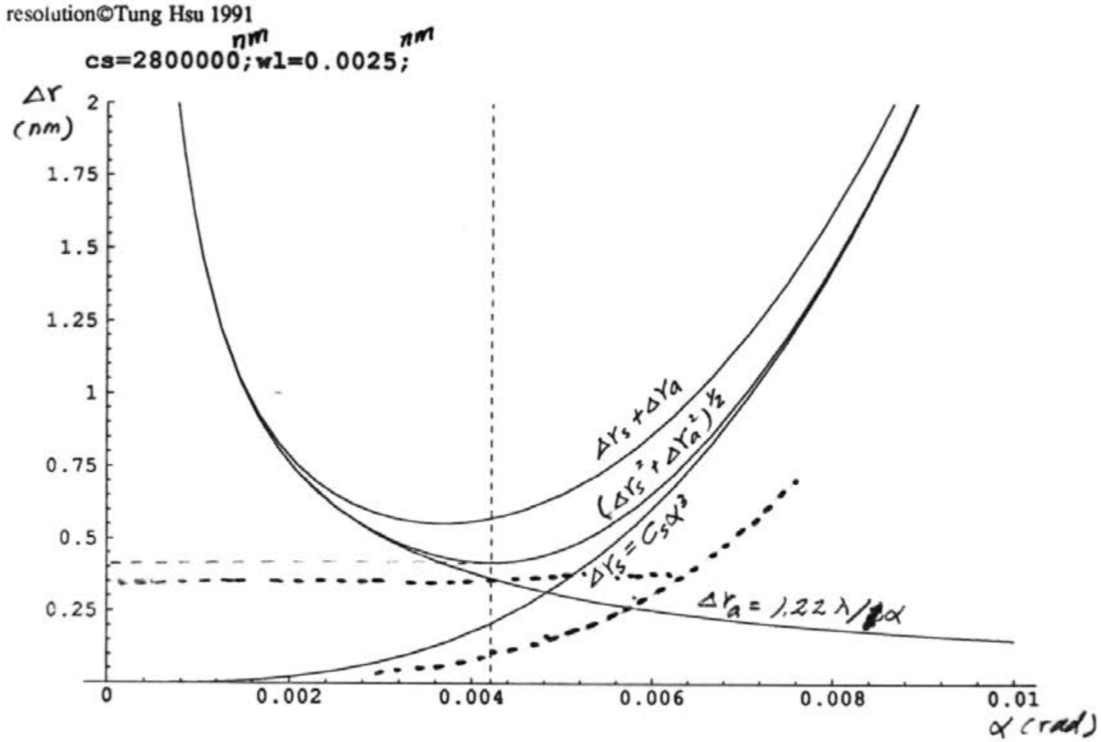
Beam/specimen interaction

- Amplitude and/or phase of the electron waves are altered by the specimen

Properties of lens

- Waves (rays) initiated from a point on the object cannot be converged by the lens to a point on the image.
  - Aperture limitation ("diffraction" related)
  - Spherical aberration
  - Chromatic aberration
  - Defocus ("diffraction" related)
  - Astigmatism

Detector: Fluorescence screen, Film, CCD, eyes



$$\alpha \approx C_s^{-1/4}\,\lambda^{1/4}$$

$$\Delta r \approx C_s^{1/4}\,\lambda^{3/4}$$

$$\lambda = \frac{h}{\left\{2mE\left(1+\frac{E}{2mc^2}\right)\right\}^{1/2}}$$

$E = 100\,keV$ $\quad \lambda = 0.0037\,nm$

$200\,keV$ $\quad 0.0025\,nm$

$15\,keV$ $\quad 0.0099\,nm$

光: $\Delta r \approx 1.22\frac{\lambda}{\alpha}$

Fig. 22

$$\lambda = 1.226\left[E(1+0.9788\times10^{-6}E)\right]^{-\frac{1}{2}}\ nm$$

volt

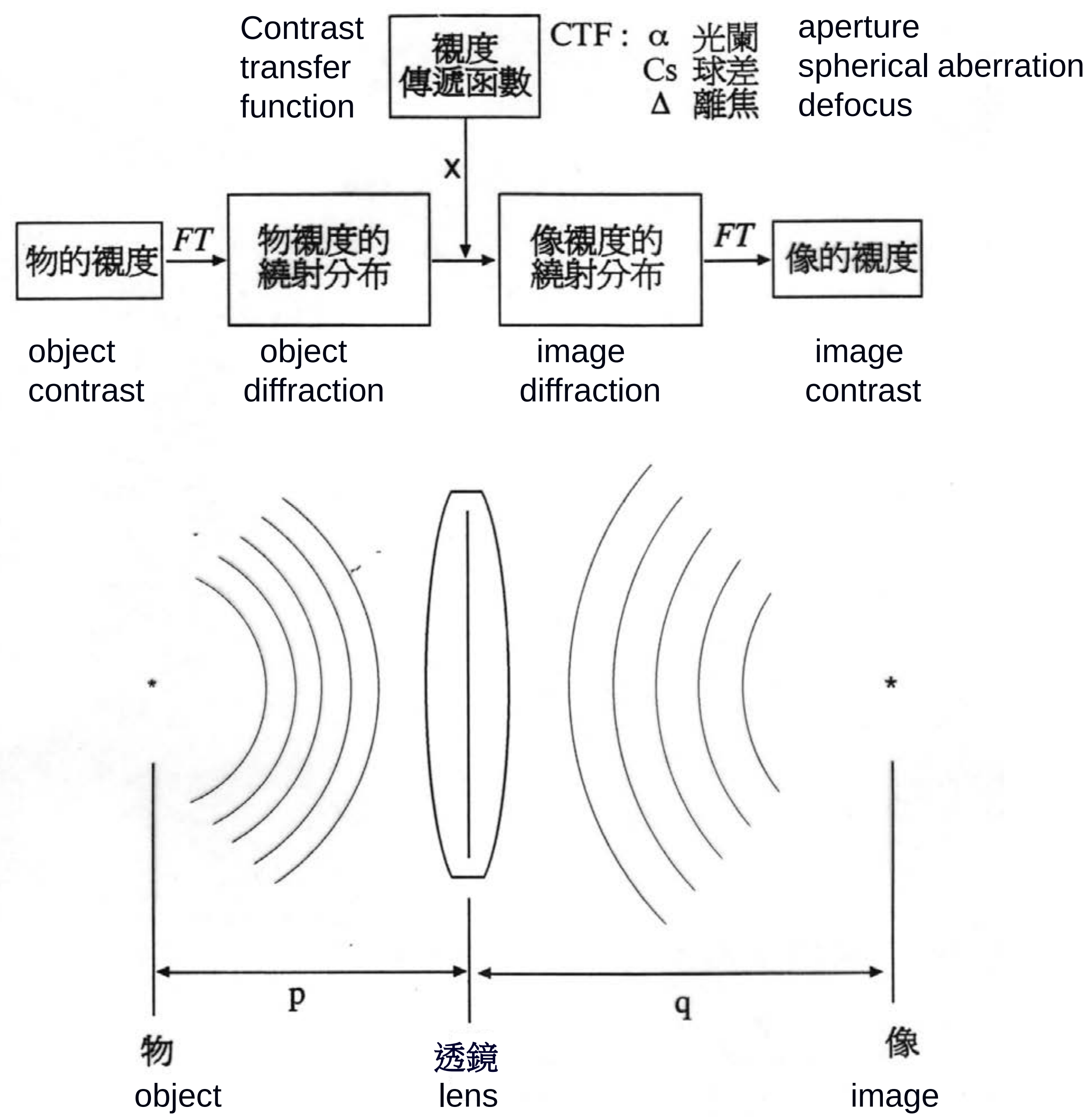
RESOLUTION:

Rayleigh's criterion

Balancing the spherical aberration effect and the diffraction effect:

Smaller aperture produces larger Airy disc (diffraction pattern of the aperture).

Larger aperture produces more diffused disc due to spherical aberration


Contrast transfer function
襯度傳遞函數
CTF : α 光闌
Cs 球差
Δ 離焦
aperture
spherical aberration
defocus
X
物的襯度
FT
物襯度的繞射分布
像襯度的繞射分布
FT
像的襯度
object contrast
object diffraction
image diffraction
image contrast
p
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物
object
透鏡
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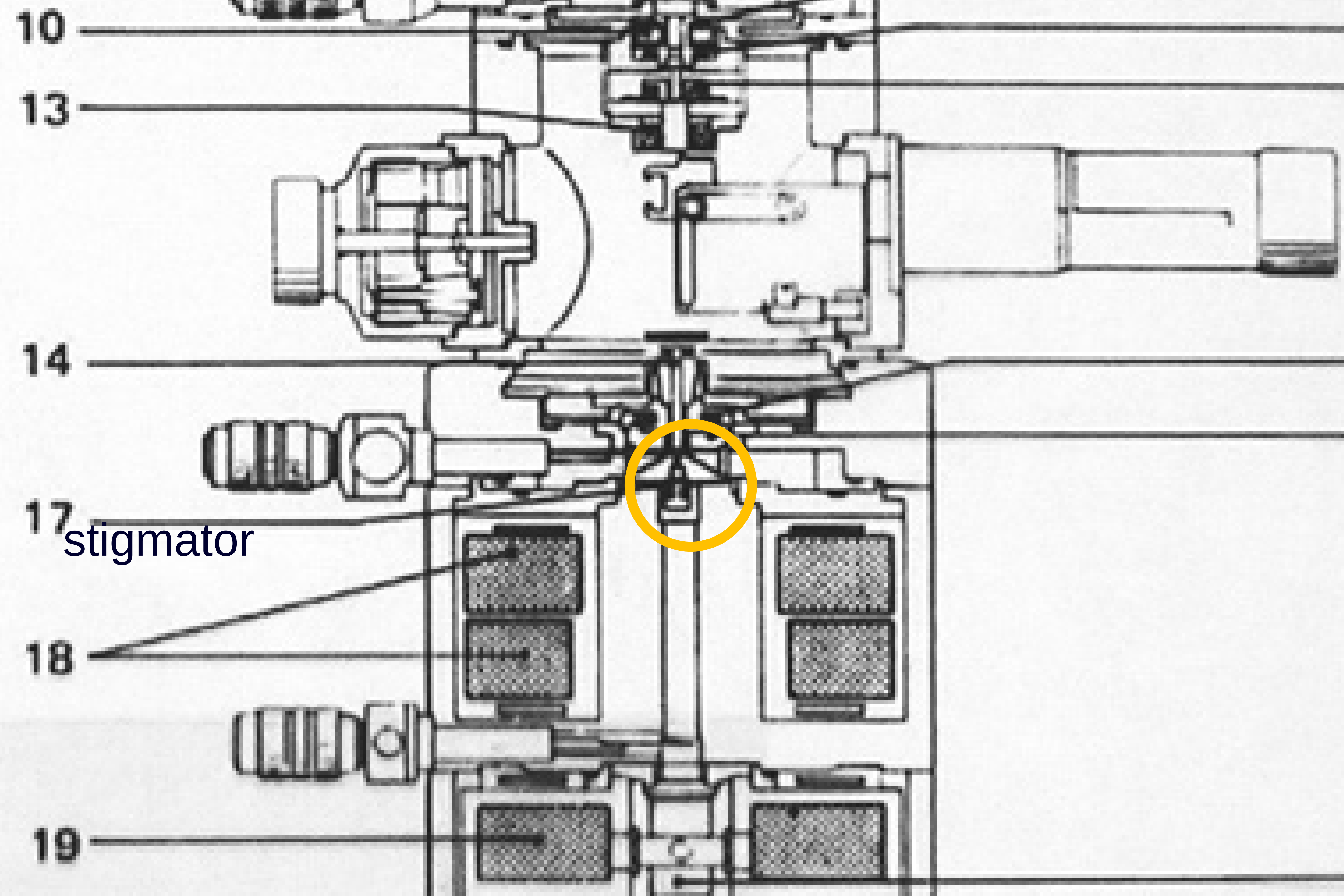
image

ASTIGMATISM

Stigma
Stigmatize
Astigmatism
Anastigmatic
Stigmator



10
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stigmator
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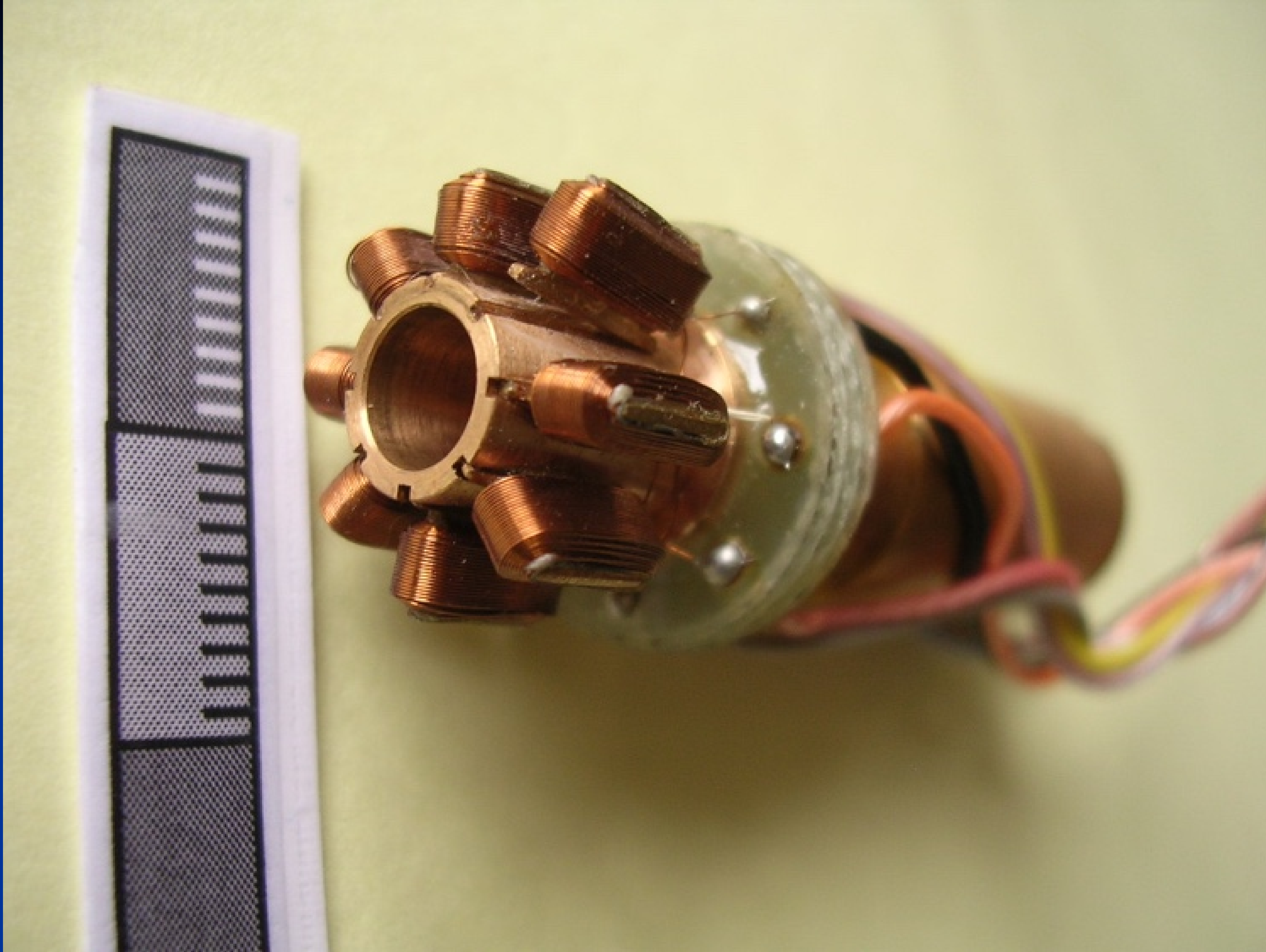


Specimen preparation –

Specimen: What characterization is all about.

the ultimate limit of resolution and detectability

General requirements:

thin, small, conductive, firm, dry

Various methods

Ultramicrotomy

Mechanical

Chemical

Ion

(Lucky for nano-materials work: Minimal preparation)

Contrast enhancement:

Staining, evaporation, decoration

Specimen support and specimen holders

Specimen support

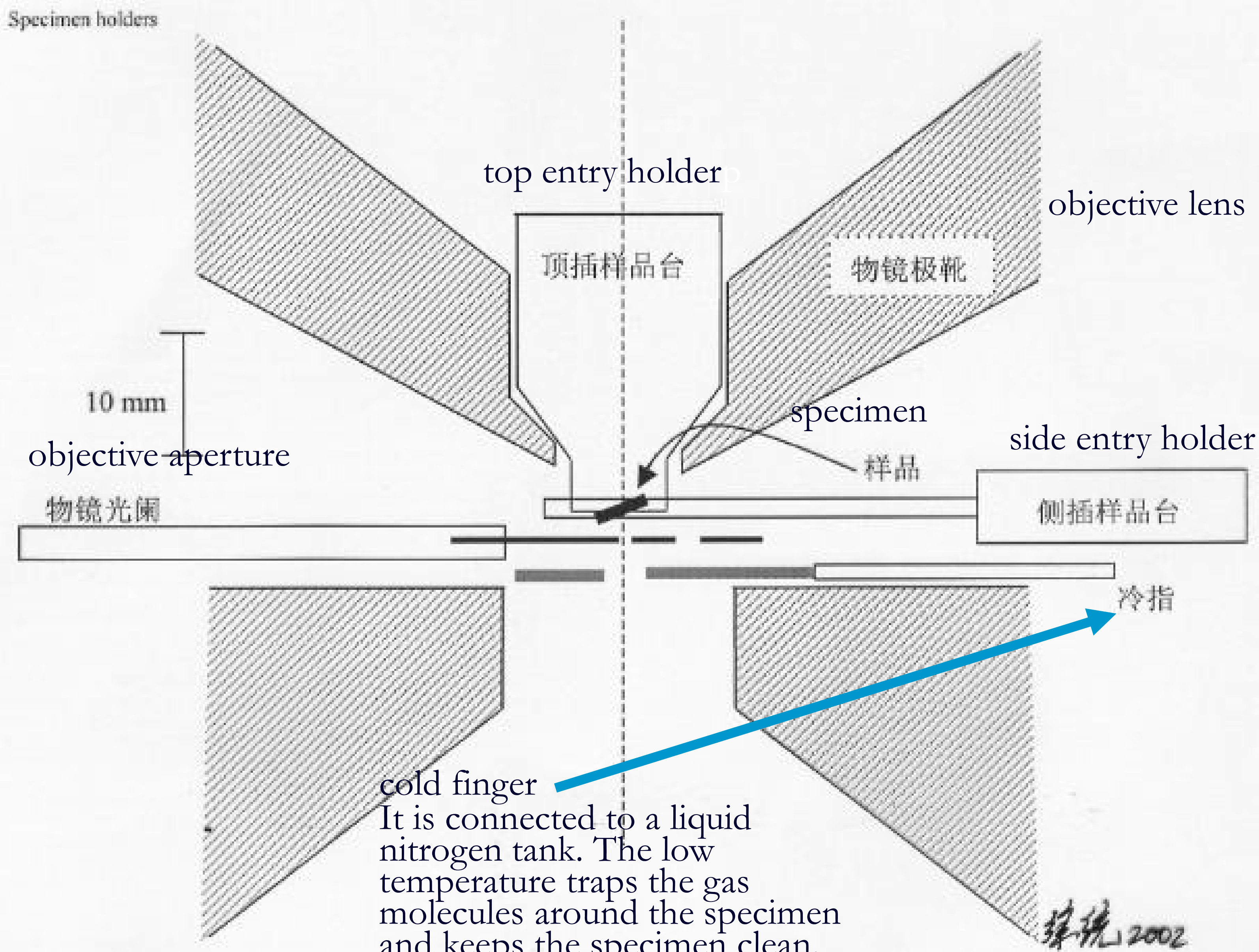
- Grid
- Holey carbon grid

Specimen holders:

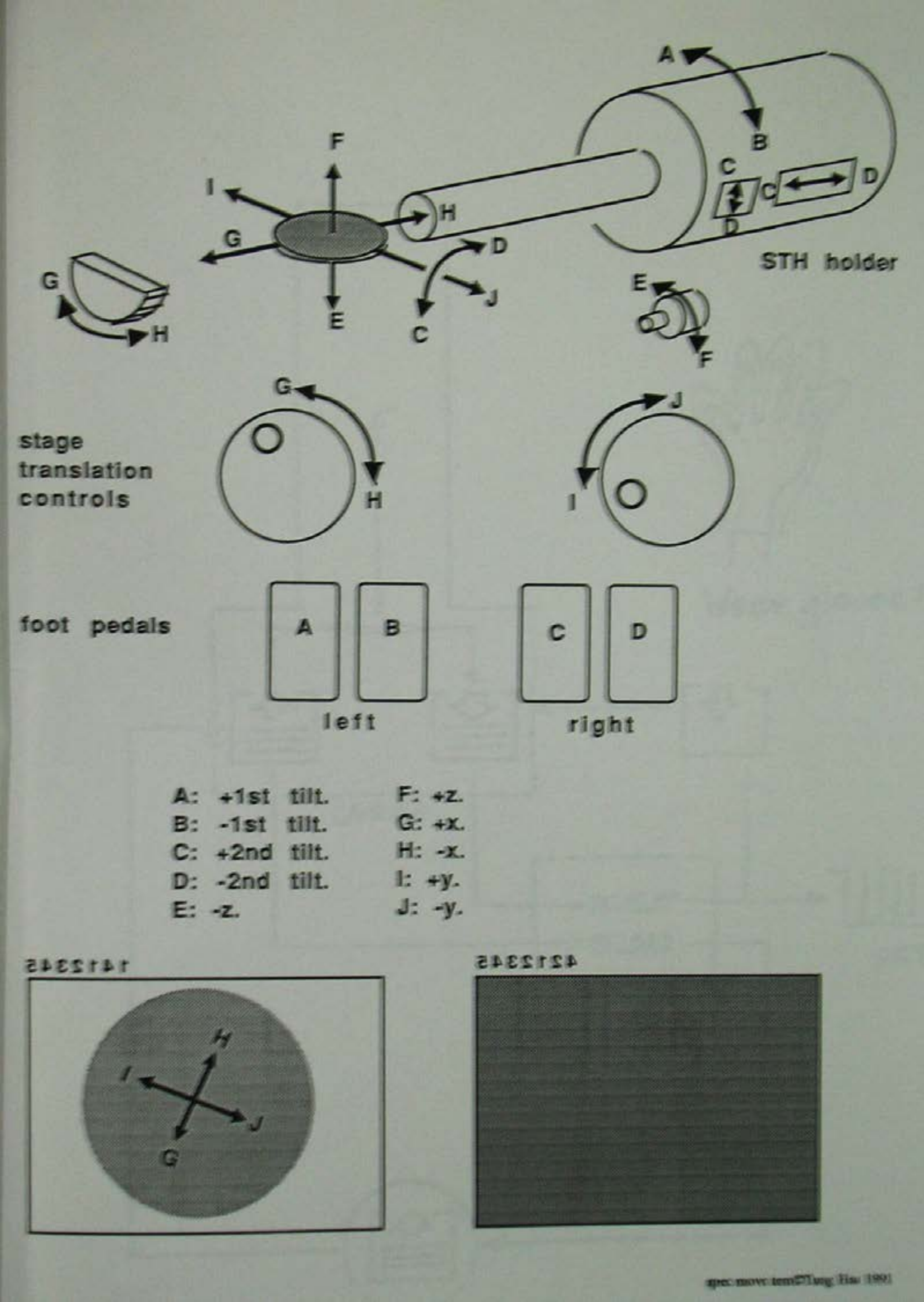
- Top entry
- Side entry
- Single/double tilt
- Heating, cooling, tensile, environmental, etc.

Performance:

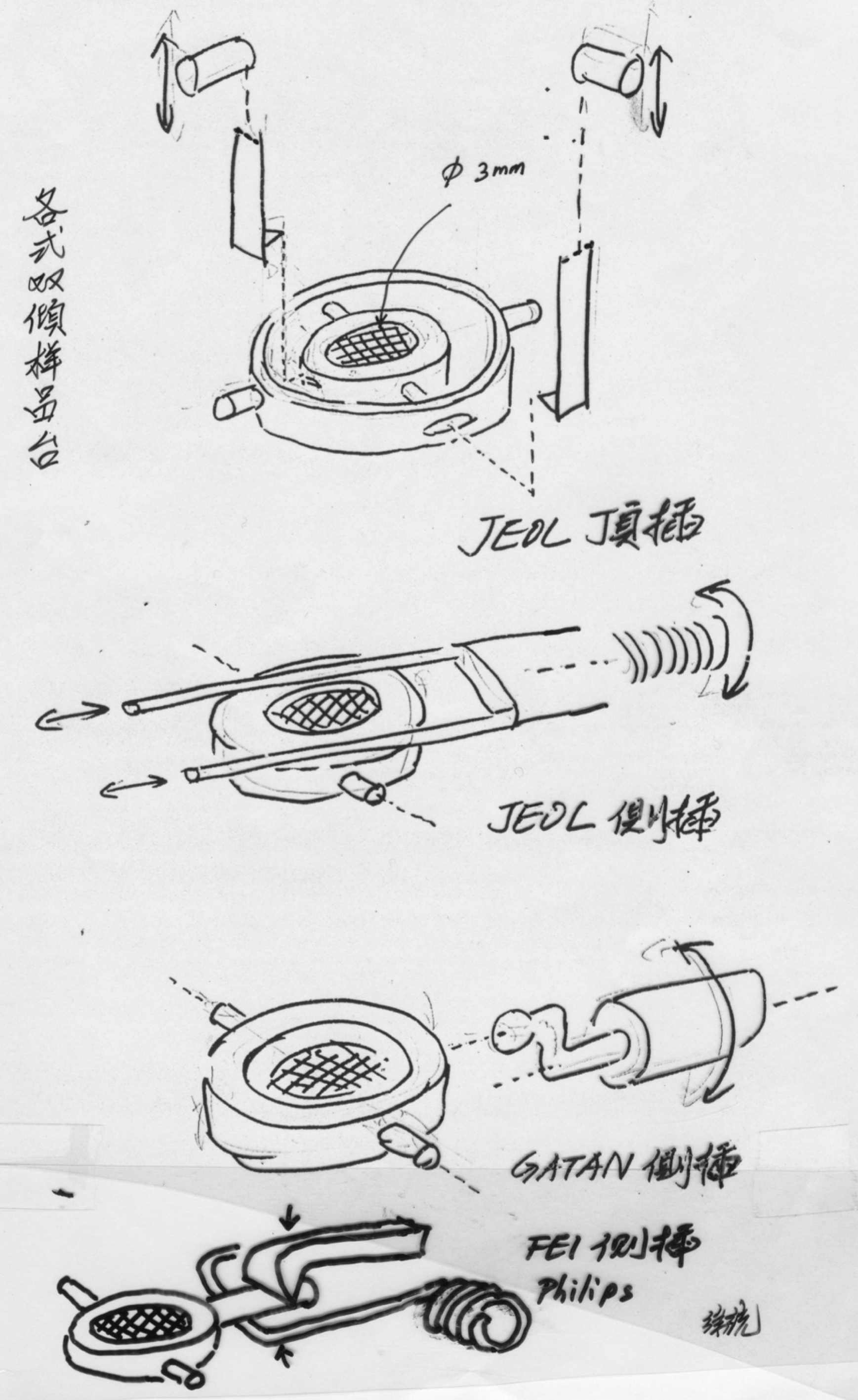
Tilt angle, working distance,



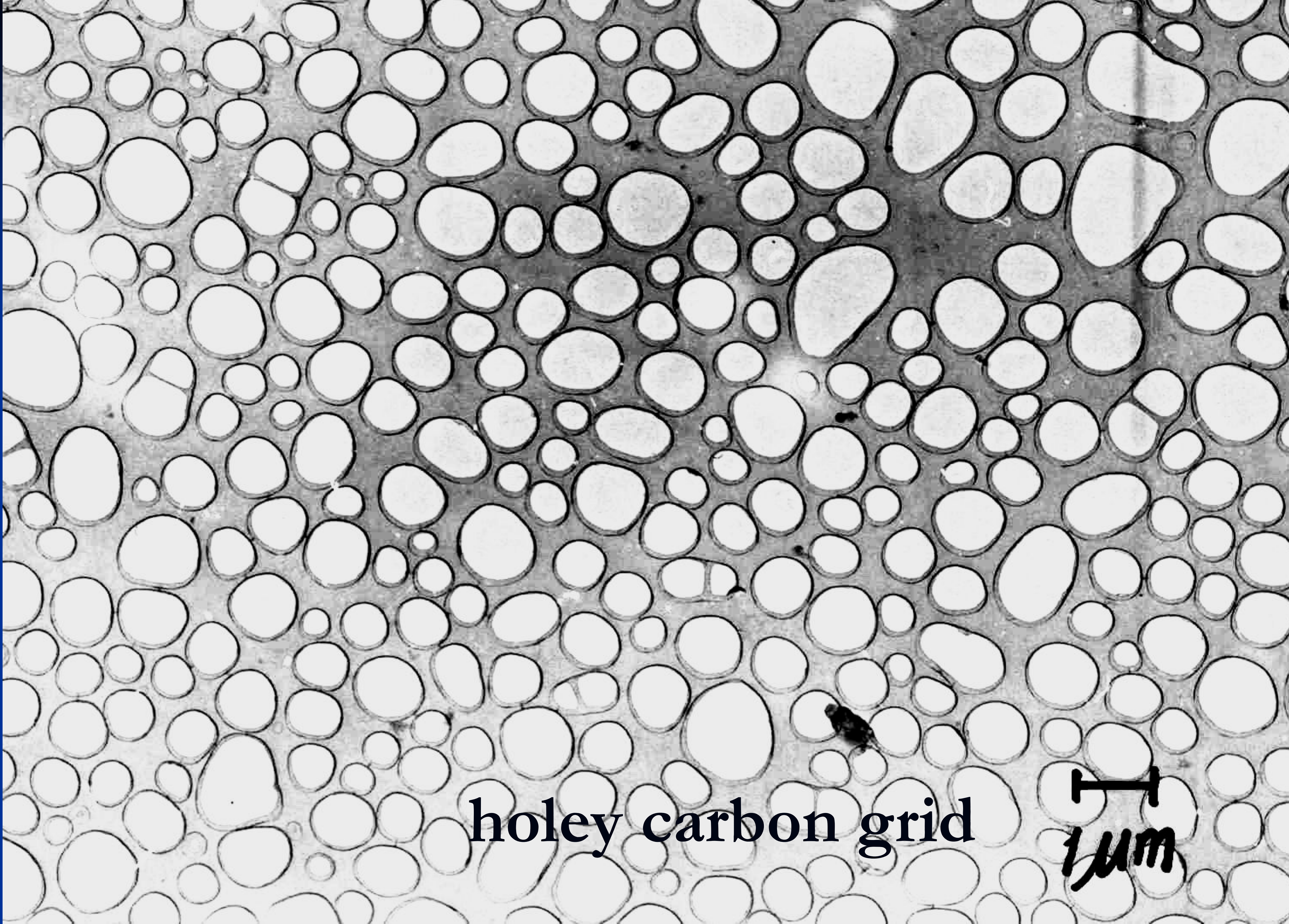
It is connected to a liquid nitrogen tank. The low temperature traps the gas molecules around the specimen and keeps the specimen clean. So it serves as a pump.



Movements and controls of the specimen



各式双倾样品台
φ 3mm
JEOL 顶插
JEOL 侧插
GATAN 侧插
FEI 侧插
Philips



holey carbon grid

correction:

The holey carbon grid used for supporting powder specimen is NOT made by carbonizing the organic film. Rather the holey organic film is coated with a thin film of carbon. The carbon coating provides electrical conductivity. Therefore it can be used under the electron beam. For high resolution electron microscopy the carbon coated organic film is often too thick as a support. Then the organic film is dissolved with a solution such as acetone, leaving only the very thin carbon film.

High Resolution Electron Microscope (HREM):

Approaching atomic resolution.

Requirements:

(Ultra) high resolution pole piece

Electronic stability

Mechanical stability

Clean environment: (Ultra) high vacuum

Specimen preparation: very very thin

In general HREM is needed for studying nano-materials.

VACUUM

三十輻共一轂當其無有車之用
埏埴以為器當其無有器之用
鑿戶牖以為室當其無有室之用
故有之以為利無之以為用

Thirty spokes share the wheel's hub;
It is the center hole that makes it useful.
Shape clay into a vessel;
It is the space within that makes it useful.
Cut doors and windows for a room;
It is the holes which make it useful.
Therefore profit comes from what is there;
Usefulness from what is not there.

Tao Te Ching, by Lao Tsu
Translation & Caligraphy by
Gia-fu Feng & Jane English

HIGH VACUUM = LOW PRESSURE

Why vacuum？
How to evacuate？
How to measure the vacuum？

Why the electron microscope has to be evacuated？

Stability of the speciman・
Filament life・
Sufficient mean free path of the electrons・
（for the required electron optical design.）

Physics of gases: Elastic gas molecules.
Constant motion of gas molecules,
colliding each others and walls of container.
System in equilibrium.
Negligible external force (magnetic, gravity).

Physical phenomena under various pressures:

Boyle's Law： $p_1V_1 = p_2V_2$ p：pressure V：volume

Gas Law： $pV = nRT$ n：number of moles
R：gas constant，8.314 J / K · mol
T：temperature

Number of molecules per unit volume at T and p：
$nA/V = p/(RT)$ A：Avogadro number，6.022×10^{23}

Unit of pressure： 1 Pa = 1 N/m^2

= 1.45 x 10^{-4} psi

= 7.50 x 10^{-3} torr (mm-Hg)

Mean free path L under pressure p torr ：

$L = 5 \times 10^{-5}/p$ (m)

Types of gas flow：

- Turbulent：irregular, many vortices.
- Smooth：regular, no vortices.
- Knudsen： L < tube diameter.
- Molecular：L > tube diameter;
  - Molecules do not interact with each others except collisions.
  - (such is the case inside the electron microscope.)

Pumping：
When evacuating a chamber one does not draw molecules. One allows gas molecules to diffuse out and prevent them from going back in.

Various pumps：mechanical, diffusion, turbo-molecular, ion, sorbtion….

Multi-state pumping is necessary for 10^{-3} torr or below.

Pumping rate： (torr)-liter/sec.

To maintain vacuum, keep on pumping to balance the leak and outgas.

leak： (torr)-liter/sec.

outgas： torr-liter/cm^2-sec.

measurement of vacuum：

based on physical phenomena at various pressure.

Vacuum (pressure) gauges：

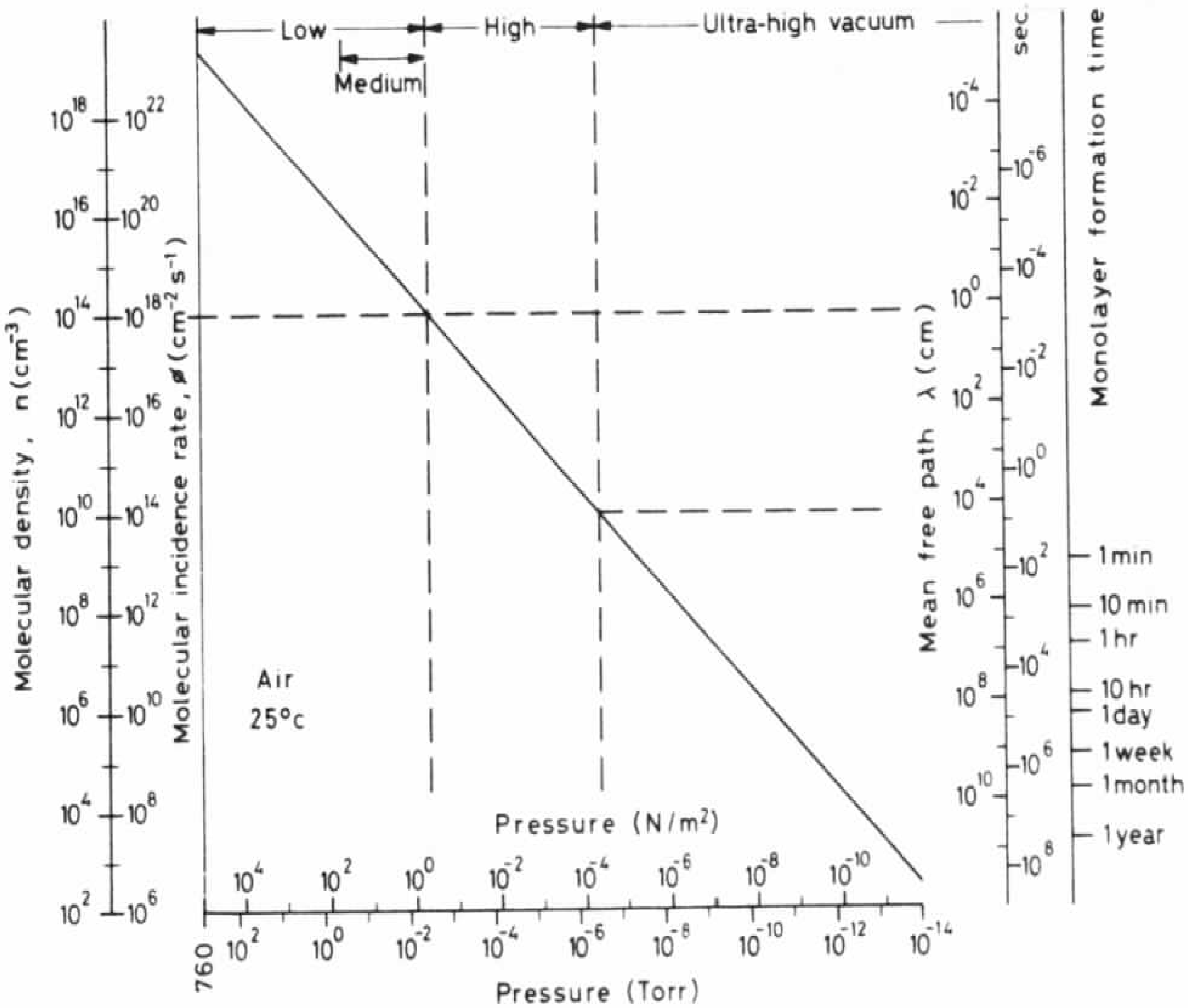
Mercury column, thermo couple, ionization current.

Maintain good vacuum：

Instrument design and operation procedure.

Operator’s good practice and skill.

Environment of the lab.



... degree of vacuum.

Pressure (Torr)

degree of vacuum.

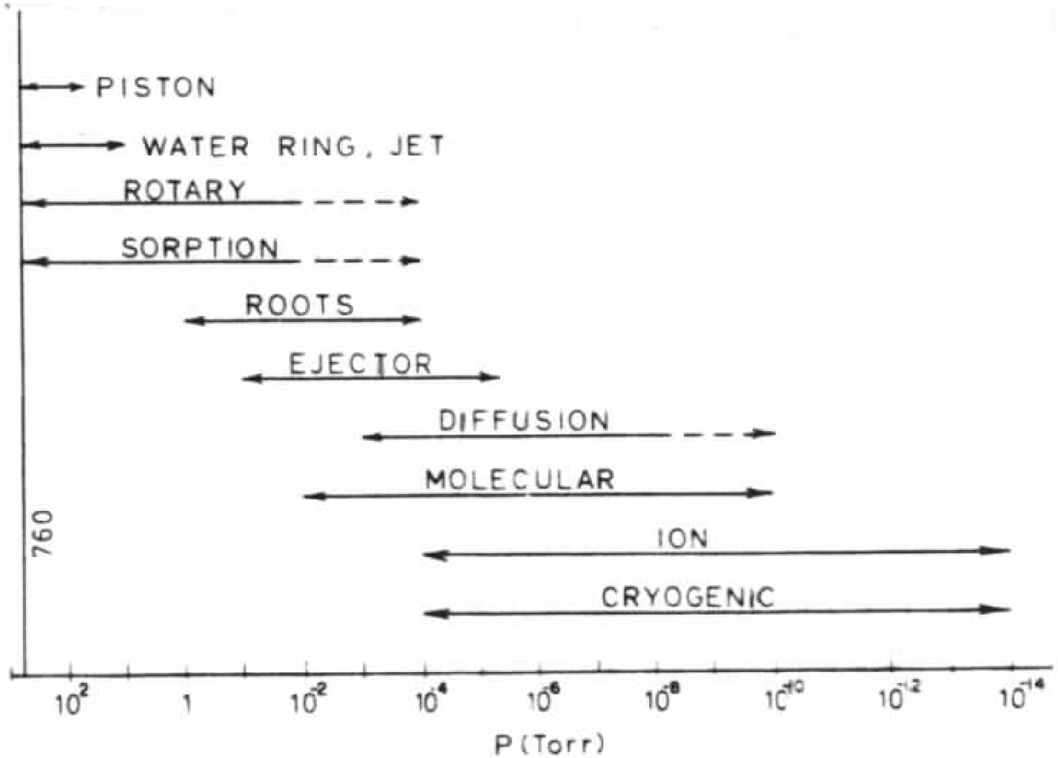


Fig. 5.1 Pressure ranges of vacuum pumps.

MEASUREMENT OF LOW PRESSURES

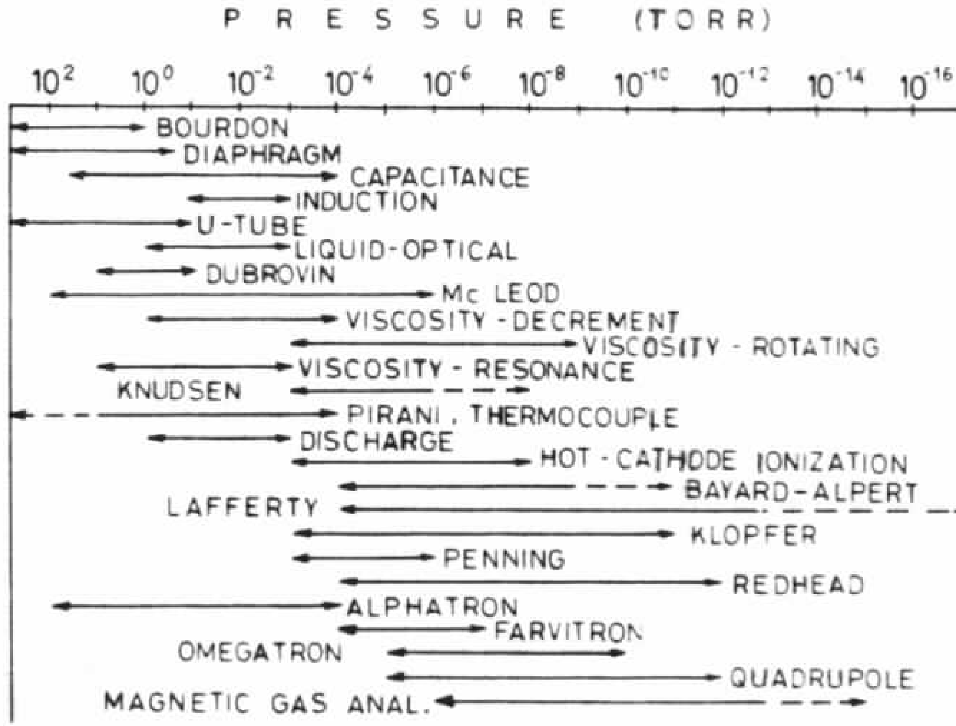
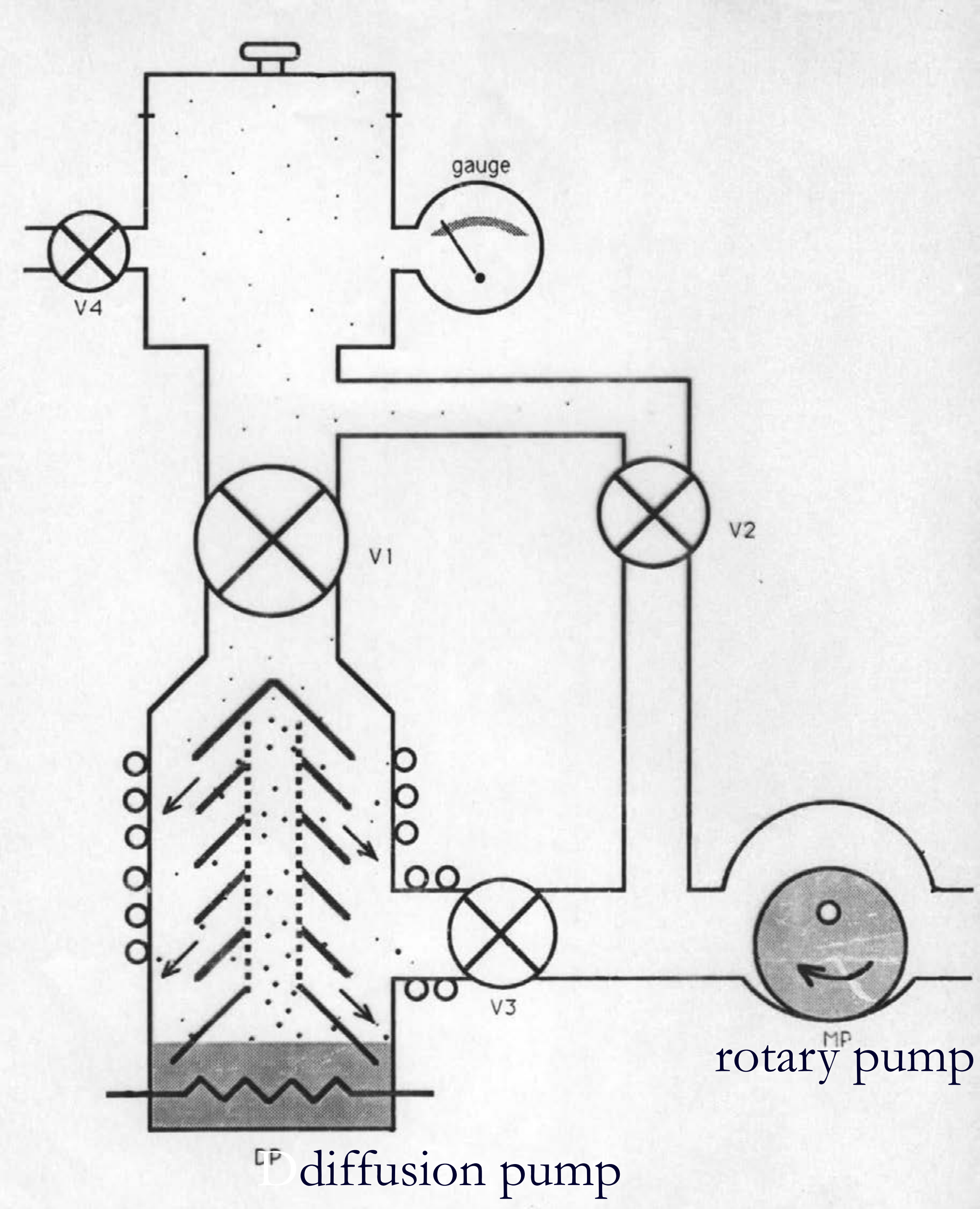
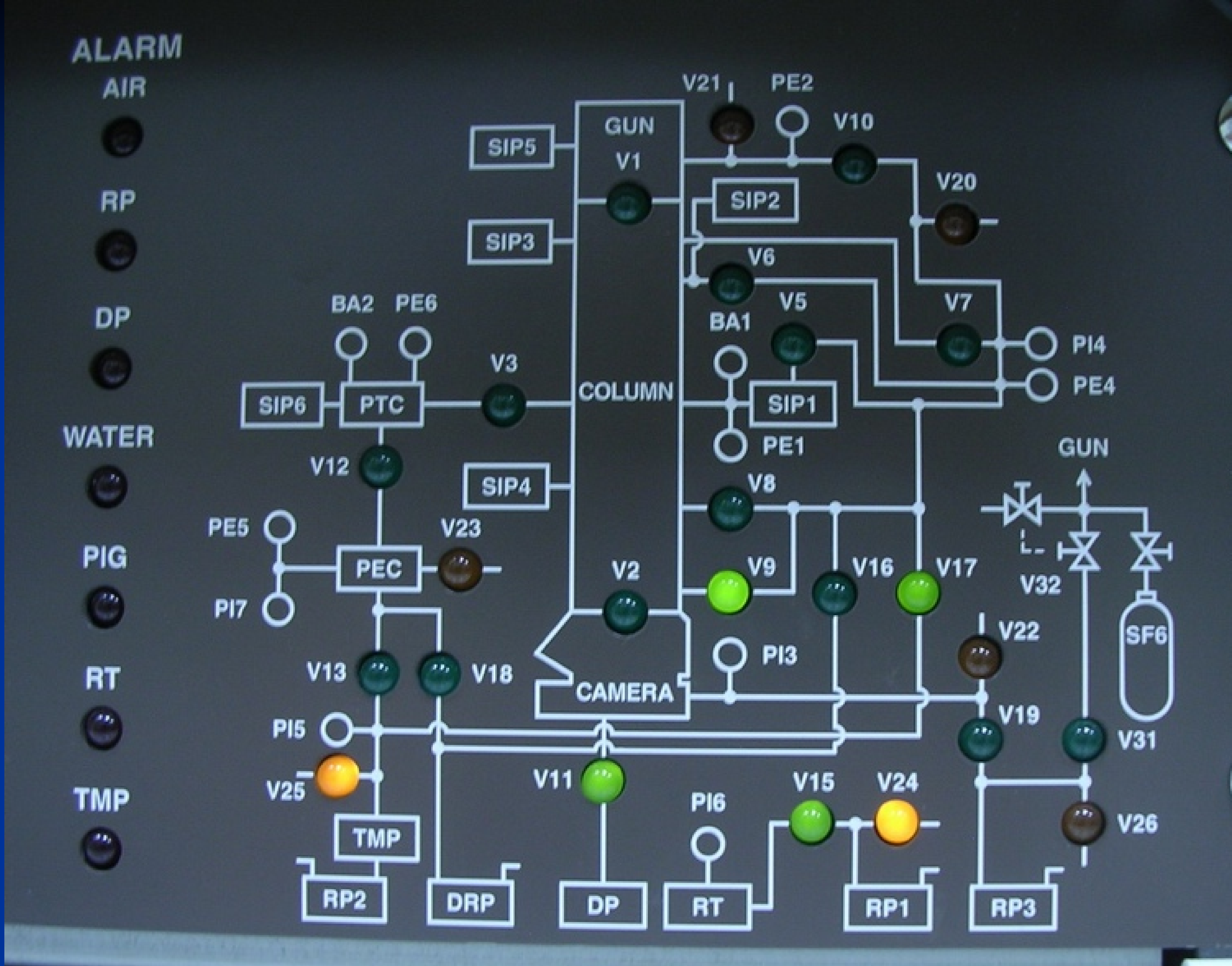
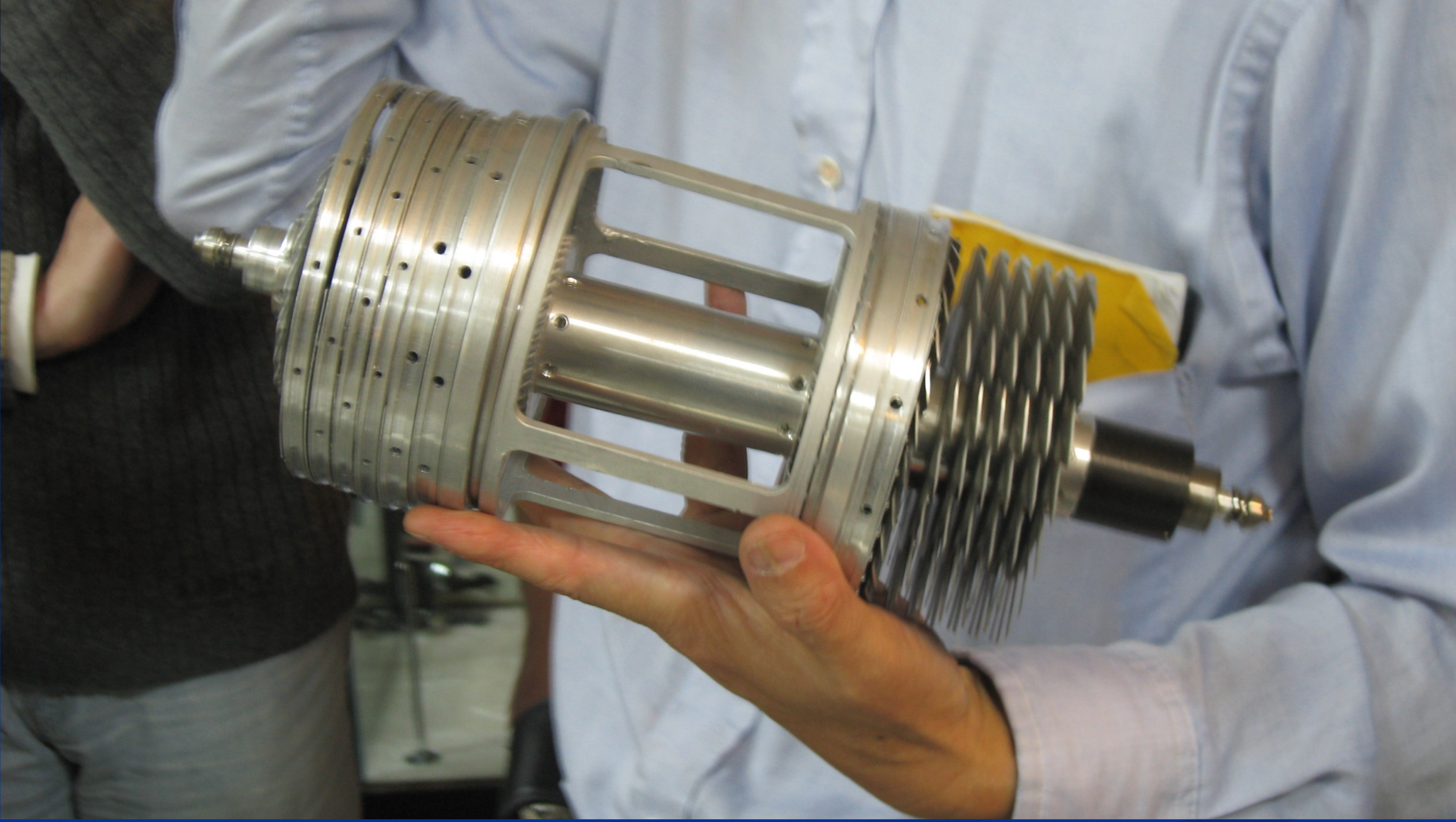


Fig. 6.1 Pressure ranges of vacuum gauges.

A. Roth. "Vacuum Technology", 2nd ed.
1982 North Holland.


gauge
V4
V1
V2
V3
MP
DP
rotary pump
diffusion pump


ALARM
AIR
RP
DP
WATER
PIG
RT
TMP
SIP5
GUN
V1
V21
PE2
V10
V20
SIP2
SIP3
V6
V5
V7
BA1
PI4
PE4
BA2
PE6
V3
COLUMN
SIP1
SIP6
PTC
PE1
V12
SIP4
GUN
V8
PE5
V23
PEC
V2
V9
V16
V17
V32
PI7
V22
SF6
PI3
V13
V18
CAMERA
V19
PI5
V31
V11
V25
V15
V24
PI6
V26
TMP
RP2
DRP
DP
RT
RP1
RP3



A turbo pump

scanning electron microscope (SEM)

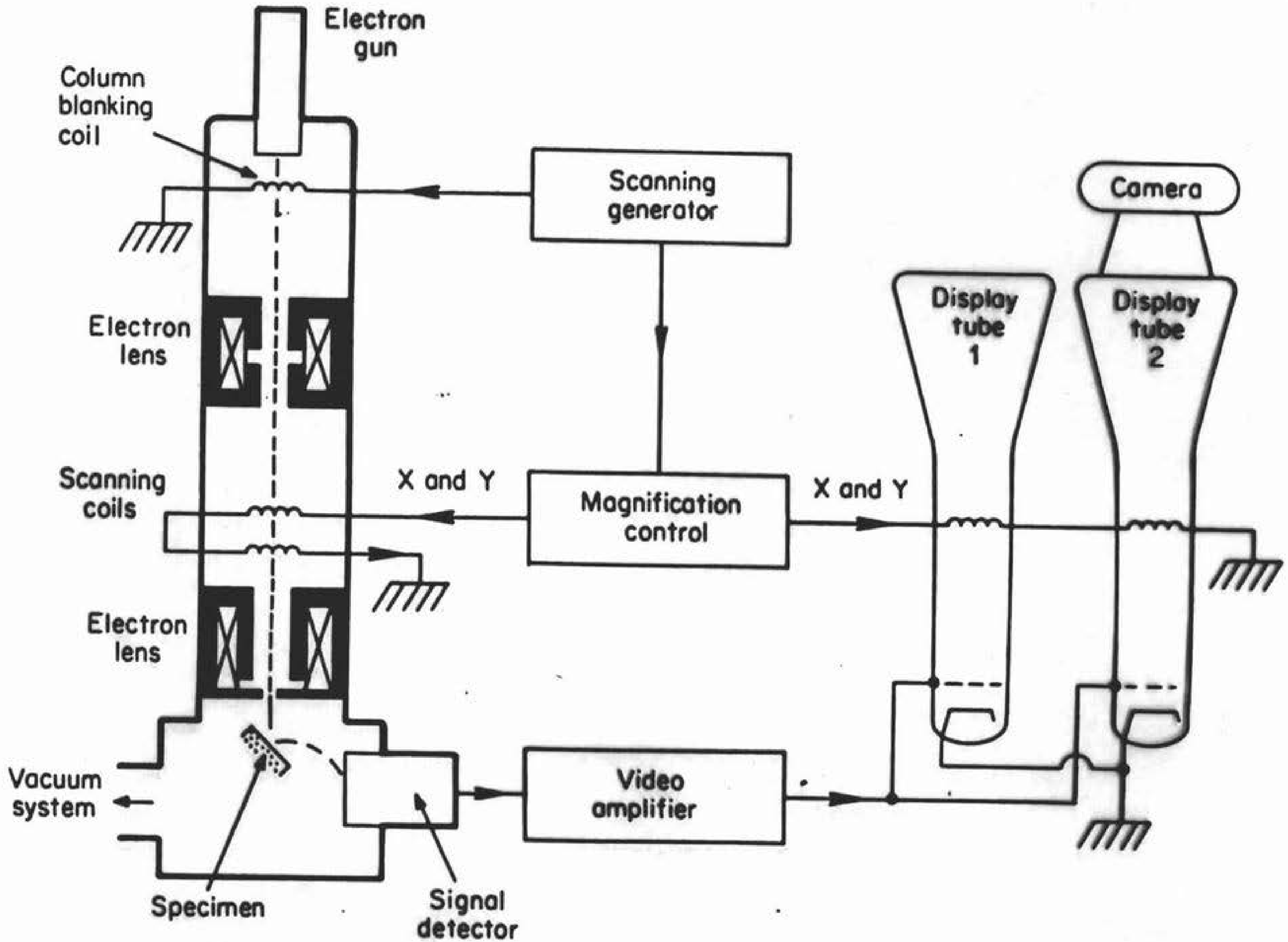


FIG. 1.2 Scanning electron microscope.

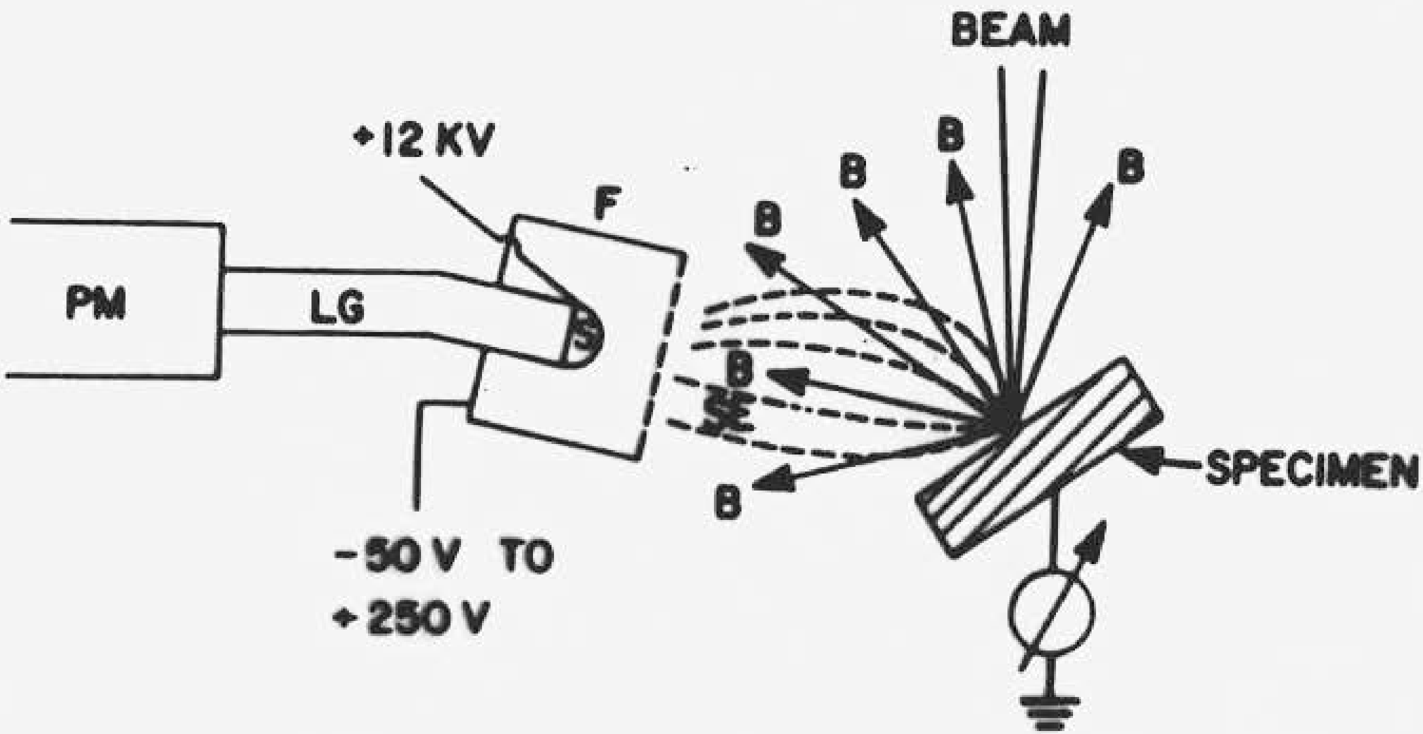
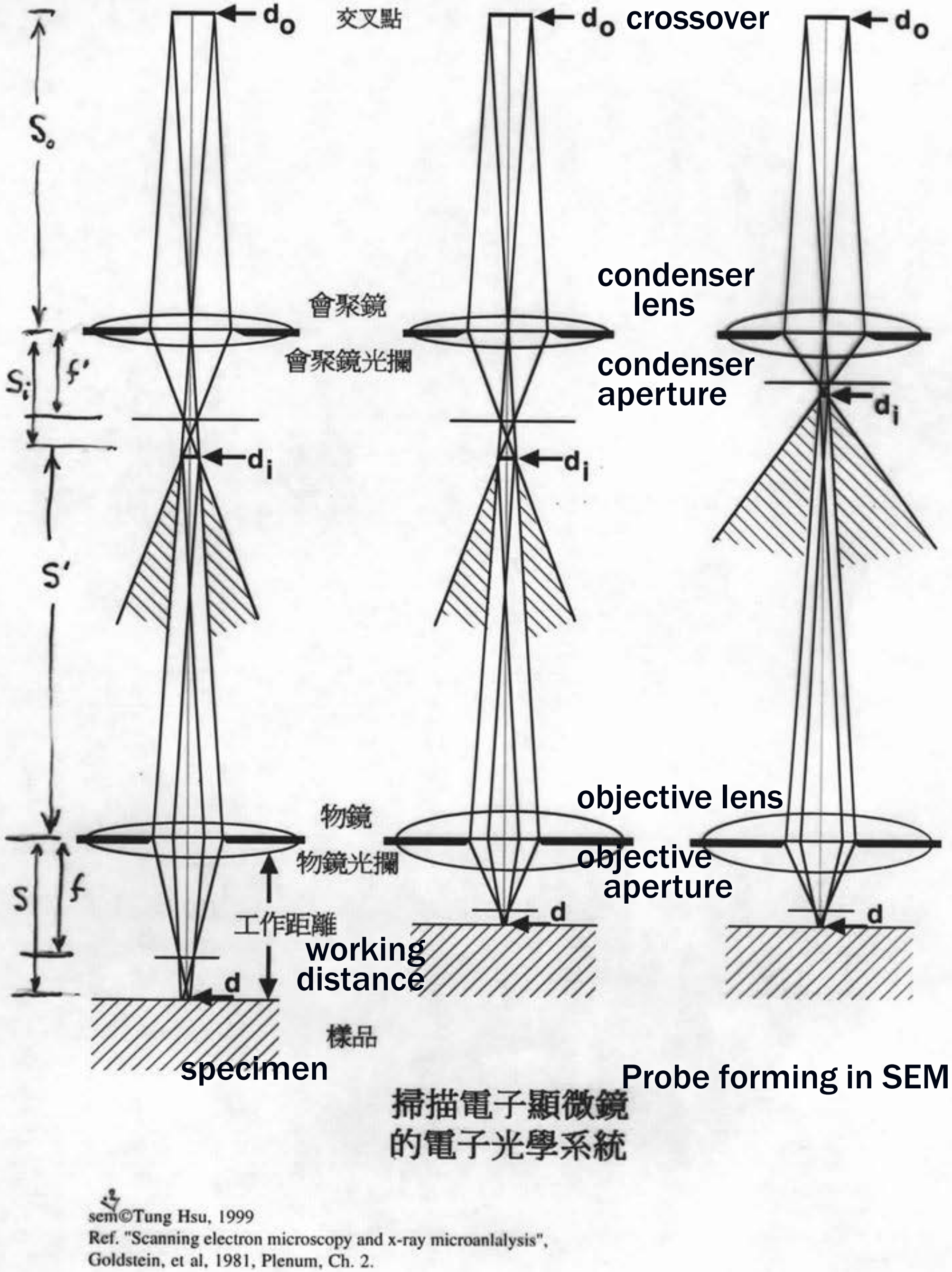


Figure 4.17. Schematic diagram of Everhart–Thornley scintillator–photomultiplier electron detector. B, backscattered electron; SE, secondary electron; F, Faraday cage; S, scintillator; LG, light guide; PM, photomultiplier.



Scanning electron microscopy – microprobe

Beam/specimen interaction: When the specimen is thick, "semi-infinite".

Monte Carlo simulation

The probe forming system:

- Forming a small probe is the same as forming a small spot in the image
- The column

Contrast mechanism:

- Secondary electrons
- Back scattered electrons
- Other signals

Resolution:

- Low mag: limited by scan rate
- High mag: limited by lens defects – same as TEM

Detector

Examples of SEM images

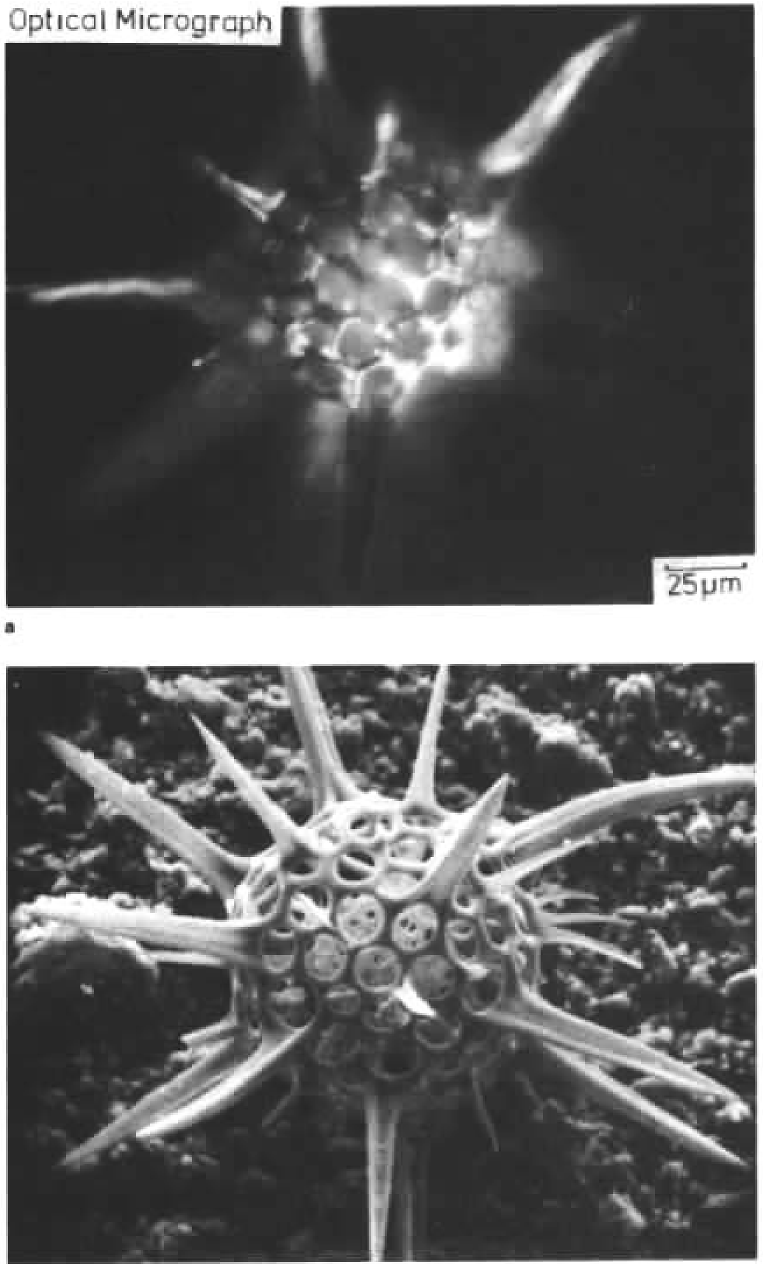
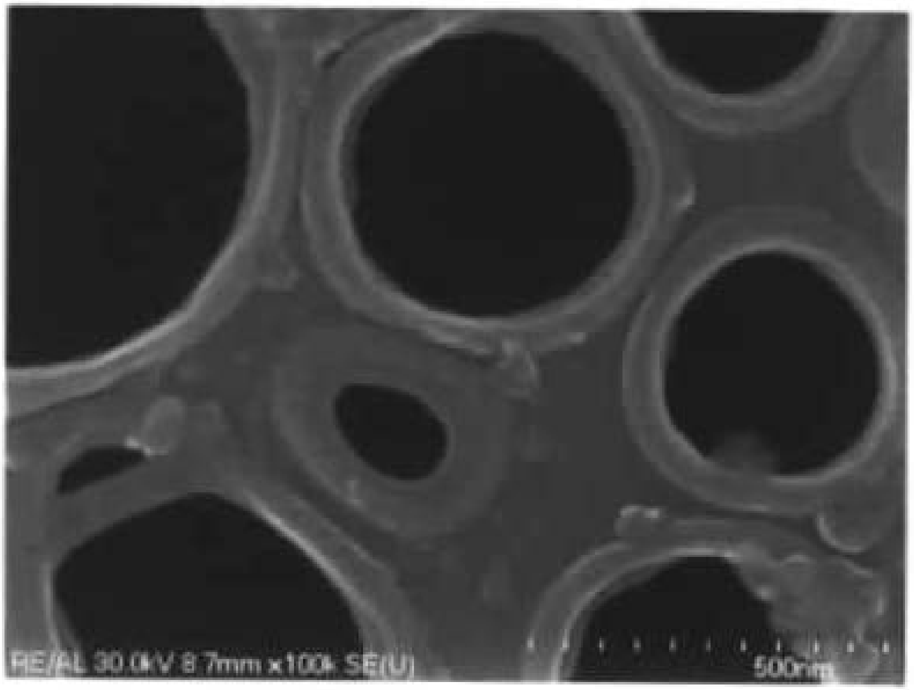
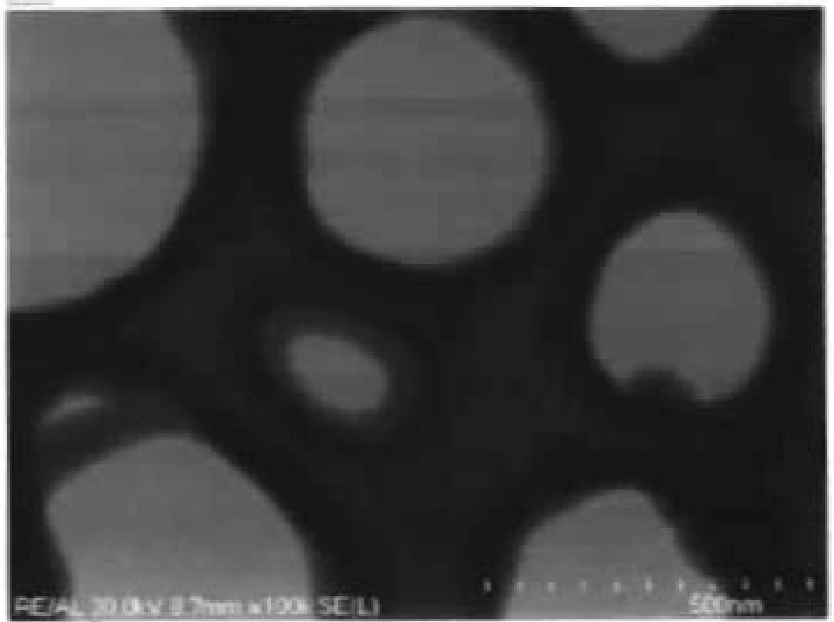


Figure 1.3. (a) Optical micrograph of the radiolarian *Trochodiscus longispinus*. (b) SEM micrograph of same radiolarian. The greater depth of focus and superior resolving capability of the SEM are apparent.





, 2001 (Hitachi S-4700)

	SEM			TEM		
E (kV)	10	20	30	100	200	400
λ (Å)	0.122	0.0859	0.0698	0.037	0.025	0.0126
Cs (mm)	10-20			1-3		
Resolution:	beam size			image point size		
	$r = \lambda^{3/4} Cs^{1/4}$			$r = \lambda^{3/4} Cs^{1/4}$		

The following material was not covered.

Electron microprobe / Analytical electron microscopy:
(EPMA)

Energy dispersive (X-ray) spectrometer, EDS (EDX)
Wavelength dispersive (X-ray) spectrometer, WDS (WDX)
Electron energy loss spectroscopy, EELS
Quantitative analysis
etc.

Ref. Dr. Yoshi Iizuka
Institute of Earth Science
Academia Sinica
He has two cutting edge EPMAs.

		Co	Ni	Te	I
Mendeleev:	A =	58.9	58.6	127.7	126.9
Moseley:	Z =	27	28	52	53

Parameter	$n\lambda$	$2d$	$\sin\theta$
diffraction	known	calculated	measured
spectrometry(WDS)	calculated	known	measured
spectrometry(EDS)	E: measured		

$E = hc/\lambda$, $\lambda = C'(Z - \sigma)^{-2}$ (for the same spectral line, $K\alpha$, $K\beta$, ...)

Instrumentation: Electron probe/microscope

Other particle beam

x-ray fluorescence

radioactive sources

WDS: X-ray optics

regular crystals ⇒ O and up

"soap" film crystals ⇒ Be and up

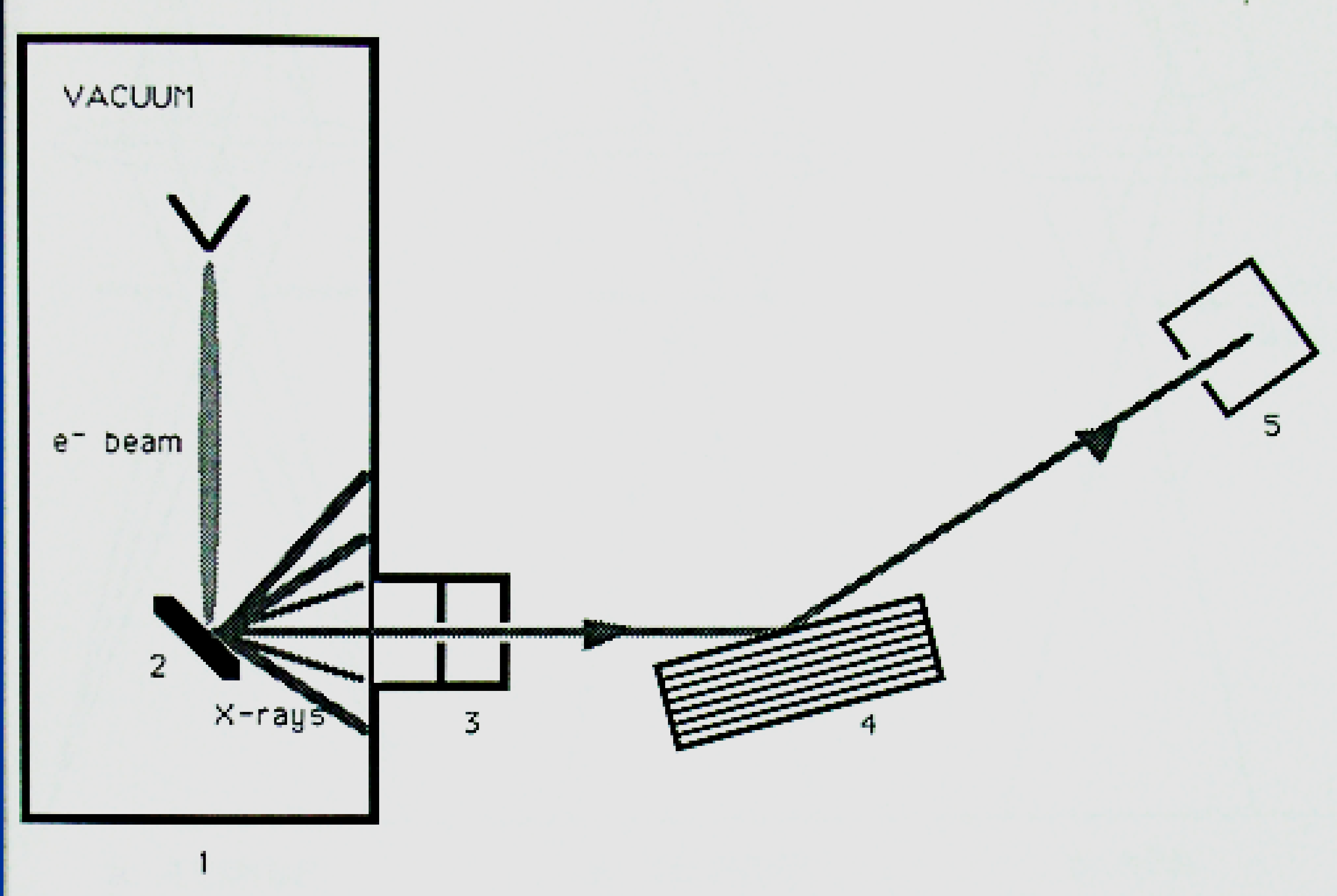
EDS: Si(Li) detector

Multi-channel analyzer (MCA)

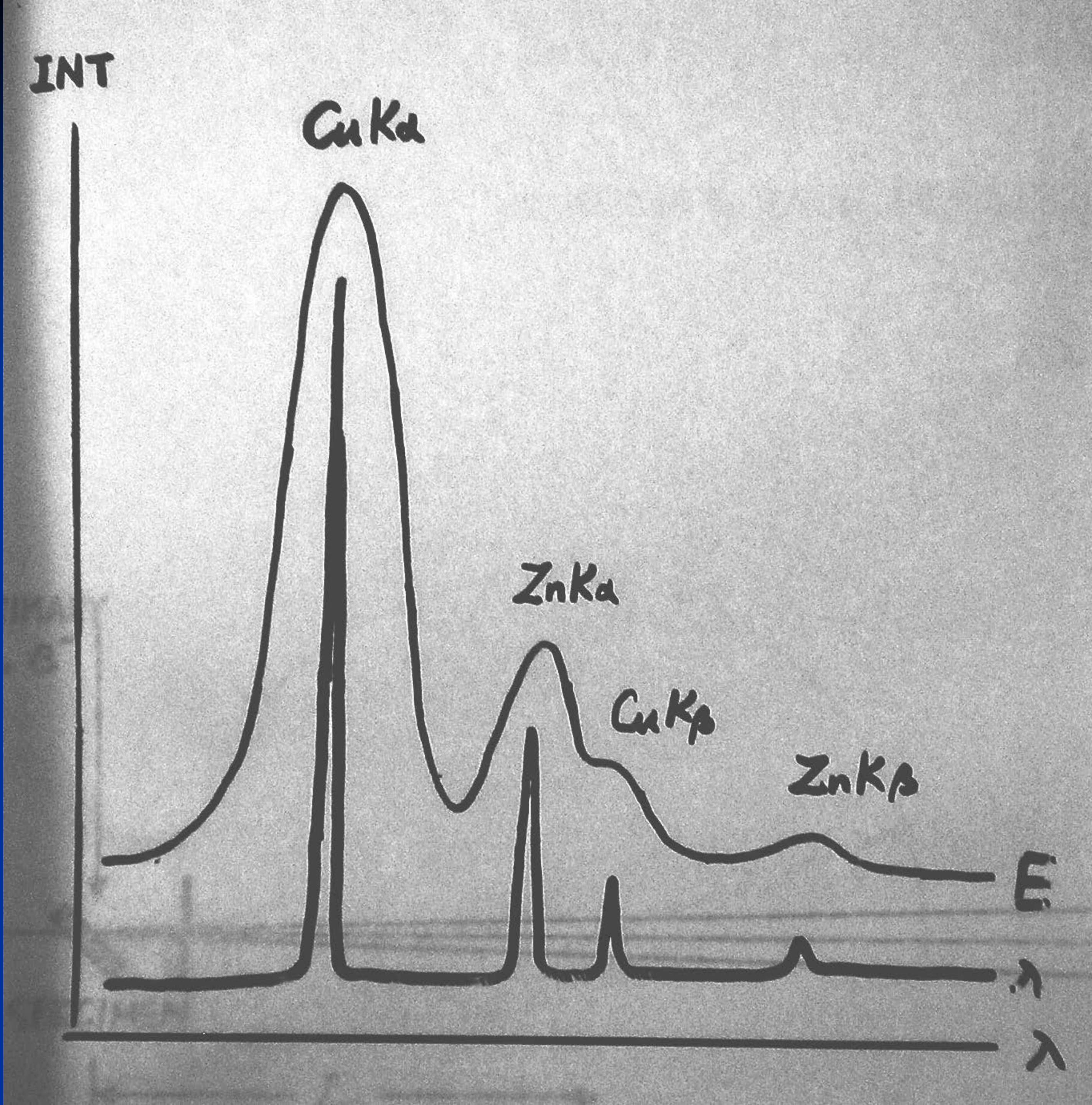
Be window ⇒ Na and up

Ultra-thin window or Windowless ⇒ B and up

Dead layer in Si(Li) detector is the limit



XRD and WDS



E

EPMA at NTHU

Microscopy Society of America Position on Ethical Digital Imaging

RESOLUTION carried as follows: Be it resolved that the MSA position on digital image processing be approved as follows:

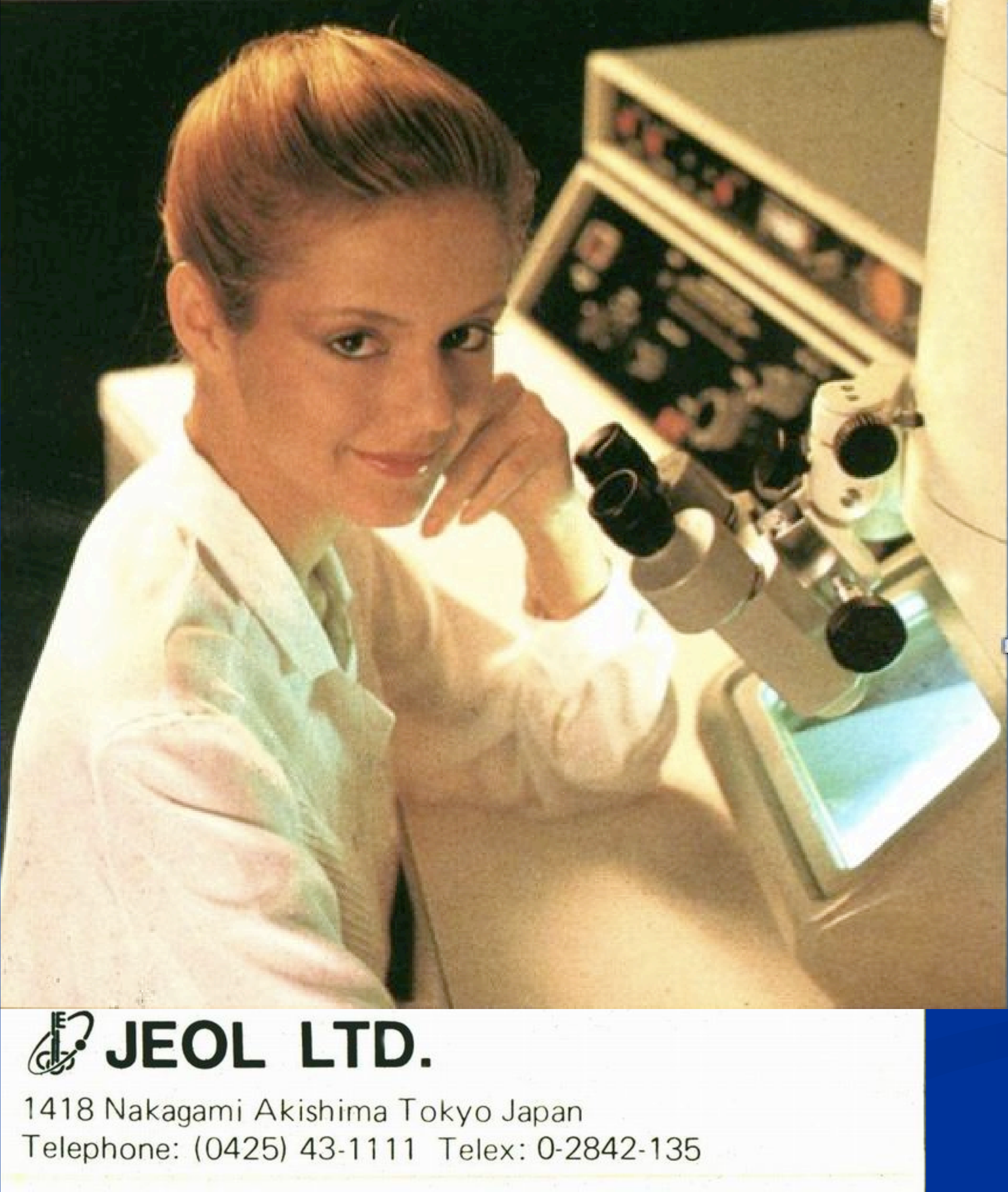
"Ethical digital imaging requires that the original uncompressed image file be stored on archival media (*e.g.*, CD-R) without any image manipulation or processing operation. All parameters of the production and acquisition of this file, as well as any subsequent processing steps, must be documented and reported to ensure reproducibility.

Generally, acceptable (non-reportable) imaging operations include gamma correction, histogram stretching, and brightness and contrast adjustments. All other operations (such as Unsharp-Masking, Gaussian Blur, *etc.*) must be directly identified by the author as part of the experimental methodology. However, for diffraction data or any other image data that is used for subsequent quantification, all imaging operations must be reported."

MSA 2003 Summer Council Meeting Minutes

Microscopy Today, 11:6(2003)61.

Protect your eyes. They are the most versatile, responsive, precious, and beautiful optical instrument in the world.




I GUESS I'M FINALLY BEGINNING TO REALIZE THAT YOU'LL ALWAYS LOVE YOUR ELECTRON MICROSCOPE MORE THAN YOU'LL EVER LOVE ME...
Inspired by Mr. Charles Schulz